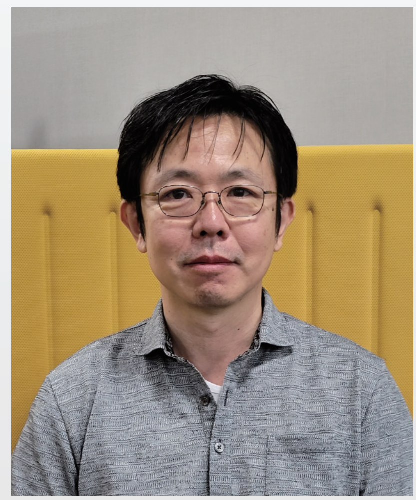
First Experimental Demonstration of a Phenomenon That Had Not Been Verified for More Than 20 Years Since Its Theory Was Proposed

Koji Muraki
Senior Distinguished Researcher, NTT Basic Research Laboratories



Abstract

In the field of condensed-matter physics, it is often the case that a theory about a phenomenon is experimentally verified 20 or 30 years after it was proposed. Koji Muraki, a senior distinguished researcher at NTT Basic Research Laboratories, and his co-researchers were the first in the world to experimentally observe a phenomenon similar to Andreev reflection, which occurs at the interface between a superconductor and normal metal, in a material other than a superconductor. This observation was achieved through research on a many-body effect, which is a phenomenon by which electrons acquire the properties that an individual electron does not possess by interacting with each other. We asked him about this achievement, research on the fractional quantum Hall effect (one of many-body effects) that led to this achievement, and his mindset as a researcher engaged in basic research.

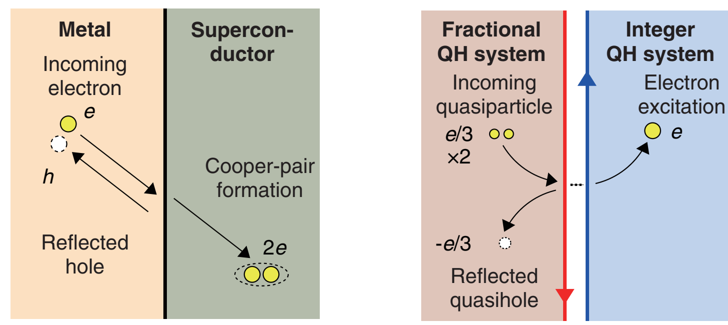
Keywords: many-body effect, quasiparticle, Andreev reflection

Exploring quantum devices with new functions that cannot be obtained with individual electrons by applying the fractional quantum Hall effect

—Would you tell us about the research you are currently conducting?

I'm researching many-body effects and correlation effects caused by interactions between electrons as well as quantum-mechanical properties of electrons such as wave nature, superposition state, and spin. By engineering and controlling these properties of electrons using the heterostructure and nanostructure of semiconductors and atomic-layer materials, I'm exploring quantum devices with new functions that cannot be obtained with individual electrons.

In my previous interview (March 2021 issue), I talked about our group experimentally demonstrating that (i) a topological insulator, which is a material that conducts electricity on its surface but is an insulator inside, can be formed using a semiconductor heterostructure and (ii) by applying a voltage to the gate electrode of the topological insulator, it can be electrically switched between a normal insulator and



(a) Andreev reflection at a conventional superconductor junction

(b) Andreev reflection of quasiparticles at a fractional-integer QH junction

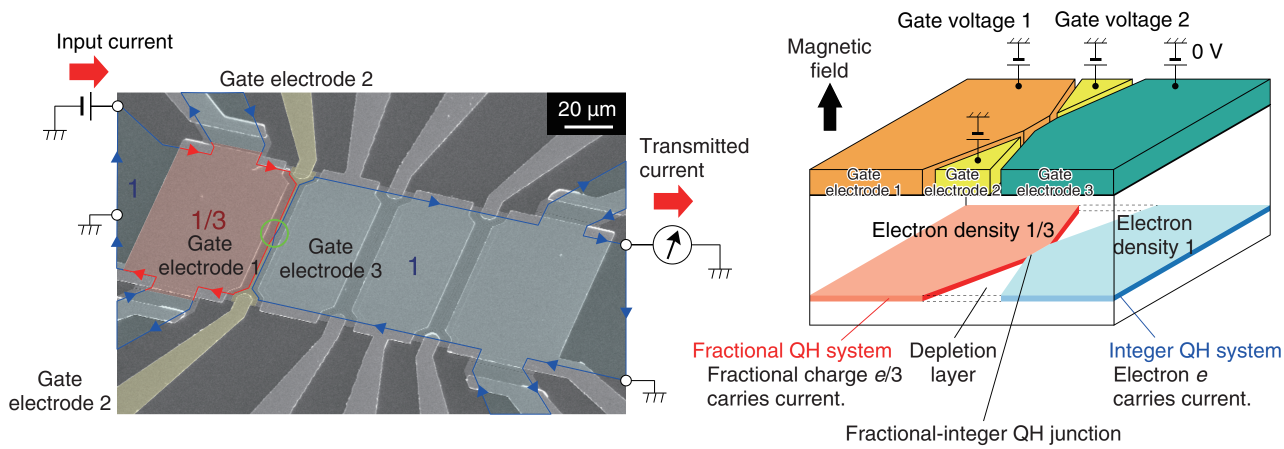
Fig. 1. Conceptual diagram of Andreev reflection.

topological insulator. In this interview, I'd like to discuss many-body effects.

A many-body effect is a phenomenon by which electrons interact with each other and acquire the properties that an individual electron does not possess. Typical examples are superconductivity and ferromagnetism. Among many-body effects, our research group focuses on a phenomenon called the fractional quantum Hall (QH) effect, in which electrons with electron charge e (< 0) try to avoid each other in a strong magnetic field; as a result, a certain kind of order is created—a uniform state like liquid without the density fluctuation. Interestingly, deviation from this uniform state of electrons occurs in units of one-third the charge on the electrons ($e/3$). The convexity of the electron density is called a "quasiparticle" and the concavity is called a "quasihole," and they behave like particles with charges $\pm e/3$. The fractional QH effect has a long history; it was discovered in 1982 and its underlying theory was published the following year, which were awarded the Nobel Prize in Physics in 1998. In the early 2000s, it was theoretically proposed that quasiparticles and quasiholes in certain states could be used for quantum computing, since then, research to verify that proposal has been ongoing.

It was experimentally clarified that quasiparticles in the fractional QH state have charge $e/3$ from measuring and analyzing the weak noise in the current. As a fundamental technology for quantum computing using quasiparticles, measuring the quasiparticle interference with a minute device fabricated in the form of a ring is necessary. In 2020, a research group in the USA reported—as a world's first—an experiment in which they successfully conducted such measurement, and that report has gained much attention. Such experiments investigate the properties of quasiparticles with charge $e/3$. The electrodes and lead wires connected to the measurement instruments are normal metals, and the electrons flowing through them are electrons with charge e. Therefore, what happens when a quasiparticle with charge $e/3$ flows into an electrode composed of a normal metal? Two theoretical papers published in 1998 considered such a question. According to the theory, when two quasiparticles with charge $e/3$ are injected into a metal, an electron with charge e flows into the metal, and a quasihole with charge $-e/3$ (> 0) is reflected back into the injection side to conserve charge. This phenomenon is similar to the Andreev reflection (**Fig. 1**) that occurs at the interface between a superconductor and normal metal, and we succeeded in observing it with a material other than superconductors in an experiment for the first time [1]. In addition to the significance of elucidating charge conservation at the level of quasiparticles, which are smaller than electrons, and the elementary processes of scattering and reflection of quasiparticles, this achievement also provides a new perspective to consider in regard to quantum circuits using quasiparticles. That is, not only quasiparticles but also quasiholes carrying charge are flowing in a quantum circuit using quasiparticles, and the effect of the quasiholes must also be considered when discussing the presence or absence of quasiparticle interference.

I was very happy to be able to demonstrate experimentally for the first time a phenomenon that had not been verified for over 20 years since its theoretical prediction. The researcher who wrote one of the above-mentioned theoretical papers in 1998 read our



(a) False-color scanning electron micrograph of the sample

(b) Fractional-integer QH junction

Fig. 2. Conceptual diagram of the experiment.

paper and sent us an email saying, “Thank you for verifying my theory.” Subsequent research has also helped us to understand the noise and heat generated during these scattering and reflection processes of quasiparticles [2]. It may sound easy when I only write about the result, but it was a long journey from the start of the research until we got the satisfying result.

Investigating the properties of quasiparticles, which have a smaller charge than electrons, requires extremely advanced experimental techniques, and only a handful of research groups in the world can conduct such experiments. It was also a significant change to have people from these research groups pay attention to our work because of this achievement. Although my role in these studies was supervising, and my main contribution was to keep asking questions to the member leading the research, being involved in research that gives a young researcher an opportunity to spread their wings and be recognized around the world gave me a different sense of accomplishment than I ever had before.

—Could you tell us about the experiment that produced impressive results in more detail?

To investigate the properties of quasiparticles, more-precise measurement techniques were needed. Thus, I asked a researcher to join our group who had similar interests as us and the necessary skills and knowledge, and he came up with an idea of this experiment.

The overview of the experiment is illustrated in **Fig. 2**. First, a magnetic field is applied perpendicular to a two-dimensional electron system in a GaAs (gallium arsenide) semiconductor heterostructure at low temperature. The magnetic-field strength is then adjusted so that the entire electron system is the integer QH state with a Landau-level filling factor* of 1. A false-color scanning electron micrograph of the sample is shown in Fig. 2(a). The red region is a fractional QH state with a Landau-level filling factor of 1/3, which is formed by applying gate voltage 1 to gate electrode 1. The blue region is an integer QH state with a Landau-level filling factor of 1, where the electrons with charge *e* play the role of a normal metal carrying current (gate electrode 3 is fixed at 0 V). The yellow regions are gate electrode 2 applied to narrow the interface between the fractional QH and integer QH states. The dark-gray regions are areas where the semiconductor is etched away, and the light-gray regions are gate electrodes not used in this experiment. A fine fractional-integer QH junction is formed in the center between gate electrodes 1 and 3 (marked with the green circle). In a QH region, current flows in one direction along the channels at the edge of the sample (red and blue arrows), so transmitted (blue) and reflected (red) currents can be measured.

* Landau-level filling factor: The ratio of electron density to a magnetic field (magnetic-flux density). When this value approaches an integer, an integer QH effect occurs, and when it approaches a certain fractional value (such as 1/3), a fractional QH effect occurs.

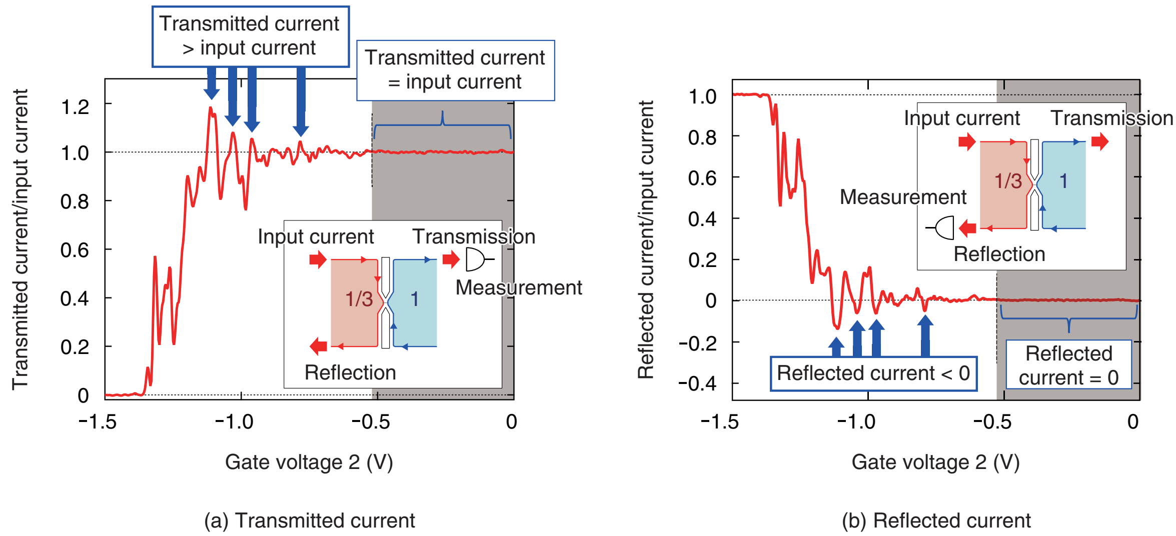


Fig. 3. Measurement results when the fractional-integer QH junction is narrowed by applying gate voltage 2.

Figure 2(b) shows a conceptual diagram of the fractional-integer QH junction, namely, the region marked with the green circle in Fig. 2(a). When gate voltage 2 is applied to gate electrode 2 and the two-dimensional electron system directly below the gate electrode is depleted, a junction (width less than 1 μm) is formed at which the fractional and integer regions contact each other. The width of the junction narrows as the negative voltage of gate voltage 2 increases and the depletion region widens.

In the experiment, a current was applied to the junction from the fractional QH side, and the transmitted current flowing out of the junction to the integer QH side was measured. We observed that the transmitted current exceeds the input current at certain values of gate voltage 2, which corresponds to changing the junction width (**Fig. 3(a)**). When we measured the reflected current returning from the junction to the fractional QH side, the current of the opposite sign to that of the input current was observed (**Fig. 3(b)**). The increase in transmitted current and a negative reflected current indicate that Andreev reflection of quasiparticles occurred. This result indicates that Andreev reflection is not a phenomenon unique to superconductors but a universal phenomenon, demonstrating an important achievement in condensed-matter physics.

—What kind of research will you be focusing on in the future?

Topological insulators and the fractional QH effect both exhibit interesting physical properties due to the nature of the sample (material) interior; however, it is at the edges and surfaces of the sample (i.e., at the interface with the vacuum or with ordinary material) that they appear as phenomena observed in experiments. Therefore, to observe theoretically predicted, interesting phenomena experimentally, it is important to create not only pure crystals but also high-quality interfaces. I haven't much time to talk about it in this interview, according to theory, the interface between a topological insulator and superconductor is also a platform where new physical properties appear. Although researchers worldwide are working to verify the predictions of the theory, a unified understanding has not yet been reached because either the results are not as the theory predicts or they are as the theory predicts but do not exclude the possibility of other interpretations. We are currently focusing on creating various interfaces, including superconducting junctions, by using methods that nobody has attempted before. The young researchers in our group are actually conducting the research, and I support them. I hope that our research will result in an ideal interface and bridge the gap between theory and experiment. This research is unprecedented, so it is a continuous process of trial and error, but it is both rewarding and fun.

Basic research is like creating a map of science. By taking on the right challenges, I want to make a positive impact on the research community and society as a whole

—What do you keep in mind as a researcher?

As I mentioned in the previous interview, I think that the basic research I'm involved in is like creating a map of science. In the field of physics, theory alone does not determine whether a proposition is correct. At this phase, a rough outline of the map is created. To update the map to be more accurate, experiments must be conducted to clarify and verify the theory. While certain Nobel Prize-winning studies significantly rewrote the map, it is also important to accumulate small updates to the map. I want to contribute to the creation of maps through my research on controlling the interface between materials and explore new properties of electrons. The social significance of that research, i.e., the new properties of electrons may be used for fault-tolerant quantum computing, motivates me.

I used to think of research as a means of self-realization, so whether it was my own idea, whether I carried it out, and how I was evaluated by others as a researcher were all important indicators for me. However, as I get older, I find myself becoming more appreciative of the importance of all the people and things that surround me. This appreciation includes not only "standing on the shoulders of giants" but also extending to all ordinary people and things. Regardless of whether it is my idea, and regardless of how I am evaluated, I want to use my energy to do something that will have a positive impact on the research community and society as a whole. In other words, I want to do things that I'm not sure that I can do and things that seem difficult but are worth doing, rather than things that I think I can do faster than others. Even if I take on a challenge that no one else is doing and the results are not what I expect, if I am doing it for the right reasons, the knowledge I gain will be useful to me and the world outside. I still want to do research that will make people exclaim, "That was a breakthrough!" but to achieve such breakthroughs, I want to continue to take on the right challenges.

—What is your message to younger researchers?

Undoubtedly, young people are more likely to accomplish great things in the future, so I want them to believe in their own potential and strive forward. In the past few years, there have been several major breakthroughs in my field of research, and all have been achieved by young researchers. I have thought about some of the things I was close to doing, but when I actually observe their breakthrough research, I realize that it was not so much that I was close but rather that I had not pursued my ideas far enough. Even if you are progressing toward an achievement, if you don't have the last piece in place, you won't know if you are close to making an achievement, and if you stop there, the possibilities that may have existed will be closed off. It is important to keep your eyes open and your ears to the ground to be sensitive to information from the outside; however, if you really have something you are aiming for, rather than convincing yourself that you have already worked hard for years or that you have done so much, you should keep asking yourself whether you have really done everything you need to do and whether there is a better way to do it. This message is not only for young people but also for myself as a reminder.

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■ Interviewee profile

Koji Muraki received a B.E., M.E., and Ph.D. in applied physics from the University of Tokyo in 1989, 1991, and 1994. He joined NTT Basic Research Laboratories in 1994. From 2001 to 2002, he was a visiting researcher at the Max Planck Institute for Solid State Research, Stuttgart, Germany. His research interests are focused on many-body effects in low-dimensional semiconductor structures. He is a member of the Physical Society of Japan and the Japan Society of Applied Physics.