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Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information: http://www.tandfonline.com/loi/gmcl19

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Version of record first published: 24 Sep 2006

To cite this article: Mitsuhiro Hirai, Shingo Mitsuya, Hiroki Iwase, Tomohiro Hayakawa, Yasuaki Aoyama, Ken Ohashi & You Sano (2001): Compact Permanent Magnetic Circuit with Periodic Magnetic Field Designed for Studies of Liquid Crystals, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 367:1, 641-650

To link to this article: http://dx.doi.org/10.1080/10587250108028685

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Compact Permanent Magnetic Circuit with Periodic Magnetic Field Designed for Studies of Liquid Crystals

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We have developed a high-performance compact magnetic circuit to investigate orientational phase behaviors of biological and synthetic macromolecular systems by using spectroscopic methods such as X-ray scattering and light scattering. This magnetic circuit can apply a periodic magnetic field and gradient to samples. The maximum values of the magnetic field strength and gradient are varied from 1.5 tesla to 0.55 tesla and from 2.4x10² tesla/m to 7.3x10¹ tesla/m. Owing to the high periodicity of the magnetic field strength and gradient macromolecules are subjected to both rotational and translational forces from the magnetic field. We show some prominent features of this magnetic circuit and its first application to the synchrotron radiation small-angle X-ray scattering (SR-SAXS) studies of supermacromolecular liquid crystals.

Keywords: magnetic circuit; liquid crystal; phase behavior; super-macromolecule; synchrotron radiation; small-angle X-ray scattering

INTRODUCTION

Previously we developed a permanent magnetic circuit which can apply a uniform magnetic field to be parallel or perpendicular to an incident X-ray beam [1]. By using this magnet and a synchrotron radiation time-resolved small-angle X-ray scattering method, we investigated phase behaviors of a rod-shaped colloidal particle system containing biological supermacromolecules (tobacco mosaic virus) under magnetic field. We clarified the mechanism of orientational relaxation of the above macromolecules and presented the phase diagram depending on both magnetic field strength and molecular concentration [2, 3]. Most of previous works including ours have studied phase behaviors and aggregative phenomena of biological macromolecular suspensions under homogeneous magnetic field [1-8]. Only a rotational force from magnetic field has been used for such studies, while a translational force from magnetic field gradient has been mostly disregarded. We expect that such a translational force not only causes various interesting behaviors of macromolecular systems under magnetic field but also is applied to a control of assembling processes of macromolecules.

From this point of view, we have developed a new magnetic circuit applying a periodic magnetic field strength and gradient to samples. We have designed a magnetic circuit to give high magnetic field strength and accurate periodicity in both strength and gradient of magnetic field. Owing to the periodicity of the magnetic field strength and gradient, macromolecules are able to be subject to both rotational and translational forces from magnetic field. We will show prominent characteristic of the new magnetic circuit and some experimental results of biological supermacromolecular liquid crystals obtained from synchrotron radiation small-angle X-ray scattering (SR-SAXS) experiments.

CONCEPTUAL DESIGN OF MAGNETIC CIRCUIT

Based on magnetic field analyses using an integrated element method, we optimized the design of the magnetic circuit to satisfy the following experimental requirements. 1) High periodicity both in magnetic field strength and in magnetic field gradient over two periods. 2) Periodic magnetic field profile can be modulated. 3) Magnetic field strength can be varied up to 1.5 tesla. 4) High uniformity of magnetic field at sample position in a large volume. 5) Compactness for light and X-ray scattering experiments with maintenance free.

Figure 1 shows the schematic perspective side view of the magnetic circuit constructed on the above design. The permanent magnets used are Nd-Fe-B intermetallic compound magnets produced by Shin-Etsu

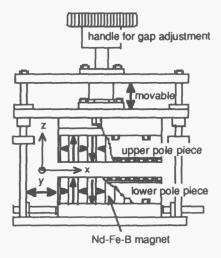


Figure 1. Schematic perspective side view of the magnetic circuit. Permanent magnets with four different magnetization axes are arranged alternatively to form a closed magnetic circuit. The magnetization axes are indicated by the arrows. Three orthogonal axes (x-,y-z-axes) are shown by the thin arrows.

Chemical Co. (type N42H; Br = 13.2 kG, $[BH]_{max}$ = 42 MGOe). The permanent magnets with four different magnetization axes are arranged

alternatively to form a closed magnetic circuit as shown in Figure 1. Five pieces of the permanent magnets constitute a unit assembly of magnet circuit, and a pair of the assemblies are placed face to face to supply one period magnetic field. The permanent magnets with the magnetization parallel to x-axis avoid a demagnetization of magnets and attain a high periodicity of magnetic field in the whole periods. If we had arranged the permanent magnets whose magnetization axes are just aligned in opposite direction alternatively, a serious decrease and heterogeneity of the magnetic field strength would have appeared at both ends of the magnetic circuit. The handle at the top in Figure 1 is used to vary the gap between the pole pieces from 5 mm to 20 mm. The pole piece area is 12 x 4.5 cm². For the modulation of the magnetic field periodicity, we can slide the lower part of the magnet in distance of about 20 mm by inserting the spacers into the edge of the right side of the lower part of the magnet. Except the handle and the permanent magnets, the yokes and other parts are made of stainless steel (SUS304). The maximum dimension of the magnetic circuit including the handle is about 25 x 20 x 10 cm³. Its weight is about 10 kg. The magnetic field strength at 0.25 m apart from the magnet along x-axis is less than ~0.5 gauss, which is comparable with the geomagnetic field strength. The magnetic field strength at 0.25 m apart from the magnet along y-axis is much smaller than that along x-axis. Some effects of the leak magnetic field from the circuit on such as detectors, therefore, can be negligible.

CHARACTERISTICS AND PERFORMANCE

The characteristic of magnetic field of the circuit was measured with a gauss meter Model HGM-8900A of ADS Co. The sensitivity of the probe was about ± 0.2 %. Figure 2 shows the observed magnitude of magnetic flux density at 5 mm pole piece gap, where Figures 2(a) and 2(b) correspond to the magnetic flux density distributions B_z along x and y axes

at the center between the pole pieces, respectively. The observed value of the magnetic flux density at each peak in Figure 2(a) was 1.499 tesla. The uniformity of the repetition of the magnetic flux density along

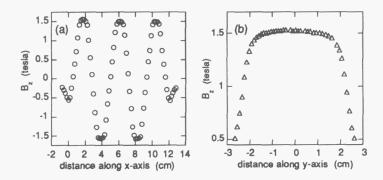


Figure 2. Observed magnitude of magnetic flux density at 5 mm pole piece gap, where (a) and (b) correspond to the magnetic flux density distributions B_z along x and y axes at the center between the pole pieces, respectively.

x-axis measured was achieved below 1.5 %. The flatness of the magnetic flux density along y-axis in the center area between the pole pieces was held below 1.3 % in width of ± 15 mm and below 0.6 % in width of ± 10 mm. High periodicity both in the peak magnetic field flux density and in the magnetic field gradient along x-axis was observed over the pole piece area. The above characteristic observed agree very well with those calculated from the magnetic field analyses. In Figure 3 we show the designed periodicity of the magnetic field flux B_z along x-axis at the center position depending on the gap distance, where the distribution of the magnetic field gradient is also displayed. By varying the gap from 5 mm to 20 mm the average peak magnetic flux density decreases from 1.50 tesla to 0.55 tesla. The maximum value of the magnetic field gradient is obtained at the mid-position of the permanent magnet with horizontal

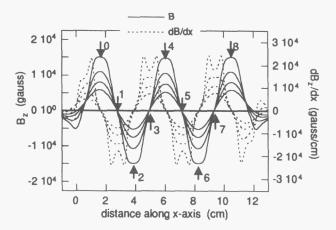


Figure 3. Pole-piece gap dependence of periodicity of the magnetic flux density and gradient along x-axis. By varying the gap from 5 mm to 20 mm the average peak magnetic flux density decreases from 1.50 tesla to 0.55 tesla. The arrows with numbers indicate the typical positions with different magnetic field direction and strength, and these numbered positions were selected for the SR-SAXS experiments shown in Figure 4.

magnetization axis, which varies from 2.4×10^2 tesla/m at 5 mm gap to 7.3×10^1 tesla/m at 20 mm gap.

APPLICATION TO PERIODIC ORIENTATIONAL BEHAVIOR OF SUPERMACROMOLECULES

The sample we used is tobacco mosaic virus (TMV) which is one of rodshaped plant viruses with 300 nm in height and 18 nm in diameter [9]. The TMV used is from the Japanese common strain OM [10]. The TMV suspension is regarded as an ideal model system of hard cylinders whose phase behavior is an attractive scientific concern relating to cooperative phenomena in liquid crystal phase transitions [11-14]. To confirm an availability of the present magnet, we have measured the orientational behavior of supermacromolecules under the periodic magnetic field by using SR-SAXS method. SR-SAXS experiments were carried out with a small-angle scattering spectrometer installed at the 2.5 GeV storage ring in the Photon Factory, Tsukuba, Japan. The scattering intensity was detected by using a one-dimensional position sensitive proportional counter (PSPC). The wavelength used was 1.49 Å and the sample-to-

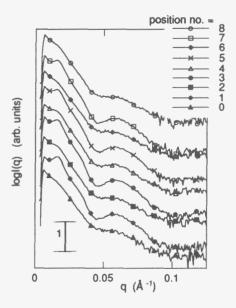


Figure 4. Scattering profile from the TMV suspension depending on the periodicity of the magnetic field at 10 mm pole-piece gap after ~3 hours for exposing the sample to the magnetic field at 25 °C. The position numbers correspond to the different positions of the magnetic circuit in Figure 4, where 1.1 tesla (position numbers of 0, 4 and 8), -1.1 tesla (position numbers of 2 and 6), and 0 tesla (position numbers of 1, 3, 5, and 7).

detector distance was 195 cm. The concentration of the TMV suspension was 90 mg/ml in 10 mM phosphate buffer adjusted at pH 7.2. The TMV suspension was contained in a rectangular sample cell with 1 mm path

length. The cell window is composed of a pair of mica sheets with ~ 50 μm in thickness and $5x140~mm^2$ in area. This rectangular cell was inserted at the center of the pole-piece along x-axis of the magnet. The direction of the x-axis of the magnet was placed to be perpendicular to the incident X-ray beam and parallel to the PSPC anode wire. The scattering curves were observed by shifting the magnetic along x-axis. The exposure time was 300 seconds for each position.

Figure 4 shows the scattering curves from the TMV suspension depending on the periodicity of the magnetic field. The scattering curves were recorded after leaving for ~3 hours under the magnetic field, which was long enough to reach the saturation of the magnetic field induced orientation at 25 °C [2, 3]. According to the phase diagram of the TMV suspension [3], the present TMV solution of 90 mg/ml is in a nematic liquid crystal phase. We also measured the time-evoluations of the scattering curves at the different positions of the magnet by SR-SAXS, and confirmed the orientational saturation after ~3 hours. In the present experimental conditions, the magnetic field strength and direction vary depending on the position of the magnet, namely, 1.1 tesla (position numbers of 0, 4 and 8), -1.1 tesla (position numbers of 2 and 6), and 0 tesla (position numbers of 1, 3, 5, and 7). The numbered positions in Figure 4 correspond the numbered arrows in Figure 3. With shifting the magnet, the scattering curve from the sample irradiated by X-ray changes alternatively at the even-numbered and odd-numbered positions, as shown in Figure 4. According to our previous results [2, 3], the observed scattering curves reflect that the long-axes of the TMV molecules in a nematic liquid crystal phase align repeatedly perpendicular or parallel to the z-axis of the magnetic circuit.

CONCLUSION

The characteristics of the magnetic circuit are summarized as follows.

1) A high periodicity of both the magnetic field strength and gradient is obtained in 2.5 periods with 4.4 cm/period. 2) The maximum value of the magnetic flux density (and its gradient) at the center between the pole pieces is variable from 1.5 tesla (2.4x10² tesla/m) at 5 mm pole piece gap to 0.55 tesla (7.3x10¹ tesla/m) at 20 mm pole piece gap. 3) The uniformity of the repetition of the peak magnetic flux density along the x-axis of the magnet is 1.5 % at 5 mm pole piece gap and 11 % at 20 mm pole piece gap. 4) The high periodicity of the magnetic flux density distribution in the center area between the pole pieces is achieved in the area of ~10x3 cm². 5) The maximum dimension and its weight including the handle are ~10x20x25 cm³ and ~10 kg, respectively, which are compact enough for a desk-top use such X-ray and light scattering experiments. 6) The lower pole-piece is able to slide for giving a phase modulation of the periodicity of the magnetic flux density distribution.

By using this magnetic circuit we have successfully demonstrated the periodic orientational behavior of supermacromolecules induced by both rotational and translational forces from magnetic field. The present finding of the orientation of the solute particles at zero-field position, namely at maximum field gradient position, should be in great interest since a translational force play an essential role for orientation. W are now carrying out further experiments on phase behavior and density fluctuation of various biological macromolecular suspensions under the periodic magnetic field.

Acknowledgments

This study was supported in part by Grant-in-Aid from the Ministry of Education, Science, Sorts and Culture Japan. The synchrotron radiation X-ray scattering experiments were done under the approval of the Photon Factory Program Advisory Committee (Proposal No. 2000G150) of High Energy Accelerator Research Organization, Tsukuba, Japan.

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