Welcome to the 8th International Conference on Highly Frustrated Magnetism

HFM 2016

National Taiwan University,
September 7th to 11th
This event is organised with the kind help of National Taiwan University:

National Taiwan University

This event is sponsored by:

Alere

APS physics

APCTP

Journal of Physics

Condensed Matter

NSRRC

Ministry of Science and Technology, R.O.C.

NCTS

Department of Information and Tourism

Quantum Design Southeast Asia

http://www.ntu.edu.tw/english/

http://www.alere.com

https://www.aps.org/

https://apctp.org/

http://iopscience.iop.org/journal/0953-8984

http://www.nsrrc.org.tw/


http://cts.nthu.edu.tw/


http://www.qd-sea.com/
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<thead>
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<th>Activity</th>
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<td>Welcome</td>
<td>NTU Convention Center</td>
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<td>18:00 - 20:00</td>
<td>Banquet</td>
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1 ORGANISERS

ORGANISING COMMITTEE

• Jason S Gardner (Chair)
• Ying-Jer Kao (Local Host)
• Leih-Jeng Chang
• Chao-Hung Du
• Jiunn-Yuan Lin
• Way-Faung Pong

SCIENTIFIC PROGRAMME EDITOR

• Laura Bovo

ADMINISTRATIVE SUPPORT

• Chia-Chi Liu

CONFERENCE SUPPORT

• Hanz Peng

CONTACT

hfm2016@gmail.com

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L. Balents
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B.D. Gaulin

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R.K. Kremer
M. Mila

R. Moessner
S. Nakatsuji
P. Schiffer
H. Takagi

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Z. Hiroi
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B. Lake
P. Mendels
I. Mirabeau

S. Onoda
O. Petrenko
K. Ross
T. Sato
N. Shannon
R. Stewart
O. Tchernyshyov
C. Wiebe (Co-Chair)
# SPEAKERS

## PLENARY SPEAKERS

- L. Balents
- Y. Tokura
- S.T. Bramwell
- B.D. Gaulin
- H. Takagi

## INVITED SPEAKERS

- P. Armitage
- S. Bhattacharjee
- C. Castelnovo
- M. Fu
- B. Grenier
- S. Grigera
- G.Y Guo
- A. Hallas
- G. Jackeli
- K. Kanoda
- Y.-B. Kim
- S.-H. Lee
- J.-Y. Lin
- Y. Matsuda
- S. Nagler
- J.-G Park
- S. Petit
- O. Petrenko
- N. Shannon
- L. Savary
The 2016 International Conference on Highly Frustrated Magnetism will be held at the GIS Convention Center at National Taiwan University, Taipei, Taiwan from September 7th-11th. This international conference will be preceded by a school on the study of magnetic materials, using large facilities hosted by the National Synchrotron Radiation Research Center which recently saw first light on its 3 GeV ring. During HFM 2016 we hope to be presented with many excellent talks and posters focusing on recent developments in the study of frustration in magnets. Approximately 60 oral presentations and 150 posters will be reporting on experimental and theoretical studies carried out over the past few years. This conference follows in the now regular series, which began in 2000 by Prof Michel Gingras and friends at Waterloo, Canada and has been followed by HFM 2003 (Grenoble, France), HFM 2006 (Osaka, Japan), HFM 2008 (Braunschweig, Germany), HFM 2010 (Baltimore, USA), HFM 2012 (Hamilton, Canada) and HFM 2014 (Cambridge, England). We hope you enjoy and learn as much from this meeting as we have all done in the past gatherings of this community.

The GIS center is in the South East side of National Taiwan University, Taiwan’s most prestigious University. It is made up of 11 colleges, 54 departments, 103 graduate institutes and 4 research centers spread over 6 campuses. The university is made up of over 30,000 students, roughly 50% of which are graduate students. We are on the main campus of NTU in Taipei City, the capital of Taiwan. Taipei is the political, economic, educational, and cultural center of Taiwan and a very safe city even with its 7 million inhabitants. I hope you all enjoy the meeting as well as the city life Taipei has to offer and most of all, I hope the rain, if any, doesn’t spoil our week in this Asian metropolis.

Jason S Gardner
HFM 2016 Conference Chair
National Synchrotron Radiation Research Center
National Taiwan University
The conference will take place in GIS Convention Center at National Taiwan University, Taipei, Taiwan from September 7th-11th. The lectures will be held at the Forum (main theater). The poster session will be in Plato and Archimedes halls. The special event meet the editors will take place in Aristotle hall.
The closest metro (MRT) station to the conference site is Gongguan Station. This is on the south side of Taipei and National Taiwan University. It is on Line 3 (Green line) of the MRT system. Take the exit 2 and make a left when you reach the surface. Keep walking for 5 mins and the red brick building on the left is the NTU student activity center. The GIS convention center is located in the basement.

**Bus Stop Name:**
National Taiwan University of Science and Technology
GIS NTU convention center
Taipower Building
MRT Gongguan Station
National Taiwan University
Section 3, Roosevelt Rd
Section 4, Keelung Rd
Section 3, Roosevelt Rd
Section 2, Xinhai Rd
Zhoushan Rd
Section 4, Tingzhou Rd
Section 3, Tingzhou Rd
Gongguan Station, Exit 2
Songshan-Xindian Line (Line 3): 254
MRT Gongguan Station (Roosevelt Rd.): 254
MRT Gongguan Station (Exclusive Bus Lane to Western District): 0 South, 1, 109, 208, 208 Shuttle, 208 Express, 236, 251, 252, 253, 278, 284, 284 Express, 290, 52, 642, 643, 644, 648, 660, 671, 672, 673, 676, 74, 907, Jingmei-T.V.G.H Express, BR12, G11, G13, BL28
MRT Gongguan Station (Exclusive Bus Lane to Xindian District): 207, 278, 280, 280 Express, 284, 311, 505, 530, 606, 668, 673, 676, Songliang Main Line, Songjiang-Xinsheng Main Line, Dunhua Main Line, BL28
Gongguan Station (Roosevelt Rd. & Keelung Rd. Intersection): 671
Gongguan Station (Keelung Rd.): 1, 207, 254, 275, 650, 672, 673, 907, NS-Shuanghe
Section 2, Ren’ai Rd Station: 214, 248, 606
XinYi-HangZhou Intersection Station (to Taipei 101): 0 East, 20, 22, 204, 670, 671, XinYi Main Line, XinYi New Main Line, 1503

**Driving**
Located on Roosevelt Rd., across from Gongguan ShuiYuan Market, near Roosevelt & Keelung Rd. Intersection
National Highway 1: Exit at Yuanshan IC, and head south on Jiahu Elevated Rd. Take the exit at Heping Rd, and continue Xinhai Rd. Take the right turn onto Keelung Rd, and turn right again onto Roosevelt Rd to drive into the indoor car park at 2nd Student Activity Center
National Highway 3: From National Highway 3A, exit at Xinhai Rd. Head to Keelung Rd, and turn right onto Roosevelt Rd to drive into 2nd Student Activity Center Car Park
Lunch will not be served at the conference site except on 9/9 when lunch-boxes will be served after the excursion. There are plenty of restaurants in the Gong-Guan area, and many places provide English menus. On the NTU campus, there are also many student cafeterias and eateries within walking distance from the conference venue.

HFM 2016 Food Map

1. 茄子 Aubergine (J-Curry)
2. 筷子 Chopstix (C)
3. 歐亞 Gugo kitchen (W)
4. 麗德羅莎 Ponderosa(W)
5. Subway (W)
6. 魯山人 Sukiyaki (J)
7. 莫凡彼 Movenpick Café (S,W)
8. 2F, Lacuz (Thai Fusion Cuisine)
9. 義饗食堂 Just Italian (W)
10. CoCo 一番屋咖哩 (J-Curry)
11. 學生餐廳 Student cafeteria (C)
12. 鹿鳴廣場 Lu-Ming Square (C, S)
13. 學生餐廳 Student cafeteria (C)
14. 小滝 2F Xiao-Fu cafeteria (C)
15. 福華文教會館 Howard Intl House (C,W)
16. 牛肉麵 Beef noodle soup (C)
17. 鳳城燒臘 Cantonese BBQ (C)
18. 温州街 Wen-Zhou St.
   Coffee shops and eateries (C, J, S, W)
19. 汀洲路3段及公館夜市
   Sec. 3, Ting-Zhou Rd & Gongguan

(C) Chinese (T) Taiwanese (J) Japanese (W) Western (S) Snack
Taipei city is located in northern Taiwan with 7 million population in the greater metropolitan area. As both the political and financial center of Taiwan, Taipei is the perfect mixture of ancient and modern worlds. Incense-veiled temples dating back several hundred years ago blend seamlessly with a neon street life of a decidedly more modern era. You can transcend through time by leaving the modern skyscraper Taipei 101 and reaching the centuries-old Longshan Temple with a short subway ride. Taipei has dozens of world-class restaurants where gourmets can sample the best regional Chinese cuisines; there are also plenty of night markets serving up scrumptious evening snacks in an environment of excitement and fun.

Minutes from the heart of the city, you can soak away the cares of the world in mineral-rich hot springs nestled in the mountain foothills ringing the Taipei Basin. Throughout the city there are plenty of trails, parks, and other oases of tranquility to lift and invigorate your spirits.

The best way to tour Taipei is to use the public transportation. Most places in the city center are within a 20-minute walk of a MRT station. Announcements and signs are in Chinese and English, as are fares and routes at ticket machines. Coins and bills are accepted and change is provided, though it’s best to buy day passes or an EasyCard.

The university was founded as Taihoku Imperial University in 1928 by the Japanese administration during the Japanese colonial era. After World War II, the government of the Republic of China resumed the administration of the University, reorganizing and renaming it National Taiwan University (NTU) in 1945.

The Taihoku Imperial University began with a Faculty of Liberal Arts and Law and a Faculty of Science and Agriculture serving 60 students. The university was intended mainly for Japanese nationals; few Taiwanese students were admitted. The Faculty of Medicine and the Faculty of Engineering were added in 1935 and 1943, respectively.

Currently, NTU has five campuses in the greater Taipei region and two additional campuses in Nantou County, amounting to nearly 1% of the total area of the island Taiwan. The university governs farms, forests, and hospitals for education and research purposes. The university comprises 11 colleges: bio-resources and agriculture, electrical engineering and computer science, engineering, law, liberal arts, life science, management, medicine, public health, science, and social sciences. The total number of students, including those enrolled at the School of Professional and Continuing Studies, has grown to over 33,000, including over 17,000 university students and 15,000 graduate students.

**POKEMON TRAINERS**

For Pokemon Trainers, there are many Pokestops and several Gyms on NTU campus.
9 EXCURSION

9.1 NATIONAL PALACE MUSEUM

The National Palace Museum (NPM) houses a collection of ancient Chinese artifacts from the Qing court originally kept in the Palace Museum in Beijing and the Jehol and the Shenyang summer palaces. It is one of the national museums of Taiwan and has a permanent collection of more than 696,000 pieces of ancient artifacts inherited from the Song, Yuan, Ming, and Qing courts. These artefacts were stored in containers and were transported to Taiwan during the Chinese civil war (1945-1949). Since its reopening in 1965, it has become one of the top tourist attractions in Taiwan.

DETAILS

Buses will depart from GIS NTU convention center at 9:15 to NPM, and return to the conference site at 12:00.

Further information can be found at http://www.npm.gov.tw/
Located in the finest district Taipei has to offer, TAIPEI 101 held the record for the tallest building in the world from 2004 to 2009. With 101 stories above ground and 5 stories below, the 508-meter-tall Taipei 101 is an engineering feat. The tower has served as an icon of modern Taiwan ever since its opening. The building was architecturally created as a symbol of the evolution of technology and Asian tradition. Its postmodernist approach to style incorporates traditional design elements and gives them modern treatments. The tower is designed to withstand typhoons and earthquakes. In addition to the city view from the observation deck, other popular attractions includes a 660-tonne tuned mass damper and the high-speed elevators.

DETAILS

Buses will depart from GIS NTU convention center at 14:30 for Taipei 101.
No return buses will be arranged.

10 SPECIAL EVENTS

10.1 WELCOME RECEPTION

We invite all the participants and their companions to join us at the welcome reception to kick off HFM 2016 at the GIS NTU convention center.

Refreshments will be served.

DETAILS
Time and location: 9/6 18:00-20:00 Hallway.

10.2 CHRIS HENLEY REMEMBERED

Professor Christopher L. Henley sadly passed away last summer, (29th June 2015) after an illness. In 1977 he received a bachelor degree in physics and mathematics from the California Institute of Technology and went on to get his doctorate in physics from Harvard University in 1983.
While working at AT&T Bell Laboratories, Boston University and Cornell University he made substantial contributions to the field of theoretical physics. He will be especially remembered for his work in biophysics, interacting electron systems, quasicrystals and numerical methods.
At this meeting, we will miss Chris’s energy, his insights and his real desire to understand what we are all working on. On Wednesday evening, you are all welcome to join us and remember Prof. Henley’s and his enthusiasm for frustrated magnets.

Refreshments will be served.

DETAILS
Time and location: 9/7, 18:00-19:30 The Forum.

10.3 MEET THE EDITORS

Editors from Journal of Physics Condensed Matter (Dr. Jason Gardner), Physical Review Letters (Dr. Yonko Millev) and Applied Physics Letters (Dr. Minn-Tsong Lin) will be available to answer questions, hear ideas, and discuss comments about the journals.

Wine and cheese will be served.

DETAILS
Time and location: 9/8 15:00 Aristotle Hall.
10.4 CONFERENCE DINNER

The conference dinner will be held on the **evening of September 8, at Ding-Xian 101 Seafood Restaurant at the 86th floor in Taipei 101.** Not only will you enjoy an excellent evening view of our host city, Ding Xian 101 will deliver a delightful menu of fresh, delicious flavours.

Attendance at the conference dinner is included in the registration fee.

**DETAILS**

Shuttle buses will leave from the GIS NTU convention center at 18:00. Banquet tickets are required for admittance. Time and location: 9/8, 19:00-21:30. Ding-Xian 101 Seafood Restaurant.


10.5 POSTER PRIZES

We are delighted that the **American Physical Society** is sponsoring the poster session at this year’s meeting. **Four posters** will be selected and will be presented with their prizes (Certificate and a financial reward) at the closing of HFM 2016. Dr Yonko Millev, from Physical Review Letters will be present to give out the certificates to the winning posters.
11  SCHOOL FOR THE MAGNETIC STUDIES, USING LARGE FACILITIES.

We are very pleased that the National Synchrotron Radiation Research Center (NSRRC) in Hsinchu will be hosting the preceding school or tutorial day for those new to frustration. This year the methods used to study magnetic materials, especially those currently in vogue with those studying Highly Frustrated Magnetism (HFM), will be introduced. These two days are aimed at graduate students, postdocs, and others new to the field of highly frustrated magnetism, and is intended to help prepare them to better participate in the main HFM 2016 conference, in Taipei.

THE FOLLOWING SPEAKERS ARE ALL CONFIRMED FOR THIS SCHOOL:

- John Chalker (U Oxford, UK)
- Lieh-Jeng Chang (NCKU, Taiwan)
- Jason S Gardner (NSRRC, Taiwan)
- Ying-Jer Kao (NTU, Taiwan)
- Michel Kenzelmann (PSI, Switzerland)
- Ching-Shun Ku (NSRRC, Taiwan)
- Philippe Mendels (U Paris Sud, France)
- Luigi Paolasini (ESRF, France)
- Kirrily Rule (ANSTO, Australia)
- Yixi Su (Juelich, Germany)
- Isao Watanabe (RIKEN, Japan)
## 12.1 FULL PROGRAMME

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<thead>
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<th>Wednesday 6th September</th>
<th>Thursday 7th September</th>
<th>Friday 8th September</th>
<th>Saturday 9th September</th>
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**Excursions**

- **Wednesday 6th September**
  - Mirebeau

- **Thursday 7th September**
  - Reim

- **Friday 8th September**
  - Jaubert

- **Saturday 9th September**
  - Canals

- **Sunday 11th September**
  - Takagi

**Coffee Breaks**

- 09:45 - 09:50
- 10:15 - 10:30
- 12:15 - 12:30
- 13:30 - 13:45
- 15:45 - 15:55

**Poster Session**

- Wednesday 6th September 10:45 - 11:15
- Thursday 7th September 10:45 - 11:15
- Friday 8th September 10:45 - 11:15
- Saturday 9th September 10:45 - 11:15
- Sunday 11th September 10:45 - 11:15

**Registration**

- Wednesday 6th September 14:00 - 19:00

**Lunch**

- Wednesday 6th September 12:15 - 13:30
- Thursday 7th September 12:15 - 13:30
- Friday 8th September 12:15 - 13:30
- Saturday 9th September 12:15 - 13:30
- Sunday 11th September 12:15 - 13:30

**Closing**

- Sunday 11th September 16:00 - 20:00

**Banquet**

- Saturday 9th September 18:00 - 20:00

**Meet the Editors**

- Wednesday 6th September 12:15 - 13:30
- Thursday 7th September 12:15 - 13:30
- Friday 8th September 12:15 - 13:30
- Saturday 9th September 12:15 - 13:30
- Sunday 11th September 12:15 - 13:30

**Registration**

- Wednesday 6th September 14:00 - 19:00
- Thursday 7th September 14:00 - 19:00
- Friday 8th September 14:00 - 19:00
- Saturday 9th September 14:00 - 19:00
- Sunday 11th September 14:00 - 19:00
## 12.2 Day by Day Programme & Abstracts

### 12.2.1 Wednesday September 7th 2016

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Institution</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:45 - 9:00</td>
<td>B. D. Gaulin</td>
<td>McMaster University</td>
<td>Quantum ground states in real pyrochlore magnets.</td>
</tr>
<tr>
<td>09:00 - 09:45</td>
<td>C. Castelnovo</td>
<td>Cambridge University</td>
<td>Emergent Coulombic criticality and Kibble-Zurek scaling in a topological magnet.</td>
</tr>
<tr>
<td>09:45 - 10:15</td>
<td>S. A. Grigera</td>
<td>Universidad Nacional de La Plata</td>
<td>Intermediate magnetisation state and competing orders in Dy2Ti2O7 and Ho2Ti2O7.</td>
</tr>
<tr>
<td>10:15 - 10:45</td>
<td>O. Sendetskyi</td>
<td>ETH and PSI</td>
<td>X-ray magnetic diffuse scattering in thermally active artificial spin ice.</td>
</tr>
<tr>
<td>10:45 - 11:15</td>
<td>B. Canals</td>
<td>Institut Neel, Grenoble</td>
<td>Artificial magnets as model systems: from the fragmentation of magnetization to the 6-vertex model.</td>
</tr>
<tr>
<td>11:15 - 11:30</td>
<td>L. Bovo</td>
<td>University College London</td>
<td>Strain-engineered frustrated magnets: Tb2Ti2O7 epitaxial thin films.</td>
</tr>
<tr>
<td>11:30 - 11:45</td>
<td>M. J. P. Gingras</td>
<td>University of Waterloo</td>
<td>Spin Ice in Thin Film Geometries.</td>
</tr>
<tr>
<td>11:45 - 12:00</td>
<td>O. Sendetskyi</td>
<td>ETH and PSI</td>
<td>X-ray magnetic diffuse scattering in thermally active artificial spin ice.</td>
</tr>
<tr>
<td>12:00 - 12:15</td>
<td>B. Canals</td>
<td>Institut Neel, Grenoble</td>
<td>Artificial magnets as model systems: from the fragmentation of magnetization to the 6-vertex model.</td>
</tr>
<tr>
<td>12:15 - 13:30</td>
<td>S. Petit</td>
<td>LLB, CEA, CNRS, Paris</td>
<td>Observation of magnetic fragmentation in spin ice.</td>
</tr>
<tr>
<td>13:30 - 14:00</td>
<td>S. Petit</td>
<td>LLB, CEA, CNRS, Paris</td>
<td>Observation of magnetic fragmentation in spin ice.</td>
</tr>
<tr>
<td>14:00 - 14:15</td>
<td>Gang Chen</td>
<td>Fudan University</td>
<td>Octupolar quantum spin ice.</td>
</tr>
<tr>
<td>14:15 - 14:30</td>
<td>R. Sibille</td>
<td>PSI</td>
<td>Coulomb spin glass in bond-disordered pyrochlore Tb2Hf2O7.</td>
</tr>
<tr>
<td>14:30 - 14:45</td>
<td>Y. Motome</td>
<td>U. Tokyo</td>
<td>Fractional Spin Fluctuation as a Precursor of Quantum Spin Liquids.</td>
</tr>
<tr>
<td>14:45 - 15:00</td>
<td>O. Tchernyshyov</td>
<td>Johns Hopkins University</td>
<td>A quantum spin liquid with a large topological degeneracy.</td>
</tr>
<tr>
<td>15:15 - 15:45</td>
<td>Coffee break</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16:15 - 16:45</td>
<td>N.P. Armitage</td>
<td>Johns Hopkins University</td>
<td>Low energy electrodynamics of the quantum spin ice Yb2Ti2O7.</td>
</tr>
<tr>
<td>16:45 - 17:00</td>
<td>L. J. Chang</td>
<td>NCKU</td>
<td>Inelastic neutron scattering studies of the Higgs ferromagnetic phase in Yb2Ti2O7.</td>
</tr>
<tr>
<td>17:00 - 17:15</td>
<td>S. Onoda</td>
<td>RIKEN</td>
<td>Resolving controversies on quantum spin ice: Yb2Ti2O7 and Tb2Ti2O7.</td>
</tr>
<tr>
<td>17:15 - 17:30</td>
<td>R. Coldea</td>
<td>Oxford University</td>
<td>Phase diagram and spin dynamics of the frustrated pyrochlore magnet Yb2Ti2O7 in applied field.</td>
</tr>
<tr>
<td>17:30 - 18:00</td>
<td>Y. Matsuda</td>
<td>Kyoto University</td>
<td>Low-energy elementary excitations in frustrated quantum magnets probed by thermal and thermal Hall conductivities.</td>
</tr>
<tr>
<td>18:00</td>
<td>Chris Henley Remembered</td>
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</table>
Quantum ground states in real pyrochlore magnets.

Bruce D. Gaulin, McMaster University

The rare-earth titanates form in the cubic pyrochlore structure from Sm to Lu and have been a continuous source for exotic frustrated magnetic ground states. These include states related to classical and quantum spin ice, as well as ordered states selected by order-by-disorder mechanisms. They are popular for experimental study as they can be grown as large single crystals, but such studies have also illustrated the sensitivity of these exotic ground states to small amounts of quenched disorder. I will review recent work on two candidate quantum spin ice pyrochlore magnets, Yb2Ti2O7 and Tb2Ti2O7; what we know about their ground states, and how these are expressed in real pyrochlore materials with trace (~1%) quenched disorder. I will also discuss new developments in how we can spectroscopically probe such weak disorder and how experiments on stoichiometric material under pressure can help us understand the fragility of these and related exotic states.

Emergent Coulombic criticality and Kibble-Zurek scaling in a topological magnet.

C. Castelnovo (Cambridge), A. Chandran (Perimeter), J. Hamp (Cambridge), R. Moessner (MPIPKS)

When a classical system is driven through a continuous phase transition, its nonequilibrium response is universal and exhibits Kibble-Zurek scaling. We explore this dynamical scaling in the context of a three-dimensional topological magnet with fractionalized excitations, namely, the liquid-gas transition of the emergent mobile magnetic monopoles in dipolar spin ice. Using field-mixing and finite-size scaling techniques, we place the critical point of the liquid-gas line in the three-dimensional Ising universality class. We then demonstrate Kibble-Zurek scaling for sweeps of the magnetic field through the critical point. Unusually slow microscopic time scales in spin ice offer a unique opportunity to detect this universal nonequilibrium physics within current experimental capability.
Intermediate magnetisation state and competing orders in
\( \text{Dy}_2\text{Ti}_2\text{O}_7 \) and \( \text{Ho}_2\text{Ti}_2\text{O}_7 \).

S. A. Grigera (Universidad Nacional de La Plata, Arg, and University of St Andrews, UK)

Among the frustrated magnetic materials, spin-ice stands out as a particularly interesting system. Residual entropy, freezing and glassiness, Kasteleyn transitions and fractionalisation of excitations in three dimensions all stem from a simple classical Hamiltonian. But is the usual spin-ice Hamiltonian a correct description of the experimental systems? In this talk I will address this issue by discussing experiments where we have measured the magnetic susceptibility of the two most studied spin-ice compounds, \( \text{Dy}_2\text{Ti}_2\text{O}_7 \) and \( \text{Ho}_2\text{Ti}_2\text{O}_7 \), using a vector magnet. Using these results, and guided by a theoretical analysis of possible distortions to the pyrochlore lattice, we constructed an effective Hamiltonian and explored it using Monte Carlo simulations. I will show how this Hamiltonian reproduces the experimental results, including the formation of a phase of intermediate polarisation, and gives important information about the possible ground-state of real spin-ice systems. Our work suggests an unusual situation in which distortions might contribute to the preservation rather than relief of the effects of frustration, a situation that seems to be confirmed by recent neutron scattering experiments.

Artificial magnets as model systems: from the fragmentation of magnetization to the 6-vertex model.

B. Canals (Institut NEEL), N. Rougemaille (Institut NEEL), I. Chioar (Institut NEEL), Y. Perrin (Institut NEEL), V.D. Nguyen (Institut NEEL), D. Lacour (Institut Jean Lamour), M. Hehn (Institut Jean Lamour), F. Montaigne (Institut Jean Lamour), A. Locatelli (ELETTRA Trieste), T. Mentes (ELETTRA Trieste)

Complex architectures of nanostructures are routinely elaborated using bottom-up or nanofabrication processes. This technological capability allows scientists to engineer materials with properties that do not exist in nature, but also to manufacture model systems to explore fundamental issues which appeared in condensed matter physics. One- and two-dimensional frustrated arrays of magnetic nanostructures are one class of systems for which theoretical predictions can now be tested experimentally. These systems have been the subject of intense research in the last few years and have allowed the investigation of a rich physics and fascinating phenomena, such as the exploration of the extensively degenerate ground-state manifolds of spin ice systems, the evidence of new magnetic phases in purely two-dimensional lattices, and the observation of pseudo-excitations involving classical analogues of magnetic charges. This talk aims at providing two examples of two-dimensional artificial magnets which allow to probe the low energy manifolds of two exotic Ising systems. The first one is related to the seminal 6-vertex model and shows that it is possible to perform a scan through the 6-vertex model phase diagram with an appropriately designed artificial magnet [1]. In particular, the symmetric point of the square ice is recovered, providing with the opportunity to study the signatures of an algebraic Coulomb spin liquid. Because of the experimental procedure used to reach the low energy manifold, quasi-particles are trapped in this disordered manifold, pointing to the need of thermal systems, but also emphasizing that these systems may be well suited to study out of equilibrium relaxation of monopole-monopole pairs in a near future. The second one refers to a recent proposal, the fragmentation of magnetization [2], in an Ising kagomé model. Here, we show it is possible to observe this intriguing phenomena, which corresponds to the splitting of the local degree of freedom into two channels, one ordering at low effective temperatures, in an AF all-in all-out ordering despite the ferromagnetic nature of the system, the other, building a Coulomb-like low energy manifold, inside which the magnetic equivalent of the Kirchhoff law at each node of the kagomé lattice is fulfilled [3].

Model magnets complement superfluids and superconductors as paradigms of quantum matter. The spin ice Dy$_2$Ti$_2$O$_7$ (DTO) [1-4] and spin liquids such as Tb$_2$Ti$_2$O$_7$ (TTO) [5-8], illustrate emergent electromagnetism, including a Coulomb phase [3] from which emerge magnetic monopole quasiparticles [2] and (possibly) emergent photons [5]. DTO is the (classical) benchmark of that physics [1] while TTO remains mysterious [6-8], its apparent spin liquid state “crystallizing” under applied pressure [6].

Epitaxial oxide films can have high purity, abrupt interfaces, and high structural uniformity. Of particular interest to frustrated magnetism is the possibility of using epitaxial strain to tailor the properties of existing materials. In recent work some of us reported the growth of high quality epitaxial pyrochlore thin films of spin ice Dy$_2$Ti$_2$O$_7$, where we show how the strain induced by the substrate can alter its magnetic behaviour [9]. This result and that of Ref. [10], have opened up new and extremely rich laboratory for studying and perturbing the properties of pyrochlore materials, which is an hitherto unexplored research direction.

In this talk I will report the fabrication and characterization of the first epitaxial thin films of TTO [11]. The films, of 5-60 nm thickness, have been grown uniformly layer-by-layer and are of very high quality. Through a combination of x-ray, specific heat and magnetization measurements we have been able to establish how the epitaxial strain strongly perturbs the crystal field energies of bulk TTO, but without establishing long-range order (down to 0.4 K). The results will be discussed in the context of theories of TTO [7,8].

Spin Ice in Thin Film Geometries.

Motivated by recent realizations of Dy$_2$Ti$_2$O$_7$ [1,2] and Ho$_2$Ti$_2$O$_7$ [3,4] thin films, and more generally by the physics of confined gauge fields in strongly correlated systems, we study models of spin ice thin films grown along the [001] cubic axis. The resulting open boundaries make half of the bonds on the surfaces inequivalent. Tuning the strength of these inequivalent "orphan" bonds above a certain threshold induces magnetic surface charges. Inspired by its success in bulk spin ice compounds, we first report results for a nearest-neighbour model of spin ice thin films, incorporating these orphan bonds. Using large-$N$ theory, Monte Carlo simulations and an effective gauge theory adapted to the confined geometry, we find from the three methods (i) a smearing of some of the characteristic "pinch point" scattering features of spin ices and (ii) temperature-dependent oscillations of the in-plane correlation length as a function of depth in the sample before it approaches the bulk limit.

To make better contact with real materials, we then performed Monte Carlo simulations of a model that includes the true long-range dipolar interactions. Most interestingly, we find that dipolar interactions induce a surface ordering equivalent to a two-dimensional crystallization of the magnetic surface charges stabilized by the orphan bonds. This surface ordering can also be expected at the surface of bulk crystals. In connection with partial wetting in soft matter, spins just below the surface are more correlated than in the bulk, but not ordered. This is exemplified in ultra-thin films made of a single cubic unit cell, where once the surfaces order, a square-ice (6-vertex model) phase is stabilized in the center of the film. This phase persists over a finite temperature window, as confirmed by its entropy and the presence of pinch points in the structure factor. Ultimately, the square ice degeneracy is lifted at lower temperature and the system orders in analogy with the well known $F$-transition of the 6-vertex model [5]. Finally, we comment on the implications of our results for pristine spin ice thin films and the ultra-clean surface of spin ice single crystals.

CONTRIBUTED

X-ray magnetic diffuse scattering in thermally active artificial spin ice.

O. Sendetskyi, L. Anghinolfi, V. Scagnoli, N. Leo, L. J. Heyderman (ETHZ, PSI, Switzerland), G. Müller (University of Kent, UK), A. Alberca, J. Kohlbrecher, U. Staub (PSI, Switzerland), J. Lüning (UPMC, CNRS, France)

Artificial spin ices consist of mesoscopic single domain magnetic islands arranged on a two-dimensional lattice and coupled via magnetostatic interactions. The advantage of constructing such artificial systems is the high tunability of the lattice and island parameters, which are produced by electron beam lithography. These frustrated systems have attracted considerable interest due to their complex magnetic phase diagrams and moment excitations resembling emergent magnetic monopoles. Most of the experimental studies have been performed using microscopy techniques, which are limited by their temporal resolution to probing slow magnetization dynamics. Here we apply x-ray resonant magnetic scattering to look at zero-field magnetic correlations in a highly dynamic regime of thermally active artificial kagome spin ice. Magnetic diffuse scattering was measured in this dynamic regime, above the blocking point of the system, revealing short-range magnetic correlations [1]. The experimental data can be understood using Monte Carlo simulations and subsequent numerical calculation of scattering patterns using kinematic scattering theory [2]. We show the emergence of quasi-pinch-points in the kagome ice I phase, and explain their relation to the pinch-point singularities in spin ice pyrochlores. As in the bulk pyrochlore spin ices, measurement of diffuse scattering from artificial kagome spin ice provides unique information on the magnetic correlations, and can be applied to a number of other frustrated nanomagnetic systems.


INVITED

Observation of magnetic fragmentation in spin ice.

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2 Institut Néel, CNRS and Univ. Grenoble Alpes, F-38042 Grenoble, France
3 Department of Physics, University of Warwick, Coventry, CV4 7AL, United Kingdom
4 Institut Laue Langevin, F-38042 Grenoble, France
5 INAC, CEA and Univ. Grenoble Alpes, CEA Grenoble, F-38054 Grenoble, France

Fractionalised excitations that emerge from a many body system have revealed rich physics and concepts, from composite fermions in two-dimensional electron systems, evidenced through the fractional quantum Hall effect to spinons in antiferromagnetic chains and, more recently, fractionalisation of Dirac electrons in graphene and magnetic monopoles in spin ice. Even more surprising is the fragmentation of the degrees of freedom themselves, leading to co-existing and a priori independent ground states. This puzzling phenomenon was recently put forward in the context of spin ice, in which the magnetic moment field can fragment, resulting in a dual ground state consisting in a fluctuating spin liquid, a so-called Coulomb phase, on top of a magnetic monopole crystal [1]. Recent neutron scattering measurements show that such fragmentation occurs in the spin ice candidate Nd\textsubscript{2}Zr\textsubscript{2}O\textsubscript{7} [2,3]. Indeed an antiferromagnetic order induced by the monopole crystallization and a fluctuating state with ferromagnetic correlations co-exist in this material. Experimentally, it manifests as the superposition of magnetic Bragg peaks, characteristic of the ordered phase, and a pinch point pattern, characteristic of the Coulomb phase. The fragmentation theory relies on the Helmholz decomposition of a charged field, widely used to describe continuous fluid media in a variety of fields, from fluid mechanics to robotics. In spin ice, the Helmholz decomposition is applied on the emergent gauge field of the Coulomb phase and on its charges, the monopoles. Our experimental findings thus give a concrete form to these concepts and we hope they will stimulate new conceptual approaches in these systems.

CONTRIBUTED

Octupolar quantum spin ice.
Gang Chen and Yao-Dong Li, Fudan University, China

The generic spin model that describes the interaction between the dipole-octupole doublets on a pyrochlore lattice has two distinct U(1) quantum spin liquid ground states. These two U(1) quantum spin liquids are dubbed dipolar quantum spin ice and octupolar quantum spin ice. While the dipolar quantum spin ice appears in many other contexts, the octupolar quantum spin ice is rather special. We explore the peculiar physical properties of octupolar quantum spin ice, elucidating the unique thermodynamic and spectroscopic properties in the magnetic field. We discuss the proximate multipolar ordered phases of the octupolar quantum spin ice and particularly emphasize the field driven Higgs’ transition in external magnetic fields. We point out the experimental relevance with the quantum spin liquid candidate materials. If time permits, I will cover the recent development of spinon Fermi surface U(1) quantum spin liquid.

CONTRIBUTED

Coulomb spin glass in bond-disordered pyrochlore Tb$_2$Hf$_2$O$_7$.

R. Sibille (PSI); T. Fennell (PSI); E. Lhotel (CNRS); M. Ciomaga Hatnean (Warwick); G. Balakrishnan (Warwick); G. Nilsen (ILL); G. Ehlers (ORNL); A. Cervellino (PSI); E. Ressouche (CEA); O. Zaharko (PSI); M. Frontzek (ORNL); V. Pomjakushin (PSI); H. Luetkens (PSI); A. Amato (PSI) and M. Kenzelmann (PSI)

Magnetic systems with competing interactions can adopt exotic ground states. The goal of our work is to identify such novel physics through the synthesis and study of novel materials. A particularly promising class is that of the geometrically frustrated magnets, such as A$_2$B$_2$O$_7$ pyrochlores, in which unusual spin liquids appear. Some of these phases feature short-range correlated states analogous to a Coulomb phase [1] and give rise to emergent quasiparticle excitations. Although cases like the classical spin ice are reasonably well understood, the theoretical expectation is that quantum fluctuations or disorder lead to novel phases such as the quantum spin ice [2] and the topological spin glass [3].

Here we present our study of a novel magnetic pyrochlore material, Tb$_2$Hf$_2$O$_7$. Peculiar crystal chemistry leads to a bond-disordered magnetic pyrochlore lattice, as evaluated using powder samples, but we found that it is possible to grow single crystals of the same material, i.e. samples with a quantitatively similar amount of defects. Using neutron diffraction with polarization analysis we show that power-law spin correlations develop, despite a massive amount of bond disorder. These correlations, characteristic of a Coulomb phase, coexist with a freezing that obeys the dynamical scaling law of spin glasses. Remarkably, the freezing temperature is of similar magnitude to that in pyrochlore magnets known to have vanishingly small levels of disorder. These observations strongly recall the recent theoretical proposal [3] of the existence of a new topological phase, called a topological spin glass, in which the spin glassiness is generated from the interplay of the disorder with the topological phase through the production and freezing of new degrees of freedom. We thus propose that Tb$_2$Hf$_2$O$_7$ could be the realization of such Coulomb spin glass in the presence of bond disorder, similar to what was theoretically predicted for ghost spins on the pyrochlore lattice [3].

Fractional Spin Fluctuation as a Precursor of Quantum Spin Liquids.


After the theoretical proposal by P. W. Anderson in 1973, the quantum spin liquid (QSL) has attracted continuous interest as a new quantum state of matter in magnets. Although several candidate materials have been synthesized, it remains elusive to prove that their low-temperature state is a QSL, mainly because of the lack of conventional order parameters that are experimentally accessible. On the other hand, one of the salient features of QSLs is the fractionalization of quantum spins. In this talk, we theoretically show that the fractionalized spins manifest themselves in the high-temperature paramagnetic state as a precursor of QSL. We address this issue in the Kitaev model on a honeycomb lattice, in which the quantum spin fractionalizes into two types of Majorana fermions in the QSL ground state. By using the newly-developed quantum Monte Carlo technique [1] and cluster dynamical mean-field theory [2] in the Majorana fermion representation, we find that many experimentally accessible quantities experience the fractionalization in their temperature dependences, such as the specific heat, entropy [3], magnetic susceptibility, NMR relaxation rate, and dynamical spin structure factor [2]. Our findings will be helpful as “smoking gun” for anticipated QSLs in candidate materials, such as Iridium oxides $\text{A}_2\text{IrO}_3$ and a Ruthenium compound $\alpha$-$\text{RuCl}_3$.


A quantum spin liquid with a large topological degeneracy.

O. Tchernyshyov, H. Wang (Johns Hopkins University), Y. Wan (Perimeter Institute)

We present an exactly solvable model of a quantum spin liquid in two dimensions with high topological degeneracy. The model has spins of length $S = 1/2$ on sites of a triangular lattice. The Hamiltonian is a sum of 6-spin terms, $H = -\sum_p W_p$, where $W_p = \sigma^x_1 \sigma^x_2 \sigma^x_3 \sigma^x_4 \sigma^z_5 \sigma^z_6$ are commuting operators first introduced in Kitaev’s honeycomb model [1]. As in the toric codes of Kitaev and Wen [2,3], elementary building blocks are strings of several distinct types. Ends of strings are elementary particles, 4 bosons and 3 fermions; particles of different types are mutual semions. Closed strings forming non-contracible loops can be used to determine the topological degeneracy. We find $2^{7-1} = 64$ ground states on a torus. Elementary excitations (hexagons with $W_p = -1$) are pairs of elementary particles (one boson and one fermion) that come in $4 \times 3 = 12$ varieties. Although we do not expect that this model will ever be found in a real material, we think that it serves as a stepping stone to building more realistic models with spin-liquid ground states—in the same was as the toric code [2] was a prototype for the honeycomb model [1].

Fermionic response from fractionalization in quantum spin liquids.

J. Nasu (Tokyo Inst. Tech.), J. Knolle (Univ. Cambridge), D. L. Kovrizhin (Univ. Cambridge), Y. Motome (Univ. Tokyo), and R. Moessner (Max Planck Inst.)

Insulating magnets provide good playgrounds for quantum many-body effects in the spin degree of freedom of electrons in solids. Although the spins are usually frozen at the lowest temperature, P. W. Anderson suggested that they could remain melting due to strong quantum fluctuations [1], which lead to a new state of matter, the quantum spin liquid (QSL). This state has attracted great interest for a number of decades as it could possess fermionic excitations emerging from fractionalization of quantum spins that are the fundamental degree of freedom in insulating magnets. Despite the fact that a lot of attempts have been devoted, the experimental observation remains elusive.

Here, we present a theoretical prediction for observing the fractional fermionic excitations. Performing quantum Monte Carlo simulations for the Kitaev model, whose ground state is a well-established QSL [2,3], we find that the fermionic nature is clearly signaled in the temperature dependence of the Raman response [4,5]. The current results show striking agreement with the experimental data for $\alpha$-$\text{RuCl}_3$ [6], indicating that the material accommodates fractional fermionic excitations instead of conventional spin excitations.


Evidence for Kitaev quantum spin liquid physics in $\alpha$ – $\text{RuCl}_3$.

S. E. Nagler (ORNL)

The magnetic semiconductor $\alpha$-$\text{RuCl}_3$ is composed of very weakly coupled honeycomb layers of edge-sharing $\text{RuCl}_6$ octahedra. The Ru$^{3+}$ ion has 5d electrons in a low spin state, and the system is expected to have an effective $J=1/2$ single ion ground state with an interacting spin Hamiltonian containing Kitaev-like terms. Inelastic neutron scattering has revealed the presence of an unusual magnetic excitation exhibiting a continuum in energy. Detailed measurements of the response show evidence for the fractionalized excitations that are characteristic of the Kitaev Quantum Spin-liquid.
In condensed matter systems, the formation of long range order (LRO) with broken symmetry is often accompanied by new types of excitations. However, in many magnetic pyrochlore oxides, geometrical frustration suppresses conventional LRO while at the same time non-trivial spin correlations are observed. For such materials, a natural question to ask then is what is the nature of the excitations in this highly correlated state without broken symmetry? Frequently the application of a symmetry breaking field can stabilize excitations whose properties still reflect certain aspects of the anomalous state without long-range order. Here we report evidence of novel magnetic excitations in the quantum spin ice material Yb$_2$Ti$_2$O$_7$, obtained from time-domain terahertz spectroscopy (TDTS) in both zero and finite applied field. In large applied fields, both magnon and two-magnon-like excitations are observed in a <001> directed magnetic field illustrating the stabilization of a field induced LRO state. The g-factors of these excitations are dramatically enhanced in the low-field limit, showing a cross-over of these one- and two-magnon states into features consistent with quantum string-like excitations proposed to exist in quantum spin ice in a small <001> applied field. In zero magnetic field, we report a combined time domain terahertz spectroscopy (TDTS) and microwave cavity study of Yb$_2$Ti$_2$O$_7$ to probe its complex dynamic magnetic susceptibility. We find that the form of the susceptibility is consistent with monopole motion and a magnetic monopole conductivity can be defined and measured. Using the unique phase sensitive capabilities of these optical techniques, we observe a sign change in the reactive part of the magnetic response. In generic models of monopole motion this is only possible through introducing inertial effects, e.g. a mass dependent term, to the equations of motion. Analogous to conventional electric charge systems, measurement of the conductivity’s spectral weight allows us to derive a value for the magnetic monopole mass, which we find to be approximately 1800 electron masses.


In our earlier studies, we proposed Yb$_2$Ti$_2$O$_7$ to be a magnetic Coulomb liquid above a transition temperature $T_c$ ~0.21 K, and that Yb$_2$Ti$_2$O$_7$ becomes a ferromagnet under Bose-Einstein condensation below $T_c$. [1]. We have carried out inelastic neutron scattering experiments to further investigate low energy excitations in the same Yb$_2$Ti$_2$O$_7$ crystal. Below $T_c$, a broad mode at ~0.2 meV with little dispersion is observed along the <111> direction on LET, ISIS. This mode corresponds to the localized quantum spin ice monopole excitations. While at the pinch point (111), the collective monopole excitations with energy gap ~0.04 meV is seen in the backscattering spectra from DNA, J-PARC. Besides, a remnant of coherent photon excitations that absorb a Nambu-Goldstone mode through the Higgs mechanism is also observed with the dispersion minimum at (111) with the energy gap of ~0.04 meV On the other hand, at ~0.35 K, i.e. above $T_c$, only gapless continuum excitations are revealed in the experiments. The theoretical understanding of these excitations will be discussed in another talk at this conference.

Resolving controversies on quantum spin ice: Yb$_2$Ti$_2$O$_7$ and Tb$_2$Ti$_2$O$_7$.

S. Onoda (RIKEN)

The U(1) quantum spin liquid ground state [1] and transitions to ordered phases in quantum spin ice (QSI) systems have attracted great interest as promising candidates to host an emergent quantum electrodynamics with a magnetic analogue. However, there remain many discrepancies on both theories and experiments, which have called for coherent understandings. Here, I present theoretical results which resolve the following current crucial controversies on two candidate QSI systems Yb$_2$Ti$_2$O$_7$ and Tb$_2$Ti$_2$O$_7$ mostly from theoretical aspects.

(i) Yb$_2$Ti$_2$O$_7$ shows a ferromagnetic order along the [001] direction, though hypothetical magnetic structures predicted in Refs. [2,3] are different by the presence [2] or absence [3] of the tetragonal symmetry. Now we show that the tetragonal [001]-ferromagnetic structure [2] is stable even in the gauge-mean-field level. Furthermore, incorporating gauge fluctuations into the gauge-mean-field approach alters the phase diagram: the first-order finite-temperature confinement-deconfinement transition [3] is replaced with a classical-quantum crossover [4] and the Coulomb ferromagnetic phase disappears. We also compute inelastic neutron-scattering spectra for the Higgs ferromagnetic phase of Yb$_2$Ti$_2$O$_7$. The results show localized QSI monopole excitations at high energies and a remnant of pyrochlore photon [1] excitations with an energy gap of the order of $T_c$, in agreement with recent experiments reported in a separate talk at the HFM2016.

(ii) Recent experiments on Tb$_{2-x}$Ti$_2$O$_7$ have shown that a fine tuning of the concentration $x$ triggers a quantum phase transition between an unordered phase and a hidden ordered phase [5]. Analyzing various experimental results on a basis of the pseudospin-1/2 model [6], we find that the hidden order should actually be either of two electric quadrupole orders predicted in Refs.[6,7] depending on the field range [8].

If time allows, I will also introduce our recent works on a first-principles material design for high-temperature QSI based on Ir moments.


Phase diagram and spin dynamics of the frustrated pyrochlore magnet Yb$_2$Ti$_2$O$_7$ in applied field.

Radu Coldea (Oxford), J. D. Thompson (Oxford), P. McClarty (Oxford and ISIS), D. Prabhakaran (Oxford), I. Cabrera (Oxford) and T. Guidi (ISIS)

The frustrated pyrochlore magnet Yb$_2$Ti$_2$O$_7$ has been proposed as a candidate “quantum spin ice” material. Here we report extensive inelastic neutron scattering measurements of the spin dynamics and complementary specific heat measurements to map the phase diagram in magnetic field applied along the cubic [001] direction, not explored experimentally in detail before. The high quality of our single crystals is evidenced by a sharp specific heat anomaly near 220 mK in zero field. At the highest magnetic fields probed (9 T) we observe in addition to dominant one-magnon excitations also a broad scattering continuum at higher energies, not detected in previous neutron scattering studies, which we attribute to two-magnon orders predicted in Refs.[6,7] depending on the field range [8]. Through fits of the dispersion relations at high field we propose a re-evaluation of the spin Hamiltonian to consistently explain all existing spin dynamics data for different field directions and propose a phenomenological model of the evolution of the spin dynamics in applied field.
Low-energy elementary excitations in frustrated quantum magnets probed by thermal and thermal Hall conductivities.

Y. Matsuda (Kyoto Univ.), Y. Tokiwa (Kyoto Univ.), M. Yamashita (Univ. of Tokyo), D. Watanabe (Kyoto Univ.), K. Sugii (Univ. of Tokyo), T. Yamashita (Kyoto Univ.), T. Shibuchi (Univ. of Tokyo), M. Udagawa (Gakushuin Univ.), Y. Yasui (Meiji Univ.), and Z. Hiroi (Univ. of Tokyo)

When quantum fluctuations suppress the underlying magnetic long-range order, a novel state so called a spin liquid state often emerges. In such a state the constituent spins are highly correlated but still fluctuate strongly down to much lower temperatures than the spin interaction energy scale. Many candidates of spin liquids have been found in materials possessing geometrically frustrated triangular, kagomé, and pyrochlore lattices.

Spin liquid states of frustrated quantum antiferromagnets often exhibit exotic physical properties, but the nature of the responsible elementary excitations remains entirely elusive. It has been shown that in the insulating quantum magnets, the thermal transport measurements can be used as a probe to unveil the ground state and elementary excitations in spin liquid states [1]. Here we report the thermal transport measurements in spin liquid states of two-dimensional (2D) kagomé volborthite $\text{Cu}_3\text{V}_2\text{O}_7\cdot2\text{H}_2\text{O}$ and 3D pyrochlore $\text{Yb}_2\text{Ti}_2\text{O}_7$.

$\text{Yb}_2\text{Ti}_2\text{O}_7$ hosts frustrated spin-ice correlations with large quantum fluctuations owing to pseudospin-$1/2$ of Yb ions. The thermal conductivity $\kappa_{xx}$ shows the presence of gapped elementary excitations. We find that the gap energy is largely suppressed from that expected in classical monopoles. Moreover, these excitations propagate a long distance without being scattered, in contrast to the diffusive nature of classical monopoles. These results suggest the emergence of highly itinerant quantum magnetic monopole, which is a novel heavy quasiparticle that propagates coherently in 3D SL [2].

$\text{Cu}_3\text{V}_2\text{O}_7\cdot2\text{H}_2\text{O}$ exhibits negative thermal Hall conductivity $\kappa_{xy}$, in analogous to the conventional Hall effect of charged electrons. We find that $\kappa_{xy}$ is absent in the high-temperature paramagnetic state and develops in accordance with the growth of the short-range spin correlations in the liquid state. The results suggest the emergence of nontrivial elementary excitations in the gapless spin liquid which acquire fictitious magnetic flux, whose effective Lorentz force is found to be less than $1/100$ of Lorentz force on free electrons [3].

### Thursday, 8 September 2016

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<td>Unveiling the hidden nematicity and spin subsystem in FeSe.</td>
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<td>09:45 - 10:15</td>
<td>Grenier, Université Grenoble Alpes</td>
<td>Longitudinal and Transverse Zeeman Ladders in the Ising-Like Chain Antiferromagnet BaCo2V2O8.</td>
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<td>10:15 - 10:30</td>
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<td>Magnetic fluctuations, Invar-like behaviour and quantum critical points in MnGe chiral magnet.</td>
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<td>10:30 - 10:45</td>
<td>Reim, Tohoku University</td>
<td>Antiferromagnetic skyrmion-lattice like spin structure in a layered kagome system.</td>
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<td>11:45 - 12:15</td>
<td>J.-Y Lin, National Chiao Tung University</td>
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<td>12:15 - 12:30</td>
<td>Rule, ANSTO</td>
<td>Complex field induced phases in the frustrated quantum spin chain, Linarite.</td>
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<td>12:30 - 12:45</td>
<td>Gibbs, MPI, Univ. of Tokyo</td>
<td>$S=1/2$ quantum critical spin ladders produced by orbital ordering in Ba2CuTeO6.</td>
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Details about the Thursday Poster Session can be found in Sec. 12.3
Skyrmions and emergent monopoles in chiral magnets.

Y. Tokura (RIKEN CEMS and Dep. Appl. Phys., Univ. of Tokyo)

Intriguing magnetoelectric responses can be anticipated to emerge from topological magnets characterized by topological indexes either in real space or in momentum space. One such example is magnetic skyrmions and emergent monopoles in noncentrosymmetric, e.g. chiral-lattice, magnets as protected by skyrmion number and endowed with real-space emergent magnetic flux. Dynamical responses of skyrmions and emergent magnetic monopoles coupled with electron transport and dielectric characteristics are investigated in terms of Lorentz transmission electron microscopy/holography, small-angle neutron/x-ray scattering, microwave spectroscopy, magneto-transport and magnetoelectric characteristics.
Longitudinal and Transverse Zeeman Ladders in the Ising-Like Chain Antiferromagnet BaCo$_2$V$_2$O$_8$.

B. Grenier (Université Grenoble Alpes and INAC–MEM, CEA–Grenoble, France), S. Petit (Laboratoire Léon Brillouin, CEA–Saclay, France), V. Simonet, P. Lejay, B. Canals (Institut Néel, Grenoble, France), E. Canévet (Institut Laue Langevin, Grenoble, France; now at PSI, Villigen, Switzerland), S. Raymond (INAC–MEM, CEA–Grenoble, France), C. Berthier (Laboratoire National des Champs Magnétiques Intenses, Grenoble, France)

The nature of the excitations in spin half antiferromagnets is a topic of considerable current interest in the field of quantum magnetism. The one-dimensional case is especially interesting as quantum fluctuations melt the classical long-range Néel order. The ground state remains disordered, with a spin excitation spectrum consisting of a continuum composed of spinons, created or destroyed in pairs e.g. by neutrons, like domain walls in an Ising magnet. Physical realizations of 1D systems, however, eventually order at very low temperature, owing to a small coupling between chains. The metamorphosis of the two-spinon continuum that accompanies this dimensional crossover towards a 3D state is an appealing issue. In this context, we explore the spin dynamics emerging from the Néel phase of the chain compound BaCo$_2$V$_2$O$_8$.

This system is a remarkable example of a quasi-1D Ising-like antiferromagnet [1], that can be described in terms of Tomonaga-Luttinger liquid physics in its field-induced gapless phase [2, 3]. It consists of Co$^{2+}$ spin–3/2 screw chains, showing a strong anisotropy and sizable frustration. The low temperature magnetic state of the Co$^{2+}$ ion is described by a highly anisotropic effective spin–1/2, yielding strong quantum fluctuations. At zero field, a Néel antiferromagnetic ordering occurs below $T_N \approx 5.5$ K [1, 4].

Our inelastic neutron scattering study in the Néel phase of BaCo$_2$V$_2$O$_8$ reveals unconventional spin excitations [5], understood in terms of two spinons bound states, so called Zeeman ladders [6]. The spectrum of these discrete states is due to the interchain potential which is linear with the distance. These excitations consist of two interlaced series of modes, respectively, with transverse and longitudinal polarization [5]. The latter modes, which correspond to longitudinal fluctuations of the ordered moment, have no classical counterpart and are related to the zero-point fluctuations that weaken the ordered moment in weakly coupled quantum chains. The nearly non dispersive character of the transverse and longitudinal modes in the direction perpendicular to the chains is attributed to strong frustration in the interchain interactions, in addition to the quasi-1D nature of this system. Our analysis of the energies of the excitation at the antiferromagnetic position together with their dispersion parallel to the chain reveals that BaCo$_2$V$_2$O$_8$ has a moderate Ising anisotropy and sizable interchain interactions. These conditions remarkably allow for the observation of long-lived longitudinal excitations.

Cubic itinerant chiral magnets show long period helical structures, governed by a hierarchy of interactions. In MnSi, for instance, these helices combine to form a lattice of vortex-like textures or skyrmions, yielding a topological Hall effect (THE) in a restricted (P, T, H) range, below $T_N \approx 30$ K. Metastable MnGe ($T_N \approx 170$ K) is perhaps the most intriguing in this family. It shows the shortest helical period and a giant THE, but no direct evidence of a skyrmion lattice in bulk state due to its powder form. In turn, other aspects of this compound actually deserve experimental focus. At ambient pressure, we have studied MnGe fluctuating chiral phase by combining neutron, Mössbauer and $\mu$SR probes [1, 2]. Magnetic fluctuations of correlated spins persist in a large temperature range (150 K), above and below $T_N$, covering a broad frequency range from MHz to THz. This behavior is clearly at odds compared to other known cubic chiral magnets. Following our seminal neutron study below $T_N$ [3], we have explored the paramagnetic state of MnGe under pressure using synchrotron probes [4]. Mn magnetism disappears in two steps, showing pressure-induced quantum critical points around 7 and 23 GPa. Coexisting high and low spin Mn-states induce elastic strains to accommodate different specific volumes. Supported by band structure models, our results suggest that magneto-elastic and strong spin orbit couplings are the key ingredients of the anomalous magnetic fluctuations. In turn, this would make MnGe the first invar chiral magnet.

Antiferromagnetic skyrmion-lattice like spin structure in a layered kagome system.

J. D. Reim (Tohoku University), M. Mostovoy (University of Groningen), M. Valldor (Max-Planck Institut Dresden), T. J. Sato (Tohoku University), W. Schweika (European Spallation Source and Jülich Centre for Neutron Science)

Since the observation of topologically protected spin swirlings called skyrmions in non-centrosymmetric ferromagnets [1] the investigation of such spin structures has been a hot topic in condensed matter physics. Experimentally such a lattice has been successfully stabilized in various bulk compounds in a small pocket of the magnetic field vs. temperature phase diagram. Recent theoretical studies even propose the existence of antiferromagnetic skyrmions [2], however there have not been any experimental reports yet.

The layered kagome system in the hexagonal swedenborgite structure [3] displays similarly to the pyrochlores a highly frustrated network of tetrahedral coordinated magnetic ions. However, its broken inversion symmetry raises further the complexity of ordering due to non-vanishing Dzyaloshinski-Moriya (DM) interactions. Investigated compounds of this family show signs for unusual geometric frustration and disordered ground states despite the typically strong antiferromagnetic (AF) exchange.[4-7]

The crystallographic structure of the compound CaBaCo$_2$Fe$_2$O$_7$ was refined in $P6_3mc$ symmetry ($a = 6.36\,\text{Å}$ and $c = 10.28\,\text{Å}$) and determined to be structural invariant within resolution limits.[8] We have observed an AF ordering below $T_N \approx 160\,\text{K}$, with a propagation vector to the $K$-point of the Brillouin zone boundary as expected for a simple Heisenberg model with only in-plane ($J_{\text{in}}$) and out-of (kagome) plane ($J_{\text{out}}$) AF nearest neighbor interactions.[5] A gradual spin reorientation with temperature is evidenced by polarization analysis. Another intriguing result is the chiral interference observed as an asymmetry of the magnetic Bragg intensities, from which a cycloidal character of the AF order can be concluded.


An introduction to quantum spin nematics.

N. Shannon (OIST, Japan)

Liquid crystals, in which molecules align to break rotational symmetries of space - without at the same time breaking translational symmetries - are ubiquitous in nature, and form the basis for many modern display technologies. The idea that a quantum magnet might also act like a liquid crystal, breaking spin-rotation symmetry without breaking time-reversal symmetry, holds an abiding fascination.

In this talk we explore some of the progress which has been made in understanding such "quantum spin nematic" states, addressing the questions: what are they, where should you look, and how would you know if you’d found one? We also explore in more detail the spin excitations of spin-nematic states, and how these might be observed in experiment [1,2].

Unveiling the hidden nematicity and spin subsystem in FeSe.

J.-Y. Lin (Institute of Physics, National Chiao Tung University) and C. W. Luo (Department of Electrophysics, National Chiao Tung University)

The nematic order is considered one of the essential ingredients to understand the mechanism of Fe-based superconductivity. In most Fe-based superconductors (pnictides), nematicity is reasonably close to the antiferromagnetic order. In FeSe, in contrast, a nematic order emerges below the structure phase transition at $T_s = 90$ K with no magnetic order. The case of FeSe is of paramount importance to a universal picture of Fe-based superconductors. The polarized ultrafast spectroscopy provides a tool to probe simultaneously the electronic structure and the magnetic interactions through quasiparticle dynamics. Here we show that this novel approach reveals both the electronic and magnetic nematicity below and, surprisingly, far above $T_s$ to at least 200 K. The quantitative pump-probe data clearly identify a correlation between the topology of the Fermi surface (FS) and the magnetism in all temperature regimes, thus providing profound insight into the driving factors of nematicity in FeSe and the origin of its uniqueness.

This work was mainly supported by MOST of Taiwan.

Complex field induced phases in the frustrated quantum spin chain Linarite.


One of the simplest models exhibiting one dimensional (1D) frustrated quantum interactions is the so called $J_1 - J_2$ model. In this model competing ferromagnetic nearest-neighbour interactions ($J_1 > 0$) and antiferromagnetic next-nearest-neighbours ($J_2 < 0$) can give rise to novel phenomena such as multiferroicity for spiral spin states. Linarite, $\text{PbCuSO}_4(\text{OH})_2$, is a natural mineral ideally suited to the study of frustration in $J_1 - J_2$ systems due to an accessible saturation field and the availability of large single crystals well suited to neutron investigations. In this material the Cu$^{2+}$ ions form spin $S = 1/2$ chains along the b direction with dominant nearest-neighbour FM interactions and a weaker next-nearest-neighbour AFM coupling, resulting in a magnetically frustrated topology [1, 2]. We present a neutron scattering study of linarite revealing a helical magnetic ground state structure with an incommensurate propagation vector of (0 0.186 1/2) below $T_N = 2.8$K in zero magnetic field [3]. From detailed measurements in magnetic fields up to 12 T ($\mathbf{B} \parallel \mathbf{b}$), a very rich magnetic phase diagram will be presented. A two-step spin-flop transition is observed, transforming the helical magnetic ground state into a collinear structure. As well, a magnetic phase with sine-wave modulated moments parallel to the field direction was detected, enclosing the other long-range ordered phases, and which exhibits phase separation in high magnetic fields. This will be discussed in the context of spin-nematic behaviour. Our data establish linarite as a model compound of the frustrated one-dimensional spin chain, with ferromagnetic nearest-neighbour and antiferromagnetic next-nearest-neighbour interactions.

$S=1/2$ quantum critical spin ladders produced by orbital ordering in $\text{Ba}_2\text{CuTeO}_6$.

A. S. Gibbs (Max Planck Institute for Solid State Research, The University of Tokyo, RIKEN, ISIS), A. Yamamoto (RIKEN), A. N. Yaresko (Max Planck Institute for Solid State Research), K. S. Knight (ISIS), H. Yasuoka (Max Planck Institute for the Chemical Physics of Solids), M. Majumder (Max Planck Institute for the Chemical Physics of Solids), M. Baenitz (Max Planck Institute for the Chemical Physics of Solids), P. J. Saines (University of Oxford), J. R. Hester (Bragg Institute), R. Stewart (University of St Andrews), S. L. Lee (University of St Andrews), D. Hashizume (RIKEN), A. Kondo (ISSP), K. Kindo (ISSP), and H. Takagi (Max Planck Institute for Solid State Research, University of Stuttgart, University of Tokyo)

The ordered hexagonal perovskite type material $\text{Ba}_2\text{CuTeO}_6$ has been recently discovered to host weakly coupled two-leg $S=1/2$ spin ladders produced by ferro-orbital ordering of $\text{Cu}^{2+}$ [1]. Our data indicate that $\text{Ba}_2\text{CuTeO}_6$ could be very close to the quantum critical point (QCP) of the coupled two-leg ladder system which has so far proved extremely difficult to access experimentally. At high temperatures the magnetic susceptibility, $\chi(T)$, of $\text{Ba}_2\text{CuTeO}_6$ is well fitted by an isolated spin ladder model with exchange coupling of $J \approx 86 \text{K}$ and $J' \approx J/2$ but below $T^* \approx 25 \text{ K}$ a deviation from the expected thermally activated behaviour is observed. An anomaly in $\chi(T)$, indicative of magnetic ordering, is observed at $T_{\text{mag}} \approx 16 \text{ K}$. However, no clear signature of long-range ordering is found in NMR, specific heat or neutron diffraction measurements at and below $T_{\text{mag}}$. Our results are fully consistent between single crystal and polycrystalline samples which are extremely magnetically clean with estimated magnetic impurity concentrations of < 0.1% $S=1/2$ impurities. In addition we confirm that there is full site ordering between $\text{Cu}^{2+}$ and $\text{Te}^{6+}$. Exchange coupling constants extracted from electronic structure calculations give $J \approx J'$ in excellent agreement with the experimentally determined ratio and in addition confirm the presence of inter-ladder couplings consistent with close proximity to the previously mentioned QCP.

The 'marginal' magnetic transition at $T_{\text{mag}} \approx 16 \text{ K}$, indicative of strong quantum fluctuations, supports the hypothesis that $\text{Ba}_2\text{CuTeO}_6$ is in close proximity to a quantum critical point between a magnetically ordered phase and a gapped spin liquid, controlled by inter-ladder couplings. We will present the results of our detailed study of the intriguing behaviour of this compound using electronic structure calculations, magnetic susceptibility, specific heat, NMR, high-field magnetization, neutron diffraction and recently acquired $\mu$SR data.

## Friday, 9 September 2016

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<td>Excursion at the Palace (includes lunch)</td>
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<td>13:45 - 14:00</td>
<td>Nakamura, University of Tokyo: Magnetization process of pyrochlore-slub SrCr9pGa12-9pO19 up to 200 T.</td>
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<td>14:00 - 14:30</td>
<td>SH Lee, Uni. Of Virginia: Love triangles, quantum fluctuations and spin jam.</td>
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<td>14:30 - 14:45</td>
<td>Lake, HZB: Physical realization of a new quantum spin liquid based on a novel frustration mechanism.</td>
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<td>14:45 - 15:00</td>
<td>Holdsworth, ENS, Lyon: Magnetic Moment Fragmentation in Spin Ice and Artificial Spin Ice.</td>
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<td>15:30 - 16:00</td>
<td>Fu, Johns Hopkins University: NMR Evidence for a Gapped Spin Liquid Ground State in the $S = 1/2$ Kagome Heisenberg Antiferromagnet $2nCu3(OH)6Cl2$.</td>
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<td>16:00 - 16:15</td>
<td>Mendals, Univ. Paris-Sud: Low-T $17^O$ NMR study of herbertsmithite crystals.</td>
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<td>Kelly, Johns Hopkins University: Electron Doping a Kagome Spin Liquid.</td>
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<td>Orain, Paul Scherre Institut: Gapless Spin Liquid Ground State in a $S = 1/2$ Vanadium Kagome Antiferromagnet: a $19^F$ and $17^O$ NMR study.</td>
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<td>16:45 - 17:15</td>
<td>Kanoda, University of Tokyo: Two routes to the emergence of spin liquids on triangular lattices and the realization of a doped spin liquid.</td>
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<td>Kimura, Osaka University: Magnetodielectric response and magnetic quadrupole order in the new chiral antiferromagnet $Ba(TiO)Cu4(PO4)4$.</td>
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<td>17:30 - 17:45</td>
<td>Normand, Scherrer Institute: Gapless Spin-Liquid Ground State in the $S = 1/2$ Kagome Antiferromagnet by Projected Entangled Simplex States.</td>
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### Session Chairs of the day:

- 12:45 - 15:00: J. Chalker
- 15:30 - 17:45: Z. Hiroi

L. Balents (UCSB)

Many great things start with $K$. First, I will discuss a spin model for Kapellasite, which has a kagomé lattice structure, but with interactions beyond nearest-neighbor. Remarkably, despite its 6-fold symmetry, it has an emergent quasi-one-dimensional description, which allows a rather complete understanding[1]. Second, I will present recent results on Kitaev’s honeycomb quantum spin liquid (QSL) phase. It is known that the QSL phase is stable to arbitrary weak perturbations, such as those which must be present in any physical realization. However, we show that its spin correlation function is qualitatively modified by those perturbations, and that the result obtained for the exactly soluble Kitaev model is wrong at low energies.


Quantum spin liquid behaviors in the random spin-$1/2$ Heisenberg antiferromagnets on the triangular and the kagome lattices.

H. Kawamura, T. Shimokawa and K. Watanabe (Osaka Univ.)

Experimental quest for the hypothetical “quantum spin liquid” state recently met a few promising candidate materials on certain geometrically frustrated lattices such as the triangular and the kagome lattices. The former includes organic salts $\kappa$-(ET)$_2$Cu$_2$(CN)$_3$ and EtMe$_3$Sb[Pd(dmit)$_2$], while the latter includes herbersmithite CuZn$_3$(OH)$_6$Cl$_2$. These spin-$1/2$ compounds exhibit no magnetic ordering nor the spin freezing down to very low temperature, while the measured physical quantities mostly exhibit gapless behaviors. We argue that these compounds might contain significant amount of (effective) quenched randomness of varying origin, i.e., the freezing of the charge (dielectric) degrees of freedom in the case of triangular organic salts and the possible Jahn-Teller distortion accompanied by the random substitution of Zn$^{2+}$ by Cu$^{2+}$ in the case of herbersmithite, which might be essential in stabilizing the quantum spin-liquid-like behaviors observed experimentally. We propose as a minimal model the $S = 1/2$ antiferromagnetic Heisenberg model on the triangular and the kagome lattices with a quenched randomness in the exchange interaction, and study both zero- and finite-temperature properties of the model by exact diagonalization and canonical thermal pure quantum state methods ([1-3]). We then find that, when the randomness exceeds a critical value, the model exhibits a quantum spin-liquid-like ground state with gapless behaviors, including the temperature-linear specific heat. The low-temperature state is argued to be a “random-singlet” (or “valence-bond-glass”) state. The results seem to provide a consistent explanation of the recent experimental observations.

Magnetization process of pyrochrore-slub SrCr$_{9}p$Ga$_{12-9p}$O$_{19}$ up to 200 T.

D. Nakamura (ISSP), S.-H. Lee (University of Virginia), J. Yang (University of Virginia), H. Ueda (Kyoto University), K. Penc (Hungarian Academy of Sciences), and S. Takeyama (ISSP)

Pyrochlore-slub compound SrCr$_{9}p$Ga$_{12-9p}$O$_{19}$ (SCGO) possesses a spin network of Cr$^{3+}$ (S=3/2), which is mainly composed by the tri-layer of Kagome lattice and triangular lattice. Although SCGO is known as a typical spin frustration material since 1980s, a large exchange coupling of around 90 K requires extremely high magnetic fields above 100 T for investigating the whole magnetization process up to a full magnetic saturation field. A non-magnetic Ga ion is selectively substituted at Kagome layer of Cr ion, which induces the disorder effect against Cr spin network. As a result, the spin-glass-like behavior was observed at temperatures below 3.5 K [1]. However, the specific heat at low temperature is proportional to the square of temperature, unlike the case for typical spin glass materials. A recent model calculation for SCGO shows that the quantum fluctuation induces a novel glassy state called as "spin jam", which can explain the temperature dependence of specific heat [2]. We expect that the high-field magnetization study of SCGO clarifies the impurity effect of spin network and novel phenomena involving the quantum fluctuation.

We prepared an SCGO (p=0.7) crystal with 0.03 mm thickness. From the optical absorption spectra, a crystal field transition (d-d transition) was observed at 2.0 eV in the absence of magnetic field. The Faraday rotation (FR) measurement was performed in magnetic fields up to 210 T, and FR angle reflects well the magnetization curve of SCGO. The ultra-high magnetic fields are generated by the single-turn coil method, which can be combined with the solid-state physics experiment at 5 K. Around 3/7 of full saturation value, a plateau in FR angle was observed at 190 T, in addition to an anomaly at 125 T. These facts suggest that there are two magnetic phases below the magnetization plateau phase. The comparison with a numerical calculation based on the classical Heisenberg model incorporating the biquadratic interaction was performed, which indicating that a spin-lattice coupling strength of SCGO is weak and Ga impurity effect might change the exchange coupling. The evolution of absorption peak spectra in magnetic fields focusing on the exciton-magnon-phonon transition will be also discussed.


Love triangles, quantum fluctuations and spin jam.

S.-H. Lee (U. of Virginia).

When magnetic moments are interacting with each other in a situation resembling that of complex love triangles, called frustration, a large set of states that are energetically equivalent emerge. This leads to exotic spin states such as spin liquid and spin ice. Recently, we presented evidence for the existence of a topological glassy state, that we call a spin jam, induced by quantum fluctuations [1,2]. The case in point is SrCr$_{9}p$Ga$_{12-9p}$O$_{19}$ (SCGO(p)), a highly frustrated magnet, in which the magnetic Cr$^{3+}$ ions form a quasi-two-dimensional triangular system of bi-pyramids. This system has been an archetype in search for exotic spin states. Understanding the nature of the state has been an intellectual challenge. In this talk, I will present our experimental data and theoretical spin jam model that provide a coherent understanding of the phenomenon. Our recent study on aging, memory, and energy landscape of the spin jam will also be discussed [3].

CONTRIBUTED

Physical realization of a new quantum spin liquid based on a novel frustration mechanism.

B. Lake, C. Balz, J. Reuther, A.T.M.N. Islam, H. Ryll (Helmholtz Zentrum Berlin, Germany), H. Luetkens, C. Baines (Paul Scherrer Institut, Switzerland), R. Schönemann, T. Herrmannsdörfer (Helmholtz Zentrum Dresden Rossendorf, Germany), Y. Singh (Indian Institute of Science Education and Research, Mohali, India), E.M. Wheeler (Institut Laue-Langevin, Genoble, France), J.A. Rodríguez-Rivera (National Institute of Standards and Technology, Gaithersburg, U.S.A), T. Guidi (STFC Rutherford Appleton Laboratory, U.K.), G.G. Simeoni (Technische Universität München, Germany)

Unlike conventional magnets where the magnetic moments are partially or completely static in the ground state, in a quantum spin liquid they remain in collective motion down to the lowest temperatures. The importance of this state is that it is coherent and highly entangled without breaking local symmetries. Such phenomena is usually sought in simple lattices where antiferromagnetic interactions and/or anisotropies favoring specific alignments of the magnetic moments, are frustrated by lattice geometries incompatible with such order. Despite an extensive search among such compounds, experimental realizations remain very few. Here we investigate the new spin-\(\frac{1}{2}\) magnet, \(\text{Ca}_{10}\text{Cr}_7\text{O}_{28}\), which has a novel unexplored lattice with several isotropic interactions consisting of strong ferromagnetic and weaker antiferromagnetic couplings. Despite its unconventional structure and Hamiltonian, we show experimentally that it displays all the features expected of a quantum spin liquid. Bulk properties measurements, neutron scattering and muon spin relaxation reveal coherent spin dynamics in the ground state, the complete absence of static magnetism and diffuse spinon excitations. Pseudo-Fermion renormalization group calculations verify that the Hamiltonian of \(\text{Ca}_{10}\text{Cr}_7\text{O}_{28}\) supports a dynamical ground state which furthermore is robust to significant variations of the exchange constants.

CONTRIBUTED

Magnetic Moment Fragmentation in Spin Ice and Artificial Spin Ice.

Peter C.W. Holdsworth (Ecole Normale Supérieure de Lyon)

The Coulomb phase [1,2], with its dipolar correlations and pinch-point scattering patterns, is now central to discussions of geometrically frustrated systems, with application to numerous frustrated magnets and to artificial arrays of magnetic nano-particles. In this talk I will concentrate on model spin ice and artificial spin ice where the Coulomb phase reflects the emergence of a divergence-free field, on the back of which the magnetic moments sit and is usually associated with the absence of long-range order.

In the presence of topological defects, the emergent field can be separated into divergence full and divergence free parts, following a Helmholtz decomposition [3]. As a consequence the configuration of magnetic moments naturally fragments into two distinct fields, one providing the magnetic charge and the other a persistent fluctuating background. Driving the system into a charge crystal phase leads to a partially ordered state, with one components providing the Bragg peaks of the ordered state and the other a magnetic fluid with all the characteristics of an emergent Coulomb phase. Specific examples include a monopole crystal phase for spin ice and the charge ordered KII phase of artificial kagomé ice [3].

Recent experiments have shown evidence of this fragmentation in three dimensions, in the frustrated pyrochlore magnet \(\text{Nd}_2\text{Zr}_2\text{O}_7\) [4], in artificial kagomé ice [5] and in the layered quasi-two-dimensional magnet \(\text{Dy}_3\text{Mg}_2\text{Sb}_3\text{O}_{14}\) [6] and I shall comment on these exciting developments.

NMR Evidence for a Gapped Spin Liquid Ground State in the S = 1/2 Kagome Heisenberg Antiferromagnet ZnCu$_3$(OH)$_6$Cl$_2$.

M. Fu (Institute for Quantum Matter and Department of Physics and Astronomy, Johns Hopkins University; NIST Center for Neutron Research; Department of Physics and Astronomy, McMaster University), T. Imai (Department of Physics and Astronomy, McMaster University; Canadian Institute for Advanced Research), T-H. Han (James Franck Institute and Department of Physics, University of Chicago), Y.S. Lee (Department of Applied Physics and Department of Photon Science, Stanford University and SLAC National Accelerator Laboratory; Department of Physics, Massachusetts Institute of Technology)

Experimental quest for a quantum spin-liquid state (QSL) in frustrated magnetic systems serves fundamental scientific interests, as this intriguing quantum phase provides excellent grounds for discovering exotic collective phenomena. The S = 1/2 kagome Heisenberg antiferromagnet ZnCu$_3$(OH)$_6$Cl$_2$ (herbertsmithite) is the leading contender for an experimental realization of a QSL. The recent discovery of a continuum of spinon excitations using inelastic neutron scattering [1] has stimulated intense research into its physical properties. However, the nature of the paramagnetic ground state in this material remains highly debated, primarily owing to the difficulty in revealing the intrinsic magnetic behavior of the kagome lattice from defect contributions.

Through single-crystal $^{17}$O NMR measurements, we demonstrated that the intrinsic spin susceptibility $\chi_{\text{kagome}}$ tends asymptotically to zero below $T \sim 0.03J$, where $J \sim 200$K is the Cu-Cu superexchange interaction. Combined with the magnetic field dependence of the $\chi_{\text{kagome}}$ observed at low temperatures, our results provide direct evidence for a QSL state with a finite gap $\Delta \approx 0.03$ ~ 0.07$J$ realized in ZnCu$_3$(OH)$_6$Cl$_2$ [2].

Low-T $^{17}$O NMR study of herbertsmithite crystals.

P. Mendels (Laboratoire de Physique des Solides, Univ. Paris-Sud), P. Khuntia (Laboratoire de Physique des Solides, Univ. Paris-Sud), F. Bert (Laboratoire de Physique des Solides, Univ. Paris-Sud), A. Legros (Laboratoire de Physique des Solides, Univ. Paris-Sud), M. Velazquez (ICMCB, CNRS Bordeaux).

Herbertsmithite ZnCu$_3$(OH)$_6$Cl$_2$ has been known for long as the best representative of spin liquid physics for the Heisenberg model on a quantum kagome lattice. While quasi-free Cu on Zn sites mask the signature of the kagome physics at low-$T$ in most experimental techniques, typically $T < J/10$, one can take advantage of the strong coupling of O to the kagome Cu’s to track this physics through $^{17}$O NMR. However, one cannot completely get rid of the Cu/Zn defects signature in NMR spectra, but the different spectral signatures from Cu spins on the kagome lattice and those on Zn site have opened the way for the discussion of the gapped character of the ground-state [1]. We will present a study on high quality single crystals. The defects contribution at low-T is clearly singled out and has been studied in great detail. Our NMR shift and $T_1$ relaxation measurements will be presented and discussed in the light of the recent findings from the Mac Master’s group [2].

Electron Doping a Kagomé Spin Liquid.

Z.A. Kelly (Johns Hopkins University), M.J. Gallagher (Johns Hopkins University), T.M. McQueen (Johns Hopkins University)

Herbertsmithite, ZnCu$_3$(OH)$_6$Cl$_2$, is a two dimensional kagomé lattice realization of a spin liquid, with evidence for fractionalized excitations and a gapped ground state. Such a quantum spin liquid has been proposed to underlie high temperature superconductivity and is predicted to produce a wealth of new states, including a Dirac metal at 1/3rd electron doping. Here we report the topochemical synthesis of electron-doped ZnLi$_x$Cu$_3$(OH)$_6$Cl$_2$ from $x = 0$ to $x = 1.8$ (3/5th per Cu$^{2+}$). Contrary to expectations, no metallicity or superconductivity is induced. Instead, we find a systematic suppression of magnetic behavior across the phase diagram. Our results demonstrate that significant theoretical work is needed to understand and predict the role of doping in magnetically frustrated narrow band insulators, particularly the interplay between local structural disorder and tendency toward electron localization, and pave the way for future studies of doped spin liquids.

Gapless Spin Liquid Ground State in a $S = 1/2$ Vanadium Kagome Antiferromagnet: a $^{19}$F and $^{17}$O NMR study.

J.C. Orain (LPS, PSI), F. Bert (LPS), P. Mendels (LPS), L. Clark (EaSTChem), F.H. Aidoudi (EaSTChem), P. Lightfoot (EaSTChem), R.E Morris (EaSTChem), B. Bernu (LPTMC)

The search for quantum spin liquid states such as the resonant valence bond state (RVB) formed by the macroscopic resonance between the various spin singlet coverings of the lattice, is a major challenge in both experimental and theoretical condensed matter research [1]. The prime candidate to host this state of matter is the $S = 1/2$ Kagome antiferromagnet (KAFM) in two dimensions.

Indeed, on the theoretical side, various studies pointed out the stabilization of a quantum spin liquid state on such lattice. Nevertheless, the nature of this ground state, with gapped or gappless excitation spectrum, is still subject to debate. On the experimental side, only few candidates exist. Various experiments on the most studied one, the herbertsmithite, have pointed out a gapless excitation spectrum, but recent NMR investigations on a single crystal revealed a gapped excitation spectrum and challenged this conclusion. Further, the influence of the different deviations to the ideal Heisenberg Hamiltonian on the ground state nature remains a difficult issue [2].

Among the rare experimental realizations of the KAFM model the recently synthesized compound, [NH$_4$]$_2$[C$_3$H$_9$(N)$_{2}$V$_2$O$_{18}$F$_{18}$] (DQVOF) [3], is the first one to host magnetically active V$^{4+}$ ($d^{1}$) ions rather than more common Cu$^{2+}$ ($d^{9}$) thus allowing to investigate the effects of different perturbations to the ideal Heisenberg Hamiltonian. Further, this compound seems to be the first experimental realization of the trimerized Kagome model, formed by two different equilateral triangles with two different interactions, $J_1$ and $J'_1$ [4].

Our low temperature magnetization and specific heat results suggest that DQVOF is a good candidate for the $S$=1/2 KAFM physics despite a complex structure with mixed $V^{4+}$ ($S = 1/2$) in the kagome planes and nearly free interlayer $V^{3+}$ ($S = 1$) [5]. Besides, the low temperature specific heat and $\mu$SR studies evidence a gapless spin liquid behavior down to 20 mK [6].

$^{19}$F and $^{17}$O NMR studies unveil the intrinsic susceptibility of the Kagome layers. The spin lattice time relaxation experiments reveal a gapless behavior in agreement with the previous studies. Further, the high temperature series analysis of the bulk susceptibility, with two different antiferromagnetic interactions $J_1$ and $J'_1$, points out a ratio $J_1/J'_1$ of about 0.7 and proposes a gapless ground state for DQVOF. Those studies suggest that the gapless behavior is rather robust in DQVOF and could be intrinsic to the trimerized kagome planes [7]. As the trimerization might close the gap, further theoretical studies of this trimerized kagome model with $J_1$ and $J'_1$ of the same order could help to understand the magnetism of DQVOF.

Two routes to the emergence of spin liquids on triangular lattices and the realization of a doped spin liquid.

K. Kanoda (Department of Applied Physics, University of Tokyo, JAPAN)

The interacting spins on geometrically frustrated lattices may exhibit non-trivial magnetic states, which have long been a focus in the physics of magnetism. The triangular lattices are the representative of such stages. The family of quasi-two-dimensional molecular materials, \(\kappa-(ET)_2X\), have quasi-triangular lattices, the anisotropy of which is varied by replacing the anion species, \(X\), constituting the insulating layers. In this conference, I first talk about the well established fact that the high degree of triangularity leads to the emergence of a quantum spin liquid, by comparing an antiferromagnetic Mott insulator with an anisotropic triangular lattice, \(\kappa-\text{Cu\[N(CN)_2\]Cl}\), and a spin-liquid Mott insulator with a nearly isotropic triangular lattice, \(\kappa-\text{Cu}_2(\text{CN})_3\). Noticeably, the antiferromagnetic order in the former material, when irradiated by X-rays, is deteriorated and eventually disappears with the emergence of gapless spin excitations, suggesting a novel role of randomness that brings forth a quantum spin liquid from a classical ordered state.

Next, I talk about another material named \(\kappa-\text{HgBr}\), in which a triangular lattice with a half-filled band is 11 % hole doped. The spin susceptibility of \(\kappa-\text{HgBr}\) is nearly perfectly scaled to that of a spin liquid insulator \(\kappa-\text{Cu}_2(\text{CN})_3\), indicating that in the spin sector \(\kappa-\text{HgBr}\) behaves like a spin liquid; note that they are distinctive in the charge sector (a metal versus an insulator). This is a clear indication of spin-charge separation and substantiates the realization of a doped spin liquid in \(\kappa-\text{HgBr}\).

The work presented here was performed in collaboration with T. Furukawa, H. Oike, J. Ibuka, M. Urai, Y. Suzuki, Y. Seki, K. Miyagawa (UTokyo), Y. Shimizu (Nagoya Univ.), M. Ito, H. Taniguchi (Saitama Univ.) and R. Kato (RIKEN), M. Saito, S. Iguchi and T. Sasaki (Tohoku Univ.).

Magnetodielectric response and magnetic quadrupole order in the new chiral antiferromagnet \(\text{Ba(TiO)}\text{Cu}_4(\text{PO}_4)_4\).

K. Kimura (Osaka Univ.); P. Babkevich (EPFL); M. Sera (Osaka Univ.); M. Toyoda (Tokyo Inst. of Tech.); K. Yamauchi (ISIR, Osaka Univ.); T. Nakano (Osaka Univ.); Y. Nozue (Osaka Univ.); H. Rønnow (EPFL); T. Kimura (Osaka Univ.)

Complex oxides \(A(\text{TiO)}\text{Cu}_4(\text{PO}_4)_4\) \((A = \text{Ba, Sr})\) are newly discovered magnetic insulators crystallizing in a tetragonal chiral crystal structure with space group of \(P4_2\_2\_2\) [1]. The key structural unit of these materials is a \(\text{Cu}_4\text{O}_{12}\) square cupola cluster, in which four corner-sharing square-coordinated metal-ligand fragments form a noncoplanar buckled structure. The unique \(\text{Cu}_4\text{O}_{12}\) geometry and its chiral arrangement can lead to interesting magnetism and associated phenomena. Here, we report magnetic and magnetoelectric (ME) properties of \(\text{Ba(TiO)}\text{Cu}_4(\text{PO}_4)_4\). Magnetic susceptibility and powder neutron diffraction data show that a complex noncollinear magnetic structure appears below \(T = 9.5\) K, which can be described by an antiferroic order of magnetic quadrupole moments on \(\text{Cu}_4\text{O}_{12}\) square cupolas. Interestingly, this magnetic quadrupole order exhibits a unique ME response, namely, an induction of antiferroelectric order by a magnetic field. To the best of our knowledge, this is the first experimental observation of the ME-activity of magnetic quadrupole moments [2].

Gapless Spin-Liquid Ground State in the $S = 1/2$ Kagome Antiferromagnet by Projected Entangled Simplex States.


We apply a tensor-network formulation, specifically the method of projected entangled simplex states (PESS), to study the ground-state properties of the $S = 1/2$ kagome Heisenberg antiferromagnet. In this approach, the lattice size is infinite, the truncation parameter is the tensor bond dimension, $D$, and we apply both simple- and full-update treatments of the tensor renormalization. For the model with only nearest-neighbour interactions, we find from simple-update results up to $D = 25$ that the ground-state energy, $E_0$, converges algebraically with $D$; the finite-$D$ ground state always has a finite $120^\circ$ magnetic order, whose order parameter, $M$, vanishes algebraically with $1/D$. We obtain essential confirmation by considering the Husimi lattice, which has exactly the same local physics but less frustration from longer paths, and allows calculations to be performed up to $D = 250$, giving reliable extrapolations to the large-$D$ limit. Because the Husimi ground state shows an identical algebraic convergence to a non-magnetic state, with $M$ always larger than in the kagome case, we conclude that the ground state on the kagome lattice is a gapless spin liquid.

Further strengthening this conclusion, full-update calculations demonstrate the accuracy of the simple-update approximation for all accessible values of $D$, finding negligible differences in $E_0$ and further suppression of $M$ values by several percent. Additional benchmarking of our result is obtained by adding a next-neighbour coupling, $J_2$, which yields a clear picture in the large-$D$ limit of magnetically ordered systems at all finite values of $|J_2|$, but with $M = 0$ at the single point, $J_2 = 0$, corresponding to the pure kagome lattice. Because we have obtained definitive numerical results for infinite system size by a method which, although based on gapped tensor-product states, has the capability to indicate its own “breakdown” in the event of algebraic convergence, the conclusion of a gapless spin-liquid ground state is robust.
### Saturday, 10 September 2016

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<td>08:45 - 09:00</td>
<td><strong>Takagi</strong>&lt;br&gt;mpi, uni. of tokyo&lt;br&gt;Strong spin-orbit coupling and exotic magnetism in complex Ir oxides.</td>
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<tr>
<td>09:00 - 09:15</td>
<td><strong>Jackeli</strong>&lt;br&gt;mpi and uni. stuttgart&lt;br&gt;Spin-orbital frustration in Mott insulators.</td>
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<td>09:15 - 10:00</td>
<td><strong>Jaubert</strong>&lt;br&gt;OIST, Japan&lt;br&gt;Cooking with spin-orbit coupling: a recipe for spin liquids.</td>
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<td>10:15 - 10:30</td>
<td><strong>Paddison</strong>&lt;br&gt;Georgia Tech&lt;br&gt;Emergent Order in the Kagome Ising Magnet Dy3Mg2Sb3O14.</td>
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<td><strong>YB Kim</strong>&lt;br&gt;University of Toronto&lt;br&gt;Quantum Spin Liquids on Breathing Kagome and Hyper-Kagome Lattices.</td>
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<td>10:30 - 12:15</td>
<td><strong>E Feng</strong>&lt;br&gt;Jcns at mlz&lt;br&gt;Neutron Scattering Studies of Rare Earth Pyrochlore Iridates.</td>
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<td>12:15 - 12:30</td>
<td><strong>Asih</strong>&lt;br&gt;Osaka university&lt;br&gt;Magnetic ordered states in pyrochlore iridates Nd2Ir2O7 and Sm2Ir2O7 studied by mu-SR.</td>
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<td>12:30 - 12:45</td>
<td><strong>YB Kim</strong>&lt;br&gt;University of Toronto&lt;br&gt;Asih&lt;br&gt;Magnetic ordered states in pyrochlore iridates Nd2Ir2O7 and Sm2Ir2O7 studied by mu-SR.</td>
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<td><strong>Petrenko</strong>&lt;br&gt;Warwick university&lt;br&gt;Hidden and conspicuous magnetic order in garnet.</td>
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**Additional Information**
- **Coffee Break**
- **Bus Pick Up**
- **Lunch**
Strong spin-orbit coupling and exotic magnetism in complex Ir oxides.

Hidenori Takagi
Max-Planck-Institute for solid state research, Stuttgart 70569, Germany
Department of Physics, University of Tokyo, Tokyo 113-0033, Japan

In 5d Iridium oxides, the relativistic spin-orbit coupling for 5d electrons is as large as ~0.5 eV and not small as compared with other relevant electronic parameters, including Coulomb $U$, transfer $t$ and crystal field splitting $D$. The large spin-orbit coupling and its interplay with the other parameters gives rise to a variety of exotic magnetic ground states. In the layered perovskite $\text{Sr}_2\text{IrO}_4$, spin-orbital Mott state with $J_{\text{eff}} = \frac{1}{2}$ is realized due to the novel interplay of those energy scales [1-3]. Despite the strong entanglement of spin and orbital degrees of freedom, $J_{\text{eff}} = \frac{1}{2}$ iso-spins in $\text{Sr}_2\text{IrO}_4$ was found to be surprisingly isotropic, very likely due to a super-exchange coupling through almost 180° Ir-O-Ir bonds [4]. The temperature dependence of in-plane magnetic correlation length of $J_{\text{eff}} = \frac{1}{2}$ iso-spins, obtained from inelastic x-ray resonant magnetic scattering, was indeed well described by that expected for two-dimensional $S = \frac{1}{2}$ Heisenberg antiferromagnet [5].

When $J_{\text{eff}} = \frac{1}{2}$ iso-spins interact with each other through 90° Ir-O-Ir bonds, very anisotropic coupling, ferromagnetic perpendicular to the bond plane, is expected, due to an interference of the two Ir-O-Ir superexchange paths. In $\alpha,\beta,\gamma-\text{Li}_2\text{IrO}_3$ with honeycomb based structure [6], $J_{\text{eff}} = \frac{1}{2}$ moments are connected with the three orthogonal 90° Ir-O-Ir bonds. Those three bonds are competing with each other, which could be a materialization of Kiteaev model with quantum spin liquid state. A long range magnetic ordering, however, was observed at low temperatures in $\alpha,\beta,\gamma-\text{Li}_2\text{IrO}_3$, which is very likely due to the presence of additional magnetic couplings not included in the original Kitaev model [7]. The exploration of Kiteaev state was recently extended to related compounds and pressure effect. We found that a quantum spin liquid state is realized in hydrogenated Ir 2D honeycomb ($\alpha$-type) and $\beta$ - $\text{Li}_2\text{IrO}_3$ under high pressure [6]. The search for possible fractionalized excitations, expected for Kiteaev spin liquid, is now underway.


Spin-orbital frustration in Mott insulators.

G. Jackeli (MPI and Uni. Stuttgart)

In Mott insulators, unquenched orbital degrees of freedom often frustrate the magnetic interactions and lead to a plethora of interesting phases with unusual spin patterns or non-magnetic states without long-range order. I will review from this perspective the theoretical concepts and experimental data on late transition metal compounds, mostly focusing on iridates. In the second part, I will present our recent theoretical study of interplay of spin and orbital degrees in double-perovskite compounds with spin one-half ions occupying the fcc sub-sublattice, such as molybdenum oxides. I will argue that this interplay might lead to a rich variety of the phases that include non-collinear ordered patterns with or without net moment, and, most remarkably, non-magnetic disordered spin-orbit dimer state.
Cooking with spin-orbit coupling: a recipe for spin liquids.

L. Jaubert, K. Essafi, O. Benton, H. Yan, N. Shannon (OIST, Japan)

Spin liquids are not only an absence of order. They are malleable magnetic textures obeying their own microscopic rules. These rules – or frustrated constraints – often take the form of emergent gauge fields able to support exotic quasi-particles and unconventional field responses, readily accessible by experimental probes such as neutron scattering and magnetic measurements for example.

In this talk we will illustrate the diversity of spin liquids that can emerge from a family of experimentally motivated models, and show how the physics of magnetic frustration fits within a global picture. More specifically, we will bring together a network of kagome spin liquids with XXZ and Dzyaloshinskii-Moriya interactions [1]. This network sheds a new light on the surprisingly rich physics of the Ising antiferromagnet and unveils the existence of ferromagnetic chiral spin liquids. When extending our theory to three dimensions, on the pyrochlore lattice, it appears possible to stabilize a spin liquid whose fluctuations are naturally described by a tensor field with a continuous gauge freedom [2]. This gauge structure underpins an unusual form of spin correlations, giving rise to pinch-line singularities – line-like analogues of the pinch-points observed in spin ice. Remarkably, these features may already have been observed in the pyrochlore material Tb$_2$Ti$_2$O$_7$.


Quantum Spin Liquids on Breathing Kagome and Hyper-Kagome Lattices

Yong-Baek Kim (University of Toronto)

Motivated by recent experiments on the vanadium oxyfluoride material DQVOF and Na$_4$Ir$_3$O$_8$, we discuss possible quantum spin liquid phases on the two-dimensional breathing Kagome lattice and three-dimensional Hyper-Kagome lattice. First, using the projective symmetry group analysis and variational Monte Carlo method, we show that the ground state of the Heisenberg model on the breathing Kagome lattice is a gapped $\mathbb{Z}_2$ spin liquid state. This state is closely related to one of the promising spin liquid phases on the ideal Kagome lattice. Relations to earlier studies of quantum spin liquid phases on the ideal Kagome system and experiments on DQVOF are discussed. Secondly, we derive the spin model with strong spin-orbit coupling for the Hyper-Kagome system. Classical and quantum phase diagrams are investigated in the presence of various anisotropic spin interactions. Possible quantum spin liquid phases in the presence of anisotropic spin interactions are discussed. Connections to recent and future experiments are made.
Spin liquids on the hyperkagome lattice.

F. Bert (Laboratoire de Physique des Solides, Univ. Paris-Sud), P. Khuntia (Laboratoire de Physique des Solides, Univ. Paris-Sud), A.C. Shockley (Laboratoire de Physique des Solides, Univ. Paris-Sud), P. Mendels (Laboratoire de Physique des Solides, Univ. Paris-Sud), Y. Okamoto (Department of applied physics, Nagoya University) B. Koteswararao (School of Physics, University of Hyderabad)

While spin liquids are intensively explored in quasi-two dimensional materials, three dimensional (3D) cases remain scarce since 3D networks usually imply a higher connectivity that plays against quantum fluctuations. Na$_4$Ir$_3$O$_8$ is a unique case of a hyperkagome 3D corner sharing triangular lattice decorated with effective quantum spins. We present a comprehensive set of NMR data taken on both the $^{23}$Na and $^{17}$O sites [1]. Disordered magnetic freezing of all Ir sites sets in below $T_f \sim 7$ K, well below $J = 300$ K. Above $2T_f$, physical properties are still relevant to the spin liquid state induced by this exotic geometry. In the less studied PbCuTe$_2$O$_6$, strong geometric frustration arises from the dominant antiferromagnetic interaction that generates a hyperkagome network of Cu$^{2+}$ ions although additional interactions enhance the magnetic lattice connectivity. Nonetheless, using NMR and muon spin relaxation down to 20 mK, we provide robust evidence for the absence of magnetic freezing in the ground state [2]. Remarkably in the spin liquid state of both compounds, the local spin susceptibility probed by the NMR shift saturates at a finite value and the $1/T_1$ NMR relaxation rate which probes the magnetic fluctuations shows little temperature dependence. We will discuss the similarities and differences in these two realizations of a frustrated 3D geometry with respect to the existing theories.

Neutron Scattering Studies of Rare Earth Pyrochlore Iridates.

E. Feng\textsuperscript{1}, Y. Su\textsuperscript{1}, T. Wolf\textsuperscript{2}, T. Brueckel\textsuperscript{3,1}

\textsuperscript{1}Jülich Centre for Neutron Science JCNS, Forschungszentrum Jülich GmbH, Outstation at MLZ, D-85747 Garching, Germany
\textsuperscript{2}Institut für Festkörperphysik, Karlsruhe Institute of Technology KIT, D-76021 Karlsruhe, Germany
\textsuperscript{3}Jülich Centre for Neutron Science JCNS and Peter Grünberg Institut PGI, JARA- FIT, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany

The pyrochlore iridate compounds $A_2Ir_2O_7$, where the $A$ sites are occupied by rare-earth (RE) local moments and the $B$ site by 5d transition metal $Ir^{4+}$ ions with strongly spin-orbit coupled (SOC) electrons, have attracted strong interests because they sit in the intersection of the two emerging research fields in condensed matter physics: quantum spin ice [1] and correlated topological phases [2]. An intriguing “all-in-all-out” magnetic order at the $Ir^{4+}$ sites has been found in recent resonant magnetic X-ray scattering experiments on $Eu_2Ir_2O_7$ [3] and $Sm_2Ir_2O_7$ [4] respectively. The magnetic order of $Ir^{4+}$ is suggested being responsible for the metal-to-insulator transition observed in earlier transport and magnetization studies [5]. However, the interplay between the $Ir^{4+}$ magnetic order and the localized magnetism of RE ions at very low temperatures has not been systematically studied, except the cases in the Tb$^{3+}$ and Er$^{3+}$ based compounds [6]. We have recently synthesized a series of high quality polycrystalline samples covering a full range of RE ions by solid-state synthesis methods. X-ray and high-resolution neutron powder diffraction were employed to determine sample quality. Heat capacity and magnetization were measured to investigate their low temperature physical properties. Comprehensive polarized neutron diffraction and inelastic neutron scattering experiments were performed to investigate their magnetic ground states in the mK regime. An updated phase diagram based mainly on new neutron scattering studies will be presented. Our results point out the important role of both RE single-ion anisotropy and the Ir-RE coupling. In metallic Pr$_2Ir_2O_7$, evidence for an exotic ground state has been obtained [7].

We thank X. Wang, V. Pecanha-Antonio, B. Schmitz, Dr. Y. Xiao and Dr. W. Klein for their support on samples preparation and characterization. We acknowledge H. Kolb, Dr. Anatoliy, Dr. P. Cemak and Dr. M. Zbiri for their help with neutron scattering measurements. We are also grateful to the people who helped us for the project.

Magnetic ordered states in pyrochlore iridates $\text{Nd}_2\text{Ir}_2\text{O}_7$ and $\text{Sm}_2\text{Ir}_2\text{O}_7$ studied by $\mu$SR.

R. Asih (Osaka Univ., RIKEN), N. Adam (Univ. Sains Malaysia, RIKEN), S.S. Mohd-Tajudin (Univ. Sains Malaysia, RIKEN), D.P. Sari (Osaka Univ., RIKEN), K. Matsuhira (Kyutech), H. Guo (MPI), M. Wakeshima (Hokkaido Univ.), Y. Hinatsu (Hokkaido Univ.), T. Nakano (Osaka Univ.), Y. Nozue (Osaka Univ.), S. Sulaiman (Univ. Sains Malaysia), M.I. Mohamed-Ibrahim (Univ. Sains Malaysia), P.B. Kumar (PSI), I. Watanabe (RIKEN, Osaka Univ., Univ. Sains Malaysia, Hokkaido Univ.).

Pyrochlore iridates $R_2\text{Ir}_2\text{O}_7$ ($R$ is a rare-earth element), which are composed of a network of corner-sharing tetrahedral structures, provide an ideal platform for a strong geometrically frustrated system. The comparable spin-orbit coupling and electron-electron correlation in these systems generates a large systematic variation in properties with changes in $R$ [1]. The $R227$ also show metal-insulator transition (MIT) at $T_{\text{MI}}$ which seems to be accompanied by magnetic transitions. The $T_{\text{MI}}$ gradually decrease by increasing the ionic radius of the $R^{3+}$ ion [2]. Many studies including $\mu$SR, neutron scattering, and resonance x-ray diffraction have been carried out to elucidate the nature of the elusive magnetic ordering. In the case of $\text{Nd}_2\text{Ir}_2\text{O}_7$, our previous $\mu$SR study [3] and neutron experiment [4] revealed magnetic orderings of $\text{Ir}^{4+}$ and $\text{Nd}^{3+}$ moments and the relevance between $\text{Ir}^{4+}$ orderings to the MIT. On the other hand, in the case of $\text{Sm}_2\text{Ir}_2\text{O}_7$, the appearance of magnetic ordering of $\text{Ir}^{4+}$ and $\text{Sm}^{3+}$ has not been well studied. The study on this system is important to understand how Ir moment orders in changing $R$ since $\text{Sm}_2\text{Ir}_2\text{O}_7$ is adjacent to $\text{Nd}_2\text{Ir}_2\text{O}_7$ in the phase diagram [2].

In this study, we report on the magnetic ordered states in pyrochlore iridates $\text{Nd}_2\text{Ir}_2\text{O}_7$ and $\text{Sm}_2\text{Ir}_2\text{O}_7$ studied from both muon-spin relaxation and density functional theory (DFT) calculations. We applied DFT calculation techniques to quantitatively discuss the $\mu$SR data. The magnetic ordering of $\text{Ir}^{4+}$ moments appeared in conjunction with the MIT, and additional magnetic ordering of $\text{Nd}^{3+}/\text{Sm}^{3+}$ moments appeared at temperatures below 10 K. In order to estimate the local magnetic ordered moments, observed internal-fields were compared with the values derived from DFT calculations. We found that the all-in/all-out spin structure was preferable to explain the present $\mu$SR results on both $\text{Nd}_2\text{Ir}_2\text{O}_7$ and $\text{Sm}_2\text{Ir}_2\text{O}_7$. Lower limits of the magnetic ordered moments were estimated to be 0.12 $\mu_B$ and 0.2 $\mu_B$ for Ir and Nd moments in $\text{Nd}_2\text{Ir}_2\text{O}_7$, and 0.3 $\mu_B$ and 0.1 $\mu_B$ for Ir and Sm moments in $\text{Sm}_2\text{Ir}_2\text{O}_7$, respectively. Further analysis indicated that the spin coupling between Ir and Nd/Sm moments was ferromagnetic for $\text{Nd}_2\text{Ir}_2\text{O}_7$ and antiferromagnetic for $\text{Sm}_2\text{Ir}_2\text{O}_7$.

Emergent Order in the Kagome Ising Magnet Dy$_3$Mg$_2$Sb$_3$O$_{14}$

J. Paddison (Georgia Tech), H. Ong (University of Cambridge), J. Hamp (University of Cambridge), P. Mukherjee (University of Cambridge), X. Bai (Georgia Tech), M. Tucker (STFC-ISIS and Oak Ridge National Lab.), N. Butch (NIST), C. Castelnovo (University of Cambridge), M. Mourigal (Georgia Tech), S. Dutton (University of Cambridge)

The kagome lattice is at the forefront of the search for exotic states generated by magnetic frustration. Such states have been observed experimentally for Heisenberg [1,2,3] and planar [4,5,6] spins. In contrast, frustration of Ising spincsonthekagomelatticehaspreviouslybeenrestrictedtonano-fabricatedsystems[7,8,9,10]andspin-icematerialsunderappliedmagneticfield[11,12]. In this talk, we will show that the layered Ising magnet Dy$_3$Mg$_2$Sb$_3$O$_{14}$[13] hosts an emergent order predicted theoretically for individual kagome layers of in-plane Ising spins [14,15]. We present an analysis of experimental neutron-scattering and thermomagnetic data, which reveal a phase transition at $T_0 \approx 0.3$ K from a disordered spin-ice like regime [16] to an "emergent charge ordered" state [14,15]. In the latter state, emergent charge degrees of freedom show long-range order while spins remain partially disordered, making Dy$_3$Mg$_2$Sb$_3$O$_{14}$ the first realisation of ordering of emergent degrees of freedom in a solid-state kagome material. Motivated by our experimental observations, we present Monte Carlo results which reveal the subtle interplay of structural disorder, spin canting, and lattice dimensionality that drives emergent charge ordering. Finally, we introduce the potential of structural analogues of Dy$_3$Mg$_2$Sb$_3$O$_{14}$ as tuneable systems to study new aspects of kagome frustration.


INVITED

Hidden and conspicuous magnetic order in garnets.

O.A. Petrenko (Warwick), N. d’Ambrumenil (Warwick), P.P. Deen (ESS), H. Jacobsen (Copenhagen), J.A.M. Paddison (Georgia Tech), A.L. Goodwin (Oxford), H. Mutka (ILL), M.T. Fernández-Díaz (ILL)

Gd$_3$Ga$_5$O$_{12}$ (GGG) is a canonical highly frustrated magnet. We use neutron diffraction to probe the magnetic ground state of GGG in zero field, as well as neutron spectroscopy to explore the excitations present in this magnet in an applied field. In zero-field, a combination of neutron-scattering experiments and reverse Monte Carlo refinements point to the existence of a "hidden" order at low temperature. This is long-range order with a diverging correlation length, in which multipoles are formed from ten-spin loops [1]. In a magnetic field, analysis of the diffraction data shows that the spins in GGG are not fully aligned, but are canted slightly as a result of the dipolar interaction. The dominant contribution to the inelastic scattering at large momentum transfers is from a band of almost dispersionless excitations. We show that these excitations correspond to spin waves localised on the ten-spin loops, and that the spectrum at higher fields is well described by spin wave theory [2].

## Sunday, 11 September 2016

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Obtaining Kagome Chiral Spin Liquid by Gauging a U(1) Symmetry Protected Topological Phase.

S. Bhattacharjee (ICTS-TIFR, Bangalore), Y.-C. He (MPIPKS, Dresden), Y. Fuji (MPIPKS, Dresden), F. Pollmann (MPIPKS, Dresden), R. Moessner (MPIPKS, Dresden)

Recent numerical studies reveal interesting quantum spin liquid (QSL) phases in Kagome S=1/2 antiferromagnets with XXZ anisotropies. This includes an interesting chiral spin liquid (CSL) phase. In this talk, I shall discuss a controlled theoretical path starting from the spin system that leads to a low-energy topological field theory. This is obtained by reformulating the microscopic model for a CSL as a U(1) lattice gauge theory with dynamic bosonic spinons and deriving the low-energy form of its continuum limit. A crucial ingredient is the realisation that the bosonic spinons of the gauge theory exhibit a U(1) symmetry protected topological (SPT) phase, which upon promoting its U(1) global symmetry to a local gauge structure (“gauging”), yields the CSL. I shall conclude by pointing out that such ideas “gauging of global symmetries” can have interesting consequences in generally stabilising deconfined QSL phases.

Unusual spin dynamics in 2d triangular lattice RMnO$_3$.

Je-Geun Park (IBS CCES & Seoul National University)

Two dimensional triangular lattice with antiferromagnetic interaction has a so-called 120 degree noncollinear magnetic structure. Over the years, it has drawn special attentions due to its inherent frustrations [1]. More recently, there have been significant developments, in particular on the theoretical side, as to a possible magnon-magnon coupling arising from the noncollinear magnetic structure [2]. Another important but less well recognized fact is that for the noncollinear magnetic structure there can also be a direct coupling between magnon and phonon, which can possibly open up new and interesting opportunities.

Motivated by the theoretical development on magnon-magnon coupling, we have examined the spin dynamics of several hexagonal RMnO$_3$ in search of such magnon-magnon coupling. Hexagonal RMnO$_3$ is an attractive choice for several reasons. First, it is rather easy to grow big single crystals with several rare-earth elements at the R-site, adding flexibility of materials to pick. Second, it is known to have a very large spin-lattice coupling, which was identified to trigger Mn trimerization below the antiferromagnetic transition temperature [3]. In this talk, we will review how the spin dynamics of RMnO$_3$ is affected by magnon-magnon and magnon-phonon coupling [4,5].

Damped Topological Magnons in the Kagomé-Lattice Ferromagnets

A. L. Chernyshev, P. A. Maksimov

We demonstrate that interactions can substantially alter the free-band description of magnons in ferromagnets on geometrically frustrated lattices. The anharmonic coupling facilitated by the Dzyaloshinsky-Moria interaction and a highly-degenerate structure of the two-particle continuum induce a non-perturbative damping of the high-energy magnon modes. We provide a detailed account of the effect for the $S = 1/2$ ferromagnet on the kagomé lattice and propose further experiments.

Quantum Anomalous Hall Effect in Magnetic Oxides with Honeycomb and Triangular Lattices.

Guang-Yu Guo, Dept. of Physics, National Taiwan University, Taipei 10617, Taiwan

Quantum anomalous Hall (QAH) phase is a two-dimensional bulk ferromagnetic insulator with a nonzero Chern number usually in presence of spin-orbit coupling (SOC). Associated metallic chiral edge states carry dissipationless current transport in electronic devices. Due to its intriguing nontrivial topological properties and great potential application for designing dissipationless spintronics, extensive theoretical and experimental studies have been made to search for real materials to host such QAHE. Indeed, this intriguing QAH phase has recently been observed in magnetic impurity-doped topological insulators, albeit, at extremely low temperatures [1]. Based on first-principles density functional calculations, we predict that the QAH phases would exist in two kinds of layered 4d and 5d transition metal oxides with honeycomb and triangular lattices at high temperatures [2-3]. Furthermore, theoretical analysis reveals that the QAH phases in these oxide systems originate from two distinctly different mechanisms [2-3], namely, the conventional one due to the presence of both the SOC and ferromagnetism in the (LaAlO$_3$)$_{10}$/(LaOsO$_3$)$_2$ perovskite superlattice along the [111] direction [2], and the unconventional one (quantum topological Hall effect) caused by nonzero spin chirality resulting from topologically nontrivial magnetic structure in noncoplanar antiferromagnetic oxide K$_{0.8}$RhO$_2$ [3]. The calculated near-neighbor exchange coupling parameters further show that in the latter case, the noncollinear antiferromagnetism is caused by the frustrated near-neighbor magnetic interactions [3], while in the former case, the neighboring magnetic interactions are ferromagnetic [2]. The speaker gratefully acknowledges that the works presented here were carried out in collaboration mainly with Hirak Kumar Chandra, Jian Zhou and Qi-Feng Liang.

The hidden chirality and diffusion path of Na layer in the honeycomb lattice of Na$_2$Ni$_2$TeO$_6$.

Sunil K. Karna (CCMS, NTU, Taiwan), Y. Zhao(NIST, USA), R. Sankar (CCMS, NTU, Taiwan), M. Avdeev (ANSTO, Australia) P. C. Tseng (Physics Dept., NTU, Taiwan), C. W. Wang (NSRRC, Taiwan), G. J. Shu (CCMS, NTU, Taiwan), K. Matan (Mahidol U., Thailand), G. Y. Guo (Physics Dept., NTU, Taiwan) and F. C. Chou(CCMS, NTU, Taiwan)

The crystal structure of $P2_1$-type Na$_2$Ni$_2$TeO$_6$ is best described as honeycomb layers that are composed of edge-sharing (Ni/Te)O$_6$ octahedra with intercalated Na ions in the van der Waals (vdW) gaps. Although the crystal symmetry has been identified in the literature using the space group $P6_3/mcm$ (No. 193), a hidden chirality in the Na layer can only be identified via inverse Fourier transform (IFT)-assisted neutron diffraction. The three major Na sites that are commonly assigned without the feedback information from the inverse Fourier transform of the diffraction data miss the additional site splitting of the Na positions, and the nuclear and electronic intensity distribution of Na ions reveals a chirality symmetry in the Na layer. The Na site occupancy and Ni$^{2+}$ spin ordering were examined in detail through electron density mapping, neutron diffraction, and magnetic susceptibility measurements. The experimental Na ion distribution from iFT-assisted neutron powder diffraction was consistent with the Na diffusion pathway, as simulated by the calculated difference valence bond sum (DVBS) map. A strong incommensurate (ICM) antiferromagnetic (AF) spin ordering and a weak commensurate (CM) signature were observed in the polycrystalline sample studied, whereas a CM AF spin ordering was confirmed by using a single crystal sample through a $k$-scan near the superlattice peak of $(\frac{1}{2}, 0, 1)$.

Topological aspects of symmetry breaking in triangular-lattice Ising antiferromagnets.

A. Smerald, F. Mila (Ecole Polytechnique Fédérale de Lausanne (EPFL))

We investigate the triangular lattice Ising antiferromagnet with coupling beyond nearest neighbour, focussing in particular on the interplay between topology and symmetry [1]. Using a specially designed Monte Carlo algorithm with directed loops, we show that a first-order phase transition from a low-temperature, broken-symmetry stripe state to the paramagnet can be split, revealing an intermediate nematic phase. Furthermore, we demonstrate the emergence of several properties of a more topological nature, such as fractional edge excitations in the stripe state, the proliferation of double domain walls in the nematic phase and the coexistence of a broken symmetry and algebraically decaying spin correlations. We investigate the nature of the second-order phase transition between the stripe and nematic phases and demonstrate that it is of the Kasteleyn type and in the Pokrovsky-Talapov universality class. Finally, we show that these concepts are relevant in dipolar coupled Ising antiferromagnets, and can therefore be realised in artificial nano-magnet arrays.

INVITED

Quantum Loop States in Spin-Orbital Models on the Honeycomb and Hyperhoneycomb Lattices.

L. Savary (Massachusetts Institute of Technology)

The search for truly quantum phases of matter is one of the centerpieces of modern research in condensed matter physics. Quantum spin liquids are exemplars of such phases. In the quest for the latter, the challenges are many: neither is it clear how to look for nor how to describe them, and definitive experimental examples of quantum spin liquids are still missing. In this talk I will show how to devise a realistic model on the honeycomb lattice whose ground state realizes Haldane chains whose physical supports fluctuate, hence naturally providing the hallmark “fractional excitations” of quantum spin liquids. When taken to the three-dimensional hyperhoneycomb lattice, the ground state becomes a full-fledged symmetry-enriched U(1) quantum spin-orbital liquid, “disordered” both in the spin and orbital channels. The phase diagram also contains an interacting bosonic topological insulator phase. Crucially, this model is expected to describe actual materials, and I will provide a detailed set of material-specific constraints which may be readily used for an experimental realization.


PLENARY

Long range interactions and emergent chemical kinetics in classical spin ice.

Steven T. Bramwell

The monopole model of spin ice enables the treatment a complex frustrated magnet in terms of the statistical mechanics and kinetic theory of electrolytes. In particular it promises an analytical approach to long-range dipole-dipole interactions and nonlinear, non-equilibrium response, that is not available to standard methods of magnetism. However there are many theoretical and experimental obstacles to surmount before this programme can be realised in practice. In this talk I shall review the current status of the field and show how recent theoretical and experimental developments have greatly clarified the applicability of the monopole model to real spin ice materials. I shall focus on specific heat, neutron scattering and magnetic relaxation experiments that establish spin ice as a model lattice electrolyte and a model for the emergent kinetics of charge-generation. It will be demonstrated how all these experiments reveal the Coulomb interactions between magnetic monopoles. Finally, I will identify a number of issues for which further theory is required.

INVITED

The XY Pyrochlores through the Lens of Chemical Pressure.

A. M. Hallas (McMaster), J. Gaudet (McMaster), M. Tachibana (NIMS), G. M. Luke (McMaster), C. R. Wiebe (U. Winnipeg), and B. D. Gaulin (McMaster)

The XY pyrochlores, Yb$_2$B$_2$O$_7$ and Er$_2$B$_2$O$_7$, are two families of materials with a remarkable diversity in their low-temperature magnetism. At the heart of their interesting physics is the proximity of their ground states to numerous competing phases. These proximate phases make the XY pyrochlores highly susceptible to the effects of chemical pressure, i.e. the substitution of a non-magnetic constituent, which alters the lattice size and, consequently, inflicts an internal pressure on the system. Using chemical pressure as a lens through which to better understand the family of XY pyrochlores as a whole, I will present our recent work on two illuminating examples, Yb$_2$Ge$_2$O$_7$ and Er$_2$Pt$_2$O$_7$. Yb$_2$Ge$_2$O$_7$ has an antiferromagnetic ordered state [1], a distinct change from the ferromagnetic states found in Yb$_2$Ti$_2$O$_7$ and Yb$_2$Sn$_2$O$_7$. Nonetheless, inelastic neutron scattering reveals that each of Yb$_2$B$_2$O$_7$ ($B =$ Ge, Ti, Sn) share a ubiquitous nature to their spin excitations [2]. These spin excitations form a gapless continuum and are highly unconventional in their own right. The second example, Er$_2$Pt$_2$O$_7$, orders into the Palmer-Chalker state. However, our neutron scattering work has revealed a number of peculiarities, including a spin excitation spectrum that forms well above the Neel transition, and an unconventional order parameter [3]. I will conclude by placing these two new materials within the context of the greater XY pyrochlore family.

Field-induced ordering in dipolar spin ice.

W.-H. Kao (NTU), P. Holdsworth (ENS Lyon), Y.-J. Kao (NTU)

We present numerical studies of dipolar spin ice in the presence of a magnetic field tilted away from the [111] axis [1]. Below the critical field of ice-rule breaking transition from the kagome ice phase to a saturated state, we find a first-order transition into a $q = X$ state when the external field is slightly tilted toward the $[\overline{1}12]$ direction. This is consistent with the anomalous critical scattering previously observed in the neutron scattering experiment on the spin ice material Ho$_2$Ti$_2$O$_7$ in a tilted field [2]. We show that this ordering originates from the antiferromagnetic alignment of spin chains on the kagome planes due to long-range dipolar interaction. This explains why the alignment and critical scattering are not captured by previous simulation of nearest-neighbor model. The residual entropy of the kagome ice is fully recovered under tilted field. Our result captures the features observed in the experiments and points to the importance of the dipolar interaction in determining ordered states in the spin ice materials. We place our results in the context of recent susceptibility measurements on Dy$_2$Ti$_2$O$_7$, showing two features for a [111] field. [1] W.-H. Kao, P. C. W. Holdsworth, and Y.-J. Kao, Phys. Rev. B 93, 180410 (2016); [2] T. Fennell, S. T. Bramwell, D. F. McMorrow, P. Manuel, and A. R. Wildes, Nat. Phys. 3, 566 (2007).

Exploration of Supercooled Spin-liquid Magnetization Dynamics in Dy$_2$Ti$_2$O$_7$ and Ho$_2$Ti$_2$O$_7$.

A. Eyal (Cornell University), A.B. Eyvazov (Cornell University), R. Dusad (Cornell University), T.J.S. Munsie (McMaster University), G.M. Luke (McMaster University), J.C.S. Davis (Cornell University)

Frustrated Lanthanide pyrochlores of the form $R_2$Ti$_2$O$_7$ have generated a great interest as possibly hosting a variety of novel magnetic states [1]. Among these are Dy$_2$Ti$_2$O$_7$ and Ho$_2$Ti$_2$O$_7$. Recent experiments [2] revealed that the magnetic state of Dy$_2$Ti$_2$O$_7$ is actually a supercooled spin-liquid. Classically, such a liquid develops when a fluid does not crystallize upon cooling below its ordering temperature and, instead, the microscopic relaxation times diverge so rapidly that equilibration eventually becomes impossible. Remarkably, low-temperature Dy$_2$Ti$_2$O$_7$ exhibits all the characteristics of a supercooled magnetic liquid. Here we report continuing studies of magnetic susceptibility measurements in boundary-free toroidal experiments on both Dy$_2$Ti$_2$O$_7$ and Ho$_2$Ti$_2$O$_7$ samples, as well as high-resolution SQUID-based measurements of magnetization dynamics on these same materials. We study the phenomenology of supercooled spin-liquid dynamics, and consider the low temperature novel magnetic glass state hypothesized for these materials.

Spin-phonon interactions in the $R_2\text{Ti}_2\text{O}_7$ ($R=\text{Tb, Dy, Ho}$) pyrochlores: spin relaxation mechanisms, magnetoelastic modes, and vibron states.

T. Fennell (PSI), M. Ruminy (PSI), M. Núñez Valdez (ETHZ), B. Wehinger (Geneva), A. Bosak (ESRF), D. T. Adroja (ISIS), U. Stuhr (PSI), K. Iida (CROSS), K. Kamazawa (CROSS), S. Chi (ORNL), S. Calder (ORNL), E. Pomjakushina (PSI), D. Prabhakaran (Oxford), M. K. Haas (Princeton), L. Bovo (UCL), D. Sheptyakov (PSI), A. Cervellino (PSI), R. J. Cava (Princeton), M. Kenzelmann (PSI), N. A. Spaldin (ETHZ)

We have studied the crystal field levels and phonon band structures of the three compounds $R_2\text{Ti}_2\text{O}_7$ ($R=\text{Tb, Dy, Ho}$). Using density functional calculations we predicted the phonon energies and eigenvectors, and verified the energies and symmetries by a combination of neutron and x-ray spectroscopy on single crystals and powders [1]. Using powder neutron spectroscopy we measured the crystal field levels of all three compounds [2]. The results of these investigations enable us to propose a model of spin flipping by Orbach processes in the spin ices ($R=\text{Dy, Ho}$), which is fully constrained in terms of symmetries and energies of modes involved [3]. The model reproduces the relaxation time throughout the high temperature regime ($50 – 600 \text{ K}$, as measured by quasielastic neutron scattering on powder samples), and we have obtained direct evidence of some of the couplings in Ho$_2$Ti$_2$O$_7$ by using inelastic neutron scattering on single crystals. We also used our understanding of the phonon band structure to cast more light on magnetoelastic coupling and excitations in Tb$_2$Ti$_2$O$_7$, where we discovered and characterized a new example of a bound state, or vibron, between crystal field and phonon excitations [2].

I will present an overview of the phonon band structure and crystal field spectra of the rare earth titanates, the various interactions between the two that we have identified, and their consequences for the physics of spin ices and Tb$_2$Ti$_2$O$_7$.


Color ice states, weathervane modes and fluctuation-driven phase transition in a pyrochlore Heisenberg antiferromagnet.

Y. Wan (Perimeter Institute for Theoretical Physics), M. J. P. Gingras (U. of Waterloo)

Phase transitions in condensed matter are both ubiquitous and multifaceted. The most familiar mechanisms driving equilibrium phase transitions are the competition between energy and entropy or simply the energetic competition between two ground states. The textbook example for the former mechanism is the finite temperature phase transition in the classical Ising model. For the latter, an example is the spin-flop transition of an antiferromagnet in an external field, where the competition between the exchange energy and the Zeeman energy produces a transition from the Néel state to the ferromagnetic polarized state as the field increases. The abundance of examples for these two mechanisms begs the question: Can there be equilibrium phase transitions purely driven by the relative entropy of two competing ground states?

In this talk, we expose a new example of fluctuation-driven phase transition in the classical pyrochlore bilinear-biquadratic Heisenberg antiferromagnet, $H = \sum_{\langle ij \rangle} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + B(\boldsymbol{S}_i \cdot \boldsymbol{S}_j)^2$, with positive biquadratic exchange interaction ($B > 0$). We will show that this model possesses remarkable properties. First of all, the ground state manifold contains an extensively large family of non-coplanar spin states known as “color ice states” [1,2], which are generalization of the familiar Ising spin ice states. Furthermore, the color ice states support two-dimensional analog of the weathervane modes in the classical kagome Heisenberg antiferromagnet. Finally, even though the bilinear and the biquadratic interactions admit a common ground state manifold, they produce different thermal fluctuations. As a result, the thermal order-by-disorder mechanism selects different states as $B/J$ changes, resulting in a phase transition purely driven by fluctuations.

Order by structural disorder: from geometrically frustrated magnets to compass models.

M. E. Zhitomirsky (CEA-Grenoble, France)

A hallmark of magnetic frustration is degeneracy between classical ground-state spin configurations, which is not related to underlying symmetries. Such a degeneracy may be lifted by thermal and quantum fluctuations via the order by disorder effect. I discuss the role of structural disorder, nonmagnetic vacancies and random exchange bonds, on degeneracy lifting in frustrated magnets. Analytic and numerical results demonstrate that the quenched disorder stabilizes a different subset of classical ground states in comparison to fluctuations. For the Heisenberg geometrically frustrated magnets these are ‘the least collinear states’ whose selection can be attributed to an effective positive biquadratic exchange generated by the disorder. Competition between quenched and thermal disorder leads to appearance of interesting and complicated phase diagrams. We describe in detail the effect of nonmagnetic dilution for the Heisenberg triangular-lattice antiferromagnet in an applied field, for the XY pyrochlore antiferromagnet Er$_2$Ti$_2$O$_7$, and for two- and three-dimensional compass models.

Phase transitions and competing order parameters in a diluted XY pyrochlore system: a model for Er$_{2-x}$Y$_x$Ti$_2$O$_7$.

Rajiv Singh (UC Davis), Jaan Oitmaa (U. of New South Wales) and Michel Gingras (U. of Waterloo)

The phenomenon of order-by-disorder (ObD) has been discussed in the field of frustrated magnetism for nearly thirty years. Three mechanisms for ObD have been considered in the literature: order via quantum fluctuations, order via thermal fluctuations and order via quenched random disorder. In the past four years, the XY pyrochlore antiferromagnet Er$_2$Ti$_2$O$_7$ has emerged as a strong candidate for cooperating quantum [1,2,3] and thermal [4] ObD, though this is not yet definitely established [5,6]. Recently, it has been suggested that diluting the magnetic Er$^{3+}$ ions by non-magnetic Y$^{3+}$ ions might further allow to explore the above third category of ObD: namely that of order by random disorder [7,8]. To address the merit of this proposal, we used high temperature series expansions to calculate heat capacities and competing $\psi_2$ and $\psi_1$ order parameter susceptibilities in the paramagnetic phase of Er$_{2-x}$Y$_x$Ti$_2$O$_7$ to identify in which thermodynamic state the systems first enters upon cooling from the paramagnetic phase. These calculations allow us to track the critical temperature, $T_c(x)$, as a function of non-magnetic dilution $x$. We find that moderate dilution (of order 10 percent) leads to a change in the order parameter from $\psi_2$ to $\psi_1$ at $T_c$. Phase diagram and heat capacity results are compared with measurements on Er$_{2-x}$Y$_x$Ti$_2$O$_7$.

We discuss the implications of our results for the competing proposals of order by disorder [1,2,3] and that of order by virtual crystal field fluctuations [5,6] in pure Er$_2$Ti$_2$O$_7$.

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01 Artificial Structures

**S0101 X-ray magnetic diffuse scattering in thermally active artificial spin ice.** O. Sendetskyi, L. Anghinolfi, V. Scagnoli, N. Leo, L. J. Heyderman (ETHZ, PSI, Switzerland), G. Müller (University of Kent, UK), A. Alberca, J. Kohlbrecher, U. Staub (PSI, Switzerland), J. Luing (UPMC, CNRS, France) — Artificial spin ices consist of mesoscopic single domain magnetic islands arranged on a two-dimensional lattice and coupled via magnetostatic interactions. The advantage of constructing such artificial systems is the high tunability of the lattice and island parameters, which are produced by electron beam lithography. These frustrated systems have attracted considerable interest due to their complex magnetic phase diagrams and moment excitations resembling emergent magnetic monopoles. Most of the experimental studies have been performed using microscopy techniques, which are limited by their temporal resolution to probing slow magnetization dynamics. Here we apply x-ray resonant magnetic scattering to look at zero-field magnetic correlations in a highly dynamic regime of thermally active artificial kagome spin ice. Magnetic diffuse scattering was measured in this dynamic regime, above the blocking point of the system, revealing short-range magnetic correlations [1]. The experimental data can be understood using Monte Carlo simulations and subsequent numerical calculation of scattering patterns using kinematic scattering theory [2]. We show the emergence of quasi-pinch-points in the kagome ice I phase, and explain their relation to the pinch-point singularities in spin ice pyrochlores. As in the bulk pyrochlore spin ices, measurement of diffuse scattering from artificial kagome spin ice provides unique information on the magnetic correlations, and can be applied to a number of other frustrated nanomagnetic systems.


**S0102 Growth tetragonal and orthorhombic SrCuO$_2$ thin films.** P.C. Chiang (NCTU), V. S. Kumar (NCTU), J. C. Yang (NCKU), Y.-H. Chu (NCTU) and J.-Y. Lin (NCTU) — We have grown SrCuO$_2$ thin films on SrTiO$_3$ and LaAlO$_3$ substrates by In-situ monitoring via reflective high-energy electron diffraction (RHEED) and Laser molecular-beam epitaxy (MBE). X-ray diffraction is used to confirm both the tetragonal and orthorhombic phase. The orthorhombic crystal structure contain the one-dimensional Cu-O spin-chains. The tetragonal crystal structure contain the two-dimensional CuO$_2$-planes. Both tetragonal phase and orthorhombic phase are investigated in the XAS Cu L-edge. We compare the tetragonal phase and orthorhombic phase also by resistivity and magnetic data. This research figured out the appropriate parameters in the growth and the properties on the SrCuO$_2$ thin films. Furthermore, the superconductivity in hole-doped or electron-doped SrCuO$_2$ will be studied.

02 General Pyrochlores

**S0201 Low temperature properties of the zirconate Dy$_2$Zr$_5$O$_7$.** R. Freitas, L. Ishida, J. Ramón, P. Bernardo (IF-USP Brazil), M. Leite, F. Vichi (IQ-USP) — The geometrical frustration observed in the pyrochlore A$_2$B$_2$O$_7$ compounds makes them highly sensitive to all levels of disorder, not only structural but also quantum and thermal fluctuations as well, leading to the emergence of a plethora of different spin states including the spin ice and spin liquid. In this work we have studied the magnetic and heat capacity properties of the disordered fluoride Dy$_2$Zr$_5$O$_7$, where the A and B sites are indistinguishable. This compound presents magnetic and calorimetric properties very similar to the ones observed in the spin ice pyrochlore Dy$_2$Ti$_2$O$_7$, with an important distinction - the absence of any indication of a residual entropy down to 200 mK. We have also analyzed the diluted Dy$_{2-x}$Y$_x$Zr$_5$O$_7$ (x = 0.1 and 0.4) and stuffed (Dy$_{2.5}$Zr$_1.5$O$_7$) zirconates. Both series of compounds behave similarly with the exception of the stuffed material presenting some degree of residual entropy, which is less than the observed value for the spin ice.

**S0202 Candidate quantum spin liquid phases in Pr$_2$Hf$_5$O$_{12}$ and Ce$_2$Sn$_2$O$_7$.** R. Siblee (PSI), E. Lhotel (CNRS), T. Fennell (PSI), N. Gauthier (PSI), M. Clomaga Hatnean (Warwick), M. R. Lees (Warwick), G. Balakrishnan (Warwick), B. Fåk (ILL), V. Ban (PSI), V. Pomjakushin (PSI), H. Luetkens (PSI), C. Baines (PSI) and M. Kenzelmann (PSI) — The classical spin ice state is a well-established paradigm in frustrated magnetism and emergent many body physics: the frustrated ground states can be seen as a vacuum in which the low-lying excitations are emergent magnetic monopoles interacting by classical magnetostatics. The quantum spin ice (QSI) state forms a particularly important ongoing challenge [1]. This ground state is a generalization of the classical spin ice state to include quantum fluctuations, such that the effective theory becomes emergent quantum electrodynamics - the classical monopoles become coherent quantum quasiparticles, and a novel excitation playing the role of the photon appears. In a more general sense, the QSI belongs to a broader class of highly-correlated electron states - quantum spin liquids - which are quantum coherent over macroscopic length scales, and emerge from a subtle long-range entanglement of the ground state wavefunction.

Here we present two separate studies in our quest for quantum spin liquids on the pyrochlore lattice. Pr$_2$Hf$_5$O$_{12}$ displays striking characteristics of the ferromagnetic correlations expected in a quantum spin ice [2], while Ce$_2$Sn$_2$O$_7$ seems to...
retain an antiferromagnetic liquid ground state with quantum fluctuations [3]. We present results ranging from macroscopic characterizations to neutron scattering and muon spin relaxation measurements. We illustrate and discuss both the single-ion and cooperative magnetic properties of these two materials.


S0203 Magnetic Susceptibility of Spin Ice. M. Twengström (KTH), L. Bovo (UCL), T. Fennell (PSI), A. Wildes (ILL), S. Bramwell (UCL), O. Petrenko (Warwick), M. Gingras (UW, CIFAR), P. Henelius (KTH) – Determination of an accurate spin Hamiltonian for the spin ice Dy$_2$Ti$_2$O$_7$ is of particular interest with respect to the low temperature behaviour of emergent magnetic monopoles and the possible metastability of spin ice with respect to ordered or spin liquid states. We present a detailed experimental and theoretical study of the bulk magnetic susceptibility and wavevector dependent susceptibility of Dy$_2$Ti$_2$O$_7$ in the temperature range 0.7 - 10 K, which has allowed us to accurately refine parameters in the low temperature effective spin Hamiltonian. We find that the experimental susceptibility is extremely sensitive to the competition of minor third neighbour coupling terms. Particularly noteworthy is a peak in the temperature-dependent bulk susceptibility that reflects the balance of the minor terms. Along the way we report new polarized diffuse neutron scattering data which confirm the presence of pinch points in Dy$_2$Ti$_2$O$_7$. We discuss the consequences of our results for the understanding of outstanding issues in spin ice physics.

S0204 The quantum origins of moment fragmentation in Nd$_2$Zr$_2$O$_7$. O. Benton (OIST, Japan) – Spin liquid states are often described as the antithesis of magnetic order. Recent neutron scattering results [2] suggest that this scenario may be realized in the pyrochlore magnet Nd$_2$Zr$_2$O$_7$. These observations show the characteristic pinch point features of a Coulombic spin liquid occurring alongside the Bragg peaks of an "all-in-all-out" ordered state. Here we explain the quantum origins of this apparent magnetic moment fragmentation, within the framework of a quantum model of nearest neighbour exchange, appropriate to Nd$_2$Zr$_2$O$_7$ [2]. This model is able to capture both the ground state order and the pinch points observed at finite energy. The observed fragmentation arises due to the combination of the unusual symmetry properties of the Nd$^{3+}$ ionic wavefunctions and the structure of equations of motion of the magnetic degrees of freedom. The results of our analysis suggest that Nd$_2$Zr$_2$O$_7$ is proximate to a U(1) spin liquid phase.


S0205 Spin Correlations in the kagomé ice phase of Ho$_2$Ti$_2$O$_7$. A. Turrini (PSI, UniGeneva), T. Fennell (PSI), P. Henelius (KTH), P. Holdsworth (ENS-Lyon) – In pyrochlore spin ices such as Ho$_2$Ti$_2$O$_7$, the tetrahedral arrangement of holmium atoms in the pyrochlore lattice splits into alternating triangular and kagomé planes upon the application of a medium strength magnetic field in the [111], precipitating a phase change from the zero field ‘spin ice’ phase to the ‘kagomé ice’ phase [1,2]. In the kagomé ice phase, the ice rule competes with the applied field, restricting the degeneracy of the three dimensional spin ice states to a subset in which the remaining degrees of freedom allowed by both ice rule and field constraints live on the kagomé planes. This kagomé ice phase is a two dimensional analog of spin ice - it is a Coulomb phase with its own distinctive pattern of pinch point scattering [3], and non-trivial topological properties [4]. In theory, tilting the field slightly away from the [111] axis further reduces the degeneracy, leading to a Kasteleyn transition [2]. Although this transition has never been observed experimentally, there are extensive predictions of the behavior of features in the diffuse neutron scattering as the transition is approached [2,5]. As a function of field/temperature/tilt angle, diffuse peaks should reorient and drift across the scattering plane. We have performed the first polarized neutron scattering experiments on kagomé ice. Polarized neutrons allow us to access two correlation functions in the model, that of spin ice spins, and that of an underlying relative, the Ising antiferromagnet on the kagomé lattice. Although the [111] axis of our crystal was extremely well aligned with the applied field, we still observed the signature of a strong tilt, suggesting strong demagnetization effects. We are investigating the effect of a lattice-intrinsic out-of-axis demagnetization component on the applied field direction [6], as well as the effect of using the full dipolar spin ice Hamiltonian [7,8], in order to explain both the observed evolution of the spin correlations and suppression of the Kasteleyn transition.


S0206 Revisiting static and dynamic magnetic correlations in spin ice Dy$_2$Ti$_2$O$_7$. Y. Su, Erxi Feng (UCS-MLZ, Germany), Th. Brueckel (UCS-2 & PGI-4, Julich, Germany), M.J.P. Gingras (Waterloo, Canada, CIFAR), M. Petrenko (Warwick), M.J.P. Gingras (Waterloo, Canada; CIFAR) – We present a detailed experimental and theoretical study of the bulk magnetic susceptibility and wavefunctions and the structure of equations of motion of the magnetic degrees of freedom. The results of our analysis suggest that Nd$_2$Zr$_2$O$_7$ is proximate to a U(1) spin liquid phase.

As one of the most widely studied dipolar spin ice materials, Dy$_2$Ti$_2$O$_7$ has played a central role in the realization of emergent magnetic monopole and its dynamics [1-2]. Owing to the combination of strong local- [111] single-ion anisotropy and large nearest-neighbor Ising exchange, the creation of magnetic monopoles as the consequence of the violation of the “2-in/2-out” ice rule becomes extremely energetically unfavorable deep in the spin-ice regime, thus leading to an almost completely suppressed spin dynamics and a frozen spin ice state possessing Pauling’s residual entropy. However, a recent report on the absence of Pauling’s residual entropy in thermally equilibrated Dy$_2$Ti$_2$O$_7$ [3] has generated considerable confusions in the community. This has thus triggered new theoretical efforts to clarify true magnetic ground state of classical dipolar spin ice [4].

We have recently succeeded in the synthesis of a new generation large isotope-enriched $^{162}$Dy$_2$Ti$_2$O$_7$ single crystal under optimal growth condition by the floating-zone method. Comprehensive polarized neutron diffraction and high-resolution inelastic neutron scattering experiments have been carried out on this single crystal over a wide temperature range but always in the thermally equilibrated regime. Both Monte-Carlo simulation and large-N calculation of spin-flip and non-spin-flip scattering cross-section $S(Q)$ based on a generalized dipolar spin ice model (g-DSM) [5] have been performed to compare with polarized neutron data. Furthermore, given that transverse non-Ising exchange interactions may be enhanced due to peculiar nature of dipole-octopole ground state doublet of Dy$^{3+}$, based on our inelastic neutron scattering data, we are able to setup an upper limit for the bandwidth of spin excitations at about 20 $\mu$eV, which is at least one order of magnitude smaller that in typical quantum spin ice candidate materials.

We thank J. Ollivier, K. Schmalzl, V. Pecanha-Antonio, V. Hutanu, A. Sazonov, X.F. Sun, L.J. Chang and P.C.W. Holdsworth for their contributions at various stages of this project.


**S0208 Oxygen vacancies and yttrium dilution in the geometrically frustrated Gd$\text{$_2$Ti$_2$O$_7$}$.

J. Ramon (IF–USP), R. Freitas (IF–USP), M. Leite (IQ–USP), F. Vichi (IQ–USP), J. Gardner (NSRRC/NTU) — The geometrically frustrated compound Gd$_2$Ti$_2$O$_7$ displays such an interesting behaviour; entering into a partially ordered magnetic state at a temperature $T_{\text{c}} \sim 1$ K, and into another phase transition at $T_{\text{c}} \sim 0.7$ K [1]; that the nature of the ordered magnetic phase is still under intense discussion. We study the low temperature properties of this compound with oxygen deficiency Gd$_{2-x}$Ti$_2$O$_{7-x}$, and yttrium dilution Gd$_{2-x}$Y$_x$Ti$_2$O$_7$ ($x \sim 0.1-0.7$). The refinement of a model for the X-ray diffraction data by the Rietveld method reveals that the oxygen vacancies are the leading defects in this material. We determine the magnetism and slight variations on the transition temperatures $T_{\text{c}}$ in Gd$_{2-x}$Ti$_2$O$_{7-x}$ and Gd$_{2-x}$Y$_x$Ti$_2$O$_7$ using magnetization and ac susceptibility measurements. Specific heat measurements in the compounds with oxygen vacancies display both transitions $T_{\text{c}}$ and $T_{\text{c}}$, in contrast to the single anomaly presented in yttrium diluted samples. The analysis of the magnetic contribution to the specific heat, $C_m(T)$, down to 50mK reveals a behaviour propor-
Short range order probed by diffuse neutron scattering in the breathing pyrochlore chromate LiGa$_{0.95}$In$_{0.05}$Cr$_4$O$_8$. R. Wawrzenzczak (ILL), Y. Tanaka (ISSP), Y. Okamoto (Nagoya U.), Z. Hiroi (ISSP), M. Takigawa (ISSP), and G. J. Nilsen (ISIS) — The breathing pyrochlore lattice is a modification of the conventional pyrochlore lattice whereby the constituent tetrahedra alternate in size. In the spinels LiGa$_{1-x}$In$_x$Cr$_4$O$_8$, adjusting the relative sizes of the A site cations (Li$^+$, Ga$^{3+}$, In$^{3+}$) offers the unique opportunity to tune the interactions between the different tetrahedra. It thus allows access to a range of magnetic behaviours spanning the uniform pyrochlore lattice and decoupled tetrahedra. Experimental observations made on end-member compounds ($x = 0$ and $x = 1$) [1-3] revealed the crucial role of spin-lattice coupling in the low-$T$ ground state selection through two concomitant structural and magnetic transitions. In the $x = 0$ case, the former, structural in nature, resolves the macroscopic degeneracy and allows for onset of magnetically ordered phase via the latter. The Ga case is more complex, with long-range magnetic order coinciding with a structural distortion at both transitions. We present the results of neutron scattering experiments on LiGa$_{0.95}$In$_{0.05}$Cr$_4$O$_8$ which, in spite of a minute change in stoichiometry, displays utterly different magnetostuctural behaviour. A single transition at $T_f \approx 11$ K, previously identified through magnetic susceptibility and heat capacity measurements as a second order [4] transition, does not lead to lowering of the lattice symmetry. In addition, no sign of magnetic long range order is observed. Using reverse Monte Carlo, a proven technique for extracting spin-spin correlations from diffuse scattering studies of other magnetically disordered materials, we find hints to the presence of the Coulombic spin liquid phase, which is characterized by power-law spin-spin correlations. The results also suggest that the thermodynamic anomaly could be assigned to the onset of a nematic phase with collinear spin orientations. This is accompanied by short-range magnetic order characterized by the propagation vector $k = (001)$. Both phases are compatible with the predictions of the bilinear-quadratic spin-only model for the isotropic pyrochlore antiferromagnet [5].

High-field magnetization of Spin-3/2 Breathing Pyrochlore Antiferromagnets. Y. Okamoto (Nagoya Univ.), M. Mori (Nagoya Univ.), A. Miyake (ISSP, Univ. Tokyo), M. Tokunaga (ISSP, Univ. Tokyo), A. Matsuo (ISSP, Univ. Tokyo), K. Kindo (ISSP, Univ. Tokyo), Z. Hiroi (ISSP, Univ. Tokyo), K. Takenaka (Nagoya Univ.) — A Cr spin oxide ACr$_2$O$_3$ with a nonmagnetic A$^{2+}$ ion at the tetrahedral site provides an interesting system for studying magnetic frustration in a pyrochlore lattice made of Cr$^{3+}$ ions with an $S = 3/2$ spin. We found a novel type of frustrated lattice called “breathing” pyrochlore lattice, which is made of Cr$^{3+}$ ions in LiGaCr$_4$O$_8$ and LiInCr$_4$O$_8$ [1]. Because of the large size mismatch between Li$^+$ and Ga$^{3+}$/In$^{3+}$ ions, they occupy the tetrahedral sites so as to form a zinc blende lattice. This transforms the conventional pyrochlore lattice into an alternating array of small and large tetrahedra, while keeping their shapes regular. LiInCr$_4$O$_8$ shows a spin-gap behavior in its magnetic susceptibility caused by a large alternation of magnetic interaction, although it finally goes to a magnetically ordered state accompanied by structural distortion [2,3]. We report the magnetization processes of LiInCr$_4$O$_8$ and LiGa$_{1.25}$In$_{0.75}$Cr$_4$O$_8$ up to 72 T measured at International MegaGauss Science Laboratory, ISSP, University of Tokyo. Magnetization of LiInCr$_4$O$_8$ measured at 1.4 K almost linearly increases with increasing magnetic field, while that of LiGa$_{1.25}$In$_{0.75}$Cr$_4$O$_8$ is small at a low magnetic field region and strongly increases above 15 T, probably corresponding to the spin gap behavior observed in magnetic susceptibility.
teristic domain selection associated with the $\varphi_2$ state, and the corresponding energy gap separating $\varphi_2$ from $\varphi_3$, vanish for $Y^{1+}$ substitutions between 10%-$Y$ and 20%-$Y$, far removed from the 3D percolation threshold of ~60%-$Y$. The resulting ground state for $\text{Er}_2\text{Ti}_2\text{O}_7$ with magnetic dilutions from 20%-$Y$ up to the percolation threshold is naturally interpreted as a frozen mosaic of $\varphi_2$ and $\varphi_3$ domains.


**S0212 Neutron Scattering Study in Breathing Pyrochlore Antiferromagnet $\text{Ba}_2\text{Yb}_2\text{Zn}_3\text{O}_{11}$**

T. Masuda (UTokyo), T. Haku (UTokyo), M. Soda (UTokyo), M. Sera (Osaka Univ.), K. Kimura (Osaka Univ.), J. Taylor (ISIS), S. Itoh (KEK), Y. Kono (KEK), Y. Matsumoto (UTokyo), D. Yu (ANSTO), R. A. Mole (ANSTO), T. Takeuchi (Osaka Univ.), S. Nakatsuji (UTokyo), Y. Kono (UTokyo), T. Sakakibara (UTokyo) and L.-J. Chang (NCKU) — Comprehensive study on breathing pyrochlore antiferromagnet $\text{Ba}_2\text{Yb}_2\text{Zn}_3\text{O}_{11}$ [1] is presented. To identify the energy scheme of crystalline electric field (CEF), we performed inelastic neutron scattering (INS) measurement in high energy range. The observed dispersionless excitations are explained by a CEF Hamiltonian of Kramers ion Yb$^{3+}$ of which the local symmetry exhibits $C_3v$, point group symmetry. The magnetic susceptibility is consistently reproduced by the energy scheme of the CEF excitations [2]. To identify the spin Hamiltonian we performed INS experiment in low energy range and thermodynamic property measurements at low temperatures. The INS spectra are quantitatively explained by spin-1/2 single-tetrahedron model having XXZ anisotropy and Dzyaloshinskii-Moriya interaction. This model has a two-fold degeneracy of the lowest-energy state per tetrahedron and well reproduces the magnetization curve at 0.5 K and heat capacity above 1.5 K. At lower temperatures, however, we observe a broad maximum in the heat capacity around 63 mK, demonstrating that a unique quantum ground state is selected due to extra perturbations with energy scale smaller than the instrumental resolution of INS. Possible mechanisms for the ground state selection are discussed [3].


**S0213 Fluctuation-dissipation relations in spin ice**

V. Raban (ENS Lyon, L2C), L. Berthier (L2C), P. Holdsworth (ENS Lyon) — Over the last decade spin ice materials, such as Dy$_2$Ti$_2$O$_7$, have been at the centre of attention in the frustrated magnetism community. In particular, the development of the so-called Dumbbell model, which pictures the low energy excitations as magnetic charges interacting through a magnetic Coulomb force, has provided an elegant way to study these materials, thanks to a mapping from the easy-axis Ising spins on the pyrochlore lattice to charges on the dual diamond lattice [1]. In parallel, some of the most significant progresses in non-equilibrium statistical mechanics in the last twenty years have come from the study of the fluctuation dissipation ratio when the system of interest evolves out of equilibrium [2]. However, there is still no such study for spin ice.

We fill this gap here. Using numerical simulations with local dynamics, we focus on the violation of the fluctuation-dissipation relation after a thermal quench for several physical observables such as the magnetization, the density of charges or the energy. This allows us to identify an aging regime in which we can extract effective temperatures and other characteristics of non-equilibrium thermodynamics. [1] Castelnovo et al., Magnetic monopoles in spin ice, Nature 451, 42-45, 2008; [2] Bouchaud et al., Out of equilibrium dynamics in spin glasses and other glassy systems, arXiv:cond-mat/9702070v1, 1997.
We have studied the newly discovered pyrochlore fluorides NaCaCo$_2$F$_7$ and NaSrCo$_2$F$_7$ using neutron scattering. These frustrated magnets with quenched exchange disorder remain in a strongly correlated paramagnetic states down to $\sim 1/60$th of their Curie-Weiss temperatures before undergoing freezing transitions. Below the freezing transitions, diffuse elastic scattering is observed that is consistent with short range correlated $XY$ antiferromagnetism. The $XY$ nature of the effective $S=1/2$ moments has been confirmed by high energy neutron spectroscopy probing the single-ion Hamiltonian. The relevant $XY$ configurations form a continuous manifold of symmetry-related states known as $G_5$, which is familiar from studies of the related $XY$ pyrochlore $Er_2Ti_2O_7$. Contrary to well-known models that produce this continuous manifold, order-by-disorder does not select an ordered state in these materials despite evidence for weak exchange disorder. Instead, the materials freeze into short range ordered clusters that span this manifold.


S0216 A phase diagram of breathing pyrochlores. K. Esso, L.D.C. Jaubert, M. Udagawa – The pyrochlore lattice is a paragon of magnetic frustration, where anisotropy is the name of the game. Anisotropy can take several forms: single ion, bond or lattice anisotropy for example. Motivated by the recently synthesized family of breathing pyrochlores (LiInCr$_4$O$_8$, Ba$_3$Yb$_2$Zn$_5$O$_{11}$...), here we shall investigate the latter kind of anisotropy, and use it as an additional knob to explore new facets of frustration.

S0217 Jahn-Teller coupling in Tb$_2$Ti$_2$O$_7$ at very low temperatures: Neutron diffraction in a [110] magnetic field. A. Sazonov (RWTH Aachen Univ. and JCMS at MLZ, Germany; LLB, Univ. Paris-Saclay, France), I. Mirebeau (LLB, Univ. Paris-Saclay, France), A. Gukasov (LLB, Univ. Paris-Saclay, France), P. Bonville (SPEC, Univ. Paris Saclay, France), C. Decorce (ICMMO, Univ. Paris-Saclay, France). – A way to investigate the ground state of a frustrated magnet is to perturb it by a magnetic field, that should provide a stringent test of the theories. An applied field induces long-range magnetic order in the geometrically frustrated cubic pyrochlore magnet Tb$_2$Ti$_2$O$_7$, which otherwise remains in a spin liquid state down to at least 50 mK [1]. The type of field-induced magnetic structures strongly depends on the direction of the applied field [2, 3]. Up to now, no model succeeded to account for all the features of the Tb$_2$Ti$_2$O$_7$ ground state. Nevertheless, we believe that part of the physical truth resides in the two-singlet model [4, 5]. In this model, the Hamiltonian is treated in a mean-field self-consistent approximation and includes the trigonal crystal field, the Zeeman interaction, and Tb-Tb interactions, i.e., anisotropic exchange and dipole-dipole coupling as well as the off-diagonal mixing term phenomenologically assimilated to a tetragonal distortion due to the Jahn-Teller effect. This model was able to reproduce successfully the low temperature experimental evolution of the Tb$_2$Ti$_2$O$_7$ bulk magnetization for different field directions [5] as well as the field-induced magnetic structure deduced from the single crystal neutron diffraction data in a magnetic field along the [111] direction which corresponds to a local easy anisotropy axis [3].

Here we compare calculations from the two single model with single crystal neutron diffraction data at very low temperatures (below 1 K) measured with the field applied along the twofold [110] axis. This field direction previously allowed us to observe original field effects, invisible in the evolution of the average magnetization, such as a field-induced spin melting [2] and a double-layered monopolar order [6]. We find that the Jahn-Teller distortion is an essential ingredient to reproduce the low-field (below 2 T) experimental data with $H \parallel [110]$, as previously observed for $H \parallel [111]$ case (Ref. [3]). It confirms that the two-singlet picture is suitable for an arbitrary direction of the applied field as already shown for bulk magnetisation data [5]. Moreover, we have studied the difference between microscopic and macroscopic realizations of the distortion, associated with static and dynamic Jahn-Teller effect, respectively. In the first variant (static Jahn-Teller effect), we assume that the Jahn-Teller distortion is static, extends over a finite domain size, and that domain orientations are equally distributed among the three cubic fourfold axes [100], [010], and [001]. In the second variant (dynamic Jahn-Teller effect), the distortion remains long-range, but its axis changes with time on each site between the three possible orientations. In the previous studies where the field was applied along the [111] axis (Ref. [3]) we found that the spin structures predicted assuming either static or dynamic Jahn-Teller effect were equally compatible with the neutron diffraction data. In the present geometry with $H \parallel [110]$, we show that the intensities of specific Bragg reflections calculated for static and dynamic variants, markedly differ at high fields, in contrast with the $H \parallel [111]$ case, where this difference was negligible. Comparison with the neutron diffraction data measured down to 60 mK shows a strong preference for the model of a dynamical Jahn-Teller effect.

**S0218** Magnetic interactions in Gd-based pyrochlore antiferromagnets.  
J R Stewart (STFC/SIS), G Ehlers (ORNL, USA), S Gardner (NSSRC and ANSTO) and J A M Paddison (Georgia Tech, USA) — We will present an analysis of the magnetic interactions in Gd-based pyrochlores using neutron diffuse magnetic scattering, and neutron inelastic scattering. The magnetic interactions are modelled via a combination of reverse-Monte Carlo (RMC), mean field and linear spin-wave theory. We find that in the case of Gd$_2$Sn$_2$O$_7$ - the measured diffuse scattering and spin-wave dispersion measured in powder samples are well described by a simple AFM $J_1$+dipolar Hamiltonian giving rise to the well-known $q=0$ Palmer-Chalker [1] ground state, whereas higher order AFM exchange is required to model Gd$_2$Ti$_2$O$_7$, and which gives rise to a much more complex magnetic structure [2]. [1] S E Palmer and J Chalker (2000). Physical Review B, 62(1), 488â–492; [2] J A M Paddison, A B Cairns, D D Khalyavin, P. Manuel, A Daoud-Aladine, G Ehlers, et al. (2015). arXiv:1506.05045

**03 Classical (Theory).**

**S0301** Multiple-$\mathbf{q}$ states of the $J_1$-$J_2$ classical honeycomb-lattice Heisenberg antiferromagnet under magnetic fields.  
T. Shimokawa, H. Kawamura (Osaka Uni., Japan) — Recent theoretical studies have revealed the presence of a variety of multiple-$\mathbf{q}$ states in the classical triangular-lattice Heisenberg model under magnetic fields [1]. Interestingly, the triple-$\mathbf{q}$ state corresponds to a topological state called the so-called skyrmion-lattice state, and this state is stabilized by the frustration effect caused by symmetric exchange interactions. In contrast to the standard skyrmion-lattice system stabilized by the anti-symmetric Dzyaloshinskii-Moriya interaction [2], both skyrmion and anti-skyrmion states are allowed. The triple-$\mathbf{q}$ state is expected in other lattices with a trigonal symmetry. In this study, we investigate whether such multiple-$\mathbf{q}$ states are realized in the $J_1$-$J_2$ classical honeycomb-lattice Heisenberg antiferromagnet under magnetic fields. While previous theoretical study showed the absence of the multiple-$\mathbf{q}$ states in zero magnetic field [3], our present numerical calculation reveals the emergence of the multiple-$\mathbf{q}$ states under magnetic fields, including the single-$\mathbf{q}$, double-$\mathbf{q}$ and triple-$\mathbf{q}$ states. Of particular interest is that the triple-$\mathbf{q}$ state here is not the skyrmion-lattice state, but is the “meron-like” lattice state. We also discuss the possible origin of these multiple-$\mathbf{q}$ states and the meron-like spin texture, paying attention to the difference from the case of the corresponding triangular-lattice model [1].


**S0302** Slow Spin Dynamics in the Classical Heisenberg Antiferromagnet on the Extended Kagome (or Swedenborgite) Lattice.  
Z. D. Tan (MOE), J. T. Chalker (Oxford) — We study the spin dynamics in the classical Heisenberg antiferromagnet on the extended kagome or Swedenborgite lattice. This lattice consists of alternating kagome and triangular layers and represents a novel topology for geometrically frustrated magnetism, realised in a class of rare-earth compounds $R$Ba$_2$Co$_3$O$_7$ ($R$ = rare-earth, Y). Neutron scattering experiments [1] on these materials find static spin correlations that are well reproduced by the Heisenberg model with nearest neighbour antiferromagnetic interactions. This model has a macroscopically degenerate ground state with static correlations that are weak in-plane but long-ranged between planes. It is known to display order-by-disorder, though with a very low transition temperature [2]. In this work, we present results for dynamical spin correlations in the disordered phase at low temperature, obtained from numerical integration of the semiclassical equations of motion. Strikingly, we find two different relaxation rates, with the kagome layer spins relaxing more quickly than the triangular layer spins: the relaxation rates $\Gamma$ vary with temperature $T$ as $\Gamma \sim T$ in kagome layers, and as $\Gamma \sim T^{3/2}$ in triangular layers [3]. We discuss how these differences arise from the anisotropic static correlations.


**S0303** The shuriken lattice: From reentrance to order- by disorder.  
R. Pohle, M, Taillefumier, L. Jaubert, N. Shannon — The two-dimensional shuriken lattice, also known as the square-kagome lattice, shows many similarities to the well-known kagome lattice. However, unlike kagome, the shuriken lattice has a large unit-cell containing two distinct types of nearest-neighbor bonds, between sites bordering on square plaquettes (AA), and sites bordering on octagonal plaquettes (AB). Providing a natural tuning parameter for different exchange parameters $J_{AA}$ and $J_{AB}$, we studied the thermodynamic phase diagram of the anisotropic shuriken lattice within the classical Ising model. We find a window in the phase diagram where magnetic disorder prevails down to zero temperature. In this region, the competition between multiple disordered ground states gives rise to a reentrant phenomenon, where both the low- and high-temperature regimes are less correlated than the intervening classical spin liquid. In addition, we present thermodynamic properties for the classical antiferromagnetic Heisenberg model on the isotropic shuriken lattice. Numerical simulations of the dynamical structure factor show harmonic spin excitations at very low temperatures, comparable to those found on the kagome lattice.

**S0304** Extended textures and collective dynamics of interacting fractional charges.  
M. Udagawa (Gakushuin U.), L. D. C. Jaubert (OIST), C. Castelnovo (U. Cambridge), R. Moessner (MPI PKS) and T. Mizoguchi (U. Tokyo) — Fractional charge is one of the characteristic features of topologically ordered systems. As
a typical example, spin ice, a representative frustrated magnet, has a degenerate ground state manifold with topological order, which supports fractional excitations, called magnetic monopoles in the presence of long-range dipolar interaction. Due to the intrinsic topological constraint, these fractional charges exhibit non-trivial collective behaviors, as observed in e.g. dynamics and transport properties of the system.

In this contribution, we consider the effect of interactions between fractional charges. Combined with the topological constraint, interactions give rise to rich cooperative phenomena of fractional charges [1]. To this aim, we adopt the $J_1-J_2-J_3$ spin ice model defined on a pyrochlore lattice, where farther-neighbor interactions introduce nearest-neighbor attraction/repulsion between fractional charges. The interaction leads to the condensation of charges, with the result that exotic charge-ordered states are stabilized. Among them, the metastability of fragmented Coulomb spin liquid [2] is allowed, providing a new avenue to engineer this novel Coulomb phase. Furthermore, if the interaction sign is chosen to be "unnatural", i.e. the like charges attract, an extended toroidal spin texture, which we call "jellyfish", is stabilized. This jellyfish structure gives rise to anomalous out-of-equilibrium dynamics with possible relevance to the spontaneous Hall effect observed in Pr$_2$Ir$_2$O$_7$ [1].


04 General (Theory).

S0401 Unveiling magnetic Hysteresis. P. Mellado, D. Aguayo, A. Concha (UAI) — Hysteresis manifests as the lack of retraceability of the magnetization curve in magnetic systems. It has been associated with rotation of magnetization and changes of magnetic domains. However, up to date there has been no realization that allows to separate these coupled mechanisms. We introduce a minimal magnetic system where hysteresis is realized in a simple and minimal fashion. The basic units are a few U(1) ferromagnetic altitudinal rotors placed along one dimensional chain. They exhibit a dissipative dynamics, interacting via magnetic coupling among them and via Zeeman interaction with the external magnetic field. The system displays a hysteretic behavior starting with N=2 rotors which remains qualitatively invariant as more magnets are added to the chain. We explain this irreversibility by using a model that includes Coulombic interactions between magnetic charges located at the ends of the magnets, zeeman coupling and viscous dissipation. We show that interactions between the unit components is the key element responsible for hysteresis and find that the ability to perceive hysteresis, depends on how the time frequencies of damping and interactions inherent to the system compare with the time frequency set by the external field ramping rate.


S0402 Spin-lattice-coupled ordering in Heisenberg antiferromagnets on the pyrochlore lattice. K. Aoyama and H. Kawamura (Osaka Univ.) — Antiferromagnets on the pyrochlore lattice are a typical example of frustrated magnets. It has been theoretically established that with the nearest-neighbor antiferromagnetic interaction alone, classical Heisenberg spins on the pyrochlore lattice do not order at any finite temperatures due to the massive degeneracy of the ground state. Weak perturbative interactions such as further-neighbor interactions would lift the degeneracy, eventually leading to the magnetic ordering, but the mechanism of the degeneracy lifting generally depends on specific materials. The spinel oxides ACr$_2$O$_4$ (A=Zn, Cd, Hg, Mg) are well-known pyrochlore antiferromagnets with spin-3/2. In ACr$_2$O$_4$, the system undergoes a first-order transition into the magnetic long-range-ordered state accompanied by a structural transition which lowers the crystal symmetry. In spite of the spin-lattice coupling (SLC) commonly seen in these chromium spinels, the spin-ordering patterns vary from material to material, and the origin of the magnetic orderings has not been well understood. In view of such an experimental situation, we investigate effects of local lattice distortions on long-range spin ordering in the antiferromagnetic classical Heisenberg model on the pyrochlore lattice.

The results of our Monte Carlo simulations show that the SLC originating from site phonons induces a first-order transition into two different types of collinear magnetic ordered states.


S0403 Weyl Magnon. FEI-YE LI (Chinese Academy of Sciences), YAO-DONG LI (Fudan Univ), YUE YU (Fudan Univ), YONG BAEEK KIM (Univ of Toronto; Korea Institute for Advanced Study), LEON BALENTS (UCSB), GANG CHEN (Fudan Univ; Perimeter Institute for Theoretical Physics) — Using a physically relevant spin model for a breathing pyrochlore lattice, we discuss the presence of topological linear band crossings of magnons in antiferromagnets. These are the analogs of Weyl fermions in electronic systems, which we dub “Weyl magnons”. The bulk Weyl magnon implies the
presence of chiral magnon surface states forming arcs at finite energy. We argue that such antiferromagnets present a unique example in which Weyl points can be manipulated in situ in the laboratory by applied fields. We discuss their appearance specifically in the breathing pyrochlore lattice, and give some general discussion of conditions to find Weyl magnons and how they may be probed experimentally. Our work may inspire a re-examination of the magnetic excitations in many magnetically ordered systems.


**S0404** Finite-Temperature Signatures of Spin Liquids in Frustrated Hubbard Model. T. Misawa (Univ. of Tokyo), Y. Yamaji (Univ. of Tokyo) — The two-dimensional $t$-$t'$-$t''$ Hubbard model is one of the simplest theoretical models that describes competition and cooperation of the strong electronic correlations and the geometrical frustrations. In this model, due to the next-nearest neighbor hopping $t''$, which induces the next-nearest neighbor antiferromagnetic interactions, the competition between two magnetic phases occurs: Simple Néel states become stable when $t''$ is small compared to the nearest-neighbor hopping $t$ while tripe states become stable for large $t''$ region ($t''/t \sim 1$). Several theoretical calculations for the ground states of the frustrated $t$-$t'$ Hubbard model including its strong coupling limit, i.e., the frustrated $J_1$-$J_2$ Heisenberg model, have been done so far. Most of previous calculations suggest that quantum spin liquid states actually appear [1-5] around intermediate region ($t''/t \sim 0.75$ or $J_2/J_1 \sim 0.5$). In spite of the huge amount of the studies for the ground states, there are few unbiased theoretical studies on the finite-temperature properties of the frustrated Hubbard model due to the lack of the efficient theoretical method.

Recently, an efficient numerically unbiased method for calculating finite temperature properties in quantum systems is proposed [6]. In this method, it is shown that the calculation within small number of pure states instead of the full ensemble average is sufficient for accurate estimates of finite-temperature properties. Such pure states are called thermal pure quantum (TPQ) states and they are easily generated by performing the imaginary-time evolution of the wave function starting with a random vector. By using the TPQ method, we systematically study finite-temperature properties of the frustrated Hubbard model. As a result, around $t''/t \sim 0.75$, we find the evidence of the spin liquid states from the calculations on temperature dependence of the spin correlations and entropy. The present unbiased and detailed numerical calculations also offer an experimental criterion of closeness to the spin liquid phase: Finite-temperature entropy at moderate temperatures $T/t \sim 0.1$ significantly correlates with closeness to the spin liquid phase. We also show that such signatures of quantum spin liquid states can be observed in an ab initio models [7] for spin-liquid candidates EtMe$_3$Sb[Pd(dmit)$_2$]$_2$.


**S0405** Demagnetizing factors for magnetic lattices. P. Henelius (KTH), M. Twengström (KTH), L. Bovo (UCL), M. Gingras (U. Waterloo), S. Bramwell (UCL) — Highly-frustrated magnetic materials are characterized by an inherently strong competition between different candidate ground states, with the true ground state often ultimately selected by perturbatively small terms in the effective spin Hamiltonian. Given this fine-tuning problem, understanding the origin of the selected state requires an accurate determination of the leading competing energy scales characterizing the spin Hamiltonian. Irrespective of the chosen experimental protocol (elastic and inelastic neutron scattering, specific heat, magnetization, susceptibility), such an experimental program often proceeds through measurements carried out in nonzero magnetic fields and requires analyzing the data with the appropriate demagnetization transformation. Given the fine-tuning problem alluded to above in the case of highly-frustrated systems, it is clearly imperative that careful "demagnetization corrections" be performed when extracting data aimed to be quantitatively described by theory. In addition, demagnetization effects will induce spatial variations in the internal field, complicating the interpretation of fine-tuned field-induced transitions. When attempting to perform the necessary demagnetization transformation a major problem has been the uncertainty in what demagnetizing factor to use for non-ellipsoidal samples. In order to resolve this issue we have developed an iterative method to calculate the demagnetizing factor for a lattice of isolated magnetic moments. Contrary to common assumptions we find that the demagnetizing factors are not only functions of the sample shape and susceptibility, but also of the underlying lattice, moment direction and symmetry. We show results for important examples such as the pyrochlore lattice, relevant for the spin ice materials. We discuss implications on experiments involving accurate determination of magnetic susceptibilities, as well as precise alignment of magnetic fields.
**S0406 Steady States of Dissipative Quantum Chains via Imaginary Time Evolution.** A. Gangat (NTU), T. I (NTU), Y.-J. Kao (NTU) — In tensor network-based approaches to non-dissipative quantum lattice systems, imaginary time evolution serves as a robust, efficient, and accurate non-variational method for determining ground states that obey an area law [1]. In particular, the infinite-size version of the time-evolving block decimation algorithm (iTEBD) allows the imaginary time evolution method to be used to find the ground states of translationally invariant infinite-size non-dissipative quantum chains directly in the thermodynamic limit [2]. Recently it was proven that the steady states of a large class of dissipative quantum systems obey an area law and exhibit exponential decay of two-point correlators [3]. In this work we show how to leverage these results in order to use imaginary time evolution of matrix product density operators with the iTEBD algorithm to find the non-equilibrium steady states of translationally invariant dissipative quantum chains in the thermodynamic limit. We demonstrate our method with the infinite-size transverse field dissipative quantum Ising chain.


**S10407 Tensor Network Studies on Antiferromagnetic Ising Chain in External Fields.** Y.-P. Lin (NTU), Y.-C. Lin (NCCU), P. Chen (NTHU), and Y.-J. Kao (NTU) — In this work, we study the quantum phase transitions of 1D antiferromagnetic (AFM) Ising model in the presence of transverse and longitudinal fields. We first consider the clean model, which is homogeneous over the whole chain. The ground state is obtained with the density matrix renormalization group (DMRG) in the fashion of matrix product states (MPS) and matrix product operators (MPO). With the discovery of MPO for powers of order parameter, we compute the Binder cumulant and determine the critical point. The results show that the separation of AFM and paramagnetic (PM) phases extends to the nonzero longitudinal field regime. Next, we set disorder to the spin couplings and transverse fields. After deriving the ground state with tree tensor network strong disorder renormalization group (TS-DRG), we find that the results of Binder cumulant incades the destruction of phase transitions in nonzero longitudinal field regime. This is due to the emergence of rare regions with ferromagnetic (FM) configurations. We also consider the distribution of energy gaps and end-end correlation functions over disorder realizations, which shows infinite randomness behavior at the critical point and Griffiths phase behavior in the disordered phase. The dynamical exponent can be determined from the finite-size scaling of these distributions.

**S0501 Evolution of Magnetic and Transport Properties in Hole Doped Y$_2$Ir$_2$O$_7$.** Harish Kumar and A. K. Pramanik (JNU, New Delhi) — Pyrochlore iridates A$_2$B$_2$O$_7$ (A = rare earth elements) are very interesting showing exotic electronic and magnetic properties [1]. With the extended 5d character of Ir they exhibit reduced electronic correlation (U), however, the heavy nature of Ir gives prominent spin orbit coupling (SOC) effect. Moreover, the interpenetrating layers of IrO$_6$ octahedra and OA$_2$ tetrahedra introduce geometrical frustration. This frustration is seen to give rise many interesting phenomena such as, spin glass, spin ice, spin liquid, etc. The physical properties interestingly evolve with A-site element: from magnetic insulating to complex metallic phases [2]. When the A$^{3+}$ ion is magnetic, there is a possibility of f-d exchange interactions between Ir$^{4+}$ and A$^{3+}$ ions which naturally induces complicated magnetic interactions in Ir-based pyrochlores [3]. The Y$_2$Ir$_2$O$_7$ is of special interest as the nonmagnetic Y$^{3+}$ resides at A-site. In this sense, Ir$^{4+}$ ion (5d$^5$) with single unpaired electron generate frustration in this material. The Y$_2$Ir$_2$O$_7$ shows an insulating behavior where the resistivity increases with decreasing temperature. Y$_2$Ir$_2$O$_7$ shows irreversibility in magnetization data around 160 K [4, 5, 6]. Given that frustration plays vital role in pyrochlore lattice the spin freezing to glassy state could also be a probable magnetic state in Y$_2$Ir$_2$O$_7$ at low temperature [4, 7, 8]. We have studied the effect of Ru doping on pyrochlore iridate Y$_2$Ir$_2$O$_7$. The purpose of Ru-substitution is to tune the electronic correlation, spin-orbit coupling (SOC), band filling and level of frustration which will help to investigate the physical properties of this material. Magnetization data of Y$_2$Ir$_2$O$_7$ show irreversibility in zero-field-cooled and field-cooled data with an onset temperature around $T_{irr} \sim 160$ K and relevant frustration parameters ($f = 2.4$). Substitution of Ru$^{4+}$ (4d$^4$) on Ir$^{4+}$ (5d$^5$) site not only reduce the SOC but also introduce a hole in $t_{2g}$ band, which reduce the level of Fermi surfaces $E_F$, therefore, the system is expected to go away from the insulating to metallic state. This substitution, however, does not introduce significant structure modification. With Ru substitution, we find that magnetic moment, Curie temperature, frustration parameters ($f$) and magnetic irreversible temperature $T_{irr}$ decreases. Moreover, Resistivity data of Y$_2$Ir$_2$O$_7$ show insulating behavior throughout the temperature range, however, on Ru substitution, resistivity is decreased.


**S0502 Charge density wave like phase transition in doped Na$_3$IrO$_4$.** K. Mehiawat, Y. Singh (IISER Mohali, India) — Uncon-
ventional spin triple superconductor and topological superconductor have been predicted to emerge with hole doping in the Kitaev-Heisenberg model on the honeycomb lattice relevant for the iridates $\text{A}_2\text{IrO}_3$ ($\text{A} = \text{Na, Li}$) [1,2]. Additionally spin/charge density waves, electronic dimerization instabilities, and bond order instabilities have been predicted on doping for antiferromagnetic Kitaev and ferromagnetic Heisenberg interaction [3]. We report [4] the density wave-like phase transitions or structural transitions in surface doped $\text{Na}_2\text{IrO}_3$ crystals. We find that the surface of $\text{Na}_2\text{IrO}_3$ crystals turn metallic by high energy Ar plasma etching which leads to removal of Na from the surface. With varying exposure time we were able to change the resistivity by several orders of magnitude and go from an insulating to a metallic surface. Temperature dependent resistivity $\hat{\rho}(T)$ for 20 and 30 minutes etched samples show charge density wave like phase transitions with abrupt change in $\hat{\rho}$ at $T_\text{J}= 220$ and 95 K, respectively. The phase transition is first order as revealed by a 10 K thermal hysteresis between cooling and warming measurements. The most metallic (30 minute etched) sample follows a T2 Fermi liquid behavior at low temperature. The surface structure of $\text{Na}_2\text{IrO}_3$ does not change by plasma etching as revealed by grazing incident small angle x-ray scattering (GISAXS).

In this presentation, we first derive a generic spin model by considering multiorbital interactions and the spin-orbit coupling for $t_{2g}$ orbitals. We obtain the generic spin model with four parameters: $J$, for the Heisenberg term, $K$, for the Kitaev term, $\Gamma$ for the symmetric anisotropic exchange term, and $D$, for the Dzyaloshinskii-Moriya term. We then show the magnetic phase diagram of this model obtained by a combination of Luttinger-Tisza analysis and classical Monte Carlo simulated annealing. We find that there are three non-coplaner $q=0$ states: $Z_6^2$, $Z_6^{2p}$, and $Z_6^p$ states. The spin configurations of these three $q=0$ states can be characterized by the underlying lattice symmetries. Finally, we present the possible explanation for the spin freezing behavior on the basis of our theoretical analysis.

[S0504] Effect of Carrier Doping on the Geometrically Frustrated Iridate $\text{Ca}_2\text{Ir}_2\text{O}_{12}$. Y. Yasukuni, R. Fukuoka, S. Maeda (Kyutech), M. Wakasima (Hokkaido Univ.), Y. Hinatsu (Hokkaido Univ.), K. Nakamura (Kyutech), Y. Yoshimoto (Univ. Tokyo) and K. Matsushita (Kyutech)—Calcium iridate $\text{Ca}_2\text{Ir}_2\text{O}_{12}$ with a mixed valance state of $\text{Ir}^{3+}$ and $\text{Ir}^{5+}$ has a hexagonal structure with space group of $\text{R6}2\text{m}$ (No. 189) [1]. As one-dimensional chains of the edge-sharing $\text{IrO}_6$ form triangular lattices, $\text{Ca}_2\text{Ir}_2\text{O}_{12}$ is geometrically frustrated 5d electron system with strong spin-orbit coupling (SOC). It is reported that $\text{Ca}_2\text{Ir}_2\text{O}_{12}$ shows a semiconducting conductivity and an antiferromagnetic ordering below 7.8 K [1,2]. We have studied the transport and magnetic properties of geometrically frustrated $\text{Ca}_2\text{Ir}_2\text{O}_{12}$ with strong SOC by using the effect of carrier doping. The electron doping by replacing $\text{Ca}^{2+}$ with $\text{M}^{2+}$ can change the ratio of mixed valence state of Ir ions. We will report the electrical conductivity, thermoelectric power and magnetic properties. Furthermore, we will discuss the electronic structure of $\text{Ca}_2\text{Ir}_2\text{O}_{12}$ derived by first-principle calculation.

[S0505] Ordered moment direction within the extended Kitaev-Heisenberg model for honeycomb magnets $\text{RuCl}_3$ and $\text{Na}_2\text{IrO}_3$. J. Chaloupka (CEITEC MU), G. Khaliullin (MPI-FKF)—We study the ordered moment direction within the extended Kitaev-Heisenberg model suggested for honeycomb magnets such as $\text{RuCl}_3$ and $\text{Na}_2\text{IrO}_3$. We utilize numerical diagonalization and analyze the exact cluster groundstates using a particular set of spin coherent states. Focusing on the experimentally relevant zigzag phases of the model, we deal primarily with the case of a ferromagnetic Kitaev interaction that...
shows a rich interplay of the Kitaev interaction and further symmetry allowed bond-anisotropic interactions in selecting the moment direction. It is found that the quantum fluctuations strongly modify the moment direction obtained at a classical level, and their inclusion is crucial for a precise quantification of the interactions. The results show that the moment direction is a sensitive probe of the model parameters in real materials. We analyze the currently available neutron and resonant x-ray diffraction data on RuCl$_3$ and Na$_2$IrO$_3$, and suggest the realistic parameter regimes in these Kitaev-Heisenberg model systems.

**S0506 Anisotropy tuned magnetic order in pyrochlore iridates.** E. Lefrançois (Institut Néel & Institut Laue-Langevin, Grenoble, France), V. Simonet, R. Ballou, L. Htel, A. Haji-Azzem, S. Kodjikian, P. Lejay (Institut Néel, Grenoble, France), P. Manuel, D. Khalyavin (RAL-STFC, Didcot, United Kingdom) and L. C. Chapon ( Institut Laue-Langevin, Grenoble, France) – Attention of the condensed matter community was recently attracted by the pyrochlore iridates R$_2$Ir$_2$O$_7$ (R = rare-earth ion) where magnetic frustration, strong spin-orbit coupling associated to the Ir$^{4+}$ ions and magnetocrystalline anisotropy associated to the rare earth ions coexist and lead to exotic magnetic phases and unprecedented electronic transport properties. These compounds exhibit in particular a spin-orbit driven metal-insulator transition at the temperature corresponding to the onset of the Ir$^{4+}$ magnetic ordering. The transition temperature and the high-temperature electronic state both depend on the rare-earth ion [1]. Moreover, topologically protected insulating phases are predicted in these materials associated to a non-collinear magnetic ordering of the Ir sublattice with all the magnetic moments pointing towards or away from the center of each tetrahedron (all-in-all-out order) [2]. This order is however very difficult to probe due to the tiny magnetic moment of the Ir.

We performed magnetization measurements and neutron powder diffraction experiment measurements on Tb$_2$Ir$_2$O$_7$ and on Er$_2$Ir$_2$O$_7$ which are characterized by different magnetocrystalline anisotropies of the rare-earth: along the local <111> directions for the Tb (easy-axis) and perpendicular to these for the Er (easy-plane). A radically different magnetic behavior of the rare-earth sublattice is evidenced: An all-in-all-out order is observed on the Tb magnetic sublattice below 40 K whereas the Er sublattice does not present long-range order down to 60 mK. This contrasting behavior is explained by the interaction between the iridium and the rare earth magnetic moments. The all-in-all-out order of the Iridium produces a local molecular field along the <111> directions on each rare earth ion site. This magnetic field is compatible with the anisotropy of the Tb, its magnetic moments getting aligned along the field in the observed all-in-all-out configuration. On the contrary, the iridium magnetic field is competing with the Er magnetic anisotropy, thus preventing the Er magnetic ordering [3]. Additional neutron powder diffraction studies realized on pyrochlores with other rare-earth ions presenting an easy-axis anisotropy (Ho and Dy) or an easy-plane anisotropy (Yb) confirmed this result either by displaying an all-in-all-out magnetic order or by remaining disordered.

Our study finally gives a unified picture of the magnetic behavior of these materials, highlighting the strong coupling between the rare-earth and the Ir atoms. This coupling allows us to establish on a firm ground the all-in/all-out magnetic order of the Ir sublattice, thus expected to be a common feature of the family, and which was awaited as a signature of the topological nature of the low temperature insulating state. Beyond these unconventional electronic transport properties, these pyrochlore iridates provide an original playground to study novel magnetic properties in rare-earth pyrochlores submitted to a well-controlled (111) local molecular field. [1] Matsuhira et al., JPSJ 80 (2011) 094701; [2] Wan et al., PRB 83 (2011) 205101; [3] Lefrançois et al, PRL 114 (2015) 247202

**S0507 Anisotropic interactions opposing magnetocrystalline anisotropy in Sr$_2$NilO$_6$.** E. Lefrançois (Institut Néel & Institut Laue-Langevin, Grenoble, France), A-M. Pradipato (CNR-SPIN, L’Aquila, Italy), M. Moretti Sala (ESRF, Grenoble, France), L. C. Chapon (Institut Laue-Langevin, Grenoble, France), V. Simonet (Institut Néel, Grenoble, France), S. Picozzi (CNR-SPIN, L’Aquila, Italy), P. Lejay (Institut Néel, Grenoble, France), S. Petit (Laboratoire Léon Brillouin, Gif-sur-Yvette, France) and R. Ballou (Institut Néel, Grenoble, France) – Oxides of the family A$_2$MM’O$_6$ (A = alkaline-earth metal, M, M’ = transition metal) crystallize in a structure where the M and M’ ions form chains distributed on a triangular lattice. This structure gives rise to a low dimensional chain magnetism with interchain geometric frustration. We studied the 5d-based compound Sr$_2$NilO$_6$, where the strong spin-orbit coupling on the Ir$^{4+}$ ions induces additional unexpected behaviors through spin-orbit entanglement.

We performed single crystal magnetization, powder neutron diffraction and single crystal resonant inelastic and elastic scattering (RIXS/REXS) measurements. The magnetization measurements revealed an anisotropic behavior with the Ni$^{2+}$ and Ir$^{4+}$ magnetic moments confined along the chain axis. Besides these measurements evidenced two characteristic temperatures at 70 and 17 K. The higher temperature is associated with the onset of a long-range magnetic order while the lower temperature marks the re-entrant competition between different ground states. The magnetic structure determined from powder neutron diffraction as well as from symmetry arguments is found to exhibit signatures of magnetic frustration [1].

The role of the Ir$^{4+}$ strong spin-orbit coupling on the magnetic properties was further established through RIXS mea-
measurements. These allowed us to probe the electronic and magnetic excitations associated to the $5d$ Ir$^{4+}$ electronic states. We were in particular able to determine a spin wave model accounting for the quasi-dispersionless magnetic excitations of the compound. Remarkably, the easy-axis magnetic structure observed in Sr$_2$NiIrO$_6$ is found to arise from highly anisotropic magnetic interactions induced by the spin-orbit coupling, counterbalancing the strong Ni$^{2+}$ easy-plane magnetocrystalline anisotropy [2,3]. Therefore Sr$_2$NiIrO$_6$ lies close to a quantum phase transition boundary separating the ordered Ising ferrimagnet from a disordered XY phase. These results overall demonstrate the potential of spin-orbit coupling and frustration in triggering emerging physics.


**S0509 Low temperature magnetic properties of frustrated pyrochlore ferromagnet Ho$_2$Ir$_2$O$_7$.** D. Kumar (NCKU), S.Y. Chen (NCKU), M.K. Lee (NCKU), I.J. Chang (NCKU), N. K. Chogondahalli M. (UCNS-SNS), R. Aldus (UCNS-MLZ), M. R. Lees (UofWarwick), A. Hillier (ISIS) – We have performed low temperature magnetic susceptibility, specific heat, neutron diffraction and $\mu$SR measurements to study the magnetic properties of pyrochlore Ho$_2$Ir$_2$O$_7$. The accumulated value of observed entropy driven from heat capacity data is Rln2, indicating the Ho$^{3+}$ doublet ground state. The Ir sublattice orders in the antiferromagnetic which is evidenced by the magnetization and $\mu$SR measurements. The best fit of the neutron diffraction spectra at 1.8 K shows the magnetic structures with two types of components. One of the magnetic structure is all-in-all-out type which is due to the strong coupling between Ho$^{3+}$ and Ir$^{4+}$ ions and develops below 18 K. It suggests the magnetic moment of Ho$^{3+}$ ions aligns in the field of Ir$^{4+}$ ordering along local (111) directions [1,2]. There is also a Ho$^{3+}$ magnetic component perpendicular to (111) below 100 K. This perpendicular component may originate from the defects in the Ir sublattice. Defects such as Ir deficiency or an Ir atom pointing at the opposite direction will cause the emergent of the perpendicular component [1].


**S0510 Low temperature Magnetic properties of iridium pyrochlores R$_2$Ir$_2$O$_7$(R=Yb, Nd, Ho, Tb).** K.-C. Chien, L.-I. Chang (NCKU, Taiwan) – Materials with the cubic pyrochlore structure have been studied extensively for the past 20 years because of their propensity to form unusual magnetic ground states resulting from geometrical frustration. Recently, iridated-pyrochlore compounds which possess 5d-electron elements have the growing interests primarily because of the interplays between electron-electron correlations and spin-orbit interactions in these materials. We will present the experimental results of resistance, DC susceptibility, magnetization, and heat capacity on the pyrochlore family of iridate compounds R$_2$Ir$_2$O$_7$(R=Yb, Nd, Ho, Tb). The resistance and magnetization measurements confirm the Ir metal-insulator transition temperature at 135, 33, 141, and 131 respectively [1,2]. We quantitatively calculated the Curie-Weiss temperature $\theta_{CW}$ and the effective magnetic moment $\mu_{eff}$ to extrapolate the antiferromagnetism ordered by R ions sublattice[3,4]. Magnetization as a function of magnetic field measured at 2 K shows a small hysteresis in Ho and Tb, which may be related to the clustering phenomenon. A peak which is in line with the form of the Schottky specific heat is observed at very low temperature in the specific heat measurements of R$_2$Ir$_2$O$_7$, and there are the long-range orders in Yb, Nd and Ho. However we did not observed long-range order in Tb down to 50 mK.


**S0511 Distance between a Kitaev spin liquid and a honeycomb iridate Na$_3$IrO$_3$ revealed by thermal and spin excitations.** Y. Yamaji (Univ. of Tokyo, Japan), S. Suzuki (Univ. of Hyogo, Japan), T. Yamada (Univ. of Hyogo, Japan), S. Suga (Univ. of Hyogo, Japan), N. Kawashima (Univ. of Tokyo, Japan), M. Imada (Univ. of Tokyo, Japan)
In the search for realization of the Kitaev’s quantum spin liquid (QSL) phases [1], a honeycomb iridate Na$_2$IrO$_3$ has attracted attention as one candidate material [2,3]. Contrary to the original expectation [2,3], however, Na$_2$IrO$_3$ is not a Kitaev’s QSL but shows a zigzag-type antiferromagnetic order [4]. Here, we propose experimental criteria to measure how a material in hand is close to the Kitaev’s QSL phase. For this purpose, we systematically study thermal and spin excitations of a generalized Kitaev-Heisenberg model studied by Chaloupka, Jackeli, and Khaliullin [3], and an effective ab initio Hamiltonian for Na$_2$IrO$_3$ proposed in Ref. [5], by employing a numerical diagonalization method and thermal pure quantum states [6]. We reveal that closeness to the Kitaev’s QSL is characterized by the following properties [7], besides trivial criteria such as reduction of magnetic ordered moments and Néel temperatures. (1) Two peaks in the temperature dependence of specific heat at $T_1$ and $T_2$ caused by the fractionalization of spin to two types of Majorana excitations [8]. (2) In between the double peak, a prominent plateau or shoulder pinned at $(R/2)$ In2 in the temperature dependence of entropy, where $R$ is the gas constant. (3) Failure of the linear spin wave approximation at the low-lying excitations of dynamical structure factors. (4) Small ratio $T_2/T_1$ close to or less than 0.03. According to the proposed criteria, Na$_2$IrO$_3$ is categorized to a compound close to the Kitaev’s QSL, and is proven to be a promising candidate for the realization of the QSL if the relevant material parameters can further be tuned by making thin film of Na$_2$IrO$_3$ on various substrates or applying axial pressure perpendicular to the honeycomb networks of iridium ions. Applications of these characterization to (Na$_{1-x}$Li$_x$)$_2$IrO$_3$ and other related materials are also discussed.


06 Kagome Based.

**S0601 Topological Hall effect in an itinerant-electron kagomé ferromagnet.** M. A. Kassem (Kyoto Univ.), K. Itou (Kyoto Univ.), Y. Tabata (Kyoto Univ.), T. Waki (Kyoto Univ.), H. Nakamura (Kyoto Univ.) — As one of the most interesting spin states, spin chirality plays principal roles in emergences of unconventional magnetic phenomena that recently attracted a great intention in the condensed matter physics. One of these phenomena is the unconventional anomalous Hall effect (UAHE) observed in geometrically frustrated spin systems [1,2]. The itinerant-electron ferromagnet Co$_9$Sn$_2$S$_2$ ($I_C \sim 174$ K) of the stacked-kagomé-layered crystal structure of space group $R3m$ is a spin-frustrated system that exhibits exotic magnetic and electronic properties by In-substitution [3,4]. Magnetization measurements show a ferromagnetic-nonnegative quantum phase transition around $\Delta H \sim 0.8$. Crystal structure analysis and resistivity measurements indicated an enhanced quasi-2D character by In-substitution [5,6]. In this work, a chiral spin state is observed in the magnetically frustrated system Co$_9$Sn$_2$In$_{0.8}$S$_2$ shandites through a combined work of the magnetization and magneto-transport measurements. We found that the transverse resistivity $\rho_{xy}$ violates the empirical relation of the anomalous Hall effect in magnetic compounds: $\rho_{xy} = R_{0B} + 4\pi R_{B}M$, where $R_0$ and $R_3$ are the ordinary and anomalous Hall coefficients, and $M$ and $B$ are the magnetization and magnetic induction, respectively. In the vicinity of the critical concentration of the ferromagnetic phase, $0.5 < x < 0.8$, a large additional topological term of the UAHE, $\Delta H$, is observed at low temperatures. The large positive $\Delta H$ indicates a uniform chirality due to a manifestation of a static chiral order. Our results suggest that chiral spin states ubiquitously emerge near quantum critical points in spin-frustrated itinerant-electron ferromagnets.


**S0602 Novel Magnetic Phenomena in the three $S = 1$ V$^{3+}$ Kagomé Lattice Antiferromagnets A$_1$BY$_3$F$_{12}$ ($A$, $B$: alkali metal).** M. Goto (Kyoto Univ.), H. Ueda (Kyoto Univ.), C. Michioka (Kyoto Univ.), A. Matsuo (ISSP, Univ. of Tokyo), K. Kindo (ISSP, Univ. of Tokyo), and K. Yoshimura (Kyoto Univ.) — Kagomé lattice antiferromagnets have been expected to exhibit exotic magnetic phenomena, such as a spin liquid ground state[1] and a 1/3 magnetization plateau[2]. We study new kagomé fluoride systems A$_2$BM$_2$F$_{12}$ ($A$, $B$: alkali metal, $M$: Ti, V), which have ordered structure of the modified pyrochlore. They crystallize in monoclinic structure, and the magnetic $M^{3+}$ ions form slightly distorted kagomé lattices. Three $S = 1/2$ Ti$^{3+}$ kagomé fluorides A$_2$BTi$_3$F$_{12}$ have quantum disordered grounds states, reflecting the combination of strong quantum fluctuation and spin frustration. In this presentation, we report structural and magnetic properties of three $S = 1$ kagomé lattice antiferromagnets Rb$_2$NaV$_3$F$_{12}$, Cs$_2$NaV$_3$F$_{12}$, and Cs$_2$KVF$_3$F$_{12}$ using single crys-
Recently a model compound for Kagome lattice where three neighbor interaction in frustrated magnets plays an impor-
tating an easy-plane anisotropy for 

Here we study the effect of the interlayer coupling (ILC) on wards magnetic LRO is to consider coupled kagome layers.

For the fully isotropic KHAF we find that the spin-liquid ground state persists until relatively large strengths of the ILC. If the strengths of the ILC exceeds about 15% of the intralayer coupling the spin-liquid phase gives way for $q = 0$ magnetic long-range order, where the transition between both phases is continuous and the critical strength of the ILC, $|J_{ILC}^c|$, is almost independent of the sign of $J_{LL}$. At larger $|J_{ILC}|$, the ILC drives a first-order transition to the $\sqrt{3} \times \sqrt{3}$ long-range ordered ground state. Introducing an easy-plane anisotropy to the kagome layers the critical strength of the ILC decreases and becomes about 5% for XY kagome layers.

Magnetic properties of $S = 1/2$ kagome lattice antiferromagnet CaCu$_3$(OH)$_6$Cl$_2$. $\frac{1}{2}$H-O.

neighbou interaction in frustrated magnets plays an important role in the determination of the magnetic ground state. Recently a model compound for Kagome lattice where three of six next-nearest neighbor (NNN) interactions are non-
negligible was reported in NaBa$_2$Mn$_3$F$_{11}$ [1]. Theoretical calculation for the Kagome-Triangular lattice predicted various phases including 120° structure and non-coplanar Cubic structure depending on the strength of the NNN interaction.

In order to reveal the magnetic state we performed powder neutron diffraction experiments using ECHIDNA diffrac-
tometer installed at OPAL and WISH diffractometer installed at ISIS. More than 10 magnetic Bragg peaks are clearly observed below $T = 2.2$ K, meaning that the ground state is a magnetically ordered state. From indexing the magnetic Bragg peaks, magnetic propagation vector of $q_0 = (0,0,0)$ and three incommensurate vectors which are close to $(1/3, 1/3, 0)$ are identified. Representation analysis and Rietveld refinement reveal that the propagation vector of $q_0$ exhibits the 120° structure on the $ab$-plane, and the incommensurate propagation vectors exhibit slight modulation of the 120° structure.


Emergence of magnetic long-range order in kagome quantum antiferromagnets.

J. Richter, O. Götze (University Magdeburg, Germany) — The existence of a spin-liquid ground state of the spin-1/2 kagome Heisenberg antiferromagnet (KHAF) is well established. Meanwhile, also for the spin-1 KHAF evidence for the absence of magnetic long-range order (LRO) was found. On the other hand, recently it has been re-
ported that magnetic LRO can be established by (i) increasing the spin quantum number to $s > 1/2$ [1] and, (ii) by including an easy-plane anisotropy for $s \geq 1$ [2]. A natural route towards magnetic LRO is to consider coupled kagome layers. Here we study the effect of the interlayer coupling (ILC) on the ground state ordering in a stacked kagome spin-1/2 XXZ antiferromagnet with easy-plane anisotropy in the layers by using the coupled-cluster method to high orders of approxi-
mation. We consider a perpendicular isotropic ILC $J_{ILC}$, where we study ferro- as well as antiferromagnetic $J_{ILC}$. Such a per-
pendicular ILC can be relevant for barlowite with selective isoelectronic substitution of interlayer Cu ions [3].

For the fully isotropic KHAF we find that the spin-liquid ground state persists until relatively large strengths of the ILC [4]. Only if the strength of the ILC exceeds about 15% of the intralayer coupling the spin-liquid phase gives way for $q = 0$ magnetic long-range order, where the transition between both phases is continuous and the critical strength of the ILC, $|J_{ILC}^c|$, is almost independent of the sign of $J_{LL}$. At larger $|J_{ILC}|$, the ILC drives a first-order transition to the $\sqrt{3} \times \sqrt{3}$ long-range ordered ground state. Introducing an easy-plane anisotropy to the kagome layers the critical strength of the ILC decreases and becomes about 5% for XY kagome layers.

CaCu$_3$(OH)$_6$Cl$_2$·0.7H$_2$O with space group $P$-3$m$1 have been reported [3]. The compound shows the weak ferromagnetic behavior at $T_N = 7$ K probably due to the DM interaction. The magnetic properties of our single crystals, however, differ from those of reported on polycrystalline sample. Magnetic susceptibilities $\chi_c$ and $\chi_{ab}$ obey the Curie-Weiss law at high temperature, and $\theta_W = -100.3$ K for the $c$-direction and $\theta_W = -94.5$ K for the $ab$-direction were estimated. The larger value of $\chi_c$ than that of $\chi_{ab}$ in whole temperature range and $g$-value $g_c = 2.45$ and $g_{ab} = 2.22$ suggests the ising anisotropy along the $c$-axis in the compound. The magnetic anomaly, however, appears only in the $ab$-direction at $T^* = 7.2$ K that is different from a temperature dependence of a typical easy-axis antiferromagnet. A peak in heat capacity at $T^*$ clearly shows the development of a magnetic order that is consistent with the anomaly in the magnetic susceptibility. Remarkably, $T$-linear term $11.7$ mJ/CumolK$^2$ in heat capacity was observed, in spite of the compound is an insulator. That indicates an existence of unprecedented magnetic excitations such as spinon on the ground state of CaCu$_3$(OH)$_6$Cl$_2$·0.6H$_2$O. Such a $T$-linear term has been observed in a spin liquid state in some organic triangular salts such as $\kappa$-(BEDT-TTF)$_2$Cu(CN)$_3$ or EtMe$_2$Sb[Pd(dmit)$_2$]$_2$. However, the ground state of our compound is featured by the magnetic ordered state with an anomalous magnetic excitation, which is different from the spin liquid state of the organic salts. Probably, the competition of magnetic interactions $J_1$,$J_2$,$J_3$ on the kagome lattice and a quantum fluctuation cause the unconventionality of the magnetic ground state of the compound. We will discuss the magnetic properties and an origin of the exotic behaviors observed on the kagome lattice antiferromagnet of CaCu$_3$(OH)$_6$Cl$_2$·0.6H$_2$O.


S0606 “Negative” vector chirality order breaking the threefold rotation symmetry of the kagome lattice in CdCu$_3$(NO$_3$)$_2$(OH)$_6$H$_2$O. R. Okuma (ISSP), D. Nakamura (ISSP), Y. Kohama (ISSP), S. Takeyama (ISSP), K. Kindo (ISSP), Z. Hiroi (ISSP) — Highly frustrated antiferromagnets with triangle-based lattices have been extensively studied both theoretically and experimentally, lured by a fascinating conjecture that the geometrical frustration enforces spins to disorder even at low temperatures and realizes exotic ground states defeating the conventional Néel order.1 Here we study the structurally perfect kagomé antiferromagnet CdCu$_3$(NO$_3$)$_2$(OH)$_6$H$_2$O$^2$ by magnetization, magnetic torque, and heat capacity measurements using single crystals synthesized by the hydrothermal transport method.3 An antiferromagnetic order accompanied by a small spontaneous magnetization that surprisingly are confined in the kagomé plane sets in at $T_N$ = 4 K, well below the nearest-neighbor exchange interaction $J/k_B = 45$ K. This indicates that a “$q = 0$” type 120° spin structure with a downward (“negative”) vector chirality, which breaks the threefold rotation symmetry and allows a spin canting within the kagomé plane, is exceptionally realized in this compound rather than a more common one with upward (“positive”) vector chirality.4 The origin is discussed in terms of the Dzyaloshinskii-Moriya interaction.


S0607 Bulk susceptibility and specific heat in some frustrated lattice models. C. Hotta (Dept. Basic Sciences, Univ. of Tokyo) and K. Asano (Dept. Phys. Osaka Univ.) — One of the difficulties in exploring frustrated magnetism had been the lack of reliable theoretical tools to explore the bulk physical properties that are directly compared with experimental results. Regarding the specific heat and susceptibility on a triangular and kagome antiferromagnet, high temperature series expansions [1] and interpolation methods [2] reported, which shall be enough reliable at high temperature and is often directly compared with experiments. However, at low temperature in two dimensional frustrated lattices, the true “bulk” data is still lacking. One of the authors have previously clarified the bulk magnetization curve of the $S = 1/2$ Kagome Heisenberg antiferromagnet by applying a method called grand canonical analysis [3]. In the present paper, we extend this idea to further obtain the specific heat and magnetic susceptibility. We demonstrate that in one dimension, even a 10-site cluster calculation reproduces the exact solution within the accuracy of $10^{-3}$ throughout the whole temperature region. This allows us to safely obtain the data in two dimension within a reliable accuracy.


S0608 Tensor network study on magnetization process of the kagome lattice Heisenberg antiferromagnets. T. Okubo (Univ. Tokyo), N. Kawashima (Univ. Tokyo) — The kagome lattice Heisenberg antiferromagnet is a typical example of the two-dimensional frustrated spin systems. Due to strong quantum fluctuations, the ground state of the $S = 1/2$ kagome lattice Heisenberg model is expected to be a spin-liquid state without any magnetic long-range orders. Under magnetic fields, it has been proposed that several magnetization plateaus at $1/9, 1/3, 5/9,$ and $7/9$ of the saturation magnetization appear based on a density matrix renormalization
group (DMRG) calculation [1]. Recently, a tensor network calculation has also shown the existence of these magnetization plateaus [2]. On the other hand, based on the exact diagonalization (ED), Nakano and Sakai proposed that the expected 1/3 plateau has peculiar critical exponents compared to other two-dimensional systems such as the triangular lattice Heisenberg antiferromagnets [3].

In this presentation, I will present the ground state properties of $S = 1/2$ kagome lattice Heisenberg antiferromagnet under external magnetic fields using an infinite Projected Entangled Pair State (iPEPS) tensor network method. In this iPEPS method, we represent the ground state wave-function as the two-dimensional network of tensors. By optimizing each tensor so as to minimize the total energy, we obtained wave-functions close to the ground state under magnetic fields. The magnetization curve obtained by iPEPS contains clear 1/9, 1/3, 5/9 and 7/9 plateaus that are consistent with the previous calculations. The 1/3-plateau state obtained by the simple update optimization was semi classical up-up-down state, which was different from a resonating state observed in DMRG [1]. We will discuss about the nature of the 1/3 plateau state by introducing a cluster update optimization. We also investigate effects of the Dzyaloshinskii-Moriya (DM) interaction, which exists in real kagome lattice compounds. Our calculation shows that the plateau width becomes smaller when we increase the amplitude of the DM interaction and the plateaus disappear for $D_z/J > 0.1$.


**S0609 Metal-Insulator Transition in the half-filled Kagome Hubbard model.** K. Asano and R. Higa (Dept. Phys. Osaka Univ.) — We study the metal-insulator transition in the half-filled Hubbard model on a Kagome lattice using the variational cluster approximation (VCA) [1]. The strong coupling limit of the model corresponds to the $S = 1/2$ Kagome Heisenberg antiferromagnet, which is considered to have a singlet ground state, i.e., either a spin liquid or some sort of valence bond crystal [2]. We have carefully examined the influence of the choice the unit cluster in VCA, finding that the clusters even number of sites are indispensable to properly describe these singlet ground states in the strong coupling parameter region. It turned out that the correlated electrons on the Kagome lattice have a strong tendency to form valence bond structures even in the intermediate coupling region, which are the resonance of electrons on a single bond or several bonds forming loops. The zero-temperature metal-insulator transition at some interaction strength is possibly driven by the formation of such short range valence bonds and shows a second order character, which is distinctive from the Brinkman-Rice scenario. The electrons on these valence bonds further localizes onto each site as the interaction increases, and the valence bonds of electrons finally turn into magnetic singlet bonds between localized $S = 1/2$ spins, which are consistent with the ground states of the Kagome antiferromagnet.


**S0610 Magnetization plateaus of an easy-axis kagome antiferromagnet with extended interactions.** X. Plat (Riken, Japan), F. Alet (LPT, France), S. Capponi (LPT, France), K. Totsuka (YITP, Japan) — I present the properties in finite magnetic field of an extended anisotropic XXZ spin-1/2 model on the kagome lattice [1,2]. The magnetization curve displays plateaus at magnetization $m = 1/6$ and $m = 1/3$ in the strong anisotropy regime. An effective quantum dimer loop model is used to discuss the nature of the $m = 1/6$ plateau phase, found to be a crystal that breaks discrete rotation symmetry. Large-scale quantum Monte Carlo simulations were carried out in particular for the $m = 1/6$ plateau on both the effective dimer model and the original spin Hamiltonian. We first map out the phase diagram of the effective quantum loop model to find stripe order around the point relevant for the original model as well as a nearby topological Z2 spin liquid. The existence of a stripe crystalline phase is further evidenced by measuring both standard structure factor and entanglement entropy of the original microscopic model, and we point out the possible misleading informations comming from entanglement observables.


**S0611 Instabilities of spin-liquid states in a quantum kagome antiferromagnet.** M. Gomišek (JSI, SI), M. Klaričič (JSI, SI), M. Pregelj (JSI, SI), F. C. Coomer (RAL ISIS, GB), H. Luetkens (PSI, CH), O. Zaharko (PSI, CH), T. Fennell (PSI, CH), Y. Li (RUC, CN), Q. M. Zhang (RUC, CN), A. Zorko (JSI, SI) — The recently synthesized ZnCu$_3$(OH)$_6$SO$_4$ (Zn-brochantite) is a representative of quantum kagome antiferromagnets (QKAs) [1], a class of spin-1/2 systems in which the interplay of geometrical frustration, low dimensionality, and quantum fluctuations provides fertile ground for novel states of matter. An especially intriguing one is a quantum spin liquid: a dynamical quantum-entangled spin state, predicted to be the ground state of the Heisenberg QKA. Its true nature, and especially its behaviour at elevated temperatures, however, remains unclear. Also unknown is the importance of a coupling between spin-liquid and impurity-spin dynamics in QKA representatives. We present the results of local-probe (NMR, μSR) and inelastic neutron scattering (INS) measurements on Zn-
brochantite. We observe a high-temperature quantum-critical regime with a crossover into a gapless spin-liquid state with decreasing temperature [2]. An instability of this spin liquid then leads to a second, distinct spin-liquid state that is stabilized at the lowest temperatures. Local-probe measurements also show a significant coupling between impurity spins and intrinsic kagome spins in this compound at low temperatures [3]. We observe a spinon-impurity Kondo-like effect which identifies the spin liquid as being gapless with a power-law spectral density of spin fluctuations. Our preliminary measurements also indicate a possible field-induced instability. We propose that the observed array of instabilities could be a common feature of many frustrated quantum spin systems. 


S0612 1/3-Magnetization Plateau Extended up to 120 T in Volborthite. S. Takeyama(ISSP), D. Nakamura(ISSP), H. Ishikawa(ISSP), and Z. Hiroi(ISSP) — The fractional plateau phases in high-field magnetization curve are in general useful for ultimate determination of a spin network and its exchange parameters, and assist verification of various model calculations. Volborthite is a spin 1/2 kagome frustrated antiferromagnet, and is known as a promising platform for an application of the kagome Heisenberg model. Furthermore, this material attracts another interests due to recent theoretical prediction of a spin-nematic phase appeared prior to 1/3-plateau. However, a spin structure and associated exchange parameters are of very critical for understanding of the nematic phase. So far, magnetization in magnetic fields of up to 74 T applied to single crystal volborthite revealed a wide 1/3-plateau, starting from 26 T and it still continues up to 74 T [1], which is almost close to a upper-limit of a magnetic field by non-destructive long-time pulse magnets available worldwide. These experimental data stimulated theoretical studies on spin interactions of volborthite. Janson et al. proposed a $J_1$-$J_2$-$J_{hc}$ model [2], regarding the system as coupled frustrated chains, based on density functional theory, which assumes two kinds of nearest-neighbor interaction, ferromagnetic $J_1$ and antiferromagnetic inter-chain $J_{hc}$ and with the next-nearest-neighbor $J_2$. Quite recently, the same authors elaborated the model with more microscopic picture taking into account of single crystal structural data [3]. The Faraday rotation measurements were carried out in the single-turn coil megagauss generator at ISSP and magnetization curve of a stress-free single crystal sample was obtained in fields of up to 180 T and temperature at 5 K. It was found that the 1/3-plateau phase ends up around 120 T and then magnetization starts to grow gradually approaching to the saturation moment. Our magnetization curve is well reproduced by theoretical calculation by Janson et al. based on a $J_1$-$J_2$-$J_{hc}$ model with $J_2/J_1 = 2$ and $J_{hc}/J_1 = 1.1$. These are contrasting to those obtained by us using a sample adhered to a substrate by plastic resin, which might cause a stress on a sample at low-temperatures [4]. 


07 Low Dimensional Spins.

S0701 Magnetic Bose–Einstein condensation, protected by frustration: a case study. K. Yu. Povarov, A. Reichtert, E. Wulf, A. Zheludev (ETH Zürich) — The validity of beautiful analogy between the field-induced ordering in gapped antiferromagnets and the phenomenon of Bose–Einstein condensation (BEC) has a requirement, never truly met in real materials: an axial symmetry of the spin Hamiltonian. However, this is the case when the presence of frustrating Heisenberg interactions may help. If an incommensurate magnetic structure occurs, the spin rotation symmetry becomes protected. A potential complication arises from the fact, that spiral structures are known to couple the magnetic and electric degrees of freedom. This multiferroicity casts a shadow of doubt on the magnetic BEC nature of disordered–incommensurate quantum-critical point.

To address this issue, we have experimentally studied this type of transition found in the frustrated spin tube material Sul–Cu$_7$Cl$_4$ [1]. Dielectric spectroscopy results, combined with calorimetric measurements, clearly show the absence of polarization fluctuations in the disordered phase down to the very critical point. At the same time, the ordered phase shows a huge nonlinearity in dielectric permittivity even for small electric fields. Analyzing the phase boundary obtained by $\epsilon(H, T)$ measurements, we find beautiful consistency with the 3D BEC universality class. We conclude, that frustration stabilizes magnetic BEC, but simultaneously gives rise to complex magnetoelectric effects in the helimagnetically ordered phase [2].


S0702 NMR study on the quasi one-dimensional antiferromagnet BaCo$_2$Si$_2$O$_7$. R. Uesugi (Sophia Univ.), M. Akaki (Osaka Univ.), M. Hagiwara (Osaka Univ.), H. Kawahara (Sophia Univ.), T. Goto (Sophia Univ.), K. Matsui (Sophia Univ.) — Quasi-one dimensional antiferromagnet BaCo$_2$Si$_2$O$_7$ consists of Co$^{2+}$-based spin chains, which run along $a$-axis and are well separated by intervening Si atoms. Each Co$^{2+}$ ions are surrounded
by four $O^2_3^-$, and these vertex-shared tetrahedra compose chains. A slight distortion and tilting of each tetrahedra cause the chains to have spatial modulation as -Co3-Co2-Co3'-Co1-Co3-. This modulation and the inevitably-associated Dzyaloshinskii-Moriya interaction may bring a system a non-collinear spin structure, and hence a novel charge anomaly based on the non-collinear spin structure.

So far, macroscopic measurements on this system [1] have revealed that it shows a long range magnetic order at $T_N = 21$ K, and a large one-axial anisotropy in both the paramagnetic and the ordered state. However, in general, divalent Co ions ($d^7$) are expected to show isotropic behavior, because of a quenched orbital momentum on $i^{5d}$. In order to investigate the spin state microscopically, we have performed $^{59}$Co-NMR under the field up to 12 T in the ordered state. We have observed several sites of egg-split $^{59}$Co-NMR spectrum, including ones with very small hyperfine field, indicating the non-trivial spin structure.


**S0703 Alternating-spin (3/2, 1/2) Heisenberg chain with isotropic three-site interactions.** N. B. Ivanov (Uni-Bielefeld, ISSP Bulgaria), S. I. Petrova (Bielefeld Uni. App. Sci.), M. Czopnik, and J. Schnack (Uni-Bielefeld) – The impact of frustrating three-site exchange interactions on Heisenberg spin systems is scarcely explored. Based on numerical density-matrix renormalization group and exact diagonalization calculations, in this work we explore the quantum phase diagram of the Heisenberg chain constructed from alternating $S = 3/2$ and $\sigma = 1/2$ site spins and containing extra isotropic three-site exchange interactions. We demonstrate that the three-site terms can stabilize some specific partially-polarized spin states as well as a doubly-degenerate non-magnetic gapped state. The latter state describes a crossover between the ground states of the spin-1 and spin-2 Heisenberg chains when increasing the strength of three-site interactions [1].


**S0704 DM-induced frustration in a system of weakly coupled Heisenberg chains.** W. Jin, O. A. Starykh (Uni. of Utah, USA) – Motivated by recent experiments on spin chain materials $K_2CuSO_4Cl_2$ and $K_2CuSO_4Br_2$ [1,2], we theoretically investigate the problem of weakly coupled antiferromagnetic spin 1/2 chains (intrachain exchange $J$, interchain $J'$) subject to a staggered between chains, but uniform within a given chain, Dzyaloshinskii-Moriya interaction (DMI) of magnitude $D$. In the experimentally relevant limit $J' \ll D \ll J$ of strong DMI, the spins on neighboring chains are forced to rotate in opposite directions, therefore frustrating the interchain interaction. This has the effect of promoting a two-dimensional collinear spin density wave (SDW) state, which preserves U(1) symmetry of rotations about the $D$-axis.

We also investigate response of this interesting system to an external magnetic field $h$ and obtain the $h - D$ phase diagrams for the two important field orientations, $h \parallel D$ and $h \perp D$. For $h \parallel D$, the magnetic field induces interchain coupling between next-nearest chains, which leads to a incommensurate Cone state, and the transition from SDW is commensurate-incommensurate (C-IC) kind. For $h \perp D$, the field is found to stabilize commensurate SDW state.


**S0705 Phase stability and higher order peaks of the skyrmion lattice in Cu$_2$OSeO$_3$.** J. D. Reim, K. Makino, D. Higashi, Y. Nambu, D. Okuyama, T. J. Sato (Tohoku University), E. P. Gilbert, N. Booth (ANSTO), S. Seki (RIKEN), Y. Tokura (QPEC) – In recent years intensive research has been conducted on the compound Cu$_2$OSeO$_3$ since it was found to feature lattices of topologically protected spin-swirlings called skyrmions. Among the compounds exhibiting skyrmion lattices, Cu$_2$OSeO$_3$ has attracted particular interest because of its insulating nature resulting in multiferroic properties. [1] However, previous studies reported somewhat contradicting phase diagrams regarding the presence of two different skyrmion phases. [2-4] Using small angle neutron scattering we have investigated the thermodynamic stability of these phases and were able to relate the deviations to a difference in the stabilization process. By cooling under finite magnetic field, the so-called skyrmion 2 phase is stabilized, whereas the 30°-rotated skyrmion 1 phase can be stabilized by heating the sample under finite field from the ordered conical phase. The zero-field results in the co-existence of the two phases, while different rates of applying the external magnetic field appear to influence the stabilization process. It is further found that once all of the skyrmion phases are formed, it is hardly destabilized on an experimental time scale even in the vicinity of the phase boundary. This indicates unusual thermal stability of the skyrmion lattice phases, possibly related to their topologically protected nature.

Furthermore, we have successfully observed two symmetrically inequivalent peak sets at higher $Q$, which are suitable candidates for higher order peaks of these skyrmion lattices. In a study on the higher order peaks of the skyrmion lattice in MnSi the existence of suitable magnetic peaks was reported, yet these peaks were identified to arise from double scattering processes.[5] In Cu$_2$OSeO$_3$ the probability of such processes is increased due to the large mosaicity of the skyrmion lattice's Bragg peaks. Studying the relation between the mosaicity of the first order peak and the possible higher order peaks (110) and (200), the observations cannot be explained by double scattering exclusively, thus indicating the presence

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of higher order Bragg peaks. In addition, the difference in the dependence of these peaks’ intensity on the external magnetic field and temperature reveals interesting variations in the structure of the skyrmion lattice.


**S0706** Absence of long range order in SrDy$_2$O$_3$ frustrated magnet due to trapped defects from a dimensionality crossover.  
N. Gauthier, A. Fennell (PSI), B. Prévost, A. D. Bianchi (Université de Montréal, Canada), B. Delley, R. Sibille (PSI), G. Nilson, L-P. Regnault (ILL), J. White, C. Niedermayer, V. Pomjakushin, M. Kenzelmann (PSI) — The simultaneous occurrence of geometrical frustration and low dimensionality is an effective way to reduce or suppress the ordering temperatures in magnets and expose strongly correlated fluctuating ground states. Both of these characteristics can be found in the one-dimensional (1D) zigzag chain model, offering a playground to study novel states of matter. In the Sr$_2$Dy$_2$O$_3$ compounds, the Ln magnetic ions form these zig-zag chains, which dominate the magnetic properties in many members of this family [1-4]. In SrDy$_2$O$_3$, the two inequivalent Dy$^{3+}$ sites are Ising-like and have perpendicular easy-axes, favouring the decoupling of neighbouring zig-zag chains. In this compound, no long range order is observed down to 60 mK in zero field but diffuse neutron scattering indicates short range order with the longest correlation length along the chains. We determined the magnetic correlations along the chains and show that they are consistent with those of the 1D Ising zig-zag chain model.

AC susceptibility measurements indicate a slowing down of the fluctuations at low temperatures. We attribute this behaviour to the domain walls in the zig-zag chains. These domains walls are free to propagate in the 1D chains and only vanish when interacting with other domain walls [5]. The presence of interchain interactions impede their propagation and reduces their decay rate. Experimental evidence of a dimensionality crossover at low temperatures in SrDy$_2$O$_3$ suggest that domains walls are trapped because of interchain interactions, precluding long-range order to the lowest temperatures.


**S0707** Dynamical properties of generalized Kitaev-Heisenberg models on honeycomb lattices.  
S. Suga (Univ. of Tokyo, Japan), T. Suzuki (Univ. of Hyogo, Japan), Y. Yamaji (Univ. of Tokyo, Japan), and T. Yamada (Univ. of Hyogo, Japan) — Quantum spin liquid is one of the focusing topics in condensed matter physics. Na$_2$IbO$_3$ and α-RuCl$_3$ are candidates for realizing Kitaev spin liquid (KSL). The effective model for these materials is considered to be described by the Kitaev-Heisenberg Hamiltonian on a honeycomb lattice whose phase diagram contains the KSL phase [1-3]. Experimentally, zigzag magnetic orders have been observed below the magnetic transition temperature [4-7]. Although ab-initio calculations have been performed to estimate coupling constants, the numerical results have shown qualitatively different features in both materials. For Na$_2$IbO$_3$ we have calculated dynamical structure factors (DSFs) using proposed five sets of the coupling constants, and have discussed the adequate model by comparing our numerical results with the inelastic neutron scattering (INS) experiments [8]. However, the adequate model for α-RuCl$_3$ is still controversial. In this study, we calculate DSFs of the proposed five sets of the coupling constants for α-RuCl$_3$ [9-11] by using a numerical diagonalization method. We compare numerical results with the INS experiments for α-RuCl$_3$ [11], and discuss the adequate model that properly explains the INS spectra. We also calculate low-lying excitations using a linearized spin-wave theory. We find that the spin-wave excitation fails to explain the low-lying excitations of the DSFs, meaning that the phase boundary to the KSL phase is placed nearby [12]. We further calculate the temperature dependence of the specific heat using the adequate model for α-RuCl$_3$. We find that the specific heat shows a two-peaks structure, which can be a criterion to measure the distance from the KSL phase in the magnetically ordered phase [12]. We discuss the two-peaks structure of the specific heat in comparison with the experiments [13]. The obtained results indicate that the α-RuCl$_3$ is placed in the vicinity of the KSL phase.


**S0708** Neutron Diffraction on the Frustrated Spin-Chain Linarite.  
S. Süllow, L. Heine (TU, Germany), B. Willenberg (TU, Germany, HZB), J-U. Hoffmann (HZB), A.U.B. Wolter-Giraud, B. Bächner(IFW, Germany), K.C. Rule, A. Studer (ANSTO), B. Ouladdiaf (ILL) — The natural mineral linarite, PbCuSO$_4$(OH)$_2$, has been established as a model compound of the frustrated one-dimensional spin-chain with ferromagnetic nearest-neighbor and antiferromagnetic next-nearest-neighbor interaction [1].
Within the last years, it has been demonstrated that it exhibits a complex magnetic phase diagram in applied fields along the crystallographic b axis for temperatures below 2.8 K. The ground state phase I exhibits helical order, phase IV has been shown to be simple antiferromagnetic, in phase III helical and antiferromagnetic order coexist. Recent neutron diffraction and NMR measurements with focus on phase V have revealed a complex spin density wave phase with an incommensurability vector $[0, k, 0.5]$ shifting with field [2]. Here, we present new neutron diffraction measurements with special emphasis on the low temperature/high field regime of the magnetic phase diagram of linarite. From these measurements, the temperature and field dependence of the magnetic moment per Cu atom was established for temperatures downto 50 mK and magnetic fields $B_{//}b$ up to 9.4 T. As well, the nature of the phase transition from phase V into phase IV being of first order was established. In addition, we find that a shift of the incommensurability vector in phase V occurs not only with magnetic field but also with temperature.


S0709 Numerical evidence for a chiral spin liquid in the XXZ antiferromagnetic Heisenberg model at $m = 2/3$ magnetization. H. Changlani (Johns Hopkins), K. Kumar (UIUC), B. Clark (UIUC), E. Fradkin (UIUC). — Frustrated magnets provide a fertile ground for discovering exotic states of matter, for example, those with topologically non-trivial properties. We focus on the kagome geometry, which has several near-ideal materials realizations, and consider the spin-1/2 XXZ antiferromagnetic Heisenberg model in a magnetic field. Motivated by a previous field theoretical study [1], we explore the XY limit for the case of 2/3 magnetization (i.e. 1/6 filling of hard-core bosons) and perform exact or accurate numerical computations to search for a chiral spin liquid phase. We provide evidence for this phase by analyzing the energetics, determining minimally entangled states and the associated modular matrices, and evaluating the many-body Chern number [2]. Finally, we also report the existence of an exact set of quantum ground states at a special point of the XXZ model, and examine how a spin liquid arises from perturbing such a highly degenerate manifold [3].


S0710 Magnetocaloric Effects on Impurity-Doped Tetrahedral Spin-Chain Systems (Cu,Zn)$_2$Mo$_2$O$_9$. Y. Ebukuro (Sophia Univ.), H. Kuroe (Sophia Univ.), M. Hase (NIMS), Y. Kohama (ISSP), K. Kindo (ISSP), K. Oka (AIST), T. Ito (AIST), and H. Eisaki (AIST). — The multiferroic material Cu$_2$ZnMo$_2$O$_9$ has a quasi-one-dimensional tetrahedral spin system made from the spin-1/2 Cu$^{2+}$ ions [1]. In this material, the canting antiferromagnetic order and the ferroelectricity coexist below $T_N = 7.9$ K [1,2]. Anisotropic magnetization plateaus have been observed at $T = 1.5$ K and the magnetic field $H$ above 47 T [3]. The detailed $H$-$T$ phase diagrams up to 23 T in Cu$_2$ZnMo$_2$O$_9$ have been reported [3]. The complex phase boundaries have been observed with $H//c$ [3]. As the first aim of this presentation, we focus on the phase boundary when the magnetization plateau is observed in the $H$-$T$ phase diagram. The phase diagram obtained by using the magnetocaloric effects (MCE) in Cu$_2$ZnMo$_2$O$_9$ under pulsed magnetic fields up to 55 T is presented. Also we report the isentropic curves in the $H$-$T$ space themselves, namely the MCE curves.

When the nonmagnetic Zn$^{2+}$ ions are randomly substituted for the magnetic Cu$^{2+}$ ions, the multiferroic properties are changed systematically. This is due to the direct cutting of magnetic chains which destroys the antiferromagnetic long-range order. The $T_N$ decreases systematically upon the Zn substitution [4,5]. The phase diagram in the Zn-5.0% sample is very different from that in Cu$_2$ZnMo$_2$O$_9$ [5]. As the second aim of this presentation, we focus on the MCE curves of the Zn substituted samples. The phase boundaries of the Zn-0.5% substituted sample shift to the lower temperature and the lower magnetic-field side in the $H$-$T$ space when we compare them to those in Cu$_2$ZnMo$_2$O$_9$. In the Zn-5.0% sample, we observe a region where the sample temperature is independent of $H$, which suggests that the spin disorder state survives even at low temperatures.


S0711 Neutron Scattering for One-Dimensional Frustrated Chain Compound NaCuMoO$_4$(OH). S. Asai (UTokyo), T. Oyama (UTokyo), M. Hagihala (UTokyo), M. Suda (UTokyo), A. Nakao (CROSS), K. Munakata (CROSS), K. Kuwahara (Ibaraki Univ.), S. Itoh (KEK), K. Rule (ANSTO), K. Nawa (Tohoku Univ.), Z. Hiroi (UTokyo), T. Masuda (UTokyo). — In $S = 1/2$ one-dimensional frustrated chain with nearest-neighbor ferromagnetic interaction $J_1$ and next-nearest-neighbor antiferromagnetic interaction $J_2$, the ground state exhibits various quantum phases depending on the ratio of $J_1$ to $J_2$ [1]. NaCuMoO$_4$(OH) is an experimental realization of such system having decent energy scale for the magnetic interactions. The ratio of $J_1$ to $J_2$ is estimated to be -1.4 from magnetic susceptibility measurement and the Neel temperature is 0.6 K [2]. In order to investigate the magnetic structure, we carried out powder neutron diffraction using TAIPAN in ANSTO and single crystal diffraction using SENJU.
in J-PARC. We observed no magnetic peaks in the powder diffraction owing to the low S/N ratio. On the other hand, we observed two magnetic peaks indicating the helical magnetic order with the propagation vector $q_1 = (0, 0.48, 0)$ below 0.6 K in the single-crystal diffraction. These intensities indicate that the helical plane is perpendicular to the crystallographic b axis.


**S0714** Thermal Transport in Kitaev-Heisenberg Ladders. W. Brenig, A. Metavitsiadis (Institute for Theoretical Physics, Techni- 
University Braunschweig, Germany) — We present results for the dynamical thermal conductivity of the Kitaev-Heisenberg model on ladders. In the pure Kitaev limit [1], and in contrast to conventional integrable low-dimensional spin systems [2], we show that heat transport is completely dissipative. We clarify this to be a direct fingerprint of fractionalization of spins into mobile Majorana matter and a static $Z_2$ gauge field, which acts as an emergent thermally activated disorder. These results will be considered versus temperature and will also be contrasted against the conductivity discarding gauge fluctuations. Turning on Heisenberg exchange, we show that the system crosses over from a complete heat insulator to a normal heat conductor, consistent with a recombination of fractionalized spins into triplons [3]. Our finding rests on several complementary calculations of the heat current correlation function, comprising a phenomenological mean-field treatment of thermal gauge fluctuations, a complete summation over all gauge sectors, as well as exact diagonalization and dynamical quantum typicality [2] treatments of the original spin model.


**S0715** Magnetic phase diagram of distorted triangular lattice antiferromagnet RbFeBr$_3$. N. Kurita (Tokyo Institute of Tech., Japan), H. Tanaka (Tokyo Institute of Tech., Japan) — A family of hexagonal compounds $\text{AFe}_x\text{X}_3$ ($\text{A} =$Rb, Cs etc.; $\text{X} =$Cl, Br etc.) has attracted much attention due to a rich variety of magnetic phase diagrams. The magnetic Fe$^{2+}$ ions with the effective spin $S = 1$ form spin chains along the c-axis. Since the spin chains form a triangular lattice in the basal $ab$-plane with antiferromagnetic (AF) exchange interactions, a spin frustration effect characteristic of the triangular-lattice antiferromagnet plays an important role in determining the low temperature (LT) magnetic properties. Unlike other $\text{AFe}_x\text{X}_3$ family, RbFeBr$_3$ undergoes successive structural phase transitions, which results in a distorted triangular lattice at LT with two kinds of nearest neighbor exchange interactions. This compound exhibits two successive magnetic phase transitions at $T_{N1} = 5.6$ K and $T_{N2} = 2.0$ K[1]. Neutron scattering experiments revealed that triangular spin structure and partially disordered structure are realized for $T < T_{N2}$ and $T_{N2} < T < T_{N1}$, respectively [2]. In this study, we have performed magnetization and specific heat measurements to establish the field-temperature...
phase diagram of RbFeBr$_3$ at ambient pressure. With increasing field up to 9 T, a broad anomaly related to $T_{N2}$ gradually becomes prominent and shifts to higher temperatures while no obvious field effect is found for the $T_{N1}$ value. This indicates that the application of magnetic field suppresses the intermediate phase and stabilizes the triangular spin phase. We have also carried out high-pressure magnetization measurements of RbFeBr$_3$. With increasing pressure, $T_{N1}$ is significantly suppressed to lower temperatures and is no more detectable at $P \geq 1.0$ GPa in the investigated temperature range. The present result is marked contrast with a stabilization of the AF phase in CsFeCl$_3$ with increasing pressure.


**S0716 Doping Effect on Quantum Spin Liquid in the frustrated One-Dimensional Magnetic LiCuSbO$_4$.** H. Shinohara (University of Cambridge), S. E. Dutton (University of Cambridge) — The changes in the magnetic properties of the one-dimensionally (1D) frustrated spin-half Cu chains in LiCuSbO$_4$ caused by doping of non-magnetic Mg ions in LiCu$_{1-x}$Mg$_x$SbO$_4$ ($0 \leq x \leq 0.1$) will be reported. Previous work has shown that LiCuSbO$_4$ has 1D spin-half chains with nearest-neighbor interactions ($J_1$) which are ferromagnetic (FM) and next-nearest-neighbor interactions ($J_2$) which are antiferromagnetic (AFM). This FM-AFM competition results in frustration with the magnetic properties determined by the relative values of $J_1$ and $J_2$. Our results show that there are only small changes to the crystal structure as determined by X-ray diffraction samples. Doping with magnesium results in free spins in addition to the underlaying short range order observed in low fields. I will discuss these results and ways of considering the role that the magnesium ions play in changes to the magnetic behavior.

**S0717 Magnetic Phase Diagram of a Frustrated Spin Ladder.** T. Sugimoto (TUS), M. Mori (JAEE), T. Tohyama (TUS), and S. Maekawa (JAEE) — BiCu$_2$PO$_6$ is a low-dimensional frustrated quantum spin system, which is attracting much attention due to successive magnetic phase transitions [1]. The corresponding magnetic model is regarded as a frustrated two-leg spin ladder, which bridges between the frustrated spin chain and the non-frustrated spin ladder with 1/2 spins. The preceding study on this model has presented that magnetization plateaux emerge at 1/2, 2/3, and 1/3 magnetizations, in addition to cusp singularities [2]. To discuss whether the magnetization plateau can appear in the real compound BiCu$_2$PO$_6$ or not, the magnetic phase diagram should be clarified. The preceding study on the magnetization plateaux shows that the quasi-spin picture is important to understand the mechanism of plateau [2]. In this picture, two 1/2 spins on a rung with certain applied magnetic fields are redefined as a quasi 1/2 spin, whose up and down spin states correspond to a triplet and the singlet states, respectively. The original spin-ladder model can be mapped onto another quasi-spin chain model with an effective magnetic field, and an anisotropy. We investigate the correlation functions of the quasi-spins with the density-matrix renormalization-group method, and discover the long-ranged order of the quasi-spin dimer operator in the 1/2 plateau. The quasi-spin dimer operator is used to determine the phase boundary of the 1/2 plateau. In addition, we calculate the gap function at 1/2, 1/3, and 2/3 magnetizations, to clarify the phase boundaries or to compare the phase boundary with that obtained by the quasi-spin dimer operator. We find that the boundaries determined by the gap function is identical to those obtained in the limit of the strong rung couplings. The result is consistent with the preceding work. The gap function at the 1/2 magnetization depends on not only the frustration but also the intrinsic anisotropy, which has been claimed by A. A. Tsirlin [3] and K. W. Plumb [4]. Therefore, a question whether the 1/2 plateau appears or not in BiCu$_2$PO$_6$, will give important information associated with the anisotropy.


**S0718 Exotic spin phases in the low-dimensional quantum magnet LiCuSbO$_4$.** S. Nishimoto, S.-L. Drechsler, U.K. Rößler, H. Rosner, V. Kataev, H.-J. Grafe (Dresden) M. Iakovleva (Dresden, Kazan), E. Vavilova (Kazan), A. Alfonsov (Dresden), H. Najiri (Tohoku), M.-I. Sturza (Dresden), S. Wurmehl (Dresden), and B. Büchner (Dresden) — Low-dimensional quantum spin systems are predicted to exhibit a variety of novel ground states beyond classical FM- or AFM phases. The quest for experimental realizations of such theoretical models is primarily focused on complex transition metal (TM) oxides where magnetic coupling between the spins of the TM ions can be confined to one or two spatial directions. Here, results of high-field NMR and sub-THz ESR studies of the quantum magnet LiCuSbO$_4$ are reported. In this material Cu$^{2+}$ ions ($S = 1/2$) are coupled along the crystallographic a-axis and form weakly interacting but strongly frustrated one-dimensional Heisenberg spin chains as confirmed by our LDA-FPLO band structure calculations. The absence of long-range magnetic order at ambient fields down to sub-Kelvin temperatures is suggestive of the realization of a quantum spin liquid state [1]. Our NMR and ESR data in strong magnetic fields above 13 T up to 16 Tesla reveal clear indications for the occurrence of a field-induced hidden phase which is likely to be of the multipolar character. To explain these experimental behaviors we propose a new mechanism of a nematic state induced by the anisotropic exchange couplings and investigate it by DMRG calculations.
Based on these calculations and the experimental data we suggest a preliminary $H$-$T$ phase diagram but with no anomalous collinear incommensurate SDW$^\alpha$-phase as in linarite [2] or in LiVCuO$_2$ below the nematic phase. The effect of the Dzyaloshinskii-Moriya interaction will be also discussed.


**S0719 Spin slush in an extended spin ice model.** J. G. Rau (Univ. of Waterloo), M. J. P. Gingras (Univ. of Waterloo & Perimeter Inst. for Theoretical Phys.) — The physics of glasses plays an important role across a wide range of systems in condensed matter and biophysics. Connections between these different contexts have proven fruitful in making progress; for example, the study of conceptually and computationally simpler spin glass models may inform the physics of super-cooled liquids and structural glasses where disorder is absent. Motivated by the diverse range of phenomena observed in glass formers, such as the dramatic slowing down of relaxation and emergence of spatially heterogeneous dynamics, we study a new classical spin liquid on the pyrochlore lattice by extending spin ice with further neighbour interactions. We find that this disorder-free spin model exhibits a rare form of dynamical heterogeneity for a translationally invariant system with extremely slow relaxation for some spins while others fluctuate quickly down to zero temperature. We thus call this state spin slush, in analogy to the heterogeneous mixture of solid and liquid water. This behaviour is driven by the structure of the ground state manifold which extends the celebrated two-in/two-out spin ice states to include branching structures built from three-in/one-out, three-out/one-in and all-in/all-out tetrahedra defects. Distinctive liquid-like patterns in the spin correlations serve as a signature of this intermediate range order. Possible applications to materials as well the effects of quantum tunneling will be discussed.

**S0720 Magnetic excitations in spin-1/2 triangular-Lattice antiferromagnets: high-field ESR studies.** S.A. Zvyagin (Dresden High Magnetic Field Laboratory (HLD-EMFL), Dresden, Germany) — The spin-1/2 Heisenberg antiferromagnet (AF) on a triangular lattice is the paradigmatic model in quantum magnetism, which was intensively studied since several decades. In spite of numerous theoretical studies (which predict a rich variety of grounds states, ranging from a gapless spin liquid to Néel order), many important details of its phase diagram remain controversial or even missing. To test the theory experimentally, a precise information on the spin-Hamiltonian parameters for the materials of interest is highly demanded. Here, we present results of high-field electron spin resonance (ESR) studies of spin-1/2 Heisenberg AF Cs$_2$CuCl$_4$ and Cs$_2$CuBr$_4$ with distorted triangular-lattice structures. In the magnetically saturated phase, quantum fluctuations are fully suppressed, and the spin dynamics is defined by ordinary spin waves (magnons). This allows us to accurately describe the magnetic excitation spectra in both materials and to determine their exchange parameters using the harmonic spin-wave theory [1].

The viability of the proposed method was first proven by applying it to Cs$_2$CuCl$_4$, revealing good agreement with inelastic neutron-scattering results. For the isostructural Cs$_2$CuBr$_4$ we obtain $J/k_B=14.9$ K and $J'/k_B=6.1$ K, [$J'/J \sim 0.41$], providing exact and conclusive information on the exchange coupling parameters in this frustrated spin system. We argue, that the proposed approach can have a broader impact, potentially used for any quantum AF with reduced (e.g., by the staggered Dzyaloshinskii-Moriya interaction) translational symmetry, resulting, as predicted, in emergence of a new exchange mode above the saturation field. In addition, we show that the presence of a substantial zero-field gap, $\sim 10$ K, observed in the ESR spectrum of Cs$_2$CuBr$_4$ below as well as above $T_N$, can be interpreted in the frame of the triangular-lattice AF model, indicating good agreement with results of spin-wave calculations [2]. The peculiarities of the ESR spectrum will be discussed taking into account the effect of staggered Dzyaloshinskii-Moriya interactions present in both materials.

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**S0721 Observation of ‘Magnetostriiction Plateau’ on Tetrahedral Spin-Chain System Cu$_4$Mo$_4$O$_{12}$.** H. Kuroe (Sophia Univ.), Y. Ebukuro (Sophia Univ.), M. Hase (NIMS), S. Kawachi (ISSP), M. Tokuhashi, Phys. Rev. B 88, 124403 (2013). — The spin structure of the magnetization plateau induced by structural distortion in frustrated magnets has been attracted much attention in the viewpoint of spin-lattice coupling, namely the spin Jahn-Teller effects [1,2]. Magnetically induced symmetry change in a three-dimensional spin frustrated system CdCr$_2$O$_4$ with a pyrochlore lattice is a good example [3]. Cu$_4$Mo$_4$O$_{12}$ has a quasi-one dimensional frustrated spin system at which the $S = 1/2$ spins form the corner-shared spin tetrahedra running along the $b$ direction of the crystal with the inversion centers at the connecting points [4]. From this crystal structure, the effects of the spin frustration and the quantum magnetism are expected to appear simultaneously. This compound shows the anisotropic magnetization under the magnetic field $H$ [5]. When $H \parallel b$, the magnetization plateau is observed above 60-3 T. When $H \perp b$, the magnetization plateau opens at $H$ lower than in the case of $H \parallel b$ axis [5]. This compound also...
shows the ferroelectricity, i.e., this compound belongs to multiferroic material [6]. The clear spontaneous electric polarization appears up to 23 T. Above this magnetic field, the coercive electric field diverges. The role of the lattice system on these multiferroic properties has not been clarified yet. In this presentation, we present the complete set of the longitudinal and the transverse magnetostrictions up to 61.0 T. We observe the plateau of the magnetostriction at the magnetic fields where the magnetization curve shows the plateau, indicating that the magnetostriction reflects the anisotropic magnetization. Moreover, at the magnetic fields where the magnetization jumps are observed, the anomalies of the magnetostrictions are found, indicating that the lattice system is closely related to the spin structure. These results clearly demonstrate the strong spin-lattice coupling in this compound.


**S0722** Continuous magnetic excitations in the triangular-lattice spin-liquid candidate YbMgGaO₃, M. Mourigal (Georgia Tech), J. Padding (Georgia Tech), Z. L. Dun (UT Knoxville), M. Daum (Georgia Tech), G. Ehlers (ORNL), M. B. Stone (ORNL), H.D. Zhou (UT Knoxville) — The rare-earth magnet YbMgGaO₃ has recently been identified as a promising candidate to realize quantum spin-liquid (QSL) physics on the triangular lattice [1,2], because Yb³⁺ ions with effective spin-½ show no thermodynamic signatures of long-range magnetic order. In this talk, we will present comprehensive inelastic neutron scattering data collected on large single crystals of YbMgGaO₃ which reveal a continuum of low-energy magnetic excitations. Our data are broad in energy and reciprocal space, revealing the absence of long-range order and the persistence of large spin fluctuations, as previously observed for quantum kagome antiferromagnets [3,4]. The observation of QSL physics in YbMgGaO₃ is surprising, however, because isotropic nearest-neighbor interactions do not yield a QSL ground state on the triangular lattice [5]. Motivated by this, we present our measurements of the effect of temperature and applied magnetic field, which provide insight into the underlying microscopic phenomena stabilizing exotic physics [6]. We discuss the implications of our results for theories of this likely QSL state [7], and suggest future experiments to advance the study of this exciting material.


**S0723** Finite-temperature dynamics of highly frustrated quantum magnets, A. Honecker (LPTM, Université de Cergy-Pontoise, France), F. Mila (Ecole Polytechnique Fédérale Lausanne, Switzerland) — Low-dimensional quantum magnets at finite temperatures present a complex interplay of quantum and thermal fluctuation effects in a restricted phase space. While some information about dynamical response functions is available from theoretical studies of the one-triplet dispersion in unfrustrated chains and ladders, little is known about the finite-temperature dynamics of frustrated systems. Experimentally, inelastic neutron scattering studies of the highly frustrated two-dimensional material SrCu₂(BO₃)₂ show an almost complete destruction of the one-triplet excitation band at a temperature only 1/3 of its gap energy, accompanied by strong scattering intensities for apparent multi-triplet excitations. We investigate these questions in a frustrated spin ladder and present numerical results for the magnetic specific heat, susceptibility, and dynamical structure factor obtained from exact diagonalization and quantum Monte Carlo studies, which we show can be rendered free of the sign problem even in a strongly frustrated system and which allow us to reach unprecedented sizes of L = 200 ladder rungs. We find that frustration effects cause an unconventional evolution of the thermodynamic response across the full parameter regime of the model, accompanied by an anomalously rapid transfer of spectral weight out of the one-triplet band and into both broad and sharp spectral features at a wide range of energies, including below the zero-temperature gap of this excitation. These features are multi-triplet bound states, which develop particularly strongly near the quantum phase transition, fall to particularly low energies there, and persist all the way to infinite temperature. Our results offer new insight into the physics of finite-temperature spectral functions in SrCu₂(BO₃)₂ and many other highly frustrated spin systems.


**S0724** Berry Curvature and Topology in a Quantum Magnet, P. McClarty (Oxford), T. Guidi (ISIS), F. Kruger (UCL, ISIS), S. Parker (ISIS), D. Prabhakaran (Oxford), K. Refson (RHUL/ISIS) — We examine in detail a recent theoretical proposal of Romhányi, Penc and Ganesh [1] that the Shastry-Sutherland material SrCu₂(BO₃)₂ is a bosonic topological insulator. We present extensive inelas-
Spin-stripe formation in a frustrated spin chain. M. Pregelj (Jožef Stefan Institute, Slovenia), O. Zaharko (PSI), A. Zorko (Jožef Stefan Institute, Slovenia), H. Nojiri (Institute for Materials Research, Tohoku University, Japan), H Berger (Ecole polytechnique fédérale de Lausanne, Switzerland), L. C. Chapon (ILL) and D. Arčon (Jožef Stefan Institute, Slovenia) – Periodic motifs occur all across the nature and typically develop as two or more rival states coexist [1]. In strongly correlated electron systems such a behavior has been most often ascribed to the competition between short- and long-range interactions, as for instance, competition between exchange and dipole-dipole interactions, which leads to domain patterns in ferromagnetic thin films [2]. Here we show that long-wavelength spin-stripe modulation may develop also in antiferromagnets, despite the absence of long-range dipole-dipole magnetic interactions. Employing high-field magnetization, specific heat, neutron diffraction and magnetic-torque measurements, we find β-TeVO4 [3] to be a nearly perfect realization of a frustrated ferromagnetic spin-1/2 chain [4]; namely, a zigzag chain with competing ferromagnetic nearest-neighbor interaction \( J_1 \) and the antiferromagnetic next-nearest neighbor interaction \( J_2 \). The ground state of this system has vector-chiral (VC) correlations, while at higher magnetic fields collinear spin-density-wave (SDW) state evolves. Remarkably, between these two states we discover an intriguing spin-stripe phase with temperature-dependent nanometer-scale modulation is established [4]. A detailed inspection reveals that spin-strips consist of the main SDW state that is intertwined with another SDW modulation, which has slightly different periodicity and perpendicular alignment of the magnetic moments. We associate the observed behavior with magnetic anisotropy and weak frustrated interchain exchange interactions that may be further assisted by the symmetry allowed electric polarization.

The concept we propose thus represents an alternative route to the stripe formation in strongly correlated electron systems and may help understanding other widespread, yet still elusive, stripe-related phenomena.


S0726 Novel valence-bond crystal phase of frustrated \( J_1 - J_2 \) transverse-field Ising model on square lattice. M. Sadrzadeh (SUT), R. Hagshenas (SUT), S. Jahromi (SUT), A. Langari (SUT) – We propose a special cluster-valence bond crystal phase for quantum ground state of transverse field Ising model on the antiferromagnetic \( J_1 - J_2 \) square lattice at highly frustrated point \( J_2/J_1 = 0.5 \) and at low fields. In zero field, the ground state of \( J_2/J_1 = 0.5 \) is highly degenerate. We investigate the effect of quantum fluctuations induced by the transverse field \( \Gamma \) to lift this extensive degeneracy toward a unique quantum ground state. We consider two types of quantum fluctuations, harmonic ones using linear spin-wave theory with single spin flip excitations above a long-range magnetic ordered background and an-harmonic fluctuations, using a cluster operator approach (COA) with multi-spin cluster-type fluctuations above a non-magnetic cluster ordered background. We found that harmonic quantum fluctuations of LSWT fail to lift the extensive degeneracy as well as signaling a violation of the Hellmann-Feynman theorem. However, an-harmonic cluster-type fluctuations of COA are able to lift the degeneracy toward a VBC phase, which is obtained from an effective theory consistent with the Hellmann-Feynman theorem as well. Such an emergent non-magnetic phase is gapped and breaks lattice rotational symmetry with only two-fold degeneracy. This phase bears a quantum continuous phase transition to a quantum paramagnet at high fields. Our results are confirmed with numerical approaches like exact diagonalization and multi-scale entanglement renormalization ansatz (MERA).

S0727 Exact diagonalization studies on the entanglement spectrum of frustrated spin ladder. Yu-Chin Tzeng (Dept. of Phys., NCHU), Ying-Jer Kao (Dept. of Phys., NTU) – By using exact diagonalization up to 32 spins, we study the entanglement structure between two spin chains with frustrated coupling. The Rényi entropies with index \( \alpha \) are also computed, as a re-parameterized entanglement spectrum. Periodic boundary conditions are used, and the entanglement spectra are analyzed by quantum numbers \( (k_A, S_A^z) \). We compare the results with unfrustrated case.[1]


S0728 Spin chains with spin-orbit driven frustration. K. Yu. Povarov, M. Hälgi, W. E. A. Lorenz (ETH Zürich), T. A. Soldatov, A. I. Smirnov (Kapitza Institute RAS), A. Zheludev (ETH Zürich) – Typically, the competing Heisenberg exchange interactions are the source of frustration in the magnetic materials. However, this is not the case in the family of model \( S = 1/2 \) spin-chain compounds \( K_x CuSO_4(Cl,Br)_2 \). While the chain exchange constant \( J \) is the only relevant isotropic parameter, anisotropic Dzyaloshinskii–Moriya interaction, which stems
from the spin-orbit coupling, plays an important role, determining unconventional properties of these antiferromagnets. The corresponding vector $\mathbf{D}$ is uniform within a chain, but staggered between the adjacent chains. In the semiclassical schematics, this stabilizes counter-rotating spirals with $D/J$ pitch angle in the neighboring chains, thus effectively canceling the possible interchain interaction. The dominant quantum fluctuations make this picture much more complicated. Taking the end material $K_2\mathrm{CuSO}_4\mathrm{Br}_2$ as an example we experimentally show, how frustrating Dzyaloshinskii–Moriya interaction modifies the fine structure of the chain excitation spectrum and leads to the peculiar competing phases at low temperatures [1,2].


08 Others - Experiments

S0801 High-field $^1$H-NMR study around a 1/4 plateau of quantum spin dimer system NH$_4$CuCl$_4$. K. Matsui (Sophia Univ., JSPS), M. Fujisawa (Tokyo Inst. of Tech.), H. Tanaka (Tokyo Inst. of Tech.) and T. Goto. — The magnetization process of quantum spin systems is attracting much interest, because some system shows the magnetization plateau which cannot be understood in terms of the conventional classical spin vector models [1]. NH$_4$CuCl$_4$ is an $S = 1/2$ three dimensional spin dimer system, which shows two-stepped magnetization plateaus at 1/4 and 3/4 of the saturation magnetization. The plateaus appear for any field directions, indicating that its mechanism roots in the quantum effect. The 1/4 plateau is between $H_{c1} = 5.0$ T and $H_{c2} = 12.8$ T, and the 3/4 plateau, between $H_{c3} = 17.9$ T and $H_{c4} = 24.7$ T [2]. The zero-field ground state is gapless, and the system shows a long range order at $T_N = 1.23$ K [3]. To explain the plateaus, the three-dimer model was proposed by Matsumoto [4]. In order to test the model experimentally, the knowledge of magnetic structure at zero and finite field is mandatory. For this purpose, we performed NMR experiments at low temperature down to 0.3 K. $^1$H-NMR spectra were measured on a single crystal in the field region 2 – 9 T, which corresponds to the 1/4 plateau, with the field parallel to the b-axis and in temperature region 0.35 – 2.35 K, which oversides the Néel temperature.

The cation NH$_4^+$ is located at interstitial sites between dimers [5]. There are four inequivalent NH$_4^+$ sites in unit cell, and we observed four distinct peaks corresponding to each four NH$_4^+$ sites in the paramagnetic state. The Knight shift of each four peaks directly reflects the sum of the local magnetization of their nearest three dimers. The field and temperature dependence of the Knight shift is expected to reveal the geometrical pattern of the magnetization of the inequivalent dimers. The splitting distance of the peaks increases with increasing field, and reproduced the uniform magnetization curve. No drastic change in the spectral profile was observed at $H_{c1}$ in the paramagnetic state. Below $T_N$, there are four peaks at field region in 1/4 plateau, and the one of the peaks splits, making five peaks at $H < H_{c1}$.


S0802 Orbital order and frustrated magnetism in $^{1/4}$ alums. G. J. Nilsen (RAL), A. A. Tsirlin (Uni. Augsburg), D. Kasinathan (MPI CPS), A. Raja (EPFL), H. Mutka (ILL), and H. M. Rønnow (EPFL) — Recent interest in materials with partly filled $d$ and $5d$ ions like Ru$^{3+}$ or Ir$^{4+}$, where the large spin-orbit coupling results in strongly anisotropic exchange interactions. In orbitally degenerate $3d$ systems, however, the spin orbit coupling is small and competes with other small perturbations, like further-neighbour contributions to the crystal field. As a result, the orbital ground state and super-exchange pathways are extremely sensitive to the details of the local environment around the magnetic ion. In this presentation, I will focus on two materials in the alum family, KTi(SO$_4$)$_2$ [1,2] and KTi(SO$_4$)$_2$:H$_2$O [3,4], where the magnetic moment arises from Ti$^{3+}$ ions with a single $3d$-electron. In both cases, ab-initio calculations reveal that the orbital ground state is not the one expected from simple crystal field arguments [2,4]. In the anhydrous compound, the result is effectively one-dimensional magnetism, with a small frustrating interchain interaction, as confirmed by the observation of a spinon continuum in inelastic neutron scattering experiments [2]. For KTi(SO$_4$)$_2$:H$_2$O on the other hand, the orientation of the active orbital results in a frustrated one-dimensional system near the Majumdar-Ghosh limit [4].


S0803 Recent developments on the D7 diffuse scattering spectrometer at the ILL. L. Mangin-Thro, G. Nilsen, K. Brown, B. Giroud, W. Clancy and A. Wildes (ILL, Grenoble, France) — D7 is a low resolution diffractometer with permanent polarization analysis. It is mostly used to investigate diffuse scattering in disordered magnetic materials, as well as for coherent/incoherent separation in soft matter. D7 can furthermore be converted into a polarized direct geometry time-of-flight spectrometer by adding a Fermi chopper.

D7 has undergone some recent upgrades. The fields around the sample are now more homogeneous due to the installation of a new set of guide-field coils. The new coils are also...
fully compatible with XYZ polarization analysis in the time-of-flight mode, which is further improved by the development of a new slit package for the Fermi chopper. Polarization quality is further improved with the installation of a radiofrequency flipper (which has 100% efficiency and transmission), which also creates the possibility for time-dependent scattering such as statistical chopping. The sample environment, namely the cryostat, has been improved for faster cooling, lower background and has a two-stage sample changer as an available option.

The most exciting development is the proposed upgrade for the primary spectrometer, which forms part of the ENDURANCE suite of upgrades at the ILL. We propose to increase flux by a factor of 20-50 by enlarging the size and divergence of the guide, installing a new double-focusing monochromator, reducing the monochromator-sample distance, and polarizing in-guide. The possibility of expanding the accessible incident wavelength range is also being explored. The upgrade will be especially beneficial in time-of-flight mode, where low flux currently renders experiments challenging.

**S0804 Photo-creating supercooled spiral-spin states in a multiferroic manganite.** Y. M. Sheu (NCTU, RIKEN), N. Ogawa (RIKEN), Y. Kaneko (RIKEN), Y. Tokura (RIKEN, U. Tokyo) — We demonstrate that dynamics of the abc-spiral-spin order in a magneto-electric multiferroic Eu0.55Y0.45MnO3 can be unambiguously probed through optical second harmonic signals, generated via the spin-induced ferroelectric polarization. In the case of relatively weak photoexcitation, the ferroelectric and the spiral-spin order remains interlocked, both relaxing through spin-lattice relaxation in the non-equilibrium state. When the additional optical pulse illuminating sample is intense enough to induced a local phase transition thermally, the system creates a metastable state of the bc-spiral-spin order (with the electric polarization P//c) via supercooling across the first-order phase transition between ab- and bc-spiral. The supercooled state of bc-spiral spin is formed in the thermodynamic ground state of ab-spiral (P//a), displaying a prolonged lifetime with strong dependence on the magnetic field along the a-axis. The observed photo-switching between the two distinct multiferroic states sheds light on novel photoinduced phenomena in spiral-spin multiferroics.

**S0805 Successive phase transitions observed in the new frustrated magnet, KCu1.03CO1.03SO4.92 (kamchatkite).** H. Kikuchi1, K. Kunieda1,2,3@ Y. Fujii2, A. Matsuo3, K. Kindo1 (Univ. of Fukui1, FIR Center. Univ. of Fukui2, ISSP. the Univ. of Tokyo) — Cu3+ (S = 1/2) ions in KCu1.03CO1.03SO4.92 (kamchatkite) form distorted tetrahedra and these spin-tetrahedra are connected along a crystallographic a axis. Because of this crystal structure, kamchatkite is expected to show spin frustration effect but no magnetic studies have been reported yet. We synthesized powder sample of kamchatkite and measured magnetic susceptibility, specific heat, high field magnetization and ESR. The specific heat result revealed three successive phase transitions at about 15, 11 and 3 K. The 15 K and 3 K transitions are considered to be a weak ferromagnetic and antiferromagnetic transitions, respectively.

**S0901 A spiral magnetic structure in the double perovskite YBaCuFeO5.** C.-H. Du, Y.-C. Lai, C.-H. Lai, C.-H. Liang (TKU, Taiwan); C.-W. Wang (NSRRC, Taiwan); K. Rule (ANSTO, Australia); W.-T. Chen, G.-J. Shu, F.-C. Chou (NTU, Taiwan) — Using magnetization, x-ray and neutron diffraction measurements on a high quality single crystal of YBaCuFeO5, we demonstrate that YBCFO displays anisotropic magnetization behavior at low temperatures which is according to the formation of a spiral magnetic structure. The crystal shows two magnetic transitions at T1 ~ 475 K and T2 ~ 175 K. The transition at T1 is correspondent with a paramagnetic to antiferromagnetic transition with a q-wavevector doubling the unit cell along three crystallographic axes respectively. Upon cooling, at T2, the commensurate spin ordering undergoes a transition to form a spiral magnetic ordering with a q-wavevector of (h k l) = (1 0 1/2 + δ), where h, k, and l are odd, and the incommensurability δ is temperature dependent. Around the transition boundary of T2, both commensurate and incommensurate spin ordering coexist.


**S0902 Low temperature magnetism of the rare-earth spinel compound CdYb2S4.** D. Yoshizawa (AHMF, Grad. Sch. Sci., Osaka Univ), T. Kida (AHMF, Grad. Sch. Sci., Osaka Univ), S. Nakatsuji (ISSP, NTU), T. Kida (AHMF, Grad. Sch. Sci., Osaka Univ), S. Nakatsuji (ISSP, NTU Convention Center)
From this point of view, we focus on the rare-earth spinel compound CdYb$_2$S$_4$, in which Yb$^{3+}$ ions form the pyrochlore lattice. This compound shows a sharp peak of the specific heat at $T=1.8$ K, indicating a long-range ordering [3]. In the present study, we have performed magnetization and electron spin resonance (ESR) experiments in pulsed magnetic fields and specific heat measurements in static fields. The magnetization and specific heat measurements were carried out below 1 K. From the ESR and specific heat results of CdYb$_2$S$_4$, the gapless feature of CdYb$_2$S$_4$ was found, and this gapless feature provides evidence for the existence of the Palmer-Chalker or the $\psi_5$ state [3, 4]. By using all the experimental results, we construct an unusual magnetic field versus temperature phase diagram of CdYb$_2$S$_4$.

**S0904 NMR measurement on LiGa$_{1-x}$In$_x$Cr$_4$O$_8$ with Breathing pyrochlore lattice.**

Y. Tanaka (ISSP), M. Yoshida (MPI), M. Takigawa (ISSP), Y. Okamoto (Nagoya Univ.), Z. Hiroi (ISSP), R. Wawrzynzczak (ILL), G. J. Nilsen (RAL) — The spinel oxides LiInCr$_4$O$_8$ and LiGaCr$_4$O$_8$ have a network of Cr$^{3+}$($S=3/2$) tetrahedra with alternating sizes called "breathing" pyrochlore lattice. In this system, antiferromagnetic (AF) exchange coefficients are different depending on the bond length and thus this system locates between uniform pyrochlore and isolated tetrahedra [1]. We report NMR studies on end-member compounds LiInCr$_4$O$_8$, LiGaCr$_4$O$_8$ and their solid solutions LiGa$_{1-x}$In$_x$Cr$_4$O$_8$.

In LiInCr$_4$O$_8$ with large alternation, nuclear relaxation rate $1/T_1$ shows an activated temperature dependence down to 18 K, indicating a singlet ground state with a spin gap [2]. This behavior, however, is disrupted by an AF transition at 13 K, which is preceded by another, most likely structural, transition at 16 K [2]. These transitions were not observed in the heat capacity measurements on the Ga doped sample ($x=0.94$) [3]. We have also investigated the ground state of the Ga doped sample by using NMR experiments. LiGaCr$_4$O$_8$ with small alternation of tetrahedra does not show spin gap but exhibits a first-order AF transition over a distributed temperature range 13–20 K. Nevertheless, $1/T_1$ of the paramagnetic component diverges toward 13 K, indicating proximity to a second-order transition. The results in-
dicate that LiGaCr$_2$O$_4$ is located in the vicinity of a tricritical point or a boundary of several competing phases [2]. This scenario is supported by the results of the thinned doped sample ($x = 0.05$), which exhibits a second-order transition at 11 K.


**S0905 Magnetic Properties of A-site Antiferromagnetic Spinel**

CoRh$_2$O$_4$ and CuRh$_2$O$_4$. Luwe Ge (Georgia Tech), J. Pad-
dison (Georgia Tech), J. Flynn (Oregon State), S. Cadler (ORNAL), M. Stone (ORNAL), M. Subramanian (Oregon State), A. Ramirez (UC Santa Cruz), M. Mourigail (Georgia Tech) — We characterize the magnetic properties of the A-site spinels CoRh$_2$O$_4$ and CuRh$_2$O$_4$ by means of thermomagnetic and neutron scattering measurements and perform group theory analysis, Rietveld refinement, mean-field theory, and spin wave theory calculations to analyze our results. Our investigation reveals that CoRh$_2$O$_4$ is a canonical $S = 3/2$ diamond-lattice Heisenberg antiferromagnet with a nearest neighbor exchange $J = 0.65$ meV and a Néel temperature of 25 K. In CuRh$_2$O$_4$, the distorted diamond lattice leads to the development of an incommensurate helical order at 24 K. Strong reduction of the ordered moment is observed for the $S = 1/2$ spins and reproduced by $1/S$ corrections to spin-wave theory.


**S0907 Spin Ice Physics in CdEr$_2$X$_6$ (X = Se, S) spinels.** O. Za-
harko (LNS, PSI, Switzerland), S. Gao (LNS, PSI, Villigen; Univ. of Geneva, Switzerland), T. Fennell (LNS, PSI, Switzerland), Ch. Rüegg (LNS, PSI, Vil-
legen; Univ. of Augsburg, Germany; Academy of Sciences of Moldova, Moldova) — Recently, the spinel compound CdEr$_2$Se$_6$ was proposed to be the first spin ice outside the rare earth pyrochlore oxides family [1]. Here we present microscopic proofs for this new spin ice state based on neutron scattering experiments and compare the crystal electric-field parameters, strength of dipolar interactions and spin dynamics of CdEr$_2$Se$_6$ with a new material CdEr$_2$S$_4$. Our study confirms the Ising character of the Er$^{3+}$ spins and proves the dominance of dipolar interactions in these compounds. As the ground state is a dipolar-octupolar doublet and it is separated from the 1st excited state by only $\approx 4.5$ meV, these compounds are promising candidates for quantum spin ice physics.


**S0908 Thermal transport properties of quantum spin liquid candidate Ba$_2$CuSb$_2$O$_9$.** Kaori Sugii, M. Shimazawa, D. Watan-
abe, Y. Suzuki, M. Halim, M. Kimata, Y. Matsumoto, S. Nakatsuji, M. Ya-
mashita (ISSP, The University of Tokyo) — The hexagonal perovskite-
type Ba$_2$CuSb$_2$O$_9$ is a candidate material of a 2d quantum orbital-spin liquid state [2], where both orbital and spin degrees of freedom of Cu$^{2+}$ ion are entangled, and neither long range magnetic order nor Jahn-Teller distortion are observed down to the absolute zero temperature [3]. In order to clarify the detailed nature of such a quantum liquid state, the thermal transport measurement is one of the most powerful methods because it is a direct probe of the elementary excitation [4,5].

Here, we investigated the longitudinal and transverse thermal conductivities of Ba$_2$CuSb$_2$O$_9$. For comparison, we also studied the thermal properties of the off-stoichiometric orthorhombic compound, which exhibits a Jahn-Teller distortion at $\sim 200$ K. In both the hexagonal and orthorhombic Ba$_2$CuSb$_2$O$_9$, the thermal conductivities are strongly suppressed, indicating that the phonons are strongly scattered by the intrinsic random structure of the Cu$^{2+}$-Sb$^{5+}$ dumbbells. We further find a distinct thermal Hall conductivity in
hexagonal $\text{Ba}_3\text{CuSb}_2\text{O}_9$, whereas it is an insulator. The thermal Hall conductivity of hexagonal compound has a power-law temperature dependence in the low temperature regime, where the spin gap opens. These results mean the presence of an unconventional elementally excitation associated with the phonon. We suggest that, through the very low longitudinal thermal conductivity and distinct Hall signals, strong phonon scatterings by orphan $\text{Cu}^{2+}$ spins formed by the random structure give rise to a phonon Hall effect.


**S02090** Spiral spin-liquid and the emergence of a vortex-like state in $\text{MnSc}_2\text{S}_4$.

Sh. Gao (LNS, PSI and Uni. of Geneva, Switzerland), O. Zaharko (LNS, PSI), Vladimir Tsukan (Uni. of Augsburg, Germany; Academy of Sciences of Moldova, Moldova), Yixi Su (UCNS), J. S. White (LNS, PSI), G. S. Tucker (LNS, PSI), B. Roessli (LNS, PSI), F. Bourdarot (CEA et Universite Grenoble Alpes, INAC-MEM-MDN, France), R. Sibille (LDM and LNS, PSI, Switzerland), D. Chernyshov (SNBL, ESRF, France), T. Fennell (LNS, PSI), A. Loidl (Univ. of Augsburg, Germany), Ch. Ruegg (LNS, PSI and Uni. of Geneva) — Spiral orders are common in magnetic solids and support emergent structures like the skyrmion and vortex lattices. A new type of spiral state, the spiral spin-liquid, in which spins fluctuate collectively as spirals, has been recently predicted to exist in the diamond lattice [1]. Here, using neutron scattering techniques, we experimentally prove the existence of a spiral spin-liquid in $\text{MnSc}_2\text{S}_4$ by observing the ‘spiral surface’ — a continuous surface of spiral propagation vectors in reciprocal space [2]. We elucidate the multi-step ordering behavior of the spiral spin-liquid, and discover a vortex-like triple-$\mathbf{q}$ phase on application of a magnetic field [2]. Our results demonstrate the effectiveness of the $J_1$-$J_2$ Hamiltonian as a model for $\text{MnSc}_2\text{S}_4$ and its spiral spin liquid, and also open a new way to realize the long-sought vortex lattice.


**S0910** Disordered spin-orbital dimer state in double-perovskite compounds.

J. Romhányi (OIST), G. Jackeli (MPI and Uni. Stuttgart) — Exotic ground states can arise as a consequence of unquenched orbital degrees of freedom. On the account of orbital degeneracy, spin exchange may become modulated and dependent on the direction of the bonds, giving rise to magnetically (and orbitally) disordered ground state with extensive degeneracy.[1] We construct a microscopic model for the frustrated magnetic insulator, $\text{Ba}_3\text{YMoO}_6$, and show that the orbital physics leads to a disordered arrangement of spin-orbital dimer singlets in the ground state. We discuss how the pseudo-spins forming the singlets alter upon changing the strength of spin-orbit interaction and show how finite Hund’s coupling enriches the phase diagram with non-collinear ordered phases. Our results support the experimentally observed amorphous valence bond state in $\text{Ba}_3\text{YMoO}_6$.[2]


**S0911** “Magnetic three states of matter”: a quantum Monte Carlo study of the extended toric codes in 2D and 3D.

Y. Kamiya (RIKEN), Y. Kato (Univ. of Tokyo), J. Nasu (Tokyo Inst. of Tech.), Y. Motome (Univ. of Tokyo) — It has been long debated where and how one can find realizations of quantum spin liquids (QSLs). This topic has become even more important after the proposal of the Kitaev Hamiltonian and the subsequent experimental efforts for searching candidate materials. Since candidates are normally in or in the proximity to other competing phases like magnetically ordered phases, it is natural to ask what type of global phase diagram one can anticipate depending on the system’s dimensionality, the type of QSLs, coupling constants, temperature, and so on. In this work, we show examples of such thermodynamic phase diagrams in 2D and 3D combining all of “magnetic three states of matter,” i.e., QSL, paramagnetic, and magnetically ordered phases [1]. Our results were obtained by world-line quantum Monte Carlo simulations of the toric code Hamiltonians extended with Ising interactions on the square and the cubic lattices. We show that the ordered phase grows continuously from the quantum critical point in 2D, while it borders on the QSL phase around the exactly solvable point by a discontinuous transition line in 3D. In both cases, peculiar proximity effects to the nearby QSLs appear at intermediate temperature even when the ground state is magnetically ordered. Such proximity effects include a fractionalization of the order parameter field at the quantum critical point in 2D and a tricritical behavior related to shrinking $Z_2$ gauge flux loops in 3D.


**S0912** Magnetic field dependence of excitations near spin-orbital quantum criticality.

A. Biffin (Laboratory for Neutron Scattering and Imaging, Paul Scherrer Institut), Ch. Ruegg (LNS PSI & Department of Quantum Matter Physics University of Geneva), J. Embs (LNS, PSI), T. Guidi (ISIS Facility, Rutherford Appleton Laboratory), A. Loidl (Experimental Physics 5, University of Augsburg), V. Tsurkan (Exp Phys 5, Univ. Augsburg & Institute of Applied Physics, Academy of Sciences of Moldova), R. Coldea (Clarendon Laboratory, University of Oxford) — In the spinel FeSc$_2$S$_4$, the combination of a diamond lattice geometry and a dominant next-nearest neighbour antiferromagnetic exchange leads to the frustration of $S = 2$ Fe$^{3+}$ moments, with no experimental signatures of magnetic order observed down to the lowest temperatures. However, frustration in the spin-sector is not the end of the story. The
cubic symmetry of these moments’ ligand environment also protects a two-fold orbital degeneracy, whose persistence down to low temperatures is evinced by the absence of structural distortions (fingerprints of the ‘usual’ Jahn-Teller mechanism for lifting orbital degeneracy). Such intriguing properties lead to the proposal that FeSc$_2$S$_4$ realizes a near-critical spin-orbital singlet (SOS) state, where entangled spin and orbital moments fluctuate in a global singlet state on the verge of spin and orbital order. Here we report powder inelastic neutron scattering measurements that observe the full bandwidth of magnetic excitations and we find that spin-orbital tripion excitations of an SOS state can capture well key aspects of the spectrum in both zero and applied magnetic fields up to 8.5 T. The observed shift of low-energy spectral weight to higher energies upon increasing applied field is naturally explained by the entangled spin-orbital character of the magnetic states, a behaviour that is in strong contrast to spin-only singlet ground state systems, where the spin gap decreases upon increasing applied field. The results of recent experiments probing the effect of pressure on the system’s structural and magnetic properties will also be presented.


10 Quantum Spin Ice.

S1001 Quadrupole order in the frustrated pyrochlore
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\text{TB}_{2+x}\text{Ti}_{2-x}\text{O}_{7+y}, \quad H. Takatsu (TMU, Kyoto Univ.), S. Onoda (RIKEN), S. Kittaka, A. Kasahara, Y. Kono, T. Sakakibara (ISSP), Y. Kato (RIKEN, Univ.of Tokyo), B. Fak, J. Ollivier (ILL), J. W. Lynn (NIST), T. Taniguchi, M. Wakita, H. Kadowaki (TMU), and H. Kageyama (Kyoto Univ.) — Geometrically frustrated magnets have attracted much attention because of a rich playground for studying new type of electronic and magnetic behaviors with unconventional order parameters [1, 2]. Spin systems with networks of triangular, kagomé, and pyrochlore lattices are examples in these studies. In particular, the pyrochlore-lattice magnet \(\text{TB}_{2+y}\text{Ti}_{2-y}\text{O}_{7+y}\) is a unique material showing an unknown, or hidden, low range order (LRO) in the vicinity \((x \geq x_c \sim -0.0025)\) of the spin liquid (SL) state [3], where the clear specific-heat peak appears at \(T_c = 0.53\) K for the sample with \(x = 0.005\), while no LRO associated with the large magnetic and/or structural phase transition was observed. This LRO is apparently different from the magnetic dipole order inferred by earlier theories on the basis of the spin ice (SI) Hamiltonian [4, 5]. Also the nature of the SL of the nominal \(\text{TB}_{2}\text{Ti}_{2}\text{O}_{7}\) has until remained elusive, which is subject of hot debate in condensed matter physics [6]. Recent theories propose that transverse superexchange interactions between quadrupole moments, which work as additional terms in the SI Hamiltonian, play an important active role for the emergence of the SL and quadrupolar LRO phases [7-9].

In this presentation, we show our recent experimental studies on a high-quality single crystal of \(\text{TB}_{2+x}\text{Ti}_{2-x}\text{O}_{7+y}\) with \(x = 0.005\) \((T_c = 0.53\) K) [10]. We have succeeded in demonstrating that the observed hidden order is actually ascribable to the electric quadrupole order, using several experiments such as specific heat, magnetization, and neutron scattering as well as calculations on the basis of the theoretical model of Ref. [7]. These results also clarified that the elusive SL of \(\text{TB}_{2}\text{Ti}_{2}\text{O}_{7}\) is most likely to a U(1) quantum spin liquid melting from the quadrupolar solid. The present results may open a new research direction of a “frustrated quadrupolar system”.


S1002 Candidate quantum spin liquid phases in \(\text{Pr}_2\text{Hf}_2\text{O}_{7}\) and \(\text{Ce}_2\text{Sn}_2\text{O}_{7}\).

R. Sibille (PSI), E. Lhotel (CNRS), T. Fennell (PSI), N. Gauthier (PSI), M. Cionaghi Hatnean (Warwick), M. R. Lees (Warwick), G. Bolakrishnan (Warwick), B. Fik (ILL), V. Ban (PSI), V. Ponomukhin (PSI), H. Luettken (PSI), C. Baines (PSI) and M. Kenzelmann (PSI) — The classical spin ice state is a well-established paradigm in frustrated magnetism and emergent many body physics: the frustrated ground states can be seen as a vacuum in which the low-lying excitations are emergent quantum monopoles interacting by classical magnetostatics. The quantum spin ice (QSI) state forms a particularly important ongoing challenge [1]. This ground state is a generalization of the classical spin ice state to include quantum fluctuations, such that the effective theory becomes emergent quantum electrodynamics - the classical monopoles become coherent quantum quasiparticles, and a novel excitation playing the role of the photon appears. In a more general sense, the QSI belongs to a broader class of highly-correlated electron states - quantum spin liquids - which are quantum coherent over macroscopic length scales, and emerge from a subtle long-range entanglement of the ground state wavefunction.

Here we present two separate studies in our quest for quantum spin liquids on the pyrochlore lattice. \(\text{Pr}_2\text{Hf}_2\text{O}_{7}\) displays striking characteristics of the ferromagnetic correlations expected in a quantum spin ice [2], while \(\text{Ce}_2\text{Sn}_2\text{O}_{7}\) seems to retain an antiferromagnetic liquid ground state with quantum fluctuations [3]. We present results ranging from macroscopic characterizations to neutron scattering and muon spin relaxation measurements. We illustrate and discuss both the single-ion and cooperative magnetic properties of these two

S1003 Frustrated Magnetism and Effects of Charge Disorder in Pr$_2$ScNbO$_7$. C. Mauws (U of Winnipeg), S. Yano (ANSTO), Y Qiu (NIST), J. S. Gardner (NSSRC), C. R. Wiebe (U of Manitoba, McMaster U, CIFAR) — The pyrochlore series has been a staple in frustrated magnetism for decades, due to their robust number of ground states [1]. Despite this, the investigation of praseodymium pyrochlores has been restricted to Pr$_2$Zr$_2$O$_7$ and Pr$_2$Sn$_2$O$_7$[1,2]. Investigation of these samples has been limited due to the difficulty of single crystal preparation. The new pyrochlore Pr$_2$ScNbO$_7$ offers a new route to investigating the praseodymium pyrochlores as well as the effect of B-site charge disorder on the pyrochlore system. Pr$_2$ScNbO$_7$ has been prepared through standard solid state synthesis methods [3], and grown as a single crystal by the floating zone technique. Crystals were grown under flowing argon to achieve the proper oxidation state, confirmed by magnetometry. Pr$_2$ScNbO$_7$ has been studied through specific heat measurements, DC magnetometry as well as elastic and inelastic neutron spectroscopy at the Multi-Angular Crystal Spectrometer (MACS) at the National Institute of Standards and Technology. Magnetometry data shows paramagnetic behavior down to below 1.8 K, with net anti-ferromagnetic interactions. Specific heat measurements show a broad anomaly from 2-40 K, followed by a sharp peak below 300 mK. Zero field, elastic measurements on MACS showed no long range magnetic order at 100 mK, but an increase in diffuse scattering at low Q. Long range magnetic order developed upon the application of a magnetic field (up to 9 T) evidenced by the appearance of the (2,0,0) peak, previously absent.


S1004 Ground-state selection under pressure in the quantum pyrochlore magnet Yb$_2$Ti$_2$O$_7$. E. Kermarrec (Université Paris Sud), J. Gaudet (McMaster Uni), K. Fritsch (HZB), R. Khasanov (PSI), Z. Guguchia (PSI), C. Ritter (ILL), K. A. Ross (Colorado State University), H. A. Dabkowska (McMaster University), B. D. Gaulin (McMaster University) — Frustrated rare-earth pyrochlore Ising magnets were long ago recognized as prime examples of classical spin liquids with fractionalized thermal excitations, described in terms of “magnetic monopoles”. In recent years, the search for a quantum spin ice (QSI), in which the magnetic monopoles become long range entangled and an emergent quantum electrodynamics arises, has been largely based on the generic $S = \frac{1}{2}$ anisotropic exchange Hamiltonian on the pyrochlore lattice [1]. The pyrochlore magnet Yb$_2$Ti$_2$O$_7$ is a promising QSI candidate as it possesses both an effective $S = \frac{1}{2}$ spin, thanks to the well isolated crystal field Kramers doublet ground-state appropriate to Yb$^{3+}$, and strong quantum fluctuations brought by anisotropic exchange interactions and an XY g-tensor. However, despite numerous studies, the magnetic properties of Yb$_2$Ti$_2$O$_7$ have eluded a global understanding and even the presence or absence of static magnetic order at low temperatures is controversial [2]. In this talk we show that sensitivity to pressure is the missing key to the low temperature behaviour of Yb$_2$Ti$_2$O$_7$. By combining neutron diffraction and muon spin relaxation techniques, we evidence a magnetic transition from a disordered, non-magnetic, ground-state at ambient pressure to a spayed ferromagnetic ground-state under hydrostatic pressure [3]. Low energy inelastic neutron scattering measurements further show that Yb$_2$Ti$_2$O$_7$ displays a continuum of gapless excitations on an energy scale $< 0.09$ meV [4], robust to the presence of weak disorder, in addition with anomalous spin dynamics detected in $\mu$SR [5].

Our results provide new insights on the origin of the sample dependence in the ground state selection for Yb$_2$Ti$_2$O$_7$ and demonstrate the proximity of the low temperature disordered phase to a ferromagnetically ordered phase. Our finding is consistent with the recent theoretical proposals that Yb$_2$Ti$_2$O$_7$’s ground state is governed by quantum fluctuations arising from phase boundaries in the generic QSI Hamiltonian phase diagram [6].


S1005 First-principles design for high-temperature quantum spin ice in Ir$_2$O$_3$. — Quantum spin ice systems have attracted current great interest for hosting an emergent magnetic analogue of quantum electrodynamics, which may open a new direction for potential applications. Here, we present first-principles electronic structure calculations of new candidate quantum spin ice materials based on epitaxial thin films of the
A-site de-intercalated spinel $\text{Ir}_2\text{O}_4$ [1]. In the ideal bulk cubic case, phase transitions occur from a paramagnetic semimetal through a $[001]$-ferromagnetic semimetal to a $\Gamma_3$ antiferromagnetic insulator as we increase the onsite Coulomb interaction $U$ on Ir conduction electrons. In the tetragonal case with the MgO$(001)$ substrate, the $[100]$-ferromagnetic structure is stabilized by an moderately large $U$. In the rhombohedral case with the LiNbO$_3$(0001) substrate, successive transitions occur from a $[111]$-ferromagnetic sem metal through a 2-in, 2-out ferromagnetic semimetal to an antiferromagnetic insulator with a distorted $\Gamma_3$ structure. On a basis of comparisons among different magnetic solutions, the nearest-neighbor exchange coupling constants for the pseudospin-$1/2$ quantum spin ice Hamiltonian [2] are estimated in the mean-field level. It is found that the exchange coupling constants increase up to several to tens of meV with increasing $U$, providing yet another laboratory for quantum spin ice physics but now with orders of magnitude larger exchange coupling constants than in magnetic rare-earth pyrochlore oxides. A possibility of realizing a quantum U(1) spin liquid from Ir$_2$O$_4$ is discussed.


**S1006 Revisiting the low temperature magnetic structure of Yb$_2$Ti$_2$O$_7$: definitive evidences.** V. Peçanha-António, E. Feng, Y. Su, Th. Brückel (JCNS at MLZ, Germany) and L. J. Chang (NCKU, Taiwan) — In this poster, we present our studies of a powder sample of Yb$_2$Ti$_2$O$_7$. A well-characterised stoichiometric sample is particularly important when studying this compound due to the strong sample-dependence of its behaviour [1,2]. We have proven the stoichiometry of our sample to the greatest extent possible with the powder neutron diffraction technique and shown that it presents the low temperature specific heat anomaly characteristic of pristine samples of Yb$_2$Ti$_2$O$_7$. We report neutron diffraction data that clearly display a phase transition to a long-range, ferromagnetic state at $T_c = 0.28$ K, in disagreement with the recent allegations that the phase transition seen in neutron scattering is unrelated to that seen in heat capacity measurements [3,4]. The observed absence of the (200) magnetic Bragg peak in our work indicates that the canting angle of the spins out of the cubic axis is much smaller than previously reported [3], making the structure a quasi-collinear ferromagnet with an ordered moment of 0.87(2) $\mu_B$. Our results therefore raise questions about the existence of gapless magnetic excitations as a universal feature of $S_{	ext{eff}} = 1/2$ Yb-based pyrochlores [5]. Additionally, we show that our sample does not adopt any other symmetry-allowed long-range magnetic order below $T_c$ and that in fact we observe no evidence of multiple phase transitions or a multi-step ordering process [6].


**S1007 Spin liquid and electric quadrupole states in $\text{TB}_{2+\delta}\text{Ti}_{2-\delta}\text{O}_{7+\delta}$.** H. Kadowaki, M. Wakita, H. Takatsu: Department of Physics, TMU, Hachioji-shi, Tokyo 192-0397, Japan; B. Fåk, J. Ollivier: ILL, BP156, F-38042 Grenoble, France — It has been being revealed that ground states of $\text{TB}_{2+\delta}\text{Ti}_{2-\delta}\text{O}_{7+\delta}$ change from a quantum spin liquid state ($x < x_c$) to an electric multipole (or quadrupole) state ($x > x_c$) [1,2]. Although this electric quadrupole state is not directly observed yet, specific heat under magnetic fields on a single crystal sample [1,3] and inelastic neutron scattering data on a powder sample [1,4] are nicely interpreted by a quadrupole state which was theoretically predicted [5]. In this study, we investigate the two ground states by inelastic neutron scattering techniques on two single crystal samples with $x < x_c$ and $x > x_c$.


**S1008 Magnetic monopoles in quantum spin ice.** O. Petrova, R. Moessner (Max Planck Institute for the Physics of Complex Systems, S. L. Sondhi (Princeton University) — The quest for spin liquids is an important enterprise in strongly correlated many body physics in an era when a huge amount of theoretical interest has focused on forms of order outside the canonical broken symmetry paradigm. The celebrated spin ice is an example of a classical three dimensional spin liquid, whose excitations constitute condensed matter analogs of Coulombically interacting magnetic monopoles. Recently, the interest in the study of spin ice has shifted to looking for quantum generalizations of this model. We study the dynamics of magnetic monopoles in quantum spin ice, where quantum fluctuations are introduced in the form of single spin flips. We find that such form of fluctuations has important consequences for the spectrum of the model due to the bipartiteness of its state graph. In particular, it leads to extensive degeneracies of the classical energy levels, whose corresponding states are immune to quantum fluctuations. We expect this phenomenon to be manifested in experiment by the presence of flat bands in scattering data. Additionally, we consider the case of a weakly diluted quantum spin ice, where we find another crisp phenomenon, namely the emergence of hydrogenic excited states in which a magnetic monopole is bound to a vacancy at various distances [1].
Via a mapping to an analytically tractable single particle problem on the Bethe lattice, we obtain an approximate expression for the dynamic neutron scattering structure factor.


S1009 Quantum Monte-Carlo study on quantum spin ice under a [111] magnetic field. T. A. Bojesen (RIKEN), S. Onoda (RIKEN) – The quest for novel quantum spin liquids has been an intriguing issue in condensed matter physics. It has been proposed that a U(1) quantum spin liquid ground state is realized by starting from a spin ice [1–3], and then turning on nearest-neighbor spin-flip exchange interactions that lift the macroscopically degenerate spin-ice ground state manifold [4]. This U(1) spin liquid accommodates an emergent fictitious quantum electrodynamic characterized by deconfined bosonic spinons carrying fractionalized spin-manifold [4]. This U(1) spin liquid accommodates an emergent fictitious quantum electrodynamics characterized by deconfined bosonic spinons carrying fractionalized spin-1/2 charges, or “spin ice monopoles”, coupled to fictitious “pyrochlore photons”. Recent quantum Monte-Carlo simulations on the nearest-neighbor frustrated XXZ spin-1/2 model have indeed demonstrated a crossover from a classical spin ice regime, showing a spin ice entropy plateau, to a U(1) quantum spin liquid regime upon cooling [5].

Now, of our interest is the fate of this U(1) quantum spin liquid under a [111] magnetic field. In classical spin ice, the magnetization shows a jump to the one-third plateau of Kagomé ice [6] having a macroscopic degeneracy, at a field smaller than the saturation field for the fully polarized 3-in, 1-out state. In quantum spin ice, on the other hand, it is natural to expect that the magnetization should evolve continuously with increasing field because of gapless “photons”, while quantum spin ice monopole excitations remain gapped. Furthermore, the extensive degeneracy of Kagomé ice is lifted at low temperatures, as in zero field, within Kagomé planes and the Kagomé planes are also coupled to each other. In spite of the relevance of the model to experiments [7], however, the nature of this three-dimensional stacking of quantum Kagomé ice, realized in quantum spin ice systems at moderately high [111] magnetic field, has not been addressed theoretically to date.

Here, we perform extensive unbiased quantum Monte-Carlo simulations on the simplest quantum spin ice model under a [111] magnetic field. It is found that the classical-to-quantum crossover on cooling, which has been confirmed at zero magnetic field in the previous study [5], continues to moderately high magnetic field: Kagomé ice entropy and magnetization plateaux appears in an intermediate temperature and field region, which is followed by a release of the entropy at lower temperatures. Predictions for the spin-polarized neutron scattering profile and transport coefficients are made on a basis of the simulations.


S1010 Semi-classical dynamics and the fate of monopoles in quantum spin ices. M. Taillefumier (OIST), O. Benton (OIST) and N. Shannon (OIST) – Quantum spin ices and their excitations are the subject of intense study for the past two decades. Much less is known about the physics of their classical counterparts. In particular, do spin models with continuous O(3) spins having spin ice states as ground states have the same properties as their quantum siblings and, if not, what differs between the two. To provide an answer to this question, we apply montecarlo simulations and semi-classical dynamics to a model of quantum spin ice in presence of a transverse XY term, $J_{\perp}$, where the spins are treated classically.

We find that for $J_{\perp} = 0$, also known as exchange ice, the semi-classical dynamics is fully integrable. The signal observed in the dynamical structure factor is incoherent and centered around precise values of the larmor frequency that depend on the local arrangements of the spins.

Introducing a finite XY term in the Hamiltonian changes the dynamics drastically while the thermodynamics remains essentially the same until the transverse term reaches the value $J_{\perp} = 1$. Contrary to the exchange ice, we observe coherent spinwave-like excitations above the gap in the low-temperature ice regime that can partially be explained using simple spinwave theory of the 2 in - 2 out ice state.

In the intermediate temperature regime where “monopole” excitations are thermally activated, the dynamical structure factor has contributions from short life time excitations and incoherent signal in the energy gap located around zone centers for positive transverse XY coupling.

To explain this signal, we consider the dynamics of spin ices in which a finite density of monopoles is artificially enforced. We find that the dynamical structure factor of these artificially doped states has similar behaviors than the dynamical structure factor in the intermediate temperature regime indicating that the diffuse signal observed in the gap is related to the ice rule violation. We argue that this signal results from the relaxation of tetrahedra in the 3-in - 1-out or 3-out - 1-in state towards the ground state configuration of the neighboring ordered phase and give evidence that “monopole” excitations which are stable in the quantum context, fade away when a transverse XY term is introduced in the Hamiltonian.


S1011 Magnetic analogue of superconductivity in the Higgs ferromagnetic phase of quantum spin ice. S. Nakosai (RIKEN), S. Onoda (RIKEN) – We propose unconventional dissipationless magnetic interference phenomena in quantum spin ice where
a magnetic analogue of quantum electrodynamics emerges at low temperatures. Quantum spin ice monopoles are deconfined bosonic quasiparticles which carry a fractionalized spin-1/2 charge. When they show a Bose-Einstein condensation as in the Higgs ferromagnetic phase of Yb$_2$Ti$_2$O$_7$, they behave as a magnetic analogue of Cooper pairs. In effect, magnetic analogues of Josephson effects are expected to occur at the interface of two samples or domains having different ferromagnetic moment directions. This shows a remarkable contrast to the conventional ferromagnets where spin waves show a gapless dispersion or a significant Gilbert damping. Here, by means of the recursive Green function technique, we report theoretical calculations that support the dissipationless quantum spin ice monopole supercurrent and the resulting spin supercurrent through the junction of quantum spin ice systems. A possible relevance of the results to ultraslow spin relaxation observed in some Yb$_2$Ti$_2$O$_7$ samples is discussed.

**S1012 Jahn-Teller coupling in Tb$_2$Ti$_2$O$_7$ at very low temperatures: Neutron diffraction in a [110] magnetic field.**

A. Sazonov (RWTH Aachen Univ. and JCNS at MLZ, Germany; LLB, Univ. Paris-Saclay, France), I. Mirebeau (LLB, Univ. Paris-Saclay, France), A. Gukasov (LLB, Univ. Paris-Saclay, France), P. Bonville (SPEC, Univ. Paris Saclay, France), C. Decorse (ICMMO, Univ. Paris-Saclay, France).

A way to investigate the ground state of a frustrated magnet is to perturb it by a magnetic field, that should provide a stringent test of the theories. An applied field induces long-range magnetic order in the geometrically frustrated cubic pyrochlore magnet Tb$_2$Ti$_2$O$_7$, which otherwise remains in a spin liquid state down to at least 50 mK [1]. The type of field-induced magnetic structures strongly depends on the direction of the applied field [2, 3]. Up to now, no model succeeded to account for all the features of the Tb$_2$Ti$_2$O$_7$ ground state. Nevertheless, we believe that part of the physical truth resides in the two-singlet model [4, 5]. In this model, the Hamiltonian is treated in a mean-field self-consistent approximation and includes the trigonal crystal field, the Zeeman interaction, and Tb-Tb interactions, i.e., anisotropic exchange and dipole-dipole coupling as well as the off-diagonal mixing terms phenomenologically assimilated to a tetragonal distortion due to the Jahn-Teller effect. This model was able to reproduce successfully the very low temperature experimental evolution of the Tb$_2$Ti$_2$O$_7$ bulk magnetization for different field directions [5] as well as the field-induced magnetic structure deduced from the single crystal neutron diffraction data in a magnetic field along the [111] direction which corresponds to a local easy anisotropy axis [3].

Here we compare calculations from the two single model with single crystal neutron diffraction data at very low temperatures (below 1 K) measured with the field applied along the twofold [110] axis. This field direction previously allowed us to observe original field effects, invisible in the evolution of the average magnetization, such as a field-induced spin melting [2] and a double-layered spin multipolar order [6].

Moreover, we have studied the difference between microscopic and macroscopic realizations of the distortion, associated with static and dynamic Jahn-Teller effect, respectively. In the first variant (static Jahn-Teller effect), we assume that the Jahn-Teller distortion is static, extends over a finite domain size, and that domain orientations are equally distributed among the three cubic fourfold axes [100], [010], and [001]. In the second variant (dynamic Jahn-Teller effect), the distortion remains long-range, but its axis changes with time on each site between the three possible orientations. In the previous studies where the field was applied along the [111] axis (Ref. [3]) we found that the spin structures predicted assuming either static or dynamic Jahn-Teller effect were equally compatible with the neutron diffraction data. In the present geometry with $H || [110]$, we show that the intensities of specific Bragg reflections calculated for static and dynamic variants, markedly differ at high fields, in contrast with the $H || [111]$ case, where this difference was negligible. Comparison with the neutron diffraction data measured down to 60 mK shows a strong preference for the model of a dynamical Jahn-Teller effect.


**S1101 Quantum Spin Fluid of the S=1/2 Kagome-Lattice Antiferromagnet.** T. Sakai(Univ. of Hyogo and QST SPring-8), H. Nakano(Univ. of Hyogo) — The S=1/2 kagome-lattice antiferromagnet is one of interesting frustrated quantum spin systems. The system is supposed to exhibit the quantum spin fluid in the ground state, which was proposed as an origin of the high-temperature superconductivity. The spin gap is an important physical quantity to characterize the spin fluid behavior. Whether the S=1/2 kagome-lattice antiferromagnet is gapless or has a finite spin gap, is still unsolved issue. Because any recently developed numerical calculation methods are not enough to determine it in the thermodynamic limit. Our large-scale numerical diagonalization up to...
42-spin clusters and a finite-size scaling analysis indicated that the $S=1/2$ kagome-lattice antiferromagnet is gapless in the thermodynamic limit\cite{1}. It is consistent with the $U(1)$ Dirac spin fluid theory of the kagome-lattice antiferromagnet\cite{2,3}. On the other hand, some density matrix renormalization group (DMRG) calculations supported the gapped $Z_2$ topological spin fluid theory\cite{4,5}. Our recent numerical diagonalization analysis on the magnetization process of a distorted kagome-lattice antiferromagnet indicated that the perfect kagome-lattice system is just on a quantum critical point\cite{6}. It would be a possible reason why it is difficult to determine whether the perfect kagome-lattice antiferromagnet is gapless or gapped. In this paper, we show another evidence to confirm the gapless behavior, based on the finite size scaling analysis of the field derivative of the magnetization\cite{7}. This analysis also confirms that the triangular-lattice antiferromagnet is gapless.


**S1102 Spin Liquid on Pyrochlore Lattice with Pinch-Line Singularities.** H. Yan, O. Benton, L. Jaubert, N. Shannon (OIST) — Magnetic frustration leads to the complex phenomenon including spin liquids, which have exponentially large variety of ground states even at zero temperature. Pyrochlore lattice is a playground for exploring such exotic phases of matter, for example, electromagnetism in Quantum Spin Ice and magnetic monopoles in Classical Spin Ice [1]. Originating from the plentitude of ground states, the effective theories of the spin liquids constitute different types of gauge symmetries. In the case of Spin Ice, it is a $U(1)$ gauge group.

We have developed a generic framework in [2] and utilized it to derive the low-energy-effective-actions from microscopic set-ups of the pyrochlore lattice to systematically search for spin liquid phases. Based on this method we have mathematically discovered a spin liquid with pinch-line singularities feature. It possesses a rank-2 tensor gauge field, with the gauge symmetry identical to a partially broken diffeomorphism symmetry of linearised general relativity, which is distinct from the $U(1)$ gauge symmetry of Spin Ice. Our discovery can explain or predict experimental discoveries, and on the theory side, it is intriguing to further understand how gauge symmetries give rise to unique properties of those materials.


**S1103 Fermionic spinon and holon statistics in the pyrochlore quantum spin liquid.** B. Normand (PSI) and Z. Nussinov (UWM) — We prove that the insulating one-band Hubbard model on the pyrochlore lattice contains, for realistic parameters, an extended quantum spin-liquid phase. This is a three-dimensional spin liquid formed from a highly degenerate manifold of dimer-based states, which is a subset of the classical dimer coverings obeying the ice rules. It possesses spinon excitations, which are both massive and deconfined, and on doping it exhibits spin-charge separation. We demonstrate that the spinons have fermionic statistics, and further that the holons introduced by doping are also fermions. We explain the origin of this counterintuitive result and establish the connection of these emerging fermions with $U(1)$ gauge fields, represented by strings, as anticipated by Levin and Wen.

**S1104 Quantum spin liquid of $s=1/2$ random $J_1-J_2$ Heisenberg antiferromagnet on the honeycomb lattice.** K. Uematsu, H. Kawamura — Quantum spin liquid (QSL) phase is receiving a lot of attention as a novel state of matter. For the realization of the QSL, frustration is usually considered to be essential in destroying the magnetic order. It was recently reported that the quenched randomness might give rise to a novel QSL state in frustrated spin systems, called the random-singlet (RS) state [1,2], which is different in nature from the QSL of regular models. Meanwhile, it is still not entirely clear to what extent the frustration is essential in realizing the RS state. To get further insight into the role of frustration and randomness, we studied the random $s=1/2$ quantum Heisenberg model on the honeycomb lattice, with the competing nearest- and the next-nearest-neighbor antiferromagnetic interactions $J_1$ and $J_2$, by means of an exact diagonalization method. Randomness is introduced by uniformly distributing the strength of $J_1$ and $J_2$ of the width $\Delta$. Since frustration and randomness are introduced respectively by $J_2$ and by $\Delta$, we can freely adjust the extents of randomness and of frustration by tuning the parameters $\Delta$ and $J_2$. For the honeycomb lattice, the number of nearest-neighbor bonds is minimum (three) among various two dimensional lattices so that the fluctuation effect due to frustration and randomness is expected to be crucial compared to other lattices such as the square lattice. We get a ground-state phase diagram of the model on the $\Delta$ versus $J_1/J_2$ plane, to find that the RS state is stable for a wide range of $J_2 > 0$ for stronger randomness (larger $\Delta$). The behaviors of the computed physical quantities in the RS state, including the specific heat, the uniform susceptibility and the dynamical spin structure factor, resemble the ones of the random triangular and kagome models [1,2,3], suggesting the ubiquitous existence and the universal property of the RS state in frustrated random systems.

\cite{1}K. Watanabe, H. Kawamura, H. Nakano and T. Sakai, J. Phys. Soc. Jpn. 83, 034714 (2014); \cite{2}H. Kawamura, K. Watanabe and T. Shimokawa, J. Phys. Soc. Jpn. 83, 103704 (2014); \cite{3}T. Shimokawa,
A quantum spin liquid with a large topological degeneracy. — O. Tchernyshyov, H. Wang (Johns Hopkins Univ.), Y. Wan (Perimeter Inst.) — We present an exactly solvable model of a quantum spin liquid in two dimensions with high topological degeneracy. The model has spins of length $S = 1/2$ on sites of a triangular lattice. The Hamiltonian is a sum of $6$-spin terms, $H = -\sum_p W_p$, where $W_p = \sigma_1^p \sigma_2^p \sigma_3^p \sigma_4^p \sigma_5^p \sigma_6^p$ are commuting operators first introduced in Kitaev’s honeycomb model [1]. As in the toric codes of Kitaev and Wen [2,3], elementary building blocks are strings of several distinct types. Ends of strings are elementary particles, $4$ bosons and $3$ fermions; particles of different types are mutual semions. Closed strings forming non-contractible loops can be used to determine the topological degeneracy. We find $2^{7-1} = 64$ ground states on a torus. Elementary excitations (hexagons with $W_p = -1$) are pairs of elementary particles (one boson and one fermion) that come in $4 \times 3 = 12$ varieties. Although we do not expect that this model will ever be found in a real material, we think that it serves as a stepping stone to building more realistic models with spin-liquid ground states—in the same was as the toric code [2] was a stepping stone to building more realistic models with spin-liquid ground states. — A. Kitaev, Ann. Phys. 321, 2 (2006). [2] A. Kitaev, Ann. Phys. 303, 2 (2003). [3] X.-G. Wen, Phys. Rev. Lett. 90, 016803 (2003).

12 Spin Nematic.

Frustrated spin-$1/2$ zigzag chains with alternating exchange coupling and anisotropy. — H. Ueda (RIKEN AICS), S. Onoda (RIKEN) — Motivated by recent experimental findings of a ferroelectricity stabilized by a weak applied magnetic field in a quasi-one-dimensional valence bond solid material $\text{Rb}_2\text{Cu}_2\text{Mo}_3\text{O}_{12}$ [1,2], a frustrated spin-$1/2$ $J_1$-$J_2$ model with ferromagnetic nearest-neighbor interactions ($J_1 < 0$) and antiferromagnetic next-nearest-neighbor interactions ($J_2 > 0$) as well as alternating amplitude and anisotropy in $J_1$ is proposed on a basis of strong-coupling perturbation theory. Here, the alternations in magnetic exchange coupling and anisotropy arise from alternations in the bond lengths and the directions of apical oxygens, respectively, in the network of $\text{CuO}_6$ octahedra in $\text{Rb}_2\text{Cu}_2\text{Mo}_3\text{O}_{12}$. Then, the ground state phase diagram and the magnetization curves are calculated by means of the infinite-size density matrix renormalization group (iDMRG). In the absence of the alternation in the amplitude of $J_1$, but with the alternating easy-plane anisotropy, there appears a gapless vector-spin-chirality long-range ordered phase sandwiched by two distinct dimer phases, as in the simple spin-$1/2$ $J_1$-$J_2$ easy-plane XXZ model [3]. These two dimer phases are distinguished by a product of two dimer order parameters [4]. The amplitude alternation in $J_1$ induces a gap in the vector-spin-chirality ordered phase, as in the case without the anisotropy alternation [4], but the transition from the vector-spin-chirality ordered phase to a dimer phase occurs much closer to the SU(2) case, as expected for spin-$1/2$ cuprates. We will also discuss the relevance to experimental observations in $\text{Rb}_2\text{Cu}_2\text{Mo}_3\text{O}_{12}$. [1] Y. Yasui, Y. Yanagisawa, R. Okazaki, I. Terasaki, Y. Yamaguchi, and T. Kimura, J. Appl. Phys. 113, 17D910 (2013). [2] Y. Yasui, R. Okazaki, I. Terasaki, M. Hase, M. Hagihata, T. Masuda, and T. Sakakibara, JPS Conf. Proc. 3, 014014 (2014). [3] S. Furukawa, M. Sato, and S. Onoda, Phys. Rev. Lett. 105, 257205 (2010). [4] H. Ueda and S. Onoda, Phys. Rev. B 90, 214425 (2014).

NMR study on the competing spin chain $\text{Rb}_2\text{Cu}_2\text{Mo}_3\text{O}_{12}$. — A. Yagi, K. Matsu, Y. Hoshiro, Y. Hosoya, T. Goto (Sophia Univ.), M. Hase(NIMS), T. Sasaki(IMR Tokoho Univ.) — Quasi-one-dimensional $S = 1/2$ Heisenberg system $\text{Rb}_2\text{Cu}_2\text{Mo}_3\text{O}_{12}$ was reported to be a competing chain having the nearest-neighbor ferromagnetic ($J_1 = -138 \text{ K}$) and next-nearest-neighbor antiferromagnetic ($J_2 = 51 \text{ K}$) exchange interactions [1]. By the measurement of magnetization down to $2 \text{ K}$, no evidence for a magnetic transition was reported. Theoretical investigations on the competing chain suggest that the Tomonaga-Luttinger liquid (TLL) or nematic TLL may appear in paramagnetic state under high fields [2]. We have investigated $^{87/85}\text{Rb}(I = 3/2, 5/2) - \text{NMR}$ on powder sample of $\text{Rb}_2\text{Cu}_2\text{Mo}_3\text{O}_{12}$ in extended field ($1-19 \text{ T}$) and temperature regions ($1.9-50 \text{ K}$). Above the saturation field $H_s = 13 \text{ T}$, the nuclear longitudinal spin relaxation rate $1/T_1$ showed the thermal activation type temperature dependence, from which we have evaluated the spin excitation gap $\Delta$. The field dependence of $\Delta$ was described by equation $\Delta = g(H - H_s)\mu_B$, where the constant $g$ found to be approximately $4$. This means that neighboring two spins are excited coherently, which is consistent with the ferromagnetic nearest-neighbor exchange interaction. Next, below $H_s$, $1/T_1$ showed the power law temperature dependence. The index of power law showed a significant field dependence, suggesting that the system is in TLL state. At still lower field, below $2 \text{ T}$, $1/T_1$ showed again thermal activation type temperature dependence, indicating that the system has a gapped ground state at zero field. [1] M. Hase et al, Phys. Rev. B 70, 104426 (2004); [2] T. Hikihara, L. Kecke, T. Momoi, and A. Furusaki, Phys. Rev. B 78, 144404 (2008).
However, its ground state at zero and finite fields is not clear until now.

We have investigated the ground state of title compound CsCu$_2$Mo$_3$O$_{12}$ by microscopic probes of $^{133}$Cs-NMR [2] under the wide range of magnetic field up to 12 T, and $\mu$-SR at zero field. In the low field region of about 1.6 - 5 T, both the abrupt broadening in the NMR resonance line and the critical divergence in $T_1^{-1}$ were observed below 1.85(5) K, demonstrating the existence of the long range magnetic order. Under zero field, $\mu$-SR depolarization rate $\lambda$ showed abrupt increase at 1.8 K. These observations suggest that the magnetic order takes place also at zero field.

In the mid field region of 6-8 T, which is still lower than the saturation field[1], the $T_1^{-1}$ decreased monotonically as $T^{2K-1}$ with decreasing temperature. The the Luttinger parameter $K$ showed a significant increase with increasing field, the behavior of which is consistent with the theory of nematic TL state[2,3]. In high field of the saturation region, $T_1^{-1}$ showed the thermal-activation-type temperature dependence, demonstrating an opening of spin excitation gap.


S1204 Frustrated $S = \frac{1}{2}$ Two-Leg Ladder with Different Leg Interactions.

T. Tongeawa (Kobe Univ. and Osaka Pref. Univ.),
K. Okamoto (Shibaura Inst. Tech.), T. Hikihara (Gunma Univ.), T. Sakai (Univ. Hyogo and QST/SPring-8) – As an example of frustrated ladder system, we discuss an anisotropic $S = 1/2$ two-leg ladder with different leg interactions, which is described by the following Hamiltonian: $\mathcal{H} = J_{1a}\sum_{j=1}^{L} S_{j,a} \cdot S_{j+1,a} + J_{1b}\sum_{j=1}^{L} S_{j,b} \cdot S_{j+1,b} + J_{ij}\sum_{j=1}^{L} \{S_{j,a} S_{j,b}^{\dagger} + S_{j,b} S_{j,a}^{\dagger} + \Delta S_{j,a}^{\dagger} S_{j,b}^{\dagger}\}$. Here, $S_{j,a}^{\dagger} = (S_{j,\uparrow}^{\dagger}, S_{j,\downarrow}^{\dagger})$ is the $S = 1/2$ operator acting at the $(j,\ell)$ site assigned by rung $j$ and leg $(\ell = a, b)$. $J_{1a}$ and $J_{1b}$ denote, respectively, the magnitudes of the isotropic leg $a$ and leg $b$ interactions; $J_{ij}$ denotes that of the anistotropic rung interaction, the $XXZ$-type anisotropy being controlled by the parameter $\Delta$. $L$ is the total number of spins in each leg, which is assumed to be even. It is noted that this system has a frustration when $J_{1a}J_{1b} < 0$ irrespective of the sign of $J_{ij}$.

The most remarkable feature of the present system is as follows [1,2]: When the condition $J_{1a}J_{1b} = 0$, which belongs to the frustrated region, is satisfied, in addition to both the direct-product singlet-dimer (SD) state in which all rungs form the SD pair and the direct-product triplet-dimer (TD) state in which all rungs form the TD pair, the nematic state with an arbitrary phase $\phi$ in which all rungs are in the state given by a linear combination of two ferromagnetic states, $\cos \phi \alpha_{j,a} \alpha_{j,b} + \sin \phi \beta_{j,b} \beta_{j,a}$, where $\alpha_{j}$ denotes the $S_{j,a}^{+} = -1/2$ state and $\beta_{j}^{\dagger}$ the $S_{j,a}^{\dagger} = -1/2$ state, is the exact eigenstate of the above Hamiltonian. Furthermore, we can analytically show under this condition that the direct-product TD state is the exact ground state of the system if $J_{1a} < 0$ and $0 \leq \Delta < 1$, and also that, the direct-product SD state is the exact ground state of the system if $J_{1b} > 0$ is sufficiently large. It is emphasized that all of the above results for the three states are applicable to systems in higher dimensions, in which units of two $S = 1/2$ spins form lattices [1].

Employing various numerical methods, we have determined the ground-state phase diagram on the $\Delta (0 \leq \Delta \leq 1)$ versus $J_{1a}$ plane in the $J_{1a} = -0.2$ and $J_{1a} = 0.2$ cases where $J_{1b} = -1.0$. The obtained phase diagram in the former case consists of the TD phase, the $XY$ phase, and the non-collinear ferrimagnetic (NCFR) phase [2,3] which has an incommensurate character, while that in the latter case consists of the Haldane phase as well as of these three phases. On the special line where $J_{1b} = 0.2 (= -J_{1a})$ in the phase diagrams, the direct-product TD state is the exact ground state when $0 < \Delta \leq 0.8$. Finally, we emphasize that the appearance of the NCFR state as the ground state is attributed to the frustration effect.


S1205 Spin and quadrupole excitations in spin nematic state.

H. Onishi (ASRC, JAERI) – A spin nematic state, which is a spin analogue of the nematic liquid crystal, is currently attracting much attention as a novel quantum state in magnetic materials. In order to clarify the properties of the spin nematic state from the viewpoint of excitation dynamics, we study dynamical spin structure factors of a frustrated ferromagnetic chain in a magnetic field by exploiting density-matrix renormalization group techniques [1,2]. In the spin nematic regime, we find gapless longitudinal and gapped transverse spin excitation spectra, in accordance with quasi-long-ranged longitudinal and short-ranged transverse spin correlations, respectively. We further analyze dynamical quadrupole structure factors to reveal excitation dynamics in the quadrupole channel. We observe gapless quadrupole excitations, signaling a quasi-long-ranged quadrupole correlation.


S1206 Magnetic Phase Diagram of the Frustrated $J_1-J_2$ Chain Magnet NaCuMoO$_4$(OH).

K. Nawa (IMRAM, Tohoku University), M. Yoshida (MPI-FFK), M. Takigawa (ISSP, University of Tokyo), Y. Okamoto (Nagoya University), Z. Hiroi (ISSP, University of Tokyo) – In a frustrated $J_1-J_2$ chain magnet with ferromagnetic nearest neighbor interactions $J_1$ and antiferromagnetic next-nearest neighbor interactions $J_2$, novel quantum states such as a spin nematic state are theoretically expected [1, 2]. We find NaCuMoO$_4$(OH) as a new model compound of a frustrated $J_1-J_2$ chain magnet. Exchange interactions are estimated as $J_1$.
cating that consistent with the formation of bound magnons [4, 5], indicating a gapless. These static and dynamic properties in low fields are transverse spectrum while longitudinal excitations become anisotropic spin fluctuations: an energy gap is present in the spin chain compounds.


\[ S1207 \text{ Theory of electron spin resonance for detecting the quasi-long-range nematic order in frustrated ferromagnetic spin chain compounds. S. Furuya (RIKEN, Japan)} \text{ — Spin nematic phase is an interesting phase characterized with presence of a quadrupolar order and with absence of any spontaneous dipolar order. Arising out of nontrivial interplay between geometrical frustration and strong correlation, the spin nematic phase has long drawn intensive attention. An } S = 1/2 \text{ frustrated ferromagnetic chain is of particular interest for its characteristic critical properties not found other systems. It exhibits a quadrupolar Tomonaga-Luttinger spin liquid phase accompanied by the quasi-long-range spin nematic order. Until today much experimental effort has been made to observe the spin nematic phase of the frustrated ferromagnetic chain. Nevertheless, it is still an issue to develop a methodology to find out a clear experimental evidence of the spin nematic order. It was only recently that the resonant inelastic X-ray scattering technique turned out to be able to probe a dispersion relation of the quadrupolar liquid excitation [1]. In this presentation we discuss another practical way of detecting the quadrupolar liquid state using a simple experimental setup of electron spin resonance (ESR). We show that the linewidth of the so-called paramagnetic resonance peak of the ESR spectrum works as a sensitive probe to the nematic correlation of spins. The dependence of the linewidth on the direction of the magnetic field enables us to distinguish the quadrupolar Tomonaga-Luttinger spin liquid state from the standard one [2]. We also comment about differences of this method from an existing detection method using another kind of magnetic resonance (nuclear magnetic resonance) [3]. [1] L. Savary and T. Senthil, arXiv:1506.04752 (2015); [2] S. C. Furuya, in preparation; [3] M. Sato, T. Momoi and A. Furusaki, Phys. Rev. B 79, 060406(R) (2009). ]

\[ S1208 \text{ Modeling volborthite with coupled magnetic trimers. T. Momoi (RIKEN, Japan), O. Janson, S. Furukawa, P. Sindzingre, J. Richter, K. Held — Though volborthite contains spin-1/2 kagome layers, recent measurements on volborthite single crystals have revealed a wide 1/3-magnetization plateau phase and, in a adjacent weaker-magnetic-field range, a novel unknown "N" phase [1], which are quite different from the kagome Heisenberg antiferromagnet. Motivated by these experiments on single crystals, we performed microscopic modeling by means of density functional theory (DFT) with the single-crystal structural data as a starting point [2]. Using DFT+U, we found four leading magnetic exchanges: antiferromagnetic } J_1 \text{ and } J_2, \text{ as well as ferromagnetic } J_0 \text{ and } J_1, \text{ where } J_0 \text{ is the strongest among them. The } J \text{ bonds form isolated magnetic trimers, while the rest of exchanges give couplings between these trimers. Numerical calculations of the magnetic susceptibility in the derived spin Hamiltonian show a good agreement with the experiment. The calculation of magnetization process shows a wide 1/3-plateau, which is consistent with measurements. The 1/3-plateau phase pertains to a polarized state of low-energy doublets in each trimer. Furthermore, we derived an effective spin model projecting onto the low-energy doublets and performing a strong-coupling expansion from the large } J \text{ (trimer coupling) limit. This effective model is characterized as a frustrated ferromagnet showing a tendency toward condensation of magnon bound states, which leads to spin nematic ordering preceding the plateau phase. This theoretical result is consistent with a recent observation of magnon bound states in volborthite [3]. [1] H. Ishikawa et al., Phys. Rev. Lett. 114, 227202 (2015); [2] O. Janson, S. Furukawa, T. Momoi, P. Sindzingre, J. Richter, and K. Held, arXiv:1509.07333; [3] M. Yoshida et al., arXiv:1602.04028. ]

\[ S1209 \text{ Topological Excitations in Quantum Spin-nematics. Y. Akagi (Univ. of Tokyo), H. T. Ueda (Toyama Prefectural Univ), and N. Shannon (OIST) — Topological excitations play an important role in both conventional liquid crystals, such as the nematic phase, and in the theory of two-dimensional quantum spin liquids [1]. However, relatively little is known about their role in the magnetic analogue of a liquid crystal — the "quantum spin-nematic", a phase which breaks spin-rotation symmetry without breaking time-reversal symmetry. Moreover, most studies on such topological excitations were carried out in the continuum limit [2-5]. Little is also known about the properties of topological excitations in microscopic lattice models. Then, we investigate such topological excitations in these nontrivial states in a microscopic model. The model which we consider is the spin-1 bilinear biquadratic model on the triangular lattice, which is known to support a number of nontrivial magnetic states [6-8]. Using homotopy analysis and numerical minimization of a variational wave function, we identify a new family of solitons at a particular point in parameter space, [1] H. Akagi, T. Ueda, and N. Shannon, Phys. Rev. B 89, 144404 (2014); [2] H. Ishikawa et al., Phys. Rev. Lett. 114, 227202 (2015); [3] O. Janson, S. Furukawa, T. Momoi, P. Sindzingre, J. Richter, and K. Held, arXiv:1509.07333; [4] M. Yoshida et al., arXiv:1602.04028. ]

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in which the system has global SU(3) symmetry. We also find that wave functions with higher topological charges spontaneously decay into elementary solitons with emergent interactions [9,10]. This result suggests that it could be possible to realize a new class of interacting soliton in experiments on cold atoms, as well as the possibility of new form of quantum spin liquid.


13 Triangular Systems.

S1301 Physical properties in the cluster-based magnetic-diluted triangular lattice antiferromagnets Li$_2$Sc$_{1-x}$Sn$_x$Mo$_3$O$_8$. Y. Haraguchi (Kyoto Uni.), C. Michioka (Kyoto Uni.), H. Ueda (Kyoto Uni.), A. Matsuo (ISSP, Uni. of Tokyo), K. Kindo (ISSP, Uni. of Tokyo), and K. Yoshimura (Kyoto Uni.) — Frustrated cluster magnets are expected to produce a novel physics emerged from competition between spin frustration effects and charge fluctuation within a cluster. We investigated the magnetic dilution effects on $S = 1/2$ frustrated magnetic cluster system Li$_2$ScMo$_3$O$_8$ of a spin liquid candidate [1]. In Li$_2$ScMo$_3$O$_8$, the valence state of Mo$_3$ is +11, and then there is a single unpaired spin on the molecular orbitals of Mo$_3$. Thus, the magnetic state of [Mo$_3$]$^{11+}$ is $S = 1/2$. In Li$_2$ScMo$_3$O$_8$, the electron doping to this system will lead the emergence of the nonmagnetic [Mo$_3$]$^{10+}$ cluster ($S = 0$) without unpaired spins on the molecular orbital, which results in the construction of a magnetic-diluted triangular lattice formed by the magnetic [Mo$_3$]$^{11+}$ and nonmagnetic [Mo$_3$]$^{10+}$. For substituted compounds Li$_2$Sc$_{1-x}$Sn$_x$Mo$_3$O$_8$, XRD patterns are demonstrated successful synthesis. And with increasing $x$, Li$_2$Sc$_{1-x}$Sn$_x$Mo$_3$O$_8$ shows the monotonical decreasing of paramagnetic moment $\rho_{PM}$ in high temperatures probed by magnetization measurement, which indicates the successful introduction to the magnetic dilution in the triangular lattice of Mo$_3$ trimers. Li$_2$Sc$_{1-x}$Sn$_x$Mo$_3$O$_8$ ($x > 0$) exhibits a crossover from paramagnetic state in high temperatures to the partial paramagnetic moment disappearing one in low temperatures. Such the disappearance is also observed in the similar magnetic cluster magnet Li$_2$Zr$_2$Mo$_3$O$_8$ with the lower $\rho_{PM} = 1.38$ than that of normal spin $S = 1/2$ systems [2]. These facts suggest that the random spin defect on the triangular lattice induces the valence bond glass formation in the low temperature [3].


S1302 Long-range order and frustration in ludwigite system Fe$_3-x$Mn$_x$BO$_5$. F. Damay (LLB, France), F. Lainé (CRISMAT, France), A. Maignan, A. Guesdon (CRISMAT, France), P. Beran (NPI, Czech Republic), F. Fauth (ALBA, Spain), S. Petit (LLB, France) and C. Martin (CRISMAT, France) — Iron ludwigite Fe$_3$BO$_5$ is characterized by two decoupled magnetic sublattices, each made of three-leg ladders (3LL) running along $c$ and linked triangularly [1]. These sublattices order orthogonally at $T_{N1} = 112$ K (3LL1, $k_1 = 0.0 0.5$) and $T_{N2} = 70$ K (3LL2, $k_2 = 0.0 0.0$) [2]. To investigate the origin of this behavior, the isostructural system Fe$_3-x$Mn$_x$BO$_5$ has been studied by low temperature neutron diffraction. A decrease of both $T_N$, more pronounced for $T_{N2}$, along with a reduced ordered moment, are observed with increasing $x$, up to $x = 1$. Interestingly, as Mn is substituted preferentially on 3LL2, only short-range ordering is observed on the latter for $x = 1$. For $x = 1.5$, 3D long-range ordering below $T_N = 100$ K is observed, which couples both 3LLs. These results show that long-range order and spin frustration actually coexist in Fe$_3-x$Mn$_x$BO$_5$ ($x \leq 1$): because of the triangular topology of the 3LL1-3LL2 coupling, antiferromagnetic ordering of 3LL1 along $c$ prevents the ordering of 3LL2. For $x = 1.5$, magnetic exchange along $c$ becomes ferromagnetic, thus lifting the frustration and allowing ordering of both ladders simultaneously within a collinear $k = 0.0 0.0$ structure. Orthogonal orderings of magnetic sublattices make of the ludwigite system a promising one to study the competition between magnetic exchange and anisotropies.


S1303 Bulk properties of new two-dimensional quantum spin systems: CuRE$_2$Ge$_2$O$_6$ (RE=Y, La). H. Cho, H. Sim, K. Choi, C. Kim (IBS-CCES, S. Korea), C. Paulsen (CNRS, France), M. Avdeev (ANSTO, Australia), D. Peets (IBS-CCES, S. Korea), Y. Jo (KBSI, S. Korea), Y. Noda (Tohoku Univ., Japan), J. Park (IBS-CCES, S. Korea), C. Paulsen (CNRS, France), M. Avdeev (ANSTO, Australia) — We found a new quantum ($S=1/2$) two-dimensional antiferromagnetic lattice of CuRE$_2$Ge$_2$O$_6$ (RE=La and Y) system. According to our analysis of the crystal structure using X-ray and neutron diffraction techniques, the Cu-network forms a new lattice with its two-dimensional (2D) triangular lattice linked via a weak bond along the $b$-axis. From our physical properties characterization covering the wide temperature range from 0.08 to 400 K, we discovered that they undergo a long range order at 1 and 0.5 K, respectively. Interestingly enough, they also exhibit field induced phase transitions at low field regions. Of
further interest, the DFT band calculations reveal that they are most likely to be a charge-transfer insulator with Cu d-band split across the Fermi level. Taken together, our observations render CuRE$_2$Ge$_2$O$_6$ (RE=La and Y) system a unusual case of low-dimensional quantum spin system with charge-transfer physics in addition to the low-temperature magnetic ordering.


**S1304 Umbrella-coplanar transition in the triangular XXZ model with arbitrary spin.** G. Marmorini (YITP), D. Yamamoto (Aoyama-Gakuin Univ.), I. Danshita (YITP) — The quantum triangular XXZ model has recently enjoyed a wealth of new theoretical results, especially in relation to the modeling of the Ba$_3$CoSb$_2$O$_9$ compound. In particular, it has been understood that in a longitudinal magnetic field the umbrella (cone) phase, classically stable in all the easy-plane region of the ground-state phase diagram, is considerably reduced by the effect of quantum fluctuations. We provide more quantitative information for this phenomenon at arbitrary value of the site spin $S$, by employing the dilute Bose gas expansion, valid in the high field regime; our results improve the available estimates of the $1/S$ expansion. We quantify the extent to which a higher spin suppresses the effect of quantum fluctuations. Besides, we show how in three-dimensional layered systems a relatively small antiferromagnetic interlayer coupling has a similar consequence of bringing back the umbrella phase in some part of the phase diagram.


**S1305 Magnetic resonance and high-field magnetization studies of Cu$_3$PO$_4$OH$_2$ (pseudomalachite) : a spin network composed of pentagons and triangles.** Y. Fujii, H. Kikuchi, S. Mitsudo, Y. Ishikawa, K. Kunieda, N. Kasamatsu(U. Fukui), A. Matsuo, K. Kindo (ISSP, U. Tokyo), S. Mitsudo, Y. Ishikawa, K. Kunieda, N. Kasamatsu(U. Fukui), A. Matsuo, K. Kindo (ISSP, U. Tokyo) — The quantum triangular XXZ model has recently enjoyed a wealth of new theoretical results, especially in relation to the modeling of the Ba$_3$CoSb$_2$O$_9$ compound. In particular, it has been understood that in a longitudinal magnetic field the umbrella (cone) phase, classically stable in all the easy-plane region of the ground-state phase diagram, is considerably reduced by the effect of quantum fluctuations. We provide more quantitative information for this phenomenon at arbitrary value of the site spin $S$, by employing the dilute Bose gas expansion, valid in the high field regime; our results improve the available estimates of the $1/S$ expansion. We quantify the extent to which a higher spin suppresses the effect of quantum fluctuations. Besides, we show how in three-dimensional layered systems a relatively small antiferromagnetic interlayer coupling has a similar consequence of bringing back the umbrella phase in some part of the phase diagram.


**S1306 Triangular-spin-unit network material Mn$_3$RhSi without inversion symmetry.** S. Shamoto (JAEA), H. Yamauchi (JAEA), K. Kondo (JAEA), M. Ishikado (CROSS), M. Hagihala (ISSP, Univ. of Tokyo), and J. A. Fernandez-Baca (ORNL) — Large spins in frustrated lattices often exhibit intriguing phenomena such as large magnetocaloric effect [1] due to large entropy change at the phase transition. Anti-perovskite compound, Mn$_3$Cu$_{1-x}$Ge$_x$N, with Mn-kagome-network in (1 1 1) plane shows large negative thermal expansion [2]. This large response is obtained near the transition from 1$^\text{st}$ order to 2$^\text{nd}$ order phase transitions [3]. As similar frustrated Mn-materials, there are β-Mn-type intermetallic compounds [4]. They have a cubic structure without inversion symmetry. Recently, the non-centrosymmetric magnetic compounds also attract much attention because they exhibit novel spin textures such as skyrmion [5] and chiral soliton lattices [6, 7]. These self-organized spin textures are formed under competing interactions such as exchange interaction between spins and D-M interaction in a non-centrosymmetric lattice. These spin textures are expected for a new type of nanoscale memory devices [5]. New room-temperature skyrmion compound, Co-Zn-Mn alloy, has β-Mn-type lattice structure. β-Mn, itself, is a well-known spin-liquid metallic material with triangular-spin-unit chiral network [8]. Ordered-β-Mn-structure has been discovered in Mn-(Co,Ir)-(Si,Ge) intermetallic compounds [4]. We also succeeded to synthesize a new compound Mn$_3$RhSi. Our neutron diffraction measurement at HFIR shows that it has the same β-Mn-type lattice structure with non-centrosymmetric P2$_1$3 space group. It exhibits an antiferromagnetic ordering at $T_N \approx 190$°K according to our magnetic susceptibility measurement. This compound does not show large magnetovolume effect whereas strong magnetic diffuse scattering is observed at $20 \approx 20^\circ$ above $T_N$, suggesting β-Mn-type spin-liquid state in this triangular-spin-unit network material.

ing interactions often evoke exotic phenomena. Magnetic and heat capacity measurements on the single crystal revealed that Cs$_2$Fe$_2$Cl$_3$ exhibited an antiferromagnetic long-range order at $T_N = 5.3$ K under zero magnetic field. Unlike a normal antiferromagnetic transition, the easy-axis magnetic susceptibility showed a sudden drop at $T_N$ and then it decreased towards zero with $T$-linear temperature dependence. The magnetization shows metamagnetic transitions below $T_N$. Moreover, successive magnetic phase transitions were observed under magnetic fields. Therefore, the $H$-$T$ magnetic phase diagram of Cs$_2$Fe$_2$Cl$_3$ for $H//c$-axis includes at least five phases up to 9 T. The comparable and competing intra-dimer $J_1 = -2.4$ K and the inter-dimer $J_2 = (J_p + J_c) = -1.2$ K magnetic interactions give rise to the abundant phases under magnetic fields on the triangular dimer lattice.


S1308 Dynamical Jahn-Teller effect in spin frustrated RBaFe$_2$O$_{7+\delta}$ (R=Y, Ho). K. Kamazawa (CROSS-Tokai), M. Ishikado (CROSS-Tokai), S. Ohira-Kawamura (JAERI J-PARC), Y. Kawakita (JAERI J-PARC), K. Kakurai (CROSS-Tokai), K. Nakajima (JAERI J-PARC) and M. Sato (Private). – The inelastic neutron scattering investigation of RBaFe$_2$O$_{7+\delta}$ (RBFO) (R = Y and Ho) powder samples revealed characteristic magnetic excitations in the energy($\omega$)-wave vector($q$) space, which are associated with geometrical spin frustration. The antiferromagnetic RBFO crystals have cubic symmetry, and Fe$^{2+}$ and Fe$^{3+}$ reside on corner-sharing-tetrahedra with a number ratio of 3 : 1. Both R = Y and Ho system do not show any static lattice distortion to the lowest temperature that we measured, even though Fe$^{2+}$ in tetrahedral symmetry is a Jahn-Teller active ion. The YBFO system shows inelastic magnetic scattering extending up $\omega \sim 80$ meV at $Q = Q_p(-1.25^{-1})$, the wave vector corresponding to a hexagon correlation of Fe-spins. We thus interpret this streak scattering along the $\omega$-axis at $Q_p$ indicating creations and annihilations state of hexagon spin clusters - that is, spins are fluctuating in the wide energy range but maintaining antiferromagnetic hexagon correlation. On the other hand, in HoBFO, dispersionless modes are dominantly observed at several discrete energy levels. Some of the energy levels cannot be attributed to crystal field levels of Ho$^{3+}$ in octahedral symmetry, and are rather explained by vibronic state of Fe$^{2+}$ dynamical Jahn-Teller effect with LS-coupling. That is, spin-orbit-lattice degrees of freedom is coupled to each other in the system. These discrete energy levels are then ascribed to a system of isolated spin clusters. The difference of R ion affects the dynamics of the frustrated system RBFO, resulting in rich varieties of characteristic excitations such as strong spin fluctuations over wide energy range at one characteristic wave vector or dynamical interaction among spin-orbit-lattice degrees of freedom of isolated spin clusters.


S1309 μSR Studies of Quantum Criticality in the Spin-Orbital Liquid Ba$_3$CuSb$_2$O$_9$: Evidence for Excitations with Semionic Character. F.L. Pratt (STFC), P.J. Baker (STFC), S.J. Blundell (Oxford), T. Lancaster (Durham), J.S. Möller (ETHZ), D. Prabhakaran (Oxford), C. Baines (PSI). – The triangular lattice system Ba$_3$CuSb$_2$O$_9$ is an intriguing example of a coupled spin-orbital liquid that avoids static ordering and retains a fluctuating state down to at least 20 mK [1-8]. This quantum spin liquid (QSL) occurs in a system with significant intrinsic short-range-correlated structural disorder [2,5,8], that appears to represent a new class of quantum liquid. Whereas the nature of the resulting arrangement of Cu spin sites was originally suggested to be a disordered hexagonal lattice [2,9,10], more recent analysis suggests that a randomly branched stripe structure is a better model [11]. μSR can provide a useful probe of QSL systems, both in confirming the absence of spin freezing or magnetic ordering at very low temperatures and also in testing the characteristic quantum critical fingerprint of the ground state [12]. For Ba$_3$CuSb$_2$O$_9$ we have now taken a detailed set of μSR data in order to study its quantum criticality. Firstly a quantum critical framework for spinon diffusion [13] is used to derive the critical parameter ν by analysing the temperature dependence of the spin diffusion rate measured using muon spin relaxation in longitudinal magnetic field. Next the field-induced broadening in the muon spin rotation signal is studied as a function of field at low temperature to provide an estimate of the critical parameter δ. Finally measurement of the finite-field broadening of the rotation signal versus temperature establishes the two further critical parameters η and γ. These four critical exponents are simultaneously compared with those of quantum critical field theories for 2D frustrated antiferromagnets [14,15] and give an excellent match to a model of a spin-orbital liquid having topological order [15] and lying close to the boundary with an antiferromagnetic state. The formulae for the critical exponents in the theory depend on the statistical angle θ of the quasi-particles that dominate the properties at the quantum critical point [15]. These are generally expected to be either bosons (θ = 0) or fermions (θ = π), as found respectively when applying the same theory to the pair of triangular-lattice molecular QSLs κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$ and κ-(BEDT-TTF)$_2$Ag$_2$(CN)$_3$ [16]. Remarkably, for Ba$_3$CuSb$_2$O$_9$ the statistical phase angle is obtained to be $\theta = 0.49(2)$ π, i.e. midway between boson and fermion and signifying that any quasi-particles with semion statistics are dominating the quantum critical behaviour.

Hidden multipolar orders on a triangular lattice. Y. Li (FDU), G. Chen (FDU) — Motivated by the recent development in strong spin-orbit-coupled materials, we consider a special type of Kramers’ doublet on the triangular lattice. We propose the most general effective spin interaction between these unusual local moments. Due to the spin-orbit entanglement and the special form of its wavefunction, the doublet has a rather peculiar property under the lattice symmetry operation. We analyze the ground state properties of this generic model and emphasize the hidden multipolar orders that emerge from the multipolar interactions. We discuss the experimental consequences of the multipolar orders and propose the rare-earth triangular materials as candidate systems for these unusual properties.


S1312 Nanomagnetism of Relaxor Magnet LuFeCoO$_4$ with Triangular Lattice. M. Soda and T. Masuda (UTokyo) — We studied one of the relaxor ferroelectrics having the magnetic ions, relaxor magnet, LuFeCoO$_4$ in order to clarify the relationships between relaxor property and magnetism. LuFeCoO$_4$ has the triangular lattice, and the Fe$^{3+}$ and Co$^{2+}$ ions are allocated randomly on the same site. In our elastic neutron study of LuFeCoO$_4$, the strong coupling between the nuclear and magnetic correlations has been found. Synchronized change in the nuclear and magnetic diffuse intensities was observed at $T \sim 190$ K. In the temperature region $70 \, K < T < 190 \, K$, spin moments having ferromagnetic component in nano-magnetic domain behave as superparamagnetic moments. From the neutron result, we propose “multiferroic nano region” (MNR) model.

S1311 Suppression of Bragg Peak Intensities of Skyrmion Crystals under Current. J. Iwasaki (Univ. of Tokyo), D. Okyama (Tohoku Univ.), T. J. Sato (Tohoku Univ.), N. Nagaosa (RIKEN & Univ. of Tokyo) — Manipulation of spin textures has been attracting a broad interest from the viewpoints of both fundamental physics and applications over decades. Recently, the current-induced motion of magnetic skyrmions is one of the main research topics since it has been revealed that an ultra-small current density $\sim 10^{-7}$–$10^{-6}$ A/m$^2$ can drive the motion of skyrmion crystals, which is order of magnitude much smaller than the typical value used to manipulate magnetic domain walls ($10^{10}$–$10^{12}$ A/m$^2$). This fact has been confirmed by the several experiment including the neutron scattering [1], the Hall measurement [2], and the real-space observation [3]. Our previous numerical study [4] suggested the more than 50 % destruction of the Bragg intensity for small currents and the associated long-time tails reflecting the deformation of the triangular lattice of skyrmions and the shape of the individual skyrmions. Here, we present another fingerprint of the current-driven motion of skyrmion crystals that would also be observed by a neutron scattering experiment: the intensities of the three kinds of Bragg peaks will be inequivalently suppressed. This behavior is seen in a micromagnetic simulation, and analyzed by a perturbation theory. Our finding will stimulate further experimental research on current-induced skyrmion motion.

### Trace Element Analysis

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#### COMPOUNDS

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