Magnetic ejection of submilimeter-sized diamagnetic grains observed in a chamber-type drop shaft

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Abstract. Mass dependence of magnetically induced translation is examined for submilimeter-sized diamagnetic grain, which is floated in a diffused gas medium of 70 Pa by the use of microgravity μG condition. Here the grains are ejected from field-center of a pole-piece magnetic circuit by field-gradient force in a direction of decreasing field; maximum field-intensity at initial point is about 0.6T. It was deduced from an energy conservation rule that magnetic potential of the grain at initial position was partially converted to kinetic energy during translation. Therefore, observed velocity was expected to be independent to mass of particle; this is because magnetic potential is proportional to mass of particle. In a given field distribution, the velocity was uniquely determined by intrinsic magnetic susceptibility χDIA of material. We report here that the magnetic ejection in μG condition is realized for sub-mm sized crystals of bismuth, graphite and magnesia. The χDIA values obtained from the ejection agreed fairly well with the published values for the three materials. The mass-independent property of translation was examined by observing the translation of two bismuth grains with different sizes. A chamber-type drop shaft having a height of 1.5 m was introduced to produce the μG condition. By the use of this drop shaft, study of field-induced motion of a single diamagnetic particle becomes possible in an ordinary laboratory.

1. Introduction
In terrestrial gravity, magnetic motion of a solid substance is generally considered to occur on materials that bear spontaneous magnetic moments or strong paramagnetic moments. It is believed that dynamic motions of weak magnetic (i.e. diamagnetic and paramagnetic) material require a strong field above \( B = 10T \) [1-4]. When a weak magnetic solid was released in μG space with negligible effect of gravity or viscous drag, two kinds of basic motions were expected to occur by low magnetic field. First, translation was caused by field gradient force, \( m\chi_{DIA}B(dB/dx) \), where \( m \) and \( \chi_{DIA} \) denoted mass and diamagnetic susceptibility per unit mass of sample, respectively. Secondly, magnetically stable axis of crystal showed rotational oscillation with respect to field direction in a homogeneous field. The two motions were expected to be a common property of a solid material, since all material possessed intrinsic diamagnetic susceptibility \( \chi_{DIA} \) and anisotropy \( \Delta\chi_{DIA} \).

Field gradient force was conventionally used in separating particles that bear strong magnetizations. Magnetic levitation of diamagnetic materials caused by field-gradient force was performed at strong field intensity above 10 Tesla at high magnetic-field facilities [1,2]. Various methods to detect susceptibility of small particles were proposed using a strong field gradient at terrestrial gravity condition in a presence of viscous medium [4]. In these studies based on high magnetic field, magnetization measurements based on free motions of particles in diffused area were not considered.

The above-mentioned properties of magnetic motions expected in μG were recently examined for mm-sized crystals of popular diamagnetic materials, using a conventional μG facility [5,6]. The \( \chi_{DIA} \) values obtained from the translations were consistent with the published values. By measuring the
period of rotational oscillation in μG condition, small $\Delta \chi_{\text{DIA}}$ at a level of $1 \times 10^{-9}$ emu/g was detected [7]. As a step to realize the above-mentioned magnetic ejection at micron-size level, translation was observed in the present study for sub-millimeter size grain of three diamagnetic materials which had different $\chi_{\text{DIA}}$ values. A chamber-type drop shaft was adopted to produce μG, for the purpose of studying the above-mentioned magnetic motions in an ordinary laboratory.

2. Experimental

The compact drop shaft used in the present study had a length of 1.5m. The experimental setup to observe the magnetic ejection was set inside a rectangle wooden box which had a size of 30cm×30cm×20cm. The box was attached to the sealing of our laboratory room by an electromagnetic lock. The free fall of the box started shortly after the power supply of the lock was shut down. The duration of μG was below 0.6 seconds. The apparatus installed in the box consisted of a cylindrical glass tube equipped with an electric actuator to operate a sample holder, a signal receptor to control the electric actuator, a magnetic circuit and the high-vision (HV) video camera (Panasonic HDC -SD3-S; spatial resolution 0.004 cm.). The magnetic circuit was composed of a couple of NdFeB magnetic plates having the size of 2.50cm×2.00cm×0.6cm. In order to describe the observed sample positions, an orthogonal co-ordinate as described in Fig.1 was defined in the above-mentioned apparatus. The center of the magnetic circuit was the origin of the co-ordinate. The magnetic line of force, directing from N to S pole at the center of circuit, was parallel to the $y$-axis; field intensity at the center of circuit was 0.72 T. The $x$-axis was parallel to the cylindrical axis of the glass tube.

The sample was released in diffused μG space 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 1; these values were determined from initial positions of the sample. The field gradient $dB/dx$ at $x = x_0$ was negative (see Fig.1), so the samples were expected to translate along the $x$-axis in a positive direction. Translation of the sample was observed from a [+z] direction by the HV camera with a time division of 0.033 s. Before the μG experiment, field distribution along the $x$-axis was measured with a spatial resolution of 0.1 cm; The result is shown schematically in the lower portion of Fig.1. Field intensity was equal to zero at a position, $x_R = 1.87 \pm 0.05$ cm, since magnetic line of force turned from [+y] to [-y] direction at this point.

Table I  Numerical data of bismuth, graphite and MgO grains that were observed in the present study. Here $m$ and $\chi_{\text{DIA}}$ denote mass of sample and diamagnetic susceptibility per unit mass, respectively. The samples were cut from a synthetic block with a purity of 99.99%. The $B_0$ values of individual samples are determined from the observed initial positions. 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 HV camera. The value of $\chi_{\text{DIA}}$ is obtained from a relationship $v_0^2 = \chi_{\text{DIA}}B_0^2$; the errors mainly derive from the ambiguity of the measured $B_0$ values.

| Sample | $m$ [g] | $x_0$ [cm] | $B_0$ [T] | $v_R$ [cm/s] | $\chi_{\text{DIA}}$[x10^{-7}emu/g] |
|--------|---------|------------|----------|-------------|-------------------------------|
|        | measured | published |          |             |                               |
| Bi-1   | $(0.50 \pm 0.05)x10^{-3}$ | 0.94±0.04 | 0.658±0.060 | 9.83±0.1 | $-16.5\pm3.0 -13.4$ |
| Bi-2   | $(5.1 \pm 0.5)x10^{-3}$ | 0.975±0.043 | 0.609±0.060 | 2.74±0.0 | $-15.8\pm3.2 -13.4$ |
| G1     | $(1.6\pm0.5)x10^{-4}$ | 0.99±0.01 | 0.629±0.006 | 13.9±0.1 | 48.7±1.5 52       |
| M1     | $(1.2\pm0.5)x10^{-4}$ | 1.02±0.01 | 0.609±0.006 | 2.74±0.02 | 2.02±0.9 2.6       |
In a previous study, determination of $\chi_{DIA}$ (per unit mass) was based on an energy conservation rule assumed for a sample that was translating in a magnetic field, namely:

$$\frac{1}{2}m \chi_{DIA} B_1^2 + \frac{1}{2}m v_1^2 = \frac{1}{2}m \chi_{DIA} B_0^2 + \frac{1}{2}mv_1^2;$$

here $v_1$ denote sample velocity at an arbitrary position $x = x_1$, whereas field intensity at $x = x_1$ is defined as $B_1$. According to the above equation, $\chi_{DIA}$ should be equivalent to the gradient of a linear relationship $v_1^2 = \chi_{DIA} (B_1^2 - B_0^2)$.

In case of millimetre-sized crystals measured in the previous study, the $\chi_{DIA}$ values obtained from the above-mentioned relationship was consistent with their published $\chi_{DIA}$ values [6]. In the present study, $\chi_{DIA}$ is calculated from a relationship $v(x_R)^2 = \chi_{DIA} B_0^2$ which is deduced from an energy conservation between position $x_0$ ($B=B_0, v=0$) and position $x_R$ ($B=0, v=v_R$).

### 3. Results and Discussions

When the effects of gravity and viscous drag of medium was negligible, a particle released in a magnetic field gradient that decreases monotonously along $x$-axis was expected to show translation that followed a motional equation [5][6] described as,

$$m \left( \frac{d^2x}{dt^2} \right) = m\gamma_{DIA} B \left( \frac{dB}{dx} \right).$$

The field-gradient force is known to be a “volume force” which derived from the localized electrons of individual atoms that composed the material. Accordingly, the two terms in eq.(1) are both proportional to $m$. It was hence expected that acceleration $d^2x/dt^2$ of particle was independent to its mass [5]. The equation of energy conservation between magnetic potential and kinetic energy, as described in the previous section, was directly deduced from the above motional equation.

Fig.2 show a time variation of sample position along the $x$-axis measured for the Bi-1 sample in Table 1. Fig3(a) shows the relationship between sample velocity $v$ and position $x$ obtained from the measured data of Fig.2. From the $v$-$x$ relationship, the velocity at $x = x_R$ was obtained as $v_R = 0.94$ cm/s. By inserting this $v_R$ and $B_0 = 0.6584$ T (see Table 1) in the above-mentioned equation of energy conservation $v(x_R)^2 = \chi_{DIA} B_0^2$, $\chi_{DIA}$ was calculated as $\chi_{DIA} = -15.8 \pm 3.2 \times 10^{-7}$ emu/g.
Using the above procedure, the $\chi_{\text{DIA}}$ values are obtained for two bismuth grains with different $m$ values. The values are compared in Table I with the published value, $-13.4\times10^{-7}$ emu/g. For both samples, the deviations of the measured values with respect to the published value are within range of experimental error. It may be concluded that no significant tendency of mass dependence is seen in the field-induced translation at least for bismuth in the range of $m = 0.5 \sim 5.0$ mg.

![Graph](image1)

Fig. 3 (a) Relationship between sample velocity $v$ and position $x$. (b) Relationship between $v_1^2$ and $B_1^2 - B_0^2$; definitions of $v_1$, $B_1$ and $B_0$ are given in the text. Both relationships are obtained from the measured variation of sample position shown in Fig.1, which were measured for a submillimeter-sized bismuth grain (Bi-1 in Table 1).

The $\chi_{\text{DIA}}$ values of graphite and magnesia obtained from the above relationship are listed in Table 1. It is seen that measured values agreed fairly well with their published values. The numerical range of $\chi_{\text{DIA}}$ observed in the present study nearly overlaps with the range of the published $\chi_{\text{DIA}}$ values compiled in a data book of diamagnetic susceptibility; the smallest published $\chi_{\text{DIA}}$ value has been reported for indium which is $1.3\times10^{-7}$ emu/g, whereas the largest is reported for graphite which is $\chi_{\text{DIA}}=5.2\times10^{-6}$ emu/g [9]. Hence for sub-millimeter sized particles, efficiency of eq.(1) seems to be confirmed over the $\chi_{\text{DIA}}$ values of existing materials.

The $\chi_{\text{DIA}}$ value of Bi-1 was also calculated from the gradient of the $v_1^2$ v.s. $B_1^2 - B_0^2$ relationship that is described in Fig.3 (b). The relationship is obtained by determining sets of $v(x)$ and $B(x)$ values at different sample positions in Fig.2. The calculated value is $\chi_{\text{DIA}}= - (1.59\pm0.32)\times10^{-6}$ emu/g which is consistent with published value; the result indicates that sum of kinetic and magnetic energy is conserved throughout the translation of the submillimeter-sized Bi grain. Whereas the agreement between measured and published $\chi_{\text{DIA}}$ values compiled in Table 1 show that an accurate $\chi_{\text{DIA}}$ value is obtained from a calculation based on the equation $v(xR)^2 = \chi_{\text{DIA}}B_0^2$; deduction of $\chi_{\text{DIA}}$ using the above equation is far more simple compared to the analysis based on the relationship of $v_1^2$ v.s. $B_1^2 - B_0^2$, which was performed in previous studies [5][6].

In a conventional method to measure magnetization, measureable sample size is limited by the following two factors; the interference by the background signal emitted from the sample holder, and the difficulty of measuring the mass of sample. The present method is free from the two factors; detection of $\chi_{\text{DIA}}$ is based on a simple conservation rule between kinetic energy and magnetic potential [6]. Accordingly, magnetization of a single diamagnetic grain smaller than mm-size, which is difficult
to perform by conventional methods, becomes detectable by the present method. The present lower-limit of measurable sample size using this system is determined by the spatial resolution of the HV camera, which is about 20 microns. In this sense, the observation of sub-millimetres sized grain achieved in the present study provides a technical step forward to realize the detection of $\chi_{\text{DIA}}$ in the region of micron size. In order to examine the generality of the above-mentioned properties of translation in the submillimeter region, it is necessary to perform the observation of Fig.3 (a) and (b) on other diamagnetic materials that posses different magnitudes of $\chi_{\text{DIA}}$.

The magnetization data on small particle is expected to provide information on electron configurations of solid insulators in the nano-meter region. According to a Pascal rule, which explains the origin of diamagnetic susceptibility of solid insulators, a $\chi_{\text{DIA}}$ value of a material is equivalent to the sum of the diamagnetic susceptibility assigned to individual orbital that compose the material [9]. It is hence expected that precise $\chi_{\text{DIA}}$ data of individual particle provide information on the distortion of bulk crystal structure that is considered to increase with the reduction of crystal size [3].

Dynamic motions in nature induced by magnetic field are commonly recognized only for materials that bear spontaneous magnetic moments or strong paramagnetic moments. The effect of field-induced potential energy should be considered in studying the dynamic behaviour of the dust particles in the process of stellar and planetary evolution. When a long duration of $\mu G$ is allowed, magnetic ejection may occur on a diamagnetic grain in general even if the field intensity is as small as the of cosmic field. The above conditions are satisfied in a greater part of inter- & intra-stellar regions, since both static field and diamagnetic dust particles are omnipresent in these regions. The mass independent property of the transition in the sub-millimeter region should be examined for dust forming materials such as ice, carbon-dioxide, forsterite and amorphous silica, since upper limit of size distribution in the circum-stellar regions range in the sub-millimetre scale.

The observation of magnetic ejection was obtainable by the compact $\mu G$ drop shaft because the small magnetic circuits composed of the Nd-Fe-B plates were introduced as the field generator. The compact $\mu G$ drop shaft is effective to carry out a $\chi_{\text{DIA}}$ measurement of a single particle as a routine analysis, since the system does not require a long machine time, and the running cost is low enough to repeat a routine process. The studies on field-induced dynamic motion of small particles (i.e. rotation and translation) become possible in an ordinary laboratory.

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