Attempt to Improve Sensitivity in Measuring Diamagnetic Anisotropy by Increasing Duration of Rotational Oscillation in Microgravity

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Abstract. Technical basis to detect small diamagnetic anisotropy $\Delta \chi_{\text{DIA}}$ is established in a method using microgravity $\mu G$. Sensitivity of $\Delta \chi$ can be improved by increasing length of measurable period of rotational oscillation of magnetically stable axis with respect to field direction. In order to achieve the above condition, position of the diamagnetic sample should be stabilized in static field area, which was realized by introducing a magnetic circuit with high field homogeneity. Function of a mobile sample stage was effective in minimizing translational motion of sample. Accordingly, magnitude of measurable anisotropy may be decreased to a level of $10^{-10}$ emu/g. $\Delta \chi_{\text{DIA}}$ of materials with high crystal symmetry, namely hexagonal ice, ZnO, SiC and BaTiO$_3$, can be obtained by the above improvement. Magnetically active property due to magnetic anisotropy may be recognized for almost all the solid materials when sensitivity reaches the above level.

1. Introduction

Property of conventional magnet has been commonly recognized by rotational motion of a compass caused by terrestrial field. Similar oscillation was reported recently on a number of ordinary solids free of spontaneous moment at a low field of a hand magnet \cite{1}; the oscillation was observed for popular materials such as biotite, calcite, forsterite, graphite, gypsum or orthoclase. The results indicate that many of the ordinary solid are magnetically active at practical low field without a use of high-costing superconducting magnet, in contrary to a common recognition. The rotation is caused by anisotropy of magnetic susceptibility $\Delta \chi$, which is generally expressed as sum of diamagnetic anisotropy $\Delta \chi_{\text{DIA}}$ and paramagnetic anisotropy $\Delta \chi_{\text{PARA}}$ \cite{2}; $\Delta \chi_{\text{DIA}}$ originates form anisotropy of localized electron distribution, whereas $\Delta \chi_{\text{PARA}}$ is derived form magnetic impurity ion contained in crystal. It is essential to study the origin of $\Delta \chi$ at atomic level in order to design an industrial process in producing a functional material; from a practical point of view, it is desirable that such process is achieved at a low field intensity\cite{3,4}.

A model was proposed to explain the origin of published $\Delta \chi_{\text{DIA}}$ recently compiled for oxide crystals with various structures\cite{5}. In the model, an uniaxial anisotropy $\Delta \chi_{\text{BD}}$ was assigned to individual bonding orbital with the bond direction being assumed as a magnetically unstable axis. This assignment was compatible with spatial distribution of orbital. The above model was consistent with published values of
various oxides provided that $\Delta \chi_{DIA}$ was larger than $1 \times 10^{-9}$ emu/g. According to numerical fitting between model and published $\Delta \chi_{DIA}$ values, $\Delta \chi_{BD}$ was assigned as $-1.1 \times 10^{-30}$ emu for a hydrogen bond, $-3.7 \times 10^{-30}$ for a T-O bond of tetrahedral [TO$_4$] unit and $-0.32 \times 10^{-30}$ emu for M-O bond of octahedral [MO$_6$] unit. It was expected that $\Delta \chi_{DIA}$ of unmeasured crystal could be predicted by using the above $\Delta \chi_{BD}$ values. Oxides with high crystal symmetry, such as a wurtzite-, a rutile- or a perovskite structure, were expected to possess small $\Delta \chi_{DIA}$ that ranges between $10^{-10}$-$10^{-11}$ emu/g.

$\Delta \chi_{DIA}$ of inorganic oxides has been considered to be negligibly small to be detected by a conventional method [6,7]. Small $\Delta \chi_{DIA}$ of many popular oxides were detected by a method using harmonic-oscillation of a sample induced by static horizontal field below $B=2$T. This oscillation was achieved in a condition where restoration torque of a fiber suspending the sample was much small compared to torque of magnetic anisotropy. $\Delta \chi_{DIA}$ of the level of $1 \times 10^{-9}$ emu/g was obtained by the above method [8]. However it was impossible to detect $\Delta \chi_{DIA}$ of the above-mentioned oxides with high crystal symmetry by this system.

It was recently proposed that sensitivity of $\Delta \chi$ may be improved limitlessly by increasing period of the above-mentioned oscillation $\tau$ in microgravity $\mu G$, where restoration torque of a fiber suspending the crystal was excluded from measuring system. A preliminary experiment was performed in microgravity $\mu G$ in order to examine the above principle [9]. However, sensitivity remained at level of $10^8$ emu/g that was comparable to sensitivity obtained from rotational oscillation performed in terrestrial gravity. This was because a sample was ejected from field centre by field-gradient force; measurable length of $\tau$ remained below 1.3s. In the present work, a neodymium-iron-boron magnet that produced homogenous field was introduced to stabilize sample position. Possibility of improving $\Delta \chi$ sensitivity is discussed based on increased duration of rotational oscillation at field centre.

2. Experimental

Microgravity was produced in a drop capsule at Micro-gravity Laboratory of Japan MGLAB (Toki, Gifu, Japan). Duration of microgravity $T_d$ was 4.5s in a single drop. Instability of $\mu G$ was less than $5 \times 10^{-4}$G; no motions due to g-jitter were observed in the experiment. An apparatus developed to measure magnetic anisotropy in $\mu G$ condition [9] is shown in Fig.1. A permanent magnetic circuit (NEOMAX X-1466) is used to generate a homogeneous field of that produced magnetic field of $B = (1.15700 \pm 0.00002)$ Tesla in a region of $5 \times 10^{-2}$ m in diameter. A single crystal of $\alpha$-quartz was placed on a mobile sample stage, which was initially at the center of the area of the homogeneous field.

![Figure1](image_url)

Figure1. Sectional view of apparatus developed to observe motion of sample caused by magnetic anisotropy [9].
3. Results and Discussions

Oscillation of magnetically stable axis with respect to $B$ was observed for $\alpha$-quartz as shown in Fig.2. $\tau$ value obtained from the images was consistent with the values calculated by the following equation that was derived from a rotational equation.

$$\tau' = 2\pi \sqrt{\frac{I}{N\Delta\chi B}} \left\{ 1 + \frac{1}{4} \sin^2 \frac{\theta_0}{2} + \ldots \right\}. \quad (1)$$

$I$ and $N$ denote moment of inertia and mass of sample, respectively. $\theta_0$ is amplitude angle. Magnetic anisotropy of $\alpha$-quartz sample was obtained as $\Delta\chi_{\text{exp}} = (2.2 \pm 0.3) \times 10^{-9}$ emu/g, by inserting observed values of $\tau = 1.92 \pm 0.1$ s, $I/m = (0.0417 \pm 0.006)$ cm$^2$, $\theta_0 = (47 \pm 2)^\circ$ and above-mentioned $B$ value in eq.(1). The value is consistent with a published value $\Delta\chi_{\text{pub}} = 2.0 \times 10^{-9}$ emu/g. Uncertainty of $\Delta\chi_{\text{exp}}$ mainly derives from uncertainty of $\tau$ and $I/m$. Here oscillation was measured for about 1.3 cycles, and uncertainty of $\tau$ was evaluated from time resolution of a video camera in the present report. It is noted that oscillation was observed as long as microgravity continued. This was possible because the high homogeneity of magnetic circuit stabilized position of the sample. Function of the above-mentioned sample stage minimized initial velocity of sample; hence sample remained inside region of homogeneous field.

![Figure 2. Visual images of $\alpha$-quartz single-crystal taken from vertical directions as described in Figure 1. The images are arranged in time sequence from left to right. Image at the left end was taken just after microgravity achievement of $\mu$G. Time interval between images was 0.667 sec. Magnetic field was applied in vertical direction in all the images. Two magnetically stable axes of a sample were initially inclined 47° with respect to filed as shown in right portion of figure.](image_url)

It is deduced from eq.(1) that smaller $\Delta\chi$ can be obtained by increasing $B$ or $\tau$, or else by decreasing $I$. It is difficult to increase $B$ or decrease $I$ in the present setup. Whereas length of $\tau$ can be increased to $T_\phi = 4.5$ sec at MGLAB if the sample position is stabilized as shown in Fig.2. This enhancement of $\tau$ realizes measurement at the level of $10^{-10}$ emu/g as shown in Fig.3. The sensitivity may be improved to a level of $10^{-11}$ emu/g in a parabolic flight where measurable $\tau$ is enhanced to 20 seconds.

Oscillation in microgravity reproduces a primitive motion deduced from a primitive equation of magnetic torque. Rotational motion of spontaneous moment has induced inventions of important devices in the past, irrespective of the refined theories in modern magnetism. In a same sense, motions of ordinary crystals, as shown in Fig.2, may induce new applications in various research fields. Compiled magnetic anisotropy data show that most of the micron-sized crystals dispersed in fluid show almost full alignment below 10 Tesla [3]. It is noted that origin of anisotropy that induce alignment is not completely solved as yet, which should be a theme of quantum chemistry or solid state physics.

The above oscillation was expected to be preserved at $T=1000K$ for most of the oxides [10]. It is a characteristic proposed for diamagnetic and paramagnetic materials in general, which is not widely recognized as yet; spontaneous moments are usually diminished above 1000K. Application of magnetic alignment in natural conditions as well as in industrial application may increase by adopting this property. For example, alignment of pre-solar grains may occur in envelopes of red giant stars ($T=1000$--$2000K$). Direction of stellar field, which is a major factor that control star evolutions, is
determined from polarization caused by the grain alignment. In this sense, the above-mentioned $\Delta \chi$ measurements should be performed in the high temperature region, in order to confirm that efficiency of alignment is preserved up to melting temperature of a solid material.

**Figure 3.** Relationship between observable $\tau$ and magnetic anisotropy $\Delta \chi$ calculated for cubic sample released in micro-gravity which has edge length of 0.3 cm. Relationship is described for field intensity of 1.0 Tesla.

### 4. Conclusion

Magnetic anisotropy can be measured over a wide range between $10^{-5}$ emu/g and $10^{-11}$ emu/g in terms of a single setup based on a rotational oscillation of sample in microgravity. Accordingly, efficiency of magnetic alignment may be quantitatively examined for most of the oxide crystal. Almost full alignment is expected at field intensity below $B = 10T$ for micron-sized crystals dispersed in fluid at room temperature.

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