Research Group for Spin-Energy Transformation Science

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Research on mutual energy conversion among various forms in condensed matters is a key to improving energy efficiency and furthering energy sustainability. We study the energy conversion using electron spins and their couplings to various types of angular momentum, including mechanical rotation.

Barnett field, rotational Doppler effect, and Berry phase studied by nuclear quadrupole resonance with rotation

We study the phenomena, which appear when a spin is exposed to classical rotational motions. The Barnett field, rotational Doppler effect (RDE), and Berry phase are known for these phenomena, but they have been proposed and studied individually, and there has been no study to clarify the relation among them. Here, applying the coil-spinning technique for nuclear quadrupole resonance (NQR) measurements, we succeeded in clarifying the associations among them in terms of the rotational degrees of freedom such as the relative rotation between a sample and a coil as a signal detector, and the absolute rotation of the sample.

The Barnett field is an inertial magnetic field, which appears when a spin is in a rotating frame of reference. To observe such an inertial field, we need to simultaneously rotate the sample and coil. We observe the NQR line splitting corresponding to the emergence of the magnetic field as shown in Fig. 1(a). On the other hand, when we rotate solely the coil, we observe the RDE caused by the relative rotational motion. As shown in Fig. 1(b), the NQR line splits into two. Note that the NQR spectra shown in Figs. 1(a) and (b) are clearly different from each other, indicating the difference between the Barnett field and RDE.

Furthermore, when we rotate solely the sample, we cannot observe the inertial field but observe the periodically driven quantum system, which causes the accumulation of the Berry phase within the adiabatic (Born-Oppenheimer) approximation. In addition, the relative rotation must be taken into account. As a result, the NQR line splits into two as indicated by the green triangles in Fig. 1 (c) and each of the resulting lines has a shoulder (the blue triangles). The NQR spectrum can be completely described by the RDE and Berry phase, offering a full understanding of the rotational effect on spins.

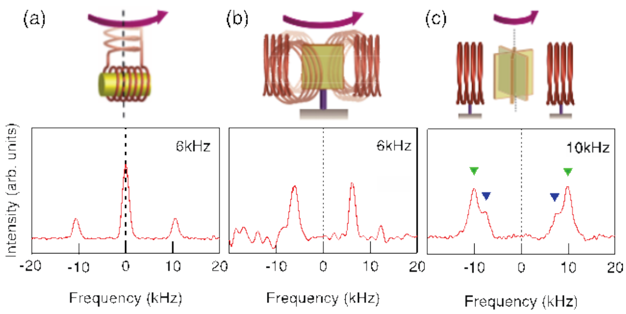

Fig. 1 NQR spectra obtained by using the setup of (a) simultaneous coil and sample rotation, (b) only coil rotation, and (c) only sample rotation.

Half-integer Shapiro-steps in superconducting qubit with a π-Josephson junction

A superconducting quantum interference device (SQUID) shows steps in the current-voltage (*I*-*V*) curve under microwave irradiation (Fig. 2). This feature called Shapiro-steps (SS) appears at the voltages $V = n(h/2e)f$ with integer n, microwave frequency f, the Planck constant h, and the elementary charge of electron e. Because the microwave frequency and the fundamental constants are precisely determined the voltage can be defined in the order of 10^{-9} accuracy. Thus, the SS is utilized to the voltage standard.

A set of two superconductors separated by a thin insulator or metal is called a Josephson junction (JJ). The maximum current through a JJ sinusoidally changes with an applied magnetic flux. In a JJ separated by a ferromagnet, the sinusoidal current-flux relation is shifted by π compared with the conventional JJ (0-JJ). The former is called π-JJ and is studied for a solid-state qubit (π-qubit) as a key to realizing quantum computers. The qubit using superconductors usually needs an external magnetic field, whereas the π-qubit does not. This is a big advantage to decoupling the qubit from environmental noises.

We studied the SS in a π-SQUID comprising a 0-JJ and a π-JJ as shown in the inset of Fig. 2. The *I*-*V* curve can be calculated as shown in Fig. 2 using the resistively shunted junction (RSJ) model with two parallel circuits of JJs. In the π-SQUID, the SS appears at voltages with half-integer multiples of microwave frequency in addition to the integer multiples. This phenomenon originates from the coupling between a 0-JJ and a π-JJ. We found that the half-integer SS and the π-qubit are two sides of the same coin. The appearance of half-integer SS means that the π-SQUID can work as π-qubit. The key parameter is J_π/J_0 meaning the asymmetry of two JJs. The half-integer SS is optimized by making the 0- and π-JJs equivalent. Making two JJs in π-SQUID equivalent yields a π-qubit.

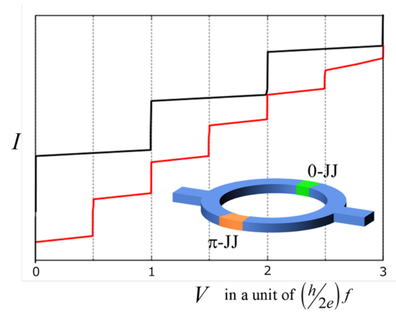

Fig. 2 *I*-*V* curves in a SQUID (black) and in a π-SQUID (red). The inset shows schematic of the π-SQUID with superconductor channels (blue) separated by a 0-JJ (green) and a π-JJ (orange).

References

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[2] M. Mori and S. Maekawa, *Appl. Phys. Express* **14**, 103001 (2021).