Magnetization of a Single Carbonaceous Grain Obtained by Field-Induced Acceleration

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Abstract. Diamagnetic susceptibility $\chi_{\text{DIA}}$ of single carbonaceous grains were detected by observing their translations induced by field-gradient force in an area of microgravity. Using the above method, $\chi_{\text{DIA}}$ of a small carbonaceous particle is obtained with no interfering signal of the sample holder; it is unnecessary to know the mass of sample. The $\chi_{\text{DIA}}$ values of various materials obtained by the above method agreed fairly well with their published values. By comparing the obtained $\chi_{\text{DIA}}$ value with a list of published values, the material of an unidentified organic grain can be determined without consuming the sample. The principle of magnetic transition is applicable to investigate the magnetic properties of nano-size carbonaceous materials.

1. Introduction

The Magnetization of a weak magnetic material becomes difficult to measure with the reduction of sample size because of the following two reasons. First of all, it is difficult to know the precise mass of a sample which has reduced sizes. Secondly, the interference of background signals emitted from the sample holder is not negligible when sample size is at sub-mm level. The above 2 difficulties was successively avoided by observing an acceleration of sample caused by a field gradient force produced by a permanent magnet [1], [2]; here the sample translated through a diffused area within a short duration of microgravity condition (~ 0.5 s). Diamagnetic susceptibility $\chi_{\text{DIA}}$ was obtained from the above translation without knowing the value of sample mass, because variation of field-induced potential between two sample positions was completely converted to kinetic energy. The mass independent property of the translation was observed because the motion was caused by a volume force. Up to now, the above-mentioned measurement of $\chi_{\text{DIA}}$ has been performed only on inorganic materials.

The difference of magnetic potential has been conventionally used in a “Faraday method” to measure magnetization. Magnetic susceptibility of small samples were recently detected by observing their translation caused by a large field-gradient at a level of ~1T/cm [3], [4]. These experiments were performed in terrestrial gravity, and sample motion was affected by a viscous drag of the medium. It is not widely recognized that dynamic motion of ordinary diamagnetic solid is caused by a small potential of permanent magnet. Various dynamical effects that were reported on weak magnetic materials required a strong magnetic field at a level of 10 Tesla [5].
In the present report, efficiency to detect $\chi_{\text{Dia}}$ by the field-induced acceleration is examined for several carbonaceous materials. Based on the obtained results, various advantages are considered in clarifying the magnetic properties of single organic materials having reduced sizes.

2. Procedure
The field gradient used in the present study was produced by a compact magnetic circuit composed of a pair of NeFeB plates [2]. The direction of magnetic line of force produced between the N pole to S pole of the circuit was defined as a [+]z-axis of a co-ordinate, and a direction which had the largest gradient of monotone decreasing field was defined as a [+]x-axis. The field centre of the circuit was defined as the origin of the co-ordinate ($B = 0.65$ T at field centre). Sub-mm size crystals of 4 carbonaceous materials, namely graphite, diamond, coronene and naphthacene were prepared for observing the field-induced translation. The weight of the samples are listed in Table I along with their published $\chi_{\text{Dia}}$ values [6]. The crystals were placed on a sample stage that was located in the area of monotone decreasing field along the x-axis. In order to realize the diffused condition of the translating sample, the above was enclosed in a glass tube, and inner pressure of the tube was reduced to 30Pa. A short $\mu$g condition (duration ~ 0.5 s) was produced in a compact drop capsule, which was operated in a shaft of 1.5 m in length. Shortly after $\mu$g was achieved, the sample stage was rapidly removed from its initial position in the [-z]-direction. The rapid motion of stage was necessary to minimize the initial momentum of the released sample, which was essential for precise measurement of the sample translation. The reduction of medium pressure was effective as well to diminish the turbulence cause by the fast motion of the sample stage. The translation of the samples were observed from the [-y]-direction 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.

3. Results and Discussion
Time dependent images of a coronene crystal are shown in Fig.1. It is seen that the sample is accelerated in the direction of decreasing field. Similar accelerations were observed for other 3 materials. As described before, a field-induced translation was expected to follow a conservation rule considered for a magnetic potential and a kinetic energy [2]. Specifically, the energy conservation of a particle between two arbitrary positions, namely $x_1$ and $x_2$ located along the x-axis, is described as,

$$\frac{1}{2}m\chi_{\text{Dia}}B_1^2 + \frac{1}{2}mv_1^2 = \frac{1}{2}m\chi_{\text{Dia}}B_2^2 + \frac{1}{2}m_{2}v_2^2. \quad (1)$$

Here field intensity at positions $x_1$ and $x_2$ are defined as $B_1$ and $B_2$, respectively; $v_1$ and $v_2$ denote the sample velocities at $x_1$ and $x_2$, respectively. In order to examine the linear relationship between $v_2^2 - v_1^2$ and $B_2^2 - B_1^2$ that is deduced from the above equation [2], about 10 sets of $v(x)$ and $B(x)$ values at different sample positions were obtained from the time-dependent images as described in Fig.1; the field intensity along the x-axis was measured before performing the translation experiments. Using the above-mentioned data sets of [$v(x)$, $B(x)$], the relationships between $v_2^2 - v_1^2$ and $B_2^2 - B_1^2$ were examined, and the linear correlations as expected in eq.(1) were reproduced in the 4 materials. According to eq.(1), the gradient of the above linear correlation is equivalent to $\chi_{\text{Dia}}$ of the translating particle. As seen in Table I and Fig.2, the experimental $\chi_{\text{Dia}}$ values obtained from the observed linear correlations agreed fairly well with the published values [6]. Errors of the experimental $\chi_{\text{Dia}}$ values are estimated from the standard deviation of the linear regression that was observed between $v_2^2 - v_1^2$ and $B_2^2 - B_1^2$.

The above consistencies between experimental and published values indicate that the method of measuring $\chi_{\text{Dia}}$ based on field-induced translation is approved for an organic material. The deviations
of the measured $\chi_{\text{DIA}}$ are attributed to an attachment of some small paramagnetic particle on the sample. Currently, the spatial resolution of the proposed method in observing the translating sample is about 20μm, which is determined by the resolution of the high-speed camera; this resolution gives the present sensitivity limits in sample size. Note that, in principle, $\chi_{\text{DIA}}$ measurement based on eq.(1) is possible if the field-induced translation of the sample is observable; here it is unnecessary to know the $m$ value. Hence, in a future study, $\chi_{\text{DIA}}$ of a μ m-size sample can be measured by installing an optical microscope in the system. The sensitivity of $\chi_{\text{DIA}}$ is improved by reducing the field gradient and by increasing the μ g duration, which is necessary to collect sufficient number of $[v(x), B(x)]$ data.

As mentioned before, the field-induced translation was previously performed for inorganic materials. According to a data book on diamagnetism, their $\chi_{\text{DIA}}$ values are usually smaller than 5x10⁻⁷ emu/g, whereas most of the $\chi_{\text{DIA}}$ values reported for organic materials range between 4.5 to 50x10⁻⁷ emu/g [6]. Therefore the field-induced translation may serve as a simple method to distinguish an organic grain from an inorganic grain, when they are included in an ensemble of heterogeneous particles. Furthermore, by comparing the $\chi_{\text{DIA}}$ value obtained by translation with the list of published values, the material of an unidentified organic grain can be determined without consuming the grain. In studying the property of an individual particle, it is desirable to identify the material of the grain by a non-destructive and simple method.

![Figure 1](image.jpg)

**Figure 1.** Visual images of translational motion of coronene particle. Field decreases monotonously [x]-direction. The images are arranged in the sequence of time from top to bottom. Time interval between the images are 0.01sec.
Figure 2. Relationship between measured and published diamagnetic susceptibilities.

Table 1. Numerical parameters of the carbonaceous material measured in the present study. The experimental \( \chi_{\text{DIA}} \) values were obtained by inserting the measured values is eq.(1). The errors are derived from the standard deviation of the regression.

| Material    | mass [g] | measured \( \chi_{\text{DIA}} \) [x10\(^{-7}\)emu/g] | published \( \chi_{\text{DIA}} \) [x10\(^{-7}\)emu/g] |
|-------------|----------|-----------------------------------------------------|-----------------------------------------------------|
| Graphite    | C        | 4.7\( \times \)10\(^{-6}\)                        | -47\( \pm \)5                                       |
| Diamond     | C        | 0.07                                               | -4.4\( \pm \)0.1                                   |
| Coronene    | C\(_{24}\)H\(_{12}\) | 5.8\( \times \)10\(^{-6}\) | -9.1\( \pm \)1.2                                  |
| Naphthacene | C\(_{18}\)H\(_{12}\) | 2.3\( \times \)10\(^{-5}\) | -6.6\( \pm \)0.2                                  |

The degree of unsaturation can be estimated from the \( \chi_{\text{DIA}} \) value of an organic grain, when its chemical composition is unknown. This is because an intrinsic \( \chi_{\text{DIA}} \) value of an organic molecule is nearly equivalent to a simple sum of diamagnetic susceptibility assigned to individual chemical bonds such as the C-H, C-C, C=C as well as the C≡C bonds [6].

Precise \( \chi_{\text{DIA}} \) data of single organic crystals may provide quantitative information on the distortion of crystal structure in the nano-size region [2]. This is because diamagnetic magnetization is directly related to the 3-dementional configuration of electron orbital in the crystal; the \( \Delta \chi_{\text{DIA}} \) values of organic crystals were explained in terms of a molecular- orbital method [7]. The degree of the above distortion is considered to increase with reduction of particle size. Necessity clarifying the structure of a single nano-sized organic particle is increasing in both industrial and fundamental researches.

References
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