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Alignments of Feeble Magnetic Particles under High Magnetic Fields

T. Takayama[*], Y. Ikezoe[*], T. Kaihatsu[*], H. Uetake[*], N. Hirota[*,**], and K. Kitazawa[*,**]
*University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033
Fax: 81-3-5841-7195, e-mail: kk16122@mail.ecc.u-tokuo.ac.jp
**Japan Science and Technology Corp., 4-1-8 Hon-cho, Kawaguchi, Saitama 332-0012
Fax: 81-48-226-5651, e-mail: kitazawa@k.u-tokyo.ac.jp

The interactions of magnetic dipoles induced in feeble magnetic substances were studied. Those interactions have been neglected so far, because of their extremely small magnetic susceptibilities. However our research revealed by minute experiments that even feeble magnetic substances do interact magnetically under magnetic fields as high as several teslas. Moreover we confirmed that these interactions could be enhanced when the environmental surroundings were selected properly.

Furthermore we found that feeble magnetic particles formed chain-like structures along the applied magnetic fields. This phenomenon would be of use for controlling the alignments of particles, for example. It seems therefore that these results suggest new applications of magnetic fields for materials processing.

Key words: feeble magnetic substances, high magnetic fields, induced magnetic dipoles, magneto-Archimedes effect alignments of particles

1. INTRODUCTION

Recently, owing to the development of the superconducting magnet technologies, it has become easier to obtain magnetic fields as high as several teslas. In this way, various effects of magnetic fields have been found in feeble magnetic substances such as para- and diamagnetic substances[1)-3)], which are usually believed not to be influenced by magnetic fields. These effects of magnetic fields were found mainly in macroscopic systems. Now, our focus is on the each particles of the system under magnetic fields, namely, magnetic dipoles, which are parallel or antiparallel to the applied magnetic fields, are induced in them. The energy of the interaction between two magnetic dipoles is expressed as follows,

$$U = \frac{\mu_0}{4\pi}\left\{ \frac{\boldsymbol{m}_a \bullet \boldsymbol{m}_b}{r^3} - \frac{(\boldsymbol{m}_a \bullet \boldsymbol{r})(\boldsymbol{m}_b \bullet \boldsymbol{r})}{r^5} \right\} \ldots (1)$$

where μ_0 is the permeability of vacuum, $\boldsymbol{m}_a$ and $\boldsymbol{m}_b$ are the magnetic moments of particles a and b, respectively, $\boldsymbol{r}$ is the vector from a to b, and r is the absolute value of that vector. The interactions among magnetic dipoles are well known in ferromagnetic substances[4),5)]. On the other hand, in feeble magnetic substances the interactions have been so far neglected because their magnetic susceptibilities are very small and the values of the induced magnetic dipoles are extremely small. However, by doing minute experiments, our research revealed that even feeble magnetic substances do interact magnetically under magnetic fields as high as several teslas[6),7)]. According to the Equation (1), these interactions become either attractive or repulsive, depending on the magnetic properties and the relative configurations of the particles. In this paper, we report the observation of the induced dipole-dipole interactions and experiments for controlling the alignments of feeble magnetic particles by using these interactions.

2. OBSERVATION OF THE INDUCED DIPOLE-DIPOLE INTERACTIONS IN FEEBLE MAGNETIC SUBSTANCES

In this section, we report on our experiments concerning the observation of the interactions between magnetic dipoles induced in feeble magnetic substances. In this study, we used a cryogen-free superconducting magnet with a 100 mmϕ room-temperature bore (Sumitomo Heavy Industry). The magnet was used vertically and the direction of the magnetic field was parallel to that of gravity. The samples used in the experiments were gold (diamagnetic, volume magnetic susceptibility $\chi = -3.45\times10^{-5}$ [in SI unit]) and palladium (paramagnetic, volume magnetic susceptibility $\chi = 7.78$

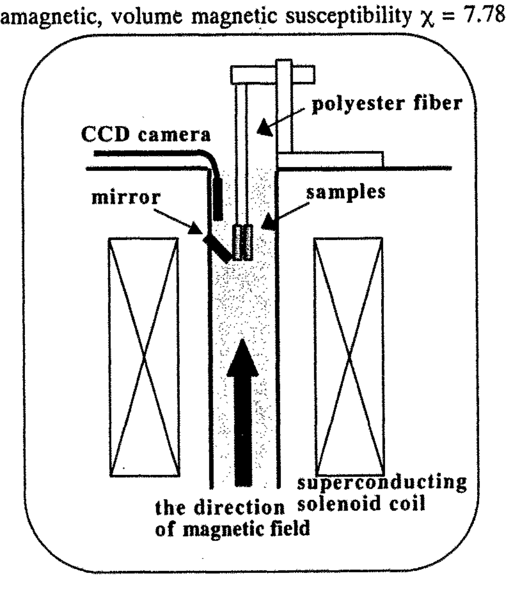

Fig. 1 Schematic figure of the experimental set-up of the observation of the dipole-dipole interactions.

$\times 10^{-4}$[in SI unit]). Both samples had cylindrical shape (1 mm in diameter and 5 mm in height). The schematic figure of the experimental set-up is shown in Fig. 1. Two samples were held side by side in the bore of the magnet with polyester fibers that were adhered on the circular faces with a small amount of varnish. The samples were held 149 mm above the center of the magnetic field, where the distribution of the magnetic field is almost flat in the horizontal direction. In this configuration, the distances between samples were observed with increasing the magnetic fields. These experiments were performed for 3 patterns such as the Pd-Pd system, the Pd-Au system and the Au-Au system. The result of the Pd-Pd system is shown in Fig. 2. The upper figure shows the state with no magnetic field and the lower one shows the state with the maximum magnetic filed of 6 T at this position. The direction of the magnetic field was parallel to this space from the lower side to the upper side. In this case, the same magnetic dipoles, which were parallel to the applied magnetic field, were induced in the two palladium samples; thus the samples went away with each other about 0.4 mm due to the repulsive interaction. In the Pd-Au system and the Au-Au system, the interactions were not clearly observed because the absolute value of the volume magnetic susceptibility of gold is about 10^{-1} times as large as that of palladium.

Then a quantitative analysis was performed on the repulsive interaction of the Pd-Pd system. The distribution of the magnetic field around the palladium sample was calculated by computer and is shown in Fig. 3. The horizontal axis in Fig. 3 represents the radial position around the sample and the applied magnetic field is assumed to be homogeneous around this area.

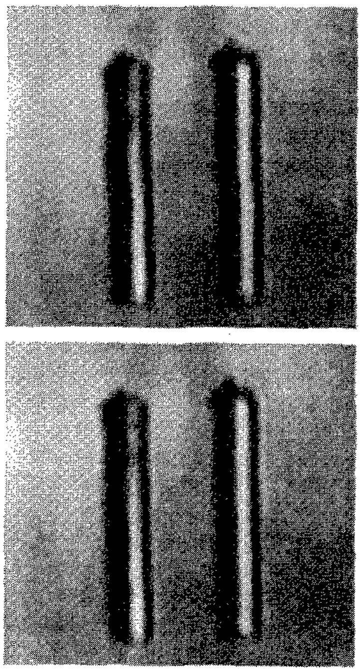

Fig. 2 The induced dipole-dipole interaction of the Pd-Pd system. The upper figure shows the state with no magnetic field and the lower one shows the state with a magnetic field of 6 T.

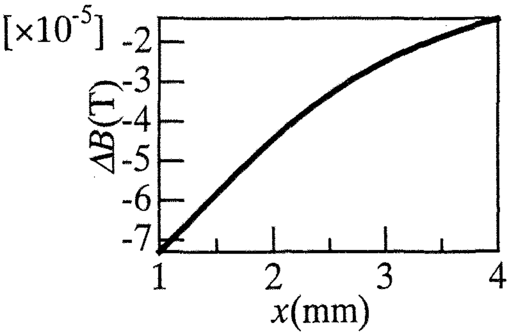

Fig. 3 Distribution of the magnetic field around the Pd sample under a high magnetic filed of 6 T. In this figure, ΔB is $B - B_0$, where B is the magnetic field around the sample and B_0 is the magnetic field when there is no sample.

According to this result, due to the induced magnetic dipole in the palladium sample, the gradient of the magnetic field appears around the sample. Therefore a magnetic force acts on the other sample and the samples go away with each other. The value of this magnetic force was calculated to be 2.4×10^{-7}[N]. On the other hand, this value can be given from the experimental result. The forces which act on the samples are the gravity forces and magnetic forces due to the distribution of the magnetic fields of the magnet in the vertical direction and the magnetic forces due to the dipole-dipole interaction in the horizontal direction. The value of the vertical forces can be calculated, and then that of the horizontal force is given geometrically from the slant of the polyester fiber. This value is found to be 8.7×10^{-7}[N]. Therefore it seems that the experimental value and the calculated one were in substantial agreement.

3. MAGNETO-ARCHIMEDES EFFECTS ON THE DIPOLE-DIPOLE INTERACTIONS

In the previous section, existence of the environmental surroundings was neglected. Therefore by considering the environmental effects, the Equation (1) should be modified as follows,

$$U = \frac{\mu_0}{4\pi}\left\{ \frac{\Delta \boldsymbol{m}_a \bullet \Delta \boldsymbol{m}_b}{r^3} - \frac{(\Delta \boldsymbol{m}_a \bullet \boldsymbol{r})(\Delta \boldsymbol{m}_b \bullet \boldsymbol{r})}{r^5} \right\} \ldots (2)$$

where $\Delta m_{a(b)}$ means the difference between the magnetic moments of the samples and those of the environmental surroundings. From this equation, it is expected that the dipole-dipole interactions can be enhanced or suppressed by selecting the environmental surroundings properly. That is, the magneto-Archimedes effect, which is observed in magnetic levitations[3)], may also appear in the dipole-dipole interactions. The effect of the existence of the environmental surroundings was observed in the Au-Au system by using a $MnCl_2$ aqueous solution (paramagnetic) as the surrounding medium. The concentration of the solution was 40 wt% and its volume magnetic susceptibility was 7.70×10^{-4}[in SI unit]. In this solution the same experiments in the previous section were performed. This result is shown in Fig. 4.

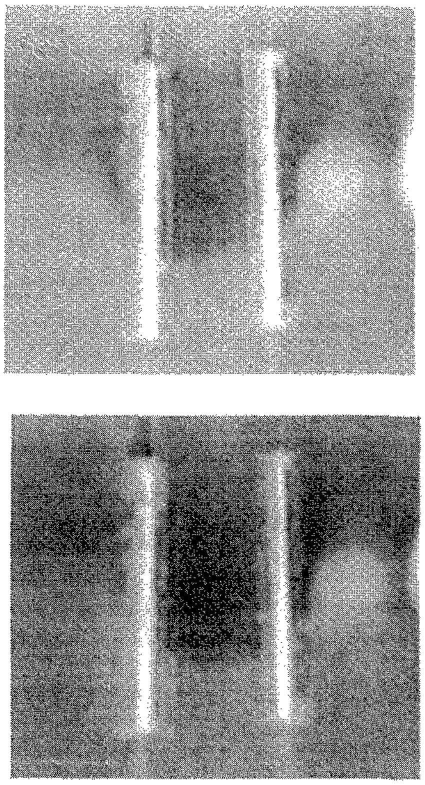

Fig. 4 The induced dipole-dipole interaction of the Au-Au system in a 40 wt% $MnCl_2$ aqueous solution. The upper figure is the state with no magnetic field, and the lower one is the state with a magnetic field of 3 T.

The upper figure shows the state with no magnetic field and the lower one shows the state with a magnetic field of 3 T. The direction of the magnetic field was the same as that in Fig. 2. In this case, the same magnetic dipoles, which were antiparallel to the applied magnetic field, were induced in the gold samples. The repulsive interaction appeared, and, this time, the diamagnetism of gold was enhanced by the paramagnetic surroundings; then the samples were observed to go away with each other about 0.3 mm. In this result as well as the previous case, the experimental and calculative values of the magnetic force due to the repulsive interaction were in agreement. The experimentally obtained value was 2.2 $\times 10^{-7}$[N], where the calculated one was 0.95×10^{-7}[N]. From this result, it was demonstrated that the dipole-dipole interactions could be enhanced when the environmental surroundings were selected properly.

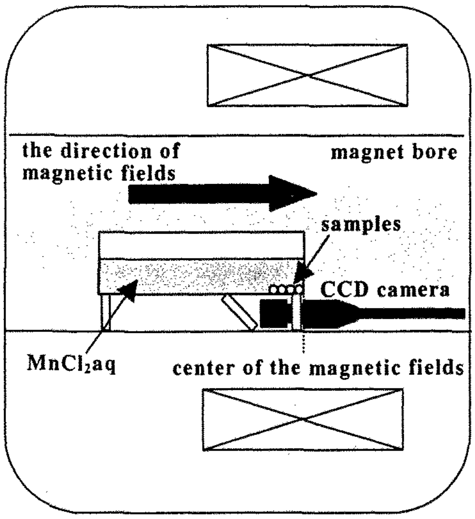

Fig. 5 Schematic figure of the experimental set-up of the dipole interactions in many-body systems.

4. ALIGNMENTS OF FEEBLE MANETIC PARTICLES UNDER HIGH MAGNETIC FIELDS

Based on the previous results, the dipole interactions in a many-body system were observed. In this section, we report on the observation of the alignment of feeble magnetic particles by applying high magnetic fields. The samples used in the experiments were glass beads (~0.8 mmϕ) or copper beads (~1.0 mmϕ). Both glass and copper are diamagnetic and their volume magnetic susceptibilities are -1.8×10^{-5}[in SI unit] and -9.7×10^{-6}[in SI unit], respectively. In consideration of *magneto-Archimedes effects*, a 40 wt% $MnCl_2$ aqueous solution was used as the medium in which these samples were dispersed. The schematic figure of the experimental set-up is shown in Fig. 5. In this experiment, the superconducting magnet (the same magnet as used in the previous experiments) was placed horizontally. The glass cell, in which the samples and the $MnCl_2$ aqueous solution had been put, was inserted into the bore of the magnet, and one of the cell edges was fixed at the center of magnetic fields. In the initial condition, the glass or copper particles were located at the side of the field center. Starting from this configuration, the magnetic field was increased gradually. Then, the diamagnetic particles began to move away from the center of the magnetic fields. These processes, in which the particles were moving away from the field center, were observed from the bottom surface of the cell with a CCD camera. These results are

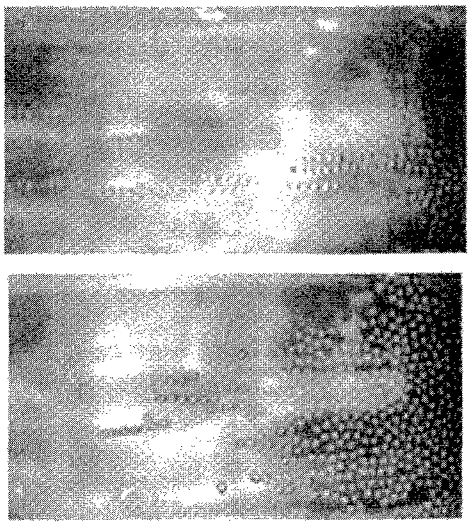

Fig. 6 The dipole interactions of many-body systems in 40 wt% $MnCl_2$ aqueous solutions. The upper figure is the case of the glass particles, and the lower one is the case of the copper particles.

shown in Fig. 6. The magnetic fields were applied parallel to this space directed from the left side to the right side. The upper figure is the case of the glass particles and the lower one is the case of the copper particles; the intensities of the applied magnetic fields were 2.5 T and 5.5 T, respectively. As seen in these figures, the feeble magnetic particles made chain-like structures, which were parallel to the applied magnetic fields, due to the dipole interactions. In addition, because the glass particles can move and magnetically interact more easily than the copper particles due to their smaller densities and the larger absolute value of their magnetic susceptibilities, they made longer chains than the copper particles. Furthermore, it was also observed that two or more chains were moving side by side with staggering their particles in the direction of motion. These phenomena are of interest because these results imply that particles make some regular alignments by applying magnetic fields.

5. SUMMARY

In this study the dipole-dipole interactions in the systems of feeble magnetic substances, which have been neglected so far, were observed and quantitatively discussed by using high magnetic fields generated by a superconducting magnet. Moreover it was confirmed that these interactions can be enhanced by selecting the environmental surroundings properly. Based on these results the dipoles' interactions in a many-body system were observed and it was found that feeble magnetic particles made chain-like structures along the magnetic fields. This phenomenon would be appleid for controlling the alignment of particles in the fields of colloidal crystals and self-assembled structures, for example. Therefore these results seem to demonstrate the new applications of magnetic fields for materials processing.

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