Welcome to Quantum Fluids and Solids (QFS) 2019, at the University of Alberta in Edmonton, Alberta, Canada

The University of Alberta respectfully acknowledges that we are located on Treaty 6 territory, a traditional gathering place for diverse Indigenous peoples including the Cree, Blackfoot, Metis, Nakota Sioux, Iroquois, Dene, Ojibway/Saulteaux/Anishinaabe, Inuit, and many others whose histories, languages, and cultures continue to influence our vibrant community.

Conference venue

The scientific program will take place in the Centennial Centre for Interdisciplinary Sciences (CCIS) North Lecture Theatres (NLT) on the University of Alberta’s North (main) campus. Talks will be held in CCIS 1-440, and poster sessions will be held in the north-east facing foyer outside this room, called the PCL Lounge. On-campus walking directions from hotels, residences, and the LRT can be found on page 13.

Wireless internet access

Wifi is readily available across campus in two ways:

- eduroam: Use the email address from your home institution as the user ID and your regular password as the password. This only works if your institution is an eduroam member.
- Guest@UofA: Free, open access to wifi across campus. Must accept user agreement.

Oral presenter instructions

You may use either your own laptop, or the PC at the podium. Either way, please make sure your presentation displays properly before your designated session.

To use the podium PC you may need to log in. Please use the following ID and password:
ID: 1343
Password: TTHykqdl

If you have any questions, please ask a volunteer.

Poster presenter instructions

Posters will be presented in three sessions, from 17:00 to 19:00 on Thursday, Friday and Saturday. Poster titles and presenters are listed in this conference booklet, beginning on page 13.

Each poster should be mounted on its own poster board, labeled with the number corresponding to the poster, e.g. P1.1, P1.2... P2.1, etc. The available space for each poster is roughly 1.8 meters wide by 1.2 meters high.

- Poster Session 1 (17:00 - 19:00 Thursday): posters can be displayed starting Thursday morning and should be removed by 19:00 Friday.
- Poster Session 2 (17:00 - 19:00 Friday): posters can be displayed starting Thursday and should be removed by 19:00 Saturday.
- Poster Session 3 (17:00 - 19:00 Saturday): posters can be displayed starting Saturday morning and should be removed by 19:00 Monday.

Opening reception

Oxford Instruments and the QFS organizers invite all QFS 2019 participants and accompanying persons to the Welcome Reception on August 7 (Wednesday). It will be held at the Students Union Building (SUB) on the University campus, from 17:00 through 19:00. Meet your QFS colleagues to enjoy beer, wine and a light meal, courtesy of Oxford Instruments.

Registration packages

QFS participants can pick up their registration packages at the opening reception location (SUB), beginning at 16:00 on Wednesday. There will also be a QFS registration desk at the conference venue (CCIS building), beginning at 8:00 Thursday.

Conference banquet

The QFS conference banquet will be held at the new Royal Alberta Museum on the evening of Monday, August 12. If you purchased tickets for the banquet, you will find them in your registration package.
The banquet will be preceded by a reception upstairs in the RAM building, with drinks and light snacks beginning at 18:00. Dinner will begin at 19:00 on the main floor and patio of the museum. A wide variety of appetizers, small items and Canadian dishes will be available. Guests will serve themselves, and there will be indoor and outdoor seating. The Strathcona String Quartet will provide music during dinner.

QFS talks will end around 15:00 on Monday, so that banquet attendees can explore Alberta’s history and cultures at the Royal Alberta Museum before the reception and dinner. All QFS participants and accompanying persons will receive a museum pass in their registration packages. These passes are valid at any time and, for example, could be used on Sunday by people who are not attending the banquet.

The Museum is directly connected to the downtown Churchill Station by an underground passage, so is easily accessible from the University campus via LRT. The total travel time from the QFS venue in CCIS to the museum is about 30 minutes.

**Getting around the city**

**Edmonton Transit:** QFS participants and accompanying persons will receive an Edmonton Transit System (ETS) pass in their registration package, valid for the duration of the conference. This pass allows unlimited travel on Edmonton's light rail transit (LRT) system and all city buses, except for the “747” bus that connects the Edmonton International Airport (YEG) to the Century Park LRT station on Edmonton's south side (there is an additional $5 charge for this service, payable on the bus).

The University Station (LRT) and transit hub (buses) are located on the University campus (see the map on page 5). The LRT is the most convenient way to reach Edmonton's city center, including many of the recommended QFS hotels and restaurants. To get downtown from the University Station, take any train going north (direction “Clareview” or “Kingsway/RAH”). To get to the University Station from downtown, take any train going south (direction "Century Park" or "Health Sciences/Jubilee").

For locations not on the LRT line, you can use your ETS pass for Edmonton’s bus network. Note that buses are less frequent on weekends and evenings, so it is worth checking schedules on the ETS website: [www.edmonton.ca/edmonton-transit-system-ets.aspx](http://www.edmonton.ca/edmonton-transit-system-ets.aspx)

**Taxi/Uber:** Other than at the airport and a few major hotels, you usually have to telephone to get a taxi in Edmonton (hotels and most restaurants will call one for you). The largest taxi companies in Edmonton are Yellow Cab (780-462-3456), Co-op Taxi (780-425-2525) and (for travel to/from the airport) Airport Taxi (780-890-7070).

Edmonton is served by Uber, which is a convenient option and usually cheaper than taxis. For Uber, you will need a phone or device with the Uber App.

**Bicycle rental:** Edmonton has a network of bicycle routes for commuting, but the best reason to rent a bike would be to explore the extensive network of trails (paved, gravel and single track) in the river valley. There are a number of businesses that rent bicycles by the hour or day, including:

- [www.rivervalleyadventure.com](http://www.rivervalleyadventure.com)
- [bikes.unitedsport.ca](http://bikes.unitedsport.ca)
- [www.edmontonbikerentals.com](http://www.edmontonbikerentals.com)

**On- and off-campus dining options:**

Edmonton has a diverse ethnic population and its restaurants reflect this diversity. The local organizers have prepared a map showing many restaurants that they are familiar with ([qfs2019.org/restaurants](http://qfs2019.org/)). Although the choices on campus are limited (mostly fast food outlets, many not open in the evenings), there are quite a few restaurants in the University area, within a 10 or 15 minute walk from the CCIS building where the QFS sessions will be held. Many more restaurants are located in the downtown area easily accessible via the LRT, and along Whyte Avenue not far from the University.
Campus map
Interior map
## Conference Program

### Wednesday, August 7th

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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</thead>
<tbody>
<tr>
<td>16:00 – 18:00</td>
<td>Registration in SUB (Students’ Union Building)</td>
</tr>
<tr>
<td>17:00 – 19:00</td>
<td>Oxford Instruments Opening Reception (SUB Patio)</td>
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<tr>
<td>Time</td>
<td>Session</td>
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<tr>
<td>8:30 – 9:00</td>
<td>Welcome and opening remarks&lt;br&gt;John Beamish, University of Alberta</td>
</tr>
<tr>
<td>9:00 – 9:30</td>
<td>Optical, mechanical, and thermal properties of superfluid drops levitated in vacuum&lt;br&gt;Jack Harris, Yale University</td>
</tr>
<tr>
<td>9:30 – 10:00</td>
<td>Real-time optomechanical detection of vortex dynamics in a superfluid helium film&lt;br&gt;Chris Baker, University of Queensland</td>
</tr>
<tr>
<td>10:00 – 10:20</td>
<td>High gains in thin films: a superfluid Brillouin laser&lt;br&gt;Yasmine Sfendla, University of Queensland</td>
</tr>
<tr>
<td>10:20 – 10:40</td>
<td>Coffee Break</td>
</tr>
<tr>
<td>10:40 – 11:10</td>
<td>How to probe non-trivial topology of a chiral superfluid $^3$He-A with MEMS&lt;br&gt;Hyoungsoon Choi, Korea Advanced Institute of Science and Technology</td>
</tr>
<tr>
<td>11:10 – 11:40</td>
<td>Stability of chiral domain structure in superfluid $^3$He-A&lt;br&gt;Yutaka Sasaki, Kyoto University</td>
</tr>
<tr>
<td>11:40 – 12:00</td>
<td>Talk moved to Monday at 14:50</td>
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<tr>
<td>12:00 – 13:30</td>
<td>Lunch</td>
</tr>
<tr>
<td>13:30 – 14:10</td>
<td>Electrons and ions on the surface of liquid helium&lt;br&gt;Kimitoshi Kono, National Chiao Tung University</td>
</tr>
<tr>
<td>14:10 – 14:40</td>
<td>Electrons on helium: Self-diffusion and mobility in a periodic potential&lt;br&gt;Mark Dykman, Michigan State University</td>
</tr>
<tr>
<td>14:40 – 15:10</td>
<td>Electrons bound to superfluid helium: Coherent mobile spin qubits&lt;br&gt;Stephen Lyon, Princeton University</td>
</tr>
<tr>
<td>15:10 – 15:30</td>
<td>Coffee Break</td>
</tr>
<tr>
<td>15:30 – 16:00</td>
<td>Layering transition in helium films adsorbed on a carbon nanotube&lt;br&gt;Adrien Noury, ICF0, The Barcelona Institute of Science and Technology</td>
</tr>
<tr>
<td>16:00 – 16:20</td>
<td>2D $^3$He probed by oscillating nanotube: A new structural transition and spectroscopy&lt;br&gt;Igor Todoshenko, Aalto University</td>
</tr>
<tr>
<td>16:20 – 16:40</td>
<td>Brute-force cooling and on-chip thermometry for microwave optomechanics&lt;br&gt;Eddy Collin, Univ. Grenoble Alpes, Institut Néel</td>
</tr>
<tr>
<td>16:40 – 17:00</td>
<td>Adiabatic melting of solid $^4$He in liquid $^3$He&lt;br&gt;Juha Tuoriniemi, Aalto University</td>
</tr>
<tr>
<td>17:00 – 19:00</td>
<td>Poster Session I, PCL Lounge&lt;br&gt;Sponsored by BluFors</td>
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</table>
**Friday, August 9th**

## Quantum gases I

**Chair: Lindsay LeBlanc, University of Alberta**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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</table>
| 8:30 – 9:00 | The quantum phases of ultracold dipolar gases near a roton excitation  
Manfred Mark, University of Innsbruck |
| 9:00 – 9:30 | Transient supersolid properties in an array of dipolar quantum droplets  
Tim Langen, University of Stuttgart |
| 9:30 – 10:00 | Observation of a supersolid phase of matter in a dipolar quantum gas  
Giovanni Modugno, University of Florence |
| 10:00 – 10:20 | Light-cone like spreading of correlations in the Bose Hubbard model at strong coupling  
Malcom Kennett, Simon Fraser University |
| 10:20 – 10:40 | Coffee Break                                                                                   |

## Cold dark matter

**Chair: Christian Enss, University of Heidelberg**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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</table>
| 10:40 – 11:10 | SuperCDMS at SNOLAB - mK for dark matter searches  
Wolfgang Rau, Queen's University/TRIUMF |
| 11:10 – 11:40 | Dark matter detection using superfluid Helium-4  
Humphrey Maris, Brown University |
| 11:40 – 12:10 | Resonant detection of gravitational waves and dark matter using superfluid helium  
Swati Singh, University of Delaware |
| 12:10 – 13:40 | Lunch                                                                                          |

## Confined Helium

**Chair: Vladimir Eltsov, Aalto University**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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| 13:40 – 14:10 | Thermal transport of helium-3 in a strongly confining channel  
Jeevak Parpia, Cornell University |
| 14:10 – 14:30 | Surface Bosonic excitations in confined topological superfluid $^3$He-B  
Takeshi Mizushima, Osaka University |
| 14:30 – 14:50 | Superfluid Helium-3 under confinement: the A-B transition and evidence for a Cooper pair density wave  
Lev Levitin, Royal Holloway, University of London |
| 14:50 – 15:10 | Superfluid Helmholtz resonators for studying the phases of liquid $^3$He under confinement  
Vaisakh Vadakkumbatt, University of Alberta |
| 15:10 – 15:30 | Coffee Break                                                                                   |

## Quantum Solids

**Chair: Eunseong Kim, KAIST**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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| 15:30 – 16:00 | Atomistic modeling of fundamental deformation mechanisms in hcp $^4$He  
Maurice de Koning, University of Campinas: UNICAMP |
| 16:00 – 16:20 | Liquid pocket formation and its crystallization onset via mass flow through solid $^4$He  
Ryuji Nomura, Tokyo Institute of Technology |
| 16:20 – 16:40 | Nuclear polarized phases of H atoms embedded in solid H$_2$ films  
Vladimir Khmelenko, Texas A&M University |
| 16:40 – 17:00 | Mass flux measurements in solid $^4$He  
Robert Hallock, University of Massachusetts Amherst |
| 17:00 – 19:00 | Poster Session II, PCL Lounge  
Sponsored by Cryomech |
### Saturday, August 10th

#### 2D Helium  
**Chair: John Reppy, Cornell University**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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| 8:30 – 9:00 | Evidence for a two-dimensional supersolid with intertwined density wave and superfluid order.  
*John Saunders, Royal Holloway, University of London* |
| 9:00 – 9:20 | Elastic anomaly as a probe for superfluidity of helium and hydrogen films                   
*Keiya Shirahama, Keio University*                  |
| 9:20 – 9:40 | Ultrasound and heat capacity study of $^4$He films on mesoporous silica                      
*Junko Taniguchi, The University of Electro-Communications, Tokyo* |
| 9:40 – 10:00 | Simultaneous measurements of superfluidity and heat-capacities of novel phases in $^4$He monolayers  
*Jun Usami, The University of Tokyo* |
| 10:00 – 10:20 | Domain wall roughening and melting transition of two dimensional quantum crystals             
*Tomoki Minoguchi, The University of Tokyo*    |

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<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>10:20 – 10:40</td>
<td>Coffee Break</td>
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</table>

#### Quantum Hall Fluids  
**Chair: Joseph Maciejko, University of Alberta**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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</table>
| 10:40 – 11:10 | Competition of a topological quantum fluid and a nematic phase in the two-dimensional electron gas  
*Gabor Csathy, Purdue University*         |
| 11:10 – 11:40 | Imaging a nematic quantum Hall liquid and its boundary modes                                  
*Ben Feldman, Stanford University*         |
| 11:40 – 12:10 | Fermi surfaces of composite Fermions                                                             
*Ravindra Bhatt, Princeton University*     |

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<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>12:10 – 13:40</td>
<td>Lunch</td>
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#### Vortices/Turbulence  
**Chair: Ladislav Skrbek, Charles University**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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</table>
| 13:40 – 14:20 | Hydrodynamics and turbulence in quantum fluids                                                  
*Makoto Tsubota, Osaka City University*          |
| 14:20 – 14:50 | Evolution of large-scale flow from turbulence in a two-dimensional superfluid                   
*Kristian Helmerson, Monash University*          |
| 14:50 – 15:10 | Damping of a micro-electromechanical resonator in the presence of quantum turbulence generated by a quartz tuning fork  
*Colin Barquist, University of Florida*         |
| 15:10 – 15:30 | Universal scaling laws of vortex reconnections                                                  
*Carlo Barenghi, University of Newcastle*        |

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<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>15:30 – 16:00</td>
<td>Coffee Break</td>
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#### Electrons on/in Helium II  
**Chair: Hyoungsoon Choi, KAIST**

<table>
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<tr>
<th>Time</th>
<th>Event</th>
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</table>
| 16:00 – 16:20 | Stability of bubbles containing few electrons                                                   
*Ambarish Ghosh, Indian Institute of Science*        |
| 16:20 – 16:40 | Energy eigenstates of electrons on helium in tilted magnetic fields                             
*Denis Konstantinov, Okinawa Institute of Science and Technology* |
| 16:40 – 17:00 | Investigation of the quantum measurement process using electrons in superfluid helium          
*Yiming Xing, Brown University*                     |

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<tr>
<th>Time</th>
<th>Event</th>
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</table>
| 17:00 – 19:00 | Poster Session III, PCL Lounge  
*Sponsored by Agilent* |
**Monday, August 12th**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Speaker(s)</th>
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<tbody>
<tr>
<td>8:30 – 9:00</td>
<td>Synthetic gauge fields with ultracold atoms in periodically-driven lattices</td>
<td>Monika Aidelsburger, Ludwig-Maximilians-Universität</td>
</tr>
<tr>
<td>9:00 – 9:30</td>
<td>Universal sound diffusion in a homogeneous strongly interacting Fermi gas</td>
<td>Martin Zwierlein, Massachusetts Institute of Technology</td>
</tr>
<tr>
<td>9:30 – 10:00</td>
<td>Observation of quantum-limited spin transport in strongly interacting Fermi gases</td>
<td>Joseph Thywissen, University of Toronto</td>
</tr>
<tr>
<td>10:00 – 10:30</td>
<td>Supersolidity in a quantum gas with cavity-mediated interactions</td>
<td>Tobias Donner, Institute for Quantum Electronics, ETH Zurich</td>
</tr>
<tr>
<td>10:30 – 10:50</td>
<td>Coffee Break</td>
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<tr>
<td>10:50 – 11:10</td>
<td>Implementing the new kelvin</td>
<td>Andrew Casey, Royal Holloway, University of London</td>
</tr>
<tr>
<td>11:10 – 11:30</td>
<td>Advances in current noise thermometry for ultralow temperatures</td>
<td>Christian Enss, Universität Heidelberg</td>
</tr>
<tr>
<td>11:30 – 11:50</td>
<td>Solving the puzzle of second-sound triangulation for hot-spot detection in superfluid helium-4</td>
<td>Wei Guo, Florida State University</td>
</tr>
<tr>
<td>11:50 – 12:10</td>
<td>Non-local thermoelectric current in a graphene Cooper pair splitter</td>
<td>Pertti Hakonen, Aalto University</td>
</tr>
<tr>
<td>12:10 – 13:30</td>
<td>Lunch</td>
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<tr>
<td>13:30 – 13:50</td>
<td>Phase crystallization near surfaces of unconventional superconductors</td>
<td>Anton Vorontsov, Montana State University</td>
</tr>
<tr>
<td>13:50 – 14:10</td>
<td>Experimental and theoretical progress on the road to one dimensional superfluids</td>
<td>Adrian Del Maestro, University of Vermont</td>
</tr>
<tr>
<td>14:10 – 14:30</td>
<td>Surface Roughness Effects on Transport of $^3$He in a Slab</td>
<td>Priya Sharma, Indian Institute of Science</td>
</tr>
<tr>
<td>14:30 – 14:50</td>
<td>Combined effects of pairing fluctuations and a pseudogap in the cuprate diamagnetic susceptibility and Hall coefficient</td>
<td>Rufus Boyack, University of Alberta</td>
</tr>
<tr>
<td>14:50 – 15:10</td>
<td>Field-theoretical approach to zero sound coupled to pairing fluctuations</td>
<td>Wei-Ting Lin, Northwestern University</td>
</tr>
<tr>
<td>15:10 - 15:30</td>
<td>Coffee Break &amp; Poster Prize Announcement</td>
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</tr>
<tr>
<td>15:10 – 18:00</td>
<td>Free time</td>
<td>Visit to Royal Alberta Museum (before banquet)</td>
</tr>
<tr>
<td>18:00 – 21:00</td>
<td>Conference reception and banquet</td>
<td>Royal Alberta Museum (Downtown Edmonton)</td>
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**Tuesday, August 13th**

<table>
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<tr>
<th>Time</th>
<th>Event</th>
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</table>
| 9:00 – 9:30   | Symmetry breaking and novel features of vortex structure and dynamics in confined superfluid $^3$He  
Vladimir Eltsov, Aalto University |
| 9:30 – 9:50   | The effect of magnetic scattering on superfluid $^3$He in aerogel  
Andrew Zimmerman, Northwestern University |
| 9:50 – 10:20  | Superfluid $^3$He in squeezed nematic aerogel  
Vladimir Dmitriev, Kapitza Institute for Physical Problems, Russian Acad. of Sciences |
| 10:20 – 10:40 | Coffee Break                                                       |
| 10:40 – 11:10 | Probing quantum fluids using mechanical oscillators  
Viktor Tsepelin, Lancaster University |
| 11:10 – 11:40 | Angular momentum in rotating superfluid droplets  
Andrey F Vilesov, University of Southern California |

**Closing session**

<table>
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<tr>
<th>Time</th>
<th>Event</th>
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</table>
| 11:40 – 12:00 | Conference Summary  
Hiroshi Fukuyama, The University of Tokyo |
| 12:00 – 12:30 | Closing remarks  
Conference chairs: John Beamish and John P. Davis, University of Alberta |
| 12:30 – 13:30 | Boxed Lunch |
| 13:30 –       | Departures |
## Poster Session I: Thursday, August 8th

### Topological superfluids / quantum Hall superfluids

<table>
<thead>
<tr>
<th>P1.1</th>
<th>Hyoungsoon Choi</th>
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<td>KAIST</td>
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How to probe non-trivial topology of a chiral superfluid $^3$He-A with MEMS

<table>
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<tr>
<th>P1.2</th>
<th>Pertti Hakonen</th>
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<td>Aalto University</td>
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</table>

De Haas-van Alphen effect in suspended graphene

### Electrons in, on, or around helium

<table>
<thead>
<tr>
<th>P1.3</th>
<th>Erika Kawakami</th>
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<td></td>
<td>Okinawa Inst. of Sci. and Tech.</td>
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</table>

Blueprint for building a quantum computer using electrons on liquid helium

<table>
<thead>
<tr>
<th>P1.4</th>
<th>Erika Kawakami</th>
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</thead>
<tbody>
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<td>Okinawa Inst. of Sci. and Tech.</td>
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Image charge detection of Rydberg states of the surface electrons on helium

<table>
<thead>
<tr>
<th>P1.5</th>
<th>Kostyantyn Nasyedkin</th>
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<tbody>
<tr>
<td></td>
<td>Michigan State</td>
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Acoustoelectric transport of electrons on helium

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<thead>
<tr>
<th>P1.6</th>
<th>Neha Yadav</th>
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<td>Indian Inst. of Science</td>
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Ultrasound Assisted Formation of Multielectron Bubbles in Helium

<table>
<thead>
<tr>
<th>P1.7</th>
<th>Shan Zou</th>
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<tbody>
<tr>
<td></td>
<td>Okinawa Inst. of Sci. and Tech.</td>
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</table>

Nanofriction in confined 2D electron system on liquid helium

### Superfluid optomechanics

<table>
<thead>
<tr>
<th>P1.8</th>
<th>Xavier Rojas</th>
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<tbody>
<tr>
<td></td>
<td>Royal Holloway</td>
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2D phononic crystals for superfluid optomechanics in the quantum regime

<table>
<thead>
<tr>
<th>P1.9</th>
<th>Sumit Kumar</th>
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<tbody>
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<td></td>
<td>Institut Néel</td>
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Optomechanical studies of a nanobeam coupled to a superconducting microwave cavity

### Other topics and model systems

<table>
<thead>
<tr>
<th>P1.10</th>
<th>Hideaki Takayanagi</th>
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<tr>
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<td>Tokyo Univ. of Science</td>
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Resonance in a Ti/MoS$_2$ Josephson Junction

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<thead>
<tr>
<th>P1.11</th>
<th>P. Bhalla</th>
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<tr>
<td></td>
<td>Univ. of Texas at Austin</td>
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</table>

Non-linear Optical Response of Topological Materials

<table>
<thead>
<tr>
<th>P1.12</th>
<th>Dylan Cattiaux</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Institut Néel</td>
</tr>
</tbody>
</table>

Nonlinear Self-Induced Oscillations in Microwave Optomechanics

<table>
<thead>
<tr>
<th>P1.13</th>
<th>Hyoung In Lee</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seoul National University</td>
</tr>
</tbody>
</table>

Vortices formed by the spin component of the Poynting vector for surface phononpolaritons with material losses

<table>
<thead>
<tr>
<th>P1.14</th>
<th>Michael Weyrauch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Physikalisch-Technische Bundesanstalt</td>
</tr>
</tbody>
</table>

Tensor network study of the spin-1/2 XXZ chain

<table>
<thead>
<tr>
<th>P1.15</th>
<th>Lev V. Levitin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Royal Holloway</td>
</tr>
</tbody>
</table>

Superconductivity in YbRh$_2$Si$_2$
### Low temperature techniques

<table>
<thead>
<tr>
<th>Paper</th>
<th>Author(s)</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1.16</td>
<td>Francis C. Bettsworth&lt;br&gt; <em>Lancaster University</em></td>
<td>Developing on-chip cooling for new physics and improved nanoelectronics</td>
</tr>
<tr>
<td>P1.17</td>
<td>Lev V. Levitin&lt;br&gt; <em>Royal Holloway</em></td>
<td>Opening Microkelvin Regime to Low-Dimensional Electron Systems</td>
</tr>
<tr>
<td>P1.18</td>
<td>Dmitry F. Zmeev&lt;br&gt; <em>Lancaster University</em></td>
<td>Modular Acrylonitrile Butadiene Styrene as a Structural Thermal Insulator Material for Cryogenic Applications</td>
</tr>
<tr>
<td>P1.19</td>
<td>Peter Skyba&lt;br&gt; <em>Institute of Experimental Physics</em></td>
<td>Properties of the 100 kHz quartz tuning forks in strong magnetic fields and very low temperatures</td>
</tr>
<tr>
<td>P1.20</td>
<td>Marcel Človečko&lt;br&gt; <em>Institute of Experimental Physics</em></td>
<td>Quartz tuning fork as a parametric resonator in strong magnetic field</td>
</tr>
<tr>
<td>P1.21</td>
<td>Mark R. Freeman&lt;br&gt; <em>University of Alberta</em></td>
<td>A cavity interferometric torsional oscillator for low temperature experiments</td>
</tr>
<tr>
<td>P1.22</td>
<td>Md. Shahidul Islam&lt;br&gt; <em>University of Alberta</em></td>
<td>Low temperature piezoelectric properties of LiNbO₃, PMN-PT and PZT-5A</td>
</tr>
<tr>
<td>P1.23</td>
<td>Wenguang G. Jiang&lt;br&gt; <em>University of Florida</em></td>
<td>An economical system for ³He purification</td>
</tr>
<tr>
<td>P1.24</td>
<td>Hugh Ramp&lt;br&gt; <em>University of Alberta</em></td>
<td>Elimination of Thermomechanical Noise</td>
</tr>
<tr>
<td>P1.25</td>
<td>Shohei Takimoto&lt;br&gt; <em>The University of Tokyo</em></td>
<td>Performances of a Compact Shielded Superconducting Magnet for Continuous Nuclear Demagnetization Refrigerator</td>
</tr>
<tr>
<td>P1.26</td>
<td>Andrew J. Woods&lt;br&gt; <em>University of Florida</em></td>
<td>Development of experimental platforms for ultra-low temperature experiments at the NHMFL High B/T Facility¹</td>
</tr>
<tr>
<td>P1.27</td>
<td>Ryundon Kim&lt;br&gt; <em>KAIST</em></td>
<td>A New Design for a Dry Adiabatic Nuclear Demagnetization Cryostat</td>
</tr>
<tr>
<td>P1.28</td>
<td>Myles Ruether&lt;br&gt; <em>University of Alberta</em></td>
<td>Table Top Dilution Refrigerator</td>
</tr>
</tbody>
</table>

### Quantum fluids (¹⁴He)

<table>
<thead>
<tr>
<th>Paper</th>
<th>Author(s)</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1.29</td>
<td>Jeonghwan Ahn&lt;br&gt; <em>Konkuk University</em></td>
<td>Superfluidity of 2D ¹⁴He clusters encapsulated within graphite layers</td>
</tr>
<tr>
<td>P1.30</td>
<td>Tapio S. Riekki&lt;br&gt; <em>Aalto University</em></td>
<td>Thermal couplings during the precooling period of an adiabatic melting experiment from 10 mK to 0.5 mK</td>
</tr>
<tr>
<td>P1.31</td>
<td>Andrew Guthrie&lt;br&gt; <em>Lancaster University</em></td>
<td>Probing Quantum Fluids with Nanomechanical Systems: Detecting the “Phonon Wind” at mK Temperatures.</td>
</tr>
<tr>
<td>P1.32</td>
<td>David Schmoranzer&lt;br&gt; <em>Charles University</em></td>
<td>Universal drag scaling in high-frequency flows of He superfluids</td>
</tr>
<tr>
<td>P1.33</td>
<td>S. I. Shevchenko&lt;br&gt; <em>B. Verkin Institute</em></td>
<td>The Third Sound as a Generator of Non-stationary Thermal EMF</td>
</tr>
<tr>
<td>P1.34</td>
<td>A. M. Konstantinov&lt;br&gt; <em>B. Verkin Institute</em></td>
<td>Superheat Conductivity and Electrical Activity of Superfluid Systems</td>
</tr>
</tbody>
</table>
| P1.35 | Yiming Xing  
*Brown University* | Investigation of the Quantum Measurement Process Using Electrons in Superfluid Helium |
| P1.36 | Yiming Xing  
*Brown University* | Effect of Pressure on the Mobility of Fast Ions in Superfluid Helium-4 |
| P1.37 | Yiming Xing  
*Brown University* | New Positive Helium Ions in Superfluid Helium-4 |

**Post-deadline**

| P1.38 | P. K. Rath  
*Indian Inst. of Science* | Collapse of vapor filled multielectron bubbles held against a surface |
| P1.39 | N. Yadav  
*Indian Inst. of Science* | Observation of Low Threshold Cavitation Events in Liquid Helium |
### Poster Session II: Friday, August 9th

**Quantum fluids (superfluid $^3$He)**

<table>
<thead>
<tr>
<th>Poster</th>
<th>Author</th>
<th>Affiliation</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2.1</td>
<td>Asher Jennings</td>
<td>Lancaster University</td>
<td>NEMS in Superfluid $^3$He: No Room at the Bottom?</td>
</tr>
<tr>
<td>P2.2</td>
<td>Samuli Autti</td>
<td>Lancaster University</td>
<td>Chasing zero-temperature damping mechanisms at super-Landau velocities</td>
</tr>
<tr>
<td>P2.3</td>
<td>Viktor Tsepelin</td>
<td>Lancaster University</td>
<td>Imaging ballistic quasiparticle beams inside a fermionic condensate</td>
</tr>
<tr>
<td>P2.4</td>
<td>Petri J. Heikkinen</td>
<td>Royal Holloway</td>
<td>Suppression of superfluidity by magnetic boundary scattering in confined superfluid $^3$He-A</td>
</tr>
<tr>
<td>P2.5</td>
<td>Takeshi Mizushima</td>
<td>Osaka University</td>
<td>Spectroscopy of surface Majorana fermions in superfluid $^3$He-B using a mechanical oscillator</td>
</tr>
<tr>
<td>P2.6</td>
<td>Jeevak Parpia</td>
<td>Cornell University</td>
<td>Memory effect and supercooling of the A phase in zero magnetic field</td>
</tr>
<tr>
<td>P2.7</td>
<td>Man D. Nguyen</td>
<td>Northwestern University</td>
<td>Corrections to the Higgs Mode Masses in Superfluid $^3$He</td>
</tr>
<tr>
<td>P2.8</td>
<td>John W. Scott</td>
<td>Northwestern University</td>
<td>Spin Waves in Superfluid $^3$He Imbibed in Aerogel</td>
</tr>
<tr>
<td>P2.9</td>
<td>Alexey N. Yudin</td>
<td>Kapitza Institute RAS</td>
<td>Anomalous Behavior of Oscillating Nematic Aerogel in Superfluid $^3$He</td>
</tr>
<tr>
<td>P2.10</td>
<td>Ryusuke Ikeda</td>
<td>Kyoto University</td>
<td>Study of Vortices in Superfluid $^3$He B Phase in Aerogels</td>
</tr>
<tr>
<td>P2.11</td>
<td>Robert C. Regan</td>
<td>Northwestern University</td>
<td>The Phase Diagram of Rotating Superfluid $^3$He-B</td>
</tr>
<tr>
<td>P2.12</td>
<td>Juho Rysti</td>
<td>Aalto University</td>
<td>Nambu-Goldstone modes with tunable effective metric in magnon BEC</td>
</tr>
<tr>
<td>P2.13</td>
<td>Alex Shook</td>
<td>University of Alberta</td>
<td>Two Dimensional Physics in Superfluid Helium-3</td>
</tr>
<tr>
<td>P2.14</td>
<td>Pramodh Senarath Yapa</td>
<td>University of Alberta</td>
<td>Exotic Phases of Confined Superfluid Helium-3: A Theoretical Study</td>
</tr>
<tr>
<td>P2.15</td>
<td>Yasumasa Tsutsumi</td>
<td>RIKEN</td>
<td>Generation of spin current in normal fluid and superfluid helium-3</td>
</tr>
</tbody>
</table>

**Quantum gases**

<table>
<thead>
<tr>
<th>Poster</th>
<th>Author</th>
<th>Affiliation</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2.16</td>
<td>Shohei Watabe</td>
<td>Tokyo Univ. of Science</td>
<td>Dipole mode of trapped Bose–Fermi mixture gas</td>
</tr>
<tr>
<td>P2.17</td>
<td>L.W. Cooke / B.D. Smith</td>
<td>University of Alberta</td>
<td>Artificial Gauge-Fields in Bose-Einstein Condensates</td>
</tr>
<tr>
<td>P2.18</td>
<td>Koichiro Furutani</td>
<td>Keio University</td>
<td>Strong-coupling Effects on Quantum Transport of an Ultra-cold Fermi Gas</td>
</tr>
<tr>
<td>P2.19</td>
<td>Tzyy-Leng Horng</td>
<td>Feng Chia University</td>
<td>Quantum thermal equilibrium and heat transfer in Bose-Einstein condensates</td>
</tr>
<tr>
<td>Session</td>
<td>Title</td>
<td>Authors</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>P2.20</td>
<td>Strong-Coupling Theory for a Non-equilibrium Unitary Fermi gas</td>
<td>Taira Kawamura&lt;br&gt;Keio University</td>
<td></td>
</tr>
<tr>
<td>P2.21</td>
<td>A Renormalization-Group Study of Interacting Bose-Einstein condensates: Absence of Bogoliubov Mode below Four ($T &gt; 0$) and Three ($T = 0$) Dimensions</td>
<td>Takafumi Kita&lt;br&gt;Hokkaido University</td>
<td></td>
</tr>
<tr>
<td>P2.22</td>
<td>Thermodynamic Stability and Effects of Bose-Bose Repulsion in an Ultracold Bose-Fermi Mixture with Strong Hetero-Pairing Fluctuations</td>
<td>Koki Manabe&lt;br&gt;Keio University</td>
<td></td>
</tr>
<tr>
<td>P2.23</td>
<td>Towards a broadband photonic quantum memory in Bose-Einstein condensate</td>
<td>Erhan Saglamyurek&lt;br&gt;University of Alberta</td>
<td></td>
</tr>
<tr>
<td>P2.24</td>
<td>Isothermal Compressibility and Effects of Induced Interaction between Preformed Cooper-pairs in the BCS-BEC Crossover Regime of an Ultracold Fermi Gas</td>
<td>Ryoei Sato&lt;br&gt;Keio University</td>
<td></td>
</tr>
<tr>
<td>P2.25</td>
<td>Progress Towards an Ultracold-Atom Hybrid Quantum System</td>
<td>Michelle A. Sullivan&lt;br&gt;University of Alberta</td>
<td></td>
</tr>
<tr>
<td>P2.26</td>
<td>Microwave-to-optical transduction and quantum memory in Rb vapors</td>
<td>Andrei Tretiakov&lt;br&gt;University of Alberta</td>
<td></td>
</tr>
</tbody>
</table>

**Quantum solids (bulk, 3D)**

<table>
<thead>
<tr>
<th>Session</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2.27</td>
<td>Internal Structure of hcp $^4$He Observed by X-Ray</td>
<td>Izumi Iwasa&lt;br&gt;Kanagawa University</td>
</tr>
<tr>
<td>P2.28</td>
<td>Ultra-slow dislocation pinning dynamics of solid $^4$He with extremely low $^3$He concentrations</td>
<td>Eunseong Kim&lt;br&gt;KAIST</td>
</tr>
<tr>
<td>P2.29</td>
<td>Scale-invariant dislocation networks in cold-worked solid $^4$He</td>
<td>Andrei I. Golov&lt;br&gt;University of Manchester</td>
</tr>
<tr>
<td>P2.30</td>
<td>Dipolar Solid Helium – A New Approach to Quantum Solids</td>
<td>Michael W. Ray&lt;br&gt;California State Univ. Sacramento</td>
</tr>
<tr>
<td>P2.31</td>
<td>Temperature-dependent Interatomic Interaction onto He-He Bond</td>
<td>Konstantin A. Chishko&lt;br&gt;B. Verkin Institute</td>
</tr>
<tr>
<td>P2.32</td>
<td>Reversible Plasticity of $^4$He and para-H$_2$: Dislocation Glide or Solid Phase Transformation?</td>
<td>Konstantin A. Chishko&lt;br&gt;B. Verkin Institute</td>
</tr>
<tr>
<td>P2.33</td>
<td>Asymmetry in Melting and Growth Relaxations of $^4$He Crystals after Manipulation by Acoustic Radiation Pressure Pulse</td>
<td>Ryuji Nomura&lt;br&gt;Tokyo Inst. of Technology</td>
</tr>
<tr>
<td>P2.34</td>
<td>Finite size effects in thermodynamics: negative compressibility and global instability in two-phase systems</td>
<td>Igor Todoshchenko&lt;br&gt;Aalto University</td>
</tr>
<tr>
<td>P2.35</td>
<td>Nuclear polarized phases of H atoms embedded in solid H$_2$ films</td>
<td>Vladimir V. Khmelenko&lt;br&gt;Texas A&amp;M University</td>
</tr>
<tr>
<td>P2.36</td>
<td>Evidence for melting of hydrogen isotope clusters trapped in solid neon at temperature below 1.3 K</td>
<td>David M. Lee&lt;br&gt;Texas A&amp;M University</td>
</tr>
</tbody>
</table>
### Vortices and turbulence

<table>
<thead>
<tr>
<th>Poster No.</th>
<th>Presenter</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3.1</td>
<td>Andrei I. Golov  &lt;br&gt;University of Manchester</td>
<td>Quantized vortex rings and loop solitons</td>
</tr>
<tr>
<td>P3.2</td>
<td>Sosuke Inui  &lt;br&gt;Osaka City University</td>
<td>Formation of localized vortex tangle around a spherical heat source in superfluid Helium</td>
</tr>
<tr>
<td>P3.3</td>
<td>Tomo Nakagawa  &lt;br&gt;Osaka City University</td>
<td>Statistical laws and self-similarity of vortex rings emitted from a vortex tangle in superfluid ( ^4\text{He} )</td>
</tr>
<tr>
<td>P3.4</td>
<td>Anna Pomyalov  &lt;br&gt;Weizmann Institute</td>
<td>Energy spectra of the turbulent He-4 counterflow.</td>
</tr>
<tr>
<td>P3.5</td>
<td>Yuto Sano  &lt;br&gt;Osaka City University</td>
<td>Anisotropy of wave-turbulent cascades in a quantum gas</td>
</tr>
<tr>
<td>P3.6</td>
<td>Yuri A. Sergeev  &lt;br&gt;Newcastle University</td>
<td>Radial turbulent counterflow in superfluid ( ^4\text{He} )</td>
</tr>
<tr>
<td>P3.7</td>
<td>Satoshi Yui  &lt;br&gt;Keio University</td>
<td>Elementary process of coupled dynamics between quantized vortex and normal fluid in superfluid ( ^4\text{He} )</td>
</tr>
<tr>
<td>P3.8</td>
<td>Hiromichi Kobayashi  &lt;br&gt;Keio University</td>
<td>Energy transfer caused by coupled dynamics between quantized vortices and normal fluid in superfluid ( ^4\text{He} )</td>
</tr>
<tr>
<td>P3.9</td>
<td>Colin S. Barquist  &lt;br&gt;University of Florida</td>
<td>Low Frequency Noise Spectrum of Quantum Turbulence Measured by a Micro-electromechanical Resonator in the Nonlinear Regime</td>
</tr>
<tr>
<td>P3.10</td>
<td>Timo Kamppinen  &lt;br&gt;Aalto University</td>
<td>Observation of single-vortex dynamics with the Kelvin-wave cascade in superfluid ( ^4\text{He} ) using nanomechanical resonators</td>
</tr>
<tr>
<td>P3.11</td>
<td>Ladislav Skrbek  &lt;br&gt;Charles University</td>
<td>Quantum turbulence in superfluid ( ^4\text{He} ) generated and detected by second sound</td>
</tr>
<tr>
<td>P3.12</td>
<td>Ken Obara  &lt;br&gt;Osaka City University</td>
<td>Observation of second sound attenuation across a macroscopic rotational flow</td>
</tr>
<tr>
<td>P3.13</td>
<td>Patrik Švančara  &lt;br&gt;Charles University</td>
<td>Visualization of macroscopic vortex rings in He II</td>
</tr>
<tr>
<td>P3.14</td>
<td>Hideo Yano  &lt;br&gt;Osaka City University</td>
<td>Size Distribution of Emission Vortices of Turbulence Induced by Vibrating Wire in Superfluid ( ^4\text{He} )</td>
</tr>
<tr>
<td>P3.15</td>
<td>Emil Varga  &lt;br&gt;University of Alberta</td>
<td>Boundary layer in thermal counterflow of superfluid ( ^4\text{He} ).</td>
</tr>
<tr>
<td>P3.16</td>
<td>Emil Varga  &lt;br&gt;University of Alberta</td>
<td>Nonlinear dissipation in superfluid ( ^4\text{He} ) at the microscale.</td>
</tr>
<tr>
<td>P3.17</td>
<td>Yutaka Sasaki  &lt;br&gt;Kyoto University</td>
<td>Measurement of Vortex Line Density in Superfluid ( ^4\text{He} ) by Pulsed QTF</td>
</tr>
</tbody>
</table>
## Low dimensional and confined systems

<table>
<thead>
<tr>
<th>Session</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3.18</td>
<td>Fabrication of phonon generator devices for study of quantum phase transition in molecular films</td>
<td>Yusuke Nago, Keio University</td>
</tr>
<tr>
<td>P3.19</td>
<td>Possible thermodynamical phase slips in superfluid $^4$He confined in a 2.5-nm channel of FSM</td>
<td>Junko Taniguchi, University of Electro-Communications</td>
</tr>
<tr>
<td>P3.20</td>
<td>NMR Studies of the Dynamics of 1D $^3$He in $^4$He plated MCM-41.</td>
<td>Chao Huan, University of Florida</td>
</tr>
<tr>
<td>P3.21</td>
<td>Short-Range and Long-Range Orderings of Bose $^4$He Films Adsorbed in Nanopores</td>
<td>Taku Matsushita, Nagoya University</td>
</tr>
<tr>
<td>P3.22</td>
<td>Substrate Corrugation Effects on Self-Binding of $^3$He in Two Dimensions</td>
<td>Masahiro Kamada, University of Tokyo</td>
</tr>
<tr>
<td>P3.23</td>
<td>Testing the survival of Fermi liquids in two dimensions</td>
<td>John Saunders, Royal Holloway</td>
</tr>
<tr>
<td>P3.24</td>
<td>Dimer Bound State and 3D Fermi liquid of $^3$He Film in 3D Nanopore</td>
<td>Taku Matsushita, Nagoya University</td>
</tr>
<tr>
<td>P3.25</td>
<td>Detection of gas adsorbed on suspended graphene</td>
<td>Masahiro Kamada, Aalto University</td>
</tr>
<tr>
<td>P3.26</td>
<td>Niobium Calorimeter for Studies of Adsorbed Helium Monolayers</td>
<td>Jun Usami, The University of Tokyo</td>
</tr>
<tr>
<td>P3.27</td>
<td>Homogeneous cavitation in liquid helium using an ink-bottle geometry</td>
<td>Fabien Souris, Institut Néel</td>
</tr>
<tr>
<td>P3.28</td>
<td>Quartz Crystal Microbalance Measurements of $^4$He Sub-monolayer Films on Graphite</td>
<td>Masashi Morishita, University of Tsukuba</td>
</tr>
<tr>
<td>P3.29</td>
<td>Elastic Anomaly of $^4$He Films Adsorbed on Graphite</td>
<td>Keiya Shirahama, Keio University</td>
</tr>
</tbody>
</table>

## Quantum solids (2D systems)

<table>
<thead>
<tr>
<th>Session</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3.30</td>
<td>The $^4$He adsorption on $\gamma$-graphdiyne: path-integral Monte Carlo study</td>
<td>Soomin Shim, Konkuk University</td>
</tr>
<tr>
<td>P3.31</td>
<td>Anomalous thermalization of $^3$He spins in a 2D $^4$He matrix: many-body localization?</td>
<td>Jan Knapp, Royal Holloway</td>
</tr>
<tr>
<td>P3.32</td>
<td>Simultaneous Measurements of Superfluidity and Heat-captacities of Novel Phases in $^4$He Monolayers</td>
<td>Jun Usami, University of Tokyo</td>
</tr>
<tr>
<td>P3.33</td>
<td>Observation of apparent superfluidity in the second layer $^4$He films adsorbed on graphite</td>
<td>Eunseoong Kim, KAIST</td>
</tr>
<tr>
<td>P3.34</td>
<td>Thermodynamic Evidence for Density Wave Order in Putative Two Dimensional $^4$He Supersolid</td>
<td>Jan Nyéki, Royal Holloway</td>
</tr>
</tbody>
</table>
Presentation Abstracts

Thursday, August 8th

Superfluid optomechanics

Optical, mechanical, and thermal properties of superfluid drops levitated in vacuum

J. G. E. Harris

Departments of Physics and Applied Physics, Yale University

One of the main goals of optomechanics is to study quantum effects in the motion of macroscopic objects. This typically requires devices that couple high quality optical and mechanical resonators at very low temperatures. Superfluid helium offers many advantages in realizing such devices: vanishing optical absorption and viscosity, high thermal conductivity, and the ability to cool itself via evaporation. However in many devices these remarkable properties are compromised by the solid materials used to confine the superfluid. To address this, we have used magnetic levitation to suspend a mm-scale drops of superfluid liquid helium in vacuum. I will describe preliminary measurements of the drops’ formation, trapping, and evaporative cooling; their mechanical resonances and optical resonances; and their potential use as quantum optomechanical systems.


Real-time optomechanical detection of vortex dynamics in a superfluid helium film

Chris Baker

University of Queensland

Two-dimensional superfluidity and quantum turbulence are directly connected to the microscopic dynamics of quantized vortices. However, surface effects have prevented direct observations of coherent vortex dynamics in strongly-interacting two-dimensional systems. In this talk, I will present how these dynamics can be observed by confining a nanometer-thick superfluid helium film to the atomically-smooth surface of an optical microcavity. Third-sound waves in the superfluid film interact with both light in the microcavity and quantized vortices, with these interactions enhanced by the small confinement area. In the presence of the background flow field created by a quantized vortex, the degeneracy between clockwise and counterclockwise propagating third-sound waves is lifted. The presence of quantized vortices manifests therefore as a vortex-position dependent splitting in the third-sound modes, which affects each sound mode in a unique fashion. By tracking this effect on multiple sound modes simultaneously, we can therefore non-destructively track both the number of vortices, as well as their spatial distribution in real-time.
High gains in thin films: a superfluid Brillouin laser

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Superfluid helium’s advantages (dissipationless flow, low optical absorption, and compliance to small forces) make it an obvious material choice for optomechanics [1, 2] and cavity-Brillouin scattering. Fundamentally, Brillouin scattering provides access to features inaccessible by traditional cavity optomechanics, such as novel quantum traveling-wave operations in continuum optomechanics [3]. Yet, one obstruction in accessing the quantum regime through Brillouin scattering in solids is the necessity of high optical powers to strain those solids, to form a grating through electrostriction. Overcoming that limitation also benefits the technological applications of Brillouin lasing, like ultra narrow linewidth on-chip lasers, inertial sensors and nonreciprocal photonic components.

Here we propose and experimentally demonstrate a new type of Brillouin resonator with ultra-high gain consisting of an evanescently coupled silica microdisk covered by a nanometer-thick superfluid $^4$He film. In contrast to conventional solid-state Brillouin lasers, we can utilize the optical tweezer effect to draw the ultra-compliant superfluid to regions of high light intensity. The resulting spatially modulated refractive index grating scatters light. With this novel platform, we demonstrate spontaneous lasing at a threshold of $0.8 \mu$W, the lowest reported value in the literature, and the first unambiguous observation of mechanically mediated strong optical coupling between counter-propagating optical fields.


Topological superfluids

How to probe non-trivial topology of a chiral superfluid $^3$He-$\Lambda$ with MEMS

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Pure liquid $^3$He has two superfluid phases in zero magnetic field, $^3$He-$\Lambda$ and $^3$He-$B$, both of which are topological phases. Despite being one of the oldest material known to be topological, direct experimental signatures of the non-trivial topology are hard to come by in superfluid $^3$He. Many of the experimental methods available for solid state topological matter, such as transport measurements, ARPES, local microscopy, neutron or x-ray scatterings, etc. are inaccessible to superfluid $^3$He due to lack of charge and extremely low $T_c$. Recent advance in micro- and nano-electromechanical systems (MEMS and NEMS), however, provides means to detect these. In specific, we will describe an experimental method involving a MEMS gyroscope with which the signature of the chiral current of $^3$He-$\Lambda$, a superfluid analogue of a quantum Hall system, can be directly measured. The method described in this talk can be applied to chiral topological superconductors as well.

Stability of Chiral Domain Structure in Superfluid $^3$He-A

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The chiral domain structure in a single thin slab of superfluid $^3$He-A was observed by our state-of-the-art ULT-MRI (magnetic resonance imaging) system. The observed image consisted of the soft domain walls, which became visible mostly because of the NMR line broadening at the wall and were anchored to the surface of the slab through the associated hard core. Although the walls had irregular shape soon after the formation just below Tc, the typical shape of the wall after some annealing procedure was straight plane, of which thickness was in the order of thickness of the slab, $100\mu$m. The location and shape of the walls were rather stable in the temperature range well below Tc. However we found that the location of the walls fluctuated in the temperature range near Tc. In some case we observed a pair annihilation of the adjacent domain walls, however, not all the walls annihilated during the fluctuation. The threshold temperature for the appearance of the fluctuation is systematically shifted from Tc for the sample with various pressures. The systematic deviation could be related to the strength of pinning force on the hard core part of the wall. However the driving force of the fluctuation is not clear at this moment.


Field-Theoretical Approach to Zero Sound coupled to Pairing Fluctuations

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Enhanced attenuation of zero sound was reported in liquid $^4$He at temperature just above the superfluid transition by Paulson and Wheatley. A semi-phenomenological theory was proposed by Samalam and Serene based on addition of a singular contribution to the collision integral for quasiparticle collisions in the Cooper channel. This approach captures the temperature dependence of enhanced attenuation, but lacks the foundation of the theory of paraconductivity in metallic superconductors formulated by Aslamazov and Larkin. We report new theoretical results for the fluctuation corrections to zero sound propagation and attenuation based on a quantum field theory for the coupling of particle-hole excitations and Bosonic fluctuations in the Cooper channel. Our theory is based on a functional integral formulation for the action for interacting fermions with the introduction of auxiliary bosonic fields in both the particle-hole and particle-particle channels. The resulting theory describes the coupling of particle-hole excitations and Bosonic fluctuations in the Cooper channel. It reduces to the collisionless Landau-Boltzmann transport equation, hosting zero sound, in the absence of Bosonic fluctuations in the Cooper channel. The leading-order pairing fluctuation corrections to zero sound derive from diagrams similar to the Aslamazov-Larkin process for the paraconductivity. The results differ in several aspects from the theory of Samalam and Serene. We compare our theory with experimental results for the fluctuation corrections to the attenuation, and also discuss related transport processes that should exhibit pairing fluctuation corrections.

Electrons and ions on the surface of liquid helium have achieved renewed interest in the last two decades. It was initiated by the paper by Platzman and Dykman [1], which proposed forming quantum bits with using electrons on liquid He. The proposal has stimulated a bunch of experimental work. For example, a microwave (MW) absorption due to a resonant excitation of quantized vertical motion of an electron was revisited. An analogy between ripplon scattering and quantum electrodynamics revealed itself when the temperature dependence of absorption frequency was analyzed. The MW absorption experiment is developed further in finding a negative magnetoconductance under perpendicular magnetic field. A detection of single electron on liquid He has been paid much attention, and there is a very recent progress. The transport of single electrons in a quasione-dimensional channel has shown another prominent progress in understanding the transport properties of Wigner solid. Ions trapped under the free surface of liquid He have turned out to be a powerful probe for the intriguing topological properties of superfluid 3He. Moreover, charged nano metallic particles are another curious objects trapped under the helium surface. In this talk, the progress of this field mainly in the last two decades will be reviewed and the future prospect will be discussed.


Electrons on helium: Self-diffusion and mobility in a periodic potential

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We discuss the effect of strong electron correlations on the electron transport in a spatially-periodic potential. The potential comes from a structure submerged into helium at a few-micron depth. In the experiment, its strength can be controlled in situ. The results refer to a broad temperature range, from an electron liquid to a Wigner crystal. We have performed molecular dynamics simulations to study the ordering in the electron system, self-diffusion, and dc transport for a one-dimensional potential. The simulations are done for 1600 electrons. The major distinction from the standard simulations is the incorporation of elastic scattering by ripplons and weak inelastic scattering by phonons in helium. Because of the strong correlations in the electron liquid, an already weak periodic potential can qualitatively change the self-diffusion and the mobility. The electron dynamics strongly depends on the interrelation between the potential period and the mean interelectron distance. We explore this dependence in a broad parameter range. It is most pronounced, even in the liquid phase, where the period is close to being commensurate with the period of the Wigner crystal that forms if the liquid is cooled to a lower temperature. In particular, this allows measuring the correlation length in the electron liquid by measuring the mobility. We find that the freezing temperature nonmonotonically depends on the commensurability parameter. We also find incommensurability solitons in the solid phase. We show that the Coulomb-coupled system in a commensurate 1D potential has long-range order, in contrast to systems with short-range coupling. We also study thermalization in the electron liquid.
Electrons Bound to Superfluid Helium: Coherent Mobile Spin Qubits

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The spin of an electron is a popular style of quantum bit (qubit). These qubits are typically hosted in isotopically-enriched silicon, where they can have coherence times of seconds, or longer, and leveraging established silicon technology may be possible. It has been proposed that surface state electrons bound to superfluid helium will make highly coherent spin qubits, with several advantages over their semiconductor counterparts. In particular there is the possibility of long spin coherence for mobile electrons on helium, which is precluded by spin-orbit effects in Si. While mobile qubits are not essential, they can simplify quantum computing architectures in the long term, and allow more flexible quantum simulators in the nearer term. I will discuss indirect evidence that the spin orbit interaction is small enough for the spins to retain a coherence of seconds while being free to move. I will also describe electron transport experiments along helium-filled channels which are fully integrated with Si chip technology. Extremely efficient control of electron motion is found, down to the level of single electrons. However, nanoscale electronic devices will require thin He films, which generally lead to low mobilities. Accurate control of quantum gates is incompatible with large disorder. I will discuss recent experiments in which amorphous metallic electrodes have shown promise for improving electron mobility in shallow channels and on thin He films.

Novel techniques

Layering transition in helium films adsorbed on a carbon nanotube

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The study of 2D helium films has led to several breakthrough in condensed matter physics including the study of third sound and topological phase transitions, the latter being rewarded by the 2016 Nobel Prize. In most experimental studies helium was adsorbed on large scale substrates, such as mm\textsuperscript{2} scale grafoil plates or Mylar. Recent advances in the field of optomechanics and nanomechanics now opens up the possibility to study fluids and superfluids of smaller dimensions. In this talk, I will present our recent experiments on helium films probed through the mechanical vibrations of a carbon nanotube. We observed a strong discontinuity in the adsorption of He on the nanotube surface, that we attributed to a layering transition. In addition, the low-temperature dependence of the mechanical mode of the nanotube exhibit a mode softening. Thanks to the tunability of the nanotube resonator, we confirmed the spring nature of this effect and drawn a link with the propagation of third sound in He 2D films.
2D $^3$He probed by oscillating nanotube: A new structural transition and spectroscopy

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We have measured oscillation spectra of suspended carbon nanotubes dressed in $^3$He. We investigated the shift and the width of nanotube resonance as a function of $^3$He coverage and temperature. We have observed a transition in the absorbed $^3$He, which would correspond to an abrupt hardening of helium layer. In the liquid phase at low coverages the transition temperature rapidly decreases with the increase of the helium density, similarly to the Fermi-degeneracy temperature measured earlier in $^3$He on grafoil. However, in the solid phase at higher coverages the transition is still present, even in the commensurate 1/3 solid phase and at higher coverages where there is no liquid phase. The transition manifests a significant hysteresis on warming/cooling indicating that it is the first-order transition. The dissipation of the nanotube resonance grows as square of the coverage. In addition, we have observed several side peaks near the main resonance, presumably due to a coupling of the mechanical oscillations of the nanotube to excitations in the helium layer. This opens a possibility to perform spectroscopic measurements on the absorbed helium to measure directly the excitation spectrum of the 2D $^3$He.

1. For the review on experimental properties of $^3$He on grafoil, see H. Godfrin, H.-J. Lauter, Prog. Low Temp. Phys., 14, 213 (1995).

Brute-force cooling and on-chip thermometry for microwave optomechanics

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We report on microwave optomechanics measurements performed on a nuclear adiabatic demagnetization cryostat, whose temperature is determined by accurate thermometry from below 500 μK to about 1 Kelvin. We describe a method for accessing the on-chip temperature, building on the blue-detuned parametric instability and a standard microwave setup. The capabilities and sensitivity of both the experimental arrangement and the developed technique are demonstrated with a very weakly coupled silicon-nitride doubly-clamped beam mode of about 4 MHz and a niobium on-chip cavity resonating around 6 GHz [1]. We describe an unstable intrinsic driving force in the coupled microwave-mechanical system acting on the mechanics that appears below typically 100 mK. The origin of this phenomenon remains unknown but has been observed in different laboratories, and deserves theoretical input. It prevents us from performing reliable experiments below typically 10-30 mK; however no evidence of thermal decoupling is observed. This instability seems to be generic in microwave optomechanical systems, at different levels of strengths, and measurements using a drumhead device in collaboration with Aalto University [2] are on-going. The described microwave/microkelvin facility is part of the EMP platform [3], and shall be used for further experiments within and below the millikelvin range.

Adiabatic Melting of Solid $^4$He in Liquid $^3$He

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We describe an experiment designed to cool helium fluids to record low temperatures below 0.1 mK by adiabatic melting of solid $^4$He in superfluid $^3$He. The performance, limiting factors, and possible improvements to the present system are discussed.
Quantum gases I

The quantum phases of ultracold dipolar gases near a Roton excitation


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Discovered in liquid helium about 80 years ago, superfluidity is a counterintuitive phenomenon, in which quantum physics and particle-wave duality manifest at the macroscopic level. Since then, it has yielded many advances in understanding quantum matter, yet leaving some of its features mysterious. A hallmark of superfluidity is the existence of so-called quasi-particles, i.e. elementary excitations dressed by interactions. Landau predicted two types of quasi-particles, the first one being the well-known phonon. The second one, much more bizarre and intriguing, are massive quasi-particles named rotons. They have large momenta, and the roton dispersion relation exhibits a minimum at a finite momentum. This unusual behaviour expresses the tendency to build up short-wavelength density modulations in space, precursor of a crystallization instability and eventually to the elusive and highly-debated supersolid quantum phase. In 2003, theoreticians suggested that a similar rotonic excitation might also occur in dipolar Bose-Einstein condensates because of the special properties of the long-rang and anisotropic dipole-dipole interaction. Here we report on the observation of roton quasiparticles in a dipolar quantum gas of highly magnetic Erbium atoms. We show the spontaneous population of the roton mode by pushing the excitation gap at the roton momentum to zero and map out the dispersion relation for finite excitation gaps employing a tuneable Bragg excitation scheme. Finally, we demonstrate hallmarks of supersolid behaviour using Bose-Einstein condensates of Erbium and Dysprosium atoms, which feature an exceptional long lifetime in the latter case.

Transient Supersolid Properties in an Array of Dipolar Quantum Droplets


5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, University of Stuttgart, Stuttgart, Germany

We study theoretically and experimentally the emergence of supersolid properties in a dipolar Bose-Einstein condensate. The theory reveals a ground state phase diagram with three distinct regimes — a regular Bose-Einstein condensate and incoherent and coherent arrays of quantum droplets. The coherent droplets are connected by a background condensate, which leads — in addition to the periodic density modulation — to a robust phase coherence throughout the whole system. We further theoretically demonstrate that we are able to dynamically approach the ground state in our experiment and that its lifetime is limited only by three-body losses. Experimentally we probe and confirm the signatures of the phase diagram by observing the in situ density modulation as well as the phase coherence using matter wave interference. Finally, we prove the supersolid nature of the coherent droplet arrays by directly observing their low-energy Goldstone mode. The dynamics of this mode is reminiscent of the effect of second sound in other superfluid systems and features an out-of-phase oscillation of the crystal array and the superfluid density. This mode exists only due to the phase rigidity of the experimentally realized state, and therefore confirms the genuine superfluidity of the supersolid.

Observation of a supersolid phase of matter in a dipolar quantum gas

G. Modugno

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The possibility that a quantum crystal might show a superfluid behavior was addressed theoretically 50 years ago by Andreev and Lifshitz. I will report the discovery that a Bose-Einstein condensate of strongly magnetic atoms, after undergoing a rotonic instability can end up in a density-modulated metastable state with phase coherence, hence with the requisites for a supersolid. A confirmation of the supersolid nature of the system comes from the observation of a bifurcation of a collective oscillation mode that reflects the appearance of two Goldstone modes due the simultaneous breaking of two symmetries: the gauge symmetry and the translational symmetry. This not only confirms the existence of two coupled sound modes as predicted by Andreev and Lifshitz, but also shows that the supersolid lattice is compressible. I will also report on progresses towards the determination of the moment of inertia of the supersolid phase through rotation experiments. In the future, it will be possible to study the two quantum phase transitions from superfluid to supersolid and from supersolid to solid by tuning a single interaction parameter.


Light-cone like spreading of correlations in the Bose Hubbard model at strong coupling

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We study the spreading of correlations in space and time after a quantum quench in the Bose Hubbard model. We derive equations of motion for the single-particle Green's function within the contour-time formalism, allowing us to study dynamics in the strong coupling regime. We discuss the numerical solutions of these equations and calculate the single-particle density matrix for quenches in the Mott phase. We demonstrate light-cone like spreading of correlations in the Mott phase in one, two, and three dimensions and calculate propagation velocities in each dimension. Our results show excellent agreement with existing results in one dimension and demonstrate the anisotropic spreading of correlations in higher dimensions.

Cold dark matter

SuperCDMS at SNOLAB - mK for Dark Matter Searches

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for the SuperCDMS Collaboration

The Super Cryogenic Dark Matter Search (SuperCDMS) is an experiment to search for interactions of dark matter particles in semiconductor detectors operated at a few tens of mK. The experiment is presently under construction at SNOLAB, the deepest underground laboratory of its size.

The core of the experiment is a set of cryogenic Ge and Si detectors, surrounded by a complex shielding structure to minimize interactions from environmental radiation, and cooled down by a combination of a pulse-tube based dilution refrigerator and a set of gas and liquid He cooling loops. With an expected completion of construction in 2020, SuperCDMS is expected to provide world-leading sensitivity for low-mass dark matter particles.

A second setup, the Cryogenic Underground TEst facility (CUTE) has just been completed at SNOLAB, next to the SuperCDMS location, and will be used to test SuperCDMS detectors under very low background conditions, with a facility that is much more easily accessible than the main experiment. Once the testing for SuperCDMS is completed, CUTE may also be available for other measurements that require mK temperatures and a very low background environment.

In this presentation, the underground cryogenic facilities will be introduced and the status and perspectives for CUTE and SuperCDMS will be discussed.

Dark Matter Detection Using Superfluid Helium-4


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At the present time the evidence for the existence of dark matter comes entirely from its gravitational interaction with ordinary matter. There has been no determination of the mass or any other property of the particles making up dark matter. Current experiments have been designed to look for particles in the mass range above about 5 GeV/$c^2$. Recently theoretical models have considered the possibility that the mass is below this range. This would have the consequence that a dark matter detector has to be able to sense a much smaller deposit of energy than is currently possible. We will describe a new approach in which superfluid helium-4 is the target material. The energy deposit results in the excitation of phonons and rotons. When these excitations reach the free surface of the liquid, helium atoms are evaporated. These neutral atoms are incident onto an array of sharp tips and field ionization results in the formation of helium positive ions with high kinetic energy. These ions can then be detected with conventional bolometric techniques.

Resonant detection of gravitational waves and dark matter using superfluid helium

Swati Singh
University of Delaware

We study the sensitivity to continuous-wave strain fields of an optomechanical system formed by the acoustic motion of superfluid helium-4 parametrically coupled to a superconducting microwave cavity. This narrowband detection scheme can operate at very high Q-factors, while the resonant frequency is tunable through pressurization of the helium in the 0.1-1.5 kHz range. For thermal noise limited sensitivity, we find that strain fields on the order of $h \sim 10^{-23} / \text{Hz}$ are detectable. Measuring such strains is possible by implementing state of the art microwave transducer technology. We show that the proposed system can compete with interferometric detectors and potentially surpass the gravitational strain limits set by them for certain pulsar sources within a few months of integration time. Additionally, dark matter particles coupling to standard model fields and particles would also produce a coherent strain signal in an elastic solid. We discuss the feasibility of searching for such scalar field couplings in the $10^{-12}$ eV–$10^{-8}$ eV range using helium devices. Finally, we comment on how these searches can complement the existing precision measurement based dark-matter searches based on atomic clocks, spin precession or equivalence principle tests.

Confined Helium

Thermal transport of helium-3 in a strongly confining channel


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I will report on an experiment observing heat transport in a strongly confining channel of height approaching the superfluid coherence length. In such a system, it is anticipated that new quantum states and excitations bound to surfaces and edges should be present. Here we report on the thermal conduction of helium-3 in a 1.1 $\mu$m high microfabricated channel. In the normal state we observe a diffusive thermal conductivity that is approximately temperature independent, consistent with work on the interference of bulk and boundary scattering in thermal\cite{1} and momentum transport\cite{2}. In the superfluid state we measure diffusive thermal transport in the absence of thermal counterflow. An anomalous thermal response is also detected in the superfluid which we suggest may arise from a flux of surface excitations.

Surface Bosonic Excitations in Confined Topological Superfluid $^3$He-B

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Using an effective field theory, we study the low-lying bosonic excitations and their couplings to phonons at ultrasonic frequencies in topological superfluid $^3$He-B under strong confinement. The theory is comprised of actions for bosonic fields, helical Majorana fermions, and fermion-boson coupling. The bosonic sector describes the space-time fluctuations of the order parameter around a stationary state of the Ginzburg-Landau (GL) functional. For bulk $^3$He-B this formalism leads to the well-known spectrum of bosons labelled by the total angular momentum, $J \in \{0, 1, 2\}$, which obey Nambu's Fermion-Boson mass relations. However, broken symmetries and dimensional confinement due to strong confinement lead to a rich structure of bosonic excitations. This includes (i) a new spectrum of surface-bound bosonic modes, (ii) fine structure of long-lived massive $J=2$ bosons, (iii) the dynamical instability of the $^3$He-B film, (iv) the selection rule for the coupling of bosons to helical Majorana fermions, and (v) the enhancement of the $\mu$-factor in surface bosonic modes. As for (iii), we find that under sufficiently strong confinement a surface-bound boson softens at finite wavevectors and develops a pole in the upper half of the complex frequency plane, signalling a dynamical instability of the translationally invariant superfluid vacuum towards pair-density-wave "crystallization". Lastly, we argue the observability of the new characteristics (i-v) inherent to low-lying bosons and fermions of confined $^3$He-B through longitudinal and transverse ultrasound spectroscopy.


Superfluid Helium-3 under Confinement: the A-B Transition and Evidence for a Cooper Pair Density Wave

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Confinement on a lengthscale comparable to the superfluid coherence length $\xi$ is a powerful tool for modifying the order parameter of the p-wave superfluid $^3$He via orbital-momentum-selective surface pairbreaking. NMR and mass transport experiments on $^3$He in $D = 0.7$ and 1.1 $\mu$m-tall nanofluidic cavities demonstrate strong modification of the phase diagram and distortion of the superfluid energy gap [1,2]. The transition between superfluid A and B phases maps to universal $D/\xi$ and only minute supercooling of the A phase is observed, with evidence for an intrinsic B phase nucleation mechanism under confinement. The confined B phase is predicted to be unstable to spontaneous formation of domains, and the stripe phase is proposed to stabilise in slab geometry [3], an example of a 1D Cooper pair density wave (PDW). Our NMR measurements of the energy gap suggest a more complex domain configuration, consistent with a 2D PDW that we term polka dot phase [4]. The formation of domains within the B phase is potentially related to the fundamental question of the B phase nucleation.

Superfluid Helmholtz resonators for studying the phases of liquid $^3$He under confinement

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The characteristics of superfluidity in liquid $^3$He are predicted to be significantly different from bulk when it is confined to a length scale comparable to its coherence length. These include suppression of $T_c$, stabilization of phases, and appearance of new phases\(^1\). Different experimental techniques have been developed to engineer the confinement and capture the physics due to confinement\(^1,2\). In our experiments, we have used a nanomechanical Helmholtz resonator for measuring the superfluid fraction\(^3\) of liquid $^3$He, where the flow is constrained to a channel of uniform thickness. The frequency of the resonator is related to the superfluid fraction, which is measured as a function of temperature and pressure. In this talk, we will present our experimental results in $^3$He, which show clear signatures of superfluid phase transitions in confined geometries.


Quantum Solids

Atomistic modeling of fundamental deformation mechanisms in hcp $^4$He

Maurice de Koning

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The plastic deformation properties of $^4$He in its hcp phase have been the subject of intense study over the past decades. In this context, the characteristics of lattice dislocations - the one-dimensional defects that carry plastic deformation in crystalline solids - are of particular interest. While there is an extensive body of experimental results, their interpretation in terms of individual defect properties is often difficult. In this light atomistic simulation techniques can be extremely helpful, allowing the study of individual lattice defects under controlled conditions. Here, we will discuss how path-integral Monte Carlo simulations can be employed to investigate both the structural as well as mobility characteristics of basal-plane dislocations in hcp $^4$He. In addition to discussing the role of quantum effects in their intrinsic mobility, we also consider their interaction with $^3$He impurities.
Liquid Pocket Formation and Its Crystallization Onset via Mass Flow through Solid \(^4\)He in Aerogel

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While \(^4\)He crystals in a 96% porosity aerogel were grown by pressurization at 0.85 K, liquid pockets remained non-crystallized in the particular aerogel, even with application of a further overpressure. This indicates that \(^4\)He crystals formed in the aerogel did not carry mass flow at the high temperatures and blocked the flow paths toward the liquid pockets. After this formation of the liquid pockets, we cooled down the system at the constant pressure and found that the liquid pockets began to crystallize via intermittent avalanches below a particular onset temperature. This implies that mass flow occurs at the low temperatures in \(^4\)He crystals in the aerogel. The onset temperature of crystallization \(T_L\) was investigated for various liquid pockets to examine the mass flow through \(^4\)He crystals in the aerogel. \(T_L\) had a wide distribution but was lower at lower pressures. \(T_L\) was slightly lower than the onset temperature of the bulk \(^4\)He crystal.


Nuclear polarized phases of H atoms embedded in solid \(H_2\) films

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We report on an experimental observation of two phases of hydrogen atoms in solid \(H_2\) films at temperatures \(0.1 - 0.8\) K, characterized by a large enhancement of the nuclear spin polarization compared to that given by Boltzmann statistics \((p = 0.15\) at \(T = 0.15\) K). The first phase with \(p = 0.35(5)\) is formed spontaneously during sample storage in a high magnetic field \((B = 4.6\) T). The second phase with an even higher nuclear polarization, \(p = 0.75(7)\), can be achieved at \(T \leq 0.55\) K by repeating sequences of Dynamic Nuclear Polarization by the Overhauser effect followed by a system relaxation. Upon warming through the temperature range \(0.55 - 0.65\) K the highly polarized phase undergoes a phase transition to the spontaneously polarized phase, which breaks down at \(T \sim 0.8\) K and the nuclear polarization gradually converges to the Boltzmann distribution. We discuss possible scenarios for explaining the nature of the observed phenomena.

Mass Flux Measurements in Solid $^4$He

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We previously determined the characteristics of mass flux through solid $^4$He that takes place from one superfluid-filled reservoir to the other through a solid-filled experimental cell off the melting curve. In doing so we showed that during mass flux there typically was an increase in the density of the solid. We measured flow characteristics that match general expectations for one-dimensional Luttinger-Liquid conductivity. We documented the effects that various concentrations of $^3$He impurity have on the temperature dependence of the flow. Our most recent experiments show that reducing the interface between the superfluid helium (contained in Vycor rods) and solid helium reduces the flux and that significantly blocking the cross section of the channel filled with solid $^4$He further suppress the flux. These results add strength to the view that the observed mass flux is due to the superfluid cores of edge dislocations as opposed to flux through liquid channels or along the solid-wall interface. A study of mass flux in the presence of in situ imposed structural changes is underway. Work supported by NSF DMR 1205217 and 1602616.

Evidence for a two-dimensional supersolid with intertwined density wave and superfluid order.

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We identify a new quantum state with intertwined superfluid and density wave order in the second layer of \(^{4}\)He on graphite. Torsional oscillator measurements show an anomalous superfluid response with four distinct coverage regimes. An ansatz for the excitation dispersion relation, which implies density wave order, accounts for the temperature dependence of the normal density. We propose a quasi-condensate wavefunction with intertwined order to account for the absence of a Kosterlitz-Thouless transition \cite{1}. While first principles simulations of the second layer \cite{2} find no crystalline order over much of the coverage range we have explored, heat capacity anomalies attributable to melting are observed \cite{3}. We further establish the existence of crystalline order in the second layer doped with a small concentration of \(^{3}\)He by measurements of heat capacity, nuclear magnetic susceptibility and spin-lattice relaxation time \cite{4}. Together these results provide evidence for a novel two-dimensional supersolid.


Elastic Anomaly as a Probe for Superfluidity of Helium and Hydrogen Films


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Thin helium films provide a unique example of 2D strongly correlated system, in which the interatomic correlation can be tuned by coverage and substrate potential. We have recently found that elasticity of localized He (\(^{4}\)He and \(^{3}\)He) films anomalously increase at low \(T\). The elastic anomaly is well explained by thermal activation of He atoms from the localized state to extended one. Both \(^{4}\)He and \(^{3}\)He films are a gapped and compressible solid. The energy gap, which is proportional to the temperature of elastic anomaly \(T_{\rho}\), fades away as \(n\) approaches a quantum critical coverage \(n_{c}\), above which helium atoms occupying extended states show superfluidity. Similar elastic anomalies have been observed in neon (\(^{20}\)Ne) and hydrogen (H\(_{2}\), D\(_{2}\), and HD) films\textsuperscript{2-3}. In these films, the coverage dependence of elastic anomaly may also be related to possible occurrence of superfluidity. In Ne films, \(T_{\rho}\) decreases down to about 5 K but not to lower \(T\), meaning that Ne films are classical and show no superfluidity\textsuperscript{2}. Interestingly, hydrogen films show multiple elastic anomalies at three different temperatures. The origins of three anomalies are identified as freezing of (1) classical thermal diffusion of molecules, (2) quantum tunneling of molecules, and (3) diffusion of molecules located at uppermost surface of films\textsuperscript{1}. The freezing temperature of the surface molecules decreases down to 1 K for H\(_{2}\) and HD films as \(n\) increases to about two layers, but do not reach 0 K. This suggests that the surface layer of hydrogen films is on the verge of quantum phase transition to superfluid state. Possibility of realizing superfluidity in hydrogen films will be discussed.

Ultrasound and heat capacity study of $^4$He films on mesoporous silica

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We have studied the static and dynamic structures of an inert layer $^4$He adsorbed on the mesoporous silica, FSM, by the heat capacity, vapor pressure, and ultrasound measurements. The heat capacity exhibits a Schottky peak, indicating the excitation of the localized solid to fluid.\(^1\) We analyzed the heat capacity over a wide temperature range according to a model that considers the contribution of the localized solid and excited fluid, and clarified that the excited fluid coexists with the localized solid at high temperatures. At the high-temperature side of that of the Schottky peak, we observed a substantial decrease in sound velocity, accompanied by an attenuation peak.\(^2\) The magnitude of the change in sound velocity is comparable to that due to the total mass loading of $^4$He, suggesting that the mass decoupling occurs at low temperature. The existence of fluid area is supposed to be relevant to sticking of the entire film.


Simultaneous Measurements of Superfluidity and Heat-capacities of Novel Phases in $^4$He Monolayers

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Experimental realization of supersolidity in bulk solid $^4$He is the subject of a long-standing debate. Rather recently, $^4$He monolayers adsorbed on graphite are attracting much attention in the context of possible 2D supersolidity or superfluidity of quantum liquid crystal (LC) phase.\(^1\) This is because reentrant superfluid responses have been observed below 0.3 K by several groups using the torsional oscillator (TO) technique at densities, which do not seem to correspond to the uniform liquid (L) phase, in the second layer of $^4$He.\(^2\) However, it is still not known exactly which phase shows superfluidity due to large uncertainties in their density scales that originate from substrate heterogeneities. We are now successful in eliminating this problem by developing a unique experimental technique with which we can measure heat capacities ($C$) and frequency shifts ($\Delta f$) of the TO simultaneously for the same sample. Phase assignment can be done precisely by measuring $C$ for a given sample.\(^1\) Here we report the first result of such simultaneous measurements on the L and LC phases in 2D $^4$He, where a large superfluid fraction ($\rho_s = 40\%$ of the second layer) and a reduced but finite $\rho_s$ ($\rho_s = 10\%$) were observed, respectively. This means that we found a novel state of matter, i.e., “superfluid crystal”, where the partially broken spatial symmetry coexists with superfluidity. An extended measurement of the 2D solid phase to seek for possible supersolidity will also be reported.

1. S. Nakamura et al., PRB 94, 180501(R) (2016).
Domain wall roughning and melting transition of two dimensional quantum crystals

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Dislocations in a He crystal are known to have a large mobility due to quantum fluctuation and can be the source of various mechanical anomalies. We present the static and dynamic properties of domain walls (DWs) existing in two dimensional quantum crystals. Taking care of the correlation between DWs explicitly into account, we find that the DW system is identical to the plane rotor model with a symmetry breaking field $H(p)$ with $p$ relating to the mean distance between DWs. The quantity $p$ is controllable by changing the thickness of the overlayers. We discuss the melting and roughning transitions of DWs at some parameter region of $p$. In the presence of superfluid overlayer, we predict that the third sound softning occurs when the solid layer is in a liquid crystal phase.

Quantum Hall Fluids

Competition of a Topological Quantum Fluid and a Nematic Phase in the Two-dimensional Electron Gas

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The two-dimensional electron gas in a perpendicular magnetic field is prototype system that supports numerous quantum liquids and solids. Some of the most intriguing of these phases form when the energy levels of the system are half filled. One example is the $\nu = 5/2$ fractional quantum Hall state, a topological quantum liquid. Another example is the quantum Hall nematic. So far these phases formed in different areas of the phase space and, therefore, a phase transition between them was not possible. In this talk I will discuss the observation of a pressure-driven direct quantum phase transition between the fractional quantum Hall state and a nematic phase at $\nu = 5/2$. The role of the pressure driving the transition and special properties of this phase transition will be discussed.
Imaging a nematic quantum Hall liquid and its boundary modes

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Nematic electronic states, characterized by wave functions that spontaneously break the rotational symmetry of their host material, represent an intriguing class of quantum fluids. In this talk, I will describe scanning tunneling microscope measurements of bismuth that enable us to directly visualize nematic behavior in real space. Spectroscopy reveals that the valley degeneracy of the bismuth surface states is fully lifted by electron-electron interactions at high magnetic field. By imaging the resulting anisotropic wave functions, we demonstrate the formation of local nematic domains with different preferred orientations. In addition, we show that the boundaries between these domains support a tunable number of counter-propagating valley-polarized modes. I will discuss the rich physics that emerges from the interplay between electronic interactions, symmetry breaking, and topology in this system.

Fermi Surfaces of Composite Fermions

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The quantum Hall state of two-dimensional electrons subject to a strong perpendicular magnetic field at half filling of the lowest Landau level is unique in several aspects. It is gapless, unlike most fractional states which are gapped. It has a Fermi surface, even though kinetic energy is quenched, and the many-body state is the result of purely potential energy terms in the Hamiltonian. In addition, the Fermi surface is that of composite fermions, electrons bound to a pair of vortices, and is characterized\textsuperscript{1} by a Berry phase, unlike Fermi surfaces in conventional non-topological materials.

This talk discusses a different property of the composite fermion Fermi surface - namely, its response to terms in the Hamiltonian that break rotational symmetry. Using the numerical infinite-Density Matrix Renormalization Group method, we study\textsuperscript{2} this quantitatively for Hamiltonians with discrete n-fold rotational symmetry present in real solids. For mass anisotropy (n = 2), we find that the composite Fermi surface responds in a non-trivial way which is in quantitative agreement with experiment with no adjustable parameters. However, the composite Fermi surface is much less responsive for higher n, in sharp contrast to Fermi surfaces of ordinary metals which come in a variety of shapes and topologies. This demonstrates another significant difference between Fermi surfaces due to kinetic energy, and those arising from pure potential energy.

Vortices/Turbulence

Hydrodynamics and Turbulence in Quantum Fluids

M. Tsubota

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Hydrodynamics and turbulence in quantum fluids\(^1\) have been long studied in superfluid helium since 1950's and recently in atomic Bose-Einstein condensates (BECs) too. In this presentation, I would review and discuss the recent developments in this field. The first topic is hydrodynamics of superfluid \(^3\)He. This system is well described by the two-fluid model. The important developments occur lately in (i) thermal counterflow and (ii) localized turbulence. The recent experiments of visualization in thermal counterflow have revealed new physics. The Tallahassee group used \(\text{He}_2\) molecular tracers and succeeded in visualizing the non-trivial profile of the normal fluid flow.\(^2\) Almost all previous simulations of the vortex filament model fixed the normal fluid flow and followed only the dynamics of quantized vortices. However, the fully coupled dynamics of the normal fluid component and quantized vortices is studied to obtain the results qualitatively similar to the observations.\(^3\) The research motivation of localized turbulence comes from some engineering aspects, and the pioneering simulations appear.\(^4,5\) The second topic is turbulence in atomic BECs. The Cambridge group succeeded in observing the cascade flux in a turbulent BEC trapped in a box potential by making the best use of the characteristics of the system and confirmed the scenario by the simulation of the Gross-Pitaevskii model.\(^6,7\)


Evolution of large-scale flow from turbulence in a two-dimensional superfluid

Kristian Helmerson

Monash University

In two-dimensional turbulent flow the seemingly random swirling motion of a fluid can evolve towards persistent large-scale vortices. To explain such behavior, Lars Onsager proposed a statistical hydrodynamic model based on quantized vortices [1], in which the persistent large-scale vortices correspond to negative temperature states. We have confirmed Onsager’s model in an experiment on a superfluid gas of atoms [2]. By dragging grid barriers, formed by an array of laser beams, through an oblate atomic gas Bose-Einstein condensate we generate non-equilibrium distributions of vortices. We subsequently use velocity-selective Bragg scattering and absorption imaging to identify the sign of the circulation and location of the vortices in order to determine the vortex distributions and resultant flow fields. We observe, in the subsequent evolution of the superfluid, signatures of an inverse energy cascade driven by the evaporative heating of vortices, leading to steady-state configurations of clustered vortices characterized by negative absolute temperatures. Our results open a pathway for quantitative studies of emergent structures in interacting quantum systems driven out of equilibrium.

Damping of a Micro-electromechanical Resonator in the Presence of Quantum Turbulence Generated by a Quartz Tuning Fork

C. S. Barquist\textsuperscript{a}, W. G. Jiang\textsuperscript{a}, K. Gunther\textsuperscript{a}, Y. Lee\textsuperscript{a}, and H. B. Chan\textsuperscript{b}

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A micro-electromechanical resonator, consisting of a $125 \times 125 \mu m^2$ center plate suspended $2 \mu m$ above a substrate, was immersed in $^4$He along with a quartz tuning fork. The tuning fork was placed $\sim 5$ mm above the resonator and was used to generate turbulence. The damping of the resonator was investigated in the presence of turbulence generated by the tuning fork. We present data for resonator velocities up to $230$ mm s$^{-1}$ for several different tuning fork velocities. We observe a critical velocity, $v_c \approx 8$ mm s$^{-1}$, above which the damping on the resonator is drastically reduced. We attribute this change in damping to the shedding and capture of vortices.

This work is supported by the National Science Foundation through DMR-1708818.

Universal Scaling Laws of Vortex Reconnections

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Vortex reconnections are fundamental events in fluid motion, randomizing the velocity field, changing the topology and redistributing energy across length scales. In superfluid helium and atomic Bose-Einstein condensates, vortices are effectively one-dimensional lines called quantum vortices (akin to mini-tornadoes of a fixed strength). Individual reconnections happen when two vortices collide and subsequently recoil, exchanging heads and tails. Recent experimental progress opens the possibility of answering the important question as to whether reconnections obey a universal behaviour. Here we show\textsuperscript{1} that the intervortex distance between reconnecting vortices obeys two fundamental scaling laws, which we identify in experimental data and numerical simulations across homogeneous superfluids and trapped condensates.

Electrons on/in Helium II
Stability of bubbles containing few to many electrons in liquid helium
A. Ghosh\textsuperscript{a}, N. Yadav\textsuperscript{b}, E. Joseph\textsuperscript{a}, V. Vadakkumbatt\textsuperscript{b}, and Y. Huang\textsuperscript{a}

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Multielectron bubbles (MEBs) are cavities in liquid helium containing many electrons, which provide a promising platform to study interacting system of electrons on a curved surface, across a wide range of electron densities. In the first part of the talk, we discuss experiments to investigate the stability of MEBs at temperatures close to the lambda point, and when the bubbles are held against a conducting substrate. In the second part, we discuss the possibility of creation of few electron bubbles (FEBs), corresponding to MEBs containing less than 20 electrons.

Energy eigenstates of electrons on helium in tilted magnetic fields
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The Jaynes-Cummings model (JCM) describes interaction between a two-level atom and quantum harmonic oscillator of an electromagnetic cavity mode. It is one of the fundamental models used in the Cavity Electrodynamics (CQED). Recently it was demonstrated that JCM can be realized using the orbital states of electrons on liquid helium in a tilted magnetic field.\textsuperscript{1} In this case, the surface-bound (Rydberg) states of an electron are coupled to the Landau levels of the electron cyclotron motion by the in-plane magnetic field. We make predictions regarding the energy spectrum of electrons in tilted magnetic fields and show that this system exhibits a number of interesting phenomena known in CQED, such as the mixing of eigenstates and sideband transitions, the light shifts and avoided crossings of energy levels, etc. These predictions are confirmed in our experiments where electrons are studied by the Stark spectroscopy method. The strong non-linearity introduced to the coupled orbital motion of an electron by the Rydberg states can be used to setup CQED-type of experiments with electrons strongly coupled to a single-mode optical cavity.\textsuperscript{2}

Investigation of the Quantum Measurement Process Using Electrons in Superfluid Helium

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We report on experiments to study the quantum measurement process. Electrons are incident onto the free surface of liquid helium. If the electron energy is a small amount above the minimum energy $V_0$ needed to enter the liquid, the wave function is only partially transmitted into the liquid. We investigate the possibility that this partial transmission results in the formation of electron bubbles which contain only a fraction of the complete electron wave function. By measuring the mobility of these bubbles we can estimate their size, and this size distribution is found to be consistent with theoretical expectations. The experiment shows that the interaction of the electron with the liquid helium does not result in a measurement that quickly determines that an electron is in the bubble or is not in the bubble. Thus it appears that it is possible to trap a part of the wave function of an electron and maintain it in this state. We find that these electron bubbles have a lifetime of at least several tens of milliseconds.
Monday, August 12th
Quantum Gases II

Synthetic gauge fields with ultracold atoms in periodically-driven lattices
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Topological phases of matter exhibit unique electronic properties. An important experimental technique for generating topological band structures with ultracold atoms in optical lattices is Floquet engineering. It relies on periodic modulation of the system's parameters to emulate the properties of a non-trivial static system. This method facilitated the direct observation of bulk topological properties and chiral currents in optical ladders with synthetic gauge fields. Floquet techniques have further been proposed to engineer density-dependent gauge fields or even complete gauge theories, which require an interaction between matter and gauge fields. Inspired by these ideas, we have developed and implemented a minimal model of a Z2 lattice gauge theory coupled to matter. The rich properties of Floquet systems can further go well beyond those of their static counterparts. The quasienergy spectrum can exhibit a non-trivial winding number, which leads to the appearance of anomalous chiral edge modes. For instance, an anomalous Floquet topological insulator has topologically trivial bulk bands and topologically protected chiral edge modes. Cold atoms offer the possibility to reveal these intriguing phases through direct measurements of the bulk and edge-state properties.


Universal sound diffusion in a homogeneous strongly interacting Fermi gas
Martin Zwierlein
Massachusetts Institute of Technology

Transport is the defining property of states of matter, but often the most difficult to understand. Strongly interacting Fermi gases are especially challenging, despite their ubiquitous presence across many fields of physics. Experiments on ultracold fermionic atoms allow the direct measurement of transport properties in ideal model systems where the hamiltonian is precisely known while transport properties are difficult to calculate theoretically. In this talk I will present transport measurements on two strongly interacting Fermi systems, the unitary Fermi gas and the Fermi-Hubbard gas, both realized in uniform box potentials. In the unitary gas, we excite first and, for the superfluid, also second sound waves and demonstrate a quantum limited sound diffusivity given by Planck's constant divided by the particle mass. Second sound waves are directly imaged via local thermometry, making use of the temperature dependence of radiofrequency spectroscopy. For the Fermi-Hubbard gas, we measure spin diffusion and spin conductivity in the Mott insulator at half filling. For strong interactions, spin diffusion is driven by super-exchange and doublon-hole-assisted tunneling, and strongly violates the quantum limit of charge diffusion. This work sheds light on the complex interplay between spin and charge transport in the Hubbard model. Our experiments provide benchmarks for the highly challenging theoretical calculations of these transport coefficients.
Observation of quantum-limited spin transport in strongly interacting Fermi gases

Joseph Thywissen
University of Toronto

How does magnetization relax in strongly interacting Fermi gases? Diffusive spin transport in liquid Helium 3 has been studied with NMR pulse sequences for over half a century. We report on similar investigations of ultracold Potassium 40 Fermi gases, in which the interaction strength between fermions can be tuned, using a Feshbach resonance. We discuss the observation of the “classic” Leggett-Rice effect, as well as a new phenomenon – the saturation of spin diffusivity in a unitary Fermi gas. Bounded transport is found both in three-dimensional and quasi-two-dimensional systems. Our observations support the broad conjecture that in systems with strong scattering, the local relaxation rate is bounded.

Supersolidity in a quantum gas with cavity-mediated interactions

Tobias Donner
Institute for Quantum Electronics, ETH Zurich

Merging quantum gases with cavity QED allows to engineer long-range interactions between the atoms. If these interactions are sufficiently strong, a phase transition to a self-organized crystalline structure of superfluid matter and light can take place, breaking a discrete $Z(2)$-symmetry. Making use of two crossing cavity modes allows us to design a system that instead breaks a continuous $U(1)$-symmetry, thus providing the basic ingredients of a supersolid. Exploiting the dissipative character of the cavities, we monitor the excitations of this system in real-time and identify the characteristic amplitude and phase modes. In a different set of experiments, we demonstrate how the dissipation can be made dominant over the coherent coupling which drives the system in a chiral instability.
**Low Temperature Techniques and Devices**

**Implementing the new kelvin**

A. Casey\textsuperscript{a}, J Engert\textsuperscript{b}, A Kirste\textsuperscript{b}, J Pekola\textsuperscript{c}, L Levitin\textsuperscript{a}, and J Saunders\textsuperscript{a}

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In May 2019 the International Committee for Weights and Measures redefined all the SI units in terms of fixed values of fundamental constants (for the kelvin this is the Boltzmann constant) to make a logical and coherent system of units. The redefinition was supported by research into new thermometers to facilitate a successful transition to the new system. Through the European Metrology Programme for Innovation and Research three novel primary thermometry methods were investigated to provide independent confirmation of established thermodynamic temperature values in the range 0.9 mK to 1 K. Descriptions of their principles of operation and uncertainty data sets have been included in the *Mise en Pratique*, the guide to a “practical realisation” of the kelvin. The thermometers reported on here are the Current Sensing Noise Thermometer\textsuperscript{1} (CSNT), the Primary Magnetic Field Fluctuation Thermometer\textsuperscript{2} (pMFFT) and the Coulomb Blockade Thermometer\textsuperscript{3}. Comparison with the $^3$He melting pressure based PLTS-2000 down to the solid Néel transition have been made for the CSNT and pMFFT.


**Advances in Current Noise Thermometry for Ultralow Temperatures**

C. Ständer, A. Fleischmann, S. Kempf, and C. Enss

Kirchhoff Institute for Physics, Heidelberg University, Germany

The options for primary thermometry at ultra-low temperatures are rather limited. In practice, most laboratories are using $^{195}$Pt NMR thermometers in the microkelvin range. In recent years, current sensing dc-SQUIDs have enabled the use of noise thermometry in this temperature range. Such devices have also demonstrated the potential for primary thermometry. One major advantage of noise thermometry is the fact that no driving current is needed to operate the device and thus the heat dissipation within the thermometer can be reduced to a minimum. Here we will discuss recent advances of current noise thermometry based on cross-correlated readout with dc-SQUIDs. We will show that easy-to-use and reliable noise thermometers can be realized with this technique that reach a statistical uncertainty of below 0.5% within 10 s and can be used in a wide temperature range spanning from 4 K to well below 100 µK.
Solving the puzzle of second-sound triangulation for hot-spot detection in superfluid helium-4

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Modern particle accelerators utilize superconducting radio frequency (SRF) cavities, cooled by He II, to accelerate particles. The maximum accelerating field is limited by cavity quenching caused by Joule heating from tiny surface defects. Locating these quench spots and subsequently removing the defects can improve the accelerator performance. A widely adopted method at accelerator labs is based on triangulation of second-sound waves in He II emitted from the quench spots. However, a mystery has been observed for decades that in order for the triangulation to converge, a second-sound speed higher than literature values is required. Here we report an innovative flow-visualization based technology for quench-spot detection. In our proof-of-concept experiment, a miniature heater mounted on a plate was pulsed on to simulate a surface quench spot. A He\textsubscript{2}\textsuperscript{m} molecular tracer line created nearby the heater deforms due to the heat flow in He II. By analyzing the tracer-line deformation, we can reproduce the heater location within a few hundred microns, which significantly advances the state-of-the-art of cavity diagnostics. Our analysis also reveals that a large fraction of the input heat energy is consumed in the formation of a cavitation zone near the heater. By analyzing the size of this cavitation zone, we propose a model that can quantitatively explain the fast second sound observed in the triangulation experiments.


Non-local thermoelectric current in a graphene Cooper pair splitter

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Splitting a Cooper pair out of a s-wave superconductor (SC) provides a natural source for two entangled electrons which can be utilized in quantum information processing. As the Cooper pairs reside at the Fermi level, energy-conserving filtering based on non-superconductive quantum dots (QD) having tuneable energy levels, for example, can be employed to single out the two emerging electrons. Besides voltage bias, the Cooper pair splitting can be driven by a thermal gradient across the QD-SC-QD systems because the occupation numbers in the quantum dots are influenced by temperature. The splitting by a thermal gradient leads to a non-local Seebeck effect, which we demonstrate in this work experimentally for the first time. In addition to the QD-SC-QD splitter carved out of monolayer graphene, our experimental sample includes a galvanically separated graphene heater and superconducting graphene junctions for thermometry. By using AC heating, we measure the double-frequency thermoelectric current, which grows linearly with the measured temperature. We observe non-local thermoelectric effects when the energy level of the two quantum dots vary around the Fermi energy of the superconductor. Our observed non-local thermoelectric currents agree well with the theoretical results calculated for two quantum dots with wide resonances.
Theory

Phase crystallisation near surfaces of unconventional superconductors

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Superconducting order owes its properties to broken symmetry of the $U(1)$ phase. Pairbreaking surfaces of unconventional superconductors and superfluids can host zero-energy bound states with large spectral weight. We show that presence of these states lead to an inherent instability in the phase of the order parameter. At this instability, with $T^\ast \sim 0.2T_c$, uniform $U(1)$ phase acquires periodic spatial modulation. Such ‘phase crystal’ appears through a second-order phase transition from a suppressed, but otherwise trivial, superconducting state. The most favorable phase distortion happens at a finite wave vector, spontaneously breaking continuous translational symmetry along the surface. Periodic phase leads to appearance of periodic superflow patterns, and circulating loop-currents. We trace the origin of the new superconducting state to the specific properties of the non-local superfluid density tensor that exist near the surface. I will describe the conditions under which this transition occurs, its geometrical properties, and connect it to other pattern-forming instabilities in many systems described by Ginzburg-Landau models.


Experimental and Theoretical Progress on the Road to One Dimensional Superfluids

A. Del Maestro

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In one spatial dimension, enhanced thermal and quantum fluctuations should preclude the existence of any long range ordered superfluid phase of matter. Instead, the quantum liquid should be described at low energies by an emergent hydrodynamic framework known as Tomonaga-Luttinger liquid theory. In this talk I will present details on some orthogonal but complimentary experimental searches for this behavior in helium-4 including: (1) pressure driven superflow through nanopores, and (2) the excitation spectrum of a confined superfluid inside nano-engineered porous silica-based structures. For flow experiments, we have devised a framework able to quantitatively describe dissipation at the nanoscale leading to predictions for the critical velocity borne out by measurements made in the Gervais and Taborek Groups. In confined porous media, with radii reduced via pre-plating with rare gases, I will discuss ab initio simulations of phase and density correlations inside the pore that are in agreement with recent neutron scattering measurements by the Sokol group. Taken together, these results indicate significant progress towards the experimental observation of a truly one-dimensional quantum liquid.

This work was supported by the NSF through grants DMR-1809027 and DMR-1808440. Some computations were performed on the Vermont Advanced Computing Core supported in part by NSF award No. OAC-1827314.
Surface Roughness Effects on Transport of $^3$He in a Slab

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Heat and momentum transport are discussed for a mesoscopic film of 3He, confined by rough walls in the normal Fermi liquid state. Inelastic binary quasiparticle scattering mediated by elastic scattering from the surface roughness gives rise to a coherent "mixed" scattering channel that drives anomalous transport over a range of temperature. The thermal conductivity and viscosity of the film can be calculated in this regime and derived in terms of the film thickness and autocorrelation function of the surface roughness, which enters the formulation as an independent input. This calculation can be useful in understanding and isolating the effects of confinement and surface roughness.

Combined effects of pairing fluctuations and a pseudogap in the cuprate diamagnetic susceptibility and Hall coefficient

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A strong piece of evidence for preformed-pair physics in the cuprates is the experimentally observed large value for the diamagnetic susceptibility, particularly in the underdoped regime where a pseudogap is also evident. This talk will present a calculation of the diamagnetic susceptibility for a fluctuation theory that includes the presence of a normal-state pseudogap. Semiquantitative agreement with the measured diamagnetic susceptibility onset temperatures is found over the entire range of hole dopings. The Hall conductivity is also of paramount importance, because its sign and magnitude directly reflect the sign of the charge carriers and the size of particle-hole asymmetry effects. An important feature of this work is that there is no sign change in the Hall coefficient above the transition temperature; rather, the temperature dependence of the Hall coefficient is due to an interplay between fermionic quasiparticles and Cooper-pair fluctuations.

Tuesday, August 13th
Superfluid $^3$He

Symmetry breaking and novel features of vortex structure and dynamics in confined superfluid $^3$He

Department of Applied Physics, Aalto University, Finland

In superfluid $^3$He confined between long nm-diameter strands, we have studied formation and fate of half-quantum vortices (HQVs) – linear topological defects carrying half quantum of circulation. We apply a sequence of the symmetry-breaking phase transitions from the normal to the polar phase (2nd order) and further to the polar-distorted B (PdB) phase either directly (2nd order) or via the polar-distorted A phase (1st order).1 HQVs form at the first transition and survive all further transitions despite the fact that in the PdB phase they lose topological protection. This is the first experimental demonstration of the cosmological scenario by Kibble, Lazarides, and Shafi, where non-topological domain wall appears between two HQVs in the PdB phase. Those KLS walls are identified based on their NMR signature, which shows striking differences for the walls produced in the 1st- and 2nd-order phase transitions.

HQVs in our experiment are formed by rotation or by the Kibble-Zurek mechanism (KZM). A possibility to suppress the KZM by a symmetry-breaking bias field and to restore the adiabatic dynamics attracted theoretical attention recently,2 in particular in the context of “shortcut to adiabaticity” in manipulation of quantum states. Since HQVs combine orbital and magnetic parts, we can provide an appropriate bias using either the spin-orbit interaction or magnetic field. In both cases we have observed the KZM suppression for the first time.3 The effect appears above the bias threshold determined by matching the characteristic length scale of the symmetry-breaking field to the Kibble-Zurek length.


The Effect of Magnetic Scattering on Superfluid $^3$He in Aerogel

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High porosity aerogel has proven to be a useful system for studying the effects of impurity scattering on the phase diagram of superfluid $^3$He. This scattering from the aerogel strands can be modified by replacing the magnetic solid $^3$He on the surface with nonmagnetic $^4$He. In recent experiments in highly anisotropic “nematic” aerogels, it was found that the presence of the magnetic solid had a large effect on the superfluid phase diagram.1 We have investigated this effect in a less anisotropic silica aerogel which has been compressed by $\sim 20\%$. In this system, we also find that the superfluid phases are affected by magnetic scattering. In particular, when the magnetic solid is removed from the system, the A-phase becomes stable over a larger region, and its order parameter is less suppressed when compared to the pure superfluid. This work is supported by the National Science Foundation, DMR-1602542.

1. V.V. Dmitriev et al. PRL, 120, 075301 (2018).
Superfluid $^3$He in squeezed nematic aerogel

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We present NMR experiments in superfluid $^3$He in two samples of nematic aerogel consisting of nearly parallel mullite strands. The samples were cut from the same piece of the aerogel, but one of them was squeezed by 30% in the direction transverse to the strands. In the absence of a paramagnetic solid $^3$He on aerogel strands, the superfluid transition of $^3$He in both samples occurred into the polar phase, where no qualitative difference between NMR properties of $^3$He in these samples was found. The difference, however, has appeared on further cooling, that is, after the transition to the polar-distorted A phase (PdA phase) with the orbital part of order parameter in the 2D Larkin-Imry-Ma (LIM) state. In the squeezed sample the 2D LIM state is anisotropic that results in changes in the NMR, which can be used as an additional marker of the PdA phase and have allowed us to measure the value of the anisotropy. We also have investigated an effect of a tiny amount (from ~0.1 down to 0 atomic layers) of paramagnetic solid $^3$He on aerogel strands on superfluid phase diagrams.

Probing quantum fluids using mechanical oscillators


Department of Physics, Lancaster University, LA1 4YB, United Kingdom

We present studies of quantum fluids, $^3$He and $^4$He, using mechanical oscillators. We have developed a wide range of high quality-factor resonators (torsional oscillator, vibrating wires, quartz tuning forks and nano-electromechanical beams) to probe and to create excitations in both fluids. Our measurements show that nanosized beams are sensitive to the presence of rotons and phonons in superfluid $^4$He and can detect a ‘phonon wind’ emitted by a heater. Nano-sized beams as well as other oscillators emit sound waves in quantum liquids. Our studies using quartz tuning forks show that the acoustic emission in the normal and the superfluid phases of both quantum liquids are similar. This allows us to predict acoustic damping of oscillators in liquid $^3$He after characterising them in more accessible superfluid $^4$He. In superfluid $^3$He, mechanical oscillators are excellent generators and detectors of thermal excitations, quasiparticles. We have built a quasiparticle source and a $5 \times 5$ quasiparticle camera to image a beam of thermal excitations and turbulence generated by an oscillator. Our measurements of quasiparticle transport indicate that quasiparticle scattering on the cell walls is neither specular nor diffuse and perhaps a scenario in-between takes place. We have also studied how the behaviour of submicron vibrating wires in superfluid $^3$He changes with their diameter tending towards the coherence length of superfluid condensate.
Angular momentum in rotating superfluid droplets

A. F. Vilesov

University of Southern California, Los Angeles, USA

In this work, the rotation of isolated prolate sub-micrometer superfluid $^4$He droplets has been studied by diffraction of x-ray pulses from a free electron laser. The analysis of the diffraction patterns gives the morphology of the droplets and of the vortex arrays they host. In capsule-shaped droplets, vortices form a distorted triangular lattice, whereas they are arranged along elliptical contours in ellipsoidal droplets. Observation of vortices enables the determination of the droplet's angular velocity and angular momentum. The angular momentum is shared between vortices and capillary waves, whose combined action results in shapes close to those of classical droplets at the same angular velocity.

Poster Session I Abstracts – Thursday, 8th August

Topological superfluids / quantum Hall fluids

P1.1
How to probe non-trivial topology of a chiral superfluid $^3$He-$A$ with MEMS

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$^a$Department of Physics, KAIST, South Korea
$^b$Korea Research Institute of Standards and Science, South Korea

Pure liquid $^3$He has two superfluid phases in zero magnetic field, $^3$He-$A$ and $^3$He-$B$, both of which are topological phases. Despite being one of the oldest material known to be topological, direct experimental signatures of the non-trivial topology are hard to come by in superfluid $^3$He. Many of the experimental methods available for solid state topological matter, such as transport measurements, ARPES, local microscopy, neutron or x-ray scatterings, etc. are inaccessible to superfluid $^3$He due to lack of charge and extremely low $T_c$. Recent advance in micro- and nano-electromechanical systems (MEMS and NEMS), however, provides means to detect these. In specific, we will describe an experimental method involving a MEMS gyroscope with which the signature of the chiral current of $^3$He-$A$, a superfluid analogue of a quantum Hall system, can be directly measured. The method described in this talk can be applied to chiral topological superconductors as well.


P1.2
De Haas-van Alphen effect in suspended graphene

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De Haas-van Alphen effect (dHvA), the oscillation of magnetization and susceptibility of a material as the intensity of applied external magnetic field is increased, has been widely used in the studies of Fermi surfaces of metals [1]. Both for massive and massless (Dirac) charge carriers in two dimensions, dHvA effect leads to a periodic saw tooth variation of magnetization as a function of inverse magnetic field [2]. In this work, we demonstrate the dHvA effect for massless Dirac fermions for the first time. We utilize a device where a suspended monolayer graphene resonator is coupled to gold beam resonators allowing a gold beam to act as a sensor for the force generated by the magnetization induced by the dHvA effect in the quantum Hall state of graphene. Additionally, graphene also provides the displacement read out mechanism to monitor the periodic dHvA-induced frequency shifts in the gold resonator. Our experimental method can be generalized for dHvA measurements of any conducting 2D material. Using our measured frequency shifts proportional to the dynamical susceptibility part of the magnetic energy, we are also able to determine the thermodynamic energy gap for integer quantum Hall states in suspended graphene. In the fractional quantum Hall regime, the 1/3 state can be investigated in similar fashion.

2. I. A. Luk’yanchuk, Fizika Nizkikh Temperatur 37, 56 (2011).
Electrons in, on, or around helium

P1.3
Blueprint for building a quantum computer using electrons on liquid helium

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Electrons on the surface of liquid helium present an extremely clean two-dimensional electron system which provides a perfect platform to realize quantum bits with [1]. In particular, spin states are expected to have an extremely long coherence time [2]. Here we propose to use the spin state of a single electron on liquid helium as one qubit and make use of the interaction between the Rydberg state and the spin state (spin-Rydberg interaction) to realize read-out, one-qubit gates and two-qubit gates of the qubit states. Although the intrinsic spin-Rydberg interaction is vanishingly small for electrons on helium, we could introduce an artificial one by a local magnetic field gradient which can be created by a ferromagnet under an external magnetic field [3]. The spin-Rydberg interaction makes it possible to realize one-qubit gates using electrically dipole spin resonance [3]. Two-qubit gates for the Rydberg states of the electrons on helium can be realized by the Coulomb interaction between the electrons [1]. Using our new detection method of the excitation of the Rydberg state [4], we should be able to detect that of one single electron. Thanks to the spin-Rydberg interaction, we can transform the two-qubit gates for the Rydberg states into that for the spin states and detection of the excitation of the Rydberg state into the read-out of the spin state.


P1.4
Image charge detection of Rydberg states of the surface electrons on helium

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We propose and experimentally demonstrate a new spectroscopic method, image-charge detection, for the hydrogen-like quantized states (Rydberg states) of many surface electrons on helium [1]. The excitation of the Rydberg states of the electrons induces an image current in the circuit to which the electrons are capacitively coupled. This method was inspired by the dispersive read-out technique used in semiconductor quantum dots [2] and in Penning traps [3]. In contrast to the conventional microwave absorption measurement [4], this method makes it possible to resolve the transitions to high-lying Rydberg states of the surface electrons. Currently, we are working on the measurement of the relaxation time of the Rydberg state using this new detection method. We also show that this method can potentially be used to detect quantum states of a single electron, which paves a way to utilize the quantum states of the surface electrons on liquid helium for quantum computing.

P1.5
Acoustoelectric transport of electrons on helium
K. Nasyedkin, H. Byeon, J. Lane, N.R. Beysengulov, R. Loloee, and J. Pollanen
Michigan State University, East Lansing, MI, USA

We report on the acoustoelectric transport of electrons on helium induced by coupling to piezoelectric surface acoustic waves (SAWs). In our device, the SAWs propagate along the surface of a lithium niobate piezoelectric crystal that is submerged beneath a thin layer of superfluid $^4$He. Electrons are deposited onto the superfluid and float 10 nm above its surface. When SAWs propagate along the lithium niobate substrate, electrons are trapped in the moving electric potential of the SAW and transported across the device at the speed of the piezoooustic wave. Electrodes positioned beneath the lithium niobate capacitively couple to the electrons and are used to detect acoustoelectric transport. We have performed time and frequency domain measurements and analysis to characterize the electric current dragged along by the SAW. To our knowledge, these measurements constitute the first demonstration of acoustoelectric charging pumping of electrons on helium.

This work is supported by the NSF (Grant no. DMR-1708331).

P1.6
Ultrasound Assisted Formation of Multielectron Bubbles in Helium
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Multielectron bubbles (MEBs) provide a unique platform to study interactions and transitions in a two-dimensional electron system, at densities which cannot be accessed using electrons on bulk helium or in semiconductor interfaces. Usually, MEBs are created by applying a large electric field, which sets an electrohydrodynamical instability on the charged helium surface. In the present study, we demonstrate a method to create this instability by employing sound waves and applying a small electric field. We have measured the thresholds for the applied ultrasound and electric fields that are required to create the MEBs.
P1.7
Nanofriction in confined 2D electron system on liquid helium

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The Frenkel-Kontorova (FK) model is one of the most basic models describing the friction between two surfaces. So far, friction phenomena have been studied in various systems, such as cold ions, colloids etc. However, few experiments have been conducted on the system of the electrons floating on the surface of liquid helium. Our goal is to build a simulator of FK model using electrons on liquid helium and investigate in detail the phenomenon of nanofriction.

Surface electrons confined in a microchannel filled with liquid helium are known to form 2D or quasi-1D electron system depending on the confining DC potential. When such a system is driven through the channel and is subjected to a commensurate periodic substrate potential, it is predicted to show the stick-slip motion depending on the strength of the periodic potential. This stick-slip motion corresponds to the Aubry transition predicted by the FK model. In our earlier experiment [1], a first-generation microchannel device was used to detect the stick-slip motion of surface electrons, however the periodicity of substrate potential was much larger than the electron spacing which prevented the detection of the stick-slip motion. Taking this research forward, we are developing the second-generation microchannel device which is scaled down to meet the commensurate condition of the substrate potential period. In addition, a shallow channel will be used to enhance the strength of the periodic potential.


Superfluid optomechanics

P1.8
2D phononic crystals for superfluid optomechanics in the quantum regime

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Engineered macroscopic quantum systems (or quantum machines) offer the prospect to probe the frontier between the quantum and classical world in previously inaccessible regimes of size and mass. In quantum optomechanics, we develop a new class of quantum machines harnessing the coupling of light to mechanical motion. This approach demonstrated that a mechanical mode can be cooled into its quantum ground state, and then act as a resource in quantum experiments. The challenge is to enhance the coherence time of the mechanical mode by minimizing losses. In this work, we confined superfluid 4He into nanoscale cavities to realize superfluid acoustic resonators. Exploiting the unique properties of this acoustic medium, we are building ultra-low loss and highly tunable mechanical elements for quantum optomechanics. By coupling these nanoscale acoustic resonators to high finesse superconducting microwave cavities, we will form innovative optomechanical systems with enhanced optomechanical coupling strengths reaching beyond the current state of the art.
P1.9
Optomechanical studies of a nanobeam coupled to a superconducting microwave cavity

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The low temperature dissipation in glass nanomechanical resonators is dominated by low energy excitations, i.e., atomic scale entities that are modeled as TLSs (tunneling two level systems). These TLSs couple to vibrational modes of nanomechanical resonators (NEMS) made of amorphous materials. Probing the mechanical mode in its ground state can give us insight into the microscopic nature of individual TLS. Following up on the work described in [1], here we present optomechanical measurements of the Brownian motion of a mechanical mode. Our 50 µm long nanostring made of silicon nitride is capacitively coupled to a Nb microwave cavity. The microwave cavity is pumped at its red or blue mechanical sidebands and we measure the noise at the cavity resonance frequency induced by the mechanical motion. We observe damping or anti-damping of the mechanical mode for red or blue detuning of the pump. When applying a probe tone near the cavity resonance in addition to the pump tone we observe optomechanically induced transparency. [1] X. Zhou et al., Brute-force cooling and on-chip thermometry for microwave optomechanics, arXiv:1903.04992v2 (2019).

Other topics and model systems
P1.10
Resonance in a Ti/MoS\textsubscript{2} Josephson Junction

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We fabricated an electric double layer transistor (EDLT) structure with a titanium electrode and a molybdenum disulfide channel, and measured its electric transport properties using a dilution refrigerator. The Josephson junction was formed in the Ti/MoS\textsubscript{2} junction, since the Josephson current was observed below the superconducting transition temperature of Ti. In addition, a plurality of peaks were observed in the differential conductance curve of the junction at a voltage higher than the voltage corresponding to the superconducting gap. In this paper, we discuss the possibility of Fiske resonance as the origin of this peak.
P1.11
Non-linear Optical Response of Topological Materials

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The non-linear optical response of clean undoped materials contains a static intrinsic term – the shift current. We show that in disordered, doped topological materials, when Kramers degeneracy is lifted, a substantial DC current emerges as a resonant excitation to the shifted Fermi surface, which we refer to as anomalous photovoltaic extrinsic excitation (APEXX). It stems from inter-band coherence induced by electric fields and disorder. We evaluate this effect in hexagonally warped topological material Bi\textsubscript{2}Te\textsubscript{3} with an in-plane magnetization. These new results will provide pathway to application in photovoltaics such as wireless networks and energy harvesters.

P1.12
Nonlinear Self-Induced Oscillations in Microwave Optomechanics

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We report on self-sustained oscillations studied on geometrically different mechanical devices embedded in a microwave optomechanical setup. A strong blue-detuned pump signal (at a frequency shifted up from the cavity by the mechanical frequency) triggers the parametric instability. Two different NEMS (Nano-Electro-Mechanical Systems) dynamics are compared: the ones of a doubly-clamped beam\textsuperscript{1} and of a drumhead\textsuperscript{2}. Measurements have been carried out from 1 K down to 10 mK for different applied microwave powers and detunings. The drum device displays much less hysteretic behavior than the beam, and the detected amplitude signal for the former is more than 3 orders of magnitude larger than for the latter. Nonlinearities (of different strengths or nature) in these systems seem to be the key to understand these facts. We analyze the results in the framework of an extended optomechanical theory including Duffing-type and coupling nonlinear terms. Quantitative understanding of this regime should enable its use as a new resource for microwave electronic circuits.

P1.13  
*Vortices formed by the spin component of the Poynting vector for surface phonon-polaritons with material losses*

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Suppose that a planar surface divides a vacuum from a silicon carbide. Consider electromagnetic waves with wavelengths encompassing the Restsrahlen band. Surface phonon-polariton waves can then be established with the main propagations along the interface. If the material losses of the silicon carbide are taken into consideration, the Poynting vector crosses the interface, thus enabling spin-orbit couplings and other loss-induced transfer phenomena. Meanwhile, the Poynting vector is decomposed into its orbital and spin parts. In the presence of material losses, these vectors are two-dimensional on the plane formed by the main longitudinal propagation direction and the depth-wise direction normal to the interface. We will show how the spin-part vector behaves when two waves with opposite longitudinal wavenumbers collide with each other. This situation is akin to the quantum-mechanical case with both creation and annihilation of electromagnetic waves. Hence, the two waves of an identical magnitude are assigned a phase difference. Resultantly, we found remarkable vortex-like streamlines of the spin part in the vicinity of the collision point. In comparison, the orbital part exhibits mostly one-way directional streamlines. In addition, I will show other evidences of the high-frequency spin part in comparison to the low-frequency orbital part.

P1.14  
*Tensor network study of the spin-1/2 XXZ chain*

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We study the spin-1/2 XXZ model in a longitudinal magnetic field using a tensor renormalization method (HOTRG)\(^1\). Build into the tensor representation of the XXZ model is the U(1) symmetry, which is systematically maintained at each renormalization step. This enables rather large tensor representations and is the major technical advance of the present study. From the fixed point tensors we extract the low lying spectrum of the model as well the longitudinal magnetization. With rather moderate numerical effort we achieve a very good accuracy as demonstrated by comparison with Bethe Ansatz calculations. The phase structure of the model can be accurately obtained. We also investigate the phase characteristics directly from the fixed point tensors as proposed in\(^1\). First results for higher spin chains will be discussed.

P1.15
Superconductivity in YbRh$_2$Si$_2$

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$^c$Institute of Physics, Goethe University Frankfurt, Germany

We report electrical transport measurements on the putative heavy fermion superconductor YbRh$_2$Si$_2$ [1]. Five high-quality single-crystal samples were probed with ultra-sensitive SQUID-based techniques down to 0.6 mK. At 10-12 mK, depending on the sample, we observe a sharp transition from normal metal into a state in which the resistance gradually decreases with decreasing temperature, until the persistent currents develop at 2-6 mK. In the intermediate regime there is evidence for strong anisotropy of transport properties, in contrast with nearly isotropic normal state resistivity. To understand the role of strain and disorder in this behaviour we have embarked on studies of microstructures machined with focussed ion beam. Complex phase diagram manifests in magnetic field. The observed signatures of superconductivity beyond the Pauli limit suggest spin-triplet pairing. Below 2 mK we observe re-entrance of the normal state, that we attribute to the influence of electro-nuclear magnetism [1]. Superconductivity develops from the antiferromagnetic state which is in close competition with ferromagnetism [2], making spin fluctuations a strong candidate for the pairing mechanism. The low transition temperatures imply that this rich system is highly-tunable with external parameters such as uniaxial strain.


Low temperature techniques

P1.16
Developing on-chip cooling for new physics and improved nanoelectronics


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The cooling of nanoelectronic systems has traditionally been limited by weak electron-phonon coupling below 10 mK. Breaching this limit to achieve sub millikelvin temperatures would greatly aid research in quantum systems, allowing the improvement of metrology standards, sensors, annealers and the search for new physical phenomena. We discuss that further electronic cooling can be achieved in commercial dilution refrigerators through the demagnetisation of on-chip electroplated metals such as copper and indium. Weak electron-phonon coupling aids this technique by isolating the cooled electrons from the warm host lattice and associated heat-leak. We have demonstrated this in cooling a coulomb blockade thermometer (CBT) which allows for primary electron thermometry throughout the cooling process. Using a copper refrigerant we have achieved 4.5 mK in a commercial dilution refrigerator with a hold time below 5 mK of 1200 s. We have also reached 1.2 mK temperatures with a hold time of 1700 s in a custom wet dilution refrigerator. We are currently seeking to use on-chip electroplated copper and indium to cool other micro and nanoelectronic systems to below millikelvin temperatures.

P1.17 
Opening Microkelvin Regime to Low-Dimensional Electron Systems

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Motivated by the predictions of magnetic and crystalline order in 1D electron chains and of exotic Fractional Quantum Hall states of electrons in 2D we developed a platform for cooling such electron systems in semiconductor heterostructures to ultra-low temperatures. We investigated the thermalisation of 2D electron gas (2DEG) in a GaAs/AlGaAS heterostructure via large AuGeNi Ohmic contacts cooled in a $^3$He immersion cell mounted on a nuclear demagnetisation cryostat. The temperature of the sample was measured with a SQUID-based noise thermometer attached to the 2DEG via another Ohmic contact. Our thermal transport measurements demonstrated a significantly reduced thermal conductance in comparison to the value inferred via the Wiedemann-Franz law from the electrical resistance measured in situ. Coincidently we found the AuGeNi Ohmic contacts to superconduct below 1 K. Attributing the thermal bottleneck to this superconductivity, we constructed a thermal model that relates the temperatures of the noise thermometer and the 2D electrons to the heat flow in the system. After carefully shielding the sample and filtering the electrical connections we measured the ultra-low heat leak of $4 \pm 2 \text{fW}$, and inferred the electron temperature of $1.2 \pm 0.3 \text{mK}$. In the future these techniques shall be extended to gated devices and high magnetic fields. This work establishes a path to experimental studies of fragile ordered states in 1D and 2D electron systems.

P1.18
Modular Acrylonitrile Butadiene Styrene as a Structural Thermal Insulator Material for Cryogenic Applications


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We report measurements of the thermal conductance of a structure made from commercial acrylonitrile butadiene styrene (ABS) modules, better known as LEGO® blocks, in the temperature range from 70 mK to 1.8 K. We have determined a power law for the sample’s effective thermal conductivity $\kappa = (8.7 \pm 0.3) \times 10^{-5} T^{1.75 \pm 0.02} \text{WK}^{-1}\text{m}^{-1}$. In our setup, 400 nW of power can heat an experimental area of 5 cm$^2$ to over 1 K, without any significant change to the base temperature of the dilution refrigerator. We conclude that this ABS-void compound material provides better thermal isolation than well-known bulk insulator materials in the explored temperature range. LEGO blocks represent a cheap and superlative alternative to materials such as Macor or Vespel.

More general ABS plastic structures are readily available and allow for ease of construction of tailored experimental environments that require measurements in wide temperature ranges. Our work also suggests that custom-built modular materials with even better thermal performance could be readily and cheaply made by 3D printing, for which ABS is already a popular base material.
P1.19  
**Properties of the 100 kHz quartz tuning forks in strong magnetic fields and very low temperatures**  
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We present the properties of the standard, commercial 100 kHz quartz tuning forks at very low temperatures and high magnetic fields up to 8 Tesla. We show that the resonance frequency of the tuning forks depends weakly on the strength of magnetic field. This makes the quartz tuning forks a promising low temperature thermometer having the B/T ratio up to 1000. We discuss the physical origin of the observed experimental results.

P1.20  
**Quartz tuning fork as a parametric resonator in strong magnetic field**  
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In general, any resonator can be driven parametrically by a suitable variation of one of its parameters e.g. the resonance frequency \(\omega_0\), the damping \(\gamma\), etc. We present the measurements of parametrically excited quartz tuning forks measured in vacuum at very low temperatures (\(~20\) mK) and magnetic fields up to 2.5 Tesla. We show that in the case of quartz tuning forks exposed to a strong static magnetic fields, the variation of the magnetic field strength is associated with gentle changes of their resonance frequencies. This phenomenon gives opportunity to study and to use the quartz tuning forks as the parametric resonators. Here we present the technique of the parametric excitation of the quartz tuning forks and we discuss the results of the measurements.
A cavity interferometric torsional oscillator for low temperature experiments

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Spin-lattice relaxation is an elusive property of spontaneously ordered magnetic systems. AC mechanical torque studies of magnetic structures implicitly contain information about spin-lattice relaxation, and offer an opportunity to elucidate the question through a new perspective, namely, that of the lattice itself. Motivated by this goal, we are constructing torsional oscillators based on sensitive Fabry-Perot optical interferometric readouts. Our modern interferometric apparatus for variable-temperature mechanical torque detection of spin resonance will be used to continue the pioneering angular momentum pumping experiments of Alzetta and co-workers [1]. Torque sensitivity and noise analysis will be presented and discussed, along with calibration magnetic measurements performed on single-crystalline yttrium iron garnet spheres.


Low temperature piezoelectric properties of LiNbO$_3$, PMN-PT and PZT-5A

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Piezoelectrics are widely used as sensors and displacement actuators in applications like ultrasonics, elastic and plastic deformation, and scanning probe microscopy. They are convenient and sensitive, but their sensitivity and stability are strongly temperature dependent. Even for the most commonly used piezoelectrics, lead zirconium titanate (PZT), lithium niobate (LiNbO$_3$) and lead magnesium niobate-lead titanate (PMN-PT), little information is available at cryogenic temperatures. We have directly measured the shear piezoelectric coefficients $d_{15}$ and the corresponding dielectric constants $K_{11}$ of these three materials, from room temperature to below 0.1 K. In all cases, both $d_{15}$ and $K_{11}$ decreased with temperature, although the total changes were only about 7% for LiNbO$_3$. At room temperature, the coefficients of PZT and PMN-PT are much larger than for LiNbO$_3$, but they decrease more rapidly when cooled. At the lowest temperatures, $d_{15}$ has dropped by factors of 4 and 10 for PZT-5A and PMN-PT, respectively, eliminating most of their room temperature advantages over LiNbO$_3$. We also studied the creep and hysteresis that limit their performance in precise positioning applications. These improve (become smaller) at low temperatures, but PMN-PT exhibits a significant and strongly temperature dependent creep even at temperatures as low as 10 K. Our results provide guidance in selecting materials for piezoelectric sensors and actuators. Although it is seldom used in actuator stacks, lithium niobate is the best choice for many cryogenic applications.

P1.23
An economical system for $^3$He purification

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A system for Helium-3 extraction and purification (SHeEP) is constructed utilizing a chromatographic column filled with activated charcoal to remove $^4$He contamination from $^3$He gas$^1$. In addition, an acoustic cavity is designed to check the impurity level of the sample mixture by measuring the speed of sound$^2,3,4$. It provides an economical alternative to a mass spectrometer. Details of the design, and results of a few test runs will be presented.


P1.24
Elimination of Thermomechanical Noise

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Mechanical motion has emerged as an important resource for quantum information applications due to the ability for phonons to interact with electromagnetic radiation across the spectrum. In particular, it has been proposed that wavelength transducers using mechanical motion to link two electromagnetic modes will allow for the transduction of quantum states between microwave and optical frequencies.

In this poster I demonstrate a step towards the creation of a quantum-level wavelength transducer by eliminating thermomechanical motion from the 2.4 GHz breathing mode of a GaAs optomechanical crystal.$^1$

1. arXiv:1812.09417
P1.25
Performances of a Compact Shielded Superconducting Magnet for Continuous Nuclear Demagnetization Refrigerator

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We have developed and successfully tested a compact shielded superconducting magnet for the nuclear demagnetization refrigerator based on PrNi\textsubscript{5} which can keep temperatures below 1 mK continuously (CNDR).\textsuperscript{1} The solenoid was wound by a 0.14 mm diameter multi-filamentary NbTi wire with copper clad, and is surrounded by a 4 mm thick cylindrical magnetic shield made of high-permeability material, FeCoV, with two FeCoV end caps. On-axis field distributions with and without the shield measured at 4.2 K agreed very well with numerical simulations. It produces $B = 1.38$ T at $I = 6.00$ A. Measured on-axis fringe field is less than 1 mT at positions 36 mm above the shield top with an access hole and calculated off-axis fringe field is less than 0.1 mT at positions 38 mm outside the cylindrical shield surface when $I = 6$ A. A total heat generated by magnetic hysteresis in the SC wire and the shield was measured to be $108 \pm 19$ mJ in vacuum, and this value is consistent with an estimated value ($\approx 100$ mJ) based on the measured magnetic hysteresis curve of a short piece of the NbTi wire. Since CNDR is designed to ramp the field between several tens mT and 1.2 T in 20 min., the magnet will generate an approximately 90 $\mu$W heat. This heat can easily be absorbed by thermally anchoring the magnet to the still of dilution refrigerator, a pre-cooling stage of CNDR.


P1.26
Development of experimental platforms for ultra-low temperature experiments at the NHMFL High B/T Facility\textsuperscript{1}

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The High B/T Facility at the National High Magnetic Field Laboratory (NHMFL) provides access for all qualified users to unique ultra-low temperature, high magnetic field and ultra-quiet environments. The facility operates nuclear demagnetization refrigerators capable of reaching 0.5 mK at 16 T and 0.1 mK at 8 T with high (1-10 nW) cooling power. This enables user experiments in diverse fields including ultrasound studies, FQHE studies in tilted fields, high sensitivity NMR, high sensitivity dielectric measurements, sub-mK susceptibility measurements, novel states (Bose glass, Wigner crystals) and studies of superfluid $^3$He. In order to support these experiments, significant time has been invested in developing experimental techniques and cell designs that can be adapted to suit a wide variety of experimental samples and geometries. Here, I summarize cell designs developed at the High B/T facility and give a brief overview of recent experiments.

1. Work supported by the NSF DMR-164479 and the State of Florida
P1.27
A New Design for a Dry Adiabatic Nuclear Demagnetization Cryostat

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We demonstrate feasibility of a copper adiabatic nuclear demagnetization cryostat set up on a cryogen-free dilution refrigerator. Despite a big heat leak of about 40 nW/mole per during the demagnetization cooling, we were able to reach 400 µK base temperature on the dry nuclear demagnetization refrigerator (DNDR). KAIST DNDR is based on a new design where the demagnetization magnet is installed on the still plate of our dry dilution refrigerator (DDR) taking advantage of the large experimental space of a DDR. The nuclear stage protrudes up towards the still plate instead of hanging down below a DDR. This design allows the magnet to be a permanent part of a DNDR and thus eliminates the process of raising/lowering a magnet and aligning nuclear stage with the magnet for each cool down. This enables a much simpler operation of a DNDR and an eventual turnkey style DNDR.


P1.28
Table Top Dilution Refrigerator

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The pursuit of emerging quantum technologies in many cases requires access to temperatures well below 1 K. Dilution refrigeration is the primary technique for achieving temperatures below 1 K continuously. Most existing dilution refrigerators, however, lack in user-friendliness and must be operated by personnel trained in cryogenics, which hinders the proliferation of sub-1 K technologies outside the laboratory. The need for a cost effective and user-friendly method of reaching low temperatures has motivated us to design and construct a compact and convenient cryogenic-free (pulse tube-based) dilution refrigerator with an ergonomic table top access to the experimental space. The design is adapted primarily from the proposal of K. Uhlig [1].

Many of the challenges of designing such a refrigerator are due to the reverse configuration of the table top style where the experimental cold plate is accessible from the top (the cold plate of the experimental space being thermally anchored to the mixing chamber being above the still). We have completed the initial stages of the design – parts sizing and placement, as well as calculations of the heat budget and approximate cooling power based on performance expectations reported in the literature [2]. A prototype of the proposed dilution refrigerator is in the initial stages of construction.

Quantum fluids

P1.29
Superfluidity of 2D $^4$He clusters encapsulated within graphite layers

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Motivated by an experimental observation of Kr nano structures intercalated into graphite$^1$, we perform path-integral Monte Carlo calculations to study structural and superfluid properties of $^4$He atoms encapsulated between a spherically-deformed uppermost carbon layer and the rest of graphite layers. We first observe the development of a disk-shaped layer of $^4$He atoms adsorbed on the flat carbon layer that form a finite-sized triangular solid when completed. Subsequently, a dome-shaped capping layer of $^4$He atoms is developed along the hemisphere of the deformed carbon layer, resulting in a shell-like structure with an inside void. When additional $^4$He atoms are encapsulated to fill the void, various structural features such as a disk-shaped liquid droplet and a close-packed solid cluster are formed depending on the helium density. A disk-shaped liquid cluster in the void region shows superfluid response at temperatures below 1 K. Furthermore, it is found that superfluid fractions computed as a function of temperature can be fitted well by a modified Kosterlitz-Thouless recursion relation. This leads to an estimation of the vortex core energy and the vortex diameter to be $\sim 2$ Å and $\sim 3$ Å, respectively, which are comparable with the corresponding values reported for a 2D $^4$He film$^2$. From this, we conclude that $^4$He atoms encapsulated by graphite layers can provide a test bed to examine superfluidity of a finite 2D $^4$He cluster.


P1.30
Thermal couplings during the precooling period of an adiabatic melting experiment from 10 mK to 0.5 mK

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The adiabatic melting method is a novel cooling technique that is capable of producing temperatures below 0.1 mK in both pure $^3$He, and saturated $^3$He-$^4$He mixture. In the method, pure solid $^4$He is melted and mixed with liquid $^3$He producing cooling power due to the latent heat of mixing. Our adiabatic melting cell consist of a large main volume and a smaller sinter-filled heat-exchanger volume connected together by a tube. The main volume is monitored by two quartz tuning fork resonators. At the lowest temperatures, their response becomes saturated and to evaluate the temperature of the system then, a computational model must be employed. The modeling requires knowledge of the thermal couplings within the system, and the amounts of liquid pure $^3$He, liquid $^3$He-$^4$He mixture, and pure solid $^4$He present at each stage. Here we focus on the thermal couplings of the system: the Kapitza coupling between the liquid helium in the main cell volume and the plain cell wall, the coupling through the sinter in the sinter volume, and via the $^3$He-filled tube connecting the two volumes. None of those components are well-known apriori at 1 mK temperature range. In particular, the available thermal conductivity data of pure superfluid $^3$He is very limited. Our analysis is based on multiple temperature sweeps from around 10 mK down to about 0.5 mK. Due to the three-phase nature of the adiabatic melting system, we can readily vary the heat capacity of the cell contents by changing the amount of solid $^4$He, which provides unique opportunity for examining such intricate thermal coupling parameters.
P1.31
Probing Quantum Fluids with Nanomechanical Systems: Detecting the “Phonon Wind” at mK Temperatures.


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Nanoscale mechanical resonators are widely utilized to provide high sensitivity force detectors. Here we present our experiments using doubly clamped, nanobeam resonators of extremely high quality factor operating in superfluid $^4$He at mK temperatures. We demonstrate the nanobeams’ sensitivity to the thermal excitations, phonons and rotons, as well as the role of acoustics in the damping at the lowest temperatures. We present the unique ability to drive nanobeams using the momentum transfer of a modulated phonon flux generated by a nearby heater. This so-called “phonon wind” is a thermomechanical effect that until now has never been demonstrated. Our work paves the way towards future low-temperature experiments using nanobeams, such as probing the complex properties of superfluid $^3$He at the lowest temperatures. In this system, the probe size becomes comparable to the quantum coherence length, $\xi$.

P1.32
Universal drag scaling in high-frequency flows of He superfluids

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To describe energy dissipation in quantum turbulence produced by oscillating bodies, it is necessary to develop a comprehensive understanding of linear dissipation mechanisms in its hydrodynamic and ballistic regimes and describe them in a universal fashion via scaling relations. We present such a unified analysis and we find that in the two-fluid regime, for high Stokes number oscillatory flows, the drag forces originating from the normal component exhibit a clearly defined universal scaling behavior with the Donnelly number [1]. We use this powerful approach to illustrate the transition from laminar to turbulent drag regime in various oscillatory flows of He II and we show that instabilities may occur first either in the superfluid (production of quantized vorticity) or in the normal component (classical instability) and we demonstrate their crossover. Building on recent experimental and theoretical advances achieved with various nano-devices (NEMS) in classical gases, we develop a formalism describing the ballistic phonon gas at $T < 0.6$ K, allowing direct comparison between measurements with NEMS devices in superfluids and in classical gases. We show that the ultra-relativistic gas of phonons exhibits the same scaling observed in classical gases and thus verify the recently proposed universality scaling relation for classical high frequency oscillatory flows [2] in superfluids. These scaling relations may be used with advantage in the design of NEMS devices for superfluids.


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P1.33
The Third Sound as a Generator of Non-stationary Thermal EMF

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We predict a new thermoelectric effect which consists in appearance of an electric field in the surrounding space during propagation of third sound in a superfluid films when the sound is excited by temperature difference between the ends of the film [1]. The reason is that the non-stationary heating is accompanied by oscillations of film thickness. This causes oscillations of dipole moment of the film induced by the substrate and, as the result, appearance of oscillating electric field in the nearby space. The potential difference is proportional to the temperature difference between the ends of the film, i.e. a non-stationary thermoelectric effect must take place, that is impossible in normal systems. The magnitude of the effect depends significantly on the substrate type and coating and is practically insensitive of the presence of vortices. The presence of thermally activated vortices leads only to renormalization of third sound speed and their effect on the electric field caused by the third sound wave is weak even in the vicinity of the superfluid transition.

It is shown that the differential thermal EMF (the ratio of electric potential amplitude to the film temperature amplitude), which is a characteristic of thermoelectric properties of a substance, can reach $10^{-4}$ V/K. For pure non-magnetic metals this quantity has the order of $10^{-8}$ V/K. Therefore the differential thermal EMF caused by third sound can be even called giant.


P1.34
Superheat Conductivity and Electrical Activity of Superfluid Systems

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The mechanism of thermopolarization, which is possible in superfluid dielectric systems in the presence of a magnetic field is considered. It is shown that in He-II in a magnetic field $H$, the heat flux under the influence of the temperature gradient $\nabla T$ leads to the appearance of an electric field $E \sim H \times \nabla T$. The effect takes place in superfluid dielectric systems due to the presence of a property called superheat conductivity. The magnitude of the field substantially depends on the shape of the sample with helium and the direction of the magnetic field relative to the sample. It is shown that the effect is realized with both static and nonstationary temperature gradients (with the propagation of a second sound). It can be said that the effect is analogous to the Nernst-Ettinghausen effect in conductors.
Investigation of the Quantum Measurement Process Using Electrons in Superfluid Helium

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We report on experiments to study the quantum measurement process. Electrons are incident onto the free surface of liquid helium. If the electron energy is a small amount above the minimum energy $V_0$ needed to enter the liquid, the wave function is only partially transmitted into the liquid. We investigate the possibility that this partial transmission results in the formation of electron bubbles which contain only a fraction of the complete electron wave function. By measuring the mobility of these bubbles we can estimate their size, and this size distribution is found to be consistent with theoretical expectations. The experiment shows that the interaction of the electron with the liquid helium does not result in a measurement that quickly determines that an electron is in the bubble or is not in the bubble. Thus it appears that it is possible to trap a part of the wave function of an electron and maintain it in this state. We find that these electron bubbles have a lifetime of at least several tens of milliseconds.

Effect of Pressure on the Mobility of Fast Ions in Superfluid Helium-4

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Studies of negatively charged helium ions in superfluid helium-4 have revealed the existence of at least 18 ions, each with a different mobility which is larger than the mobility of the normal electron bubble. In previous work these ions have been generated by producing a plasma discharge in the helium vapor above the surface of the liquid, but this method has the disadvantage that it cannot be used to study the effect of pressure on the ion mobility. In the present work we have used a 300 $\mu$Ci alpha source immersed in the liquid. By applying a suitable field we can collect negative or positive ions that have been produced along the track of the alphas. Only one species of negative ion has been detected; this is the so called "fast ion" first seen by Doake and Gribbon.\(^1\) We have measured the mobility of this ion in the temperature range between 1 and 1.2 K, and as a function of pressure up to 5.5 bars. The mobility varies with pressure because of the variation of the roton energy gap and because there is a decrease in the size of the ion. We compare the mobility change with the mobility change of the normal electron bubble and the positive helium ion.

New Positive Helium Ions in Superfluid Helium-4

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Helium positive ions in superfluid helium have been studied in many experiments. Atkins noted that the strong electric field near the ion polarizes the surrounding atoms, and results in a region of solid helium around the ion. This has become known as the snowball. A value of 0.6 nm for the radius of the snowball has been obtained by measurement of the effective mass of the ion. This is in reasonable agreement with theoretical values. In the present work we have studied the mobility of positive ions and used this to estimate the snowball radius. We have used a 300 µCi alpha source immersed in the liquid or the vapor to generate ions and in this way been able to obtain signal with good signal to noise. We are able to detect several positive ions with different mobilities, and therefore different size. We will discuss the possible origin and structure of these ions.


Post-deadline

Collapse of vapor filled multielectron bubbles held against a surface.

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Multielectron bubbles (MEBs) refer to charged cavities in liquid helium containing a layer of electrons pinned to inner surface of the bubbles. Previous experimental work by our group carried out with MEBs in bulk helium (above lambda point) showed MEBs can contain vapor, which condenses in a time approximately proportional to volume of the bubble, and this observation was further confirmed by numerical simulations. In the present work, we describe experiments where the MEBs are held against a solid substrate but where the rate of collapse was found to be orders of magnitude faster compared to MEBs in bulk. We discuss a numerical model and the associated difficulties to explain this difference.
Observation of Low Threshold Cavitation Events in Liquid Helium.

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Acoustic cavitation is a powerful technique to probe electrons bubbles inside liquid helium. The critical pressure to explode a bubble depends on the number and quantum state of electrons inside the bubble, as well as if the bubble is trapped on a vortex. Here, we report cavitation events that occur at pressure magnitudes approximately 81\% lower compared to single electron bubbles. We have varied the experimental conditions and have tried to eliminate the obvious possibilities, e.g. single electron bubbles trapped on vortex lines or primary electrons depositing energy at the acoustic focus. It is possible that these new species of bubbles are multielectron bubbles with small ($< 20$) number of electrons.
Quantum fluids

P2.1
NEMS in Superfluid $^3$He: No Room at the Bottom?


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One of the characteristic features of a superfluid is its ability to flow with very little dissipation in the zero-temperature limit. Mechanical resonators have traditionally been used to probe dissipative mechanisms in the superfluid experimentally. Some experiments [1,2] have caught glimpses of the fundamental dissipation mechanisms taking place near the coherence length ($80 \text{ nm}$) in superfluid $^3$He, but conclusive understanding is commonly believed to require nano-sized probes.

Here we present ongoing measurements of a nano-electromechanical device (NEMS) with diameter $400 \text{ nm}$ and resonant frequency $5 \text{ kHz}$ in superfluid $^3$He-B. The results are compared to a similar resonator with diameter $900 \text{ nm}$. Remarkably, the resonance widths of these two probes are almost identical in the entire ballistic regime at zero pressure, whereas for larger devices down to $1 \mu\text{m}$ diameter the resonance width of such probes is roughly inversely proportional to diameter. We suggest that this observed relative decrease in damping with decreasing probe size is indicative of approaching the coherence length and, hence, a window into the nanoscale structure of the superfluid.


P2.2
Chasing zero-temperature damping mechanisms at super-Landau velocities


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It is experimentally established that a macroscopic object moving quasi-uniformly in superfluid $^3$He-B can exceed the predicted Landau velocity at the zero-temperature limit without a large increase in damping.\(^1\) That work was carried out using of a large goal-post-shaped ("floppy") superconducting wire immersed in superfluid $^3$He and measuring the thermal response resulting from the damping experienced by the moving wire. No satisfactory theoretical work that explains this observation has been published.

We have devised and recently started using a versatile setup intended to shed light on the damping mechanisms involved. Improvements and changes implemented are threefold: (1) A piece of Nafen aerogel is attached to the floppy wire, allowing us to probe the properties of several superfluid phases with varying Landau velocities. (2) The aerogel is surrounded by a pick-up coil for NMR measurements, also moving with the wire within the bulk superfluid. This allows us to measure the direct response of the phase within the aerogel. (3) We use nano-sized oscillators (NEMS) in measuring the thermal response, intended to provide more sensitivity and higher time resolution than traditional probes, which we believe will allow distinguishing the response from different parts of a ramp between two positions in space.

Here we report preliminary results obtained using these instruments.

**P2.3**  
**Imaging ballistic quasiparticle beams inside a fermionic condensate**

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Superfluidity in $^3$He, the coldest fermionic liquid available, is governed by Cooper pairs formed from weakly interacting quasiparticles. At ultra-low temperatures in $^3$He-B, the ambient thermal quasiparticles are expected to propagate ballistically. We have used a black box radiator (BBR) as a quasiparticle source and a $5 \times 5$ quasiparticle camera to image a beam of thermal excitations emitted by the BBR. To describe the measured profile of a quasiparticle beam we have conducted a series of simulations taking into account the cylindrical geometry of the BBR orifice and its actual thickness. In these simulations we have altered the angular distribution of quasiparticles from a uniformly illuminated disk representing an ideal BBR to a distributed point-source along with the scattering mechanism of quasiparticles on the orifice surface. The simulations show that neither specular nor diffuse scattering models perfectly describe the measured data and perhaps a scenario in-between takes place. Our measurements and simulations show that for our geometry an ideal BBR model with zero thickness orifice is a good compromise, as it is simple to use and describes the measurements well. Our measurements underpin future visualization of topological defects in the superfluid $^3$He.

**P2.4**  
**Suppression of superfluidity by magnetic boundary scattering in confined superfluid $^3$He-A**

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We have studied superfluid $^3$He confined in a single nanofabricated cavity of height $D = 200$ nm, using SQUID NMR. The internal surface of the cavity is that of smooth silicon wafers, coated by a magnetic surface boundary layer of solid $^3$He. The strong confinement stabilises the A phase at all pressures and suppresses the superfluid transition temperature $T_c$. The effective confinement $D/\xi_0$ is adjusted by studying sample at pressures ranging from zero to 5.5 bar, over which the superfluid coherence length $\xi_0$ is reduced from 77 to 40 nm. Remarkably, we find that the measured suppression of $T_c$ significantly exceeds that predicted for a diffusely scattering surface and is shifted towards that expected for a maximally pair-breaking, retro-reflecting, surface. This result extends previous work with a $^4$He surface boundary layer in which surface scattering was varied between diffuse and fully specular, with the elimination of $T_c$ and gap suppression in the latter case. The result can be accounted for by enhanced surface pair breaking caused by magnetic exchange scattering of $^3$He quasiparticles by localised $^3$He atoms bound to the surface. The model requires the surface to be sufficiently smooth so that momentum scattering is at least partially specular. The detected larger $T_c$ suppression implies an excess of zero energy surface-bound states.
P2.5
Spectroscopy of surface Majorana fermions in superfluid $^3$He-B using a mechanical oscillator

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The superfluid $^3$He-B is a prototype of DIII topological superconductors. Helical Majorana fermions residing on the surface are massless fermions protected by the chiral symmetry, and only a particular orientation of a magnetic Zeeman field can generate the mass gap, which is referred to as Majorana Ising spins.\(^1\) Here we show that the surface Majorana fermion of the superfluid $^3$He-B can be detected through the low-temperature damping of a microelectromechanical system (MEMS) device. Using the quasiclassical Keldysh transport theory together with a random $S$-matrix model,\(^2\) we calculate the stress tensor on the surface of a laterally oscillating plate embedded in $^3$He-B. In the diffusive limit the anomalous damping observed by P. Zheng \textit{et al.}\(^3\) is understandable with the momentum transfer through the diffusive scattering of surface bound quasiparticles by surface roughness. We demonstrate that the low-temperature behaviors of the damping rate are sensitive to surface specularity and mass gap induced by magnetic Zeeman fields. The power law of the damping rate in low temperatures may provide spectroscopy for the mass acquisition of surface Majorana fermions and the topological phase transition in the superfluid $^3$He-B.


P2.6
Memory effect and supercooling of the A phase in zero magnetic field

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We experimentally study the metastability of the A phase of superfluid $^3$He, as either temperature ($T$) or pressure ($P$) is varied. In our experiment we find significant supercooling, with the A-B transition occurring well below the temperature of the thermodynamic phase boundary in bulk. The observed transition shadows the thermodynamic A-B line in the $T-P$ plane, but extends below the polycritical point and terminates in the B phase (and not at $T_c$). We find significant path dependence (memory effect) in the metastability: When we sweep pressure at fixed temperature, the region of metastable A is larger than when we sweep temperature at fixed pressure. We find U-shaped depressurizing-cooling-pressurizing paths in the $T-P$ plane which enable the metastable A phase to exist in parameter regimes well below the polycritical point at 21.2 bar that cannot be reached by a temperature sweep. While cooling at constant pressure, we observe A-B transitions down to 20.85 bar. While depressurizing, A-B transitions are seen down to 19.5 bar in a small chamber. Our cell, designed for these and thermal transport studies, consists of two chambers separated by a 1.1 \(\mu\)m tall channel in which the A-phase is stabilized by confinement. When the A-phase is thermodynamically stable in the channel, the observed A-B transition occurs at different temperatures in each chamber, indicative of independent nucleation. Otherwise the transitions occur simultaneously.
P2.7
Corrections to the Higgs Mode Masses in Superfluid $^3$He

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Superfluid $^3$He has a rich spectrum of collective modes with both massive (gapped) and massless (gapless) excitations. The masses of these modes can be precisely measured with acoustic spectroscopy and fit to theoretical models to extract interaction strengths of the underlying superfluid. Prior comparisons between theory and experiment accounted for Fermi-liquid effects, $f$-wave interactions, and the strong-coupling energy gap. However, strong-coupling corrections to the mode mass itself were not included. In this work, we employ a simple procedure to incorporate these corrections\cite{Wiman2018}\cite{Sauls2017} to the mode which improve the determination of the $f$-wave pairing strength, $(1/x_\lambda)$. Results from several independent experiments are brought into better agreement with the improved theoretical model. This work is supported by the National Science Foundation, DMR 1602542.

\begin{thebibliography}{9}
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P2.8
Spin Waves in Superfluid $^3$He Imbibed in Aerogel

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The presence of spin waves in superfluid $^3$He in the B phase has been reported in continuous wave NMR experiments\cite{Osheroff1977}\cite{Smith1977}. The spin waves appear as secondary resonance peaks displaced periodically from the main peak, and are induced by order parameter textures created by the confinement of $^3$He\cite{Osheroff1977}\cite{Smith1977}\cite{Hakonen1989}\cite{JIA2014}.

Similar spin waves have also been observed in both the A and B phases in superfluid $^3$He when imbibed in anisotropic aerogel with negative uniaxial strain\cite{JIA2014}. Pulsed NMR resolves the frequency and the linewidth of these peaks displaying strong dependence on the tipping angle, as well as on the static magnetic field and the temperature. Here we present the results of recent experiments on spin waves in superfluid $^3$He.

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P2.9
Anomalous Behavior of Oscillating Nematic Aerogel in Superfluid $^3$He

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We present experiments on nematic aerogel oscillating in superfluid $^3$He. This aerogel consists of nearly parallel mullite strands and is attached to a vibrating wire (VW) moving along the direction of the strands. The sample has a porosity about 96%, and NMR measurements show that the superfluid transition of $^3$He in this aerogel occurs into the polar phase and the transition temperature ($T_{ca}$) is only slightly suppressed with respect to the superfluid transition temperature of bulk $^3$He.$^1$ In contrast to VW experiments with silica aerogel$^2$ we observe, just below $T_{ca}$, an additional resonance mode which is coupled to conventional (high-temperature) VW resonance. We assume that our results can be explained by generation of the 4th sound wave in the polar phase.

1. V.V. Dmitriev, M.S. Kutuzov, A.A. Soldatov, and A.N. Yudin, This symposium.

P2.10
Study of Vortices in Superfluid $^3$He B Phase in Aerogels

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It is well known that the vortex excitation in the bulk superfluid $^3$He B phase at lower pressures and under rotation has double-cores which can be regarded as a half-quantum vortex (HQV)-pair connected by a planar string [1,2]. Recently, it has been found that a long pair of HQVs stabilized in the polar phase [3,4] at higher temperatures survives through the transitions to the polar-distorted B phase in strongly anisotropic aerogels [3]. Its stability should have a different origin from those known so far which include the repulsive correlation [1] and the disorder [5]. In this work, the double-core vortex in the polar-distorted B phase in strongly anisotropic aerogels is examined theoretically, and it is pointed out that both the strong anisotropy and the Fermi liquid correction are necessary for this vortex to be stabilized as a long pair of HQVs. Vortices in B phase in isotropic aerogels [5] will also be discussed.

P2.11
The Phase Diagram of Rotating Superfluid $^3$He-B

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We present theoretical calculations of the pressure-temperature-field phase diagram for the vortex phases of rotating superfluid $^3$He-B. The low-pressure, low-temperature phase is characterized by an array of singly-quantized vortices that spontaneously break axial rotation symmetry, exhibit anisotropic vortex currents and an axial current anomaly (D-core phase). The high-pressure, high-temperature phase is characterized by vortices with both A-phase and $\beta$-phases in their cores (A-core phase). This high-temperature phase supercools down to a minimum temperature, $T^\ast (p, H)$, below which it is globally unstable to an array of D-core vortices. The theoretical supercooling phase transition line is in good agreement with the experimentally observed phase transitions in rotating $^3$He-B.\textsuperscript{1} The evolution of the phase diagram for rotation-aligned magnetic fields up to 300 G is reported. The A- to D-core phase transition is sensitive to the Zeeman energy, particularly for pressures near the bulk polycritical pressure, and cannot be treated perturbatively for fields above $H \approx 50$ G and $\vec{H}|| \pm \vec{\Omega}$. Our theoretical results are discussed in comparison with earlier calculations reported by E. Thuneberg\textsuperscript{2} and Salomaa and Volovik.\textsuperscript{3} Analysis of the topology of the A-core and D-core vortices suggests the mechanism driving the A- to D-core transition. We propose a new experiment to detect the axial currents of the D-core phase.


P2.12
Nambu-Goldstone modes with tunable effective metric in magnon BEC

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In superfluids, phonons, which are Nambu-Goldstone (NG) bosons related to spontaneously broken U(1) symmetry, propagate in an effective metric created by the superflow velocity. This is used, for example, in proposals to simulate a black-hole horizon in the laboratory. In superfluid $^3$He another collective mode exists, the magnon, which is a quantized spin wave. As bosonic quasiparticles, magnons can undergo Bose-Einstein condensation (BEC). Magnon BEC was recently discovered in the polar phase of $^3$He.\textsuperscript{1} The broken U(1) symmetry of the BEC supports a different kind of phonon, which is a low-frequency oscillation of the magnetization on top of the coherently precessing spins. For this mode the metric can be controlled simply with the profile of the applied magnetic field.\textsuperscript{2} Additionally, the symmetry can be explicitly broken with imposed time-dependent magnetic field, and the NG mode acquires a mass.\textsuperscript{1}

Recently, structure of the metric gained much attention, as it was suggested that the Big Bang itself was a transition in the metric.\textsuperscript{3} One possibility is a transition from the Euclidean to Minkowski signature.\textsuperscript{4} The NG mode of magnon BEC in the polar phase offers the possibility to study precisely such a transition by reorienting the external field. We have measured the propagation velocity and mass of NG bosons with different effective metrics. Within our experimental range, the results agree well with theory. In future we hope to extend the measurements to the metric transition.

P2.13
Two Dimensional Physics in Superfluid Helium-3

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Helium-3 is an unconventional superfluid characterized by p-wave pairing. Many of its unique properties can be traced back to the uniquely rich symmetry group of the liquid phase.

1. The breaking of these symmetries allows for the formation of multiple different superfluid phases, making it among the most complex condensed matter systems. The bulk properties of these phases have been well explored, however 2D geometries open the possibility of new phases which break translational symmetry, as well as gapless Majorana surface states. Until recently experimental investigation of these predictions has been limited due to the technical challenges involved.2,3 Using modern nanofabrication techniques our lab has developed a novel mechanical resonator system for probing the properties of superfluid helium. Our experiments on helium 3 show dramatically non-bulk like behavior which is highly suggestive of new 2D physics.


P2.14
Exotic Phases of Confined Superfluid Helium-3: A Theoretical Study

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We present a theoretical investigation into the stable phases of helium-3 when confined in a slab geometry and compare the results to experiments performed at the University of Alberta. The calculations were performed by numerically solving the Ginzburg-Landau equations with boundary conditions ranging from specular to maximally pairbreaking. Pressure-temperature phase diagrams calculated for slab thicknesses of \( D = 805 \) and 1067 nm show excellent agreement with theory for the well-known A and planar-distorted B phases. However the experiments also show the presence of an unknown phase not captured by current calculations. The thinnest slab of \( D = 636 \) nm shows both significant deviations from theory and a large unknown phase, which provide glimpses of new physics present in ultra-confined geometries. The unknown phase may be a spatially-modulated phase, such as the stripe phase [1] or the polka-dot phase [2].

P2.15
Generation of spin current in normal fluid and superfluid helium-3

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In the field of spintronics, the generation of spin current of electron spins has been investigated extensively. By utilizing the coupling of mechanical rotation and spin angular momentum,\(^1\) we can expect the generation of spin current in various systems without spin-orbital interaction. Indeed, spin current has been generated in a copper film, which has only a weak spin-orbital interaction, by using a surface acoustic wave.\(^2\) The generation of spin current by hydrodynamic flows in liquid-metals, Hg and GaInSn, also has been demonstrated.\(^3\) This spin hydrodynamic generation will be utilized for generating spin current of nuclear spins in the liquid helium-3. A hydrodynamic flow in the liquid helium-3 provides a vorticity gradient which is regarded as a gradient of effective magnetic field. The effective field gradient generates nuclear spin current owing to the Stern–Gerlach effect. We can quantitatively estimate the field gradient at the order of 1 G/cm by the hydrodynamic flow under pressure with 1 Pa/cm gradient at 100 mK. Since the magnitude of the field gradient corresponds to that used in the spin echo experiments,\(^4,5\) the effective field will be observed by NMR measurement. We will also discuss super spin current carried by spin-triplet Cooper pairs in the superfluid helium-3.


Quantum gases

P2.16
Dipole mode of trapped Bose–Fermi mixture gas

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We study collective oscillations in a trapped Bose–Fermi mixture gas, composed of the single species bosons and the single species fermions, in the normal phase. In the extremely low temperature regime, collisions between fermions and bosons are limited by the Pauli-blocking, while collisions between bosons may be enhanced by the Bose-enhancement. These quantum statistical properties may give rise to an interesting temperature dependence of collective modes. In fact, in the case of a spatial uniform system, there exists a long-lived sound mode in the intermediate temperature region \(^1\). In this paper, we study temperature dependence of the dipole oscillations of the trapped Bose–Fermi mixture gas. Applying the moment method to the linearized Boltzmann equation, we study the crossover of the dipole mode between hydrodynamic and collisionless regimes. We also obtain analytic results in the two limiting regimes.

P2.17
Artificial Gauge-Fields in Bose-Einstein Condensates

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Using the popular Raman laser dressing technique, we modify the dispersion of a Bose-Einstein condensate (BEC) of rubidium-87 atoms. The resulting atomic Hamiltonian is analogous to that of charged particles subjected to gauge potentials. Atoms can also be prepared in two different spin states, each of which may see a different set of gauge fields. Tuning system parameters allows us to simulate the effects of various time-dependent artificial gauge fields. In one part, we study the effects of an oscillating synthetic electric field on a BEC. In the second part we look at a strong synthetic magnetic field which produces vortices in each spin component of a spinor-BEC. The results from numerical simulations and progress towards an experimental implementation are both discussed. This work is expected to further expand the quantum simulation toolbox, leading to new venues in quantum simulation.

P2.18
Strong-coupling Effects on Quantum Transport of an Ultracold Fermi Gas

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We theoretically investigate quantum conductance $\sigma$ in the normal state of an ultracold Fermi gas in the BCS-BEC crossover region. The observation of this transport coefficient has recently become possible in cold atomic gas physics, by virtue of the realization of a two-terminal setup. In this paper, we include a tunable pairing interaction associated with a Feshbach resonance and resulting pairing fluctuations, within the framework of a strong-coupling $T$-matrix approximation. We then evaluate the tunneling current through a junction between two Fermi gases, by using the Keldysh Green’s function technique. While pairing fluctuations suppress the contribution of Fermi quasi-particles to the conductance, they are found to remarkably enhance $\sigma$ near the superfluid phase transition temperature $T_c$ in the BCS-BEC crossover region. In the strong-coupling BEC regime, however, the latter contribution is also suppressed. The calculated conductance agrees well with the recent experiment on a $^6$Li Fermi gas, as well as the theoretical result in the Gaussian fluctuation theory near $T_c$. Since transport properties have recently attracted much attention in ultracold Fermi gas physics, our results would be useful for the understanding of strong-coupling corrections to quantum transport phenomena.

P2.19
Quantum thermal equilibrium and heat transfer in Bose-Einstein condensates

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We present a quantum analogue of thermalization in a binary mixture consisting of Bose-Einstein condensates (BECs). In our previous studies\textsuperscript{1,2}, we found random potential will turn the ordered kinetic energy into a disordered one. A procedure analogous to kinetic energy dissipation into heat by friction in classical thermodynamics. This disordered kinetic energy features the temperature, and Boltzmann entropy can be defined accordingly. We extend this study to a two-component BEC. We let each component settle at different equilibrium temperatures. Then we turned on the interaction between these two components and turn off the random potential, and they eventually reach new thermal equilibrium with the final temperature being the average of individual temperatures earlier. During this heat exchange process, heat flows from the hot BEC to the cold one, and we observed the thermal expansion of cold BEC, accompanied by the shrinkage of hot BEC. The entropy of the cold BEC increases and the entropy of the hot one decreases, but the total entropy increases that satisfies the second law of thermodynamics.


P2.20
Strong-Coupling Theory for a Non-equilibrium Unitary Fermi gas

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We theoretically investigate non-equilibrium properties of a unitary Fermi gas coupled with two baths with different values of chemical potential. For this purpose, we extend a $T$-matrix approximation (TMA), which has extensively been used for the study of BCS-BEC crossover physics in the equilibrium case, to the nonequilibrium steady state, by employing the Keldysh Green’s function technique. Using this non-equilibrium strong-coupling theory, we clarify how the superfluid phase transition temperature $T_c$ is suppressed, when the system becomes out of equilibrium. In the normal state near $T_c$, we also examine non-equilibrium effects on the so-called pseudogap phenomenon associated with strong-pairing fluctuations discussed in an equilibrium Fermi gas in the unitary regime\textsuperscript{3}. Recently, a non-equilibrium ultracold Fermi gas with tunable dissipation has been realized\textsuperscript{2}. In addition, the strongly-correlated non-equilibrium steady state discussed in our work is deeply related to exciton-polariton condensates\textsuperscript{3}. Thus, our results would contribute to the further development of many-body physics extended to the non-equilibrium case.

P2.21
A Renormalization-Group Study of Interacting Bose-Einstein condensates: Absence of Bogoliubov Mode below Four \( (T > 0) \) and Three \( (T = 0) \) Dimensions

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I derive exact renormalization-group equations for the \( n \)-point vertices \( (n=0,1,2,\cdots) \) of interacting single-component Bose–Einstein condensates based on the vertex expansion of the effective action.\(^1\) They have a desirable feature of automatically satisfying Goldstone’s theorem I, which yields the Hugenholtz-Pines relation \( \Sigma(0) - \mu = \Delta(0) \) as the lowest-order identity. Using them, it is found that the anomalous self-energy \( \Delta(0) \) vanishes below \( d_c = 4 \) \( (d_c = 3) \) dimensions at finite temperatures (zero temperature), contrary to the Bogoliubov theory predicting a finite “sound-wave” velocity \( v_s \propto [\Delta(0)]^{1/2} > 0 \). In other words, Bose-Einstein condensates are free from interactions at the excitation threshold. It is also shown that the one-particle density matrix \( \rho(\mathbf{r}) \equiv \langle \hat{\psi}^\dagger(\mathbf{r}_1)\hat{\psi}(\mathbf{r}_1 + \mathbf{r}) \rangle \) for \( d < d_c \) dimensions approaches the off-diagonal-long-range-order value \( N_0/V \) asymptotically as \( r^{-\frac{d+2}{2}} \eta \) with an anomalous dimension \( \eta > 0 \). The additional exponent \( \eta \) at finite temperatures is predicted to behave for \( d = 4 - \epsilon \) dimensions \( (0 < \epsilon \ll 1) \) as \( \eta = 0.181\epsilon^2 \). Thus, the interacting Bose–Einstein condensates are subject to long-range fluctuations similar to those at the second-order transition point, and their excitations in the one-particle channel are distinct from the Nambu-Goldstone mode with a sound-wave dispersion in the two-particle channel.


P2.22
Thermodynamic Stability and Effects of Bose-Bose Repulsion in an Ultracold Bose-Fermi Mixture with Strong Hetero-Pairing Fluctuations

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We theoretically discuss the thermodynamic stability of a normal-state Bose-Fermi mixture with a heteronuclear Feshbach resonance. Including a tunable inter-species pairing interaction associated with the Feshbach resonance within the framework of an improved \( T \)-matrix approximation\(^1\), we evaluate the compressibility-matrix, to assess the instability of the system against an induced attractive Bose-Bose interaction mediated by Fermi atoms. Using this result, we also clarify how the mechanical collapse of a Bose-Fermi mixture associated with this instability can be avoided by a direct Bose-Bose repulsive interaction. In the presence of this competing phenomenon between the induced Bose-Bose attractive interaction and the direct repulsive one, we determine the superfluid phase transition temperature, as a function of the Bose-Fermi pairing interaction strength. Since the thermodynamic stability is crucial for the experimental realization of a resonant Bose-Fermi mixture, our results would contribute to the research for many-body properties of this system.

Towards a broadband photonic quantum memory in Bose-Einstein condensate

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Atomic quantum memories for photons are building blocks for quantum information technologies. Efficient and long-lived storage in combination with high-speed (broadband) operation are key features for practical applications. Despite enormous progress, the development of a practical quantum memory has been a great challenge due to limitations arising from most popular atomic platforms and/or light-matter interaction protocols. Implementation of the recently proposed Autler-Townes splitting (ATS) protocol in Bose-Einstein condensate (BEC) is a promising approach towards overcoming these limitations. While the ATS protocol offers inherently broadband memory operation, BEC serves a high-performance platform due to the absence of atomic diffusion (leading to seconds-scale storage times) and intrinsically large atomic density for high efficiency.

Here, we present our preliminary experimental results for broadband ATS quantum memory in a BEC. We demonstrate the storage of 20-ns-long laser pulses for up to 10 µs time in an ultracold gas of $^{87}$Rb atoms, including BEC. We discuss our current experimental limitations, and future steps in view of other potential applications including quantum transduction and non-linear interactions.


Isothermal Compressibility and Effects of Induced Interaction between Preformed Cooper-pairs in the BCS-BEC Crossover Regime of an Ultracold Fermi Gas


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We theoretically investigate the isothermal compressibility $\kappa_T$ in the normal state of an ultracold Fermi gas. To include pairing fluctuations associated with a strong pairing interaction between Fermi atoms, as well as an effective repulsion between (fluctuating) preformed Cooper-pairs (which is caused by virtual dissociation and recombination of two preformed pairs), we employ the self-consistent T-matrix approximation (SCTMA). We show that, when the latter interaction is completely ignored in the non-self-consistent T-matrix approximation (TMA), $\kappa_T$ diverges everywhere in the BCS-BEC crossover region at the superfluid phase transition temperature $T_c$. This divergence is, on the other hand, absent in SCTMA, due to the inclusion of the inter-pair interaction. The SCTMA result is shown to agree well with the recent experiment on a $^6$Li unitary Fermi gas, indicating the essential importance of the correlation between preformed Cooper pairs in $\kappa_T$. Since normal-state properties near $T_c$ are dominated by pairing fluctuations (preformed Cooper-pairs) in the BCS-BEC crossover region, our results would be useful for the further understanding of strong-coupling physics in ultracold Fermi gases.

P2.25
Progress Towards an Ultracold-Atom Hybrid Quantum System

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We present plans for a new hybrid quantum system, which couples ultracold atoms to cryogenically cooled devices. Atoms will be laser cooled in a vacuum chamber using standard techniques, before being transported into a dilution fridge. Inside the fridge, we hope to couple the atoms with macroscopic quantum devices, including optomechanical components, microwave cavities, and superconducting qubits. In this poster, we focus on the cold-atoms components of this new system, including a discussion of the apparatus under construction and the proposed transport process. The overall goal is to use this hybrid set up to explore quantum information storage, manipulation, and transduction via wavelength conversion.

P2.26
Microwave-to-optical transduction and quantum memory in Rb vapors

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Quantum memory, which stores quantum information and retrieves it on demand, is an essential part of a quantum computer. Working with signals at microwave frequencies is of particular interest since it is the range of common quantum processors, i.e. superconducting devices and highly-excited atoms. On the other hand, for efficient transfer of a signal, optical wavelengths are preferable. In this project, we study the interaction between a rubidium-87 vapor and an oscillating magnetic field inside a high-Q microwave resonator for quantum memory and wavelength conversion applications. We focus on demonstrating microwave-to-optical signal conversion and storage in warm vapor using nonlinear wave-mixing. To improve the transduction efficiency we consider repeating these experiments using an ultracold gas, in which case the microwave resonator will be placed inside our ultracold quantum gases apparatus under ultra-high vacuum conditions.
Quantum solids (bulk, 3D)

P2.27
Internal Structure of hcp $^4$He Observed by X-Ray

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The mechanism for mass flow through solid $^4$He at low temperatures is possibly a superflow through dislocation network,\(^1\) but nearly nothing is known about the microscopic structure of the dislocation network inside the sample and its change during the mass flow experiment. Study of the internal structure of solid $^4$He can be made through X-ray diffraction imaging. I present results of a new analysis on the X-ray topography on solid $^4$He.$^2$ Three-dimensional (3-d) images of the internal structure of a single crystalline hcp $^4$He are reconstructed from about twenty horizontal X-ray topographs taken with a 50 $\mu$m interval. There are several small-angle grain boundaries and one of them is branching. Each grain boundary is almost planar and thought to be consist of an array of edge dislocations. I will explain the 3-d structure of the grain boundaries and their relation to dislocations and discuss what will be observed if the mass-flow experiment is combined with X-ray imaging.


P2.28
Ultra-slow dislocation pinning dynamics of solid $^4$He with extremely low $^3$He concentrations

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Solid helium made with commercially-available UHP $^4$He exhibits fast relaxation to a stiffened state below approximately 0.2 K. As $^3$He impurity concentration decreases down to 0.6 ppb, the relaxation time grows substantially. This extended relaxation cannot be explained by the simple dislocation pinning by $^3$He impurity. In addition, the critical strain for softening solid $^4$He with $^3$He concentration lower than 300 ppb shows unexpectedly weak $^3$He concentration dependence. Although the characteristic length of dislocations pinned by $^3$He impurities is expected to be smaller than the lattice constant of a hcp helium crystal below 0.03 K, the critical stress apparently shows $^3$He concentration dependence. However, the $^3$He dependence is much weaker much weaker than predicted by the classical homogeneous pinning mechanisms by $^3$He impurities.

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P2.29
Scale-invariant dislocation networks in cold-worked solid $^4$He

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Polycrystalline samples of $^4$He were studied after cold working by high-amplitude torsion at 0.03 K and during annealing at 0.55–0.7 K. From the amplitude dependence of the shear modulus, the distributions of network lengths of gliding dislocations $n(L)$ were calculated. Hence, the total length of dislocations per unit volume $\Lambda$, average length $\bar{L}$, and the average as well as the scale-dependent structural parameter $\Delta L^2$ and $L^4n(L)$, were determined.

In cold-worked samples, $L^4n(L) = $ const from $L \sim 100 \mu \text{m}$ down to at least $0.4 \mu \text{m}$ – indicating that the structure of the dislocation network is self-similar over many length scales. Thermal annealing of cold-worked samples, on the other hand, restores a homogeneous dislocation network characterized by a single length scale with $\bar{L} \sim 20 \mu \text{m}$.

Dislocation avalanches have been observed in samples subjected to a strong AC strain at temperatures below 0.3 K. Together with the observed multi-scale distribution of dislocation lengths, this is consistent with theories advocating the creation of fractal scale-invariant dislocation cells after a low-temperature plastic deformation of crystals with easy glide but no climb of edge dislocations.

Certain analogies between the current state of understanding of the dynamics of dislocations in deformed crystals and dynamics of vortex lines in quantum turbulence will be discussed.

P2.30
Dipolar Solid Helium – A New Approach to Quantum Solids

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Despite the last fifteen years of intense research on solid helium, there are still mysteries and questions that persist. In an effort to address some of these questions the newly formed low temperature physics laboratory at Sacramento State University is preparing a set of experiments that take a different tack in studying solid helium. Specifically we plan to use an electric field in an attempt to control the dipole-dipole interactions between helium atoms. This technique brings a new level of control to solid helium experiments, and opens the door to a possible new route to creating solid helium, as well as some other interesting directions. We will describe the setup and technique along with the experiments we plan to undertake.
Temperature-dependent Interatomic Interaction onto He-He Bond

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The quantum-mechanical problem of bound state for $^4\text{He}_2$ dimer (two spinless nuclei with four interacting spin-possessed electrons) has been solved within exact diagonalization approach [1]. It has been found that the low temperature behavior of the He-He interatomic bond within a $^4\text{He}$ condensed phase (liquid or solid) is principally determined by the low-energy states of the four-spin subsystem (with energy of ten Kelvins) coupled with four the electrons which are involved into the pair atomic bond and placed over electronic ground state with energy of order ten Rydberg. Taken into account both pair- and four-spin exchange we have found that the spin subsystem has odd (relative to spin permutations) ninefold degenerated ground state coupled with evidently symmetric electronic ground state. Exchange in the four-spin subsystem on the individual interatomic bond is antiferromagnetic (as it is within simple two-electron atomic shell of $^4\text{He}$) with exchange constant of approximately 4K. The ninefold degenerated spin state will be splitted due to internuclear motion (the temperature-dependent spin-phonon coupling), and such interaction is the cause of the specific temperature-dependent shape of the phonon spectrum in the He II phase (including so-called ‘roton’ minimum). As a result, within partially ordered He II phase (below $\lambda$-line at low pressures) and completely ordered solid phase (at higher pressures) the $^4\text{He}$ condensed matter can be characterized as 'spin ice' with ordering in the spin subsystem which can be realized through corresponding crystalline ordering in condensed helium phases. Thus, we conclude that only spin-spin and spin-phonon interactions are the nature of the specific properties of the $^4\text{He}$.


Reversible Plasticity of $^4\text{He}$ and para-$\text{H}_2$: Dislocation Glide or Solid Phase Transformation?

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We have paid attention to the perfect coincidence between low temperature anomalies (at $0.1 \leq T \leq 0.4K$) in shear modulus [1] and an excessive heat capacity [2] of the purest $^4\text{He}$ solid, which means a common physical mechanism of the two experimentally observed phenomena. We proposed an explanation based on multilayered polytypic structure of the hcp $^4\text{He}$ crystalline phase [3], and support this suggestion by analyzing of the reversible quasi-elastic deformation reported for the hcp para-hydrogen tested with uniaxial compression or tension. Evolution of the crystalline polytype under external loading can be considered as a solid phase transformation during local twinning-detwinning or reversible stacking faults formation in the thermodynamically stabilized at given $P$ and $T$ stack of the closely packed basal planes on triangular lattice. The polytype built of random stacking faults (RSF) can serve a model for partially ordered He II phase, which was characterized by L. Shubnikov in 1936 as ‘liquid crystal’. Under external pressure at constant temperature the disordered in the $c$-direction RSF phase transforms through series of long-periodic polytyps and, finally (above 25 atm), it possesses two-plane-periodic hcp lattice. The polytype model allow us to interpret the reversible plasticity (including hysteresis during loading-unloading or thermocycling) experimentally found on many cryocrystals.

2. X. Lin, et.al., PRL 102, 125302 (2009).
P2.33
Asymmetry in Melting and Growth Relaxations of $^4$He Crystals after Manipulation by Acoustic Radiation Pressure Pulse

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The relaxation dynamics of the crystal-superfluid interface of $^4$He after deformation induced by acoustic radiation pressure was investigated. The interface was initially horizontally flat due to the gravity, and the acoustic waves were applied perpendicular to the interface. When the wave hit from the crystal side from beneath, it induced the growth of the crystal. When it hit from the liquid side from above, it induced the melting. The relaxation processes to the initial flat surface was examined for both the melting and growth separately, after the acoustic wave pulse was turned off. The melting relaxation after growth was approximately 10 times slower than the growth relaxation after melting for vicinal surfaces and facets. However, both relaxation times were on the same order for rough surfaces. The melting relaxation showed various anomalous shapes such as needle-like and irregular shapes, depending on temperature. The growth relaxation was much simpler and showed no anomalies. This asymmetric behavior indicates a significant effect of superflow induced during the relaxation process.


P2.34
Finite size effects in thermodynamics: negative compressibility and global instability in two-phase systems

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We have measured for the first time the equilibrium melting pressure of $^4$He as a function of the crystal size. We show theoretically that a liquid with an inclusion of solid seed has negative compressibility. $^4$He at low temperatures possesses very fast mass and heat transport, which results in a very short, of order of 1 s, relaxation times, in contrast to usual systems where relaxation is extremely long. We have demonstrated experimentally the negative compressibility of $^4$He crystal-superfluid system at 0.15 K. With the high precision pressure gauge we were able to measure the increase of the melting pressure by 60 $\mu$bar with the decrease of the size of the crystal from 0.4 to 0.1 mm. This two-phase system was shown to be stable if the crystal size is large enough, which was also proven by the experiment. Crystal seeds that are too small are not stable but spontaneously either melt completely or grow to a large enough size. These conclusions are valid also for vapour-liquid systems.
P2.35
Nuclear polarized phases of H atoms embedded in solid H\(_2\) films

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We report on an experimental observation of two phases of hydrogen atoms in solid H\(_2\) films at temperatures 0.1 – 0.8 K, characterized by a large enhancement of the nuclear spin polarization compared to that given by Boltzmann statistics \((p = 0.15\) at \(T = 0.15\) K\).\(^1\) The first phase with \(p = 0.35\)\(^5\) is formed spontaneously during sample storage in a high magnetic field \((B = 4.6\) T\). The second phase with an even higher nuclear polarization, \(p = 0.75\)\(^7\), can be achieved at \(T \leq 0.55\) K by repeating sequences of Dynamic Nuclear Polarization by the Overhauser effect followed by a system relaxation. Upon warming through the temperature range \(0.55 – 0.65\) K the highly polarized phase undergoes a phase transition to the spontaneously polarized phase, which breaks down at \(T \sim 0.8\) K and the nuclear polarization gradually converges to the Boltzmann distribution. We discuss possible scenarios for explaining the nature of the observed phenomena.


P2.36
Evidence for melting of hydrogen isotope clusters trapped in solid neon at temperature below 1.3 K.

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We report on an electron spin resonance study of H and D atoms stabilized in solid mixtures of neon and molecular hydrogen isotopes: \(\text{H}_2\), HD and \(\text{D}_2\). We observed that H and D atoms can be stabilized in pure clusters of pure molecular hydrogens formed in pores of solid Ne as well as being trapped in solid Ne. Raising temperature from 0.1 to 1.3 K results in a rapid recombination of a significant fraction of both H and D atoms in clusters of hydrogen isotopes. The recombination rate of hydrogen isotope atoms appears to be from five to seven orders of magnitude faster than in solid bulk samples of the solid hydrogens. We explain this recombination rate enhancement by melting of clusters of molecular hydrogen isotopes. Our observations do not provide evidence for superfluid behavior of these clusters at temperatures of 0.1-1.3 K.

Vortices and turbulence

P3.1 Quantumized vortex rings and loop solitons

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The vortex filament model is used to investigate the interaction of a quantized vortex ring with a straight vortex line and also the interaction of two solitons traveling in opposite directions along a vortex. The most likely outcome when a ring reconnects with a line is the formation of a loop soliton. For the case of interacting solitons, we find that loop solitons reconnect as they overlap each other producing either one or two vortex rings. These simulations are relevant for experiments on quantum turbulence in the zero-temperature limit where small vortex rings are expected to be numerous. It seems that loop solitons might also commonly occur on vortex lines as they act as transient states between the absorption of a vortex ring before another ring is emitted when the soliton is involved in a reconnection.

P3.2 Formation of localized vortex tangle around a spherical heat source in superfluid Helium

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We have carried out a numerical study on vortex tangles formed around a spherical heat source submerged in a bulk superfluid \textsuperscript{4}He based on vortex filament model. While majority of the proceeding studies have mainly focused on statistical properties of vortex tangles in homogeneous or inhomogeneous counterflows in channels \textsuperscript{1,2}, in this study a spherically symmetric thermal counterflow is considered. We investigate the formation process of a vortex tangle (i) at the vicinity of and (ii) at some distance away from the hot spot. In both cases, we confirm that crust-like vortex tangles are formed, and each constituent vortex ring tends to orient itself so that the superfluid velocity induced by it is anti-parallel to that induced by the heater. It turns out, however, that the tangle-growth mechanism for these two cases differ significantly: In case (i) the growth mechanism of a tangle is governed by the Donnelly-Glaberson instability; on the other hand, in case (ii), that is rather governed by the dynamics of individual vortices and reconnections among them. We also report our observation that the growth in the total vortex length within a tangle in case (ii) is well-described by a Vinen equation-like expression with production and decay terms.

P3.3
Statistical laws and self-similarity of vortex rings emitted from a vortex tangle in superfluid $^4$He

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Experiments of making quantum turbulence by oscillating objects in superfluid $^4$He have been conducted for a long time. Yano et al. have made a series of experiments using vibrating wires and found some statistical laws about vortex rings emitted from a vortex tangle. We calculate the dynamics of quantized vortices with the vortex filament model in order to find the statistical laws. By injecting a number of vortex rings from two opposite directions to make them collide with each other, we make a tangled region as an equilibrium state of vortex rings. We investigate the size distribution of vortex rings emitted from the tangle and their time of flights. Two statistical laws consistent with the experiments are found. The first is a Poisson process that the time of flight of vortex rings emitted from a tangle exhibits a single exponential distribution. It means that the vortex tangle emits vortex rings randomly with a certain mean frequency. The second is that the relation between the frequency of emission and the vortex ring size follows a power law, which is related to the self-similarity structure of a vortex tangle in the real space.


P3.4
Energy spectra of the turbulent He-4 counterflow.

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Recently we have shown that energy spectra in the superfluid Helium counterflow are very different from the energy spectra in the classical turbulence. They are non-scale-invariant and much steeper that their classical counterparts[1,2]. Moreover, this effect is much stronger in the streamwise direction, such that the spectra become quasi-two dimensional, with most of energy concentrated in the plane, orthogonal to the counterflow direction [3]. The angular dependence of the correlation between the velocity fluctuations of the superfluid and the normal fluid components drives this selective energy dissipation [3,4]. We discuss various aspects of this phenomenon, including its temperature dependence and possible ways of experimental verifications.


91
P3.5
Anisotropy of wave-turbulent cascades in a quantum gas

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Turbulence is characterized by universal laws describing cascade of conserved quantities from large to small scales or vice versa. Navon \textit{et al.}\textsuperscript{1,2} observed a direct cascade after pumping energy at the largest scale of a uniform Bose-Einstein condensate, characterized by a power law momentum distribution. The turbulent cascade was numerically confirmed by simulations of the Gross-Pitaevskii(GP) model. In this work, we present a detailed numerical investigation of anistropy of the turbulent cascades in the GP model through the momentum distributions. Our simulations uncover that this anisotropy strongly depends on the strength of the driving force. When we weakly excite the system, the cascade front propagates slowly and anisotropically. On the other hand, when the driving force becomes enough strong, the anisotropy rapidly vanishes and the system reaches the isotropic turbulence. This behavior is qualitatively consistent with the observations.\textsuperscript{1}


P3.6
Radial turbulent counterflow in superfluid \textsuperscript{4}He

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We report the results of theoretical and numerical study of radial turbulent counterflow generated by a heated cylinder in superfluid \textsuperscript{4}He. Such a counterflow is encountered in various experimental contexts; e.g. it is the dominating mechanism of heat transfer from the hot-wire anemometry probe\textsuperscript{1}. The turbulent counterflow, generated by a small heat flux from the heated cylinder maintained at temperature $T_0$, in liquid helium whose bulk temperature is $T_b < T_\lambda \approx 2.17$ K, was simulated by the vortex filament method based on the Biot-Savart law\textsuperscript{2}. We found that a statistically stationary solution can be obtained only if the temperature in the close proximity of the heated surface is higher than $T_b$. We analyzed the radial profiles of the line density and of the normal, superfluid, and counterflow velocities, and determined the spatial extent of the vortex tangle.

In the case where the heat flux is large (as it is in e.g. hot-wire anemometry experiments\textsuperscript{1}), we applied the HVBK equations to model the statistically steady-state counterflow. We showed that, for $T_0$ between 1.95 K and $T_\lambda$, a time-independent solution can be found only if a spatial non-uniformity of temperature and the dependence on temperature of the thermodynamic properties are accounted for. We demonstrated the formation of the thermal boundary layer, whose thickness grows from zero at $T_0 = 1.95$ K to several cylinder radii at $T_0 = 2.15$ K, within which the temperature rapidly decreases, and the flow properties, including the local average line density, rapidly change with the distance from the cylinder.

P3.7
Elementary process of coupled dynamics between quantized vortex and normal fluid in superfluid $^4$He

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In the present study, we performed some numerical simulations of the locally coupled dynamics of two fluids in a superfluid $^4$He. Previous theoretical studies of quantum turbulence basically addressed only superfluid component. Recent studies showed that we should take into account of both of two fluids. A visualization experiment$^1$ observed a non-trivial deformation of the normal fluid velocity. Motivated by the experiment, a fully-coupled simulation$^2$ of the two fluids was constructed, and showed that the velocity deformation can be caused by a mutual friction with a tangle of quantized vortices. The previous work$^2$ assumed the laminar flow of the normal fluid via coarse-grained mutual friction. In our simulation, the vortex filaments and the normal fluid affect locally each other, namely the sub-volume of the mutual friction is smaller than the mean spacing of the vortex filaments. First, we investigated some elementary processes such as a propagating vortex ring and a reconnection. We found that vortex tubes of the normal fluid are generated around the moving vortex filaments. Second, we studied statistical properties of the normal fluid velocity in thermal counterflow. We analyzed fluctuations of the normal fluid velocity, and discovered an unusual large structure of the velocity fluctuation.


P3.8
Energy transfer caused by coupled dynamics between quantized vortices and normal fluid in superfluid $^4$He

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We numerically investigated energy transfer between superfluid and normal fluid in a superfluid $^4$He. We used the vortex filament method for superfluid and the finite difference method for normal fluid described by the Navier-Stokes equations. Those two fluids are coupled by an interaction through mutual friction$^1$. In the present study, we used the smaller grid spacing of normal fluid than the vortex line spacing. The energy transfer is caused by locally coupled dynamics between quantized vortices and normal fluid. In this study, we found that the energy spectrum of normal fluid is separated by a wavenumber $k_l$ corresponding to a mean vortex line spacing. The energy spectrum in higher wavenumber than $k_l$ seems to show $k^{-2}$ dependence generated by Kelvin waves of the quantized vortices. This wavenumber dependence has been observed in the experiment$^2$. The energy spectrum in the low wavenumber is produced by the events of vortex ring propagations and reconnections. The vortex ring generates a normal fluid jet in the same direction as the propagating ring and a large flow structure of normal fluid remains after the shrink of the ring. In the reconnection, large energy transfer from two quantized vortices to normal fluid occurs and twisted thick vortex tubes of normal fluid are produced around the quantized vortices.

P3.9
Low Frequency Noise Spectrum of Quantum Turbulence Measured by a Micro-electromechanical Resonator in the Nonlinear Regime

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A micro-electromechanical resonator, consisting of a 125 \times 125 \mu m\textsuperscript{2} center plate suspended 2 \mu m above a substrate, was immersed in \textsuperscript{4}He at 14 mK and driven into the nonlinear (Duffing) regime. In this regime, the phase of the oscillation is sensitive changes in the damping. In our cell, we situated a quartz tuning fork ~ 5 mm above the resonator, which we used to drive quantum turbulence. By measuring the fluctuations in the phase of the oscillation we can extract information about the fluctuations of the damping on the resonator and, in turn, information about the turbulent flow on the scale of the resonator, ~ 125 \mu m. We present the Noise spectrum from 5 mHz to 10 Hz for several different tuning fork velocities. For all tuning fork velocities we observe a peak in the noise spectrum around 0.6 Hz.

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P3.10
Observation of single-vortex dynamics with the Kelvin-wave cascade in superfluid \textsuperscript{4}He using nanomechanical resonators

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Modern nanofabrication technology enables construction of ultra-sensitive force sensors. We have produced nanomechanical resonators (NEMS) for measuring dynamics of a single quantized vortex [1]. Here we report on measurements of vortices trapped between the resonator and the sample wall in superfluid \textsuperscript{4}He at 50 mK. The vortex configuration is altered by driving the resonator in the turbulent regime, while it is probed in the linear regime at low drive. We have observed discrete values of the resonance frequency and of the corresponding line width, distinguishing cases with \( N = 0, 1, 2, \) and 3 attached vortices. With increasing \( N \), the resonance frequency increases due to vortex tension. Simultaneously oscillations of the vortex end pinned on the NEMS device generate Kelvin waves on the vortex, which increases damping of the NEMS. The observed damping agrees with the energy flux predicted for the Kelvin-wave cascade [2].

The Kelvin-wave cascade amounts to about 3\% of the total NEMS damping, while the major contribution originates from the tunneling two-level systems (TTLS) in the resonator material and their interaction with phonons. For devices of different geometries, hosting 1D or 2D phonons and in the frequency range of 30–400 kHz we found good agreement of the TTLS damping with theoretical expectations. In our experiments, immersing NEMS into vortex-free \textsuperscript{4}He below 0.1 K does not increase damping, while the frequency decreases dramatically, up to 50\%. This gave us unique possibility to study frequency dependence of TTLS damping in a wide range using the same device, i.e. with identical TTLS configuration.

P3.11
Quantum turbulence in superfluid $^4$He generated and detected by second sound

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Following [1,2], we report an experimental study of quantum turbulence generated by second sound in a brass 32 mm long channel of square cross-section 10 mm side. Fundamental mode as well as few overtones of longitudinal second sound standing waves of large amplitude are generated, at three temperatures, 1.45 K, 1.65 K and 1.83 K, by passing an ac current of frequency $f$ through a flat heater that makes one square wall of the resonator and detected at the frequency $2f$ on the opposite side of the resonator by a sensitive miniature thermometer. Upon exceeding the critical amplitude of second sound, quantum turbulence is created around antinodes of the standing longitudinal resonances of second sound and its amplitude saturates. Additionally, the attenuation of low amplitude second sound of much higher frequency, oriented perpendicularly to the long axis of the resonator in the middle of it, is used to detect the amount of quantized vortices thus created. We determine critical parameters for the onset of instabilities in oscillatory counterflow, present measurements of the temporal decay of the vortex line density and discuss them on the basis of Vinen- and Kolmogorov-types of quantum turbulence.


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P3.12
Observation of second sound attenuation across a macroscopic rotational flow

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Recently, the authors succeeded in generating a superfluid suction vortex, which is a giant vortex with a hollow core, driven directly by a cryogenic centrifugal pump$^{1,2}$. The ultimate goal of this study and related work is to determine the distribution of the local density of the quantum vortex lines as a function of the rotational speed and the magnitude of the suction flow. Although the flow of superfluid helium in a rotating bucket, in which the vortex lines are arranged to form a triangular lattice, is known to show rigid-body motion, the vortex line distribution of the suction vortex remains an open question. In this study, the attenuation of the second sound across the suction vortex and the macroscopic rigid-body rotation were measured. As a result, it was found that the damping factors of the second sound increased with increasing rotational speed; however, it was found that the apparent vortex line density is not proportional to the rotational speed despite the fact that the total circulation has been previously shown to be proportional to the rotational speed. A possible picture of the quantum vortex lines around the suction vortex will be discussed.

Visualization of macroscopic vortex rings in He II

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Vortex rings are generated thermally in He II, between 1.30 and 1.95 K. We apply a brief voltage pulse to a resistive heater located below a circular tube of 5 mm diameter and 20 mm high. The rings form above the tube and move upward. We visualize their cross section, of size comparable with the tube diameter, by capturing the motions of small solid deuterium particles, previously dispersed in the quiescent bath of superfluid $^4$He. We employ particle positions and velocities to compute the flow pseudo-vorticity\(^1,2\), which allows us to identify and track these objects. We thus obtain time-dependent positions, velocities and sizes of the vortex rings. Preliminary results show that, in the range of investigated parameters, these kinematic quantities follow similar scaling laws as turbulent vortex rings moving in classical viscous fluids\(^3\).

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Size Distribution of Emission Vortices of Turbulence Induced by Vibrating Wire in Superfluid $^4$He

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Vortex rings are produced by reconnection of vortex lines in a superfluid turbulence, moving away from the turbulence region. We report the spontaneous emission of vortex rings from a turbulence induced by a vibrating wire in superfluid $^4$He, to investigate the growth and formation of quantum turbulence. Using a set of vibrating wires as a turbulence generator and a vortex detector, we measured the distribution of vortex detection times, estimating the emission rate of vortex rings as a function of time from the beginning of the turbulence generation. The emission rate remains low until the beginning of high-rate emissions, suggesting that some of the vortex lines produced by the generator wire combine to form a vortex tangle, until an equilibrium is established between the rate of vortex line combination with the tangle and dissociation.

By setting the limit on the detection diameter of a vortex ring, we find that the emission rate during an equilibrium state exhibits a power law behavior with ring diameter. Since the diameter of a vortex ring is associated with a vortex line spacing when reconnection occurs, the distribution of vortex line spaces in a turbulence is considered to be reflected in the size distribution of emission rings. Therefore, the power law dependence of the vortex emission suggests the fractal structure of vortex lines in a turbulence.
Boundary layer in thermal counterflow of superfluid $^4$He.

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Heat transport in superfluid $^4$He (He-II) occurs almost entirely through a hydrodynamic process called thermal counterflow, in which the two fluid components of He-II – the normal fluid and the superfluid components – flow in opposite directions with zero net mass flow and with the normal fluid moving on average away from the heat source. Heat transport facilitated by flow – thermal convection – also occurs in classical fluids, where the flow is driven by buoyancy, whereas the thermal counterflow is driven by the generation of normal fluid by the heat input.

A boundary layer adjacent to heating and cooling plates is a fundamental feature of classical turbulent thermal convection. A similar region of increased vorticity near the heat source was recently claimed to exist in thermal counterflow of He-II [1,2]. Motivated by these experiments and considering a possibility of a deeper connection between thermal counterflow and convection, we confirm the presence of the boundary layer experimentally, by directly measuring the temperature profile of turbulent counterflowing He II near the heater using a miniature movable thermometer. The details of the temperature profile across the boundary layer are found to slightly depend on the heater geometry, which leads us to hypothesise the role of inhomogeneous forcing in the creation of such a boundary layer. We support this hypothesis by numerical simulations of the vortex dynamics in inhomogeneous counterflow.


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Nonlinear dissipation in superfluid $^4$He at the microscale.

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Microscopic lithographically manufactured Helmholtz resonators [1] provide a versatile tool for the study of superfluids confined, in one dimension, to microscopic and nanoscopic sizes. These well-characterised devices [2] allow for, e.g., precise measurement of the effects of confinement on the superfluid density. Although the linear behaviour of these devices is well-understood, when driven sufficiently strongly they exhibit strong nonlinear dissipation and an apparent drive-independent maximum possible velocity, both of which have so far evaded detailed explanation. This nonlinearity is likely connected to the quantum turbulence which develops in the oscillating superfluid $^4$He. We study this quasi two-dimensional turbulence with the aid of direct numerical simulations based on the vortex filament model, which indicate an onset of turbulence at velocities higher than those observed in the experiment. This discrepancy suggests an additional mechanism for the creation of quantized vortices. Two related possibilities arise: (i) inhomogeneous enhancement of flow velocity in the vicinity of sharp corners triggers the onset of turbulence at lower drives than suggested by the homogeneous simulations; (ii) vortices are intrinsically nucleated near favourable spots in the flow field. This inhomogeneous nucleation would also account for the experimentally observed saturation of flow velocity.


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P3.17
Measurement of Vortex Line Density in Superfluid $^4$He by Pulsed QTF

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We have developed pulsed quartz tuning fork (QTF) measurement system, which is sensitive and stable enough to detect vortex tangle in He-II. With this device we observed spontaneous rise and fall of the line width of QTF soon after the filling of pressurized He-II at 1.5K, while the spontaneous fluctuation was never observed after a quiet extended hours like half day. We attributed this observation to the detection of vortex tangle, which was generated during filling and was floating in the sample cell. Additionally, we succeeded in generating much intense cloud of vortex tangle by applying sudden pressure change and hence generating a violent flow in filling capillary to the cell. Decaying time constant of the vortex line density was measured after the generation at various temperatures below the lambda point.

Low dimensional and confined systems

P3.18
Fabrication of phonon generator devices for study of quantum phase transition in molecular films

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Helium films adsorbed on porous glass materials exhibit a quantum phase transition at zero temperature limit. We have recently found an anomalous elastic behavior and a superfluid transition in helium films adsorbed on a porous Gelsil glass from torsional oscillator measurements at low temperatures$^1$. These phenomena can be well described by thermal activation of helium atoms from the localized to the extended states with a distributed energy gap. The thermal activation model expects that the molecules in the localized state can be excited to the extended state via absorption of external energy exceeding the gap, likely causing a superfluid transition. In this study, we have fabricated Josephson junction devices consisting of a Nb superconducting tunnel junction for usage as high-frequency phonon generators$^2$. Using the junction devices, we will investigate non-equilibrium superfluidity in helium films caused by phonon absorption and also search for superfluidity in other material films such as hydrogen and neon in which we have observed an elastic anomaly but not a superfluid transition$^3$.

P3.19
Possible thermodynamical phase slips in superfluid $^4$He confined in a 2.5-nm channel of FSM

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$^4$He confined in a straight nanometer-sized channel is one of the suitable systems to study the superfluid of Tomonaga-Luttinger (TL) liquid. Theorists predict that the superfluid coherence of TL liquid is broken by phase slips, which are excited thermally$^1$ or dynamically$^2$. In the former case, the superfluid shows a gradual temperature dependence, and in the latter, the superfluid onset becomes sharp. We have performed the torsional oscillator measurements for $^4$He confined in a 2.5-nm channel (FSM-14). We found that the dissipation peak accompanying the superfluid growth is suppressed to $\sim$0.3 K, and the superfluid growth is gradual. This temperature dependence is well fitted to the former one. Furthermore, the dissipation peak temperature is close to the excitation energy of the phase slip.$^3$ It seems that in the 2.5-nm channel the phase slip which is thermally excited play a dominant role in breaking the superfluid coherence. In our poster, we also discuss the difference from the superfluid behavior in a 2.8-nm channel (FSM-16), where the contribution of the dynamical phase slip is dominant.

3. Private communication with M. Oshikawa.

P3.20
NMR Studies of the Dynamics of 1D $^3$He in $^4$He plated MCM-41.

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Pulsed NMR techniques have been used to study the dynamics of $^3$He confined to the interior of the hexagonal nanochannels of MCM-41 for which the walls were coated with a monolayer of $^4$He as determined by isotherm measurements. The $^3$He was added afterward to form a 1D $^3$He line density of about 0.1 Å$^{-1}$, corresponding to a Fermi temperature of $T_F \sim 120$ mK. A distinct and appreciable departure from the Curie law was observed for the nuclear spin magnetization below 0.5 K. The temperature dependence of the nuclear spin-lattice relaxation times, $T_1$, for temperatures $0.05 < T < 2.5$ K, followed the expected linear behavior at low temperatures and a peak was observed at $T \sim 2T_F$ consistent with Luttinger liquid theory as predicted by Polini et al.$[1]$. The observed temperature dependence of the nuclear spin-spin relaxation times, $T_2$, differed considerably from that observed for $T_1$, with a minimum at $T = 0.8$ K, similar to the tendency reported by Matsushita et al.$[2]$

P3.21

Short-Range and Long-Range Orderings of Bose $^4$He Films Adsorbed in Nanopores

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In three-dimensionally-interconnected 2.7nm pores of HMM-2, adsorbed $^4$He films at low coverages have a superfluid transition with a sharp heat-capacity peak at the onset temperature, showing the 3D long-range ordering reflecting the 3D film connectivity. In contrast, at coverages higher than a coverage, an additional broad hump appears in the heat capacity at higher temperatures than the superfluid onset, which suggests a short-range ordering into a 2D degenerate state within films, prior to the 3D superfluid transition. These dimensionality of $^4$He film orderings depending on the coverage can be explained by length relations among the 3D and 2D mean interatomic distances, and the length of the 3D pore connectivity.$^1$

To examine generality of such a picture for $^4$He films adsorbed in nanopores, we have also investigated heat capacities of $^4$He films in several 1D and 3D nanopores with different geometries from that in HMM-2. As expected, the phase appearances in $^4$He films strongly depend on the pore geometry. And, it was found that critical behaviors and scalings of sharp heat-capacity peaks indicating the 3D long-range ordering and humps for the 2D degenerate state are universal even for $^4$He films adsorbed in different nanopores. They suggest that orderings of $^4$He films in various nanopores have a common nature, though the appearances are determined by the length relations in films and pores.


P3.22

Substrate Corrugation Effects on Self-Binding of $^3$He in Two Dimensions

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Recently, Sato et al.$^1$ found experimentally that $^3$He atoms confined in two dimensions self-bind forming liquid puddles at least below 90 mK. They observed a clear kink at 0.6 nm$^{-2}$ in the areal density ($\rho$) dependence of $\gamma$, the coefficient of the $T$-linear term of the heat capacity ($C$). Below this critical density $\rho_c$, $\gamma$ decreases linearly with decreasing $\rho$. The subsequent quantum Monte Carlo calculations$^2,3$ were successful to represent the self-binding as a metastable or stable state by considering the band effect due to the substrate potential corrugation and the quasi-two dimensionality. However, these are still not fully consistent with the experiment, since nearly the same $\rho_c$ values are observed$^1$ on largely different underlayers for $^3$He, i.e., $^3$He/gr, $^3$He/$^4$He/gr, and $^3$He/$^3$He/$^4$He/gr.

Here, we report new heat capacity data with a further different underlayer, a bilayer of HD ($^3$He/HD/HD/gr) where, again, we obtained almost the same results as those by Sato et al.$^1$. To deduce this conclusion, we carefully examined $T$ and $\rho$ dependences of heat capacities ($C_{\text{amor}}$) associated with nuclear spin degrees of freedom of amorphous $^3$He trapped in substrate heterogeneities. Unlike the assumption by previous workers, $C_{\text{amor}}$ has a weak but finite $T$-dependence, and it can be largely reduced in magnitude by annealing the HD layers.

P3.23
Testing the survival of Fermi liquids in two dimensions

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The singular behaviour of correlated fermions in two dimensions (2D) has been the subject of intense theoretical controversy, dating from Anderson’s proposal [1] that Landau Fermi liquids (LFL) are destroyed in this case. Subsequent experimental [2] and theoretical [3] work appears to show that the LFL survives, but with non-analytic behaviour which determines the sub-leading term in the temperature dependence of the heat capacity. Here we measure the heat capacity and magnetic susceptibility (using SQUID NMR) of a uniform 2D $^3$He system on the surface of a four layer $^4$He film on graphite. For $n_3 < 0.3$ nm$^{-2}$ the uniform density $^3$He surface layer is unstable, while for $n_3 > 4$ nm$^{-2}$ a second 2D Fermi system built on the first excited $^3$He surface bound state is formed. The advantages of this model system are: a simple circular Fermi surface; negligible spin-orbit coupling; wide tunability of surface density; absence of Wigner-Mott quantum criticality. We determine the Landau parameters $F_0$ and $F_1$, and their dependence on $^3$He surface density. Using Hartree-Fock theory we infer the interaction potential as a function of momentum transfer at the Fermi surface $v(q)$, which we find to be quadratic with small repulsive $v(0)$, over the 2D density range studied. Unusually s-wave interactions are repulsive and p-wave interactions are attractive, and of comparable strength, leading to strongly asymmetric scattering.


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P3.24
Dimer Bound State and 3D Fermi liquid of $^3$He Film in 3D Nanopore

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On $^4$He-preplated walls of substrates, $^3$He atoms can move rather freely being bounded on the surface. The mobility of $^3$He atoms are widely modified by a change in the $^4$He film thickness, and in nanopores, correlation between $^3$He is also considered to vary depending on the $^4$He thickness and $^3$He density, which results in a rich variety of 3D strongly-correlated Fermi fluid behaviors. Here, we have studied $^3$He films adsorbed in 3D-connected 2.7nm nanopore of HMM-2 by the heat capacity and NMR measurements, systematically changing the $^4$He thicknesses and $^3$He densities. When preplated $^4$He thickness is below 1.9 layers, bound states, where the heat capacity decreases exponentially as $T$ decreases, were observed for dilute $^3$He. Although the temperature region of the bound state becomes lower with increasing $^4$He thickness, the state remains even on superfluid $^4$He film, which suggests that it is caused by interaction between $^3$He atoms rather than the substrate interaction. In the bound states, a decrease of the susceptibility from the Curie law is also observed, suggesting that the bound state accompanies formation of spin-singlet $^3$He dimers, which has been theoretically predicted but clear evidences have not observed in the other $^3$He films so far. On the other hand, on thicker $^4$He films, typical Fermi liquid behaviors of $^3$He were observed. Even though $^3$He forms a film, the heat capacities and Fermi temperatures agree with 3D liquid in smaller effective volume, due to the 3D connectivity. While the analysis of the Wilson ratio indicates that the correlation between $^3$He is ferromagnetic, it was found to be weakened, as $^4$He thickness decreases, consistently with existence of antiferromagnetic dimers on thinner $^4$He films.
P3.25
Detection of gas adsorbed on suspended graphene

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Exfoliated graphite has long been used to study molecular/atomic monolayers as the adsorption substrate thanks to its large specific surface and atomically flat surface. Recently, graphene have attracted much attention as another intriguing playground for the adsorbed system [1]. We have studied gas adsorption on suspended graphene using it as a mechanical resonator device [2]. A doubly clamped suspended graphene is capacitively coupled to the back gate and mechanical vibration is excited by applying AC voltage to source-drain. Since the whole body of the suspended graphene is surface, the device has extreme sensitivity to mass change which is detected as a shift in the resonance frequency. Low frequency noise (1/f noise) is also useful to detect adsorbed gases because adsorbants behave as scattering centers and the initial number of scatterers is small due to its high conductivity. We report preliminary results of the mechanical resonance and 1/f noise measurements with 4He and Ne in the temperature range of 4.2–100 K. Adding the amount of gas leads to increased noise in our devices. With increasing temperature, the noise begins to increase when the adsorbants become mobile, just before the atoms are evaporated off from the substrate. Dynamic theories of 1/f noise have been considered and compared with the data. The general features of our results agree with mobility fluctuations as the main source of 1/f noise.


P3.26
Niobium Calorimeter for Studies of Adsorbed Helium Monolayers

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We have constructed a calorimeter made of superconducting niobium (Nb) for studies of adsorbed helium (He) films, particularly the proposed gas-liquid transition of 3He monolayer adsorbed on graphite.1 The critical temperature, $T_c$, of this transition is expected between 90 and 760 mK. The lower bound is the highest measured $T_c$ in Ref. 1, and the upper bound is the $T_c$ of 4He monolayer on graphite. To test any finite size effects on the transition, the calorimeter contains ZYX substrate, an exfoliated graphite with a single crystalline size ten times larger than that of Grafoil used in Ref. 1. Since the specific surface area of ZYX is ten times smaller than that of Grafoil, it is crucial to reduce the addendum heat capacity as much as possible. We thus made the sample container with Nb due to its exceedingly small specific heat at $T$ well below 9.3 K, the superconducting transition temperature. Before testing, there were several unknown factors about the usage of Nb, such as He leak tightness, excess specific heat or heat generation due to the ortho-para conversion of hydrogen contamination, etc. As a matter of fact, it is He leak tight ($\lesssim 10^{-10}$ ccSTP/s) at room temperature, and the measured addendum heat capacity of the calorimeter made of non-heat treated commercial Nb is approximately 8 times smaller than the previous calorimeters made of hard silver (Cd $\leq 1$ at%)1 at 0.1 K and almost the same as Nylon2 at $0.1 \leq T \leq 1$ K. We will present design details, results of numerical simulations, and heat capacity data taken by the heat pulse method using a thin copper wire thermal link as an effective heat switch.

P3.27
Homogeneous cavitation in liquid helium using an ink-bottle geometry

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We report the first observation of helium homogeneous cavitation using the so-called artifical tree technique\textsuperscript{1}. In contrast to previous acoustic cavitation experiments, this technique allows to obtain static, tunable, negative liquid pressures by connecting a cavity filled with liquid to an undersaturated vapor reservoir through a narrow constriction. Our sample is a porous silicon membrane presenting parallel pores of typical diameter 20 nm. The pores mouth is reduced down to less than 10 nm by alumina coating. Volumetric isotherms measurements performed between 2.4 and 4.8 K show that, above 3.4 K, evaporation proceeds by cavitation and, below, by meniscus recession in the constriction, this crossover temperature being fixed by the constriction diameter. The temperature dependence of the cavitation pressure is found to agree with the classical nucleation theory when assuming that thermal activation allows to pass a barrier of 55 kT. The corresponding liquid pressure at the lowest temperature is computed to be about -4 bar. We discuss the implications of these results and the extension of our method to larger and smaller cavity diameters to evidence the predicted effect of confinement on cavitation\textsuperscript{2}.


P3.28
Quartz Crystal Microbalance Measurements of $^4$He Submonolayer Films on Graphite

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The dynamical response of $^4$He submonolayer films on graphite was measured using the quartz crystal microbalance technique. The mass of the $^4$He monolayer films was fully decoupled from the oscillating graphite substrate at least below 10 K. This mass decoupling can be explained by the slip of the $^4$He films against the substrate. When decreasing the temperature the mass of the $^4$He films coupled again with the oscillating graphite substrate around 0.4 K only for areal densities larger than the $\sqrt{3} \times \sqrt{3}$ phase. This second mass coupling is consistent with our hypothesis that $^4$He films exhibit fluidity inside the domain walls of adsorption structure and that $^3$He atoms dissolved into $^4$He solid films behave as 1D fermions or Dirac fermions. This hypothesis has been proposed following the results of heat capacity measurements of the small amounts of $^3$He dissolved into $^4$He films. If the $^4$He films exhibit superfluidity inside the domain walls, the mass decoupling by the slip can be suppressed by the superfluid counter flow inside the domain walls against the slipping solids. By decreasing the temperature further, the coupled mass of the $^4$He films decoupled again from the oscillating substrate. Although the origin of the second mass decoupling has not yet been understood, the mass decoupled at higher temperatures by increasing the oscillating amplitude, and this observation shows that the second mass decoupling is enhanced by the oscillation. The second mass decoupling was accompanied by a dissipation ($Q^{-1}$) peak, whose height appeared to be inversely proportional to the corresponding peak temperature.
P3.29
Elastic Anomaly of $^4$He Films Adsorbed on Graphite

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$^4$He films on graphite is a model 2D Bose system with tunable interatomic correlation by changing coverage $n$. Recent studies have proposed novel quantum phases in which superfluid and crystalline orders may coexist\textsuperscript{1}. We try to address the question by elastic measurement. We have recently found that localized (nonsuperfluid) $^4$He films adsorbed on a porous glass show an elastic anomaly, an increase in elastic constant at low temperature accompanied with a dissipation peak\textsuperscript{2}. The anomaly is related to a coverage dependent energy gap and it fades away as $n$ approaches a quantum critical coverage $n_c$, above which the film shows superfluidity. Therefore, elasticity can provide useful information for understanding nature of phases and can probe phase boundary between superfluid and solid phases. Here we report preliminary studies of elasticity of $^4$He films on grafoil. We measure elasticity by a torsional oscillator in which a stack of grafoil sheets is installed in torsion rod and elastic anomaly is detected by measuring resonant frequency and dissipation. Up to monolayer completion, two elastic anomalies have been observed: One occurs in the films with $1 < n < 8$ nm$^{-2}$ at around 0.4 K with little coverage dependence. The temperature of second anomaly decreases from $T \approx 2$ K at 8 nm$^{-2}$ to 1.5 K at 10 nm$^{-2}$, and the overall characteristics are similar to the elastic anomaly observed on the porous glass. Measurements are underway together with a standard torsional oscillator measurement that detects superfluidity.


Quantum solids (2D systems)

P3.30
The $^4$He adsorption on $\gamma$-graphdiyne: path-integral Monte Carlo study

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Path-Integral Monte Carlo simulations have been performed to study the adsorption of $^4$He atoms on $\gamma$-graphdiyne, a recently-synthesized two-dimensional carbon structure with benzene rings connected by diacetylenic linkages.\textsuperscript{1} To prevent $^4$He atoms from penetrating through a porous graphdiyne sheet, we placed graphdiyne on top of a graphite surface. The $^4$He-graphdiyne interaction was described by a pairwise sum of empirical $^4$He-carbon inter-atomic potentials while a laterally-averaged one-dimensional potential was employed for the $^4$He-graphite interaction. Radial density distributions reveal a layer-by-layer growth of $^4$He atoms on the substrate. Firstly, a single $^4$He atom was observed to be embedded onto each irregular hexagon center of graphdiyne. The first layer of $^4$He atoms formed at the distance of $\sim 2.10$ Å above the $^4$He-embedded graphdiyne surface was found to exhibit a rich quantum phase diagram including several commensurate solid phases at different areal densities. At the areal density of 0.039 Å$^{-2}$, the first layer shows a commensurate solid structure with respect to the underlying graphdiyne lattice with each irregular hexagon center and each regular hexagon center being occupied by a single $^4$He atom. Another commensurate structure emerges at the helium density of 0.0910 Å$^{-2}$ where each big irregular hexagon and each small regular hexagon accommodate three $^4$He atoms and one $^4$He atom, respectively. Some domain structures are developed between two commensurate structures at 0.039 Å$^{-2}$ and 0.0910 Å$^{-2}$.

**P3.31**

**Anomalous thermalization of $^3$He spins in a 2D $^4$He matrix: many-body localization?**

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The spin-lattice relaxation of $^3$He doped into the second solid layer of $^4$He on graphite has been studied by NMR, using pulsed SQUID NMR techniques. The stability of 4/7 or 7/12 triangular lattice superlattice structures has been extensively investigated by first principles simulations. Measurements were performed at fixed $^3$He coverages 0.5 and 0.7 nm$^{-2}$, for which heat capacity and magnetization data reported elsewhere at this conference provide evidence for the quantum degeneracy of delocalised $^3$He “impuritons” in a solid $^4$He matrix. Here we find the onset of an anomalous regime of long spin-lattice relaxation, which increases approximately exponentially with decreasing temperature. This onset is most dramatic at the superlattice density, where it occurs around 30 mK. Below this temperature, the observed saturation of the magnetization with small angle tipping pulses, as a function of repetition rate and tip angle, shows universal behaviour, and is described by a stretched exponential. We expect long range strain mediated interactions between $^3$He, which are weak relative to the $^3$He bandwidth and Fermi energy. Of interest is whether this system is an experimental candidate for 2D many-body localisation, as sought for interacting bosons in optical lattices.


**P3.32**

**Simultaneous Measurements of Superfluidity and Heat-capacities of Novel Phases in $^4$He Monolayers**

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Experimental realization of supersolidity in bulk solid $^4$He is the subject of a long-standing debate. Rather recently, $^4$He monolayers adsorbed on graphite are attracting much attention in the context of possible 2D supersolidity or superfluidity of quantum liquid crystal (LC) phase. This is because reentrant superfluid responses have been observed below 0.3 K by several groups using the torsional oscillator (TO) technique at densities, which do not seem to correspond to the uniform liquid (L) phase, in the second layer of $^4$He. However, it is still not known exactly which phase shows superfluidity due to large uncertainties in their density scales that originate from substrate heterogeneities. We are now successful in eliminating this problem by developing a unique experimental technique with which we can measure heat capacities ($C$) and frequency shifts ($\Delta f$) of the TO simultaneously for the same sample. Phase assignment can be done precisely by measuring $C$ for a given sample. Here we report the first result of such simultaneous measurements on the L and LC phases in 2D $^4$He, where a large superfluid fraction ($\rho_s = 40\%$ of the second layer) and a reduced but finite $\rho_s (= 10\%)$ were observed, respectively. This means that we found a novel state of matter, i.e., “superfluid crystal”, where the partially broken spatial symmetry coexists with superfluidity. An extended measurement of the 2D solid phase to seek for possible supersolidity will also be reported.

P3.33
Observation of apparent superfluidity in the second layer $^4$He films adsorbed on graphite

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Apparent evidence of superfluidity in the second layer $^4$He adsorbed on the atomically flat surface of graphite was observed with a double resonance torsional oscillator (TO). The evidence of reentrant superfluidity of $^4$He on a Grafoam substrate was first reported by Crowell and Reppy, which was reproduced recently on $^4$He films on Graphite substrates by Shibayama et al. and Nyéki et al.. Both experiments suggest the existence of a possible 2D supersolid phase, although an ab initio Monte Carlo simulation disagrees with the interpretation. We placed an in situ pressure gauge directly connected to TO in order to measure the second layer promotion and completion of helium film directly. We also investigated $^4$He films on graphite by utilizing a TO with two different resonant frequency because a TO with a single resonant frequency cannot distinguish the genuine superfluidity from the elasticity dependent response. The measurements were performed in the atomic coverages ranging from 17 to 20 atoms/nm$^2$ and the 2nd layer promotion was confirmed with the in situ pressure gauge. We found no frequency dependent TO responses that can be attributed to the rigidity change. Instead, frequency independent response appeared with a dissipation peak, demonstrating the evidence of superfluidity in the 2nd layer helium films on graphite. We propose experiments with micromechanical resonator to study the various physical properties of $^4$He films together with the apparent superfluidity.

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P3.34
Thermodynamic Evidence for Density Wave Order in Putative Two Dimensional $^4$He Supersolid

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A state with intertwined density wave and superfluid order has recently been reported for the second layer of $^4$He adsorbed on graphite $^{1,2}$. We report direct thermodynamic evidence for the density wave order, by doping the layer with a small concentration of $^3$He atoms. Measurements of $^3$He magnetization by NMR have been performed over a wide temperature range from 500 mK to 200 $\mu$K in which the amount of $^4$He is increased through the second layer at fixed $^3$He coverages 0.5 and 0.7 nm$^{-2}$. Magnetization isotherms provide clear evidence for a change of state in the second layer film with increasing $^4$He coverage, consistent with solidification of the second layer. We also report earlier heat capacity measurements of the $^3$He doped second layer of $^4$He, at $^3$He coverages of 0.1, 0.7, 1.0, and 2.6 nm$^{-2}$. Taken together, the thermodynamic data appear to show that in this quantum solid the $^3$He is delocalised and quantum tunnels through the $^4$He matrix. As the temperature is reduced we observe signatures of quantum degeneracy of the $^3$He, while at the lowest temperatures there is a significant degree of localisation of the $^3$He. Alignment of magnetization and heat capacity isotherms of the $^3$He doped sample with isotherms of the torsional oscillator frequency shift of a pure $^4$He sample, support the identification of a 2D $^4$He supersolid.

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Presenting-Author Index

Ahn, Jeonghwan. P1.29, 14, 66
Aidelsburger, Monika. Quantum Gases II, 11, 43
Aitti, S. P2.2, 16, 72

Baker, Chris. Superfluid optomechanics, 8, 20
Barenghi, Carlo. Vortices/Turbulence, 10, 40
Barquist, C. S. P3.9, 18, 94
Barquist, Colin. Vortices/Turbulence, 10, 40
Bettsworth, F. C. P1.16, 14, 59
Bhalla, P. P1.11, 13, 57
Bhatt, Ravindra. Quantum Hall Fluids, 10, 38
Boyack, Rufus. Theory, 11, 48

Casey, Andrew. Low Temp. Techniques and Devices, 11, 45
Cattiaux, D. P1.12, 13, 57
Chishko, K. A. P2.31, 17, 87
Chishko, K. A. P2.32, 17, 87
Choi, HyoYoungsoon. P1.1, 13, 52
Choi, HyoYoungsoon. Topological superfluids, 8, 21
Človečko, M. P1.20, 14, 61
Collin, Eddy. Novel techniques, 8, 25
Cooke, L. W. P2.17, 16, 80
Csathy, Gabor. Quantum Hall Fluids, 10, 37
de Koning, Maurice. Quantum Solids, 9, 32
Del Maestro, Adrian. Theory, 11, 47
Dmitriev, Vladimir. Superfluid 3He, 12, 50
Donner, Tobias. Quantum Gases II, 11, 44
Dykman, Mark. Electrons on/in helium I, 8, 23

Eltsov, Vladimir. Superfluid 3He, 12, 49
Enss, Christian. Low Temp. Techniques & Devices, 11, 45

Feldman, Ben. Quantum Hall Fluids, 10, 38
Freeman, M. R. P1.21, 14, 62
Fukuyama, Hiroshi. Conference summary, 12
Furutani, K. P2.18, 16, 80

Ghosh, Ambarish. Electrons on/in Helium II, 10, 41
Golov, A. I. P2.29, 17, 86
Golov, A. I. P3.1, 18, 90

Guo, Wei. Low Temp. Techniques & Devices, 11, 46
Guthrie, Andrew. P1.31, 14, 67

Hakonen, P. P1.2, 13, 52
Hakonen, Pertti. Low Temp. Techniques & Devices, 11, 46
Hallock, Robert. Quantum Solids, 9, 34
Harris, Jack. Superfluid optomechanics, 8, 20
Heikkinen, P. J. P2.4, 16, 73
Helmerson, Kristian. Vortices/Turbulence, 10, 39
Horng, Tzyy-Leng P2.19, 16, 81
Huan, C. P3.20, 19, 99

Ikeda, Ryusuke. P2.10, 16, 76
Inui, S. P3.2, 18, 90
Islam, Md. P1.22, 14, 62
Iwasa, I. P2.27, 17, 85

Jennings, A. P2.1, 16, 72
Jiang, W. G. P1.23, 14, 63

Kamada, M. P3.22, 19, 100
Kamada, M. P3.25, 19, 102
Kamppinen, T. P3.10, 18, 94
Kawakami, E. P1.3, 13, 53
Kawakami, E. P1.4, 13, 53
Kawamura, T. P2.20, 17, 81
Kennett, Malcolm. Quantum gases I, 9, 28
Khmelenko, V. V. P2.35, 17, 89
Khmelenko, Vladimir. Quantum Solids, 9, 33
Kim, Eunseong P2.28, 17, 85
Kim, Eunseong. P3.33, 19, 106
Kim, RyunDon. P1.27, 14, 65
Kita, T. P2.21, 17, 82
Knapp, J. P3.31, 19, 105

Kobayashi, H. P3.8, 18, 93
Kono, Kimitoshi. Electrons on/in helium I, 8, 23

Konstantinov, A. M. P1.34, 14, 68
Konstantinov, Denis. Electrons on/ Helium II, 10, 41
Kumar, Sumit. P1.10, 13
Kumar, Sumit. P1.9, 13, 56

Langen, Tim. Quantum gases I, 9, 27
Xing, Y. *P1.36, 15, 69*
Xing, Y. *P1.37, 15, 70*
Xing, Yiming. *Electrons on/in Helium II, 10, 42*

Yadav, N. *P1.39, 15, 71*
Yadav, N. *P1.6, 13, 54*
Yano, H. *P3.14, 18, 96*

Yudin, A. N. *P2.9, 16, 76*
Yui, S. *P3.7, 18, 93*

Zimmerman, Andrew. *Superfluid $^3$He, 12, 49*
Zmeev, D. F. *P1.18, 14, 60*
Zou, S. *P1.7, 13, 55*
Zwierlein, Martin. *Quantum Gases II, 11, 43*