Press Release

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March 17, 2022
Keio University

Discovery of a Mechanism for Producing Electromotive Forces from Magnetic Materials via the Gyromagnetic Effect: Toward Applications of Spintronic Devices by Sound Waves

Takumi Funato, a Project Assistant Professor at the Global Research Institute at Keio University (Spintronics Research and Development Center), and Mamoru Matsuo, an Associate Professor at the Kavli Institute for Theoretical Science at the Chinese Academy of Sciences, have theoretically demonstrated that the gyromagnetic effect induces electromotive force when sound waves are injected into magnets. The gyromagnetic effect, discovered by Einstein and de Haas and Barnett, is a historically significant phenomenon indicating that the origin of magnetism in matter is the rotation of electrons called "spin."

The gyromagnetic effect, however, is so small that it was considered impossible to apply to spintronics devices, where magnetic control of materials is essential. In a recent experiment, researchers demonstrated that it is possible to generate spin current via the gyromagnetic effect by utilizing sound waves to rotate lattices more than a billion times per second. Researchers have also discovered methods to convert the spin currents into charge currents; however, they require sophisticated device structures and precious metals. To overcome these limitations, the research group in this study theoretically clarified the interplay of magnetization, electron spin, and lattice rotation in ferromagnetic metal monolayers, where injected sound waves induce lattice rotational motion.

The researchers demonstrated that the gyromagnetic effect could induce electromotive force with a simple device structure. The mechanism discovered in this study is expected to significantly contribute to applications of the gyromagnetic effect in spin devices, which has been difficult so far. The results of this research were published online in the American physics journal *Physical Review Letters* on February 18, 2022 (Eastern Standard Time).

1. Main Points of Research

- The gyromagnetic effect, or the interconversion between macroscopic rotation and magnetism, is a universal effect based on the conservation of rotating motion.
- According to previous studies, inducing gyromagnetic phenomena, realized by sound waves accompanied by mechanical rotations of atoms at a rate of more than one billion times per second, requires precious metals and sophisticated device structures.
- This study proposed that a sound wave induces electromotive force via the gyromagnetic effect in a simple device structure, such as a single ferromagnetic metal layer.
- The results are expected to resolve the difficulties of applying the gyromagnetic effect in spin devices, as the methods proposed do not require rare metals or complicated device structures.

2. Background of Research

Electrons have magnetic properties that originate in their rotation (microscopic angular momentum[1]), called "spin," and electric properties. In spintronics, which simultaneously utilizes these two properties, researchers have studied the control of spin by magnetic fields and charge currents, and realized applications for these phenomena. The interconversion between electron spin and mechanical rotation (macro angular momentum) was experimentally demonstrated by Barnett[2], Einstein and de Haas[3] about a century ago. This important phenomenon, discovered in the course of fundamental scientific questioning into the origin of magnetism, is called the "gyromagnetic effect." The faster the rotation of the material, the more significant the gyromagnetic effect; however, even at high-speed rotations, which are achievable with state-of-the-art technology capable of rates of around 10,000 times per second, the effect is extremely weak—inferior to even the Earth's magnetic field. Due to this, the gyromagnetic effect has not received much attention in spintronics. In 2013, however, a theoretical prediction made by Associate Professor Mamoru Matsuo and colleagues renewed interest in the interaction between magnetism and mechanical rotations [1]. Subsequently, a research group led by Professor Yukio Nozaki experimentally demonstrated that the gyromagnetic effect induced by mechanical rotation of atoms at a rate of more than one billion times per second, accompanied by a sound wave, generates spin currents [2,3]. Professor Nozaki and colleagues generated an ac spin current in copper and ferromagnetic metal composites by injecting a surface acoustic wave traveling along the surface of materials. Through this experimentation, it was confirmed that magnetic waves were excited in ferromagnetic metals by the ac spin current flowing from copper. The research group also electrically detected the spin current generated via the gyromagnetic effect by joining platinum, a highly efficient spin-to-charge conversion material, to composites [4]. However, these methods carried certain limitations, such as the requirement of precious metals including platinum and multilayer device structures.

3. Content of Research and Results

The present research group theoretically proposed that electromotive force can be induced via the gyromagnetic effect in a simple device structure consisting of a ferromagnetic metal monolayer. When sound acoustic waves (SAWs) are injected into ferromagnetic metals, free-electron spins are subjected to the gyromagnetic effect by the rotational motion of lattices. Magnetic waves are simultaneously induced by the magnetoelastic effect[4] that changes the direction of the magnetism associated with the elastic deformation [5,6]. Electromotive force is generated by coupling magnetic waves and free electron spins. The present research group discovered that electromotive force originated from the gyromagnetic effect, circumventing conventional restrictions of materials and device structures, by combining the gyromagnetic effect and magnetoelastic effect. In this study, they analyzed the electromotive force generated by Rayleigh waves[5], one type of SAW. The results suggest that electromotive force is induced in the direction of SAW propagation and in the direction of the thickness of the material. In addition, the results suggested that electromotive force has nonreciprocity[6] in the directions of SAW propagation and magnetism. According to the researchers' estimations, an experimentally observable magnitude of electromotive force can be induced in a polycrystalline nickel system.

4. Future Developments

The mechanism discovered in this study is expected to significantly contribute to the application of the gyromagnetic effect, a feat which has been difficult so far. Previously, microfabrication and precious metals were necessary for utilizing spin currents induced by the gyromagnetic effect. This study enables the application of the gyromagnetic effect for a variety of spin devices without any limitations other than the ability to utilize SAWs. The results of this study are expected make magnetic devices more energy efficient as they do not rely on Joule heat, unlike electric devices, and contribute to the development of rare-metal-free technologies.

Acknowledgements

This research was sponsored by the Japan Science and Technology Agency's (JST) Strategic Research for Evolutional Science and Technology initiative CREST: "Development of functionally graded materials and application to spin devices by combining nano-structure control and computational science" (Research Director: Yukio Nozaki. Project Number: JPMJCR19J4). Additional support came from the JSPS Grants-in-Aid for Scientific Research Program (KAKENHI) 21K20356, 20H01863, and 21H04565.

References

1 M. Matsuo, J. Ieda, K. Harii, E. Saitoh, and S. Maekawa: Mechanical Generation of Spin Current by Spin-Rotation Coupling, Phys. Rev. B **87**, 180402(R) (2013).

2 D. Kobayashi, T. Yoshikawa, M. Matsuo, R. Iguchi, S. Maekawa, E. Saitoh, and Y. Nozaki: Spin Current Generation Using a Surface Acoustic Wave Generated via Spin-Rotation Coupling, Phys. Rev. Lett. **119**, 077202 (2017).

3 Y. Kurimune, M. Matsuo, and Y. Nozaki: Observation of Gyromagnetic Spin Wave Resonance in NiFe Films, Phys. Rev. Lett. **124**, 217205 (2020).

4 S. Tateno, G. Okano, M. Matsuo, and Y. Nozaki: Electrical evaluation of the alternating spin current generated via spin-vorticity coupling, Phys. Rev. B **102**, 104406 (2020).

5 M. Weiler, H. Huebl, F.S. Goerg, F.D. Czeschka, R. Gross, and S.T.B. Goennenwein: Spin Pumping with Coherent Elastic Waves, Phys. Rev. Lett. **108**, 176601 (2012).

6 T. Kawada, M. Kawaguchi, T. Funato, H. Kohno, M. Hayashi: Acoustic spin Hall effect in strong spin-orbit metals, Sci. Adv. **7** eabd9697 (2021).

Details of Journal Article

T. Funato and M. Matsuo: "Spin Elastodynamic Motive Force", *Physical Review Letters*, (Vol. 128, No. 7) 077201 (2022)

DOI: 10.1103/PhysRevLett.128.077201

Glossary

[1] **Angular momentum**: a vector quality that describes the direction and magnitude of rotation. Electrons have microscopic angular momentum called spin, which is known to be the origin of magnetism.

[2] **Barnett effect**: the effect in which the magnetism strength changes when a magnet is rotated. It

was discovered by Barnett in 1915 through an experiment.

[3] **Einstein-de Haas effect**: the effect in which a magnet begins to rotate when its magnetic strength is changed. It was experimentally verified by Einstein and de Haas in 1915. It is said to be the only experiment conducted by Einstein.

[4] **Magnetoelastic effect**: an effect different from the gyromagnetic effect, in which the direction of magnetism changes when the magnet is elastically deformed, or conversely, the magnet is elastically deformed depending on the direction of magnetism.

[5] **Rayleigh wave**: a type of surface acoustic wave that propagates on the surface of a material, in which the local elliptical motion of the atoms that make up the material propagates as a wave.

[6] **Nonreciprocity**: a phenomenon in which different magnitudes of electromotive forces are generated when the directions of Rayleigh waves are reversed.

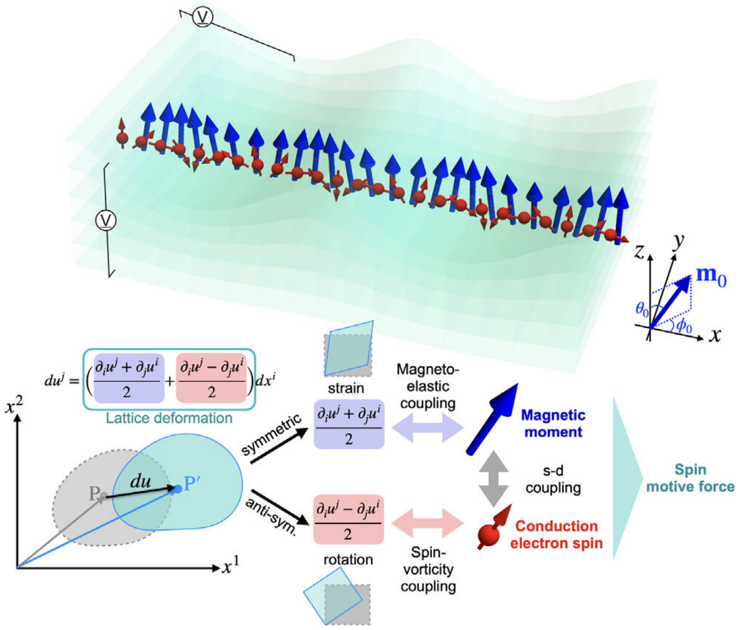

Figure 1. Schematic diagram of the mechanism of electromotive force generation derived from the gyromagnetic effect of sound waves

The magnetoelastic coupling driven by elastic deformation works on the magnetism of ferromagnetic materials, and the gyromagnetic effect driven by rotational deformation works on the spin of free electrons. The combination of these two effects generates an electromotive force derived from the gyromagnetic effect without the need for precious metals or sophisticated device structures.

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・Inquiries about research

Project Assistant Professor Takumi Funato

Keio University Global Research Institute (KGRI) Project

TEL: +81 45-566-1677 FAX: +81 45-566-1677

Email: t_funato@keio.jp

・Inquiries about press release

Keio University Office of Communications and Public Relations (Mr. Sawano)

TEL: +81 3-5427-1541 FAX: +81 3-5441-7640

Email: m-pr@adst.keio.ac.jp https://www.keio.ac.jp/en/