Magnetization measurement of a solid CO₂ grain based on its field-induced translation under microgravity conditions

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Abstract. Diamagnetic susceptibility χ_DIA per unit mass was obtained in a dry-ice (CO₂) grain using a simple method in which translation of the grain induced by a field-gradient force was observed in an area of T =196 K using a short-microgravity (μg) condition. It was not necessary to know the value of the sample mass m in the measurement because the field-gradient force induced in the sample was proportional to m. The proposed method is hence effective in measuring χ of a small volatile grain that would require additional operations to obtain its m value. By comparing the obtained χ_DIA value with a list of published values, the material of an unidentified volatile grain can be determined in a simple manner without consuming the sample.

1. Introduction
The spatial variation of the field-induced potential that is produced by a static electromagnet has been conventionally used in a magnetic balance to measure the magnetization of a material. Diamagnetic susceptibility χ_DIA was recently detected in small samples based on the translation in a fluid medium due to the effect of a large field gradient at a level of ~10⁴ Oe/cm [1][2]. This translation proceeded under the balance between the field-gradient force and the viscous drag of the medium. Acceleration of diamagnetic solids caused by a field-gradient force [3][4] was recently observed in a diffuse area using a short μg condition (< 0.6 s); here, the field gradient was produced by a centimetre-size magnetic circuit and [emu/g] was obtained from this translation without knowing the value of the mass m. This was possible because in this translation, the variance of the field-induced potential between two arbitrary sample positions was completely converted to kinetic energy. In general, magnetization measurement of a weak magnetic material becomes more difficult with the reduction of sample size because of the difficulty in measuring m. Additionally, the interference of background signals emitted from the sample holder is not negligible when the sample size is at the sub-millimetre level. Hence, the above-mentioned method based on field-induced translation could be a breakthrough in solving these two problems [4], although currently the field-induced translation is realized only at room temperature.

In this report, the efficiency of the detection of χ_DIA by the field-induced acceleration is examined at a reduced temperature of T=196 K. Based on the results obtained on the CO₂ grains, the remaining problems in measuring the magnetic properties of single volatile materials of reduced sizes are considered.

2. Experimental Methods
The field gradient used in the present study was produced by a compact magnetic circuit composed of a pair of NeFeB plates, as shown in Fig. 1. The [+z]-axis of a coordinate was defined as the direction of the magnetic line of force produced between the N pole and S pole of the circuit, and the [+x]-axis was defined as the direction in which the gradient of the monotone-decreasing field is largest.
A solid CO$_2$ block was separated into small sample pieces with diameters of less than 1 mm, and the sample pieces were placed at a point where the field-gradient force was expected to attain its maximum value, according to field-distribution measurements. At this position, the sample pieces were expected to be spontaneously released in the area of monotone-decreasing field due to the field-gradient force. The sample, together with the magnetic circuit, was contained in a two-fold glass tube, which was used to maintain the cryogenic conditions; in the present experiment, the interior of the tube was filled with dry ice blocks to keep the experimental area at $T=196\pm1$ K.

Translational motions of the samples were recorded by a high-speed camera (CASIO EX-F1), which could observe the sample motions with a spatial resolution of 0.004 cm and a time resolution of 0.033 fps. The camera was set outside the transparent glass tube.

As the capsule descends, the residual gravity caused by air resistance is expected to increase inside the capsule. Therefore, a two-fold box system was introduced in the present experiment. Specifically, the (inner) drop box is enclosed by an exterior box composed of cardboard. Immediately after the release of this two-fold box, the samples were released into the $\mu g$ environment and translated in the $[+x]$ direction by the field-gradient force.

### 3. Results and Discussion

For a diamagnetic particle that is translating in an area of monotone-decreasing field, the sum of the kinetic energy and the field-induced potential is conserved, and $\chi_{DIA}$ of the of the translating particle is described as

$$\chi_{DIA} = \frac{v_T^2}{B_0^2},$$

where $B_0$ denotes the field intensity at the initial position, and $v_T$ denotes the terminal velocity in the area of $B=0$. The conservation rule was adopted in the analyses of the field-induced translation in the previous studies [3][4].

An example of a field-induced translation observed in a CO$_2$ grain is shown in Fig. 2 as a sequence of photographs. It is confirmed by the experiments that by using the method adopted for the proposed apparatus, the acceleration of a volatile solid released in an area of monotone-decreasing field is observable under reduced-temperature conditions. Using the two-fold capsule, the samples reached the area of $B=0$ with the terminal velocity that was expected from the above-mentioned energy conservation rule. When the single capsule was used in the experiment, the residual gravitation in the setup gradually increased, and the maximum velocity was only 70–80% of the expected $v_T$ value.

As shown in Table 1, the experimental $\chi_{DIA}$ values of the three materials agreed fairly well with the published values, which indicates that the proposed method for detecting $\chi_{DIA}$ is successful at $T=196$ K. The deviations of the measured $\chi_{DIA}$ values from the published values are attributed to the attachment of some micro-sized magnetic contamination on the sample. The $\chi_{DIA}$ value of the translating particle is simply obtained by inserting the numerical $v_T$ and $B_0$ values into the above equation without measuring $m$. As mentioned before, this is possible because the field-gradient force that is induced in a particle is proportional to $m$. Accordingly, the method has an advantage in the measurement of volatile solids in general; if the volatile grains sublimate at room temperature, the measurement of the grain mass $m$ will require some additional treatment compared to the refractory grains. It is expected that the principle of the present system for detecting $\chi$ will be operational at lower temperatures, and it can be applied in observing the field-induced translation of other volatile grains, for example, CO, CH$_4$, and N$_2$.

To realize the non-destructive material identification using the $\chi_{DIA}$ measurement as previously proposed [4], the precision of the $\chi_{DIA}$ values should be improved to the standard level; i.e., the values should be obtained by three orders of magnitude. This can be achieved by reducing the erratic
reading of the scale recorded in the images of the translation. It is also important to extend the \( \mu \)g duration so that a translating sample with a small \( \chi_{\text{DIA}} \) value can reach its terminal velocity. These technical improvements are now in progress for measuring the CO\(_2\) grains as well as the solid H\(_2\)O grains.

**References**

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**Figure 1.** Schematic view of an apparatus for observing field-induced translation of a volatile particle of sub-millimetre size.
Figure 2. Visual images of translational motion of a CO$_2$ particle. The field decreases monotonously in the direction of the +x-axis. The images are arranged in sequence of time from left to right; the time interval between the images is 1/30 s.

Table 1. Numerical data of graphite, bismuth and CO$_2$ measured in the present study.

| Material | mass [g] | measured $\chi_{\text{DIA}}$ [x10^{-7}emu/g] | published $\chi_{\text{DIA}}$ [x10^{-7}emu/g] [5] |
|----------|---------|---------------------------------|---------------------------------|
| Graphite | 0.8x10^{-3} | -54±5 | -52 |
| Bismuth  | 2.7x10^{-3} | -17±1 | -16 |
| CO$_2$   | 4.8x10^{-3} | -4.8±1.2 | -4.7 |
| CO$_2$   | 2.4x10^{-3} | -5.8±1.4 | -4.7 |