Floating-Electron-Based Quantum Information RIKEN Hakubi Research Team
(2024)
RIKEN Hakubi Team Leader, Erika Kawakami, Ph.D. Degree

(0) Research field

CPR Subcommittee**:** Physics, Engineering

Keywords: microwave, qubit, quantum computer, electrons on helium, Rydberg state

(1) Long-term goal of laboratory and research background

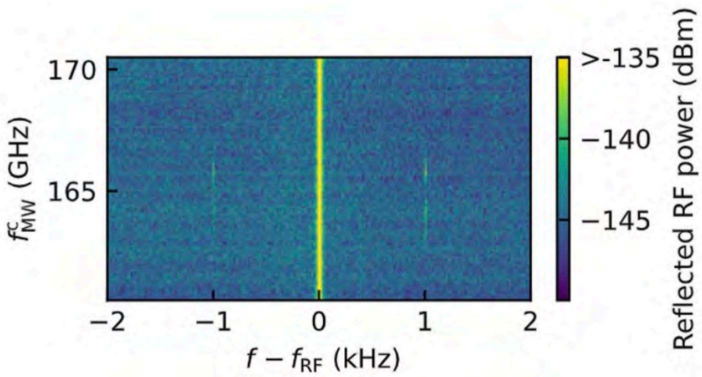
Our team is working on the application of electrons floating on liquid helium to quantum information. This physical system has a high potential for providing an ideal platform on which to realize a quantum computer, since it is free of impurities and defects. The quantized states normal to the liquid helium surface are called Rydberg states. The Rydberg-ground state and the Rydberg-1st-excited state are located 10 nm and 30 nm away from the liquid helium surface, respectively. The Rydberg state of different electrons can be coupled via the long-range Coulomb interaction, which allows us to place electrons at a moderate distance while keeping a considerable interaction between them to realize a two-qubit gate.

We are also working on the development of cryogenic microwave sources for large-scale quantum computation. In most cases, qubits are placed at low temperature and microwaves are sent to control and read out the qubits' states. For a small-scale quantum computer that is presently existing, we use thick cables that connect microwave generators at room temperature and qubits at low temperature. However, it is difficult to prepare a so high number of such thick cables inside a cryogenic refrigerator as to be required for large-scale quantum computation. In order to overcome this circumstance, we propose to develop small-sized and low-power consumption microwave generators which function at low temperature and place them inside the cryogenic refrigerator.

(2) Current research activities (FY2024) and plan

(A) Realization of qubits using floating electrons

Electrons on liquid helium offer a clean platform for quantum computing, with spin states expected to have long coherence times. However, spin-state detection remains challenging. A promising approach maps the spin state onto a Rydberg state, detectable via an LC tank circuit with high sensitivity and small footprint. As a proof of concept, we detect Rydberg transitions of an electron ensemble using frequency-modulated microwaves. Adiabatic transitions induce measurable quantum capacitance. The achieved sensitivity allows resolving the Rydberg transition of a single electron, paving the way for scalable spin-state readout and helium-based quantum technologies.

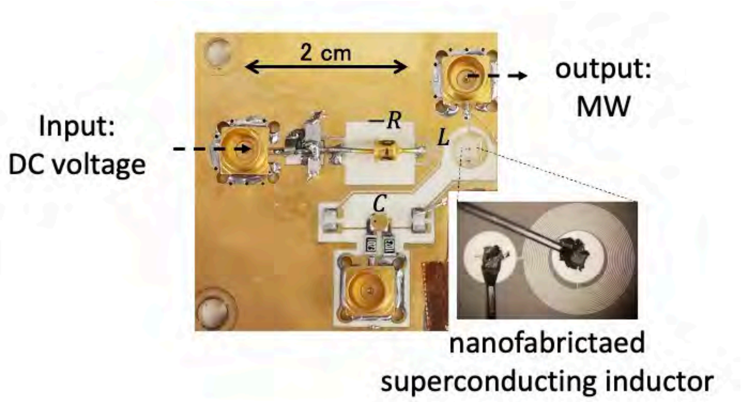


Caption: Reflected RF power measured with a spectrum analyzer as a function of the microwave (MW) carrier frequency f_{MW}. The frequency modulation (FM) parameters are f_{mf} = 1 kHz and f_{ma} = 768 MHz. Sideband signals appear at $f = f_{RF} \pm f_{mf}$ around f_{MW} = 165 GHz, corresponding to the Rydberg transition.

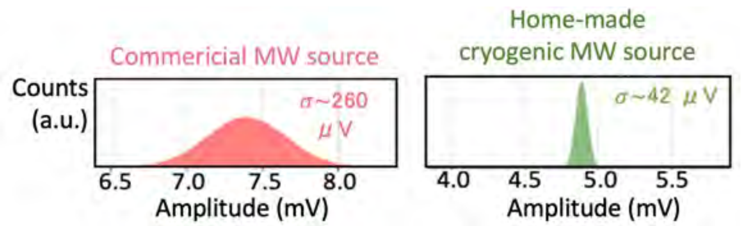
Future plan: We realize the floating qubits experimentally.

(B) Development of a cryogenic microwave source

To realize a large-scale quantum computer, it is necessary to connect qubits operating at cryogenic temperatures with room-temperature instruments via coaxial cables. However, the number of such cables is physically constrained, making it essential to develop measurement devices that function at low temperatures. Since qubits are controlled by microwaves, we developed a compact microwave oscillator based on a tunnel diode that operates reliably under cryogenic conditions. By connecting a tunnel diode, which exhibits negative resistance, to an LC resonator and applying a DC voltage, microwave signals are generated. The oscillator is compact (2×2 cm), operates stably at low temperatures, and exhibits smaller amplitude fluctuations than commercial microwave sources. Because amplitude stability directly impacts qubit readout fidekity, this oscillator enables more precise quantum state measurements.



Caption: The developed microwave oscillator successfully operates at cryogenic temperatures (10 mK). In the circuit diagram, –*R* represents the tunnel diode. The capacitor (*C*) is a varactor diode used to tune the frequency in the range of 10 MHz, and the inductor (*L*) is a microfabricated superconducting inductor to minimize resistive losses.



Caption: Comparison of amplitude stability between a commercial microwave oscillator and the cryogenic microwave oscillator developed in this work.

Future plan: We will use this scheme to detect the qubit state.

(3) Members

	Name
RIKEN Hakubi Team Leader	Erika Kawakami
Technical Scientist	Ivan Grytsenko
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IPA	Yiran Tian
Secretarial assistant	Yumi Nakashima Rie Ishikawa
Research Part-timer	Oleksiy Rybalko

(4) Representative research achievements

1. A. Jennings, I. Grytsenko, Y. Tian, O. Rybalko, J.Wang, I. J. Barabash, E. Kawakami, "Probing the Quantum Capacitance of Rydberg Transitions of Surface Electrons on Liquid Helium via Microwave Frequency Modulation", Physical Review Letters, 135, 087001 (2025) (Editor's Suggestion)
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3. E. Kawakami, Jiabao Chen, M´onica Benito, Denis Konstantinov, "Blueprint for quantum computing using electrons on helium", Physical Review Applied, 20, 054022 (2023).
4. A. Jennings, X. Zhou, I. Grytsenko, E. Kawakami, "Quantum computing using floating electrons on cryogenic substrates: Potential And Challenges", *Appl. Phys. Lett.* 124, 120501 (2024).
5. E. Kawakami, A. Elarabi, and D. Konstantinov "Relaxation of the excited Rydberg States of Surface Electrons on Liquid Helium", *Phys. Rev. Lett*., 126, 106802 (2021).

Laboratory Homepage

https://sites.google.com/view/febqi/
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