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# Magnetic ejection of diamagnetic sub-millimeter grains observed by a chamber-type $\mu$G generator orientated to identify material of a single particle

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A principle to identify the material of a single particle without destroying the sample is examined by an experiment in microgravity ($\mu$G). Such an identification is important as a first stage of analyzing various grains of primitive materials. The identification was based on diamagnetic susceptibility $\chi_{\mathrm{DIA}}$ obtained from translation of the grain induced by a magnetic field. When a grain is released in an area of a monotonously decreasing field under $\mu$G conditions, it will be ejected in the direction of the field reduction; here, the area is occupied with diffused gas medium. The material identification of a primitive grain is possible by comparing the measured $\chi_{\mathrm{DIA}}$ with published values; an intrinsic $\chi_{\mathrm{DIA}}$ value is assigned to a material according to a molecular orbital model. We report here that the ejection is realized for sub-mm-sized crystals of various organic and inorganic materials. By developing a short drop shaft ($\mu$G duration ~0.5 s), the proposed material identification can be easily performed in an ordinary chamber. Using conventional methods, $\chi_{\mathrm{DIA}}$ cannot be detected for a small sample of diameter below the level of a millimetre. The achieved result is a step to realize the identification of micron-sized grains that compose primitive materials.

**Key words:** Magnetic ejection, chamber-type drop shaft, graphite, bismuth, polyethylene.

## 1. Introduction

It is generally considered that primitive materials, such as carbonaceous chondrites, are aggregates of small particles that are randomly mixed together. Such particles are composed of different materials, the estimated origins of which are heterogeneous. It is necessary to identify the materials of individual grains before performing a refined analysis of the isotopic, chemical or optical properties. Such a method of material identification should be non-destructive and easily performed. Moreover, the method should be based on a well-established physical or chemical concept.

Under conditions of normal gravity, the magnetic translation of a solid particle caused by a field gradient force has been commonly used to separate a magnetic particle composed of spontaneous magnetic moment. However, the possibility of magnetic translation has not yet been considered intensively for ordinary diamagnetic solids (Beaugnon and Tournier, 1991; Ikezoe *et al.*, 1998). When a diamagnetic solid is placed in a gradient of a static field, with a negligible effect of gravity or viscous drag of the surrounding medium, free motion caused by the field gradient force $\chi B(dB/dx)$ is expected to be observed on diamagnetic solids in common (Hisayoshi *et al.*, 2009; Uyeda *et al.*, 2010). This is because the material possesses an intrinsic diamagnetic susceptibility, $\chi_{\mathrm{DIA}}$, per unit mass, according to general considerations on the origin of diamagnetic magnetization. The diamagnetic moment has been quantitatively explained in terms of a molecular orbital method (Guputa, 1983). Hence, by comparing the observed $\chi_{\mathrm{DIA}}$ with published values, the material of the translating particle can be identified. According to Newton's equation of motion assumed for a field gradient force, the acceleration $a$ of a particle is expected to be independent of the mass $m$ of the particle in a given field distribution; it is uniquely determined by the intrinsic $\chi_{\mathrm{DIA}}$ value of the material. This means that a $\chi_{\mathrm{DIA}}$ measurement, thereby enabling material identification, is possible for limitlessly small samples (Uyeda *et al.*, 2010).

In the present study, the field-induced ejection are newly observed for sub-millimeter-sized diamagnetic particles, namely graphite, bismuth and polyethylene, which have different values of $\chi_{\mathrm{DIA}}$. The sample was released in a $\mu$G area, of reduced pressure in a monotonously decreasing field, with a negligibly small initial velocity. The energy conservation is expected for a particle of mass $m$ is described as $1/2m\chi_{\mathrm{DIA}}B_0^2 = 1/2mv_{\mathrm{R}}^2$. Here, the field intensity at the initial sample position is defined as $B_0$, whereas the sample velocity, at a point where the field intensity is equal to $B = 0$, is defined as $v_{\mathrm{R}}$. The $\chi_{\mathrm{DIA}}$ values are directly obtained by inserting the measured values of $B_0$ and $v_{\mathrm{R}}$ in the relationship $\chi_{\mathrm{DIA}} = v(x_{\mathrm{R}})^2 B_0^2$, which was derived from the conservation rule between magnetic potential and kinetic energy. The possibility of identifying the material of a single micron-sized particle is discussed, based on the

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Table 1. Numerical data of the diamagnetic grains studied in the present report. Here, $m$ and $\chi_{\mathrm{DIA}}$ denote the mass of the sample, and the diamagnetic susceptibility per unit mass, respectively. The samples were cut from a synthetic block having a purity of 99.99%. The $\chi_{\mathrm{DIA}}$ values of graphite-1 and bismuth-1 were measured in a previous study (Hisayoshi *et al.*, 2011).

| Sample | $m$ [g] | $x_0$ [cm] | $B_0$ [T] | $v_{\mathrm{R}}$ [cm/s] | $\chi_{\mathrm{DIA}}$ [$\times 10^{-7}$ emu/g] | |
|---|---|---|---|---|---|---|
| | | | | | Measured | Published |
| graphite-2 | $(1.6 \pm 0.5) \times 10^{-4}$ | 1.00±0.01 | 0.624±0.006 | 12.1±0.1 | 42.3±1.5 | 52 |
| bismuth-2 | $(7.8 \pm 0.1) \times 10^{-4}$ | 0.94±0.04 | 0.660±0.060 | 8.84±0.10 | 18.0±0.1 | 13.4 |
| polyethylene-1 | $(3.2 \pm 0.3) \times 10^{-4}$ | 1.09±0.01 | 0.574±0.053 | 5.62±0.23 | 9.58±0.80 | 9.0 |
| polyethylene-2 | $(16 \pm 0.3) \times 10^{-4}$ | 0.95±0.01 | 0.652±0.053 | 5.89±0.23 | 8.00±0.25 | 9.0 |
| graphite-1 | $(1.6 \pm 0.5) \times 10^{-4}$ | 0.99±0.01 | 0.629±0.006 | 13.9±0.1 | 48.7±1.5 | 52 |
| bismuth-1 | $(5.0 \pm 0.1) \times 10^{-4}$ | 0.94±0.04 | 0.658±0.060 | 9.83±0.10 | 16.5±3.0 | 13.4 |

experimental data.

## 2. Experimental

The numerical data of the measured samples are listed in Table 1. The graphite and bismuth were both cut from synthetic material of a high quality (~99.99%). The concentration of magnetic impurity ions were below 1 ppm for both samples, according to magnetic and chemical analysis carried out in previous studies (Uyeda *et al.*, 2010). The published $\chi_{\mathrm{DIA}}$ values of the three materials are also listed in Table 1 (Guputa, 1983). Of these, graphite has the largest published $\chi_{\mathrm{DIA}}$, which is $5 \times 10^{-6}$ emu/g, whereas the published $\chi_{\mathrm{DIA}}$ of bismuth is $9.0 \times 10^{-7}$ emu/g, which is an order of magnitude smaller (Guputa, 1983). The data of graphite and bismuth observed in a previous report are listed in the table (Hisayoshi *et al.*, 2011).

The $\mu$G condition was generated by a drop shaft that had a length of 1.5 m: It was designed and constructed at the Graduate School of Science, Osaka University. The drop box had a rectangular shape with an inner size of 35 cm × 30 cm × 20 cm. The experimental setup developed to observe the magnetic ejection was installed inside the box. The setup consisted of a cylindrical Pyrex vacuum chamber coupled with a mobile sample-holder, a sample-holder controller, an IR signal receptor to operate the controller, a compact magnetic circuit and a high-vision (HV) video camera (Panasonic HDC -SD3-S). The compact magnetic circuit was assembled from a couple of Nd-Fe-B magnetic plates of size 2.5 cm × 2.0 cm × 0.6 cm. By adopting this magnetic circuit, a size reduction of the drop box became possible (Hisayoshi *et al.*, 2011).

In order to describe the time-dependent position of the sample, $x$, $y$, $z$-coordinates are defined in the area of the field gradient. The field center of the attached circuit was defined as the origin of the co-ordinates. The $y$-axis of the coordinates was directed from the N pole to the S pole of the circuit, whereas the $x$-axis was parallel to the cylindrical axis of the vacuum chamber: The samples were expected to translate along the $x$-axis. The field distribution along the $x$-axis was measured prior to the experiment with a spatial division of 0.1 cm. The field intensity was equal to zero at a position of $x_{\mathrm{R}} = 1.87 \pm 0.05$ cm, since the magnetic line of force turned from the $[+y]$ to $[-y]$ direction at this position. The experiment of magnetic ejection using the chamber-type $\mu$G generator was realized by the development of the small magnetic circuit. The initial sample position is defined as $x_0$ for each sample. The field intensity at $x = x_0$ is defined as $B_0$. According to the measured field distribution, the position of $x_0$ is in an area of negative field gradient ($dB/dx < 0$). The numerical values of $x_0$ and $B_0$ are listed in Table 1.

The drop box was attached to the ceiling of the laboratory room by an electromagnetic lock system. The free fall of the box started shortly after the power supply of the lock was switched off. The duration of $\mu$G was 0.4 seconds. After a duration of 0.05 seconds from the beginning of $\mu$G, the sample was released from the sample holder in a gas medium that was contained in the vacuum chamber. The diffused condition of the medium to minimize viscous drag was realized by reducing the gas pressure to ~100 Pa. The reduced pressure was also effective in minimizing turbulence caused by the fast movement of the sample holder. The movement of the sample along the $x$-axis was observed by the HV video camera from the $[+z]$ direction. The time and spatial resolutions of the HV video camera were 0.033 s and 0.004 cm, respectively. Prior to the experiment using the chamber-type $\mu$G drop shaft, an operational test of the above-mentioned setup to observe the ejection was performed in a conventional drop shaft at the National Institute of Advanced Technology (AIST) which had a $\mu$G duration of 1.35 seconds; the gravitational acceleration was 1 Gal. It was confirmed that the image of the translation was successfully recorded within 0.4 second, which was the $\mu$G duration of the chamber-type system (gravitational acceleration was 30 Gal at after-fall 0.3 seconds).

## 3. Results and Discussions

The observed magnetic ejections of mm-sized diamagnetic grains were previously analyzed by an energy conservation rule between kinetic energy and field-induced potential. The $\chi_{\mathrm{DIA}}$ values obtained from the relationship between sample velocity and field intensity, measured at different sample positions, agreed fairly well with their published values for some popular diamagnetic materials (see Fig. 2) (Uyeda *et al.*, 2010).

Time variations of sample positions of the sub-millimeter-sized grains measured in the present study are shown in Fig. 1. As expected for diamagnetic materials, the grains of polyethylene-1 in the direction of the monotonously decreasing field ($x$-axis). Velocity at $x_{\mathrm{R}}$ was $v_{\mathrm{R}} = 5.62$ cm/s for polyethylene-1. The $\chi_{\mathrm{DIA}}$ values are calculated with the above-mentioned relationship $v(x_{\mathrm{R}})^2 = \chi_{\mathrm{DIA}} B_0^2$. The $\chi_{\mathrm{DIA}}$ values obtained from the above relationship are compiled in Table 1 and Fig. 2 for the three

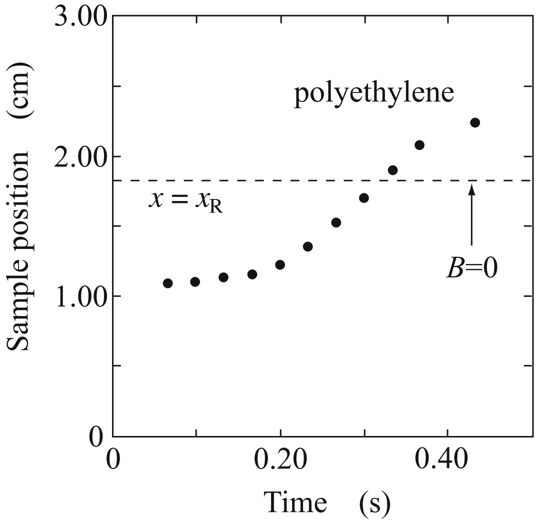

Fig. 1. Time variation of sample position measured for a sub-millimeter-sized sample of polyethylene-1 (in Table 1). The sample was released at $t = 0$. The values of $x$ were determined by a scale that was attached along the $x$-axis. The images of the scale and the sample were recorded by a high-vision camera. A line $x = x_R$ denotes the position where $B = 0$. The measured distribution of magnetic field along the $x$-axis is shown in the figure (Hisayoshi *et al.*, 2011).

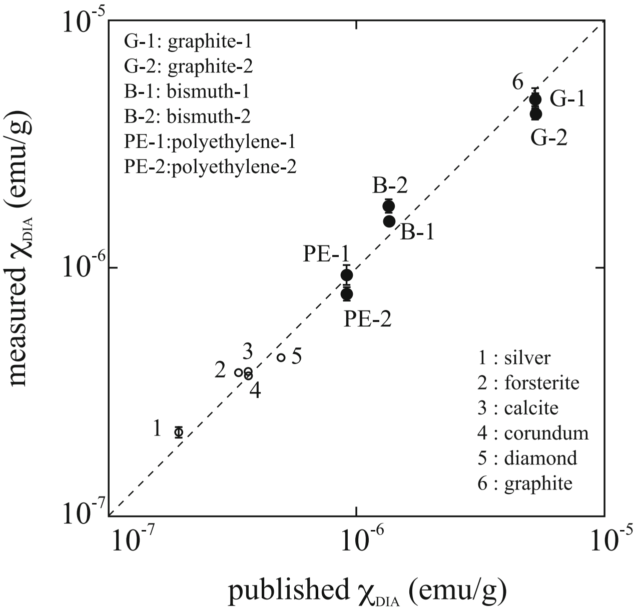

Fig. 2. Relationship between measured and published diamagnetic susceptibility of graphite (G-1, 2), bismuth (B-1, 2), and polyethylene (PE-1, 2) measured in the present study. The values are also compared in Table 1. Results of previous measurements on mm-sized samples are shown by open circles (Uyeda *et al.*, 2010). Published values of real materials range from about $1 \times 10^{-7}$ to $5 \times 10^{-6}$ emu/g (Guputa, 1983).

materials. It is seen that measured values agree fairly well with their published values. The reduction of sample velocity due to gas friction is estimated to cause an error of about 3% in the obtained $\chi_{\rm DIA}$ values. It is confirmed from Table 1 that no significant tendency of mass dependence is seen for the $\chi_{\rm DIA}$ values, between two different samples composed of the same material. According to Fig. 2, the range of $\chi_{\rm DIA}$ observed in the present study almost coincides with the range of published $\chi_{\rm DIA}$ values compiled in a data book (Guputa, 1983). It may be considered, therefore, that material identification is possible for a sub-millimeter-sized solid, in general, by observing the magnetic ejection.

It was pointed out that the $\chi_{\rm DIA}$ measurement based on the above-mentioned magnetic ejection is free of a background signal of the sample holder; it is also free of a mass measurement of the sample (Uyeda *et al.*, 2010). In the conventional method, the minimum size of a measurable sample was limited by the above-mentioned two factors. This means that, in principle, magnetic susceptibility is obtained on samples of a limitlessly small size, as long as the motion of the sample can be detected. The lower limit of the sample size may reach several microns by introducing an optical microscope in the drop box. Accordingly, the identification of an individual grain, based on the above $\chi_{\rm DIA}$ measurements, will become possible for a micron-size particle.

As mentioned before, a non-destructive method to identify the material of a single particle without destroying the sample is desired at the first stage of analyzing primitive grains. Up to now, such a method has not been established. The present results achieved on sub-millimetre-sized diamagnetic grain have a large significance as a step to realize the identification of micron-sized grains that compose the primitive materials. The technique described is useful in the search for new types of pre-solar grains that are as yet identified.

## 4. Conclusions

(1) In $\mu$G conditions, field-induced translation is commonly expected to occur on a single sub-millimeter-sized solid. The translation is independent of the mass of the particle because the field gradient force is a volume force that is derived from the localized electrons of individual atoms. A field-induced translation of an ordinary solid, free of spontaneous moment, has not been previously recognized.

(2) In a given field distribution, the induced velocities are determined by the value of $\chi_{\rm DIA}$. The value of $\chi_{\rm DIA}$ is obtained for a limitlessly small grain, provided that its motion is observable. The present size of observable size is 100 $\mu$m. Material of a single sub-millimeter-sized particle is expected to be identified non-destructively, simply by observing the translation. This is because a material generally possesses an intrinsic $\chi_{\rm DIA}$ value.

(3) The field-induced motion is observable using a chamber-type $\mu$G generator, which was realized by introducing small Nd-Fe-B plates. The material identification of a single grain that composes primitive materials becomes possible by a routine process that can be performed in an ordinary laboratory. Such non-destructive identification is important as a primary stage of refined analysis on various samples.

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