Barnett effect in paramagnetic states

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We report the observation of the Barnett effect in paramagnetic states by mechanically rotating gadolinium (Gd) metal with a rotational frequency of up to 1.5 kHz above the Curie temperature. An *in situ* magnetic measurement setup comprising a high-speed rotational system and a fluxgate magnetic sensor was developed for the measurement. Temperature dependence of the observed magnetization follows that of paramagnetic susceptibility, indicating that any emergent magnetic field is proportional to the rotational frequency and is independent of temperature. From the proportionality constant of the emergent field, the gyromagnetic ratio of Gd is calculated to be -29 ± 5 GHz/T. This study revisits the primordial issue of magnetism with modern technologies to shed new light on the fundamental spin-rotation coupling.

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I. INTRODUCTION

The Barnett effect is a phenomenon that a rotating object is magnetized. The effect was discovered in 1915 [1,2] and is categorized together with the Einstein−de Haas effect [3–8] as a gyromagnetic effect for which the relationship between rotation and magnetism such as gyromagnetic ratio has been investigated [9–13]. The Barnett effect can be described by introducing an emergent magnetic field [14]

$$B_\Omega = \Omega/\gamma, \tag{1}$$

where Ω is the angular frequency of rotation and γ is the gyromagnetic ratio of the sample. In recent times we studied effects of the emergent field, the so-called Barnett field, on nuclear spins such as line shift [15,16] and line split [17] in nuclear magnetic resonance. Furthermore, spin-current generation in liquid metals is observed, where the Barnett field is induced by local rotational motion of fluid [18].

Despite its own generality, no experiments on the Barnett effect have been conducted in paramagnetic states. The main reason lies in its measurement method, i.e., to observe the Barnett effect in paramagnetic materials with zero coercivity and small susceptibility, *in situ* observation under rapid rotation is required, which has been the major obstacle to explore the effect in paramagnetic states.

In this study we observe the Barnett effect in paramagnetic Gd metal. To this end, we developed an *in situ* magnetic measurement setup comprising a high-speed rotational system and a fluxgate magnetic sensor, both of which were unavailable in previous studies [1,2]. The sample used in the present study shows ferromagnetic transition at a Curie temperature T_c of 292.5 ± 0.5 K [19]. The Curie constant is large because of Gd's $4f$ local moment with $J = 7/2$ ($S = 7/2$, $L = 0$). Therefore, magnetic susceptibility χ around room temperature is high, which allows us to measure small stray fields from the magnetized Gd sample due to rotation, even in paramagnetic states.

II. EXPERIMENTAL DETAILS

The apparatus used in the present study mainly comprises a high-speed rotational system and a magnetic field sensor equipped outside the rotor to monitor any stray field created by the magnetization of a rotating sample [Fig. 1(b)]. We used a commercial high-speed rotational system (produced by JEOL) that can generate rotation frequencies of up to 8 kHz, almost 100 times higher than that in the previous study [1,2]. The rotational system is driven by airflow to avoid the severe electromagnetic background noise caused by an electric-driven system. A polycrystalline Gd sample formed in a cylindrical shape with a size of $\varphi 6 \times 20\,\mathrm{mm}^3$ was installed in a nonmagnetic rotor comprising a ZrO_2 capsule and an impeller made of a polyimide resin, as shown in Fig. 1(a). Fluctuation in the rotation frequency was ±30 Hz. The rotation direction could be switched by changing the direction of airflow. For magnetic field measurement, we used a fluxgate magnetic sensor (Stefan Mayer Instruments) with a high sensitivity of 0.1 nT. The magnetic field fluctuation in the shield is suppressed to within ±0.1 nT. The directions of rotation, magnetization, and sensor polarity are defined in Fig. 1(b). The rotation experiments were performed at temperatures of 297–305 K. During rotation, the sample temperature increases to a value greater than the room temperature because of friction between the rotor and air. Therefore, we measure the sample temperature by attaching a thermocouple to the capsule just after stopping the rotation. The deviation in the sample temperature is ± 0.1 K.

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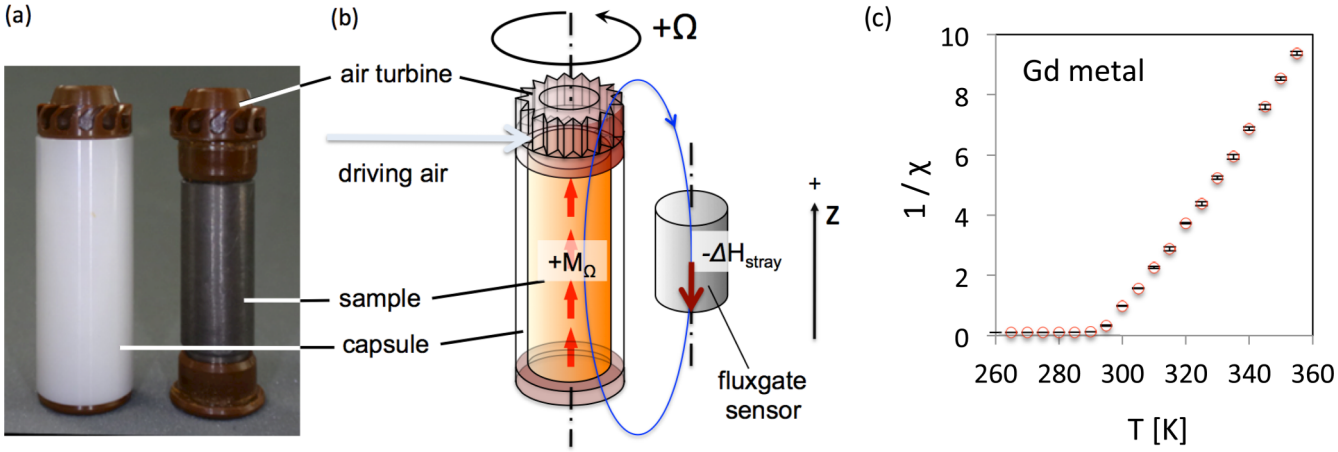

FIG. 1. (Color online) Experimental apparatus for observation of Barnett effect. (a) Capsule (left) and Gd sample (right). (b) Schematic of setup. The positive directions of magnetization, stray field detected by the sensor, and rotation are defined as indicated by arrows. (c) Temperature dependence of inverse magnetic susceptibility. The rotational experiments were performed in paramagnetic states between 297 and 305 K.

III. RESULTS AND DISCUSSIONS

To characterize the sample for the present measurements, we measured the temperature dependence of the magnetic susceptibility χ for the same polycrystalline Gd metal sample measuring $1.2 \times 1.3 \times 3.5\,\mathrm{mm}^3$ using a commercial magnetometer (MPMS, Quantum Design). Figure 1(c) shows the temperature dependence of its inverse magnetic susceptibility in an external field of 1 mT. At experimental temperatures, $1/\chi$ shows linear temperature dependence, following the Curie-Weiss law. Effective magnetic moment was estimated from the slope of $1/\chi$ to be $8.5\,\mu_B$ which is good agreement with the theoretical value $2[J(J+1)]^{1/2}\,\mu_B$ for $J = 7/2 (S = 7/2, L = 0)$.

Figure 2 shows the rotational frequency dependence of the magnetization of the Gd sample at 300 ± 0.5 K and that of a blank capsule. Each data point was averaged over three measurements, the error bar in the standard deviation 1σ includes the fluctuation in rotational frequency. We estimate the magnetization of the rotating sample M_Ω from the stray field $\Delta H_{\mathrm{stray}}$ [20,21] measured by the fluxgate magnetic sensor using a dipole model as follows:

$$M_\Omega = -4\pi\mu_0 (R^2 + L^2/4)^{3/2} \Delta H_{\mathrm{stray}}/V, \qquad (2)$$

where μ_0 is the magnetic constant, $R = 15$ mm is the sensor-sample distance, $L = 20$ mm is the sample length, and V is the sample volume [22]. We found that the magnetization was proportional to the rotational frequency and its polarity changed with the rotation direction. For the blank capsule, no rotation frequency and direction dependence were observed. Thus, the magnetization arose from the rotating Gd sample.

In Fig. 3(a) we plot the temperature dependence of the Gd sample's magnetization or different rotational frequencies ($\Omega/2\pi = \pm 0.5,\ \pm 1.0$, and ± 1.5 kHz). Each data point was averaged over three measurements, with the vertical error bar being the same as in Fig. 2 and the horizontal error bar indicating the fluctuation in sample temperature during measurement. All data curves for fixed rotational frequencies show systematic temperature dependence. The magnetization decreases with increasing temperature. In Fig. 3(b) we plot the values of magnetization divided by susceptibility M_Ω/χ as a function of temperature. The values of M_Ω/χ are constant against temperature, indicating that the temperature dependence of the observed magnetization arises from the material's susceptibility. This result implies the existence of an emergent magnetic field B_Ω due to rotation because in paramagnetic states, the magnetization is proportional to the magnetic field as follows:

$$M_\Omega = \chi B_\Omega. \qquad (3)$$

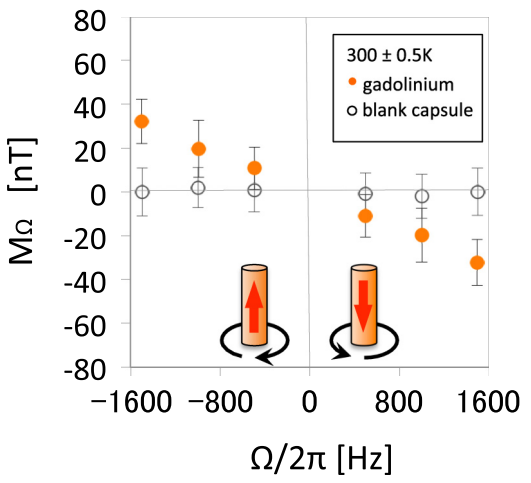

FIG. 2. (Color online) Rotational frequency dependence of magnetization observed at 300 ± 0.5 K for Gd sample (orange solid circles) and blank capsule (black open circles). Each data point is averaged over three measurements with the error bar in the standard deviation 1σ, including the fluctuation in rotational frequency. The insets indicate the rotational directions of the capsule (black arrows) and magnetization (red arrows).

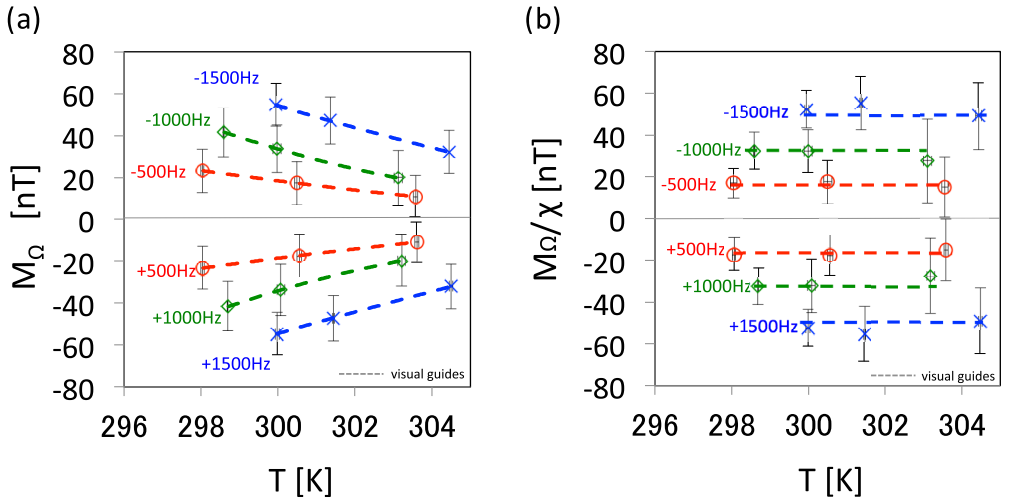

FIG. 3. (Color online) Temperature dependence of (a) magnetization M_Ω and (b) M_Ω/χ for rotational frequency of $\Omega/2\pi = \pm 0.5$ (red open circles), ± 1.0 (green open diamonds), and ± 1.5 kHz (blue crosses). Each data point is averaged over three measurements with the error bar in the standard deviation 1σ, including the fluctuation in rotational frequency. The sample temperature fluctuation during the measurements is within ± 0.1 K, as indicated by the horizontal error bars. The dotted curves serve as visual guides.

Figure 4 summarizes the values of M_Ω/χ as a function of rotational frequency. All data follow the linear dependence of rotation frequency within the experimental accuracy. The dotted line in the graph is the linear fit of all experimental results. According to Eqs. (1) and (3), the inverse of the line's slope gives the gyromagnetic ratio $\gamma/2\pi = -29 \pm 5$ GHz/T. This value is comparable to $\gamma_e/2\pi = -28$ GHz/T for an electron in a vacuum or Gd compounds [23–26].

More precise values can be obtained by improving the present apparatus. It is worthwhile to revisit the investigation of the difference in g factors measured by spectroscopic and gyromagnetic methods [10–12] using current technologies. This mechanical method can be applied to estimate gyromagnetic ratio in a variety of paramagnetic materials. These studies are worth pursuing in the future.

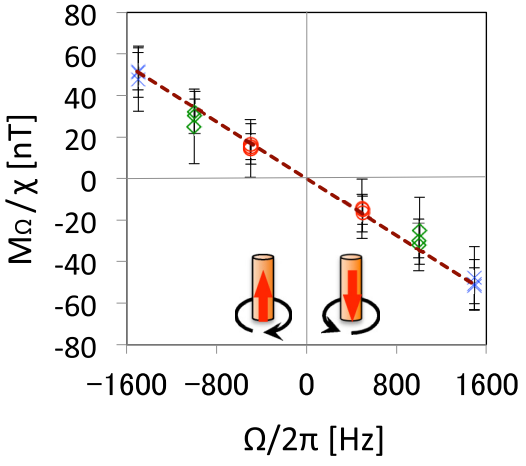

FIG. 4. (Color online) Rotational frequency dependence of M_Ω/χ. The dotted line is the linear fit of all experimental results in the temperature range of 297–305 K. The inverse of the slope of this fitting line is -29 ± 5 GHz/T.

Furthermore, because of recent progress in spintronics, increasing attention has been paid to the interconversion of angular momentum between spin and rotational motion by relying on the Barnett field concept [27–29]. The present study provides evidence of the Barnett field in paramagnetic states and paves the way for "spin mechatronics," in which spin and mechanical rotation are harmonized.

IV. CONCLUSIONS

We have observed the Barnett effect in paramagnetic states using Gd metal by developing an apparatus for *in situ* magnetization measurements of a rapidly rotating sample. The temperature and rotation frequency dependence of the observed magnetization were identified with paramagnetic susceptibility and the Barnett field emerging in the Gd sample, respectively. The Barnett field analysis shows the gyromagnetic ratio of Gd as -29 ± 5 GHz/T.

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