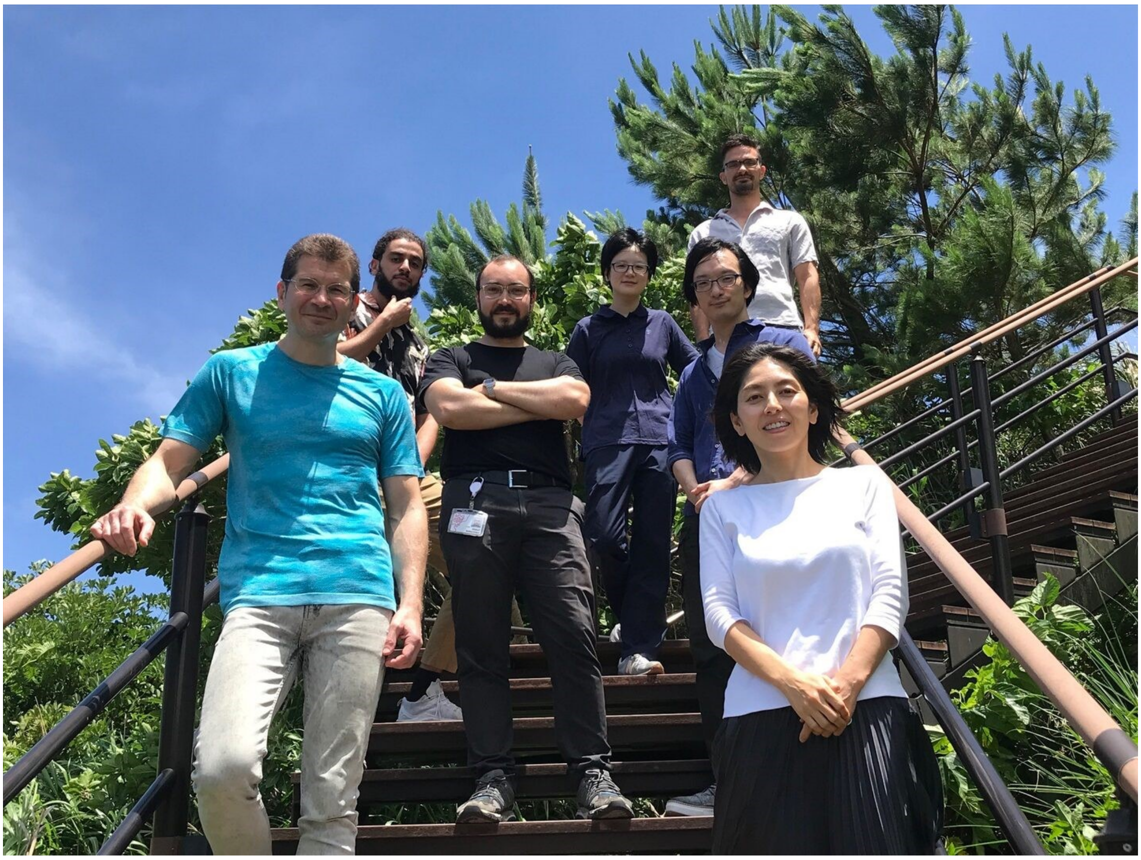
FY2021 Annual Report

Quantum Dynamics Unit

Professor Denis Konstantinov



(From left to right) Denis Konstantinov and Taki Tazuke (front row), Mikhail Belyanchikov and Tomoyuki Tani (starting from FY2022) (second row), Mohamed Hatifi and Shan Zou (third row), Ivan Kostylev (top)

Abstract

In the beginning of FY2021, we said farewell to Dr. Yuimaru Kubu (and his entire team) who took an independent PI position in the Science and Technology Group at OIST to lead his research on color centers in diamond. Since FY2021, our group has completely concentrated on the research on the electron-on-helium system, in particular its implementation for quantum computing.

During FY2021, we said farewell to Dr. Oleksiy Zadorozhko, who took a research staff position at Chalmers University, and to Jason Ball who successfully defended his PhD degree and moved to USA to work in a quantum computing startup company Bleximo Co. We also welcomed two new postdocs from Russia, Dr. Kirill Shulga and Dr. Mikhail (Misha) Belianchikov.

1. Staff

- Dr. Oleksiy Zadoroshko, Technical Staff
- Dr. Ivan Kostylev, Postdoctoral Scholar
- Dr. Mohamed Hatifi, Postdoctoral Scholar
- Dr. Kirill Shulga, Postdoctoral Scholar
- Dr. Mikhail Belianchikov, Postdoctoral Scholar
- Jason Ball, Graduate Student
- Shan Zou, Graduate Student
- Taki Tazuke, Research Unit Administrator
- Sachie Matsuoka, Research Unit Administrator (temporary)

2. Collaborations

2.1 Proposal for a scalable quantum computer using electron spins on liquid helium

- Description: Theoretical proposal demonstrating all key elements of a quantum computer based on spin states of electrons trapped on superfluid helium
- Type of collaboration: Joint research
- Researchers:
  - Dr. Erika Kawakami, Floating-Electron-Based Quantum Information Hakubi Research Team, RIKEN, Japan

2.2 Quantum-state detection of trapped electrons on superfluid helium

- Description: Detection of orbital and spin quantum states of electrons on superfluid helium for their potential implementation as qubits
- Type of collaboration: Joint research
- Researchers:
  - Professor Tomohiro Otsuka, Tohoku University, Japan
  - Dr. Erika Kawakami, Floating-Electron-Based Quantum Information Hakubi Research Team, RIKEN, Japan

2.3 Cryogenic amplification of single-electron image current for spin-state detection

- Description: Development of a sensitive current detection circuit for quantum-state detection of electrons on superfluid helium
- Type of collaboration: Joint research
- Researchers:
  - Dr. Asem Elarabi, Electrical Engineering Support Staff, OIST, Japan
  - Dr. Jui-Yin Lin, High Energy Physics Laboratory, National Center University, Taiwan

3. Activities and Findings

3.1 Spin-state coherence of an electron trapped over a superfluid helium substrate (Denis Konstantinov, in collaboration with Erika Kawakami from RIKEN and Shan Zoe from OIST)

Our idea of spin-state implementation of electrons on helium for quantum computing is centered on the artificial spin-orbit coupling to the Rydberg states of the electron motion perpendicular to the liquid helium surface. Such coupling can be introduced by a sufficiently strong gradient of an applied magnetic field. For example, we envision to trap an individual electron by an electrostatic potential applied to a cylindrical magnetized post covered by superfluid helium. Our FEM simulations show that for a typical superfluid helium depth of 500 nm and a post diameter of 100 nm (see Fig. 1(a)), a sufficient magnetic field gradient can be achieved to cause the Zeeman splitting difference between electrons occupying the two lowest Rydberg states to be about 140 MHz (see Fig. 1(b)), which by far exceeds the intrinsic linewidth of the Rydberg states of about 1-10 MHz.

It is clear that the coupling of spin states to the Rydberg states unavoidably affects the spin coherence. However, it is crucial to maintain the latter to be sufficiently long in order for the spin-qubit operations to be useful. We carried out the second-order perturbation theory calculations and established that the spin relaxation time due to the second-order ripplon-assisted spin-flip transtions exceeds 100 ms, while the spin dephasing exceeds 100 s for the magnetic field gradient presented in Fig. 1. This result demonstrates spins of such trapped electrons to be a potentially viable resource for quantum computing.

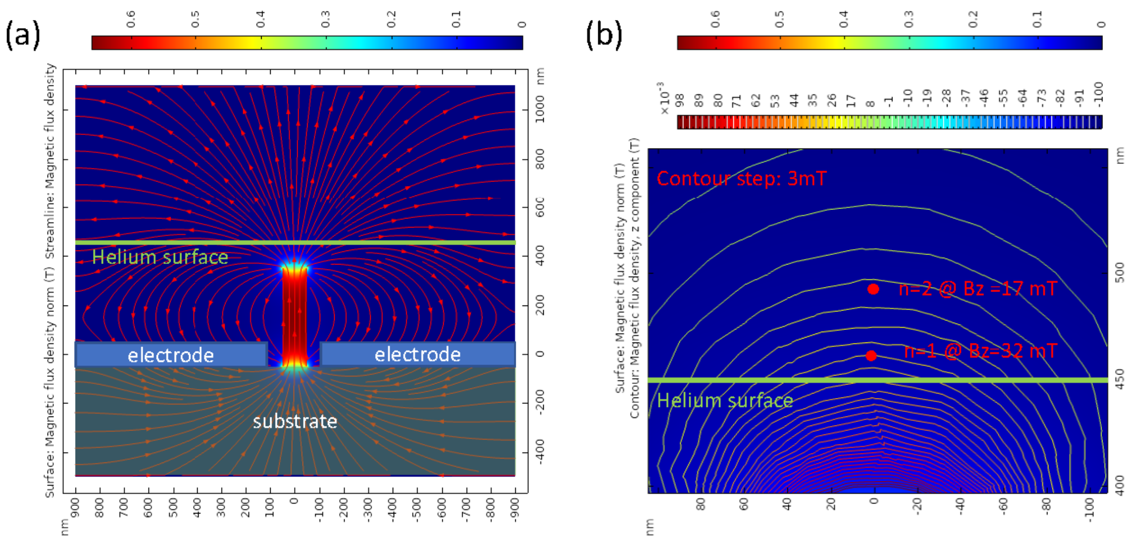


Figure 1: FEM simulations of the magnetic field gradient for a single electron trapped over a 100 nm-diameter magnetic post covered with superfluid helium (COMSOL simulations by Shan Zou).

3.2 Solution of Landau-Zener-Stuckelberg problem for readout of the Rydberg states of electrons on helium (Denis Konstantinov, in collaboration with Erika Kawakami from RIKEN)

Landau-Zener-Stuckelberg (LZS) problem is formulated for a generic two-level quantum system (TLS) subject to a harmonic driving through an avoided crossing between the system's energy levels (link). In particular, it produces a periodic component of the excited state population of TLS, which is relevant for the proposed readout of the Rydberg states of electrons on liquid helium by the capacitance spectroscopy method (link). Thus, it is important to find solution of the LZS problem for the whole set of relevant experimental parameters, such as the Rabi frequency ω_1, resonance detuning $\Delta\omega_0$, driving amplitude A, as well as the driving frequency ω_m.

We derived a simple method to solve LZS problem and find all components of the time-dependent excited state population ρ_{22} as a function of the above parameters by introducing the Fourier series expansion of the density matrix elements, which reduces the problem to a set of readily solvable linear equations. Fig. 2 shows an example of solutions for the in-phase component of ρ_{22} with respect to the harmonic driving for three different driving frequencies ω_m. The advantage of our method is that it can be readily extended to the case of an ensemble of TLS with an inhomogeneous broadening of their transition frequency, which is most relevant for an ensemble of electrons on liquid helium.

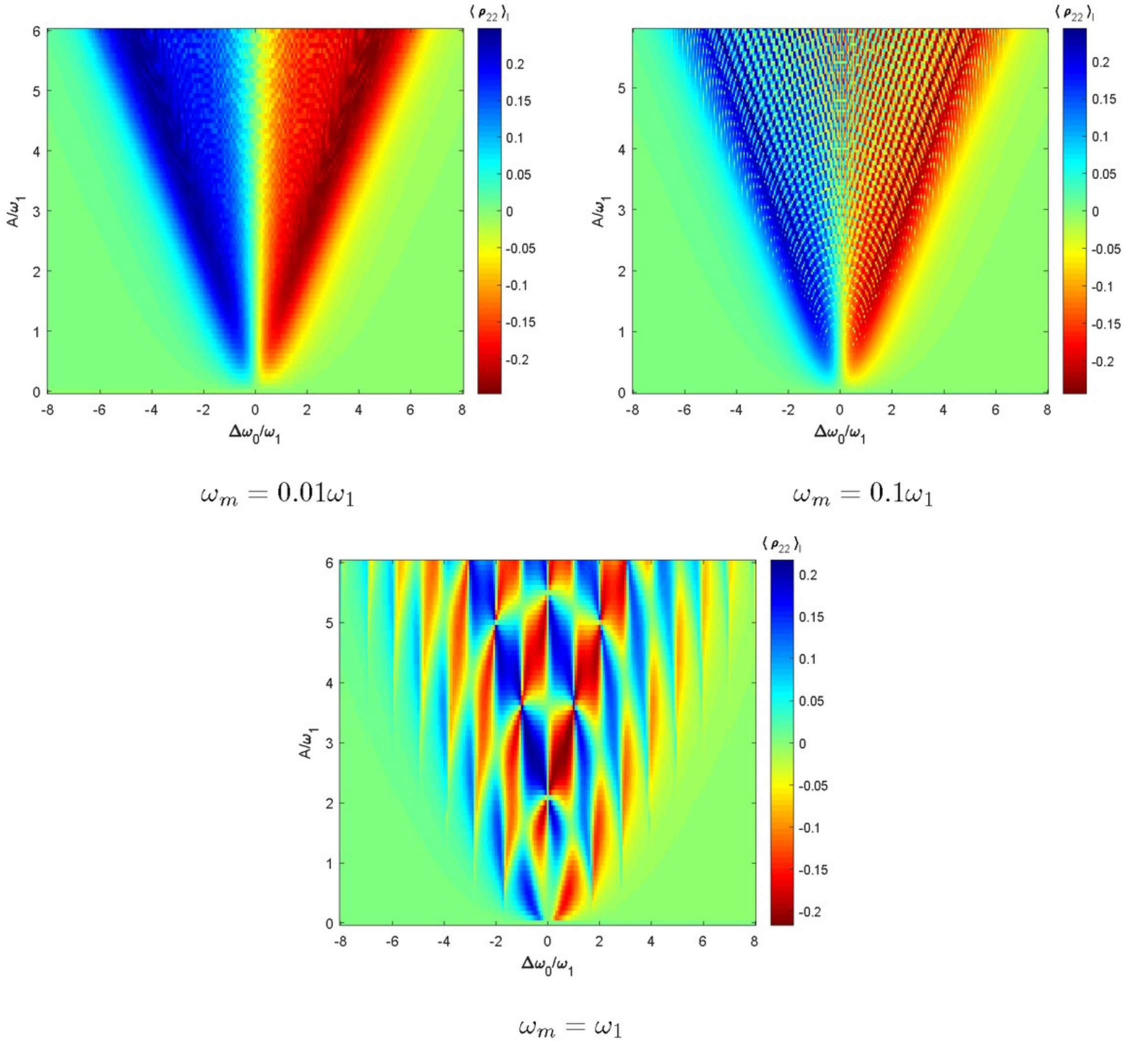


Figure 2: In-phase component of the excited state population for a periodically driven TLS with $T_1=\omega_1/400$ and $T_2=2T_1$ for three different driving frequencies ω_m.

3.3 Conductive detection of the Rydberg transition in a Wigner crystal confined in a single 4 um-wide channel (Shan Zoe, in collaboration with Sebastian Grossenbach from University of Konstantz)

Detection of the Rydberg transition of electrons on superfluid helium confined in microchannel devices is the first essential step towards realizing control of both the orbital and spin states of floating electrons for qubit implementation. In particular, our proposed scheme of the electron spin state detection is based on the detection of its Rydberg transition, by virtue of the artificial spin-orbit coupling. In addition, the microchannel devices (see Fig. 3(a)) can provide an excellent experimental platform for electron manipulation.

In our first work, we accomplished the Rydberg transition detection in a Wigner crystal comprised of many electrons transported through a single 20 um-wide and 4 um-deep channel filled with superfluid helium, see Fig. 3(b). The detection scheme is based on the change of the electron conductivity, thus the measured current of electrons ΔI through the channel, as the Wigner crystal is melted by the microwave (MW) absorption due to the Rydberg transition, see Fig. 3(c). Our experiment demonstrates the transition frequency for the two lowest Rydberg states to be in the range 400-500 GHz and the transition linewidth on the order 10 GHz. The latter is determined by the inhomogeneous broadening due to the Stark shift of the transition frequency caused by the external electric field, which is typical for a many electron system on liquid helium.

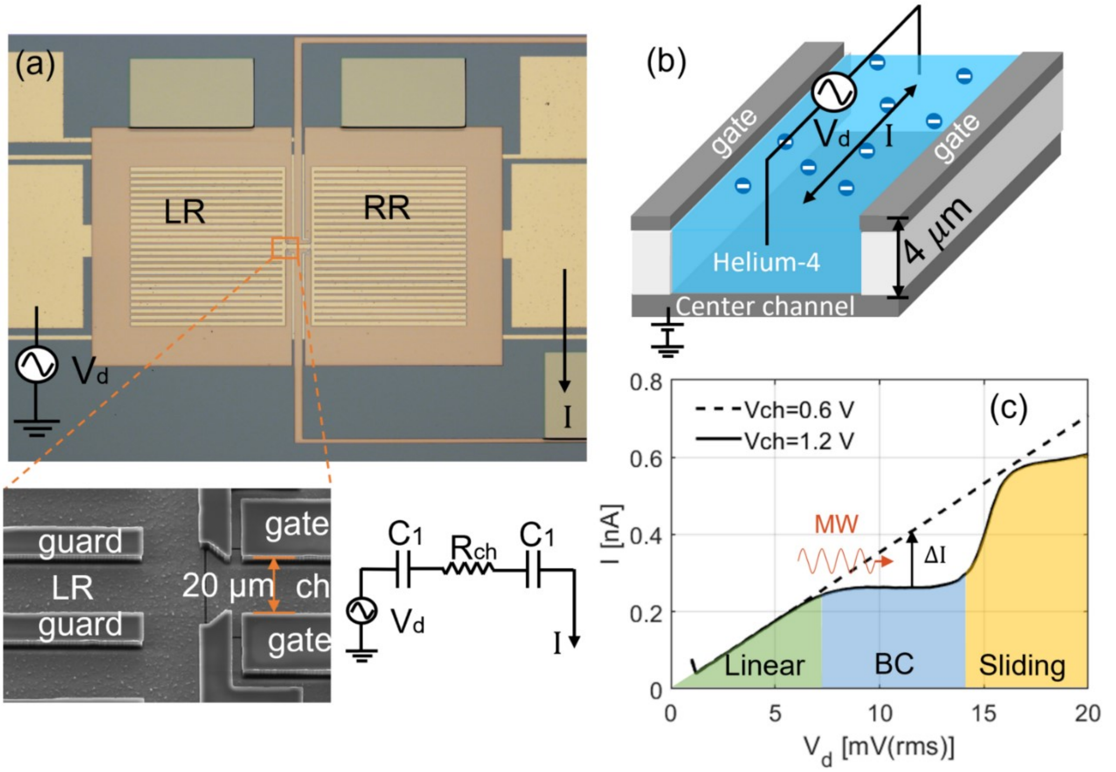


Figure 3: (a) Photo of the microchannel device for electron manipulation; (b) schematic view of a central 4 um-deep channel filled with electrons; (c) IV-curve of the Wigner crystal (solid line) and electron liquid (dashed line) demonstrating an idea of the conductive detection of the microwave (MW) induced Rydberg transition.

3.4 Image-charge detection of the Rydberg transition of electrons confined in a multi-channel array (Shan Zoe)

The image-charge detection of the Rydberg transition, which was previously developed in our group (link), presents a powerful tool that can be potentially scaled to a single electron. In our new work, we demonstrated this method of detection for electrons on superfluid helium confined in a 47-channel array of 20 um-wide and 4 um-deep microchannels containing about 100,000 electrons. The schematics of the detection method is shown in Fig. 4(a). The electrons excited by microwaves (MW) are capacitively coupled to a bottom channel electrode and induce an image-current in a circuit. This current is amplified by a two-stage cryogenic amplifier developed in our group (link) and detected as a voltage signal at the room temperature.

Fig. 4(b) shows the detected voltage signals due to the excited electrons for several MW frequencies as the transition frequency of electrons is tuned in resonance by the DC voltage applied to the channel electrode via the Stark shift. As in the previously described resistive detection of the Rydberg transition (see Section 3.3), the transition linewidth on the order of 10 GHz is due to the inhomogeneous broadening of a many-electron system. This work presents our first step towards scalability of the image-charge detection to the single-electron quantum state readout.

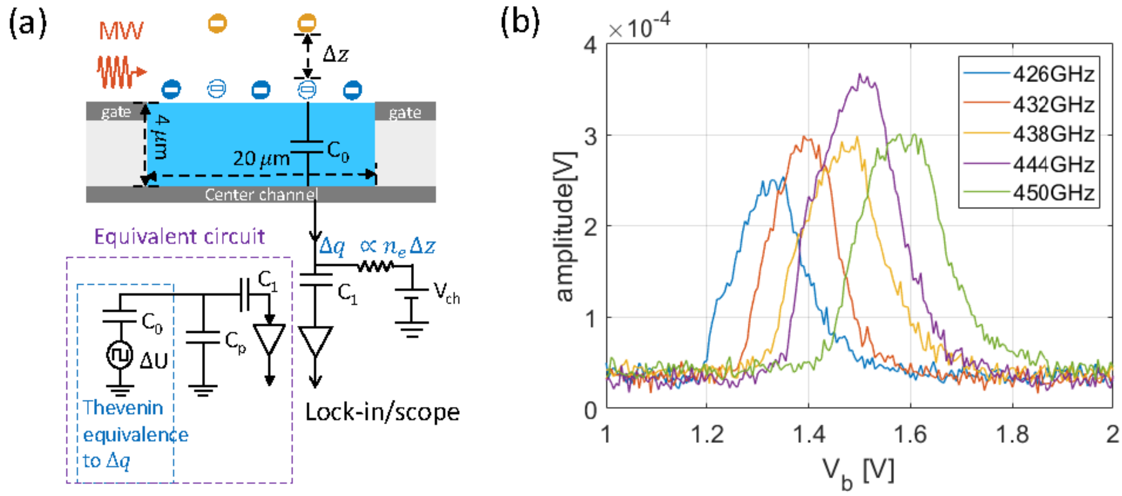


Figure 4: (a) Image-current detection scheme and its equivalent Thevening circuit; (b) the observed Rydberg transition signal for several MW excitation frequencies.

3.5 Tank circuit image-charge readout of the Rydberg transition for electrons confined in a single channel (Mikhail Belyanchikov, Shan Zoe)

Scalability of the image-charge detection method to the level of a single electron currently presents the most promising route towards realizing the qubit state readout. In order to bring sensitivity of the image-current detection to such a level, we employ superconducting helical resonators, also known as LC or tank circuits. In particular, a parallel LC circuit can realize a very high resistive load at the circuit resonance, which in turn can convert an image-current due to a single electron into a detectable voltage signal. In addition, such a circuit provides an impedance matching between the voltage-measuring device and the electron setup by "absorbing" the stray capacitance of the device into the tank circuit.

In our first tank-circuit experiment, we employed a superconducting helical resonator with a loaded quality factor Q~800 to detect the Rydberg transition of about 10,000 electrons in a single 4 um-deep channel, see Fig. 5(a,b). Fig. 5(c) shows the Rydberg transition signal detected using the pulse-modulated MW radiation at the modulation frequency which coincides with the resonance frequency of the tank circuit (835.45 kHz). For comparison, the signal obtained at the modulation frequency far from the resonance (650 kHz) is also shown, thus clearly demonstrating the advantage of using a resonant tank circuit to enhance the signal-to-noise ratio of the image-charge detection method. This work demonstrates the most promising route towards the Rydberg-state readout of a single electron.

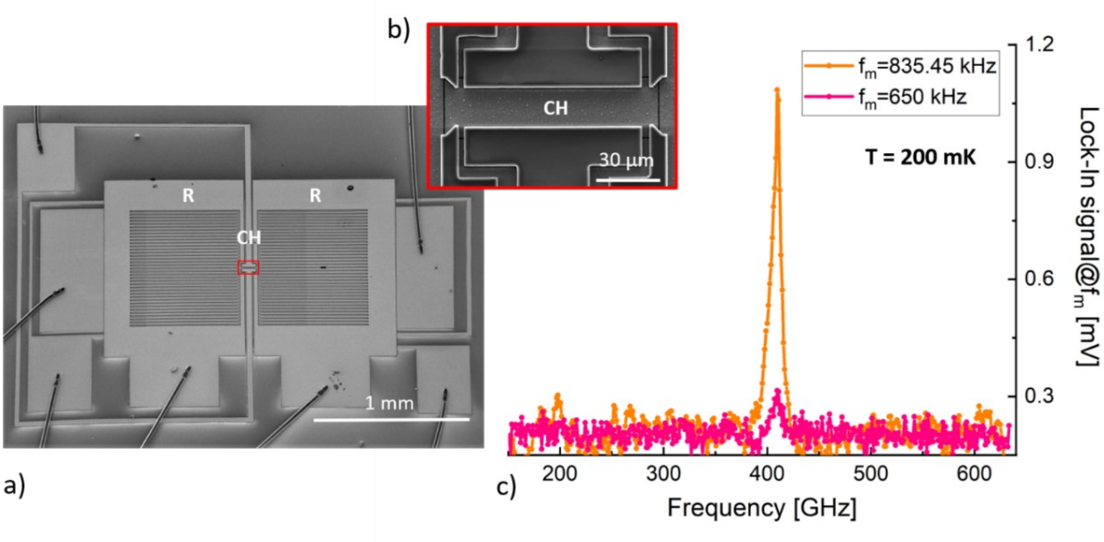


Figure 5: (a) Microchannel device for electrons-on-helium manipulation; (b) the central 4 mu-deep channel; (b) the observed Rydberg transition signal for two different MW modulation frequencies.

4. Publications

4.1 Journals

1. I. Kostylev, A. A. Zadorozhko, M. Hatifi, and D. Konstantinov, "Thermoelectric transport in a correlated electron system on the surface of liquid helium", Phys. Rev. Lett. 127, 186801 (2021); https://doi.org/10.1103/PhysRevLett.127.186801
2. S. Zou, D. G. Rees, and D. Konstantinov, "On dynamical ordering in a 2D electron crystal confined in a narrow channel geometry", Phys. Rev. B 104, 045427 (2021); https://doi.org/10.1103/PhysRevB.104.045427
3. A. D. Chepelinaskii, D. Konstantinov, and M. Dykman, "Many-electron system on helium and the color center spectroscopy", Phys. Rev. Lett. 127, 016801 (2021); https://doi.org/10.1103/PhysRevLett.127.016801
4. J. F. da Silva Barbosa, M. Lee, P. Campagne-Ibarcq, P. Jamonneau, Y. Kubo, S. Pezzagna, J. Meijer, T. Teraji, D. Vion, D. Esteve, R. W. Heeres, and P. Bertet, "Determining the position of a single spin relative to a metallic nanowire", Journal of

Applied Physics **129**, 144301 (2021); https://doi.org/10.1063/5.0042987

4.2 Books and other one-time publications

Nothing to report

4.3 Oral and Poster Presentations

1. D. Konstantinov, "Nonlinear transport of Wigner crystal on liquid helium in microchannels", APS March Meeting, Invited Talk, March 15, 2022
2. S. Zou, "On dynamical ordering in a 2D electron crystal confined in a narrow channel geometry", International Symposium on Quantum Fluids and Solids, Poster Presentations, August 12, 2021
3. S. Zou, "Detection of Rydberg states of electrons on helium confined in microchannel devices", International Symposium on Quantum Fluids and Solids, Poster Presentation, August 13, 2021
4. D. Konstantinov, "Spins of floating electrons for quantum computing", NEC-OIST Meeting on Quantum Tech., Flash Talk, November 2, 2021

5. Intellectual Property Rights and Other Specific Achievements

Nothing to report

6. Meetings and Events

Nothing to report

7. Grants

- Grant-in-Aid for Early-Career Scientists, Grant Number 20K15118: "Detection of quantum states of single electron on liquid helium" (FY2020-FY2023)
- OIST Internal Grant "KICKS" for Promoting External Collaborations: "Quantum state detection of electrons on helium for qubit implementation" (FY2021)