International Conference on Ultra Low Temperature Physics

2022 August 25-28, Otaru, Japan

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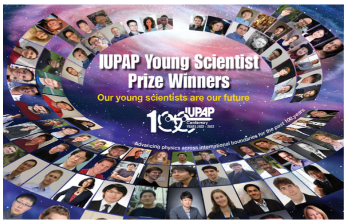

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Conference Program: Timetable

ULT2022 Timetable

Japan JST (*1)		1st day	2nd day	3rd day	4th day	US West (DST)	US East (DST)	UK (UTC /BST)	Western Europe (CEST)	India (*1)
	24-Aug	25-Aug	26-Aug	27-Aug	28-Aug					
	Wed	Thu	Fri	Sat	Sun					
8:30		Registration				16:30	19:30	0:30	1:30	5:00
9:00	LT29 (Sapporo Convention Center)		Session 4: Quantum Computing: Carroll, Abe, Steinke	Session 8: Ultracold Atoms: Jo, Taie, Fujimoto	Session 12: Dark Matter and Electrons on He: Xue, Pollanen, Kawakami	17:00	20:00	1:00	2:00	5:30
9:30						17:30	20:30	1:30	2:30	6:00
10:00		(9:50-)Opening and Session 1: Superfluid 3He Halperin, Haley, Tsutsumi				18:00	21:00	2:00	3:00	6:30
10:30			(10:25-)Coffee	Coffee	Coffee	18:30	21:30	2:30	3:30	7:00
11:00			(10:55-)Session 5: Low-D Quantum Fluids: Fukuyama, Kim, Tajiri	(-12:10) Session 9: Superconductivity: Cazalilla, Marra, Yang	Session 13: ULT with New Techniques: Djadaojee, Murakawa, Noble, Kawae	19:00	22:00	3:00	4:00	7:30
11:30						19:30	22:30	3:30	4:30	8:00
12:00		Luncheon Webinar by Oxford Inst.	(12:05-) Lunch			20:00	23:00	4:00	5:00	8:30
12:30				(12:10-13:40) Lunch	Lunch	20:30	23:30	4:30	5:30	9:00
13:00						21:00	0:00	5:00	6:00	9:30
13:30		Session2: Novel Electronic Systems Hakonen, Ikegami, Ueki, Clovecko	(13:35-) Session 6: Superfluid 3He: Sauls, Hindmarch, Zmeev			21:30	0:30	5:30	6:30	10:00
14:00				(13:40-) Session 10: Confined Systems: Mäkinen, Lin, Huan, Heikkinen, Taniguchi	Session 14: Solid Systems: Todoschenko, Tsepelin, Bangma, Minoguchi, Eltsov	22:00	1:00	6:00	7:00	10:30
14:30						22:30	1:30	6:30	7:30	11:00
15:00		Coffee	(14:50-) Coffee			23:00	2:00	7:00	8:00	11:30
15:30		Session 3: Frontiers in ULT: Kempf, Bunkov, Bettsworth, Kirichek	(15:20-) Session 7: Quantum Turbulence: Skrbek, Yano, Midlik, Yui	Coffee		23:30	2:30	7:30	8:30	12:00
16:00				Session 11: Novel Physics in ULT: Knapp, OXINST, Levitin, Kamppinen, Jones	(15:55-) Closing	0:00	3:00	8:00	9:00	12:30
16:30						0:30	3:30	8:30	9:30	13:00
17:00		(17:05-18:35) On-site Poster Session				1:00	4:00	9:00	10:00	13:30
17:30	LT29 Closing		(17:45-19:15) Online Poster Session			1:30	4:30	9:30	10:30	14:00
18:00						2:00	5:00	10:00	11:00	14:30
18:30	(*2) Bus transpotation to hotel					2:30	5:30	10:30	11:30	15:00
19:00						3:00	6:00	11:00	12:00	15:30
19:30						3:30	6:30	11:30	12:30	16:00
20:00	Check-in					4:00	7:00	12:00	13:00	16:30

(*1) In Japan and India, daylight saving time is not in effect.
(*2) The bus will depart at 18:30 from Convention Center, and arrive at around 20 o'clock at Grand Park Otaru.

Conference Program

August 25 (Thu) First Day

Venue: Grand Park Otaru, Ballroom "Jurin" (5th Floor)

8:30 Registration
9:50 Opening and Announcement

Session 1: Superfluid ^{3}He: New Perspective

Chair: Eunseong Kim

10:15 **William Halperin** (Northwestern University, USA)
(Plenary) New directions for superfluid ^{3}He

11:00 **Richard Haley** (Lancaster University, UK)
(Invited) Helium-3 in the microkelvin regime

11:30 **Yasumasa Tsutsumi** (Kwansei Gakuin University, Japan)
(Invited) Nuclear-spintronics in liquid helium-3

12:00
Luncheon Webinar by Oxford Instruments

Session 2: Novel Electronic Systems

Chair: Johannes Pollanen

13:30 **Pertti Hakonen** (Aalto University, Finland)
Multipartite continuous-variable entanglement generation using Josephson metamaterials

13:55 **Hiroki Ikegami** (RIKEN, Japan)
Circuit-QED-based investigations of two-dimensional Josephson junction arrays in the quantum regime

14:20 **Hikaru Ueki** (Northwestern University, USA)
Electromagnetic response of superconducting RF cavities

14:40 **Marcel Človečko** (Slovak Academy of Sciences, Slovakia)
Spontaneous emergence of phase coherence of oscillating electric dipoles in quartz piezo-resonators at low temperatures

15:00 Coffee break

Session 3: Frontiers in ULT

Chair: Ladislav Skrbek

15:30 **Sebastian Kempf** (Karlsruhe Institute of Technology, Germany)
(Invited) Magnetic microcalorimeters: Forefront technology for next-generation physics experiments (Online)

16:00 **Yuriy Bunkov** (Russian Quantum Center, Russia)
Experimental observation of magnon superfluidity at room temperature (Online)

16:20 **Francis Bettsworth** (Lancaster University, UK)
Breaking the millikelvin barrier for on-chip electrons

16:40 **Oleg Kirichek** (STFC ISIS, UK)
Revealing the complexity of helium mixture films by neutron reflectometry

Poster session 1

17:05 – 18:35 On-site (Grand Park Otaru, Ballroom "Jurin")

August 26 (Fri) Second Day

Session 4: Quantum Computing

Chair: Oleg Kirichek

9:00 **Malcolm Carroll** (IBM, USA)

(Invited) TBA (Quantum Computing in IBM) (Online)

9:30 **Eisuke Abe** (RIKEN, Japan)

(Invited) Scaling up superconducting quantum circuits

10:00 **Lucia Steinke** (University of Florida, USA)

Thermometry and refrigeration of microscopic samples at ultra-low temperatures and high magnetic fields (Online)

10:25 Coffee break

Session 5: Low Dimensional Quantum Fluids

Chair: Vladimir Eltsov

10:55 **Hiroshi Fukuyama** (University of Tokyo, Japan)

Current perspective on quantum spin liquid state in ^{3}He monolayers

11:20 **Eunseong Kim** (KAIST, Korea)

Microwave cavity optomechanics coupled with a micromechanical graphene resonator to investigate the nature of two-dimensional helium films

11:45 **Hiroo Tajiri** (Japan Synchrotron Radiation Research Institute, Japan)

Development of surface X-ray diffraction at low temperatures

12:05 Lunch

Session 6: Superfluid ^{3}He

Chair: Mark Meisel

13:35 **James Sauls** (Northwestern University, USA)

Strong-coupling thermodynamics of superfluid ^{3}He

14:00 **Mark Hindmarsh** (University of Sussex, UK)

Cosmology and the A/B transition in superfluid helium three

14:25 **Dmitry Zmeev** (Lancaster University, UK)

Dynamics of quasiparticles in the surface-bound two-dimensional superfluid ^{3}He

14:50 Coffee break

Session 7: Quantum turbulence

Chair: Hiroshi Fukuyama

15:20 **Ladik Skrbek** (Charles University, Czechia)

In memory of Joe Vinen

15:30 **Hideo Yano** (Osaka Metropolitan University, Japan)

(Invited) Vortex emission of counter flow turbulence in superfluid ^{4}He

16:00 **Simon Midlik** (Charles University, Czechia)

(Invited) Acoustic emission in normal and superfluid He-3

16:30 **Satoshi Yui** (Osaka Metropolitan University, Japan)

Numerical study on superdiffusion of ultra-quantum turbulence in superfluid helium-4

16:55 Break

Poster session 2

17:45 – 19:15 Online

August 27 (Sat) Third Day

Session 8: Ultracold Atoms

Chair: Makoto Tsubota

9:00 **Gyu-Boong Jo** (HKUST, Hongkong, China)
(Invited) Thermodynamic study of bosonization in interacting SU(N) fermions (Online)

9:30 **Shintaro Taie** (Kyoto University, Japan)
(Invited) Quantum simulation of SU(N) magnetism in optical lattices (Online)

10:00 **Kazuya Fujimoto** (Tokyo Institute of Technology, Japan)
(Invited) Surface roughness dynamics in a one-dimensional Bose-Hubbard model

10:30 Coffee break

Session 9: Superconductivity

Chair: John Saunders

11:00 **Miguel Cazalilla** (Donostia International Physics Center, Spain)
Pair excitations of a quantum spin on a proximitized superconductor

11:25 **Pasquale Marra** (University of Tokyo, Japan)
1D Majorana Goldstinos and partial supersymmetry breaking in quantum wires: From Majorana pumps to braiding

11:50 **Weican Yang** (Osaka Metropolitan University, Japan)
Vortex motion and dissipation mechanism in strongly coupled holographic superfluid

12:10 Lunch

Session 10: Confined Systems

Chair: Yutaka Sasaki

13:40 **Jere Mäkinen** (Aalto University, Finland)
Half-quantum vortices in confined ^{3}He superfluids

14:05 **Wei-Ting Lin** (Northwestern University, USA)
Incipient pair-fluctuation effects on quasiparticle transport in liquid ^{3}He

14:30 **Chao Huan** (University of Florida, USA)
Pulsed NMR studies of a 1D ^{3}He system

14:50 **Petri Heikkinen** (Royal Holloway University of London, UK)

Broadband NMR for studies of confined superfluid helium-3

15:10 **Junko Taniguchi** (University of Electro-Communications, Japan)

Superfluid measurements of ^4He confined in a nanochannel by a 100 kHz tuning fork

15:30 Coffee break

Session 11: Novel physics in ULT

Chair: William Halperin

16:00 **Jan Knapp** (Royal Holloway University of London, UK)

Electro-nuclear transition in $YbRh_2Si_2$; evidence for a spin density wave (Online)

16:20 **Sui Mengqiao** (Oxford Instruments, UK)

(Invited) Recent advances in dilution refrigerator (Online)

16:50 **Lev Levitin** (Royal Holloway University of London, UK)

Interplay between superconductivity and magnetism in $YbRh_2Si_2$ (Online)

17:10 **Timo Kamppinen** (Aalto University, Finland)

Detection of quantized vortices in superfluid ^3He by a nanoelectromechanical oscillator (Online)

17:30 **Alex Jones** (STFC ISIS, UK)

(Invited) Measurements of helium mixtures by neutron absorption

18:00

August 28 (Sun) Fourth Day

Session 12: Dark Matter and Electrons on Helium

Chair: Richard Haley

9:00 **Wei Xue** (University of Florida, USA)
(Invited) Superfluid Effective Field Theory for Dark Matter Direct Detection (Online)

9:30 **Johannes Pollanen** (Michigan State University, USA)
(Invited) Hybrid systems and quantum computing with electrons floating on the surface of superfluid helium

10:00 **Erika Kawakami** (RIKEN, Japan)
(Invited) Detection of the Rydberg state of electrons on helium with an LC circuit

10:30 Coffee break

Session 13: ULT with New Techniques

Chair: Junko Taniguchi

11:00 **Lionel Djadaojee** (Laboratoire Kastler Brossel, France)
Stimulated Brillouin gain spectroscopy of metastable superfluid helium-4

11:25 **Satoshi Murakawa** (University of Tokyo, Japan)
Study for Surface States of Superfluid ^{3}He-B Phase with Angle Resolved Quantum Andreev Reflection Detector

11:45 **Theo Noble** (Lancaster University, UK)
Imaging topological defects in fermionic superfluid ^{3}He-B (Online)

12:05 **Tatsuya Kawae** (Kyushu University, Japan)
` Andreev point contact spectroscopy study of Kondo insulator SmB_6

12:25 Lunch

Session 14: Solid systems

Chair: Ryuji Nomura

14:00 **Igor Todoschenko** (Aalto University, Finland)
Mobile solid ^{3}He promoted by topological frustration (Online)

14:25 **Viktor Tsepelin** (Lancaster University, UK)
Real-time interaction of NEMS with quantum vortices in superfluid ^{4}He (Online)

14:50 **Femke Bangma** (HFML-FELIX, Netherlands)

Hyperfine interactions at ultra-low temperatures: their role in $PrOs_4Sb_{12}$

15:10 **Tomoki Minoguchi** (University of Tokyo, Japan)

Mobility of solid helium films on a curved substrate near commensurate - incommensurate transition

15:30 **Vladimir Eltsov** (Aalto University, Finland)

Transitions in vortex skyrmion structures in superfluid ^{3}He-A

15:55 Closing

16:20

Poster Presentations

001 **Kazuyuki Matsumoto** On-site
Phase Transitions Between BCC and HCP Phases in Solid Helium

002 **Atsuki Kumashita** On-site
Surface X-ray Diffraction from Monolayer ^{4}He Film on Graphite: Simulations and Preliminary Observations

003 **Tomo Nakagawa** On-site
Dynamics of Quantized Vortices between Oscillating Parallel Plates with Pinning Sites

004 **Yuto Sano** On-site
Anisotropic dynamics of formation of a quantized vortex lattice in a rotating Bose-Einstein condensate

005 **Max Taylor** On-site
Microwave devices using graphene Josephson junctions

006 **Liam Colman** On-site
Building a Superfluiid ^{3}He-B Bolometer using Aluminium Composite Nanobeams

007 **Reio Kida** On-site
Development of an instrument for experimental study of Quantized Vortex

008 **Ivan Grytsenko** On-site
Using a cryogenic tunable resonance circuit to image-charge detection of surface electrons on He II

009 **Tetta Nakamura** On-site
Anomalous thermoelectric properties in $LaO_{0.5}F_{0.5}Bi_{1-x}Pb_xS_2$ (x = 0.9, 0.1)

010 **Quang Zhang** Online
Cosmological Phase Transition in Superfluid Helium Three

011 **Courtney Cain Everett Elmy** On-site
Low-Stokes-number Oscillatory Flows in the Hydrodynamic Regime of Helium-3

012 **Christopher Lawson** On-site
Neutron Imaging of an Operational Dilution Refrigerator

013 **Richard Down** On-site
Sub 1K Sample Environment at the ISIS Neutron and Muon Source

014 **Sosuke Inui** On-site
Fully coupled simulation of a superfluid based on one-fluid extended model

015 **Yoshiyuki Shibayama** On-site
Development of a cryogenic current pre-amplifier using an HBT OPamp

016 **Keita Onodera** On-site
Dripping character of superfluid ^{4}He droplets

017 **Keita Onodera** On-site
Increasing the film flow rate of ^{4}He by coating

018 **Ryuma Nagatomo** On-site
Dripping Period of Superfluid ^{4}He via Film Flow

019 **Ken Obara** On-site
Structure of Superfluid Suction Vortex

020 **Tomoyuki Tani** On-site
Observation of Phase Slip Phenomenon in Superfluid ^{4}He Flow through a Newly Developed Micro-sized Channel

021 **Nathan Eng** On-site
Engineering boundary conditions in stepped-height superfluid ^{3}He nanofluidic cells

022 **Searbhán Ó Peatáin** On-site
Miniature Plastic Dilution Refrigerator for Small Thermal Load Experiments

023 **Junko Taniguchi** On-site
Superfluid measurements of ^{4}He confined in a nanochannel by a 100 kHz tuning fork

024 **Kenta Asakawa** On-site
Breathing Mode of the Bose-Einstein Condensate Trapped by the Self-Gravity

025 **David Schmoranzer** On-site
NbTi Vibrating Wires as Detectors of Quantum Turbulence in Thermal Counterflow of He II

026 **Mark Meisel** On-site
Update on ULT at University of Florida

027 **Camille Mikolas** On-site
Coupling electrons on helium to superconducting quantum circuits

028 **Kamil Goliaš** On-site
Temperature Dependent Instabilities of Duffing Resonator Based on Sn-whisker at Low Temperatures

029 **Oleksandr Podopryhora** On-site
Plug-in & Cool nuclear demagnetization stage for cryogen-free dilution refrigerators

030 **Vladislav Zavjalov** Online
Role of surface layer in cooling of superfluid ^3He in a demagnetization cryostat

031 **Petra Knappova** Online
Study of thermal boundary resistance between metal and ^3He at ultralow temperatures

032 **Tatsuya Kawae** On-site
Hydrogen transfer via phonon-assisted quantum tunneling in metallic nanocontacts

033 This poster moved to an oral session

034 **Yoma Miyakoda** On-site
Emission of Vortex Rings from Thermal Counterflow Turbulence in Superfluid Helium 4 —TII Turbulence State—

035 **Marijn Lucas** Online
Opening Microkelvin Regime to Quantum Materials and Quantum Devices

036 **Jan Nyeki** Online
NMR evidence for density wave order in the two dimensional ^4He supersolid doped by ^3He

037 **Jan Nyeki** Online
Anomalous thermalization of ^3He spins in a 2D ^4He matrix

038 **Andrew Fefferman** Online
Development of continuous sub-mK refrigeration for ground-state cooling of mechanical resonators

039 **Taku Matsushita** Online
NMR study of 1D 3He in nanochannels

040 **Kensuke Yoshida** On-site
Study of Surface States in Superfluid Helium 3-B Phase by Using an Angle Resolved Quantum Andreev Reflection Detector

041 **Emily Gamblen** On-site
Exploring Applications of Graphene-Based Josephson Junctions

042 **Michal Moravec** On-site
Origin of resistivity upturn in Mg doped delafossite $CuRhO_2$

043 **Miguel Cazalilla** On-site
Enhancement of Spin-charge Conversion in Dilute Magnetic Alloys by Kondo Screening

044 **Miguel Cazalilla** On-site
Topological Lifshitz Transitions, Orbital Currents, and Interactions in Low-

dimensional Fermi Gases in Synthetic Gauge Fields

045 **Lev Levitin** Online

Tuning the phase diagram of superfluid ^{3}He with electric field

046 **Dmitry Zmeev** On-site

A System for Precise Control of a Levitating Sphere in Helium Fluids

047 **Yuto Ikegai** On-site

Effect of Flow on the Spatial Arrangement of Chiral Domains in Superfluid ^{3}He-A

048 **Man Nguyen** On-site

Transverse Sound in the Fermi Liquid and Superfluid States of ^{3}He

049 **John Scott** On-site

Anomalous Low-Temperature Phase in Superfluid ^{3}He Imbibed in Anisotropic Aerogel

050 Samuli Autti On-site

NbTi Nanowire Oscillators with Circular Cross-section

New Directions for Superfluid ^{3}He

William P. Halperin

Department of Physics, Northwestern University
2145 Sheridan Rd, Evanston, Illinois 60208, USA

This year marks the 50th anniversary of the discovery of superfluid ^{3}He by Douglas Osheroff, Robert Richardson, and David Lee. This event followed a breakthrough in cryogenic technology that we recognize now has opened up a new world of science, the physics of quantum materials. In the context of the rich history that has evolved since then, first announced in 1972, I imagine five possible developments. These include pushing technology that will enable further discovery, testing predictions concerning liquid ^{3}He that remain open, and exploiting the high degree of quantum coherence of the superfluid as a medium with unparalleled sensitivity for detection of new phenomena.

Helium-3 in the microkelvin regime

Richard P. Haley[1]
[1] *Department of Physics, Lancaster University, Lancaster LA1 4YB, United Kingdom*

At temperatures on the order of 100 microkelvin, around $0.1T_c$, helium-3 is in the pure condensate limit. Here the superfluid is in the regime of pure potential flow and broken Cooper pair quasiparticle excitations travel ballistically between the surfaces of experimental cells and measurement probes, having mean free paths which far exceed any container length scale. Sustaining helium-3 in this zero temperature limit requires novel cooling technologies and strategies for insulating the condensate from external disturbance.

Over the years we have probed the dynamical properties of the ballistic superfluid flowing around immersed mechanical objects, developed tools for calorimetry and quasiparticle bolometry, manipulated applied magnetic fields to measure AB nucleation and properties of the phase interface, and exploited the exotic behaviour of the condensate and its topological defects to investigate sometimes far-removed physical phenomena such as turbulent flow and cosmological processes. Highlights include demagnetizing solid helium-3 on cell surfaces to cool the bulk liquid, the discovery of super-critical flow at speeds above the Landau velocity, and the imaging of tangles of quantized vortices within the superfluid.

As our insight into flow-induced Andreev scattering and pair-breaking around moving objects in the B phase has grown, so has our understanding of the role of bound state excitations in regions of gap suppression within the ~100 nm coherence length of any solid surface. We are currently developing new tools and techniques to probe the bulk condensate and surface states such as levitating mm-sized spheres and nano-scale wires. In turn, we are exploiting these techniques by incorporating them in quasiparticle bolometers to enhance their sensitivity to background radiation and collaborating with others to investigate their potential as detectors of dark matter.

Nuclear-spintronics in liquid helium-3

Yasumasa Tsutsumi
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Efficient generation of electron spin current has been investigated extensively in the field of spintronics. The spin current generation with high efficiency had been performed by utilizing the spin-orbit coupling in some rare metals, such as Pt, with the strong spin-orbit interaction. Recently, the coupling of spin angular momentum and mechanical rotation, the spin-rotation coupling [1], has been attracting attention as an alternative mechanism to generate the spin current without the spin-orbit interaction. Indeed, spin current was generated in a copper film, which has only the weak spin-orbit interaction, by using surface acoustic waves [2]. The generation of spin current by hydrodynamic flows in liquid-metals, Hg and GaInSn, was also demonstrated [3, 4]. Although qualitative features of the generated spin current was predicted in those systems theoretically, quantitative evaluation of the efficiency of the spin current generation is difficult without fitting parameters due to a coarse-grained model of electron motion.

The spin-rotation coupling 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 [5]. The effective field gradient generates nuclear spin current owing to the Stern–Gerlach effect. Since the microscopic motion of helium-3 quasiparticles is well described by the Fermi liquid theory, we can evaluate the generated spin current from the hydrodynamic flow quantitatively. In this work, we solve the linearized Boltzmann equation for the quasiparticle distribution function assuming that the deviation of the distribution from the local equilibrium is small. Here, we discuss two types of flow of the liquid helium-3 in the normal state.

First, we consider steady flow by pressure difference in a channel between parallel plates. The channel flow is similar to the Poiseuille flow except for the presence of the fluid slip on the boundary [6] and makes vorticity in the liquid helium-3 corresponding to the effective magnetic field on the helium-3 nuclear spin. We can quantitatively estimate the field gradient of the order of 1 G/cm by the hydrodynamic flow under the pressure gradient with 1 Pa/cm at 100 mK. The effective field gradient is large enough to be detected by NMR measurements. This steady flow generates local spin polarization, but spin current does not flow in the equilibrium state.

Second, we consider dynamical flow by an oscillating wall of a vessel containing the liquid helium-3. The velocity field of the dynamical flow was calculated by the linearized Boltzmann equation in the previous work [6]. We calculate spin polarization and spin current under dynamical effective field by the vorticity of the fluid velocity. The obtained spin current is sensitive to the boundary condition at the oscillating wall.

[1] M. Matsuo *et al.,* Phys. Rev. Lett. **106**, 076601 (2011).
[2] D. Kobayashi *et al.,* Phys. Rev. Lett. **119**, 077202 (2017).
[3] R. Takahashi *et al.,* Nature Phys. **12**, 52 (2016).
[4] R. Takahashi *et al.,* Nature Commun. **11**, 3009 (2020).
[5] Y. Tsutsumi and S. Maekawa, J. Low Temp. Phys. **203**, 255 (2021).
[6] D. Einzel *et al.,* J. Low Temp. Phys. **53**, 695 (1983).

Multipartite continuous-variable entanglement generation using Josephson metamaterials

Pertti Hakonen
Low Temperature Laboratory, Department of Applied Physics
Aalto University School of Science

Generation of quantum resources, most notably quantum entanglement, is an essential task for the new emerging industry employing quantum technologies. While entanglement in discrete variables represents the standard approach for quantum computing, continuous variable entanglement between microwave photons is a cornerstone for more robust quantum computing, sensing and communication schemes.

We have developed a low-loss Josephson metamaterial comprising superconducting, non-linear, asymmetric inductive elements to generate frequency-entangled photons from vacuum fluctuations at a rate of 2 Giga entangled bits per second spanning over 4 GHz bandwidth. The device is operated as a traveling wave parametric amplifier under Kerr-relieving biasing conditions that allow us to generate microwave entanglement over previously inaccessible bandwidth. Furthermore, we successfully demonstrate single-mode squeezing in such devices, -3.1 dB below the zero-point level at half of the modulation frequency.

As we demonstrated, the broadband features of the TWPA allow operation over a few gigahertz bandwidth, and in combination with multiple pumps, pave the way toward the generation of "frequency-based" multimode entanglement. We propose a method for high-quality generation and control of entanglement between microwaves in multiple frequency ranges. Using the developed scheme, we present the first demonstration of an on-demand tunable entangled 3-partite and 4-partite states in a lumped-element Josephson parametric amplifier [1].

Multimode schemes can be employed for various quantum applications, such as CV computing with cluster states, secure and robust communications, distributed quantum-limited sensing, and search for dark matter [2]. We envision that generated quantum resources offer enhanced prospects for quantum data processing using parametric microwave cavities [3].

[1] K. Petrovnin *et al*., arXiv:2203.09247 (2022).
[2] M. Perelshtein, *et al.*, arXiv:2111.06145 (2021).
[3] T. Elo *et al*., Appl. Phys. Lett. 114, 152601 (2019).

Circuit-QED-based investigations of two-dimensional Josephson junction arrays in the quantum regime

Hiroki Ikegami

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Recent progress in the field of quantum information processing with superconducting qubits is allowed by the development in circuit-QED (cQED) techniques. There, dynamics of a qubit - the simplest quantum system - is studied directly by cavity microwave photons at the single-photon level. Here we apply the cQED technique for the study of quantum many-body physics realized in superconducting Josephson junction arrays (JJAs) [1,2]. The JJAs composed of small superconducting islands connected via Josephson junctions offer model systems for studying various many-body phenomena, such as the Berezinskii-Kosterlitz-Thouless (BKT) transition and the quantum phase transition between the superconducting and insulating phases.

In this presentation, we discuss many-body dynamics in JJAs observed in cQED investigations. In particular, we show that, when the Josephson energy is dominant and the JJA shows the superconducting BKT transition, the internal loss of cavity exhibits a peak at the transition temperature [2]. The increase of loss at the transition temperature is caused by dissipative motion of free vortices generated by the BKT mechanism, as similar to the dissipation peak observed at the superfluid BKT transition in ^{4}He films [3]. In the quantum critical regime realized when the Josephson energy competes with the charging energy, the JJA exhibits the quantum phase transition between the superconducting and insulating phases. In this regime, we observe that the internal loss of cavity at the zero-temperature limit increases steeply as the system approaches the quantum critical point. In the talk, we discuss this observation in connection with the quantum phase transition.

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Electromagnetic response of superconducting RF cavities

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Niobium superconducting radio-frequency (SRF) cavities have been improved in terms of the quality factor Q by infusing Nitrogen into the Nb surface [1], and then unprecedented quality factors $Q \sim 10^{11}$ have been achieved [2]. These high-Q cavities provide a new technology platform for quantum processors, and quantum sensors for axions [3,4], which are dark matter candidates, and light-by-light scattering of low-energy quantum electrodynamics [3], i.e. the Euler-Heisenberg (EH) term. These axion and EH terms contribute to cubic nonlinearities in Maxwell's equations. The sensitivity to axion and EH signals depends on the Q of SRF cavity, and preliminary experiment for the nonlinearity has recently been performed [5]. Therefore, it is important to investigate the N-impurity effects on the Nb surface of SRF cavities.

To understand the fundamental limitations on Q of these SRF cavities, we have developed nonequilibrium theory of superconducting Nb with non-magnetic impurity disorder based on the Keldysh formalism [6] and the coupling of the charge currents to Maxwell's equations, including numerical methods to calculate the quality factor and frequency shift of N-doped Nb cavities. We show that for strong disorder, $\hbar/2\pi\tau T_c \gg 1$, i.e., the dirty limit, pair breaking due to the anisotropic gap energy of Nb limits the Q, but for intermediate disorder, Q has a peak of upper convexity as a function of the quasiparticle-impurity scattering rate $\hbar/2\pi\tau T_c$, suggesting that with "impurity engineering" $Q \sim 10^{12}$ are possible. The anisotropic gap for pure Nb is computed based on Eliashberg's equations and phonon band structures computed from density functional theory [7]. We also present new theoretical results for the effects of inhomogeneous disorder on the transition temperature T_c and frequency shift of SRF cavities. Our theoretical results are excellent agreement with experimental results on both the T_c and frequency shift reported in Ref. [8], and provide a new tool for characterization of high-Q SRF cavities.

This research was supported by National Science Foundation Grant PHY-1734332 and the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359.

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Spontaneous emergence of phase coherence of oscillating electric dipoles in quartz piezo-resonators at low temperatures

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Our experimental results reveal a spontaneous formation of the phase coherence in the system of oscillating electric dipoles in quartz piezo-resonators due to emergence and strengthening of the van der Waals interaction acting between dipoles on cooling. The phase coherence in this system is manifested: (i) via temperature-dependent, extremely accurate tune-up of the tuning fork's resonant frequency, typically in 9^{th} order with very narrow relative spectral line-width $\delta f_0/f_0$ less than 3.10^{-8} (see figure below), and (ii) the high frequency stability characterized by the low value of the Allan variation. Moreover, the phase coherent state is spontaneously formed even when the incoherent (noise) excitation signal is applied. It is worth to note that all above-mentioned characteristics are typical signatures for formation of a Bose-Einstein condensate of excitations.

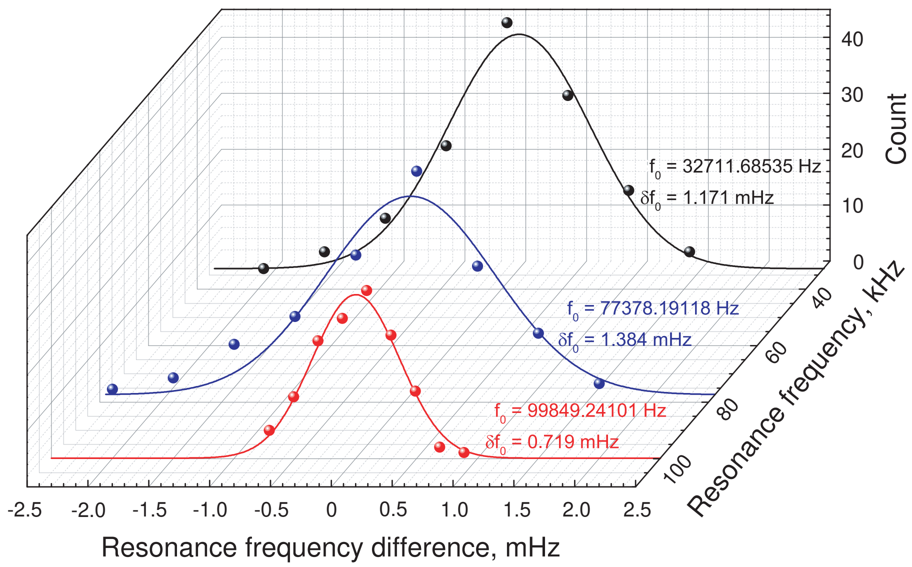

Figure 1: Distributions of the tuning forks' resonance frequencies measured at constant temperature of $\sim$ 8 mK. Lines show the Gaussian fits to experimental data.

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Magnetic microcalorimeters: Forefront technology for next-generation physics experiments

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Magnetic microcalorimeters (MMCs) are cryogenic particle detectors that are strongly advancing the state of the art in energy-dispersive single particle detection. They rely on the outstanding interplay between a highly-sensitive magnetic thermometer and a superconducting quantum amplifier, ultimately allowing to combine an excellent energy resolution, a fast instrinsic signal rise time, a large energy dynamic range as well as an almost ideal linear detector response in a single device. These key features make MMCs eminently suited for a variety of applications including atomic and nuclear physics, searches for dark matter and the neutrinoless double beta decay , direct neutrino mass determination, nuclear safeguards, Q-spectroscopy, radiation metrology, X-ray astronomy and laboratory astrophysics, heavy ion physics, mass spectrometry, and material analysis. More applications are continuously being developed and work is underway to establish MMCs as a standard technique for high-resolution spectroscopy.

In general, MMCs consist of a massive particle absorber suited for the particles to the detected that is coupled via a weak thermal link to a heat bath kept at a constant operation temperature well below 1 K as well as to a paramagnetic or superconducting temperature sensor that is placed inside a weak external magnetic field. The latter transduces the temperature rise of the detector upon the absorption of an energetic particle into a change of sensor magnetization that is precisely measured as a change of magnetic flux by means of a superconducting pickup coil and a superconducting quantum interference device (SQUID). The actual detector arrangement, i.e. the detector geometry and layout as well as the utilized readout technique, are routinely adjusted to the application the detector is developed for, ultimately allowing to built optimized detector for particular applications. Here, the use of modern methods micro- and nanofabrication, MMC detector comes along with high flexibility that allows to for detector customization.

In this talk, I will first shortly summarize the basics of magnetic microcalorimeters and related readout techniques as well as the present state of the art. I will then highlight two particular applications, i.e. the development of MMCs for X-ray spectroscopy with sub-eV energy resolution as well as MMCs for radiation metrology. I will conclude the talk by discussing our most recent advances related to the readout of ultra-large-scale MMC based detector arrays by means of SQUID based multiplexing techniques that are optimized for MMC readout.

Experimental observation of magnon superfluidity at room temperature

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In 1984 the new state of magnetically ordered matter has been discovered in antiferromagnetic superfluid ^{3}He-B - the spontaneously self-organized phase-coherent precession of spins [1]. It is the quasi-equilibrium state, which emerges on the background of the ordered magnetic state, and which can be represented in terms of the Bose condensation of magnetic excitations – magnons (mBEC). The magnon BEC state forms at a high density of excited, non-equilibrium magnons, when it is higher then the critical density of magnon BEC formation at given temperature. The 1000-fold narrowing of the resonance line due to mBEC was observed. The magnon BEC exhibit all the properties of magnon superfluidity, including phase-slippage at critical current, Josephson effect, quantum vortices ets. [2]. Later, we were able to observe mBEC-related phenomena in solid antiferromagnets at helium temperature [3] and recently in yttrium iron garnet (YIG) at room temperature [4].

In this presentation, we will give an overview of current experiments with non-planar magnetized YIG film that have been carried out at room temperature. The dynamic properties of magnons in this configuration have many analogues with magnons in superfluid ^{3}He. We will present the result of spatial superfluid transport of magnons [5], the optical detection of magnon BEC [6], and the results of the transformation of spin dynamics from the spin wave regime to the BEC state. We also present the observation of coherent magnon-phonon states [7]. The mBEC state can be seen as a promising platform for quantum computing at room temperature.

This work was supported by Russian Science Foundation(Grant 22-12-00322).
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Breaking the millikelvin barrier for on-chip electrons

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Cooling micro- and nanoelectronic systems to low temperatures is typically limited by weak electron-phonon coupling below 10 mK. Achieving sub-millikelvin electron temperatures would benefit research in quantum systems, allowing for further improvements in applications such as metrology and sensing, as well as aiding the search for new physical phenomena. The demagnetisation of on-chip electroplated metals, such as copper and indium, can yield effective electronic refrigeration below the base temperature of dilution refrigerators. The technique has been demonstrated by using copper and indium nuclear refrigerant to cool Coulomb blockade thermometers, which allow for primary electron thermometry throughout the cooling process. Several groups have been able to record low-millikelvin and sub-millikelvin temperatures [1-3]. Here we report on our work in cooling custom thin-film thermometers and progress made to understand the factors involved in optimising on-chip refrigeration.

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Revealing the complexity of Helium Mixture Films by Neutron Reflectometry

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Superfluid helium films have proved to be one of the most elusive quantum fluid systems for experimental investigation [1]. In this work we use neutron reflectometry at the ISIS Neutron & Muon Source to study liquid ^{4}He and 0.1% ^{3}He in ^{4}He mixture films. Thanks to the exceptional sensitivity and precision of this method, we were able to observe and study a 165 Å thick superfluid helium film formed on a silicon surface, over a temperature range of 170 mK to 1.5 K. In the temperature range of this experiment the change in reflectivity signal from a solely ^{4}He film is insignificant. However, the addition of 0.1% of ^{3}He dramatically changes the film behavior. In Fig.1 we present neutron adsorption against the normal direction to the substrate's surface. In the helium mixture film almost all adsorption comes from neutron scattering from ^{3}He atoms, therefore Fig.1 represents the distribution of ^{3}He atoms inside the film. At the lowest temperature of 170 mK, we observe a phase-separated ^{3}He -^{4}He mixture film with ^{3}He situated close to the surface. As the temperature increases, we witness a gradual dissolution of this ^{3}He top layer into the ^{4}He. At around 300 mK the entire helium film almost vanishes from the surface of the silicon substrate, leaving just clusters of mostly ^{3}He atoms. The observed anomaly in the film behavior may be associated with a phase transition. In the experiment we also discovered an unexpected restoration of the layered structure at 1.5 K. Our results could be important for the development of powerful dilution refrigerators which, to a significant extent, are limited by film flow effects.

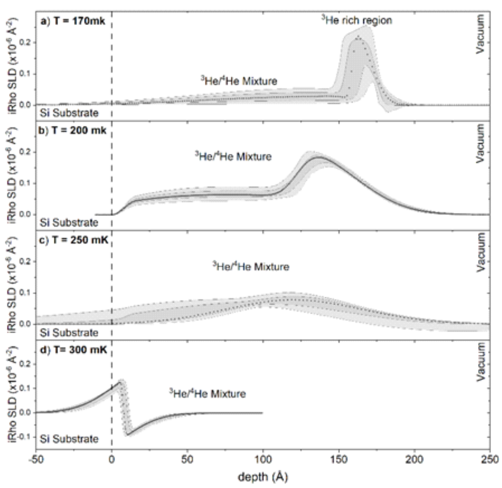

Fig. 1: Neutron adsorption

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Dynamics of Superconducting Qubit Relaxation Times

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Superconducting qubits are a leading candidate for quantum computing but display temporal fluctuations in their energy relaxation times T_1. This introduces instabilities in multi-qubit device performance. Furthermore, autocorrelation in these time fluctuations introduces challenges for obtaining representative measures of T_1 for process optimization and device screening. These T_1 fluctuations are often attributed to time varying coupling of the qubit to defects, putative two level systems (TLSs). In this work, we develop a technique to probe the spectral and temporal dynamics of T_1 in single junction transmons by repeated T_1 measurements in the frequency vicinity of the bare qubit transition, via the AC-Stark effect. Across 10 qubits, we observe strong correlations between the mean T_1 averaged over approximately nine months and a snapshot of an equally weighted T_1 average over the Stark shifted frequency range. These observations are suggestive of an ergodic-like spectral diffusion of TLSs dominating T_1, and offer a promising path to more rapid T_1 characterization for device screening and process optimization.

Scaling up superconducting quantum circuits

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Coherent control of a superconducting quantum device, called a Cooper-pair box, was first demonstrated more than twenty years ago in Japan [1], triggering the worldwide research on superconducting quantum bits (qubits). Consecutive efforts to improve design, materials, qubit coherence, and control fidelity since then have led to a recent dramatic increase in the number of available qubits. Still, there are many things to be done to scale up superconducting quantum circuits in order to move from noisy intermediate-scale quantum (NISQ) devices to error-correctable, and ultimately fault-tolerant, quantum computers. Modern designs of superconducting quantum circuits almost exclusively adopt the circuit QED architecture [2], in which the qubits are controlled and read out by microwave pulses. A key issue to be addressed then is a method to deliver microwave signals to respective qubits that are separated by just a few hundreds of microns. When qubits are arranged on a chip, i.e., two-dimensionally, the scalability of signal lines (wiring) poses a particular challenge. We adopt a square-lattice qubit arrangement with the coaxial cables addressing the chip from the vertical direction [3, 4]. In this talk, I will discuss the details of our superconducting qubit hardware as photographed in Fig. 1.

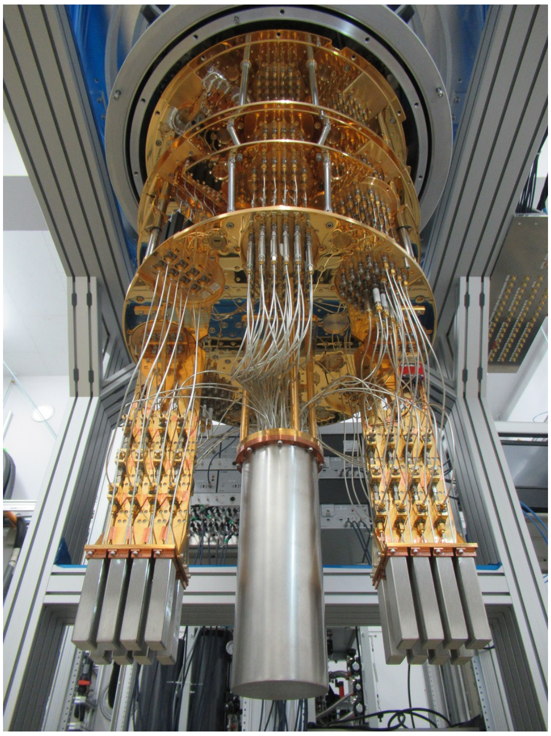

Fig. 1: Inside of a dilution refrigerator designed for multi-qubit superconducting quantum circuits.

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Thermometry and refrigeration of microscopic samples at ultra-low temperatures and high magnetic fields

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The NHMFL High *B*/*T* facility at the University of Florida in Gainesville pursues the mission to enable user experiments at the combined extremes of high magnetic fields and ultra-low temperatures (ULT) below one millikelvin. Calorimetry and thermal transport are particularly challenging in this environment, due to a lack of suitable thermometry, yet these are essential probes of quantum states like quantum spin liquids, topological surface and edge states, superconductors, or quantum criticality. To meet user demand for such experiments, especially on small samples of quantum materials, our group is developing fast and compact high-resolution ULT thermometers based on quartz tuning forks in liquid ^{3}He. I will report on recent progress in the miniaturization of such tuning fork thermometers, and their possible application in user experiments. Another recent area of interest has been electronic nanostructures, where extremely low electron temperatures are desired. I will discuss approaches to reduce electron temperatures both via passive cooling and via an innovative solid state cooling mechanism using an electron gas as the working medium in a heat pump.

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Current perspective of nuclear spin-liquid state in ^{3}He monolayers

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Quantum spin liquid (SL) has long been a hot topic in condensed matter physics since the original prediction in 1973 [1]. The first SL candidate was found in the nuclear spin system of ^{3}He monolayer adsorbed on graphite in 1997 [2]. This problem acquired wider interests after the similar SL candidate was found in a layered organic compound in 2003 [3]. In spite of extensive studies in the past two decades, the microscopic understanding of SL still remains unsatisfactory. This is due to disorders, the lack of exact knowledge on spin interactions, and the existence of long-range ordering at very low temperatures in most of the candidate materials.

In this talk, I would remind advantages of ^{3}He monolayer for the SL research, i.e., material cleanness, structural simplicity, point-like magnetic moment with nuclear spin 1/2 (absence of spin-orbit interaction), and quantitative knowledge on the spin Hamiltonian (ring-exchange interactions J_P). Then, I would introduce recent manifestations of such advantages, that are experimental and theoretical findings of crucial roles of *intrinsic* density fluctuations in stabilizing the SL state in ^{3}He monolayers in two different circumstances. One of them is ^{3}He monolayer adsorbed on graphite preplated with ^{4}He or ^{3}He monolayer (^{3}He/^{4}He/gr or ^{3}He/^{3}He/gr), and the other is that with HD bilayer (^{3}He/HD/HD/gr). They have essentially the same SL state exhibiting the specific heat (c) $\propto T$ and the magnetic susceptibility (χ) $\rightarrow$ const. below $T \leq 0.1J_c$, where J_c is the characteristic exchange energy. Interestingly, these features are shared by some of the electronic candidate materials [4], which suggests a common mechanism behind. The phase hosting the ^{3}He SL state is most likely a new quantum phase characterized by a large compressibility. It exists as a distinct phase between the known Fermi liquid and quantum solid phases in the phase diagram. I would call the phase "quantum liquid crystal" (QLC), in which a partially broken spatial symmetry coexists with quantum fluidity. Such a finite quantum fluidity seems to be supported by recent simultaneous thermodynamic and transport measurements for a similar new phase found in ^{4}He monolayer (^{4}He/^{4}He/gr) [5].

It could be challenging to apply the existing ring-exchange theory [6] developed for well localized systems to the QLC phase with density fluctuations. However, if the time scale of the fluctuations is much longer than that of J_P, the fluctuation effects might be taken into account as distributions of J_P. Recently, such an attempt has been carried out with quite encouraging results [7]. The so called "random-bond ring-exchange" model involving the effective two-spin exchange (J_{eff}), the four-spin exchange (J_4) and their distributions ($\pm$30%) can explain most of the known experimental properties, for example, the gapless SL ground state, $c \propto T$, $\chi \rightarrow$ const, and the half-magnetization plateau. The key ingredient here is not *quenched* disorders inevitably embedded in electronic materials but intrinsic quantum density-fluctuations.

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Microwave cavity optomechanics coupled with a micromechanical graphene resonator to investigate the nature of two-dimensional helium films

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We propose an experimental method to investigate the properties of the helium films adsorbed on graphite. Because of the complexity in the exfoliated graphite substrate and the extreme inaccessibility to identifying the structural ordering, the nature of 2D helium films has not been clearly understood yet. An optomechanically coupled cavity with a micromechanical graphene resonator may facilitate the simultaneous measurements of the superfluidity and crystallinity of the helium films. Both resonance frequency and dissipation of the graphene mechanical resonator are mainly altered by the appearance of the two orders. The shift in the resonator response can be measured with extremely high sensitivity by capacitively coupled superconducting coplanar wave guide using by the optomechanically induced transparency. Here, we present the progress in the fabrication the microwave superconducting coplanar waveguide cavity, capacitively coupled to a graphene mechanical resonator. We expect that this measurement scheme can be utilized as an ultimate platform to study the 2D nature of quantum and classical gases.

Developement of surface X-ray diffraction at low temperatures

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Surface at low temperatures around/below 1 K is a frontier in surface science. For example, two-dimensional superconductors with forms of ultra-thin films and a few atomic layers of reconstructed surfaces such as Si(111)-($\sqrt{7} \times \sqrt{3}$)-In have been extensively studied [1]. Likewise, helium atomic layered films on graphite are providing wide variety of systems to study quantum phenomena in low dimensions and, hence, are the prototype of low temperature physics [2]. However, structural information of these systems have definitely been lacking. An experimental probe to extract structural information of those systems is therefore eagerly awaited.

With the increase in the brilliance of synchrotron radiation source, surface X-ray diffraction (SXRD) has grown and expanded the scientific field of application [3]. SXRD has a potential to be such a structural probe, provided that we prepare a low temperature environment of a sample, since weak interactions of X-rays with matter become advantageous to suppress thermal inflow by X-ray irradiation.

At the synchrotron facility SPring-8, we are developing the cooling system combined with the existing ultra-high vacuum (UHV) instrument for in-situ synchrotron observation using SXRD. To realize low temperatures around 1 K of a sample, we employ combination of a 0.1 W Gifford-Mcmahon cryostat with an evaporative cooling of liquid helium. The system reaches a sample base temperature of 1.4 K for more than 2 hours without additional helium supply, consisting of a small chamber for a sample environment inside the UHV instrument so that a helium gas (or inert gas) can be introduced to the sample.

As a prototypical substrate, we use a highly oriented pyrolitic graphite (HOPG). For an HOPG, because of its high in-plane thermal conductivity, synchrotron SXRD is possible with our system that suppresses the increase of temperature by X-ray irradiation within 4.9 mK at 1 K of the substrate under the well-defined irradiation condition with a photon flux of 2×10^{11} photons/s for X-rays of 20 keV in energy [4].

We report the current status of developing the cryogenic system for SXRD at around 1 K and preliminary results of helium layers on HOPG at low temperatures using SXRD. This work was supported in-part by the JSPS KAKENHI Grant Number 22H03883.

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Strong-coupling thermodynamics of superfluid ^{3}He

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Cosmology and the AB transition in superfluid ^{3}He

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The extreme purity and precise control of pressure and temperature achievable in the laboratory make the superfluid ^{3}He AB transition ideal for testing the theory of first order phase transitions in the early Universe. Such a phase transition, which appears naturally in many extensions of the Standard Model of particle physics, could provide the departure from equilibrium needed for a dynamical explanation of the baryon asymmetry of the Universe. It could also produce gravitational waves of a frequency observable by future space-based detectors such as the Laser Interferometer Space Antenna (LISA).

All calculations of the gravitational wave power spectrum rely on a relativistic version of the classical nucleation theory of Cahn-Hilliard and Langer, due to Coleman and Linde. Yet when the A phase of superfluid ^{3}He is supercooled, the B phase appears far faster than classical nucleation theory would predict. If the appearance of B phase is due to a new rapid intrinsic mechanism, gravitational wave production could be rendered negligible.

Here we discuss studies of the AB phase transition dynamics in ^{3}He, both experimental and theoretical, emphasising the importance of understanding the mechanisms behind the observed transitions. We outline the experiments of the QUEST-DMC collaboration designed to eliminate extrinsic nucleation mechanisms, and show how the technology for cosmological phase transition simulations can be used to better understand the dynamics of the AB transition.

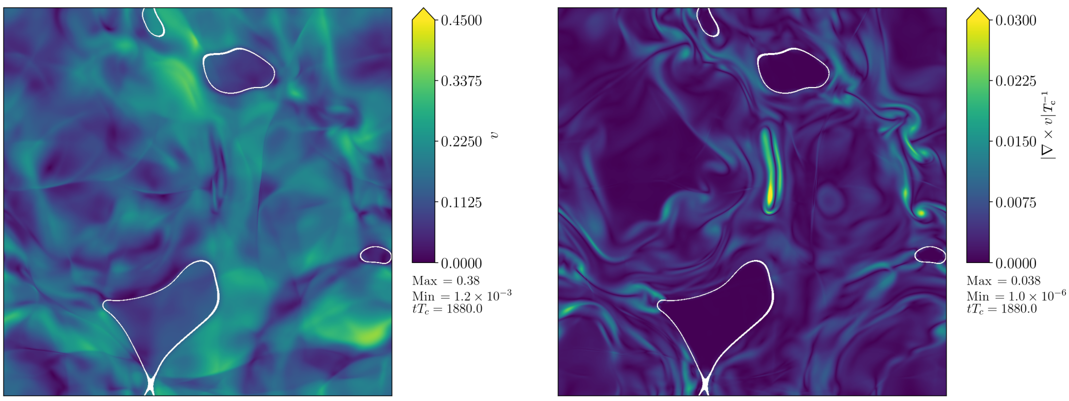

Figure 1: Normal fluid velocity distribution after a supercooled first order phase transition in the early Universe [1], (left) with vorticity (right).

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Dynamics of quasiparticles in the surface-bound two-dimensional superfluid ^{3}He

S. Autti[1], R. P. Haley[1], A. Jennings[1], G. R. Pickett[1], M. Poole[1], R. Schanen[1], A. A. Soldatov[2], V. Tsepelin[1], J. Vonka[1], V. V. Zavjalov[1], and D. E. Zmeev[1]

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^{3}He-B is a topological superfluid, which serves as a model system for many phenomena in strongly-correlated materials. Here we report the discovery of an anomalously high lifetime of quasiparticles in the system of surface Andreev-bound excitations in superfluid ^{3}He-B [1]. We also infer the dynamics of the quasiparticles.

In our experiments, we can empty the edge states into bulk in a controllable manner by imposing superflow along the surface. The excess quasiparticles in bulk can be readily detected using a bolometric measurement scheme. We measure the lifetime of the surface quasiparticles to be 6 milliseconds, which is a lot longer than any other characteristic timescale in the system. We interpret this lifetime as characterizing the diffusive flow of the quasiparticles along the circumference of our cylindrical probe. We also find that the bulk Bogoliubov excitations and the edge quasiparticles practically do not interact (Fig. 1).

Our discovery can explain two unexpected non-equilibrium phenomena: the flow of supercurrent at velocities by far exceeding the critical Landau velocity [2] and anomalously high thermal conductivity in a strongly confined superfluid channel [3].

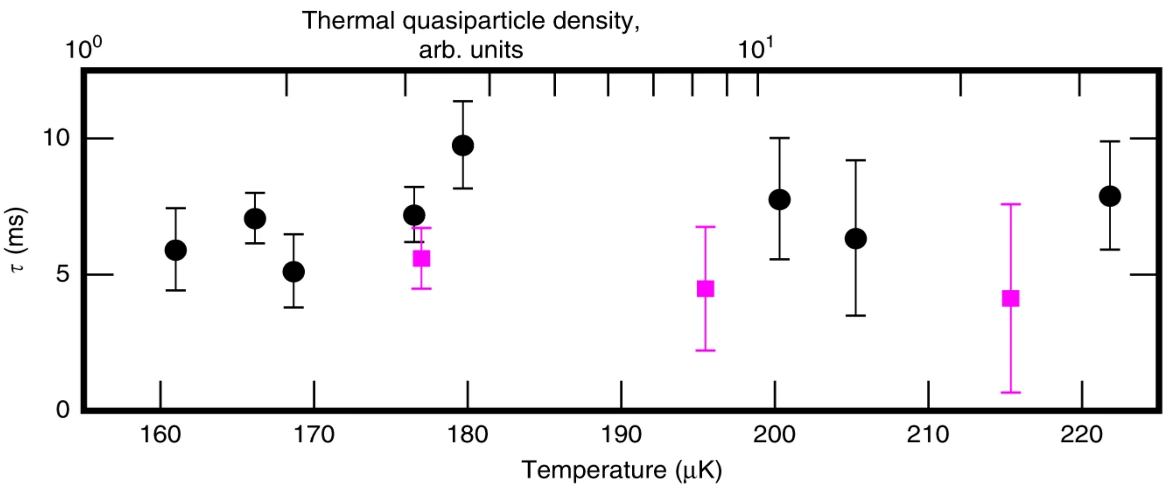

Fig. 1: Independence of the surface-bound superfluid and the bulk superfluid. The characteristic lifetime τ is independent of the temperature (bottom axis), and therefore the density, of bulk quasiparticles (top axis).

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In memory of Joe Vinen

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(Abstract written by K. Shirahama)
William Frank "Joe" Vinen, a pioneer in low-temperature physics, passed away on June 8. Professor Ladik Skrbek, one of his closest collaborators, will tell us about his memory.

Vortex Emission of Counter Flow Turbulence in Superfluid ^{4}He

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We report the vortex emission of counter flow turbulence produced in a narrow channel in superfluid ^{4}He. In a channel, vortex lines emerge in thermal counter flow above a critical velocity. We generated turbulence in a circular channel with an inner diameter of 0.3 mm by thermal counter flow, to study the emission of vortex rings detected by a vibrating wire mounted outside on the axis of the channel. Since a superfluid vortex tends to move on a superfluid flow, the emission of vortex rings are observable outside the channel when the superfluid flows out. In the opposite direction, the emission is likely to reduce considerably, though we observed higher detection rate of vortex rings for the opposite flow. This behavior suggests that vortex rings can move against the superfluid flow without dissipation in a counter flow.

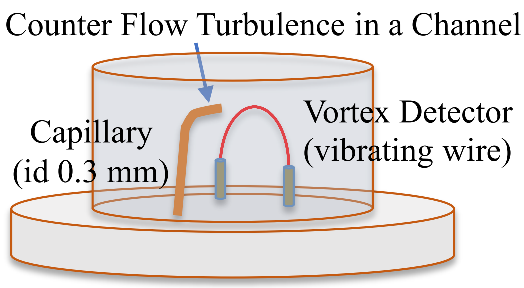

Fig. 1: Experimental setup in a box. The capillary connects the box to an outer helium bus. The end of the capillary is faced with the vibrating wire, which can detect a vortex ring. A heater is also mounted to produce counter flow in the capillary (not shown). During generating counter flow turbulence, vortex rings are emitted outside the capillary, colliding with the vibrating wire.

Acoustic emission in normal and superfluid He-3.

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We present our experimental work characterizing the damping experienced by custom-made quartz tuning forks submerged in ^{3}He over a wide range of frequencies and temperatures. Our tuning forks had identical width and thickness and we used the fundamental and first overtone modes with a range of lengths (0.7 mm - 1.9 mm, see Fig. 1) to cover frequencies from 20 kHz to 600 kHz. We have measured tuning fork damping with in normal ^{3}He from 1.5 K down to 12 mK temperatures and in superfluid ^{3}He-B well below the transition temperature, in the ballistic regime. Our data complements previous work on tuning fork damping where forks were encapsulated in mm-sized cavities [1] and removes any ambiguities associated with supression of acoustic emission in the enclosed volume.

At low frequencies, the obtained temperature scaling of hydrodynamic damping in normal ^{3}He agrees well with present theoretical models [2] over the whole investigated temperature range. The acoustic damping starts to dominate around 100 kHz in both normal and superfluid ^{3}He for our devices. For the acoustic damping regime, we employ the 3D model originally developed for ^{4}He [3], describing prong tips as a longitudinal acoustic quadrupole and consider independently the device geometry and fluid properties. In accordance with the model, we observe steep frequency dependence of the damping with $f^{5.5}$, strongly limiting the use of similar devices as sensors. The similarity of our results with ^{4}He points towards the same mechanism of wave emission of first sound in normal ^{3}He and liquid ^{4}He and zeroth sound in superfluid ^{3}He. Therefore, the model can be used to predict the limiting frequencies for devices of various shapes and sizes, playing an important role for designing of novel NEMS/MEMS structures for quantum turbulence and single vortex dynamics research.

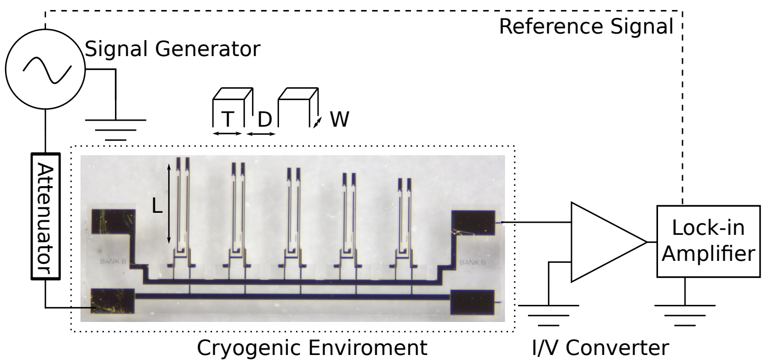

Fig. 1: The array of custom-made quartz tuning forks with resonant frequencies covering the range from 20 kHz to 600 kHz.

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Numerical study on superdiffusion of ultra-quantum turbulence in superfluid helium-4

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In classical fluid dynamics, turbulent diffusion has been extensively studied. On the other hand, the knowledge of the diffusion of quantum turbulence (QT) has been limited. Recently, the visualization experiment [1] observed the diffusion of quantized vortices in ultra-quantum turbulence (UQT) driven by a thermal counterflow, and discovered that the quantized vortices exhibit the superdiffusion scaling $\langle \Delta x^2 \rangle \propto t^\gamma$ with the exponent $\gamma = 1.6$ at small times, where $\langle \Delta x^2 \rangle$ is the mean-squared displacement of quantized vortices. Such a scaling law can be a new way to understand the physics of QT.

The aim of this study is to uncover the nature of the superdiffusion of UQT using numerical simulation. We use the numerical simulation of the vortex filament model with the tracer particles of the vortex filaments. First, we study the isotropic UQT at 0 K in order to know the turbulent diffusion of the pure superfluid. To generate the UQT at 0 K, we constantly inject randomly oriented vortex rings into the system. As a result, we confirmed that the quantized vortices obey the superdiffusion scaling of the exponent $\gamma = 1.6$ at small times even at 0 K. The obtained diffusion scaling transits from superdiffusion to normal diffusion at large times, and this behavior agrees with the experiment [1]. Our analysis shows that this transition of the diffusion scaling comes from the reconnection between quantized vortices. As a theoretical insight on the superdiffusion, we found that the superdiffusion is related to the temporal velocity correlation of quantized vortices. Second, to investigate the finite temperature effects, we performed simulation of the ring injection above 1 K (*i.e.*, 1.1 K, 1.3 K, 1.6 K, and 1.9 K). Our results show that the superdiffusion scaling is sustained above 1 K, and the scaling exponent γ is around 1.6. Third, we performed simulations for a thermal counterflow above 1 K. Our results of scaling exponent are consistent with the counterflow experiment [1].

This study made some important understandings for diffusion of UQT. The obtained knowledge may lead to future studies of diffusion scaling in various quantum systems. The details of this study can be seen in our preprint [2].

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Thermodynamic study of bosonization in interacting SU(N) fermions

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Advances in cooling and trapping neutral atoms enabled the investigation of ultracold fermions with an enlarged SU(N) spin symmetry, and offered unique possibilities for exploring correlated quantum many-body systems with high spin. In such a fermionic system of ultracold two-electron ytterbium, multi-component fermions interact identically with others owing to SU(N) symmetry. In this talk, we report our progress toward a quantitative thermodynamic study of SU(N) fermions in the Fermi liquid regime, including experiments on measuring Tan's contact and compressibility, revealing bosonization. We highlight the highly tunable features of the system, such as spin multiplicity, spin imbalance and dimensions. These developments, together with recent experiments from other groups, set the stage for exploring SU(N) spin symmetry in the context of magnetic correlations both in bulk and lattices.

Quantum simulation of SU(N) magnetism in optical lattices

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Ultracold atomic gases has been served as useful quantum simulators for a variety of many-body systems as its simplicity and high controllability. Especially, optical lattices have made it possible to reproduce the behavior of solid electrons in an ideal environment. Study of the Hubbard model, a paradigmatic theoretical model for strongly correlated electrons, with optical lattices is one of the most fruitful quantum simulation experiments and with the aim of understanding high-Tc superconductivity.

Making use of high degree of freedom of ultracold atoms, we can also consider quantum simulation of models that are of theoretical interest but have no or few counterparts in real materials. The SU(N) Hubbard model is obtained by enlarging the spin SU(2) symmetry of the standard Hubbard model to the general SU(N) symmetry [2]. It is predicted to have very rich ground-state phase diagram including the possibility of chiral spin liquids, whereas the realization in solids material is limited to some special cases such as transition metal compounds.

Ultracold alkaline-earth-like atoms have natural SU(N) symmetric interactions, and when loaded into optical lattices, they are able to realize the SU(N) Hubbard model to the very high accuracy. We have investigated the property of the SU(6) Hubbard model with ^{173}Yb atoms with nuclear spin $I = 5/2$. One of the important features is magnetic correlations realized at low temperatures. As in the case of SU(2) symmetry, the SU(N) Hubbard model on simple cubic lattices exhibits anti-ferromagnetic correlations at unit filling. We have measured nearest-neighbor spin correlations in the SU(6) Hubbard model with the technique of singlet-triplet oscillations [3] and revealed that highly correlated states are realized especially in lower dimensional lattices. By carefully comparing the observed correlations to state-of-the-art theoretical calculations, we were able to deduce the temperature in the lattice to be 10% of the tunneling energy [4], which is the lowest among those reported in ultracold atomic Fermi-Hubbard systems. This result will strongly encourage the quantum simulation of the SU(N) Hubbard models with optical lattices.

In addition, I also would like to talk about the results of the correlation measurements on a square plaquette lattice, together with recent experiments in the presence of dissipation [5].

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Surface roughness dynamics in a one-dimensional Bose-Hubbard model

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Dynamical scaling is one of the most fundamental concepts for uncovering universal aspects behind non-equilibrium phenomena. Among them, surface growth physics has played an essential role in deepening our understanding of such universal dynamics [1]. Previous literature has investigated the Kardar-Parisi-Zhang (KPZ) equation, being a theoretical minimum model for the classical surface growth, and has found the dynamical scaling in the surface-height correlation. Furthermore, one has unveiled nontrivial connections between the height distribution and the random matrix theory, and now the celebrated KPZ universality class is established [2].

In recent years, such universal surface growth dynamics has been explored in isolated quantum systems. Ljubotina *et al.* studied a spatial and temporal spin-correlation function in the spin-1/2 XXX model, finding the emergence of the KPZ universality in the infinite temperature case [3]. Stimulated by this intriguing result, several theoretical groups have investigated quantum dynamics from the perspective of universal surface growth [4,5]. Very recently, using cold atoms in optical lattices, Wei *et al.* reported the experimental observation of the KPZ superdiffusion in the spin-1/2 XXX model by focusing on the cumulants of polarization transfer [6].

In our talk, based on Refs. [7,8], we will show our theoretical results of the surface growth dynamics in a one-dimensional Bose-Hubbard model. The essential ingredient for our work is a surface-height operator defined by the summation of the particle-number fluctuation operator over the partial system. One can introduce this operator by employing a nontrivial correspondence between the KPZ equation and the fluctuating hydrodynamics [9]. We solve the time-dependent Schrödinger equation for the hard-core boson limit, compute the surface roughness defined by the standard deviation of the surface height operator, and find that the surface roughness exhibits the dynamical scaling called the Family-Vicsek scaling. The estimated dynamical scaling exponent is $z = 1$, which corresponds to the ballistic transport. Furthermore, we use a dephasing Lindblad equation, investigating how dissipation affects this dynamical scaling. Our exact numerical calculation finds that the Family-Vicsek scaling still emerges while the scaling exponents become the exponents of the Edwards-Wilkinson equation, which is the classical surface growth model with the diffusive dynamical exponent $z = 2$. We can analytically explain this drastic change in the Family-Vicsek scaling by applying a perturbative renormalization-group analysis to the Lindblad equation.

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Pair excitations of a quantum spin on a proximitized superconductor

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A magnetic impurity interacting with a superconductor exhibits a rich excitation spectrum resulting from the superposition of quasiparticles and spin excitations which appear as Yu-Shiba-Rusinov and spin-flip excitations in the tunneling spectra.

In this talk, we report how tunneling electrons can also excite pair-breaking excitation in the superconductor in the presence of magnetic impurities. This process, which is forbidden for electrons tunneling into clean superconductors, it is shown to become possible in the presence of magnetic impurities. In addition, by combining scanning tunneling spectroscopy with theoretical modeling, we map the excitation spectrum of a Fe-porphyrin molecule on the Au/V(100) proximitized surface and uncover a manifold of many-body excitations while following their behavior across a parity-changing quantum transition. Pair excitations emerge in the tunneling spectra as peaks outside the gap in the strong coupling regime of the magnetic impurity, and their energy scales with the substrate quasi-particle gap. Our results unravel the quantum nature of magnetic impurities on superconductors and prove that pair excitations behave as parity detectors for magnetic impurities.

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See two Figures in the second page.

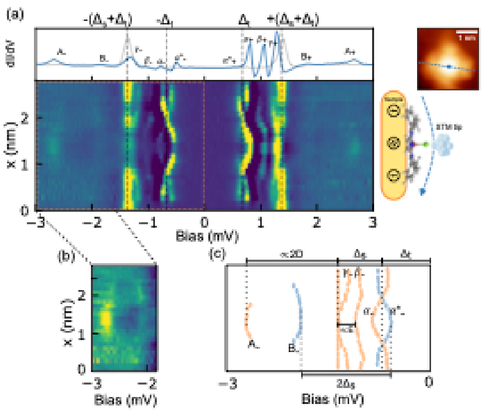

Fig. 1: a) Line of dI/dV spectra measured across a 4-fold FeTPPCl molecule (topography and sketch on the right) at constant current (V_S = 3 mV, I = 75 pA). The single spectra on top is measured in the center and serves as a reference. b) Contrasted part of the out gap portion of the line-scan to highlight the signals A and B. c) Trace of the peaks energy positions along the line profile in the negative bias portion.

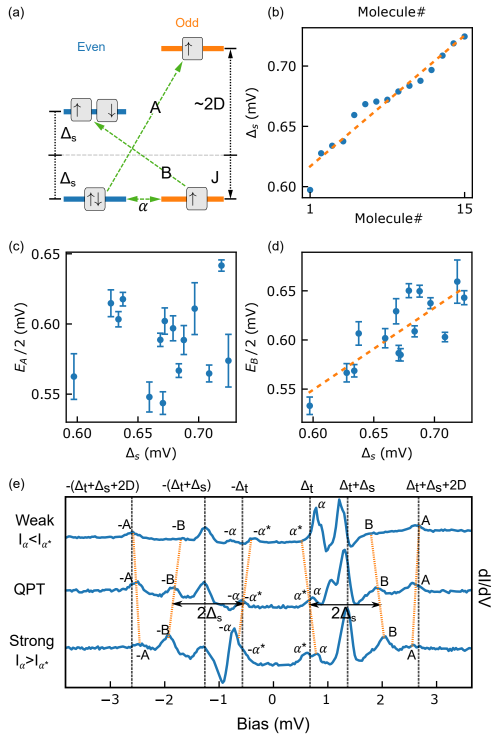

Fig. 2: (a) Scheme of A and B excitations (J fixed to the QPT point); Peak A scales with anisotropy D and Peak B with Δ_s. b) Value of Δ_s measured close to 15 different molecules lying on different positions on the substrate, and on film with different thickness. c) Evolution of the position of peak A for the 15 molecules, showing no correlation with Δ_s. d) Evolution of the position of peak B with Δ_s, showing a linear dependence. e) Spectra of three molecules of the set, in weak, strong and at QPT (detected through their particle hole asymmetry). It shows the renormalization of the anisotropy, peak A shifts lower for higher J. Peak A is more intense in the weak coupling case, while peak B with in strong coupling regime.

1D Majorana Goldstinos and partial supersymmetry breaking in quantum wires: From Majorana pumps to braiding

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Extended supersymmetry with central charges (centrally-extended SUSY) has been one of the most important notions in quantum field theory and string theory since the second string revolution in the 90s and the revolution of quantum field theory by Seiberg and Witten. Despite its great importance in formal aspects of quantum field theory and string theory, centrally-extended SUSY seems to be not directly related to reality, because the extended N=2 SUSY does not allow chiral fermions relevant for elementary particles such as quarks and leptons. In high energy phenomenology, only N=1 SUSY and its breaking are considered.

In our recent works[1,2], we provide the first experimentally accessible example of centrally-extended SUSY and partial spontaneous SUSY breaking in condensed matter. Specifically, we describe the realization of a periodic chain of partially-overlapping 0D Majorana modes in 1D Majorana nanowires, by applying periodically and spatially-modulated potentials or magnetic fields. This system realizes a dispersive 1D Majorana fermion which we identify with the Nambu-Goldstone mode (Goldstino) of the spontaneously and partially broken SUSY. Notice that the famous Witten's no-go theorem prohibiting partial SUSY breaking can be evaded only by the presence of a central extension in the extended SUSY algebra, as realized in our model. Despite the several proposals to realize SUSY in condensed matter, our proposal gives the first condensed matter realization of centrally-extended SUSY.

Moreover, we will show how periodic chains of partially-overlapping 0D Majorana modes can realize a sliding lattice of Majorana modes, a "Majorana pump", via the adiabatic translation of one Majorana mode for each half rotation of an externally applied field. We propose the realization of this sliding lattice to engineer an alternative braiding protocol in trijunction geometries.

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Vortex motion and dissipation mechanism in strongly coupled holographic superfluid

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We report a new mechanism of vortex motion and dissipation by using holographic model of extreme Reissner-Nordstrőm black hole background[1], which is a naturally strong coupled system. We used an external flow to push a single vortex, and then found that the vortex in the holographic model has a non-negligible inertial mass, which increases with decreasing temperature. At low temperature, vortex can be thought of as having a hard core, which can be proved by using baym formula to match the vortex mass.

We found that deformation occurs in the process of vortex motion, and the deformation greatly affects the friction coefficient. By comparison, we found that the friction coefficient obtained by vortex dipole motion is the friction coefficient after vortex deformation.

The results of the holographic model are completely different from those of the general fluid and GP equation. We believe that this is caused by the fact that the superfluid components in the vortex core are pushed out and the normal particles are accumulated to form the hard core in the strongly coupled superfluid, just like what happens in the strongly coupled superconductor[2].

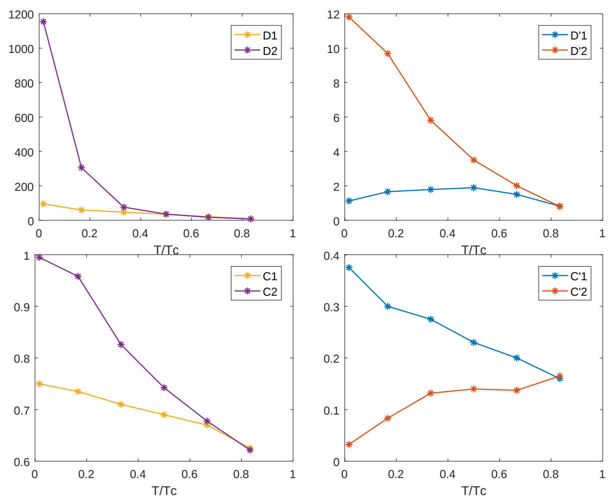

Figure 1: The friction coefficient of holographic model before and after deformation.

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Half-quantum vortices in confined ^{3}He superfluids

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Superfluids are often described via a macroscopic wave function, also called the order parameter, of the form $\Psi = |\Psi|e^{i\phi}$, defined by the amplitude $|\Psi|$ and phase ϕ. The mass flow in the superfluid is proportional to the phase gradient $\mathbf{v}_s \propto \nabla\phi$, resulting in a condition that the superfluid is irrotational, i.e. $\nabla \times \mathbf{v}_s = 0$ for a smoothly varying phase. Rotation is, however, allowed via quantum vortices – line defects at which $|\Psi| \to 0$. The flow around the vortex core is quantized in the sense that the path integral of the superfluid velocity field, called circulation, around the vortex can only take discrete values given by the condition that the order parameter remains singly valued. From this condition it follows that the phase winding around the vortex can only take values $2\pi N$, where N is an integer. For a typical singly quantized vortex $N = 1$.

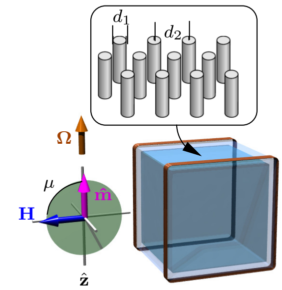

Fig. 1: The superfluid order parameter is modified in the presence of a matrix of parallel strands oriented along a common axis $\hat{\mathbf{m}}$ with typical parameters $d_1 \approx 9\,\mathrm{nm}$ and $d_2 \sim 30 - 50\,\mathrm{nm}$.

In some instances, such as for the superfluid phases of ^{3}He, the order parameter takes on a more complicated form. Depending on the remaining symmetries of the superfluid phase in question, such an order parameter may support half-quantum vortices (HQVs) with $N = \frac{1}{2}$. The order parameter around the HQV remains singly valued since the mass flow is accompanied by spin current which introduces an additional sign change on a closed path around the HQV. Of the bulk phases of ^{3}He HQVs were predicted to exist in ^{3}He-A [1], but were never observed. The introduction of nematic nanostructured confinement led to the discovery of novel superfluid phases in ^{3}He [2], soon followed by the observation of HQVs in the polar phase [3]. Additionally we will discuss the properties of HQVs in the polar-distorted phases [4] and demonstrate that HQVs can be created even in stationary experiments, where their density is controlled by quench rate and applied magnetic field via the Kibble-Zurek mechanism [5].

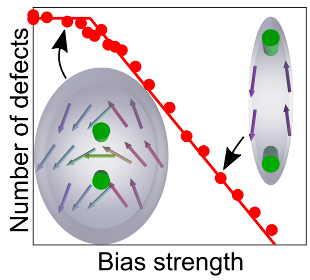

Fig. 2: Applied bias field may be used to suppress the number of HQVs created by the Kibble-Zurek mechanism in the phase transition from the normal fluid to the polar phase.

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Incipient Pair-Fluctuation Effects on Quasiparticle Transport in Liquid ^{3}He

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Nonequilibrium properties of a Fermi liquid are well described by a Boltzmann-Landau kinetic equation for the quasiparticle distribution function. For such a system at temperatures near the superfluid/superconductor phase transition, Cooper pair fluctuations are long-lived and can influence physical properties of the normal phase. We report new results for the leading corrections to the Landau kinetic equation using the Keldysh method that result from quasiparticle emission and absorption of long-lived pair fluctuations [1].

As an application of our theory we calculate the increase in the attenuation of zero sound attenuation that results from the scattering of quasiparticles by long-lived pair fluctuations, shown in Fig. 1. The theoretical results are in excellent agreement with both the temperature and pressure dependence of the excess attenuation of zero sound reported by Paulson and Wheatley [2]. We also predict a correction to the zero sound velocity which should be observable.

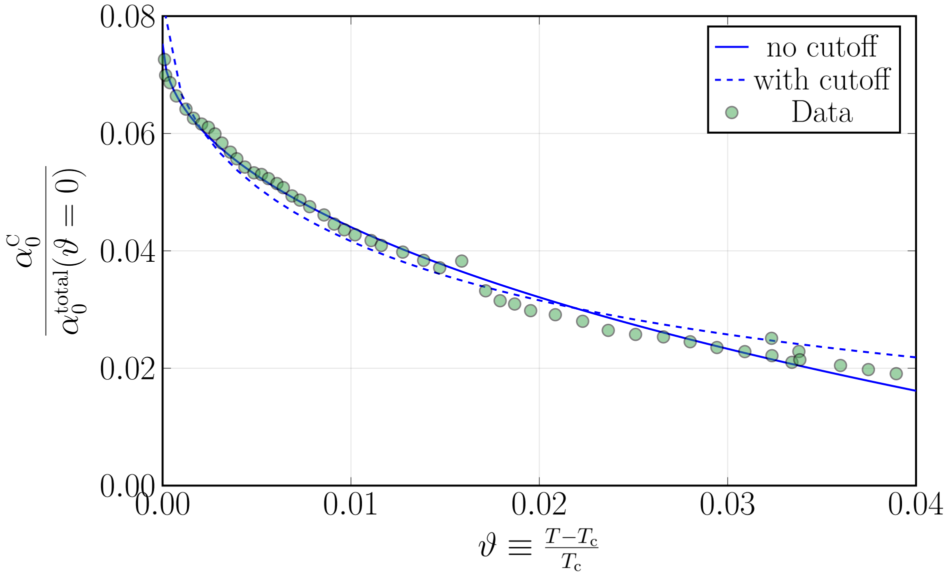

Fig. 1: This plot shows the comparison between our theory and the data taken from the paper by Paulson and Wheatley [2]. The calculation of zero sound attenuation needs renormalization. The dashed line is obtained from the method used by Samalam and Serene [3], which has a cutoff, and the solid line is calculated without the cutoff.

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Pulsed NMR studies of a 1D ^{3}He system

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It has been demonstrated theoretically that for quantum fluids (^{3}He, ^{4}He, H_2, HD) constrained to nanoscale dimensions where the thermal de Broglie wavelength and/or the Fermi length become comparable to or larger than available pore or channel size, new quantum states can emerge [1,2]. In this presentation, we report on an experimental study of such systems using pulsed NMR techniques. The nuclear spin lattice relaxation times at various low temperatures are measured to investigate the dynamics of highly degenerate ^{3}He confined to the surface of ^{4}He preplated nanotubes of MCM-41. The ^{3}He line density determined from *in situ* isotherm measurement was about 0.93 nm^{-1} corresponding to a Fermi degeneracy temperature of $T_F \approx 0.1$ K. To enhance the thermalization of the sample, fine silver power is uniformly mixed with the MCN-41 sample. Experiments conducted down to 10 mK reveal a close to linear temperature dependence of the nuclear spin-lattice relaxation times (T_1) for $T < T_F$ and a peak at $2T_F$, which is predicted for a Luttinger liquid (LL) in the density range [3].

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Broadband SQUID NMR for studies of confined superfluid helium-3

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Anisotropic pair breaking modifies the order parameter of unconventional p-wave superfluid ^{3}He in the vicinity of surfaces and interfaces. Strong confinement in a cavity of height comparable to the coherence length, tuneable between 20 and 80 nm by pressure, extends this effect over the whole sample volume, favouring the stability of chiral ^{3}He-A over time-reversal invariant ^{3}He-B [1]. Quasiparticle scattering boundary condition other than specular on the surfaces results in additional pair breaking, thus suppressing both the superfluid order parameter and the superfluid transition temperature T_c. Since ^{3}He is an extremely pure and defect-free system, and thus not affected by impurity-related pair breaking, we can experimentally study the sole effect of the surface scattering boundary condition on the phase diagram [2].

Tuning the boundary condition between diffuse and specular in situ is achieved via addition of controlled amount of ^{4}He impurities coating all the sample surfaces with ^{4}He film. Our earlier extremely sensitive SQUID-NMR experiments probing superfluid ^{3}He in a nanofabricated atomically smooth 200 nm high cavity show that with no added ^{4}He, the presence of a magnetically active surface boundary layer of solid ^{3}He may affect the superfluid order beyond the modifications caused by momentum scattering boundary condition alone [2]. 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, implying also an excess of low-energy surface-bound states.

The earlier experiments were done using a tuned pick-up circuit at ^{3}He precession frequency close to 1 MHz [2, 3, 4, 5]. At lower magnetic fields the interpretation of superfluid frequency shifts in the presence of the solid ^{3}He boundary layer becomes clearer and should allow the precise determination of superfluid energy gap. Here we have built a new broadband SQUID-NMR setup [6, 7] to study the confined ^{3}He in a freely adjustable magnetic field, targeting precession frequencies as low as 100 kHz. We give a summary of the technical aspects of the new setup and report on the progress of the experiments probing the phase diagram at low magnetic fields in a 200 nm high cavity.

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Superfluid measurements of ^{4}He confined in a nanochannel by a 100 kHz tuning fork

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^{4}He confined in a straight nanochannel is one of the suitable systems to study the superfluid response of bosonic Tomonaga-Luttinger (TL) liquids. Due to the strong quantum fluctuation, the superfluid response of the TL liquid is thought to show a strong measuring frequency dependence.[1] We have performed quartz crystal microbalance (QCM) measurements of ^{4}He confined in a nanochannel at 100 kHz, which is two orders of magnitude higher than those of conventional torsional oscillator measurements. The nanochannel is 3.4 nm in diameter and is synthesized in 0.1-μm pores of a porous alumina membrane. The membrane is attached to the side of an arm of a quartz tuning fork, in order to arrange the channel direction parallel to the oscillation direction.

Figure 1 shows the temperature dependence of resonance frequency (f) and the inverse of Q-value for various introduced amounts of ^{4}He. For clarity, we subtracted the data of 0.39 mmol, where only the inert solid layer is formed in the channel, as a background. For 0.50 mmol of ^{4}He, with decreasing temperature the frequency has a rise at 0.84 K ($T_{\rm oh}$), accompanied by a dissipation peak at 0.82 K ($T_{\rm ph}$). Further decreasing temperature, it drops rapidly at 0.27 K ($T_{\rm d}$) due to the capillary condensation in the pores of porous alumina. As the ^{4}He amount is increased, $T_{\rm oh}$ and $T_{\rm ph}$ shift to high temperatures, and another rise appears in frequency at the lower temperature ($T_{\rm ol}$) above 0.75 mmol, accompanied by a dissipation peak ($T_{\rm pl}$). From the magnitudes of the rise in frequency,$T_{\rm oh}$ and $T_{\rm ol}$ are attributed to the superfluid response in the pores of porous alumina and the nanochannel, respectively. At the conference, we will present the details of the superfluid behavior of ^{4}He in the nanochannel.

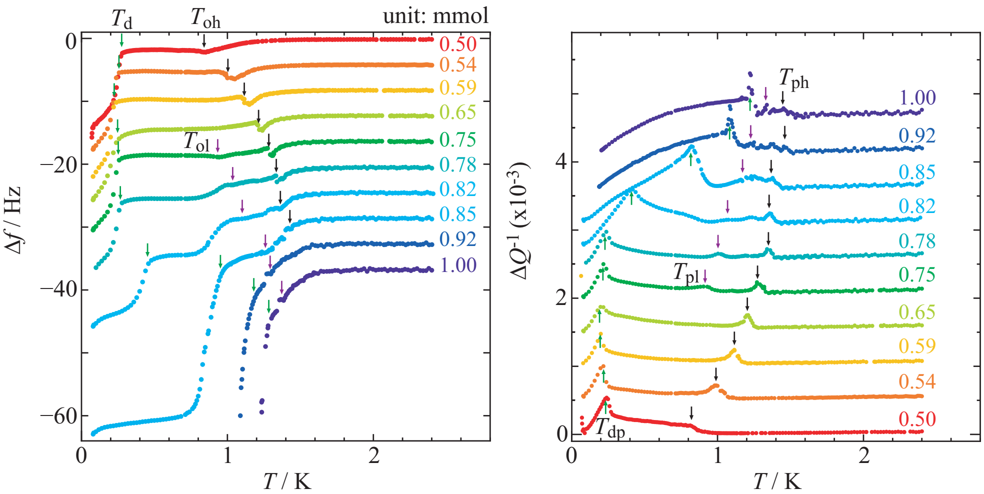

Fig. 1: Temperature dependence of Δf and ΔQ^{-1} for various introduced amounts of ^{4}He.

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Electro-nuclear transition in $YbRh_2Si_2$; evidence for a spin density wave

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The nature of the antiferromagnetic order in the heavy fermion metal $YbRh_2Si_2$, its quantum criticality, and superconductivity, which appears at low mK temperatures [1], as well as the interplay between magnetism and superconductivity remain open questions. We report measurements of the heat capacity over the temperature range 180 µK - 80 mK, performed in a novel cell which uses current sensing noise thermometry over the full temperature range. Measurements were made at magnetic fields in the range 0 to 70 mT, applied perpendicular to the c-axis. In zero magnetic field we observe a sharp heat capacity anomaly at 1.5 mK, which coincides with a transition in superconducting transport. The entropy agrees with the expected Yb nuclear spin entropy. The nuclear moments detect, through the hyperfine interaction, the local magnitude of the electronic moment. This is small above the transition, consistent with $0.002\mu_B$ along hard c-axis, and we precisely determine the quadrupole energy. Below the anomaly the data are well described by an incommensurate electronic spin density wave (SDW) of amplitude 0.1 μ_B at the lowest temperatures. This can be accounted for by a re-orientation of the electronic spins into the ab-plane, previously observed under the influence of in plane field [2]. With increasing magnetic field, up to 22 mT, the anomaly in the nuclear spin heat capacity broadens and shifts to lower temperatures. Together these results demonstrate that superconductivity and antiferromagnetism coexist and demonstrate SDW order of as yet unknown q-vector.

*This work is supported by the European Microkelvin Platform.

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Interplay between electro-nuclear magnetism and superconductivity in $YbRh_2Si_2$

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We report a study of canonical heavy-fermion metal $YbRh_2Si_2$ with two novel complementary SQUID-based techniques, calorimetry and electrical transport, down to 0.2 mK. In zero magnetic field two heat capacity anomalies are observed; the onset of antiferromagnetism at $T_N = 70$ mK and a transition between two phases with different magnetic order parameters at $T_A = 1.5$ mK. From high-resolution heat capacity measurements we identify the low-temperature phase ($T < T_A$) to be an incommensurate spin-density wave with electronic moments on Yb sites of order 0.1 μB, in contrast with much smaller staggered moments ~0.002 μB reported in the high-temperature phase ($T_A < T < T_N$). We propose the magnetic transition at T_A to be driven by the hyperfine interactions in ^{171}Yb and ^{173}Yb.

The superconductivity was explored by measuring the complex electrical impedance of high-quality single crystals of $YbRh_2Si_2$ and microstructures fabricated with focussed ion beam milling. Four distinct transport signatures of superconductivity are observed below $T_B = 10$ mK, one of which, a step-like change in the sample inductance, coincides with the magnetic transition T_A.

A rich phase diagram emerges in magnetic field, with evidence of inhomogeneous superconductivity. Strong anisotropy between the field applied in the ab plane of the tetragonal $YbRh_2Si_2$ crystals and along the c axis is observed. Some signatures of superconductivity are Pauli-limited, while others are not, indicative of spin-triplet pairing and opening the possibility of multiple distinct superconducting order parameters. The Pauli-unlimited superconductivity extends up to the magnetic quantum critical field. Both re-entrant normal state upon cooling and re-entrant superconductivity upon increasing magnetic field are observed. The change of the superconducting response at T_A demonstrates close interplay between the superconductivity and magnetism.

Application of uniform uniaxial strain is a promising route to tuning the superconducting order parameter in $YbRh_2Si_2$ with intriguing prospect of stabilising distinct spin-triplet phases of non-trivial topology.

Detection of quantized vortices in superfluid ^{3}He by a nanoelectromechanical oscillator

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We report the first observations of dynamics of fermionic quasiparticles and quantized vortices in superfluid ^{3}He-B at temperatures below $0.2T_c$ with an immersed nanoelectromechanical oscillating device. In the fully gapped B phase of superfluid ^{3}He, density of thermal excitation decreases exponentially with temperature and non-trivial flows involve weakly damped motion of quantized vortex lines, often leading to quantum turbulence. In the low-temperature regime, dissipation in quantum turbulence is theoretically linked to wave exitations on individual vortices via the Kelvin-wave cascade, on which so far there is only limited experimental evidence [1]. In fermionic ^{3}He, such dynamics is especially interesting due to expected interaction of vortex waves with topological bound states in the vortex cores and connection to dynamics of neutron stars. Vortex detection techniques, employed so far in ^{3}He at ultra-low temperatures, include nuclear magnetic resonance [1] and quasiparticle reflection [2] and are sensitive only to arrays of many vortices. We developed a nanoscale device with the goal to track individual vortex lines.

Our device has a goal-post shape with the legs and the paddle of approximately 100μm length, 20μm width and 250 nm thickness, manufactured from bare aluminum over a window in a silicon substrate and driven and detected magnetomotively [3]. Intrinsic damping in such devices is determined by tunneling two-level systems [4] and is a sensitive probe of the device temperature. In ^{3}He-B at 19 bar pressure, the frequency of the device is 15 kHz and the lowest resonance width achieved in the experiment is 7 Hz at the temperature of about $0.14\,T_c$, which is still well above the intrinsic damping. In stationary liquid, the device resonance width is proportional with a factor of about 100 to a resonance width of a commercial quartz tuning fork placed next to the device. Much larger width offers better sensitivity to quasiparticle density and faster response time. No anomalous zero-temperature damping reported in [5] is observed, making such devices an ideal sensor for a quasiparticle camera [2].

At larger drives, the device shows the Andreev reflection and the pair-breaking behaviour expected for an oscillator in superfluid ^{3}He-B. We find that this non-linear response is modified in the presence of a stable array of vortex lines in the rotating ^{3}He sample. Additionally, we observe jumps of fixed size in the damping and frequency of the device when vortices are moving after change in the angular velocity. We discuss interpretation of these observations in particular via trapping and untrapping of individual vortex lines by the device.

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Measurements of Helium Mixtures by Neutron Absorption

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We present a new, non-invasive, and real-time technique for investigating the properties of helium 3/4 mixtures via neutron absorption. The significant difference in microscopic neutron absorption cross section between ^{4}He (σ_4 = 0.0075 b for 1.8 Å neutrons) and ^{3}He (σ_4 = 5333 b) allows extremely high contrast observations of different phases, and measurements of the relative concentrations of each isotope in each phase. We demonstrate this with a proof-of-concept measurement made in conjunction with our imaging of an operational dilution refrigerator [1] on the IMAT neutron imaging instrument [2] at ISIS Neutron & Muon Source.

In this proof-of-concept, we were able to observe (Fig. 1) the boundary between the concentrated ^{3}He and dilute ^{3}He phases in the mixing chamber of a dilution refrigerator (DR). With this, we could examine how the relative concentrations and quantities of the two phases changed as the mixing chamber temperature was varied and whilst ^{3}He was extracted during a single-shot procedure. We were also able to demonstrate our ability to make neutron absorption measurements at different locations throughout the DR without any changes to the setup, and hence could examine and diagnose the behavior of a DR operating in a degraded state with insufficient ^{3}He (Fig. 2).

Going forward, we suggest the expansion of this technique to observing phase boundaries in other helium systems, e.g., solid ^{3}He, and the advantages it will bring for measurements of systems which have varying properties with position.

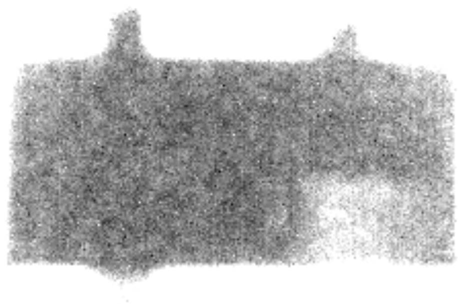

Fig. 1: Neutron image of the mixing chamber of a DR, showing the difference in neutron transmission through the highly absorbing ^{3}He rich phase and the weakly absorbing ^{3}He poor phase.

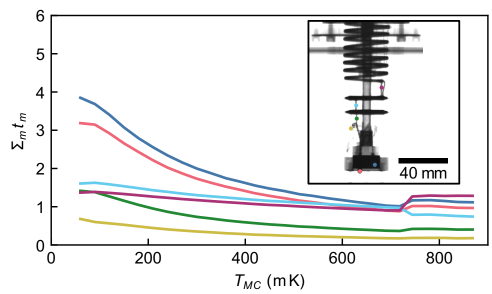

Fig. 2: Variation in neutron absorption cross-section, Σ_m with mixing chamber temperature, T_{MC}, for a DR operating with insufficient ^{3}He in the mixture. Each colored line corresponds to the corresponding location in the inset.

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Superfluid Effective Field Theory for Dark Matter Direct Detection

Wei Xue

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I will present an effective field theory (EFT) framework for superfluid ^4He to model the interactions among quasiparticles, helium atoms, and probe particles. The proposed EFT framework and results can be used to understand the dynamics of thermalization in the superfluid. They can be further applied to sub-GeV dark matter direct detection with superfluid ^4He.

Hybrid systems and quantum computing with electrons floating on the surface of superfluid helium

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Hybrid Rydberg-spin qubits of electrons on helium

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Fault-tolerant quantum computing requires a high enough number of interacting qubits placed in two-dimensions. Despite the recent significant progress on the development of quantum computers, preparing such a system while realizing high-fidelity qubit operations is still challenging.

One of the ideal physical systems to realize a quantum computer with is surface electrons (SE) on liquid helium [1,2]. Here, we theoretically propose a new way to realize qubits: a hybrid qubit of the Rydberg state and the spin state of electrons floating on the surface of liquid helium. An artificially introduced interaction between the Rydberg state and the spin state allows us to transfer the qubit state between the Rydberg and spin states. In this way, we can benefit from both the long coherence time of the spin state and the long-range interaction of the Rydberg state in the course of qubit operation. The long coherence time of the spin state is essential to realize high-fidelity qubit operations and the long-range interaction of the Rydberg state allows us to align electrons with a moderate distance while keeping a considerable interaction between them, which is a key characteristic for realizing a high number of qubits in a two-dimensional array. Basically, we use the spin states to store the qubit states. Thanks to the Rydberg-spin interaction, we can realize a universal one-qubit gate for the spin state with electrical excitation. A two-qubit gate can be performed via Coulomb interaction by exciting an electron to the 1st-excited Rydberg state.

We explicate that the Rydberg-spin interaction degrades the relaxation rates but only to 50 ms. In our proposed framework, the one-qubit gate fidelity and the two-qubit gate fidelity can exceed 99.999% and 99.9%, respectively, and the read-out can be realized in a quantum-non-demolition manner making use of the previously reported image charge detection [3].

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Stimulated Brillouin gain spectroscopy of metastable superfluid helium-4

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Stimulated Brillouin gain spectroscopy is a powerful optical method to probe the acoustic properties of liquid helium with moderate optical power and fast acquisition rates. A stimulated Brillouin gain spectrometer has been developed in our team in order to measure the compressibility of a liquid in a narrow spatio-temporal domain (30 µm, 170 ns)[1]. We used this spectrometer to determine the velocity of first sound hence the compressibility of stable[2,3] and acoustically driven metastable [4] superfluid helium-4 around 1 K. These spectrometric measurements allowed us to determine experimentally the Equation of State (EoS) of stable superfluid helium-4 by measuring the Brillouin frequency at 1 K as a function of the liquid pressure between 0 and 10 bars[3]. The results are in excellent agreement with previous measurements and with theoretical EoS. Measurements of the Brillouin frequency in the metastable (negative pressure) states of superfluid helium-4[4], combined with interferometric measurements of the density, will allow us to determine experimentally the EoS of metastable superfluid helium-4. This is important to check the possible role of quantized vortices in the destabilization (cavitation) of the metastable states of this quantum liquid[5].

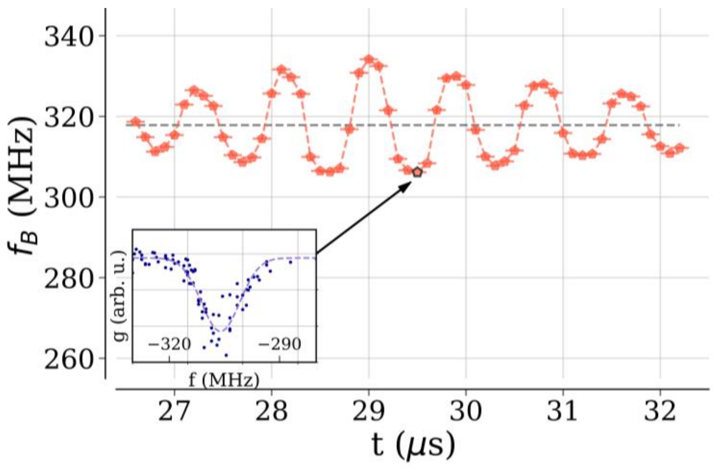

Figure 1: Time evolution of the Brillouin frequencies (fB) at acoustic focus of a sound field creating metastable states of superfluid helium-4 around 1 K. The point linking lines are guides to the eye. Horizontal dashed line: static value of the Brillouin frequency f_{B0} = 317.8(3) MHz. Inset: Brillouin gain spectrum obtained at t=29.5 µs which corresponds to a metastable (negative pressure) state, crosses: data, solid line: gaussian fit.

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Study of Surface States in Superfluid Helium 3-B Phase by Using an Angle Resolved Quantum Andreev Reflection Detector

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Superfluid ^{3}He B phase provides an opportune platform for research of topological matters. On the free surface of the superfluid, topological aspects appear such as the gap suppression. One of the previous experiments revealing surface states has been conducted to directly observe the quantum Andreev reflection (QAR) [1]. In that study, the quasi-particles (quasi-holes) were excited by an inner heater and ejected toward the liquid surface (angle of incidence : 20°), by using a black body radiator (BBR) type equipment which is dome-shaped device with a pinhole installed in the superfluid ^{3}He. They measured the extra temperature rise caused by the unusual characteristics of QAR that the quasi-holes (quasi-particles) go back to the BBR on the same path.

On the other hand, a theoretical result [2] shows the angle and energy dependence of QAR rate based on the spatial change of the order parameter near the surface, and that the quasi-particles with larger incident angles and smaller energies tend to have a higher proportion of QAR other than normal reflection.

In this study, we have developed an experimental device for the measuring the QAR rate over various angles and energies. Its measurement unit is composed of a copper box with an orifice and the aperture, which is rotated by a flexible bellows driven by the pressure of ^{4}He (Fig.1). The excited quasi-particles beam intensity from the BBR can be calculated by the molecular flow Monte Carlo simulation program we made, and can be directly compared with the experimental results by inputting the theoretical values of the QAR rate. In our device, by controlling the liquid level to the center of rotation, it is possible to perform measurements under the same conditions without changing the distance to the surface at any angle.

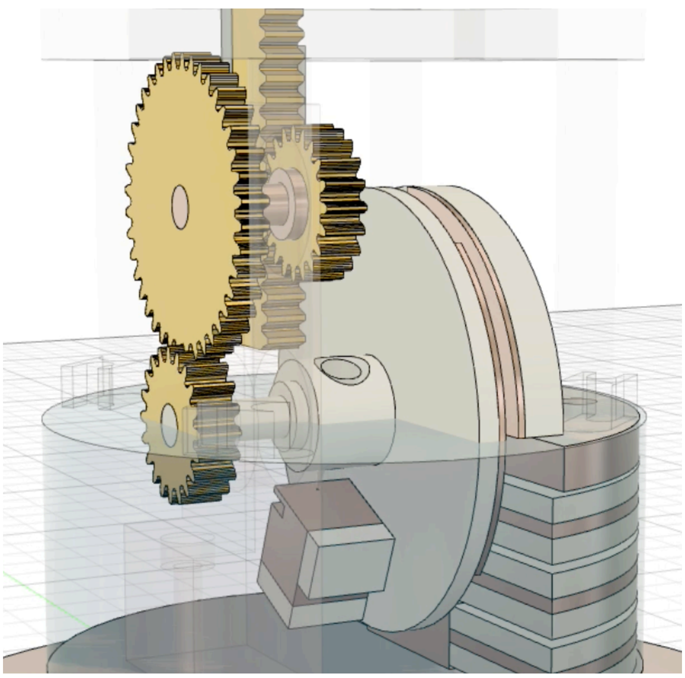

Fig.1 CG image of rotating BBR unit.

In this presentation, we report the outline of the measuring device and the progress of the experiment.

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Imaging Topological Defects in Fermionic Superfluid ^{3}He-B

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Here we will demonstrate that we can image topological defects in fermionic superfluid ^{3}He-B at ultra-low temperatures. In these conditions any remaining thermal energy splits the constituent Cooper pairs into quasiparticles that travel ballistically through the fluid. Using the quasiparticles as 'light' we shine a beam of quasiparticles onto a tangle of quantum vortexes. These topological defects create a superfluid flow field that blocks a portion of the quasiparticles and casts a shadow behind them that we picture with a 5 by 5-pixel camera. Each pixel contains a quartz tuning fork that can detect an indecent quasiparticle flux. Our measurements show that the distribution of the quantum turbulence about the wire is asymmetrical, with vortices preferentially being seeded on top of the turbulence generator instead uniformly of all around.

Andreev point contact spectroscopy study of Kondo insulator SmB_6

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We investigate the electrical density of states (DOS) of SmB_6 through the differential conductance measurements at low temperatures using point contact Andreev reflection (PCAR) spectroscopy [1] to reveal the existence of the hybridization gap, spin polarized current, and Dirac-like dispersion, directly. Below the superconducting transition temperature, the sharp drop of the spectrum due to the spin polarized current is observed inside the superconducting gap while a dip shape background reproduced by Fano resonance appears outside the gap, reflecting the Kondo insulating state of the bulk. The spin polarization estimated from the PCAR spectra is estimated to be ~ 0.6, which is almost constant down to $T \sim 2$ K. Additionally, at a very small contact size, the conductance changes almost linearly with the bias voltage, implying the emergence of Dirac-like dispersion on the surface. These results strongly suggest that a topological surface state covers on a bulk state that the conductance is characterized by a Kondo hybridization.

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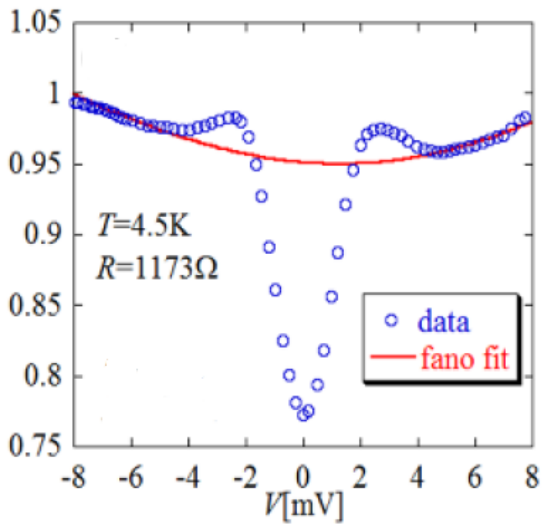

The differential conductance *dI/dV* spectrum in SmB_6/Nb interface at 4.6 K with the interface resistance of 1173 Ω. The solid line represents a Fano curve fitting.

Mobile solid ^{3}He promoted by topological frustration

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Low dimensional quantum systems reveal exceptional phenomena, such as topologically protected excitations, edge states, frustration, and fractionalization. Helium monolayer absorbed on graphite at low temperatures forms an ideal system to study low-dimensional physics[1]. Decreasing the dimensions leads to more profound quantum behavior due to the promotion by spatial restrictions of zero-point motion. In our experiment we decreased the dimension of helium even more, to quasi-1D, where ^{3}He showed a striking quantum phase transition from normal, rigid solid to the new, soft and mobile solid. The mobility of the new solid state has been argued to be due to delocalized vacancies which are provided due to the topological mismatch between the helium lattice and the carbon lattice. The two solids, rigid and soft, are composed from single atoms and from dimers, respectively. The observed transition between these solids is very exceptional, being the transition between fermionic and bosonic matter. We propose that the topologically protected vacancies should Bose-condense below 10 mK and provide non-dissipative mass transport, the so-called supersolidity.

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Real-Time Interaction of NEMS with Quantum Vortices in Superfluid-4

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We utilize nano-electromechanical systems (NEMS) to measure processes taking place in superfluid helium-4 at temperatures down to 10mK. Aluminum-based nanoscale double-clamped resonant beams have recently emerged as highly sensitive probes of hydrodynamic and ballistic helium-4. We have used such NEMS beams for the real-time detection of quantum turbulence and demonstrate a single-vortex capture, and subsequent release via reconnection with a nearby vortex. Quantum turbulence appears to behave as an ensemble of independent quantum vortices on short length scales but mimics classical turbulence on larger scales. A critical scale is the typical vortex separation and NEMS beams allow us to probe turbulence behavior on scales shorter than this, opening a new experimental regime. We detect and monitor capture of singly quantized vortices via simultaneous tracking of 42 frequencies using multifrequency lock-in amplifier and have measured the response times faster than 1ms.

Hyperfine interactions at ultra-low temperatures: their role in $PrOs_4Sb_{12}$

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Many strongly correlated electron systems develop ordered phases at low temperatures that can be well understood in terms of an electronic order parameter. At ultra-low temperatures, however, the hyperfine interaction between nuclei and electrons becomes increasingly important, and we have to consider how this affects ordered phases and phase transitions close to zero temperature.

$PrOs_4Sb_{12}$ is a superconductor below 1.85 K and 2.2 T, and develops antiferroquadrupolar (AFQ) order in magnetic fields between ~ 4 T and 14 T. The hyperfine constant of Pr is relatively large at 52 mK and the Pr crystal electric field levels are closely involved in both the superconducting and AFQ phase. This combination of properties makes $PrOs_4Sb_{12}$ an ideal material to study the effects of the hyperfine interaction on multiple ordered phases [1].

I will describe magnetic susceptibility experiments performed at the London Low Temperature Laboratory to study the phase diagram of $PrOs_4Sb_{12}$ at temperatures down to 1 mK and in magnetic fields up to 5.4 T. A big part of the project involved designing, building, and testing the susceptibility set-up, such that it was suitable for these extreme environments. Our experiments show that the phase boundaries in $PrOs_4Sb_{12}$ continuously develop down to temperatures as low as a few mK, indicating that the hyperfine interaction in this material suppresses superconductivity and enhances AFQ order.

We explain our results in terms of a ground state composed of hybrid nuclear-electronic states. That is, the low temperature Pr energy levels can no longer be considered as purely electronic entities, but must be described in terms of both electron and nuclear quantum numbers. Thus, hybrid nuclear-electronic order develops with novel low energy excitations.

*This work was supported by the European Microkelvin Platform, EU’s H2020 project under grant agreement no. 824109 and HFML-RU/NWO-I, member(s) of the European Magnetic Field Laboratory (EMFL).

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Mobility of solid helium films on a curved substrate near commensurate-incommensurate transition

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It is known that the finite curvature of substrate gives a geometric potential (or 'gravity') to the adsorbed particle [2]. We here investigate how this potential affects the mobility of single solid layer of helium near commensurate-incommensurate transition, where domain walls (DWs) are the main mobile component. We preliminarily find that the curvature generates kinks and fragmentation in DW which promotes floating behavior of solid. Also, we apply this observation to our modeling of the solid bilayer of helium on graphite, where DWs in the second layer are mobile on the first layer, i.e., the first layer is regarded as a deformable substrate for the second layer [1]. Even if the first layer is flat, it can have a finite effective curvature when topological defects (disclinations) are introduced (See Figure 1) [2]. We expect that switching of floating and non-floating behavior of the DW system is possible by introducing the topological defects mechanically.

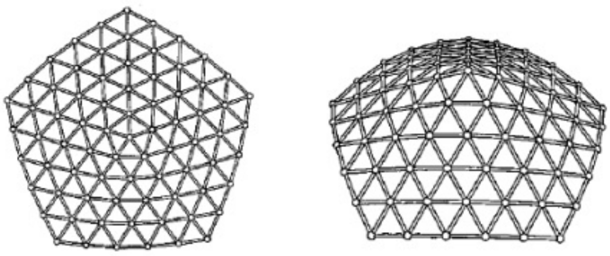

Fig. 1: A flat triangular lattice with a five-fold disclination at the center (Left) is identical to the triangular lattice with curvature (Right). The figure is extracted from [2].

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Transitions in vortex skyrmion structures in superfluid ^{3}He-A

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In the chiral A phase of p-wave superfluid ^{3}He, the orbital momentum of Cooper pairs is aligned along the unit vector $\hat{\mathbf{l}}$. Variation of $\hat{\mathbf{l}}$ in space allows superflow in ^{3}He-A to carry continuous vorticity. According to the Mermin-Ho relation, a region where $\hat{\mathbf{l}}$ directions cover 2π solid angle carries exactly one quantum of circulation. Such distribution of $\hat{\mathbf{l}}$ is topologically protected and is called a meron. The most common vortex structures observed in experiments on ^{3}He-A are double-quantum vortex (DQV) – a bound pair of merons, and vortex sheet (VS) – a chain of merons. Merging of DQVs to VS has been found experimentally [1]. We present numerical simulations of rotating ^{3}He-A which show details of this process, demonstrate the opposite process of emitting DQVs from VS and discuss how possibility of merging/splitting is related to the axial superflow along vortex cores following from chirality of ^{3}He-A. We also explain similarity between energies controlling $\hat{\mathbf{l}}$ variation in space to those governing magnetic skyrmions, as demonstrated, for example, by nearly identical structures of the DQV and a skyrmion called bimeron [2].

The $\hat{\mathbf{l}}$ vector determines locations of two Weyl energy nodes in the spectrum of Bogoliubov quasiparticles in ^{3}He-A. Variation of $\hat{\mathbf{l}}$ creates synthetic electromagnetic field for the quasiparticles and is predicted to result in analogue of the zero-charge effect of quantum electrodynamics with logarithmic divergence of one of the energy terms in the $T \to 0$ limit [3]. We have performed numerical calculations of the vortex structures in this limit and found a transition with increasing vortex density between the usual structure of the VS with vorticity uniformly distributed along the sheet to a cell-like distribution of vorticity in the form of staggered rings and crosses. Formation of the rings of vorticity is in line with the earlier prediction [3].

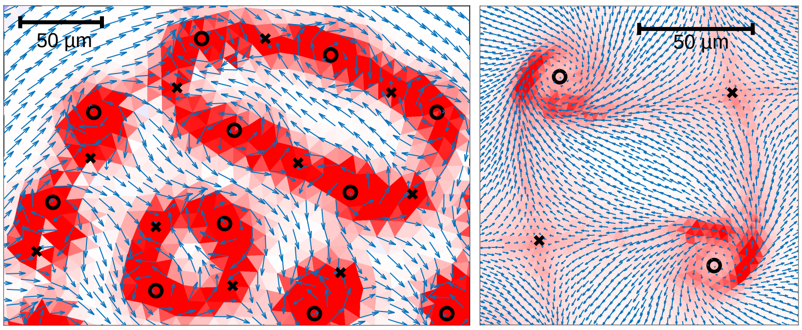

Fig. 1: Vortex skyrmion structures in rotating ^{3}He-A calculated for realistic experimental geometry. Arrows show $\hat{\mathbf{l}}$ direction and color represents vorticity. Circles and crosses show centers of circular and hyperbolic merons, respectively. *(Left)* Mixture of DQVs (blobs of vorticity connecting two merons) and VS (extended structures with multiple merons) after some DQVs merge to VS on increase of the angular velocity. *(Right)* Ring-cross distribution of vorticity in the zero-charge regime.

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Phase Transitions Between BCC and HCP Phases in Solid Helium

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In the phase diagrams of the helium system, we observe only one HCP phase for the solid ^{4}He, and the two BCC (low density) and HCP (high density) phases for the solid ^{3}He. [1] The difference between the solid ^{4}He and the solid ^{3}He would be due to the atomic mass difference, since a difference in the particle statistics, i.e. bosons or fermions, has little effect on the lattice structure, HCP or BCC, because of the small characteristic energy of exchanges. A lighter ^{3}He system would favor BCC than HCP in the low-pressure region of the phase diagram, and a heavier ^{4}He system would favor HCP. [2] To elucidate this atomic mass dependence concerning what is the stable lattice structure, we calculate the ground state energy of the solid ^{3}He and the solid ^{4}He based on the T-matrix theory, which takes into account the two-body correlation at short distances. [3] In Ref. 3, the ground state energy was calculated for BCC ^{3}He and HCP ^{4}He, but there is no discussion about the phase transition between BCC and HCP.

In this study, I calculated the ground state energy of the solid ^{4}He and the solid ^{3}He by following Ref. 3 as a function of the molar volume, respectively. The numerical results of the calculation are shown in Fig. 1. From this figure, we find out that the phase transition from BCC to HCP is observed for the solid ^{3}He with decreasing the molar volume and the transition pressure $P_{\mathrm{BCC-HCP}} \cong 5$ atm. Although the phase transition is also found for the solid ^{4}He, the details are unclear due to an insufficiency of numerical accuracy or the limitation of approximation. We could not estimate $P_{\mathrm{BCC-HCP}}$ precisely for the solid ^{4}He.

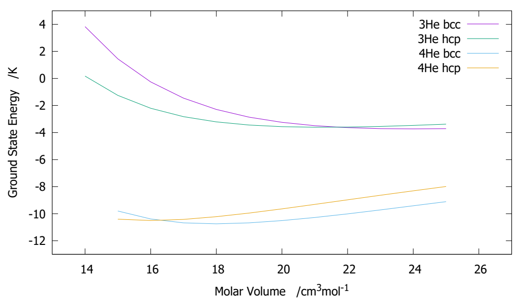

Fig. 1: Ground state energy of the solid ^{3}He and ^{4}He as a function of the molar volume V_m: For $V_m \leq 15.0\mathrm{cm}^3/\mathrm{mol}$ of ^{4}He, the numerical calculation becomes unstable.

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Surface X-ray Diffraction from Monolayer ^{4}He Film on Graphite: Simulations and Preliminary Observations

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Helium films adsorbed on graphite exhibit various quantum states due to two dimensionality and large zero point energy. Heat capacity [1] and neutron diffraction [2] measurements indicate monolayer ^{4}He below 2 K forms gas-liquid, $\sqrt{3} \times \sqrt{3}$ commensurate solid, domain wall, and triangular lattice incommensurate solid phases depending on coverages of helium. These phase diagram is not, however, fully understood from a structural aspect. Therefore, we recently started surface X-ray diffraction (SXRD) study around 2 K at synchrotron radiation facility, SPring-8 [3]. In particular, crystal truncation rod (CTR) scattering gives us information on surface structure with atomic resolution [4]. We simulate $00L$ rod scattering from monolayer helium film adsorbed on a graphite substrate. The $00L$ rod is sensitive to surface atomic positions perpendicular to the surface. In our simulations, we assume a monolayer helium with various coverages on a semi-infinite layer of graphite, where we concern modifications of topmost and second layer of graphite due to surface relaxation. The $00L$ rod intensities depending on height of helium from the substrate exhibit characteristic modulations inbetween Bragg points. In this conference, we discuss comparison between these simulations and preliminary observations around 2 K in detail.

* This work was supported by JSPS KAKENHI Grant Numbers: 22H03883, 20H05621.

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Dynamics of Quantized Vortices between Oscillating Parallel Plates with Pinning Sites

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Pinning is a phenomenon that the vortex is captured by an object on the solid surface. The dynamics of qunatized vortices with pinning sites has been studied for long years. The major studies are about vortices pinned by vibrating objects in superfluid helium. Objects in superfluid helium pin quantized vortices and their motion excites the vortices. Quantum turbulence, which is the phenomenon that the number of vortices explosively increases, can be generated by this process and the turbulence dampens the motion of objects. This mechanism is found in various shapes of objects, such as a sphere, a wire and a fork, and is still useful for quantum turbulence studies[1].

In recent years, nano-engineered systems are often used in experiments[2,3]. They make it possible to observe the interaction between quantized vortices and the nano-engineered systems. They can observe the influence on motion of the system from vortices even when the number of vortices is small. This technique is paving the way to the new possibilities of quantum hydrodynamics.

There are no studies that have investigated the dynamics in such systems, and the demand for understanding it is increasing. In this study, we model the experimental system[2] and do research on the dynamics of a vortex with pinning sites numerically. We put a vortex between two parallel plates with hemispherical pinning sites and make one plate oscillate. This simple simulation is a first step in revealing the new experiments.

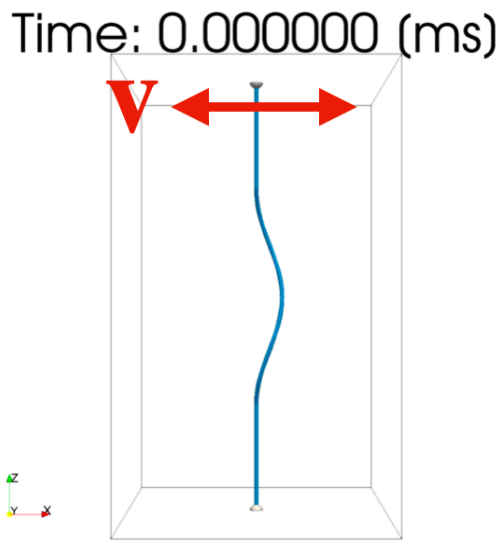

Fig. 1

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Anisotropic dynamics of formation of a quantized vortex lattice in a rotating Bose-Einstein condensate

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Rotating turbulent flow is ubiquitous in nature and is a common phenomenon in hydrodynamic, geophysical, and astrophysical flows. The scale-to-scale energy transfer in hydrodynamic rotating turbulence has been studied in detail and is affected by the Coriolis force yielding a coherent structure around the rotation axis. The effect of this rotation actually causes a dual cascade [1], anisotropic kinetic-energy distribution, and energy transfer [2]. On the other hand, in a trapped Bose-Einstein condensate (BEC), rotation gives rise to the formation of lattice of quantized vortices [3]. The number of quantized vortices in the rotating BEC is evaluated by Feynman's rule of vortex and is related to angular frequency [4]. However, the energy transfer and dynamics of formation in the wavenumber space are little known.

The purpose of this work is to study numerically the dynamics of rotating BEC trapped in isotropic harmonic potential, and we discuss the anisotropy of the momentum distributions, energy spectrum, and energy flux in the Gross-Pitaevskii model. Initially, the BEC is in equilibrium and begins to rotate, resulting in the formation of a vortex lattice at $t = 400$ as shown in Fig. 1(a). We uncover anisotropic energy spectrum in the vortex lattice and that the peak corresponding to a mean distance of vortices emerges in incompressible and compressible energy spectrum, which are shown in Fig. 1(b).

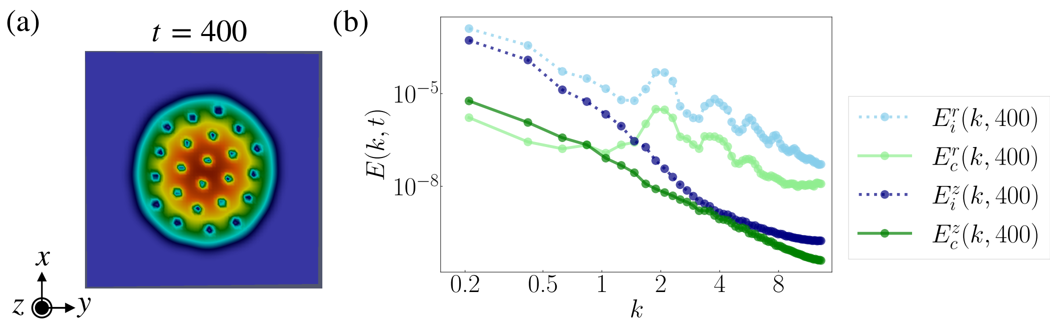

Fig. 1: (a) Cross-sectional density $|\psi(x,y,0)|^2$. (b) Incompressible and compressible energy spectrum in direction $r = \sqrt{x^2+y^2}$ and z, where BEC rotates around the z axis.

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Microwave Devices Using Graphene Josephson Junctions

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Using encapsulated graphene to bridge the gap between superconducting electrodes introduces an active material into a robust Josephson junction (JJ) structure. The semimetal graphene becomes superconducting through the proximity effect, working in a similar way to more conventional SNS junctions. The difference is that these active junctions can have their critical currents controlled by controlling the graphene's charge carrier concentration with local electrostatic gating [1]. These properties can continue to be used in the more complex circuits that use graphene JJs as a building block, including superconducting interference devices (SQUIDs).

Single flux quantum (SFQ) pulses are a superconducting phenomenon that forms the basis of SFQ logic [2]. This logic basis delivers low power digital logic at inherently fast clock frequencies. An SFQ pulse is generated by briefly biasing a JJ above its critical current, so that it undergoes a 2π phase shift, producing a voltage pulse which is quantised to the magnetic flux quantum $\Phi_0 = 2.07$ ps $\cdot$ mV. This makes the critical current of each junction in an SFQ circuit very important for proper operation, as pulses will be used to trigger further pulses throughout the circuit. Therefore, graphene JJs could help to optimise and reconfigure the performance of these devices post-fabrication.

A test device using graphene JJs was fabricated with the potential to act as a simple SFQ circuit for signal propagation. This device is being characterised using a dry dilution refrigerator operating at 15 mK. We investigate the device's low-frequency characteristics while being driven with a microwave source. This will inform further measurements involving the propagation of alternating current signals in the device.

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Building a Superfluid ^{3}He-B Bolometer using Aluminium Composite Nanobeams

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Previous attempts at creating superfluid ^{3}He bolometers have achieved energy resolutions in the keV range at temperatures as low as 130 µK for a wire thickness of 4.5 µm [1 - 3]. This demonstrates the potential for use as a non-baryonic dark matter detector due to the maximum theorised interaction energy of 6 keV [3]. We propose the use of nanoelectromechanical resonators to improve the sensitivity of the detector by an order of magnitude, due to their smaller size and high quality factors [4, 5]. Here we present plans to use a doubly clamped aluminium composite nanobeam inside of a 5x5x5 mm box that forms a weak link with the bulk via a small hole, creating a sensitive bolometer. Thermal excitations produced from incident particles, heat up the superfluid and can be detected through the change in damping when the nanobeam is driven at its resonant frequency. Additional signal rejection can be provided by a transition edge sensor (TES) to detect scintillation from helium collisions [6].

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Development of an instrument for experimental study of quantized vortex

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^{4}He is phase-transferred into the superfluid phase at approximately 2.17 K under the saturated vapor pressure. Superfluid ^{4}He is typical quantum liquid, and the vortices in it are quantized since the macroscopic wave function is unique. The study of quantized vortex motion is important in elucidating the dynamics of quantum fluids. However, the motion is complicated by boundary conditions such as the walls of the equipment and the liquid surface.

Our motivation is to experimentally explore the reconnection process of quantum vortices in superfluid ^{4}He with quantized vortex rings whose quantity, size, and movement direction are controlled, that is, well-controlled quantized vortex rings. To create the well-controlled vortex rings in superfluid ^{4}He, we have developed a quantized vortex ring generator. In this presentation, we report the design and the preliminary results of our instruments.

The instrument is a cylinder made of copper, whose inner and outer diameters are 20.0 mm and 39.0 mm, respectively, and the length is 20.0 mm. A commercial piezoelectric diaphragm is attached to one end of the cylinder. On another end, a sharp-edged orifice is attached, whose typical inner diameter is 0.1-0.6 mm. Filling the equipment with superfluid ^{4}He, and applying impulse voltage to the piezoelectric diaphragm causes impulse motion of the diaphragm. The superfluid ^{4}He is pushed out by the diaphragm and spouts through the orifice. When the velocity of the jet achieves the critical velocity of superfluidity, vortex rings are emitted from the orifice.

*This work was supported by JSPS KAKENHI Grant Number 19K03734.

Using a cryogenic tunable resonance circuit to image-charge detection of surface electrons on He II

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One of the ideal physical system to realize a quantum computer is surface electrons (SE) on liquid helium [1]. In order to use a single SE as one qubit, it is necessary to detect the quantum state of a SE. It was shown previously that the image-charge detection method can be used for a quantized state (Rydberg state) of many SE [2]. We need to increase the sensitivity of this method to use it for a single SE and propose to use an LC-tank circuit with a varactor diode as a variable capacitance. Preliminary results show that the quality factor (Q) of the circuit ~ 1000 at room temperature and $Q \sim 1300$ at $T \leq 1$ K. Varying the bias across the varactor diode leads the change of the resonance frequency by a several MHz.

The capacitance sensitivity was measured after the circuit optimization [3]. The capacitance sensitivity (S_C) was 6.7 aF/√Hz at the resonance frequency (f_0) 67 MHz at room temperature and $S_C = 7$ aF/√Hz with $f_0 = 84$ MHz at $T \leq 1$ K. According to our estimation, the transition between different quantized states of a single SE would give an AC capacitance change of 40 aF which is detectable using the image-charge detection.

We also report our recent experimental results of the detection of the Rydberg state of SE using the LC circuit.

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Anomalous thermoelectric properties in $LaO_{0.5}F_{0.5}Bi_{1-x}Pb_xS_2$ (x = 0.09, 0.1)

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$LnO_{1-y}F_yBiS_2$ (*Ln*: lanthanoid) is one of BiS_2-based superconductors [1]. Recently, BiS_2-layered-compounds have been also receiving attention as thermoelectric materials having a relatively high figure of merit [2]. Thermoelectric Power, which is an important factor for thermoelectric materials, is an essential physical quantity in investigations of electronic states of metal, because the Seebeck coefficient is proportional to temperature T and the proportional coefficient is associated with the density of states at the Fermi Level. In this study, we report temperature dependence of $S(T)$ for $LaO_{0.5}F_{0.5}Bi_{1-x}Pb_xS_2$ (x = 0.09, 0.1) along *ab*-plane in a temperature range between 4 K to 300 K.

We measured $S(T)$ by an ordinary four-probe method using two 0.07% Aufe-chromel thermocouples. The maximum temperature gradient in the sample is not more than 5% of the sample temperature. Observed $S(T)$ is negative over the entire temperature range, which means electrons are majority carriers. $S(T)$ decreases slightly down to 150 K. Then it drops sharply in the temperature range 100 K and 150 K, where temperature hysteresis of $S(T)$ is observed. Below 100 K, $S(T)$ is roughly proportional to the temperature, which means ordinary metallic states of the sample. The sharp reduction with thermal hysteresis of $S(T)$ indicates that the structural phase transition induces the change in the density of states.

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Cosmological Phase Transition in Superfluid Helium Three

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ULT2022: Low-Stokes-number Oscillatory Flows in the Hydrodynamic Regime of Helium-3 Gas

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The Stokes number St can be used in fluid dynamics to characterise the behaviour of the fluid flow an oscillating body gives rise to, with low Stokes numbers ($St \ll 1$) describing the advection of the fluid about the oscillator and large Stokes numbers ($St \gg 1$) describing a fluid largely unperturbed by the oscillator. The number can be calculated using $St = D^2/(\pi\delta^2)$, where D denotes the size of the body, and δ the viscous penetration depth [1].

A previous study [1] successfully derived a universal scaling law to describe the drag forces acting on oscillatory bodies submerged in superfluid helium-4 in the high-Stokes-number limit; however, this law breaks down in the low-Stokes-number limit. Our study investigates low-Stokes-number oscillatory flows in the hydrodynamic regime of helium-3 gas at 4.2 K.

A combination of experimental and computational methods were used to explore and characterise the damping of micromechanical and nanomechanical oscillators in helium-3 gas. Superconducting NbTi vibrating wire resonators with diameters in the range of 0.45–4.5 μm were implemented as mechanical probes. The small diameters resulted in high pressure sensitivities and low resonant frequencies (of the order of kHz), allowing low-Stokes-number oscillatory flows in the hydrodynamic regime to be investigated. Superconducting Ta vibrating wire resonators with diameters of 127 μm were also implemented, allowing a comparison to high-Stokes-number oscillatory flows. The observed dependence of the drag force as a function of peak velocity for low-Stokes-number oscillatory flows was explained using Lamb's law of viscous drag on a cylinder [2,3].

* This work was supported by UKRI (Grant Nos EP/P024203/1 and ST/T006773/1), and EU H2020 European Microkelvin Platform (Grant Agreement 824109).

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Neutron Imaging of an Operational Dilution Refrigerator

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The dilution refrigerator is a low temperature workhorse, used worldwide to provide temperatures in the millikelvin range for devices ranging from quantum computers through to dark matter detectors. Since its inception more than 50 years ago[1], the mechanism by which refrigeration occurs has been well understood. However, until this point, the only visual representations of this process were illustrations in reference textbooks.

Likewise, neutron radiography has been in existence since last century, and is widely used by both science and industry to investigate material properties at facilities such as the ISIS Neutron & Muon Source. The current state-of-the-art imaging instrument at our facility, IMAT, provides neutron radiography, neutron tomography and energy-resolved neutron imaging.[2]

In this work we combine dilution refrigeration and neutron imaging to showcase a new capability for the field of low temperature physics. Previous work has proved the potential for discerning ^{3}He from ^{4}He using neutrons[3], here we take the next step by imaging an entire dilution refrigerator during operation.

Our setup allows the capture of high-quality images and videos showing condensation of fridge mixture, ^{3}He/^{4}He phase separation, and 'single shot' diagnostic procedures. In addition, it is possible to demonstrate the changing concentration of ^{3}He in the mixing chamber.[4] We expect this work to have a wide-ranging impact for educators, technicians, and dilution refrigerator engineers.

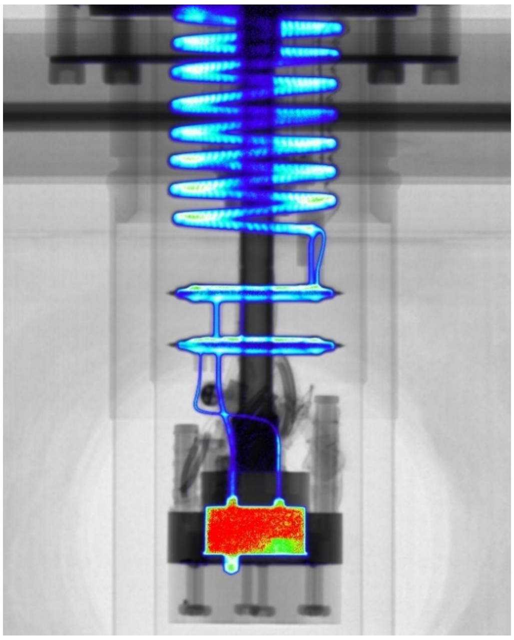

Figure 1: A neutron radiograph of an operational dilution refrigerator, with false colour overlay showing the neutron absorption. The phase boundary can be seen as the border between green and red on the right-hand side of the mixing chamber.

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Sub 1K Sample Environment at the ISIS Neutron and Muon Source

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ISIS, the world's most successful pulsed spallation neutron and muon source, provides beams of neutrons and muons that enable scientists to probe the microscopic structure and dynamics of matter. ISIS has 34 neutron and 7 muon instruments that deliver ~700 experiments per year, 2/3 of all experiments require cryogenic sample environment

The Sample Environment Cryogenics team at ISIS can supply a large array of ultra-low temperature equipment. The equipment includes ^{3}He adsorption and dilution cryostats, parasitic adsorption and dilution refrigerator inserts that can be used at temperatures as low as 15mK, in combination with magnetic fields (≤13.2 Tesla) and pressures (SVP to few kbar). The equipment is supplied on an almost industrial scale with some 100 sub 1K experiments on average carried out per year. Extreme parameters are crucial for a number of neutron experiments that require a combination of physical conditions.

Experimental successes include magnetic and non-magnetic phases of a quantum spin-liquid [1] where measurements were made with muons to see how the rotation rate varies with magnetic field at 120mK. Spin excitation spectrum of the Heisenberg spin ladder material [2] where experimental data at 70mK and 2.55 Tesla was compared with a theoretical model. Extremely long timescale dynamics in Spin Ice [3] the longest in situ magnetic susceptibility diffraction experiment ever carried out the ISIS facility at 1.5 months with a range of temperature between 50 – 650 mK.

The author presents equipment used to support the scientific user community and some experimental successes.

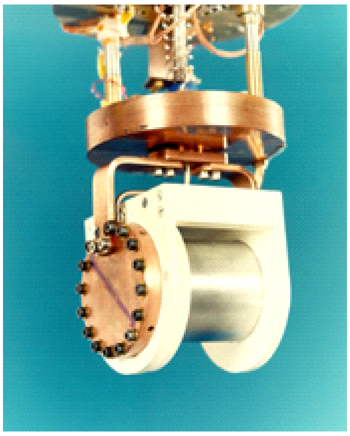

Fig. 1: Shows a standard vapour pressure sample set up used to study Helium films in porous media at 300mK in an adsorption cryostat.

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Fully coupled simulation of a superfluid based on one-fluid extended model

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We have developed a numerical scheme to simulate the coupled dynamics of normal-fluid and superfluid components and present the detail of the method and the underlying concepts. We treat the velocity fields of normal fluid and curl-free part of superfluid together according to the framework of one-fluid extended (OFE) model [1,2], which is an alternative framework to construct a hydrodynamical description of superfluids based on extended irreversible thermodynamics (EIT) [3].

The essential fields in OFE model are barycentric velocity and heat flux, but **not** the superfluid and normal-fluid velocity fields as in the framework of two-fluid (TF) model. We argue that the heat flow can be treated as a vectorial advection-diffusion problem, i.e., while the heat flux is advected by the barycentric velocity, it diffuses at a cirtain rate depending on the diffusion constant and the presence of quantized vortices. Such a problem is suitably dealt with lattice Boltzmann method (LBM) [4], where we keep track of distribution functions, instead of directly dealing with the fields themselves. Since LBM is a mesoscopic model, it is not only convenient to calculate the time evolution of the system, but also the interaction between the fields and the quantized vortices becomes more straightforward than that in a macroscopic framework. The actual application of our numerical scheme to a rotating superfluid was also presented in LT29 [5].

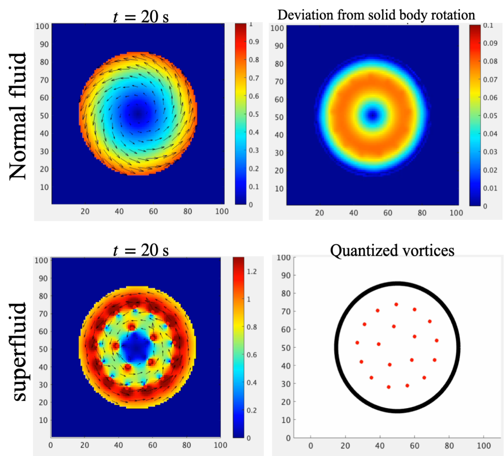

Fig. 1: Dynamics of normal fluid component (top panels) and superfluid component (bottom panels) at a steady state with 18 quantized vortices at $T = 2.0$ K.

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Development of a cryogenic current pre-amplifier using a HBT OPamp

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In order to avoid self-heating of the sensors and the samples in cryogenic measurements, the magnitude of an excitation source for sensors installed in a refrigerator is suppressed. As a result, electrical signals from the sensors are quite small and the quality degraded by external electrical noise. In order to improve the signal quality, a cryogenic pre-amplifier is effective. Successful employment of a commercial complementary metal oxide semiconductor operational amplifier (CMOS OPamp) ICL7611 and application for a current to voltage converter using ICL7611 at liquid helium temperature have been reported [1, 2]. Recently, performance of a heterojunction bipolar transistor (HBT) OPamp LMH6629 at 60 K has been also reported [3]. In this study, we have developed a current pre-amplifier using LMH6629 and have investigated the performance down to 4 K. The pre-amplifier is mounted on the cold head of a commercial refrigerant-free helium-4 refrigerator in the vacuum can. The total supply voltages are maintained ±1.5 V in the entire temperature range. In the temperature range between room temperature and 10 K, its capability of a gain and a bandwidth were 10^4 V/A and 50 kHz, respectively. At 4 K, however, the pre-amplifier did not operate correctly.

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Dripping character of superfluid ^{4}He droplets

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It is interesting to know how superfluid helium's non-dissipative flow differs from the viscous flow of classical fluids, especially in highly non-equilibrium situations. We used a high-speed video camera to visualize the behavior of superfluid droplets dripping from the bottom of a top-open glass cup via film flow.

The droplet grew at the bottom of the cup as ^{4}He constantly flowed into the droplet from inside of the cup via the superfluid film flow. When they became too large to adhere to the bottom, they were pinched off and dropped. This is a well-known phenomenon in which superfluid ^{4}He spontaneously flows out from a container via film flow. When the droplet was attached to the bottom, it was found to oscillate with a large amplitude during the pinch-off event. Although the interval between pinch-off events is largely determined by the film flow rate, it was also found to be affected by the vibration of the droplets. The vibration is accompanied by the contact line motion of the droplet on the cup. This contact line motion inevitably induces fluid motion near the cup surface, which should be damped for viscous fluids. To make this comparison, similar observations were made for water droplets falling from the bottom of a container with a hydrophilic surface. The results showed that the oscillations of the water droplets were much smaller in amplitude and indeed highly damped. Therefore, we conclude that the observed oscillations of superfluid ^{4}He droplets are unique in the dynamics of inviscid fluids in highly non-equilibrium situations.

Increasing the film flow rate of ^{4}He by coating

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One of the classical demonstrations of superfluidity is the phenomenon of ^{4}He superfluid liquid flowing out of a container with an open top. This is caused by the film flow of superfluid liquid formed on the surface of the container. This has been used as a demonstration of superfluidity because only non-viscous fluid can flow through such a thin film with a depth of a few tens of nm. It is known that the film flow rate is higher on rougher surfaces with larger effective surface areas. Therefore, coating surfaces with solid air has been used to increase the film flow rate. However, it is not easy to control the condition of air application, and the film flow can be unstable. For a stable demonstration of the superfluid phenomenon, it is of use to enhance the film flow rate by a simple method.

We have found that simply applying a commercially available coating for car mirrors, Graco Miler Coat Zero (Soft 99 Inc.), to the surface of the container dramatically enhances the film flow of the superfluid ^{4}He. Only one has to do is to spray it on the surface several times and dry it before cooling. The film flow rate was then increased by a factor of about 10. This 10-fold improvement is reasonably explained by the increased effective perimeter of the coated surface [1]. A major advantage of this coating over solid air and other surface decorations is that it is very transparent. This is important to clearly show the superfluid profile for demonstrations.

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Dripping Period of Superfluid ^{4}He due to Film Flow

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Film flow is a characteristic phenomenon in the superfluid state. When the container is sinked in a superfluid ^{4}He and pulled up, the superfluid liquid can be observed to drip from the bottom of the container even if the container does not have a hole for the liquid to leak. This is because a film of superfluid liquid is formed on the surface of the container and the superfluid liquid in the container passes through the film to the bottom. The flow rate of superfluids through the film depends on the effective surface area of the vessel [1].

Here, we investigated the dripping dynamics of superfluid ^{4}He due to the film flow by a high-speed video camera. We measured the shape change of the droplets dripping from the bottom of the container and their dripping period. The droplet was found to vibrate in a large amplitude on the bottom of the container due to the superfluidity and influence the dripping period greatly. The dripping period correlated with the number of vibrations and was discretized. A similar system of water dripping from the faucet has been known to show a chaotic behavior in the dripping period [2]. In superfluid ^{4}He, however, the chaos was strongly suppressed due to the large amplitude vibration, which seems to be characteristic of the superfluid with negligible dissipation.

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Structure of Superfluid Suction Vortex

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Although a suction vortex is the one of the popular flow phenomena appearing in our everyday life, little is known about its flow pattern due to its complexity. We investigated a suction vortex produced in superfluid helium as inviscid liquid for the sake of the simplicity [1,2]; in contrast to the fact that the vorticity of the suction vortex in classical fluids takes a continuous distribution, superfluid suction vortices can be understood as a complex of quantized vortex lines, whose density profile can be measured by the sound mesurements [3].
Figure 1 (a) shows the macroscopic circulation of the suction vortex, Γ_z, measured by the pulsed first sound flow meter. We found that Γ_z was proportional to the rotation speed of the turbine, which can be interpreted considering the transport and dissipation of total angular momentum in the fluid. By assuming the core-radius to be equal to the radius of the suction opening, $R_{\mathrm{C}} = 2.5$ mm, the local vortex line density in the core, $L_{\mathrm{C}}^{\mathrm{fs}} = \Gamma/2\pi\kappa R_{\mathrm{C}}^2$, was revealed. Figure 1 (b) shows the local vortex line density in the core, $L_{\mathrm{C}}^{\mathrm{ss}}$, measured by the attenuation of the second sound. We found that $L_{\mathrm{C}}^{\mathrm{ss}}$ is about six times larger than $L_{\mathrm{C}}^{\mathrm{fs}}$, revealing that most of the vortex lines in the core do not contribute to the macroscopic rotation, i.e., the vortex lines are inclined in the horizontal direction. This picture agrees with the numerical simulation by Inui *et al* [2].

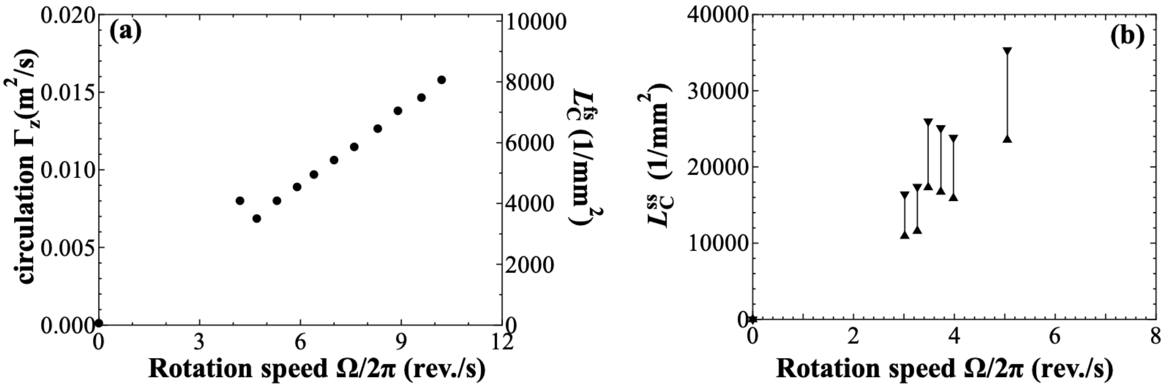

Figure 1: Estimated local vortex-line densities: (a) from ultrasound circulation meter, (b) from second sound resonance. The upward and downward facing triangles represent the lower and upper limits, respectively. Both measurements were performed at $T = 1.6$ K.

* The research was supported by the Japan Society for the Promotion of Science, KAKENHI Grants 15H03694, 17K18761, and 20K03865, and the Osaka City University, Strategic Research Grant 2019/2020 for top- priority research.

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Observation of Phase Slip Phanomenon in Superfluid ^{4}He Flow through a Newly Developed Micro-sized Channel

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Quantum vortex is one of the most significant consequences of the macroscopic quantum properties of superfluids. The direct confirmation of quantum vortex has been achieved by the observation of the 2π phase slip phenomena where generation and motion of a single quantum vortex across the superflow induces the discontinuous decrease in the difference of the phase of the order parameter along the channel by 2π, using Helmholtz resonator techniques with micro-sized rectangular or square apertures [1]. These apertures used in the previous studies are very thin, i.e. the aspect ratios were small so as to realize the superfluid weak link. On the other hand, micro-sized channel with high aspect ratio is required for studies of novel phenomena in quasi - 2D topological superfluid ^{3}He [2].

In the present study, we developed microslit structure, a micro-sized well-defined channel with high aspect ratios: 2 μm $\times$ 100 μm rectangular hole with 50 μm in length, as shown in Fig 1. The advantage of the present method is that multiple parallel channel structure can be realized with almost the same shapes so that the superfluid response is expected to be ideally integrated. We also performed a preliminary measurements of ^{4}He mass current through the microslit using a Helmholtz resonator and successfully observed distinct phase slip phenomena. Some instances of the observed time development of the phase difference along the microslit calculated from the resonant oscillation amplitude are shown in Fig. 2. However, our observed signals unexpectedly correspond to quantum numbers higher than 1. The possible origin of the phase slip with higher quantum numbers as well as the expected applicability to the future studies of topological superfluid ^{3}He will be discussed.

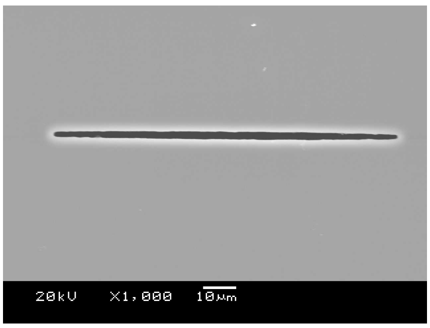

Fig. 1: SEM image of the microslit.

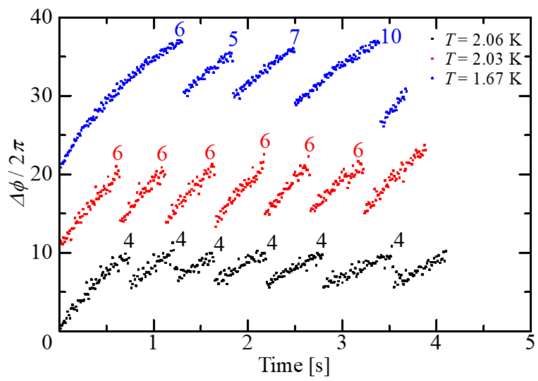

Fig. 2: Instances of the time developing phase difference $\Delta\phi$ for three temperatures. The numbers indicate reduction in $n = \Delta\phi/2\pi$

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Engineering boundary conditions in stepped-height superfluid ^{3}He nanofluidic cells

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Superfluid ^{3}He has a rich phase diagram which is predicted to lead to exotic excitations at interfaces between phases. Previous work has demonstrated the ability to control the phase diagram of ^{3}He by confinement within a uniform cavity [1-5]. Here, we report on the successful fabrication of new cells, in which well-defined interfaces are created between different superfluid phases, or between normal and superfluid phases. The introduction of interfaces allows us to approach two longstanding problems: simulating early universe phase transitions which are thought to have produced gravitational waves and probing exotic surface excitations of topological superfluid ^{3}He.

To simulate early universe phase transitions, we use the 1st order phase transition of time-reversal invariant ^{3}He-B nucleating from chiral ^{3}He-A as a model system for the nucleation of the Higgs phase from the symmetric phase. The speed at which the phase boundary propagates during this transition is a key parameter in cosmological nucleation theories. Our new stepped-height cells allow for measuring this parameter in a well-controlled manner by creating a deep "lake" in which the A-B transition can occur surrounded by a shallow "shore" which will only stabilize A phase. This geometry isolates the phase transition region from bulk ^{3}He, ensuring that the formation of B phase is due to intrinsic effects, not propagation from a less-well-controlled volume.

The introduction of interfaces to our nanofluidic cells also enables further study into edge, surface, and interface states of topological superfluid ^{3}He. Previous work has demonstrated that surface excitations contribute the anomalous thermal conductivity of ^{3}He within strongly confining channels [6]. Stepped-height cells enable the creation of "bridges" connecting two superfluid regions where the phase of both the bridges and superfluid regions can be tuned through careful choice of parameters. The simplest example of such cells contain two regions of superfluid ^{3}He connected via a normal fluid "bridge," analogous to superconductor-normal metal-superconductor (SNS) junctions. Local noise thermometers positioned on either side of the normal fluid bridge will enable thermal transport measurements, providing further insight into interface states.

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Miniature Plastic Dilution Refrigerator for Small Thermal Load Experiments

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Dilution refrigeration is the base technology underpinning most ultra-low temperature experiments. However, its significant drawback is the long cooldown times and the expensive external hardware that adds complexity to the operation. We present here our proposed design for a compact plastic dilution refrigerator for use in a helium bath. Using an internalized cryo-pumping scheme for helium circulation, we expect to achieve temperatures below 100 mK with a full thermal cycle performed within a single day.

This platform would cut costs on external pumping apparatus, simplify operation of the cryostat and minimize the required operational quantity of ^{3}He. Such a scheme would be ideal for experiments that require low temperatures, high magnetic fields and a quick turnover. The compact design of the refrigerator leads to a trade-off of quick cooldown times and low permittable heat load at base temperature which limits the refrigerator's applications for complex measurements.

Superfluid measurements of ^{4}He confined in a nanochannel by a 100 kHz tuning fork

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^{4}He confined in a straight nanochannel is one of the suitable systems to study the superfluid response of bosonic Tomonaga-Luttinger (TL) liquids. Due to the strong quantum fluctuation, the superfluid response of the TL liquid is thought to show a strong measuring frequency dependence.[1] We have performed quartz crystal microbalance (QCM) measurements of ^{4}He confined in a nanochannel at 100 kHz, which is two orders of magnitude higher than those of conventional torsional oscillator measurements. The nanochannel is 3.4 nm in diameter and is synthesized in 0.1-μm pores of a porous alumina membrane. The membrane is attached to the side of an arm of a quartz tuning fork, in order to arrange the channel direction parallel to the oscillation direction.

Figure 1 shows the temperature dependence of resonance frequency (f) and the inverse of Q-value for various introduced amounts of ^{4}He. For clarity, we subtracted the data of 0.39 mmol, where only the inert solid layer is formed in the channel, as a background. For 0.50 mmol of ^{4}He, with decreasing temperature the frequency has a rise at 0.84 K ($T_{\rm oh}$), accompanied by a dissipation peak at 0.82 K ($T_{\rm ph}$). Further decreasing temperature, it drops rapidly at 0.27 K ($T_{\rm d}$) due to the capillary condensation in the pores of porous alumina. As the ^{4}He amount is increased, $T_{\rm oh}$ and $T_{\rm ph}$ shift to high temperatures, and another rise appears in frequency at the lower temperature ($T_{\rm ol}$) above 0.75 mmol, accompanied by a dissipation peak ($T_{\rm pl}$). From the magnitudes of the rise in frequency,$T_{\rm oh}$ and $T_{\rm ol}$ are attributed to the superfluid response in the pores of porous alumina and the nanochannel, respectively. At the conference, we will present the details of the superfluid behavior of ^{4}He in the nanochannel.

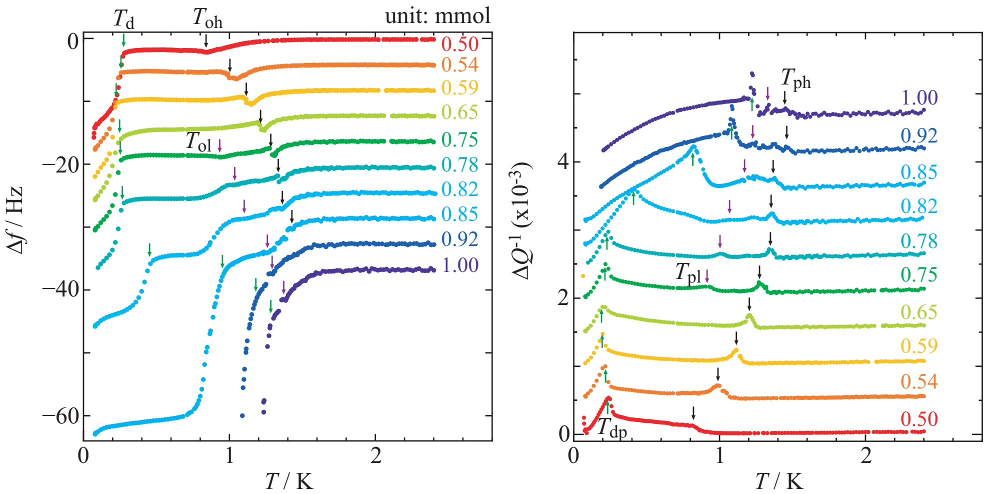

Fig. 1: Temperature dependence of Δf and ΔQ^{-1} for various introduced amounts of ^{4}He.

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Breathing Mode of the Bose-Einstein Condensate Trapped by the Self-Gravity

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[2] *Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP), Osaka 558-8585, Japan*

Self-gravitating Bose-Einstein condensates (BEC) recently have received attention in cosmology and astrophysics because they could be a candidate of dark matter. Dark matter is a hypothetical material that has mass but does not interact with photons. While dark matter can play an important role in cosmology and astrophysics as a source of gravity, the identity is one of great mysteries in modern physics. Some cosmologists assumed that dark matter is an ultralight and spin-zero boson or has self-interaction. These assumptions can resolve discrepancies at small scales between observational results and theoretical ones based on the cosmological model that takes account of non-relativistic dark matter. Such ultralight bosons have the de Broglie wavelength of the galactic scale and the high critical temperature for Bose-Einstein condensation. Hence ultralight bosons can form a BEC trapped in local space by the self-gravity.

The Gross-Pitaevskii-Poisson (GPP) equation can describe the dynamics of self-gravitating BEC[1,2]. It contains two kinds of nonlinear interaction, namely the gravitational interaction of BEC itself and the contact interaction. The competition between these interaction terms shows the unique nonlinear dynamics but it is difficult to solve the GPP eq. analytically and numerically in general cases. Therefore, most previous studies applied some drastic approximations or imposed several symmetries on the system to avoid the difficulties[2,3].

An important topic about the self-gravitating BEC is the breathing mode. Breathing mode is the spherical oscillation of BEC that expands and shrinks periodically. This phenomenon is related with the stability of the equilibrium state. There exist a few papers of the oscillation mode of self-gravitating BEC[4,5]. However, most numerical studies neglect the contact interaction and solve the Schrödinger-Poisson equation. When the total mass is large, the radius of the equilibrium state depends on the existing of the contact interaction of the self-gravitating BEC. Thus, the contact interaction affects the criterion of the oscillation.

We simulated numerically the breathing mode of self-gravitating BEC using the GPP eq. in the three-dimensional system. Our numerical method can reproduce the equilibrium state quantitatively. We will report the comparison with the previous study[4].

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NbTi Vibrating Wires as Detectors of Quantum Turbulence in Thermal Counterflow of He II

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Oscillating structures such as vibrating wires or tuning forks have become established and traditional tools in research of cryogenic fluid dynamics and quantum turbulence. A significant body of literature exists on turbulence generated by these devices, with only a few works related to detection of externally applied turbulent flows. In view of recent developments of our field, where nanoscopic devices found use as sensitive detectors of quantized vortices [1,2], it is important to understand how mechanical resonators, in general, interact with external flows and what are the benefits and expected limitations of such measurements. While measurements with nanoresonators are extremely well-suited to study interactions with a small number of vortices, or possibly a single vortex pinned to the device, a micro-scale device is useful to investigate the effects of a highly turbulent vortex tangle.

In our work, we present an application of a vibrating NbTi wire loop as a detector of quantized vortices generated in thermal counterflow of He II. Second sound attenuation is used simultaneously to determine vortex line density, allowing for an *in situ* calibration of the mechanical resonator. Devices of this type, or their downscaled versions, can subsequently be used as local probes of dense vortex tangles in various flows of superfluid helium.

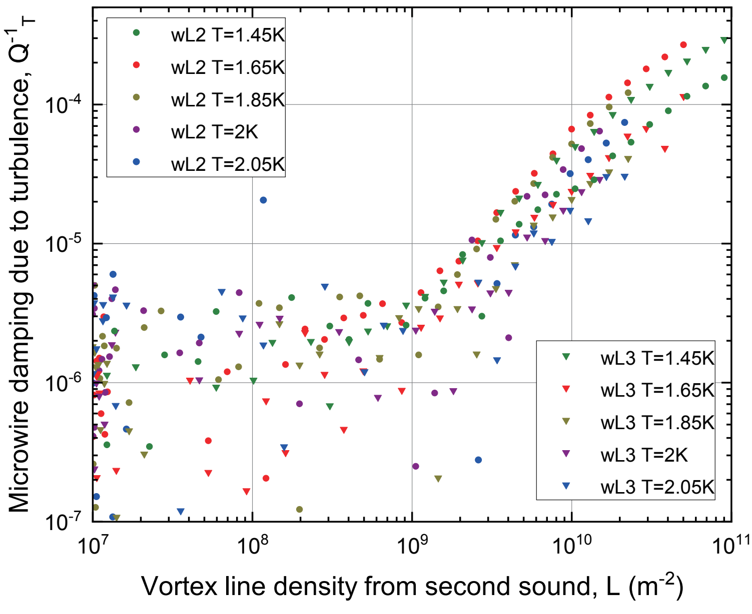

Fig. 1: Additional damping of two different NbTi microwires due to counterflow turbulence in the form of an inverse quality factor, Q_T^{-1}, plotted against the vortex line density, L, determined from second sound attenuation.

[1] T. Kamppinen and V.B. Eltsov, JLTP **196**(1-2), 283 (2019).
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Update on ULT at University of Florida

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ULT2022: Coupling electrons on helium to superconducting quantum circuits

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Electrons floating above the surface of superfluid helium, or electrons on helium (eHe), provide an interesting platform to study electron interactions in the form of Wigner molecules as well as providing a promising platform for qubits with long coherence times. Here, we show our progress in developing a hybrid quantum system in which electrons trapped above the surface of superfluid helium are coupled to superconducting quantum circuits that live below the superfluid surface. Microchannels in our device architecture allow us to control these electron systems and realize different phases with distinct electron dynamics, e.g. multi-electron row Wigner solids or strongly correlated electron liquids. Coupling electrons to coplanar waveguide resonators provides us with a tool to explore these electronic phases. These types of devices open a pathway to new methods for coherent control and readout of electronic degrees of freedom for a realization for an eHe qubit.

Temperature Dependent Instabilities of Duffing Resonator Based on Sn-whisker at Low Temperatures

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Nano- and micro- mechanical resonators offer an excellent opportunity to study the crossover between linear and nonlinear processes occurring at the lattice level[1−3]. Duffing micro-resonators based on Sn-whisker is an example of a periodically forced resonator with such nonlinear elasticity[4,5]. Not much is known about the physical processes acting at atomic scale when it comes to the origin of this phenomenon in contrast to advancements made by theoretical description. Here we present measurements of the temperature dependence of non-linear processes, i.e. instabilities - the jumps in velocity observed at certain frequencies in Sn-whisker under magneto-motive excitation at very low temperatures and in magnetic fields up to 100 mT. We suggest a physical model describing the origin of this phenomenon based on temperature fluctuations and a locality of the driving force.

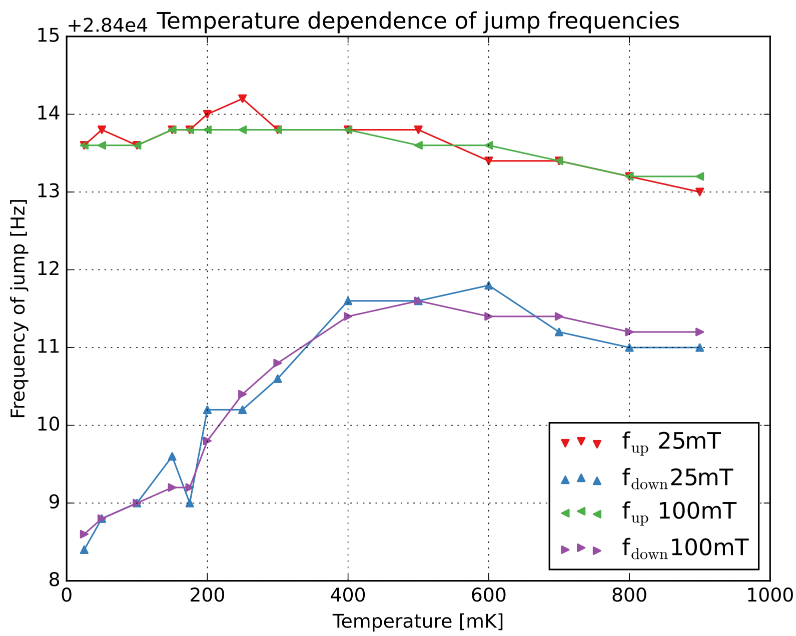

Fig. 1: Temperature dependence of "jump frequencies" for magnetic fields $B = 25$ mT and 100 mT.

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Work is supported by European Microkelvin Platform (EMP), H2020 project No. 824109.

"Plug-in & cool" nuclear demagnetization stage for cryogen-free dilution refrigerators

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Commercial cryogen-free dilution refrigerators are currently readily available on demand, and this have opened the access to milli-kelvin temperature range for broader spectrum of the physicists/scientists. With the intention to help to achieve even lower temperatures, we have invested our effort to design and development of a copper nuclear demagnetization stage, an additional "cooling extension" for these commercial cryogen-free dilution refrigerators. Here we present design and performance of a novel, modular nuclear copper stage. The main advantage of our design is a "plug-in & cool" concept, thus simplifying assembly and disassembly process. Its modular form offers a straightforward modifications and adaptations to follow the construction requirements of the most cryogen-free dilution refrigerators commercially available on the market.

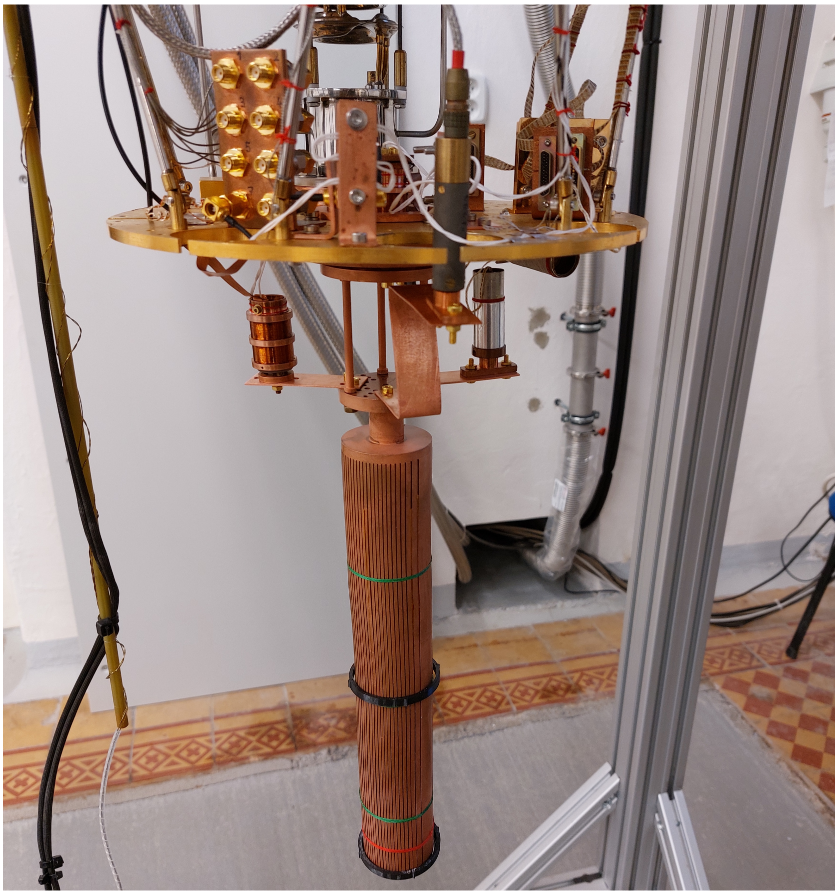

Figure 1: Photograph of the "plug-in & cool" copper nuclear demagnetization stage .

Work is supported by European Microkelvin Platform (EMP), H2020 project No. 824109.

Role of surface layer in cooling of superfluid ^{3}He in a demagnetization cryostat

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Most experiments with superfluid ^{3}He use demagnetization of paramagnetic metals, such as copper, to reach sub-millikelvin temperatures. To have a good thermal contact between the metal and ^{3}He a heat exchanger with big surface area is always used. It is known that surfaces are covered with thin layer of solid ^{3}He which has certain magnetic ordering and field- and temperature-dependent heat capacity. At low temperatures the surface heat capacity can be comparable or larger than heat capacity of bulk superfluid.

We study a simple system with copper plates covered with sintered silver powder and immersed in liquid ^{3}He. We can apply magnetic field up to 8T, measure temperature of liquid helium with vibrating wire, and apply heat to the liquid with another vibrating wire.

We observe that this system can be described by a model with at least four thermal reservoirs: copper, liquid, and two surface systems. Thermalization process between these systems have very different time scales: sub-second for liquid and first surface system, a few minutes between them and the second surface system, hours between liquid plus surface and copper. By overheating liquid we can see all these processes and extract heat capacity of each part of this model and thermal conductances between them. We can see that both surface systems have field-dependent entropy and take part in the demagnetization process.

Study of thermal boundary resistance between metal and ^{3}He at ultralow temperatures

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The thermal contact between liquid helium and solids at ultralow temperatures is a long-standing puzzle. Acoustic mismatch theory predicts the thermal boundary resistance to have a stronger temperature dependence than found in many experimental measurements. The possibility of heat transfer via magnetic channels has been extensively investigated and discussed theoretically. Sintered metal powders of relatively high specific surface area are commonly used in these investigations, with the drawback that poor thermal conductance of helium within the sinter pores needs to be taken into account. For recent work see [1].

In this experiment we exploit our recent advances in thermometry and control of heat leaks to measure the thermal boundary resistance between small area metal samples (foils or wires) and liquid helium. This is similar to the approach taken many years ago [2], with the advantage of significantly lower area samples and the ability to reach lower temperatures through the reduction of heat leaks to a few fW. A compact SQUID-based current sensing noise thermometer is used to measure the increase in temperature of the foil on application of heater power (a few pW at low mK temperatures).

The set-up allows for systematic study of heat transport across a well-defined boundary to liquid ^{3}He, using well characterised foil material. We can investigate the influence of magnetic impurities, as well as the role of the helium surface boundary layer by preplating with ^{4}He. For example, a high purity (99.999%) copper foil, of thickness 25 μm shows relatively small deviations from $R_K T^3$ = constant. On the other hand, a 4 cm^2 gold foil, of thickness 7 μm with a variety of impurities (including Pd and Pt at levels up to 9 ppm), shows a temperature independent R_K below 5 mK. Similar results are found with a gold wire of diameter 25 μm.

With our set-up potential magnetic coupling can be further characterised by measurements of the field dependence of the thermal boundary resistance. See [3] and references therein. Furthermore changes in thermal resistance arising from onset of superfluidity in ^{3}He should also be characterised. The cell is compact and versatile and will enable the test of novel designs for future heat exchangers, of importance in improved dilution refrigerators and the cooling of quantum materials and quantum sensors.

The research leading to these results has received funding from the European Union's Horizon 2020 Research and Innovation Programme, under Grant Agreement No 824109. This work was also supported by EPSRC (UK) through EP/R04533X/1, and Oxford Instruments.

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Hydrogen transfer via phonon-assisted quantum tunneling in metallic nanocontacts

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We studied the quantum character of hydrogen (H) transfer in niobium (Nb) nanocontacts, where H atoms are loaded from liquid H_2 by applying a bias voltage between the nanocontacts, using point-contact spectroscopy [1, 2]. At an intermediate H concentration of the nanocontacts, the differential conductance spectra show several spikes without polarity and hysteresis in the bias sweep as shown in Fig. 1, reflecting the lattice distortion due to H transfer between the occupied and vacant sites. For the spectra plotted as a function of the product of current and voltage, $I \times V$, the spike positions show excellent agreement between different sized contacts. Similar features are observed in different metallic nanocontacts, e.g., Pd, where H atoms are loaded from liquid H_2 by applying a bias voltage. These suggest that non-equilibrium phonons emitted by accelerated electrons in the contact induce the H transfer between the interstitial sites in the similar manner to phonon assisted tunneling. When the H energy level of the occupied sites excited by the phonon injection agrees with that of the vacant ones, many H atoms move collectively via quantum tunneling.

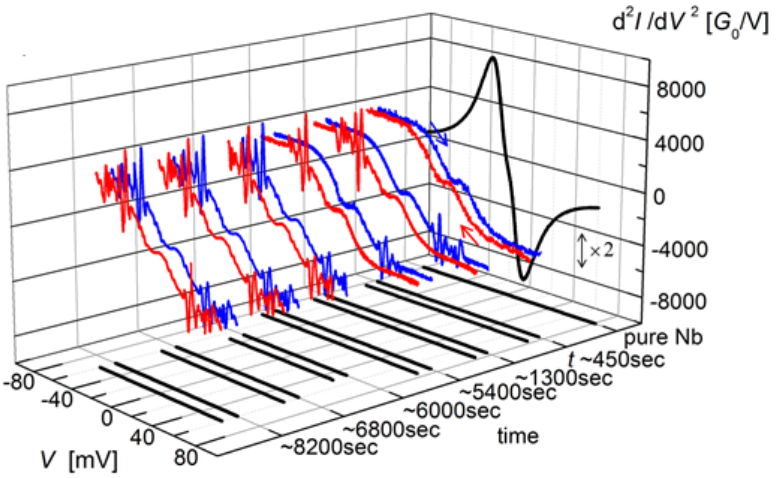

Fig. 1 The time evolutions for the differential conductance d^2I/dV^2 spectra at 16 K with contact diameter ~7.8 nm measured by point-contact spectroscopy. The spectra show several spikes, reflecting the lattice distortion due to H transfer due to the tunneling between the occupied and vacant sites.

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Emission of Vortex Rings from Thermal Counterflow Turbulence in Superfluid Helium 4 —TII Turbulence State—

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We report the quantized vortex emission from a quantum turbulence produced by thermal counterflow in superfluid ^{4}He. K. P. Martin and J. T. Tough have measured the vortex line density of counterflow turbulence as a function of counterflow velocity [1], finding a laminar flow regime and two turbulent regimes TI and TII. They found that the vortex line density in TII regime is larger than that in TI regime. In TII regime, both the superfluid flow and the normal fluid flow are expected to be in the turbulence state. In the present work, we investigate the vortex emission from the turbulence in TII regime.

A counterflow turbulence is generated in a circular channel with a diameter of 0.3 mm at 1.26 K. A vibrating wire is mounted outside at the front of the channel end as a vortex ring detector. We controlled the counterflow direction by changing a heater position to observe vortex ring emission both parallel and antiparallel to the superfluid flow of counterflow.

We have detected vortex rings emitted from the channel in TII regime. The detection rate of emitting vortex rings is estimated from the distribution of the detection times between the beginning of generation and the detection of a vortex ring. We find that the detection rate of the vortex rings emitted antiparallel to the superfluid flow is larger than that for the opposite direction, discussing the relation among the detection rate, the counterflow direction and the counterflow velocity.

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ULT2022: Opening Microkelvin Regime to Quantum Materials and Quantum Devices

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Refrigeration to ultra-low temperatures of order 1 mK and below has long been firmly established, underpinning studies of quantum fluids and solids. However, reaching sub-millikelvin temperatures is much more challenging for many other strongly-correlated quantum systems, mainly due to the large thermal resistance between the cooling stage and the sample and the thermalisation of the sample or device itself.

In contrast to *in-situ* coolers, we utilise a large remote nuclear demagnetisation stage, and establish strong thermal links to samples using high-conductivity metals and cryoliquids. This strategy of individually thermalizing the samples, involves engineering and characterising low heat leak rf-shielded environments and addressing their cooling, as well as developing ultra-sensitive low-dissipation measurement techniques. This flexible approach allows independent control of sample temperature and field, opening the door to new many-body ground states in quantum materials and enhanced performance of quantum devices.

We demonstrate cooling of both quantum devices, including electrons in a 2-dimensional electron gas in a semiconductor heterostructure [1], and diverse quantum materials, such as electrons and nuclear spins in intermetallic compounds $YbRh_2Si_2$ and $PrOs_4Sn_{12}$.

At Royal Holloway we provide user-access to four microkelvin systems with distinct sample environments. Most recently we have developed a high performance cryogen-free microkelvin platform, equipped with a large volume for mounting experiments in a low electromagnetic noise environment. For this system the hold-time below 1 mK represents a duty cycle of 95 %. Such a system should contribute to the improved accessibility of the microkelvin temperatures regime for future research in quantum materials for quantum information science and for applications of quantum sensors for fundamental physics.

* Projects mentioned in this abstract are supported by the European Microkelvin Platform (European Union's Horizon 2020 Research and Innovation Programme, under Grant Agreement No 824109), the EPSRC Programme grant EP/K004077/ and the HFML-RU/NWO-I, member of the European Magnetic Field Laboratory (EMFL).

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NMR evidence for density wave order in the two-dimensional ^{4}He supersolid doped by ^{3}He

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The second layer of ^{4}He adsorbed on graphite is a model 2D quantum system to study the interplay of superfluidity with film structure. The coverage range corresponding to 4/7 and 7/12 commensurate phases is of particular interest. Torsional oscillator (TO) experiments in the millikelvin range revealed a state with intertwined density wave and superfluid order [1,2]. A frequency independent superfluid response was reported in [3]. Heat capacity studies were interpreted as melting peaks of a quantum liquid crystal [4]. Recent theoretical work has, for the first time, found superhexatic and stable supersolid 7/12 phases in the $T = 0$ limit [5].

We report direct thermodynamic evidence for density wave order in the second layer, by doping with a small concentration of ^{3}He atoms. SQUID NMR on ^{3}He has been performed over a wide temperature range from 500 mK to 0.2 mK 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. Alignment of magnetization and heat capacity isotherms of the ^{3}He doped sample with isotherms of the TO frequency shift of a pure ^{4}He sample support the identification of a 2D ^{4}He supersolid. In the coverage range corresponding to 4/7 and 7/12 commensurate phases we observe a power-law temperature dependence of magnetic susceptibility and distribution of relaxation times T_1, which will be discussed in detail on our sister poster at this conference [6].

[1] J. Nyéki *et al.,* Nature Physics **13**, 455 (2017).
[2] J. Nyéki *et al.,* J. Low Temp. Phys. **187**, 475 (2017).
[3] J. Choi *et al.,* Phys. Rev. Lett. **127**, 135301 (2021).
[4] S. Nakamura *et al.,* Phys. Rev. B **94**, 180501(R) (2016).
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Anomalous thermalization of ^{3}He spins in a 2D ^{4}He matrix

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We have studied the spin-lattice relaxation of ^{3}He doped into the second ^{4}He layer adsorbed on graphite, which is a model 2D quantum system to study the interplay of superfluidity with film structure [1].

Measurements were performed using pulsed SQUID NMR technique at fixed ^{3}He coverages of 0.5 and 0.7 nm^{-2}. The total coverage and concentration of ^{3}He in the second layer was tuned by adding ^{4}He into the system. The coverage range corresponding to 4/7 and 7/12 commensurate phases is of particular interest.

The temperature dependence of the magnetic susceptibility follows a power law $\chi = C/T^{\alpha}$, where $\alpha < 1$, across the whole coverage range where the superfluid response measured by the torsional oscillator can be collapsed using a single scaling parameter [1].

We discover a dramatic increase of the characteristic spin lattice relaxation time $T_1^{\dagger}$ reflecting a distribution of relaxation times T_1 which peaks at the putative 7/12 commensurate phase.

On cooling $T_1^{\dagger}$ increases exponentially with characteristic temperature ~ 200 mK, before being limited by a parallel Korringa-type relaxation channel at the lowest temperatures, below 10 mK. Our analysis is able to extract the distribution of relaxation times within the film.

We will discuss this system as an experimental candidate for many body localisation, arising from ^{3}He strain mediated interactions in the 2D layer subject to periodic potential of first layer atoms.

[1] J. Nyéki *et al.,* Nature Physics **13**, 455 (2017).

Development of continuous sub-mK refrigeration for ground-state cooling of mechanical resonators

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Ground state mechanical systems are usually prepared by passively cooling GHz frequency modes to 10 mK or using optomechanics to actively cool lower frequency modes. In contrasting recent work, a 15 micrometer diameter Al drum was passively cooled below 1 mK, thereby decreasing the average phonon occupation of the 15 MHz fundamental flexural mode below unity [1]. In this approach, the environment of the mechanical mode is cold and the ground-state center-of-mass motion is relatively large. This facilitates studies of foundations of quantum mechanics, quantum thermodynamics and individual tunneling two level systems. We report our development of a continuous nuclear demagnetization refrigerator with a target base temperature of 1 mK. Its design is compatible with cryogen-free dilution refrigerators, so that researchers working at microkelvin temperatures can operate without a helium liquefier and benefit from the large experimental space and automated operation of dry systems. The design relies on our recently demonstrated ultra-high conductance heat switch [2]. We expect this technology to propel several fields on the frontiers of science and technology.

1. D. Cattiaux, I. Golokolenov, S. Kumar, M. Sillanpää, L. Mercier de Lépinay, R. R. Gazizulin, X. Zhou, A. D. Armour, O. Bourgeois, A. Fefferman & E. Collin, *Nature Comm.*, **12**, 6182 (2021).

2. J. Butterworth et al., Superconducting aluminum heat switch with 3 nΩ equivalent resistance, *Rev. Sci. Instrum.* **93**, 034901 (2022).

NMR study of 1D ^{3}He in nanochannels

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In order to examine possible realization of ^{3}He Tomonaga-Luttinger liquid (TLL), we have studied the fluid state of 1D ^{3}He adsorbed in ^{4}He-precoated nanochannels of FSM a few nm in diameter, using ^{3}He NMR. At dilute ^{3}He densities (on the order of 0.01 atomic layers) where the ^{3}He motional states with azimuthal motion in 1D channels are not occupied even at zero temperature, the quantum-mechanically genuine 1D fluid of ^{3}He adatoms is realized at low temperatures. The experimental 1D condition for the temperature and ^{3}He density can be determined by a characteristic maximum of the heat capacity [1] and density-independent decrease of the susceptibility [2]. In this 1D state, characteristic increases of the spin-spin relaxation time T_2 below 0.12K have been observed with decreasing temperature [3]. Such increase proportional to the inverse of the temperature was observed only when prepared ^{3}He satisfied the condition for the genuine 1D state, and the behavior agrees with that expected for possible TLL state. On the other hand, that increases of T_2 are observed similarly in both degenerate and non-degenerate regions, in contrast with a qualitative difference of spin-lattice relaxation, which remains as an issue to be clarified. To further investigate the motional state of 1D ^{3}He in nanochannels, we are preparing NMR experiments to observe spin diffusion of ^{3}He. The preliminary results will be shown.

[1] J. Taniguchi *et al.*, Phys. Rev. Lett. **94**, 065301 (2005).
[1] T. Matsushita *et al.*, J. Low Temp. Phys. **183**, 251 (2016).
[2] T. Matsushita *et al.*, Phys. Rev. B **103**, L241403 (2021).

Study of Surface States in Superfluid Helium 3-B Phase by Using an Angle Resolved Quantum Andreev Reflection Detector

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Superfluid ^{3}He B phase provides an opportune platform for research of topological matters. On the free surface of the superfluid, topological aspects appear such as the gap suppression. One of the previous experiments revealing surface states has been conducted to directly observe the quantum Andreev reflection (QAR) [1]. In that study, the quasi-particles (quasi-holes) were excited by an inner heater and ejected toward the liquid surface (angle of incidence : 20°), by using a black body radiator (BBR) type equipment which is dome-shaped device with a pinhole installed in the superfluid ^{3}He. They measured the extra temperature rise caused by the unusual characteristics of QAR that the quasi-holes (quasi-particles) go back to the BBR on the same path.

On the other hand, a theoretical result [2] shows the angle and energy dependence of QAR rate based on the spatial change of the order parameter near the surface, and that the quasi-particles with larger incident angles and smaller energies tend to have a higher proportion of QAR other than normal reflection.

In this study, we have developed an experimental device for the measuring the QAR rate over various angles and energies. Its measurement unit is composed of a copper box with an orifice and the aperture, which is rotated by a flexible bellows driven by the pressure of ^{4}He (Fig.1). The excited quasi-particles beam intensity from the BBR can be calculated by the molecular flow Monte Carlo simulation program we made, and can be directly compared with the experimental results by inputting the theoretical values of the QAR rate. In our device, by controlling the liquid level to the center of rotation, it is possible to perform measurements under the same conditions without changing the distance to the surface at any angle.

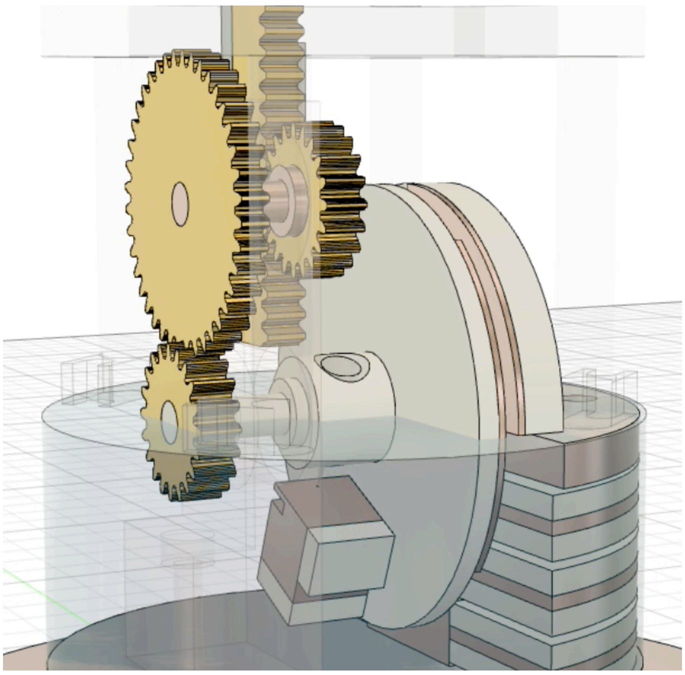

Fig.1 CG image of rotating BBR unit.

In this presentation, we report the outline of the measuring device and the progress of the experiment.

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Exploring Applications of Graphene-Based Josephson Junctions

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Local control over the critical currents and inductances of Josephson junctions is desirable for expanding functionality beyond what is possible with oxide tunnel junctions. Junctions where monolayer or bilayer graphene acts as a bridge between two bulk superconducting electrodes have shown to exhibit Josephson effects and a critical current which can be tuned using a local gate. This has been used to build Superconducting Quantum Interference Device (SQUID) magnetometers, qubits and parametric amplifiers. This poster will describe two other applications for controllable two-dimensional material (2DM) Josephson junctions: Andreev interferometers and local magnetometry of 2DMs.

Hybrid quantum interference devices (HyQUIDs) consist of a proximitised junction in a superconducting loop with normal metal contacts to measure the junction resistance. We have fabricated HyQUIDs with graphene junctions that have controllable carrier concentration. Transport across the junction is ballistic, allowing us to observe interference between a small number of conducting channels within the graphene.

Two-dimensional crystals are subject to significant interest due to their potential uses in Van der Waals heterostructure devices. Magnetic characterisation of these materials presents several challenges due to the small signals involved and the environmental requirements of some 2DMs. We are exploring experimentally how to use graphene-based SQUIDs [1] to measure magnetic properties of 2DMs on the same chip, taking advantage of the similarities between the fabrication processes of 2DMs and graphene SQUIDs.

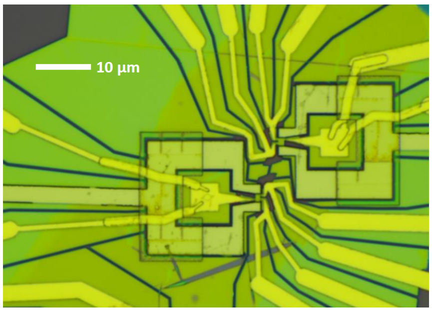

Figure 1: Two Hybrid Quantum Interference Devices with monolayer graphene bridges. The superconducting phase difference across the junction can be controlled by applying magnetic flux through the large NbTi loop.

[1] M. Thompson *et al.*, Appl. Phys. Lett. **110**, 162602 (2017).

Origin of resistivity upturn in Mg doped delafossite $CuRhO_2$

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Ultra-pure delafossite metals have in the recent years attracted significant attention with the observation of hydrodynamic electron flow [1] and macroscopic scale quantum coherence effects [2]. Doped semiconducting counterparts of delafossite metals, that show promising thermoelectric properties [3] and evidence for phonon drag [4], have on the contrary not been extensively studied with electrical transport at sub-helium-4 temperatures, nor using spectroscopy.

Here we have taken a semiconducting delafossite $CuRhO_2$ doped to a metallic state with 10% Mg and performed a comprehensive study on its single crystals using angle-resolved photoemission spectroscopy (ARPES), x-ray absorption spectroscopy (XAS), electron spin resonance (ESR) and electrical transport. From our ARPES measurements in combination with density functional theory calculations (DFT), we identify a rich Fermi surface structure featuring both a quasi-2D sheet with interesting out-of-plane helical warping and a 3D-like pocket that gives rise to a relatively flat in-plane band structure in the vicinity of the Fermi level. Our XAS and ESR data point to the presence of Cu^{2+} ions with unpaired spin $\frac{1}{2}$ and our transport measurements exhibit a non-saturating resistivity upturn with a negative magneto-resistance. We discuss possible scenarios of the resistivity upturn origin in this system in terms of Kondo coupling and disorder-driven localisation.

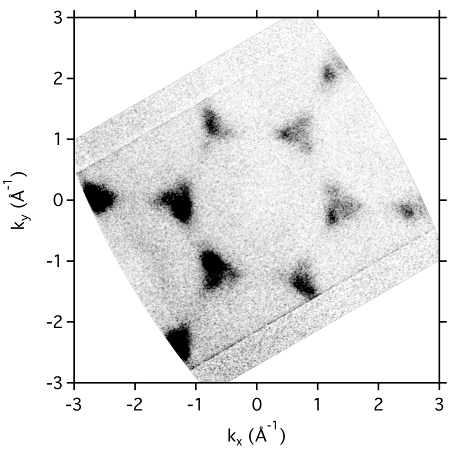

Fig. 1: ARPES measurement of the Fermi surface of 10% Mg doped $CuRhO_2$.

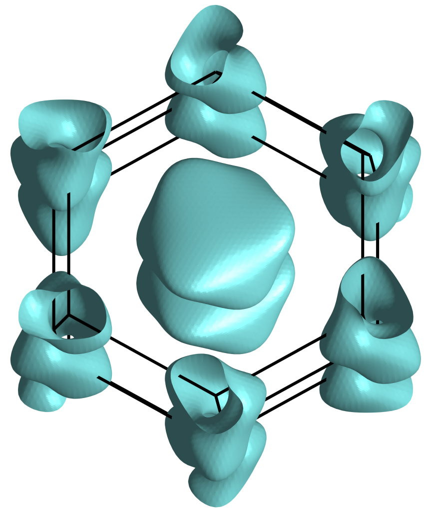

Fig. 2: Fermi surface of 10% Mg $CuRhO_2$ from DFT. The black lines mark the 1st Brillouin zone boundary.

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Enhancement of Spin-Charge Conversion in Dilute Magnetic Alloys by Kondo Screening

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We report the derivation of a kinetic theory capable of dealing with both large spin-orbit coupling and Kondo screening in dilute magnetic alloys [1]. We have obtained the collision integral of the Boltzmann equation nonperturbatively and uncovered a contribution proportional to the derivative of the impurity scattering S matrix with respect to the momentum. The latter yields an important correction to the spin diffusion and spin-charge conversion coefficients, and fully captures the so-called side-jump process without resorting to the Born approximation (which fails for resonant scattering), or to otherwise heuristic derivations. We apply our kinetic theory to a quantum impurity model with strong spin- orbit, which captures the most important features of Kondo-screened Cerium impurities in alloys such as $Ce_xLa_{1-x}Cu_6$. We find (1) a large zero-temperature spin-Hall conductivity that depends solely on the Fermi wave number and (2) a transverse spin diffusion mechanism that modifies the standard Fick's diffusion law. Our predictions can be readily verified by standard spin-transport measurements in metal alloys with Kondo impurities.

PACS numbers:

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Topological Lifshitz Transitions, Orbital Currents, and Interactions in Low-dimensional Fermi Gases in Synthetic Gauge Fields

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Low-dimensional systems of interacting fermions in a synthetic gauge field have been experimentally realized using two-component ultra-cold Fermi gases in optical lattices. Using a two-leg ladder model that is relevant to these experiments, we have studied the signatures of topological Lifshitz transitions and the effects of the inter-species interaction U on the gauge-invariant orbital current in the regime of large intra-leg hopping Ω. Focusing on non-insulating regimes, we have carried out numerically exact density-matrix renormalization-group (DMRG) calculations to compute the orbital current at fixed particle number as a function of the interaction strength and the synthetic gauge flux per plaquette. Signatures of topological Lifshitz transitions where the number Fermi points changes are found to persist even in the presence of very strong repulsive interactions. This numerical observation suggests that the orbital current can be captured by an appropriately renormalized mean-field band structure, which is also described here. Quantitative agreement between the mean-field and the DMRG results in the intermediate interaction regime where $U \leq \Omega$ is demonstrated. We also have observed that interactions can change the sign of the current susceptibility at zero field and induce Lifshitz transitions between two metallic phases, which is also captured by the mean-field theory. Correlation effects beyond mean-field theory in the oscillations of the local inter-leg current are also reported. We argue that the observed robustness against interactions makes the orbital current a good indicator of the topological Lifshitz transitions.

PACS numbers:

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Tuning the phase diagram of superfluid ^{3}He with electric field

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The superfluid ^{3}He inside a thin parallel-plate capacitor is considered within Ginzburg-Landau theory. The electric field induces polar distortion of the superfluid order parameter via the electric dipole interactions, which competes with the planar distortions due to confinement inside the capacitor. A rich phase diagram emerges, containing the A, polar, and distorted A and B phases. Stabilizing the polar phase with electric field is found to be experimentally challenging but feasible, opening the prospects of studying and manipulating half-quantum vortices in the absence of disorder.

A System for Precise Control of a Levitating Sphere in Helium Fluids

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We have developed an apparatus for fine control of the motion of a superconducting sphere. The sphere can levitate in the bulk of a superfluid and is promising to be suitable for a wide range of measurements in both superfluid ^{4}He and ^{3}He [1]. Our finite elements analysis shows that the sphere can be driven in oscillatory motion, which will make a connection with numerous previous experiments in superfluids. Most importantly, the sphere can be made to move at a uniform velocity in a circle as well as in a straight line. This opens up a whole new multitude of approaches to quantitative studies of superfluid quantum matter, including quantum turbulence and dynamics of Andreev-bound states on the edges of topological superfluid ^{3}He-B [2], potentially hosting Majorana fermions.

The sphere represents a very tractable geometry for numeric interpretation of the results of drag force measurement as a function of its velocity and frequency of oscillations. This setup can also serve as a prototype for a facility utilizing cryogenic helium gas as a wind tunnel test fluid in classical turbulence experiments [3].

We also report a successful experimental realization of this system (Fig. 1).

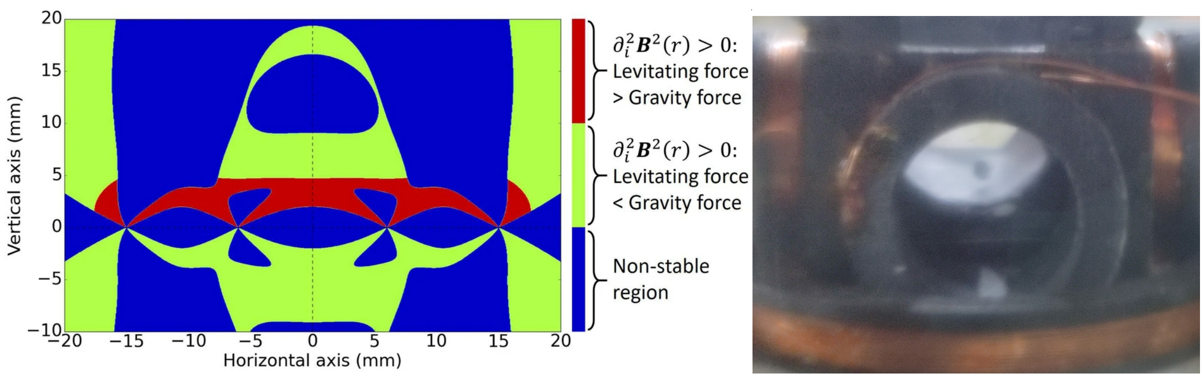

Fig. 1: Calculation of the stability regions within the experimental setup (left) and the indium-plated plastic sphere levitating in superfluid helium at 1.5 K (right).

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Effect of Flow on the Spatial Arrangement of Chiral Domains in Superfluid ^{3}He-A

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In the superfluid ^{3}He-A in a cell, texture of $\hat{l}$ is formed under a constraint of the boundary conditions of the cell. Kasai *et al*. performed MRI measurement of the superfluid ^{3}He-A confined between parallel plates with an interval of 100 μm and they discovered chiral domains with aligned $\hat{l}$ and domain walls formed between these domains [1]. In each domain $\hat{l}$ is aligned perpendicular to the parallel plates, either in the forward or backward direction, as shown in Fig. 1. Since these domain walls are accompanied by gradient energy, they should be formed in the vertical direction as shown in Fig. 1 to reduce their surface area. Some of the domain walls observed by Kasai *et al*. indeed formed in the vertical direction. However, the others have slanted straight shape, as shown in Fig. 2. (The black streaks in the MRI image in Fig. 2 are the domain walls.)

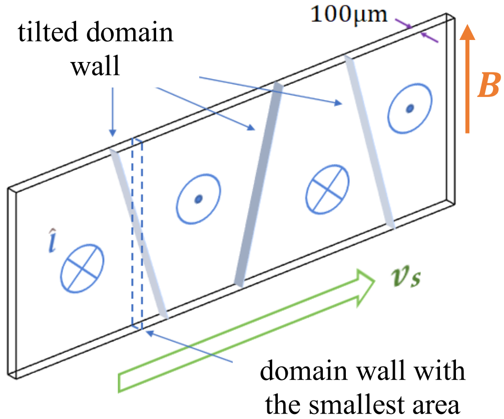

Fig. 1. schematic diagram of chiral domains

Feature of the slanted domain wall is that each adjacent domain wall tilts in the opposite direction at the same angle. This means that the tilting angles are not determined by the location of pinning sites on the upper and lower edge of the parallel plates. The tilt should be determined by global quantity such as supercurrent flowing along the parallel plates.

Those observations were performed with the parallel plate cell with a side path, which enabled the existence of a trapped supercurrent along the parallel plates. When we closed the side path of the cell, domain walls did not tilt, as shown in Fig. 3. This suggests that the trapped supercurrent tilted the domain walls.

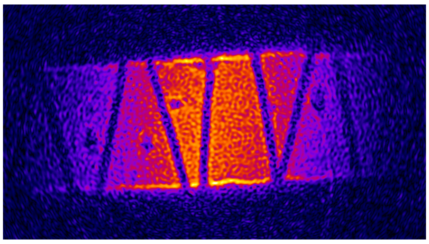
Fig. 2. MRI image of tilted chiral domain walls

The supercurrent is related to the texture of $\hat{l}$ through the gradient energy. A model analysis on the effect of the supercurrent suggests that each adjacent domain wall is tilted in the opposite direction by the supercurrent. This direction is determined by the direction of the current and the chirality of the domains. According to this model analysis, 10 ° of tilt corresponds to a supercurrent of 0.2mm/s along the parallel plates, which corresponds to about 30 quanta of trapped circulation. This current is smaller than the typical critical velocity. Our results indicate that the direction of chirality of each domain can be measured through the tilt of domain walls under a supercurrent crossing the walls.

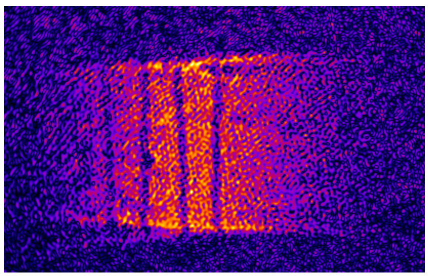
Fig. 3. MRI image of domain walls without bias current

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Transverse Sound in the Fermi Liquid and Superfluid States of ^{3}He

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One of Landau's last unverified predictions is that a Fermi liquid with sufficiently strong interactions can support propagating transverse zero sound (TZS). The normal state of liquid ^{3}He satisfies this condition but previous experiments were shown to be inconclusive. The attenuation length of TZS is expected to be 1-10 microns, meaning cavities designed to observe TZS need to be on this length scale. Here we discuss the fabrication of precise acoustic cavities from "silicon-on-insulator" wafers with cavity size varying between 2 to 10 microns. Ongoing experiments with the smallest of these cavities will be able to definitively verify or rule out the existence of TZS in the degenerate Fermi liquid state. In addition, these cavities will also be used to study the effects of topological surface states on the boundaries of superfluid B-phase, where TZS couples to these surface states.

Anomalous Low-Temperature Phase in Superfluid ^{3}He Imbibed in Anisotropic Aerogels

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Recent nuclear magnetic resonance experiments on superfluid ^{3}He imbibed in 12% stretched aerogels with surface magnetic scattering suppressed by a layer of solid ^{4}He have revealed a low temperature phase with novel properties. At temperatures below a window of A-phase, this unidentified phase displays a frequency shift behavior characteristic of the B-phase, but maintains constant susceptibility to a very low temperature. Under the same conditions, superfluid ^{3}He imbibed in a 7% stretched aerogel sample show evidence of a similar B-like phase with a separate critical temperature and a supressed temperature-dependent susceptibility decrease. This behavior contrasts with prior experiments on superfluid ^{3}He in 14% stretched aerogels, where the anisotropy stabilized the A-phase over the entire phase diagram [1,2]. The temperature-independent susceptibility indicates the anomalous low temperature phase in the 12% stretched aerogel may be either a strongly planar-distorted B-phase or a novel equal-spin pairing phase.

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