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研究課題名（和文）Hydrodynamic behaviour of electrons on the surface of superfluid helium

研究課題名（英文）Hydrodynamic behaviour of electrons on the surface of superfluid helium

研究代表者
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研究成果の概要（和文）：本研究の目標は、ヘリウム表面電子の流体力学的な側面を明らかにすることであり、この２次元電子系は、そのための格好の舞台である。この目標のもと研究を行い、電子と表面波との結合により生じる新しい電子輸送現象を観測した。電子が直線的に流れる、あるいは90度折れ曲がって流れるという３つ股マイクロチャネルを用いて電子の輸送現象を測定した。オームの法則からは、直線方向、90度方向ともに同じだけ電流が流れることが予想される。その予想に反し、実験結果は、直線方向にほとんど流れるというものであった。これは、電子がヘリウム表面とポーラロン状態を作り、それが大きな運動量を持つため直進するという事で理解できる。

研究成果の学術的意義や社会的意義
Our result should have wide academic impact, as it is relevant to a variety of polaronic-like systems.
In addition, possibility to use surface waves on helium to carry electrons without employing electric fields is interesting in the context of mobile spin qubits based on electrons on helium.

研究成果の概要（英文）：The original goal of the project was to demonstrate signatures of hydrodynamic behavior of electrons on the surface of superfluid helium, as this two-dimensional electron system looked particularly appealing for this purpose. As a result, we observed a novel transport regime in the system, however, of a different origin. Surface electrons are known to couple to surface capillary waves of helium, forming polaronic particles. We studied the transport of surface electrons through a microchannel structure in which the charge flow splits into two branches, one flowing straight and one turned at 90 degrees. According to Ohm's law, an equal number of charges should flow into each branch, however, when the polaronic particles have sufficiently large effective mass, all the charge follows the straight path, due to momentum conservation. The underlying physical picture is that electrons are carried along the straight path by surface waves, which tend to propagate straight.

研究分野：Physics

キーワード：Electrons on helium　2D electron system　Electron viscosity　Polaron

１．研究開始当初の背景

In strongly correlated electron systems, such as high-Tc superconductors or graphene, electron-electron interactions can be treated using a hydrodynamic formalism. It has been argued that basic properties, such as resistivity, can be significantly affected by electron viscosity, therefore understanding “electron hydrodynamics” is of great interest. Experimental signatures of hydrodynamic behavior of electron systems have been observed in graphene and nanowires. However, it remains a major challenge to find or create a system for which the contribution to transport properties from electron viscosity is dominant and can be analyzed unambiguously.

The main condition for hydrodynamic electron transport to be observed is that electron-electron scattering, which conserves total momentum, must be the fastest process in the system. In most solid-state materials this is not the case, because momentum-dissipating scattering from impurities, quasiparticles, boundaries, etc. prevail.

The proposal of this project was to look for manifestations of electron viscosity in a two-dimensional electron system on the surface of superfluid helium. This system has long been known as a model system to study electron correlation in two dimensions. The unique feature of the system is extreme purity: electrons float in vacuum about 11 nm above the helium surface. The only scattering which occurs is from helium vapor atoms and surface capillary waves, and characteristic timescales can be up to 10^-7 s. At the same time, the electron-electron scattering time can be as low as 10^-12 s. Thus, conditions for observing a clear hydrodynamic transport regime are very favorable.

At the time of the grant application, my collaborators and I had already performed some preliminary experiments. We designed a device which allowed a splitting of the surface electron current into two branches (Fig.1). We observed that the measured currents were not in agreement with Ohm’s law. However, they were in qualitative agreement with simulations of viscous flow in the device geometry. This suggested that indeed we might be observing hydrodynamic properties of surface electrons, and a more systematic investigation might be very fruitful.

２．研究の目的

The project was aimed at the demonstration of a hydrodynamic electron transport regime in the electrons-on-helium system. The objectives were: (1) to perform a much more detailed experimental study of the non-Ohmic behavior observed during the preliminary experiments, to investigate the dependence on temperature, surface electron density, different electron flow configurations possible within our device, and to ensure the reproducibility of the results by measuring different samples during different cooldowns; (2) to develop an adequate theory relating the observed phenomena to hydrodynamic electron transport. The impact of the positive outcome was anticipated to be high, as it would be relevant to a variety of strongly correlated electron systems where the hydrodynamic formalism is applicable, ranging from ultra-cold atoms, to solid-state systems such as high-Tc superconductors and graphene, to ultra-hot nuclear matter.

In the course of the project, we first successfully performed the experimental objective. However, after analyzing the obtained dataset in its complete form, it became apparent that the hydrodynamic electron transport model could not explain the observed behavior. Instead, a different theoretical model emerged, that related the observed phenomena to the hydrodynamic properties of surface waves of the helium substrate, which are coupled to the surface electrons and, hence, affect electron transport.

At this point the initial objective of the project shifted towards further developing this new theoretical model, as it also constituted a novel and unexpected result with potentially high impact. We succeeded in doing so, and the results were published in Physical Review Letters shortly before the end of the project.

３．研究の方法

We employ a well-established experimental technique of controlling surface electron transport in a microchannel device. Our device consists of three arrays of microchannels forming electron reservoirs, connected to each other by a T-shaped microchannel structure (Fig.1(a,b)). This device is placed in a vacuum-tight cell, mounted on a dilution refrigerator, and filled with liquid helium-4. The helium level is placed somewhat below the top surface of the device, and the channels are filled with superfluid helium by capillary action. Electrons are then produced by thermionic emission from a tungsten filament and are confined in the channels on the helium surface (Fig.1(c)). Several electrodes are integrated into the device, which are capacitively coupled to surface electrons, and allow us to induce, control, and detect surface electron transport in the device.

A novel point of our design is that using three electron reservoirs instead of two (as in many previous works) allows us to split the surface electron flow through the channel structure connecting the reservoirs. Also, the symmetry of the entire structure with respect to the conjunction point should result in symmetry in the flow splitting. In the experiment, by changing the potential of one of the reservoir electrodes by applying a linear voltage ramp, transient currents in to or out of the two other reservoirs were induced and measured. Considering the equivalent circuit of the experiment (Fig.1(d)), Ohm's law dictates that the currents in the two drain reservoirs should always be equal, disregarding which reservoir acts as a source and in which direction with respect to this reservoir (in or out) electrons are flowing.

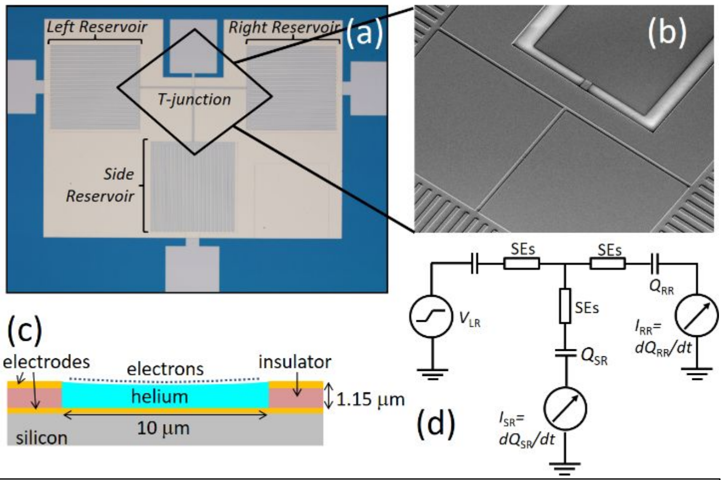

Figure 1. (a) Image of our device taken by optical microscope; (b) SEM image of the T-shaped microchannel structure connecting three reservoirs; (c) Schematic cross-section of a microchannel; (d) Simplified equivalent circuit of the device.

４．研究成果

A representative result of such measurements is shown in Fig. 2(a-c). Here the potential of the left reservoir is ramped more negative (Fig. 2(a)), causing electrons to flow out of the left reservoir, through the T-junction, and into the right and side reservoirs. After all transient currents have stopped and a new equilibrium is established, the potential of the left reservoir is ramped back to its initial value, causing reverse currents that return the system to its initial state. In the case of electrons flowing out of the left reservoir, there is a striking difference in the current flow observed at higher (0.8 K) and lower (0.4 K) temperatures. At 0.8 K, for the whole duration of flow it splits equally at the conjunction, as expected. In contrast, at 0.4 K for a certain period all flow goes into the right reservoir and nearly zero flow goes to the side reservoir.

This so-called unidirectional flow appears only for specific flow configurations when electrons are flowing *out of* either left or right reservoir *towards* the junction. In other possible flow configurations, it is always symmetric (Fig. 2(d)). The effect also has strong temperature dependence (Fig. 2(e)). The flow asymmetry completely disappears at temperatures above about 0.7 K. Notably, this threshold value is about the same for a range of electron densities.

An understanding of the interaction between electrons and the helium substrate is crucial in understanding this behavior. The coupling of electrons to the surface capillary waves of helium results in a polaronic state, corresponding to an electron self-trapped in a shallow dimple on the surface of the liquid. This effect becomes significant at sufficiently low temperatures and high densities, when electrons form a two-dimensional crystalline structure, known as a Wigner solid. When the Wigner solid is brought into motion, coherent resonant emission of surface waves with wave vectors equal to the reciprocal lattice vectors of the Wigner solid occurs. The resonant condition is met when the velocity of the Wigner solid approaches the phase velocity of the emitted surface waves. The polaronic effective mass in this regime becomes strongly enhanced, corresponding to an electron lattice moving together with a resonantly deepened dimple lattice with the terminal velocity, regardless of the magnitude of the driving force.

In Figs. 2(b,c), electrons in the Wigner solid state flow out of the left reservoir towards the conjunction with the terminal velocity, corresponding to the resonant surface-wave emission

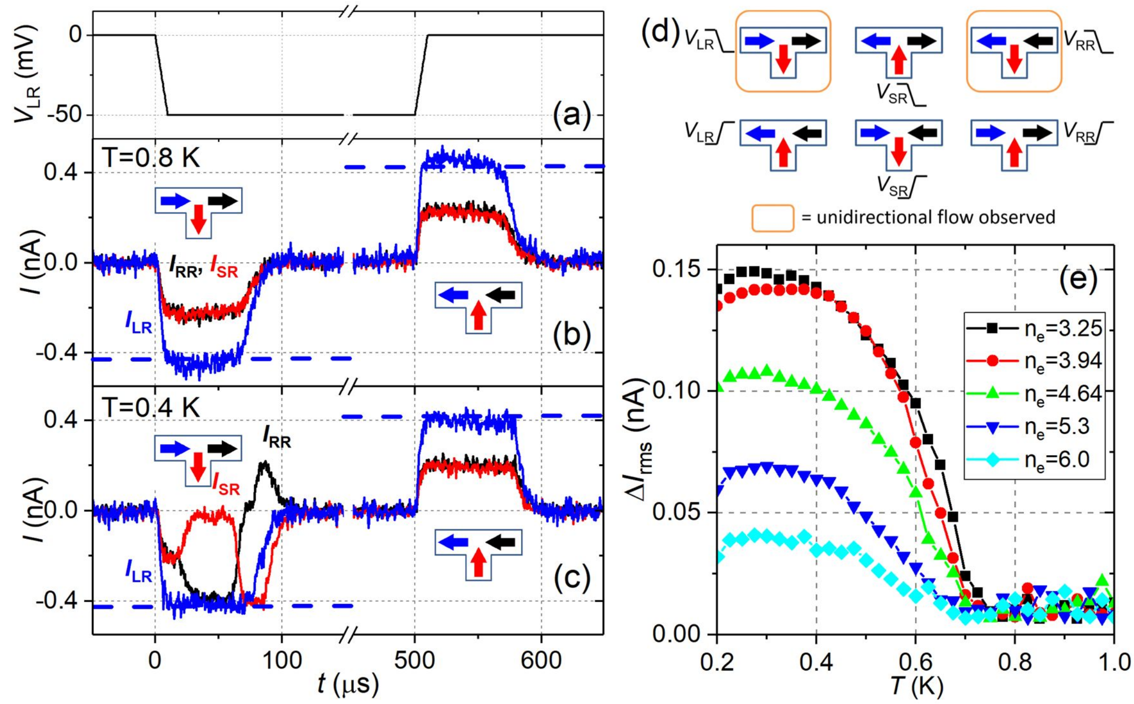

Figure 2. Time-resolved surface electron current measurements, taken at electron density in the T-junction n_e =3.25 × 10^9 cm^{-2} and two different values of temperature. (a) Voltage waveform applied to the left reservoir electrode. (b,c) Currents in the right (I_{RR}, black line) and side (I_{SR}, red line) reservoirs measured at T = 0.8 (b) and 0.4 K (c). The current in the left reservoir (I_{LR}, blue line) is determined as the sum of I_{RR} and I_{SR}, assuming conservation of charge. The dashed lines show calculated values of current corresponding to resonant surface-wave emission regime. (d) A diagram, summarizing possible flow configurations for our device, and highlighting configurations where unidirectional flow is observed at T = 0.4 K. (e) ΔI_{rms}, defined as the rms time-averaged value of (I_{RR}(t) − I_{SR}(t)), against temperature for different electron densities in the T-junction. The corresponding densities are indicated in the legend in units of 10^9 cm^{-2}.

condition. Hence, the dimple lattice is resonantly deepened. The electrons in the other two segments move away from the conjunction at a velocity that is twice smaller, so the resonant condition is not satisfied. At the conjunction, while electrons would tend to go with the electric field, the dimples would tend to preserve the direction of motion, due to momentum conservation. The observed unidirectional flow results from the resonantly deepened dimples propagating straight through the conjunction and carrying the electrons together. This explanation is fully consistent with dependence on flow geometry. When electrons flow out of the left or right reservoir, one possible path is straight and the other involves a 90-degree turn, so the unidirectional flow is observed. When electrons flow out of the side reservoir, both paths are not straight, and the effect is not observed. In the case of merging flow configurations (as in Fig. 2(b,c), reverse voltage ramp), when electrons are pulled into one of the reservoirs out of the two others, the resonantly deepened dimple lattice moves away from the conjunction and does not affect the transport of charge carriers through it.

The temperature dependence arises from the propagation length of the surface waves, which increases rapidly with decreasing temperature. For electrons flowing out of the left reservoir, the dimple lattice would be resonantly deepened on the way to conjunction, however, beyond the conjunction it would decay due to the surface wave damping. At higher temperatures, the surface waves dissipate over a distance much shorter than the length of the microchannel connecting the conjunction and the right reservoir, therefore, electrons cannot be carried all the way to the right reservoir. At lower temperatures, however, the propagation length becomes comparable to or larger than this length, and the unidirectional flow occurs.

In summary, we have observed a new transport regime of surface electrons on superfluid helium, where electrons are carried through the conjunction of microchannels by resonantly enhanced surface waves. Our result suggests an interesting possibility to use electro-mechanically generated surface waves on superfluid helium to carry electrons without employing driving electric fields, which might be potentially used for mobile spin qubits based on electrons on helium. For more detailed discussion of the result, we refer the reader to:

A. Badrutdinov *et. al.*, Phys. Rev. Lett. 124, 126803 (2020).

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　1件）

１．著者名 J.-Y. Lin, A. V. Smorodin, A. O. Badrutdinov, D. Konstantinov	４．巻 98
２．論文標題 Sliding of an electron crystal of finite size on the surface of superfluid 4He confined in a microchannel	５．発行年 2018年
３．雑誌名 Physical Review B	６．最初と最後の頁 85412
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevB.98.085412	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 J.-Y. Lin, A. V. Smorodin, A. O. Badrutdinov, D. Konstantinov	４．巻 195
２．論文標題 Transport Properties of a Quasi-1D Wigner Solid on Liquid Helium Confined in a Microchannel with Periodic Potential	５．発行年 2019年
３．雑誌名 Journal of Low Temperature Physics	６．最初と最後の頁 289-299
掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1007/s10909-018-2089-7	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 A. O. Badrutdinov, D. G. Rees, J. Y. Lin, A. V. Smorodin, D. Konstantinov	４．巻 124
２．論文標題 Unidirectional charge transport via ripplonic polarons in a three-terminal microchannel device	５．発行年 2020年
３．雑誌名 Physical Review Letters	６．最初と最後の頁 126803
掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1103/PhysRevLett.124.126803	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計1件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 A. O. Badrutdinov, D. Rees, A. V. Smorodin, J. Y. Lin, D. Konstantinov
２．発表標題 Non-ohmic currents of Wigner solid on helium in 3-terminal microchannel structure
３．学会等名 International Symposium on Quantum Fluids and Solids（国際学会）
４．発表年 2018年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
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研究協力者	Ｄｅｎｉｓ　Ｋｏｎｓｔａｎｔｉｎｏｖ (Denis Konstantinov)	ＯＩＳＴ－Ｊａｐａｎ	
研究協力者	Ｊｕｉ－Ｙｉｎ　Ｌｉｎ (Jui-Yin Lin)	ＯＩＳＴ－Ｊａｐａｎ	
研究協力者	Ｏｌｅｋｓａｎｄｒ　Ｓｍｏｒｏｄｉｎ (Oleksandr Smorodin)	ＯＩＳＴ－Ｊａｐａｎ	