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as of 02-Aug-2022

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STEM Degrees:

STEM Participants:

Major Goals: The goal of this DURIP program is to integrate a helium reliquefier with the milli-Kelvin microwave impedance microscope for the study of topologically ordered quantum states. The instrument will enable the continuous operation of a dilution-refrigerator-based microwave microscope with minimal helium consumption. The microscope is capable of imaging the local conductance of topologically non-trivial phases such as quantum spin Hall state, quantum anomalous Hall state, and Axion insulator state. It is expected that the electrical properties of edge and bulk states at the frequency spectrum of 0.1 – 10 GHz will be of particular interest for defense applications. The program introduces a novel tool to study the nanoscale electronic structure of topologically ordered quantum states at ultralow temperatures. The work will establish a new research direction and augment existing Defense programs at University of Texas at Austin.

Accomplishments: The helium reliquefier has been delivered to the PI's lab. The PI's group is currently working on the lab renovation and installation of the system. Details of the accomplishment are included in the attached document.

Training Opportunities: Two graduate students (all personnel supported by other funding sources) in the PI’s group have been involved in the lab renovation and system installation. In addition to the construction work, they also had the opportunity to learn the basic cryogenic techniques, microwave network analysis, transport and optical measurements, and scanning probe skills in the laboratory. The interpretation of the real-space conductivity images at ultra-low temperatures requires a thorough understanding of the relevant physics on complex quantum materials, which are of great interest to the DoD.

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)

Participant: Zhanzhi Jiang
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

Partners

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Signature Date: 8/2/22 5:59PM

Final Report: Helium-efficient Cryogenic Microwave Impedance Microscopy for Research on Topological Quantum States

Defense University Research Instrumentation Program (DURIP)

Army Research Office Grant #W911NF-20-1-0049

PI: Keji Lai, University of Texas at Austin, Department of Physics, Austin, TX 78712

Statement of the Problem

The objective of this DURIP award is to implement a helium-efficient cryogenic microwave impedance microscope (MIM) based on a dilution refrigerator platform, which will substantially advance our knowledge on topological phases such as quantum spin Hall state, quantum anomalous Hall state, and Axion insulator state. The MIM is capable of achieving a spatial resolution of 10 ~ 100 nm, which is below one millionth of the free-space wavelength at 1 GHz. The base temperature below 100 mK in the dilution refrigerator is crucial for us to study the spatial distribution of local conductance in these systems. The reliquefier will ensure the efficient usage of helium, a precious natural resource undergoing global supply shortage in the present time. Moreover, with the recondensation of helium, the system will be continuously running without being interrupted by helium transfer, which is desirable for careful studies on topological states at cryogenic temperatures.

The significance of the program lies in the fundamental understanding of nanoscale electronic structures of topologically ordered quantum states at ultralow temperatures. The spatially resolved conductivity maps will provide critical feedback for material scientists to improve the sample quality towards device applications. Moreover, the electrical properties of the edge and bulk states will be studied at the frequency spectrum of 0.1 – 10 GHz, which is the regime of strong interest for many defense applications.

Summary of Results

Due to the COVID-19 pandemic, the manufacturing of the equipment, HeRL36 Helium Reliquefier from Cryomech Inc., was delayed by one year. Fortunately, it was delivered to the PI's lab in early 2022. The system includes the following components.

- Two sets of PT420-RM remote-motor cold head, CPA1114 helium compressor package, and cold head motor cord.
- Pressure controller and the required sensors and heaters.
- Reliquefier stand, remote motor stand, and pump filter.
- Stainless steel flexible lines for pumping recovery system.
- Stand tool and installation tool kits.

In the meantime, the PI's institution (University of Texas at Austin, College of Natural Sciences) has just completed the lab renovation to accommodate the reliquefier at the time of this report writing. As shown in Fig. 1, the building chilled water system (Fig. 1a) is now installed in a separate pump room that hosts the helium compressors and a secondary water chiller (Fig. 1b). The reliquefier stand (Fig. 1c) is moved to the instrument room, in preparation of final installation and testing. It should be noted that, thanks to the continuous support from ARO, the cryogenic microwave microscope (Fig. 1d) is fully up and running with a base temperature of ~ 100 mK. Once the reliquefier is installed, the helium consumption will drop from 35 liters per day to 1~2 liters per day. The system is not only helium-efficient but also allows much longer operation time without being interrupted due to helium transfer. This instrument will play a crucial role for the understanding of local conductance in topologically non-trivial phases such as quantum spin Hall insulator, quantum anomalous Hall insulator, axion insulator, and fractional quantum Hall state.

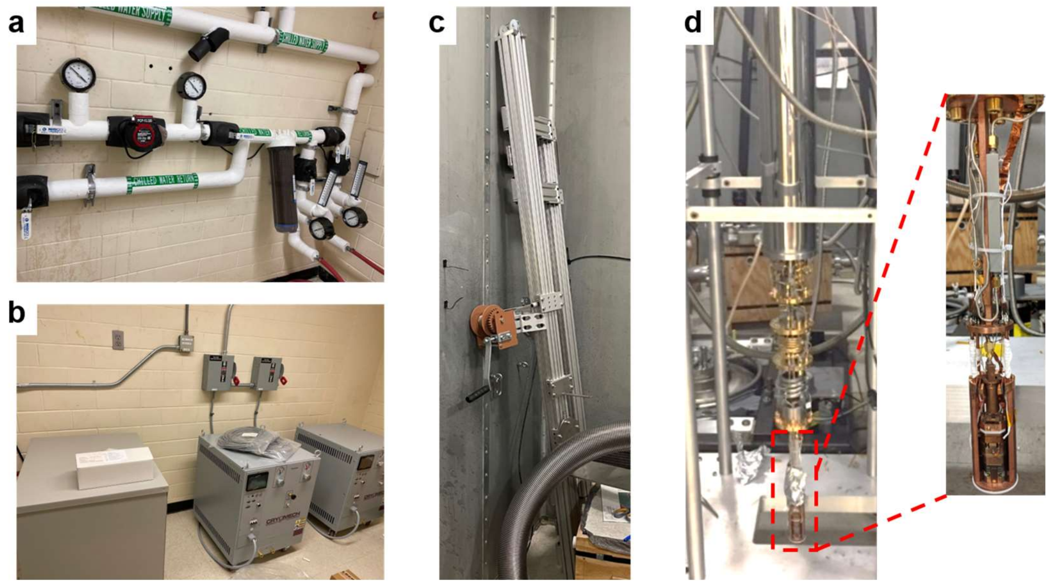

Figure 1. (**a**) Building chilled water system after lab renovation. (**b**) Secondary water chiller (left) and two helium compressors (right) in the pump room. (**c**) Reliquefier stand in the instrument room. (**d**) Picture of the dilution refrigerator and the microwave microscope. The inset shows a close-up view of the microscope insert with various microwave components, tuning-fork probe, and cryogenic positioner and scanners.

To summarize, thanks to the DURIP support, the PI's group has acquired a helium reliquefier and completed the lab renovation for installing the equipment. The instrument will enable helium-efficient investigations of nanoscale edge channels in topological quantum materials. The work will establish a new research direction and augment existing DoD programs at UT-Austin. The research is of fundamental importance for Army applications of high-speed and low-power electronics.