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An Experimental System to Release Solid Particles in Microgravity Area Designed to Observe Field-induced Motions of Weakly Magnetic Particles

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Abstract

Efficiency of observing translation and rotation of a sub-millimeter size sample at low magnetic field has considerably increased by improving the system to release small samples in microgravity (μG) area of reduced pressure. By measuring the period of rotational oscillation induced in a homogeneous field of 0.2T, anisotropy of paramagnetic susceptibility $\Delta\chi_{PARA}$ was detected on a small paramagnetic crystal. By observing velocity v_R of a translating grain at a position of $B \sim 0$, diamagnetic susceptibility χ_{DIA} is detected in a small grain. Here the position of sample stage was controlled for the purpose of releasing the samples in a μG area with small momentum. The obtained techniques to observe field-induced motions of sub-mm sized samples are a step forward to detect magnetization of a weakly magnetic particle of μm size.

Keyword(s): Diamagnetic anisotropy, Diamagnetic particle, Field-induced translation, Dust alignment, Field-induced rotational oscillation, Release of sample

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1. Introduction

The field-induced dynamical motions of weakly magnetic (i.e. diamagnetic and paramagnetic) materials have not been studied intensively, partly because the magnetization energy induced in the material was not strong enough to exceed the effect of terrestrial gravity even by applying a strong magnetic-field above 10T. Rotation[1)] and translation[2)] caused by low static field produced by a permanent magnetic were recently reported on various diamagnetic materials in a microgravity (μG) condition; here the samples were released in a medium of reduced pressure with negligibly small initial momentum.

A diamagnetic grain released in an area of reduced pressure was ejected toward a direction of monotone decreasing field[2)]. The ejection was caused by a field gradient force. Provided that field-intensity at initial sample position was identical, terminal velocity v_T of the sample outside the field (B~0) was independent to mass m of particle; v_T was uniquely determined by the diamagnetic susceptibility χ_{DIA} (emu/g) assigned to individual material. The χ_{DIA} value of a single grain was obtained from the above-mentioned ejection.

Rotational oscillation of magnetically stable axis with respect to direction of homogeneous field was recently observed for diamagnetic crystals released in a medium of reduced pressure; the oscillation was caused by field-induced anisotropy energy[1)]. Small $\Delta\chi_{DIA}$ were obtained for mm-sized crystals by observing period of rotational oscillation τ of its magnetically stable axis with respect to direction of magnetic field.

The field gradient force has been used to levitate diamagnetic materials[3)]. The levitation was realized by a gradient caused by a high magnetic field produced by specific field generator. Magnetic orientation (or alignment) caused by magnetic anisotropy $\Delta\chi$ was reported for diamagnetic particles dispersed in fluid medium[4)]. The mechanism of the above orientation was first studied quantitatively on various organic materials[4)] and later on inorganic materials including natural silicates[5)]. Furthermore, the orientation was applied to innovate functional materials from grain-aggregates with its magnetically-stable axes aligned in one direction[6)].

In the present study, $\Delta\chi$ value was newly measured in μG condition for a paramagnetic grain of sub-mm size, namely hydroxyl apatite. Mass dependence of the magnetic ejection were examined for three Bi grains with different sizes and compared with the previous results on Bi grains. The position of the sample stage was controlled, for the purpose of releasing the sample grains in the diffused area. Based on the observed results, the significance of observing field-induced motions of μm- and nm-sized grain is discussed for various categories of magnetic materials.

2. Experimental

The μG conditions were produced by a short drop shaft (1.5 m long) which was designed at Graduate School of Science, Osaka University[1)]. The experimental setup of the 2 experiments were developed separately. Both setups were attached in an area of 35×30×20 cm inside a drop box. The experimental setups were enclosed in a Pyrex tube, and the motions of the samples were

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observed from the outside of wall by a hi-speed video camera (Casio, EX-F1); the time and spatial resolution of the camera was 0.033 s and 0.004 cm, respectively. Inner pressure of the tube was reduced to $P \approx 100$ Pa, which was effective to minimize the viscous drag to a negligible level. The box was tentatively attached to the laboratory sealing by an electro-magnet, and free fall of the box started by cutting off the power of the magnet. Duration of μG inside the box was about 0.5s, with residual gravity of 10^{-2}G. Before performing the two types of experiments in the compact drop shaft, operational tests of the setup were carried out in a conventional drop shaft at the National Institute of Advanced Technology.

In the experiments of rotational oscillation, the paramagnetic crystals were placed on a metal sample stage located at the center of the N and S poles of the magnetic circuit, which was composed of NdFeB plates (2.5× 2.0 × 0.6 cm) as described in **Fig 1**. The field intensity at the center of the circuit was 0.63 T. Shortly after the beginning of μG condition, the paramagnetic samples were spontaneously floated from the sample stage with a negligibly small angular momentum. The sample gradually translated toward the upper magnetic plate (N pole) by an attractive field-gradient force; the μG conditions were stopped before the sample made contact with the upper plate. In case of the diamagnetic samples, the sample stage was set near the surface of the lower magnetic plate (S pole), and a repulsive field-gradient force induced the release of the sample from the stage. Samples are listed in **Table 1**.

In the experiment of field-induced translation, three pieces of synthetic bismuth having the purity of 99.99 % were measured separately. Numerical details of the samples are given in **Table 2**, with the data of the samples measured in previous studies. An orthogonal co-ordinate, as described in **Fig. 1**, was introduced in the apparatus. The co-ordinate was necessary for assigning the positions of the translating sample. The center of the magnetic circuit was defined as the origin of co-ordinate, and x-axis was parallel to the cylindrical axis of the Pyrex tube. **Figure 2** show the distribution of magnet field produced NdFeB magnet. The sample was released in μG area of reduced pressure at a position $x = x_0$ with negligibly small initial-velocity (v_0=0); field intensity at $x = x_0$ was defined as $B= B_0$. The B_0 values determined for individual samples are listed in **Table 2**. The errors of x_0, B_0 and v_R derive from the ambiguity of sample positions that were determined from the images of the hi-speed video camera.

3. Results

The two apatite crystals showed rotational oscillation, with the equilibrium direction (i.e. c-axis) being parallel to field direction. The $\Delta\chi$ value is obtained from the formula of the period of harmonic oscillation, $\tau = 2\pi\,(I/m\Delta\chi\, B^2)^{½}$ 1), here the numerical values of τ and I/m of the crystal were determined from the images of the hi-speed camera. The obtained $\Delta\chi$ values of the 2 samples are listed in **Table 1**. The deviation of $\Delta\chi$ between the two apatite grains is within the range of the observed I/m values. Attempt to measure the temperature dependence of $\Delta\chi$ is now in progress for the purpose of quantitatively separating the diamagnetic and paramagnetic component of the experimental $\Delta\chi$ value.

It was confirmed from the experiment that the position of the sample stage, located at the center of N and S pole, was effective to spontaneously release the sample by an attractive field gradient force. In previous μG experiments, release of sample was often prevented by a Coulomb attractive force between sample and holder due to electric charges. The above-mentioned field-gradient force is effective to reduce the interference of the attractive force.

As it was so in the equation of field-induced translation, m appears in the inertial term and the magnetic term of the rotational

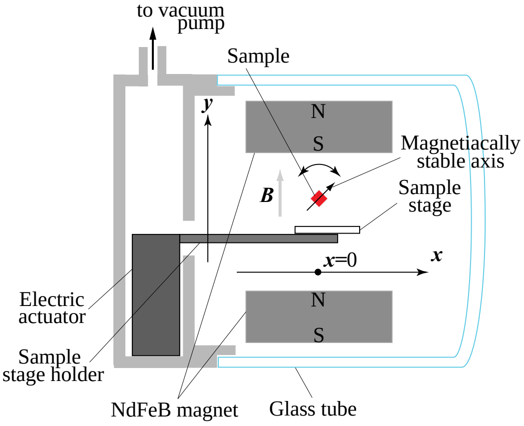

Fig. 1 Schematic view of the experimental inside a drop box to observe field-induced rotational oscillation of the magnetically stable axis in a paramagnetic crystal, using a chamber-type drop shaft. Rotational oscillation was observed with a hi-speed video camera from the z axial direction.

Table 1 Specifications of the measured apatite.

Sample	m (mg)	period of oscillation τ(ms)	Δχ (x10^{-8}emu/g)
1	6.17±0.80	26.7±3.0	4.8±1.5
2	26.7±3.0	0.39±0.02	4.1±2

Table 2 Specifications of the measured Bi grains.

Sample	m [g]	x_0 [cm]	B_0 [T]	v_R [cm/s]	χ_{DIA} [x10^{-7}emu/g]
Bi-1	(0.50±0.05)x10^{-3}	0.94±0.04	0.658±0.060	9.83±0.1	-16.5±3.0
Bi-2	(5.1±0.5)x10^{-3}	0.975±0.043	0.609±0.060	2.74±0.0	-15.8±3.2
Bi-3	(0.77±0.05)x10^{-3}	0.93±0.04	0.660±0.060	8.84±0.2	-18.03±3.6
Bi-4	(1.9±0.4)x10^{-3}	1.08±0.04	0.575±0.060	7.43±0.1	-16.67±3.3
Bi-5	(2.7±0.4)x10^{-3}	1.04±0.04	0.602±0.060	7.76±0.2	-16.25±3.2

equation, period τ of oscillation is independent to m, and $\Delta\chi_{\mathrm{DIA}}$ is obtained without the need of measuring m. It is not necessary to consider the interference of the fiber that suspends the sample in the method of rotational oscillation, which were used in the conventional methods$^{2)}$.

In the experiments of field-induced translation, the energy conservation rule of a diamagnetic particle is expressed as $\frac{1}{2}m\chi_{\mathrm{DIA}}B_0^2 = \frac{1}{2}mv_1^2 + \frac{1}{2}m\chi_{\mathrm{DIA}}B_1^2$; here B_1 denote field intensity at $x = x_1$, whereas, sample velocity at $x = x_1$ is defined as v_1. From observation between position x_0 ($B = B_0$, $v=0$) and position x_R ($B=0$, $v = v_R$), χ_{DIA} is simply expressed as $\chi_{\mathrm{DIA}} = v(x_R)^2B_0^{-2}$.

The relationship between measured χ_{DIA} and m are shown in **Fig. 4** for five Bi grains. The χ_{DIA} values show no tendency of m dependence, as expected from the energy conservation rule. The errors of χ_{DIA} mainly derive from ambiguity of the B_0 values. The χ_{DIA} obtained form translation is rather large compared to the published value of bismuth, which is probably caused by the deviation of grain position from the x-axis during translation. Attempt to control the locus of translation to remain along the x-axis is now in progress. Furthermore, it will be possible to increase the magnitude of the field gradient by improving the design of the magnetic circuit used in the present setup; the enhancement of field gradient will improve the sensitivity of the χ measurement.

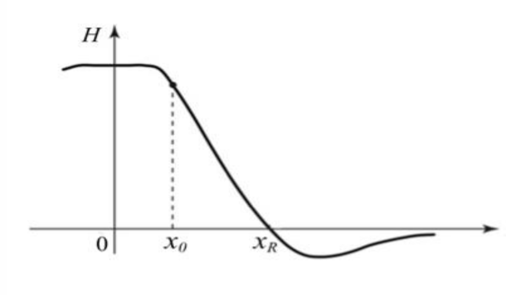

Fig. 2 Field distribution designed to observe magnetic translation of a bismuth grain. Details of position x_0, x_R and the x-, y- axes are given in the text. Translation of particle was observed from the $+z$ axis. Before the μG experiment, field intensity was equal to zero at a position, x_R = 1.87±0.05 cm, since magnetic line of force turned from [+y] to [-y] direction at this point. The magnetic line of force, directing from N to S pole at the center of circuit, was parallel to the y-axis.

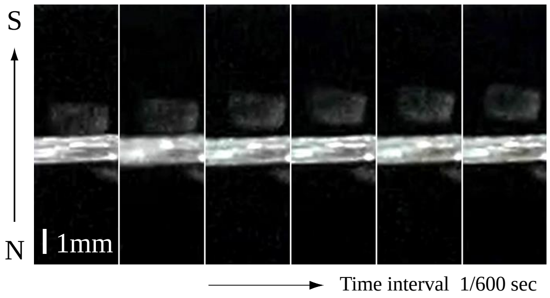

Fig. 3 Time dependent image that shows the release of an apatite sample in a μG area. The sample is set on a stage that is located center of N and S pole. The sample was released by an attractive field gradient force. Time intervals between the images are 1/600sec.

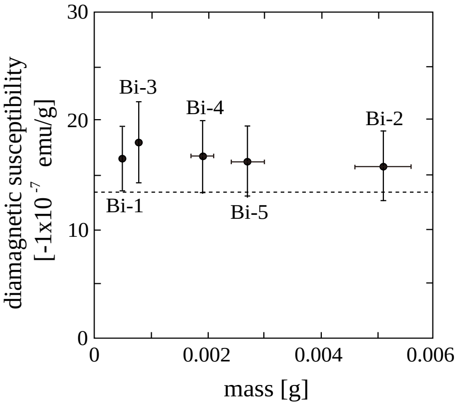

Fig. 4 Relationship between χ_{DIA} and m measured for five Bi grains. Bi-1 and Bi-2 are measured in previous studies.

The mass independent property is a promising factor to measure magnetization of a weak magnetic grain with reduced sizes, because χ_{DIA} is obtained simply by inserting v_T and B in the relation $v_T^2 = \chi_{\mathrm{DIA}}\,B_0^2$. Using this method, detection of χ_{DIA} is possible as long as the translation of the grain is observed$^{2)}$. The method is free of the interference signal emitted from the sample holder, which causes another difficulty in detecting magnetization of a small sample in a conventional apparatus. The mass independent characteristics of the field-induced translation, as confirmed for the 3 bismuth grains in **Fig. 4**, occurs because the motion of grains are induced by a field-induced volume force. The characteristics were conventionally used in the “Faraday method”. The force has been recently applied in the technique of magnetic levitation$^{3)}$. However the possibility of a free motion, based on a simple motional equation that consists of a inertial and a magnetic term has not been intensively considered$^{8)}$.

4. Discussion

The results of the present experiments confirms that placing the sample stage in the center of the N and S poles (**Fig. 1**) was effective in achieving the spontaneous release of a paramagnetic sample through the attractive field-gradient force. Furthermore, setting the sample stage at a position of 1 mm above the surface of S pole was effective in inducing the release of a diamagnetic sample through a repulsive field-gradient force. In various μG experiment, the release of a solid particle from the sample stage toward a μG area is generally prevented by attractive forces between the sample and the stage; The above attractions are caused for example by the Coulomb force between electric charges or by an adhesive force caused by the presence of small contaminants. The effect of the field-gradient force adopted in this study may represent a technical breakthrough in solving the problem of releasing solid particles into the areas of reduced pressure.

Grain alignment caused by $\Delta\chi$ has been applied to improve the functionality of grain-aggregate materials. In general, the functionality of a grain-aggregate is significantly increased by aligning a certain crystalline-axes of the grain in one direction. For example, alignment of c-axes in the hydroxyl-apatite grain has been applied to increase the hardness of industrial-bone material (6). It was previously believed that the above alignment occur only in the presence of a strong field above several Tesla (6). Minimum field intensity to achieve the alignment has not been considered intensively, which is essential factor to popularize the effect in the field of practical applications. In this sense, the large $\Delta\chi_{\mathrm{PARA}}$ of apatite, caused by paramagnetic Fe ions (7), may be a breakthough to realize alignment at a practical low field produced by a low-costing permanent magnet.

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