Spin current generation from heat and mechanical motion

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Angular momentum conversion between spins and mechanical rotation is a promising candidate of a mechanism for micro driving devices. Fundamental phenomena of the angular momentum conversion are the Einstein-de Haas effect (body rotation due to its magnetizing) [1], and the Barnett effect (magnetizing by body rotation) [2]. An essential Hamiltonian of both effects is spin-rotation coupling

$$H_\Omega = -\hbar S \cdot \Omega,$$

where S and Ω are a spin and angular velocity of mechanical rotation, respectively. The Hamiltonian is effective for all particles which have angular momentum $\hbar S$ and expected to play a central role for generating spin current from the mechanical rotation. In order to explore the spin-rotation coupling Hamiltonian, we have observed the Barnett effect acting on the nuclei by using nuclear magnetic resonance (NMR) method [3].

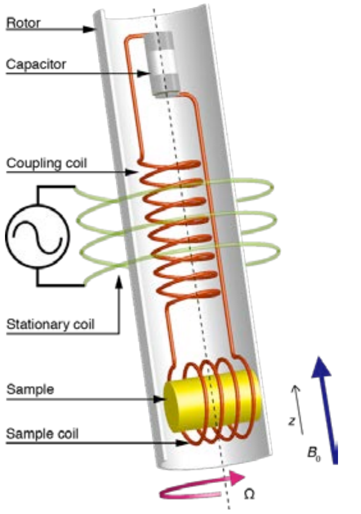

Fig. 1 Illustration of an experimental setup.

The Barnett effect implies that an effective magnetic field arises in a rotating body. The emergent field B_Ω, called Barnett field, can be derived theoretically from quantum relativistic theory [4]. B_Ω acting on a particle is linearly depends on the angular velocity of rotation Ω:

$$B_\Omega = \frac{2m}{gq}\Omega:$$

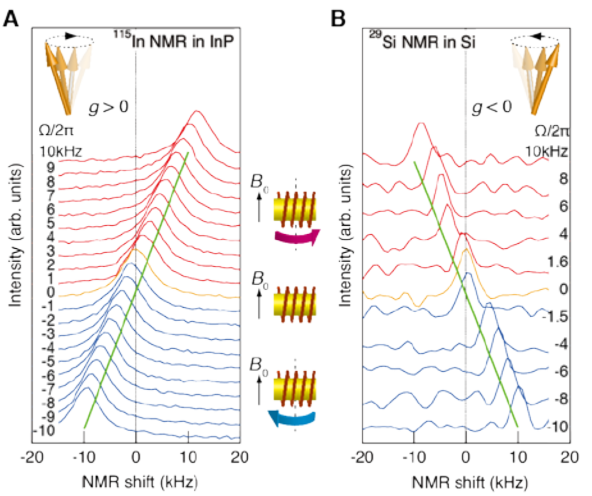

Fig. 2 NMR spectra for positive and negative g-factor. Spectra for (A) ^{115}In and (b) ^{29}Si NMR obtained at various angular velocities. The origin of the transverse axis is difined as the peak position of the NMR spectrum at Ω=0.

where m, q, and g are mass, charge and g-factor of the particle. The Barnett field is in proportion to the particle's rest mass. Since nuclei are much more massive than electrons, relatively large Barnett fields are expected to act on nuclei. In addition, the Barnett field acting on the nucleus depends on the nuclear g-factor.

To measure the Barnett field by nuclear magnetic resonance (NMR) method, the detection has to be done on the rotating frame same as the body. The reason for this is that, if there are relative velocity between the signal detector and the body (signal emitter), an extrinsic NMR frequency shift arises from the relative velocity (rotational Doppler effect). To overcome the difficulty, we developed a new detection method in NMR, and directly measured the Barnett field. The detection on the rotating frame was realized by the newly developed tuning circuit that consists of a sample and detection coil both installed in the same rotor.

Figure 1 shows the schematic illustration of the experimental assembly. The assembly comprises two components: the stationary coil placed along external field B_0 and connected to an NMR spectrometer, and a high-speed rotor consisting of a cylindrical capsule in which a specially arranged tuning circuit is installed.

This circuit is composed of two small coils placed perpendicularly and connected in series, and a small capacitor. One of the two coils is arranged parallel to the stationary coil to establish a coupling by a mutual inductance between the tuning circuit and the stationary coil (coupling coil). The other, the sample coil, holds a sample inside. The RF field in the coupling coil is transmitted to the sample coil and generates an oscillating RF field to induce an NMR signal. Under this configuration, the sample coil rotates at exactly the same angular velocity as the sample. The rotor is put inside the stationary coil and, during measurements, it is rotated up to $|\Omega/2\pi|$=10 kHz.

In Fig. 2A, we plot the ^{115}In NMR spectra at various values of the angular velocity Ω. Clearly, the NMR frequency increases linearly with Ω. Furthermore, by reversing the rotation direction, the direction of the NMR shift is also reversed; thus, the sign of B_Ω is reversed. The sign of the g-factor of ^{115}In is known to be positive; that is, the nuclear magnetic moment is parallel to its angular momentum. Next we measured the shifts for nuclei with negative g-factors. From the NMR spectra for ^{29}Si having negative g-factor, the direction of the NMR shift is clearly opposite to that for ^{115}In, indicating that the emergent Barnett field is opposite in direction to that for ^{115}In (Fig. 2B). We collected the NMR shifts for various nuclei as a function of rotation speed in Fig. 3. In each sample, the NMR shift exhibits linear dependence on Ω. The g-factor for ^{7}Li, ^{19}F, ^{23}Na, and ^{115}In are known to be positive, while those for ^{29}Si and ^{119}Sn are negative. All the nuclei with positive g-factor display positive slopes, while all the nuclei with negative g-factors display a negative slope. These results mean that the nuclei feel additional magnetic field to the external field. It is a direct evidence for the existence of Barnett field.

In conclusion, we develop a new coil spinning NMR method of detecting the Barnett field. The Barnett field is observed as an NMR shift proportional to the rotation speed. The sign of the Barnett field depends on the both the sign of the nuclear magnetic moment and the rotation direction against the external magnetic field. These features can be used to determine the unknown sign of the nuclear magnetic moment. Our findings provide direct evidence of the coupling between the nuclear magnetic moment and mechanical rotation, and will produce new technology in which mechanical motion manipulates the nuclear spin angular momentum as well as the electron spin angular momentum.

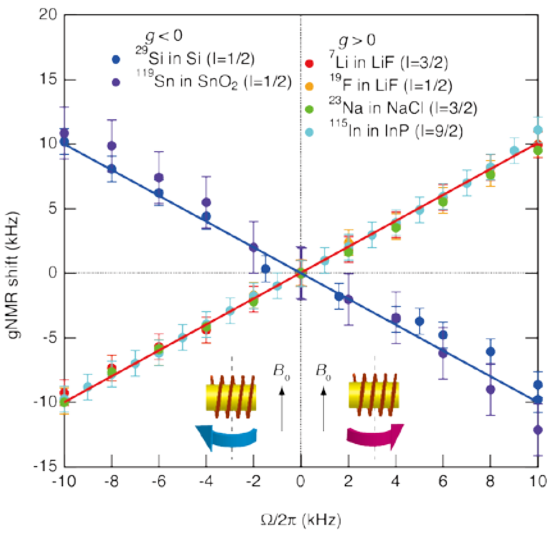

Fig. 3 Universal behavior of NMR shifts as a function of the angular velocity W. Vertical axis represents NMR shifts; its origin is determined by the center frequency at Ω=0.

reference

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