Diamagnetic Susceptibility of Single Micro-Particles Detected by Free Translational Motions in Field Gradient

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Abstract. Free translational motion of a solid particle from magnetic-field centre, caused by a repulsive force due to field gradient \(\frac{dB}{dx}\), was observed in microgravity \(\mu G\) with negligible effect of viscous drag. The translation was visually obtained for Rochelle salt and silicon carbide and corundum. Acceleration \(a\) was obtained for corundum by use of a high vision camera, and it was experimentally confirmed that diamagnetic susceptibility \(\chi_{\text{DIA}}\) per unit mass of the particle was described as proportional to \(a\). By using this method, \(\chi_{\text{DIA}}\) of small particle becomes measurable since the new method does not require a sample holder.

1. Introduction
Necessity of detecting magnetic properties of a single particle has increased recently, in connection with the growing interest on nano-sized materials [1]. Diamagnetic susceptibility \(\chi_{\text{DIA}}\) of small particles were detected recently by introducing large field gradient [1, 2]. Magnetic levitation of diamagnetic materials caused by field-gradient force was realized in strong field above 10 Tesla [3-6]. The above-mentioned effects were all observed in normal gravity in a presence of viscous drag. Field gradient force has been conventionally used in separating particles that possess ferromagnetic or paramagnetic susceptibility.

Free translational motion has been recently observed for a diamagnetic sample released in microgravity \(\mu G\) [7]. The sample was ejected from field center the motion in a course of observing field-induced rotational-oscillation of mm-sized sample; diamagnetic anisotropy \(\Delta\chi_{\text{DIA}}\) of mm-sized sample was obtained with high sensitivity from period of the above oscillation. It is expected that \(\chi_{\text{DIA}}\) of a small particle can be obtained from acceleration \(a\) of the above translation, provided that spatial field-distribution is known. In the present report, possibility of detecting \(\chi_{\text{DIA}}\) on micron-sized particles is discussed based on observed results on mm-sized samples. \(\chi_{\text{DIA}}\) and \(\Delta\chi_{\text{DIA}}\) values are not obtained as yet for most of the inorganic materials. It is important to compile these values, since they are basic parameters that characterize various magnetic field effects that are recently reported on diamagnetic materials [8].

2. Experimental
Motion of translation from field center was observed for mm-sized crystals of Rochelle salt, silicon carbide and corundum that were released in microgravity. An apparatus that was newly developed to observe translation is shown in Fig.1, which is based on a system previously developed to measure magnetic anisotropy [7]. The system was composed of a permanent dipole magnet (NEOMAX X-
1466) which can produce a homogeneous field of $B = 1.18T$ in a spherical region of $1.5 \times 10^{-2} \text{ m}$ in diameter at center of pole pieces. Radial direction of dipole is defined hereafter as $x$-axis, whereas an axial direction (direction between the poles) is defined as $z$-axis; field centre is identical to origin. Spatial distribution of field intensity along $x$-axis was measured prior to transition experiment. Field intensity reduces monotonously along $\pm x$-axis.

Crystal samples were placed on a mobile sample stage, at a position just out side above-mentioned homogeneous field along $x$-axis ($x = 1.73 \text{ cm}$) as described in figure 1. Experiment was performed in a reduced pressure of 10 Pa, in order to exclude viscous drag of the gas. The apparatus was loaded on a drop capsule at a $\mu G$ facility; the $\mu G$ experiments were performed at two facilities, namely at Micro Gravity Laboratory of Japan (MGLAB, Toki, Gifu, Japan) and at National Institute of Advanced Industrial Science and Technology, AIST, (Sapporo, Hokkaido, Japan). Duration of $\mu G$ at MGLAB was 4.5 s with remaining gravitational acceleration of $2.0 \times 10^{-5}$ Gal [9]. At AIST, the duration was 1.3s with remaining gravitational acceleration of $5.0 \times 10^{-3}$ Gal [10]. The stage was removed from its initial position with high velocity (~ 0.4 m/s) shortly after achievement of microgravity (~ $5 \times 10^{-3}$ s) following a procedure used in previous studies [7, 11]; this procedure was effective to minimize initial velocity of sample. Measured samples were synthetic single-crystals and their sizes were about $2 \times 2 \times 2 \text{ mm}^3$. Concentration of magnetic ion was below 1ppm for all samples according to magnetic and chemical analyses. Increase of $\chi$ value caused by paramagnetic susceptibility is below $10^{-9} \text{ emu/g}$ when 1ppm of magnetic ion is contained in a diamagnetic oxide. The translational motion of sample was visually observed using a video camera from a direction of $x$-axis and $z$-axis. In case of corundum, value of acceleration $a$ was analyzed with static images transformed from moving images recorded by hi-vision video camera. The spatial resolution of static images was 0.08mm and the time resolution between static images was $1/29.97$ sec. The above resolution gives the upper limit of $\chi_{DIA}$ sensitivity, since $\chi_{DIA}$ is dependent on value of $a$ obtained from the static images.

3. Results and Discussion
Examples of observed translations are shown in figure 2 for the three samples. It is seen that diamagnetic samples are accelerated by field gradient as expected. In a free space with negligibly
small effects of gravity and viscosity, acceleration \( a \) is described as \( ma = \text{grad} \left( \frac{1}{2} m \chi_{\text{DIA}} B^2 \right) \) for diamagnetic particle of mass \( m \). Accordingly \( \chi_{\text{DIA}} \) is described as

\[
a = \chi_{\text{DIA}} \left( \frac{dB}{dx} \right) B
\]

\( \chi_{\text{DIA}} \) of the particle is obtained by inserting measured values of \( a \), \( B \) and \( dB/dx \) in the above equation.

Efficiency of the above method to obtain \( \chi_{\text{DIA}} \) was quantitatively examined using numerical relationship between \( a \) and \( (dB/dx)B \) observed for corundum. \( \chi_{\text{DIA}} \) was obtained from gradient of a regression line of eq.(1) based on 11 sets of \([a, (dB/dx)B]\) data as described in figure 3. Numerical values of \( a \), \( B \) and \( dB/dx \) used in the calculation are listed in Table 1. Correlation coefficient of between experimental data and regression lines using least-squares method was 9.7, which indicate that the observed translation is consistent with eq.(1) for corundum. Obtained \( \chi \) value is \(-2.64 \pm 0.03\) x10\(^{-7}\) emu/g which is rather small compared to a published value of corundum which is \(-3.63\times10^{-7}\) emu/g; the deviation between measured and published \( \chi_{\text{DIA}} \) may derive from a paramagnetic impurity grain that is accidentally attached to crystal during sample setting. In order to examine the generality of the relationship described in eq.(1), the above-mentioned experiment should be performed on many diamagnetic materials with different \( \chi \) values, and in different field distributions. According to quantitative evaluations based on eq.(1) as well as on size of experimental area, it is expected that the new method is capable of detecting \( \chi_{\text{DIA}} \) between 1x10\(^{-7}\) and 1x10\(^{-5}\) emu/g in microgravity with

\[\text{Figure 2. Visual image of translational motion of (a) Rochelle salt, (b) silicon carbide and (c) corundum. The images are arranged in the order time from left to right; time intervals between the images are (a) 0.167sec, (b) and (c) 0.334sec. Length of scale bar is 1cm in (b) and (c). Magnetic field is applied in the vertical direction in all the figures. Upper side of the images is } B = 0. \text{ High vision images were recorded only for corundum; acceleration } a \text{ is obtained from these images.}\]
Figure 3. Relationship between acceleration $a$ and $(dB/dx)B$ for corundum. Error bar of acceleration derives from measurement of position.

Table 1. Numerical data measured for corundum.

| position$^a$ (cm) | acceleration $a$ (cm/s$^2$) | $B$ (G)   | $dB/dx$ (G/cm) | $\chi^D_{DA}$ (x10$^{-7}$ emu/g) |
|-------------------|----------------------------|-----------|----------------|----------------------------------|
| 2.19              | 3.4                        | 11068.2   | -1182          | -2.63                            |
| 2.22              | 3.9                        | 11026.3   | -1339          | -2.66                            |
| 2.31              | 4.2                        | 10888.8   | -1464          | -2.64                            |
| 2.35              | 4.5                        | 10835.6   | -1702          | -2.44                            |
| 2.40              | 4.9                        | 10742.4   | -1703          | -2.69                            |
| 2.46              | 5.3                        | 10632.7   | -2003          | -2.47                            |
| 2.49              | 6.0                        | 10554.4   | -2003          | -2.86                            |
| 2.57              | 6.1                        | 10392.5   | -2301          | -2.55                            |
| 2.63              | 6.7                        | 10237.8   | -2473          | -2.66                            |
| 2.71              | 7.3                        | 10027.9   | -2684          | -2.71                            |
| 2.78              | 7.9                        | 9818.5    | -2975          | -2.69                            |

$^a$ Distance from the centre of magnetic field along x-axis (see text).
duration of 4.5s. According to a Pascal rule, $\chi_{\text{DIA}}$ of a material is approximately equivalent to sum of diamagnetic susceptibility numerically assigned to individual atoms. An approximate $\chi_{\text{DIA}}$ value of unmeasured material is predicted from this rule; most of the calculated values are within the above-mentioned range. Sensitivity of susceptibility measurement in a conventional SQUID method is $10^{-8}$ emu. In contrast, this new method has sensitivity of $10^{-10}$ emu.

Lower limit of spatial resolution is improved to a level of an optical microscope for observing the above-mentioned translation. Hence $\chi_{\text{DIA}}$ becomes measurable on micron-sized sample. According to preliminary experiments in $\mu$G, a diamagnetic sample translate along a rigid pass having minimum magnetic potential. Hence motions of particle may be observed by a microscope with shallow focus depth. Field induced translational motion of micron-sized particle dispersed in fluid has been observed by an optical microscope. [1].

4. Conclusion
Detection of $\chi_{\text{DIA}}$ becomes possible on micron-sized sample by observing acceleration of free translation in field gradient as described in eq.(1). This is because the new method is free of a sample holder, and the observed motion is caused only by magnetic force; conventional magnetization measurements in normal gravity are generally prevented by background signal of sample holder when size of sample is smaller than 1mm in diameter.

References
[1] Suwa M and Watarai H 2002 *Anal. Chem* 74 5027-5032
[2] Tanimoto Y, Fujiwara M, Sueda M, Inoue K and Akita M 2005 *Japan. J. Appl. Phys.* 44 6801-6803
[3] Brant E H 1989 *Science* 243 349-355
[4] Beaugnon E and Tournier R 1991 *Nature* 349 470
[5] Berry M V and Geim A K 1997 *Eur. J. Phys.* 18 307-313
[6] Kitamura N, Makihara M, Sato T, Hamai M, Mogi I, Awaji S, Watanabe K, Motokawa M 2001 *J. Non-Crystalline Solids* 293-295 624-629
[7] Uyeda C, Mamiya M, Takashima R, Abe T, Nagai H and Okutani T 2006 *Japan. J. Appl. Phys.* 45 L124-127
[8] Various papers appering in Proc. Int. Symp. New Magneto-Sci. Tsukuba 1999 Jpn. Sci. and Tech. Corp., NIMS
[9] Iwakami T 2005 Proc. 7th Drop Tower Days (Berlin) p 137
[10] Okutani T, Minagawa H, Nagai H, Nakata Y, Ito Y, Tsurue T and Ikezawa K 1999 *Ceram.Eng.Sci.Proc.* 20 215
[11] Uyeda C, Tanaka K and Takashima R 2003 *Japan. J. Appl. Phys.* 42 L1226