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Experiment and numerical simulation of interactions among magnetic dipoles induced in feeble magnetic substances under high magnetic fields

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Abstract

Using a two-dimensional closed vessel filled with an aqueous solution, we present triangle-lattice alignments with some spacing formed by interactions among magnetic dipoles induced in feeble magnetic substances under high magnetic fields. We conducted an experiment and a numerical simulation using Au particles with a 1 mm diameter dispersed in a $MnCl_2$ aqueous solution and compared their configurations quantitatively using a three-body distribution function. We confirmed that the numerical simulation demonstrates the formation of triangle-lattice alignments in a two-dimensional plane as obtained in the experiment and also verified that the interaction among induced magnetic dipoles is a significant force that governs the structure formed by feeble magnetic substances under high magnetic fields. On the basis of the results obtained in the experiment and the numerical simulation, it is clear that the distance among particles and the interaction force depend on the number of particle at a steady state and they are closely correlative with each other. The distance among particles can be estimated from the correlative relation.

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1. Introduction

In recent years, it has been possible to generate high magnetic fields with the strength of several Tesla using superconducting magnets, so that significant effects on para- and diamagnetic substances, namely, feeble magnetic substances caused by such magnetic fields are recognized [1–5]. These effects are mainly based on interactions between fields and feeble magnetic substances. In a series of studies using high magnetic fields, however, Takayama et al. [6,7] observed interactions acting among magnetic dipoles induced in feeble substances and triangle-lattice alignments formed by them in the air–liquid surface without friction. Since almost all the materials on the earth are feeble magnetic substances, these results suggest that high magnetic fields make it possible to arrange substances and to control the internal structure of a substance. Therefore, the application of the interaction among the induced magnetic dipoles under high fields is expected to contribute to various aspects of material processing, for example, the structural control of colloidal and photonic crystals, and so forth.

In this study, attention is given to the triangle-lattice alignments formed by gold particles with a 1 mm diameter in a $MnCl_2$ aqueous solution [6,7]. This phenomenon is explained as follows. The gold particles levitate as a result of the magneto-Archimedes effect due to the vertical magnetic force and are trapped in the surface of the solution in order to avoid the influence of friction.

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Simultaneously, the gold particles gather at the center of the superconducting magnet due to the slight horizontal magnetic force. These particles are not packed closely and form the triangle-lattice alignments with some spacing. This spacing is caused by the repulsive interactions among each magnetic dipole induced in the gold particles. This structure is constructed and arranged in a two-dimensional plane perpendicular to the direction of the applied magnetic fields.

It is important to develop a numerical model of the above physical phenomenon because the numerical model can be used to verify quantitatively that the induced magnetic dipole interactions among feeble magnetic particles under high magnetic fields are a significant force. In addition, such a model can become a powerful tool to apply this effect of high fields to various aspects of material processing. Furthermore, such modeling will result in information about magnetic fields that can be used to produce a new material and device with a unique structure.

In the present study, we investigate two-dimensional triangle-lattice alignments with some spacing by means of an experiment and a numerical simulation. First, in order to eliminate the influence of the air–liquid surface on gold particles, we carried out an experiment in which the gold particles were dispersed in a closed vessel filled with the medium. Next, we developed a simulation model based on the molecular dynamics (MD) method and investigated the motion of particles in an aqueous solution. The results between the experiment and the numerical simulation were quantitatively compared by changing the number of particles. The relationship between the particle–particle distances and forces at a steady state is discussed here on the basis of the results obtained in the experiment and the numerical simulation.

2. Experiment

2.1. Experimental conditions

The experimental setup is shown in Fig. 1, and the physical conditions for the experiment and the numerical simulation are indicated in Table 1. The superconducting magnet used in this experiment is composed of two layers of solenoid coil. The bore of the superconducting magnet is 100 mm in diameter, and the maximum magnetic flux density at the center along the center axis of the bore is about 9.5 T (the maximum capacity: 12 T).

The triangle-lattice structure of gold particles on the air–liquid interface with a petri dish was observed by Takayama et al. [6,7]. When there is an air–liquid interface, it is difficult to accurately evaluate the magnetic dipole moment because the particle levitates and its head is exposed to the air. In addition, the air–liquid interface also exerts surface tension on particles. Therefore, in order to eliminate these unknown factors, we used a closed vessel and observed the structure that formed in it. Here, gold

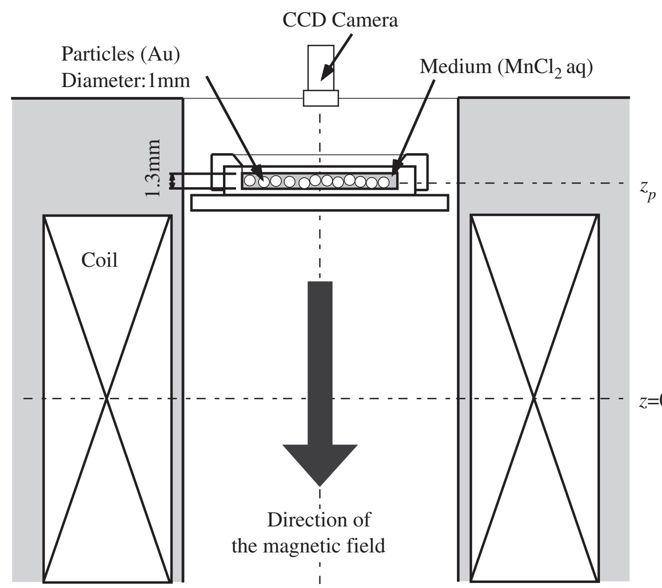

Fig. 1. Experimental setup.

Table 1
Physical conditions for the experiment and the numerical simulation

	Nomenclature		Value
Particle (Au)	Diameter	d_p (mm)	1.0
	Volume magnetic susceptibility	χ_p (–(SI))	-3.45×10^{-5}
	Density	ρ_p (kg/m^3)	1.93×10^4
Medium ($MnCl_2$ aq)	Concentration	C (wt%)	40
	Volume magnetic susceptibility	χ_f (–(SI))	7.99×10^{-4}
	Density	ρ_f (kg/m^3)	1.39×10^3
	Viscosity	η_f (mPa s)	$8.32 \pm 1\%$[a]
Imposed magnetic field	Amplitude	B_0 (T)	(4.9)[b]
	Direction	—	z[c]
	Position of particle	z_p (mm)	148 ± 1[c]

[a]Measurement value at 18 °C.
[b]Value at $z = 148$ mm, calculated from the input current in the superconducting magnet.
[c]see Fig. 1.

particles were dispersed in the closed space with 1.3 mm in thickness, as shown in Fig. 1.

However, a problem occurred when the structure was observed in the two-dimensional closed vessel. Friction was evident between the particles and the glass. It was difficult to cause all the particles to levitate in the middle of a space with a width of 1.3 mm between the upper and lower glass without any contact. In order to decrease the friction between the particles and the glass, the surface of the glass was treated with a hydroxyl radical coating, which did not affect the gold particles or the aqueous solution. As a result of this coating, the particles moved without friction.