ON THE CONCENTRATION DEPENDENCE OF BIREFRINGENCE AND DICHROISM IN MAGNETIC FLUIDS

Nihad A. Yusuf

Department of Physics
Faculty of Science
Yarmouk University
Irbid, Jordan

الخلاصـــة :

تـمّ قياس معامل الانكسار المزدوج ، ومعامل التلون الثنائي لسوائل مغناطيسية تحتوي على دقائق صغيرة من Fe_3O_4 بتركيزات مختلفة . وأظهرت النتائج ان كلا الخاصيتين (الانكسار المزدوج والتلون الثنائي) تتزايدان طرديّـاً مع تركيز السائل المغناطيسي وتتوافقان بذلك مع الحسابات النظرية لتلك الخاصيتين .

ABSTRACT

The birefringence and dichroism of Fe_3O_4-particle magnetic fluids with different magnetic concentrations have been measured. The results show a linear dependence of both birefringence and dichroism on the concentration of the fluid, in agreement with theory.

ON THE CONCENTRATION DEPENDENCE OF BIREFRINGENCE AND DICHROISM IN MAGNETIC FLUIDS

1. INTRODUCTION

Magnetic fluids, often called ferrofluids, are colloidal suspensions of single domain ferromagnetic particles (Fe_3O_4, iron, or cobalt) in a suitable liquid carrier. The occurrence of magnetically induced birefringence in magnetic fluids was first reported by Majorana [1]. Measurements of the induced birefringence in magnetic fluids, produced by both steady and pulsed magnetic fields have been reported by several workers [2–8]. In addition to induced birefringence, magnetic fluids exhibit other magneto-optic effects such as Faraday rotation, Faraday ellipticity, and linear and circular dichroism. Martinet [3] has measured the linear dichroism in a magnetite ferrofluid. Davies and Llewellyn [8] have measured Faraday rotation, Faraday ellipticity, birefringence, and dichroism in two magnetic fluids: one containing Co and the other Fe_3O_4 particles. Yusuf *et al.* [9] have measured Faraday rotation for Fe_3O_4-particle magnetic fluid and studied the concentration dependence of Faraday rotation [10] and the light transmission in magnetic fluids [11]. The same authors have also investigated the wavelength dependence of Faraday rotation [12].

In this article results are reported on the concentration dependence of both birefringence and dichroism. The results show a linear dependence of both birefringence and dichroism on the concentration of the magnetic particles in the fluid.

2. EXPERIMENT

Measurements of birefringence and dichroism were carried out using an optical setup consisting of a He–Ne laser, cell, Soleil–Babinet Compensator, analyzer, and a photomultiplier. By using a compensator in the experimental setup we were able to directly measure the relative retardation, δ, of the two components of light transmitted with their planes of polarization parallel and perpendicular to the applied magnetic field even when dichroism was exhibited by the sample. Similar to the arrangement used by Davies and Llewellyn [8], the compensator is driven by a high precision linear motor and the analyzer is driven by a high precision rotary motor. The direction of polarization of the incident light was set at 45° with the applied magnetic field. The use of this experimental setup enables a simultaneous measurement of dichroism and birefringence as discussed by Llewellyn [13].

With the field off, the readings of the compensator l_o and that of the analyzer θ_o were adjusted to give minimum photomultiplier output; then with the field on their readings l_B and θ_B were readjusted to give a minimum output once more. The difference in the corresponding readings $(l_B - l_o)$ and $(\theta_B - \theta_o)$ were recorded.

From the difference $(l_B - l_o)$ and the calibration of the compensator the relative retardation, δ, was obtained and consequently, the birefringence, Δn, is calculated using the relation:

$$\Delta n = \lambda\delta/2\pi t \,, \tag{1}$$

where λ is the wavelength of the light and t is the thickness of the sample.

From the difference $(\theta_B - \theta_o)$ the dichroism, ΔA, was calculated using the relation [13]:

$$\Delta A = -2ln\left[\frac{1+\tan(\theta_B-\theta_o)}{1-\tan(\theta_B-\theta_o)}\right]. \tag{2}$$

The experiment was carried out on Fe_3O_4-particle magnetic fluid with Isopar M as a liquid carrier. The magnetic particles (Fe_3O_4) was produced by following the method given by Schimoiisaka *et al.* [15]. This method, commonly known as the "wet" method is based on a reaction between ferric chloride ($FeCl_3$) and ferrous sulfate ($FeSO_4$) in an acidic medium. Dispersing the particles in the carrier is achieved by adding a surfactant, usually oleic acid, to the mixture. The concentration of the magnetic fluid is determined from the saturation magnetization of the fluid measured by a vibrating sample magnetometer (VSM).

Dilution of the sample is achieved by adding proper amounts of the liquid carrier to a fluid of known concentration. The concentrations of the magnetic particles in the fluid used in this work range from 10^{-3} G to 10 G (1 G = 0.2% volume solid fraction). Although the particles in the fluid have size and shape distributions, the average diameter of the particles is ~8 nm. In this work the contributions of the cell and liquid carrier to the birefringence and dichroism were subtracted.

3. RESULTS

The birefringence of the samples was measured at four different magnetic field strengths (134, 670, 1340, and 2680 G). The measured birefringence at fields 134 G and 2680 G are plotted as $\log(\Delta n)$ *versus* $\log(c)$ in Figure 1 and Figure 2, respectively. The results presented in these figures fall on straight lines. The slopes of the lines were calculated by performing least square fit calculations. The values of the slopes range between (0.99 ± 0.01) and (1.01 ± 0.01) with correlation coefficients better than 0.99. Taking into account the difficulty of preparing samples with accurate concentration over such a wide range, one may safely regard the slopes to be unity.

The dichroism of the samples was also measured at four different magnetic field strengths. Figures 3 and 4 show plots of $\log(-\Delta A)$ *versus* $\log(c)$ at field strengths 670 G and 2680 G, respectively. The results in the figures fall on straight lines. The slopes of the lines were again calculated by least square fits and their values range between (0.98 ± 0.02) and (1.01 ± 0.02). Once more, taking into consideration the uncertainty in the concentration, we regard the slopes to be unity. Hence our results show a linear dependence of both birefringence and dichroism on the concentration of the fluid.

4. DISCUSSION

The induced birefringence is due to the induced anisotropy of the magnetic fluid when a magnetic field is applied. Although the particles in a magnetic fluid may have intrinsic anisotropy (shape anisotropy), the fluid itself will have no anisotropy due to the random orientation of the particles in the absence of an applied field. However, when a magnetic field is

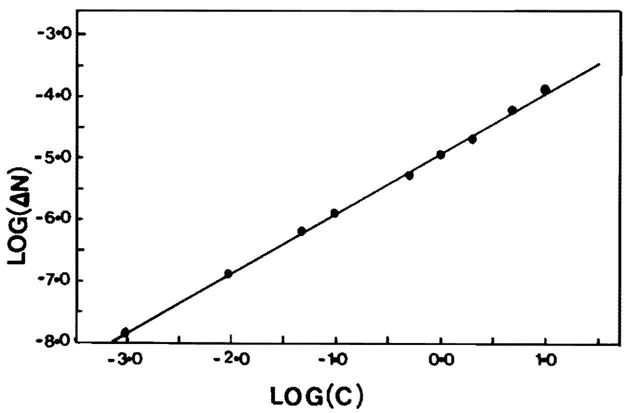

Figure 1. Log(Δn) versus Log(c) at Field Strength B = 134 G.

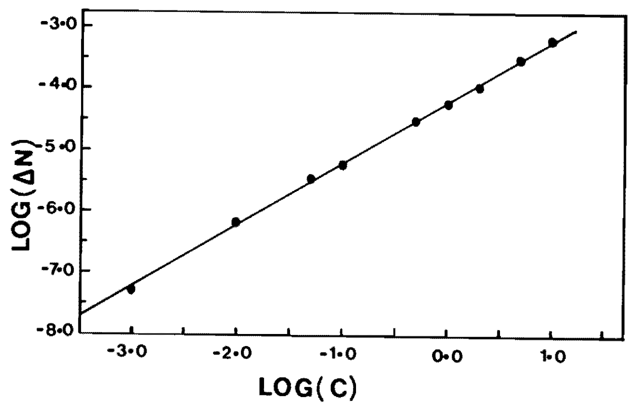

Figure 2. Log(Δn) versus Log(c) at Field Strength B = 2680 G.

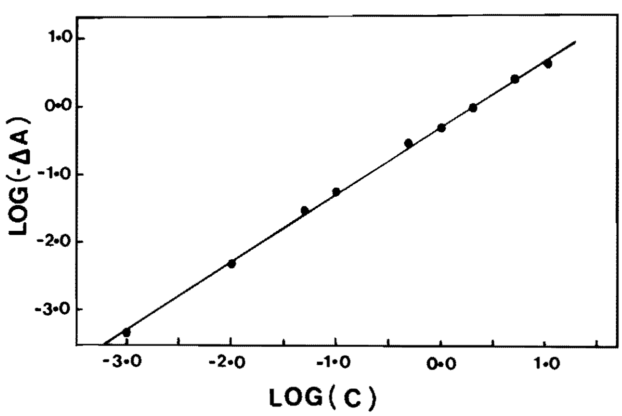

Figure 3. Log(−ΔA) versus Log(c) at Field Strength B = 670 G.

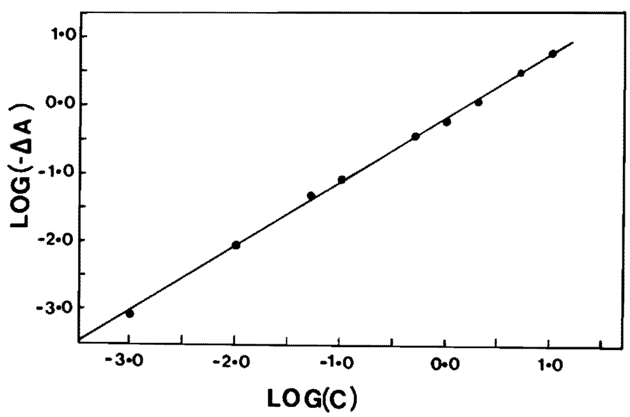

Figure 4. Log(−ΔA) versus Log(c) at Field Strength B = 2680 G.

applied the particles due to their permanent dipole moments tend to align along the field direction; and through dipole–dipole interactions from needle-like chains. It is this alignment of the particles and chain formation that produce the anisotropy and induced birefringence. The birefringence of a completely oriented fluid, Δn_s, is called the saturation birefringence and is for a dilute fluid given by [14]:

$$\Delta n_s = \frac{2\pi c_v(g_\parallel - g_\perp)}{\bar{n}} , \tag{3}$$

where c_v is the volume fraction of the particles in the fluid, $\bar{n}$ is the average index of refraction and $g_\parallel$ and $g_\perp$ are the optical anisotropy factors of the particles.

The induced birefringence, Δn, of an incompletely oriented fluid can be related to the saturation birefringence Δn_s. The birefringence, Δn_θ, due to the particles making an angle θ with the applied field is given by [14]:

$$\Delta n_\theta = \Delta n_s \left[\frac{3\cos^2\theta - 1}{2}\right] . \tag{4}$$

The birefringence of the incompletely oriented fluid is then obtained by integrating Δn_θ over all possible values of θ

$$\Delta n = \Delta n_s \int_0^\pi f(\theta) \left[\frac{3\cos^2\theta - 1}{2}\right] \sin\theta \, d\theta , \tag{5}$$

where $f(\theta)$ is an angular distribution function giving the probability of finding the particle axis at an angle between θ and $\theta + d\theta$, *i.e.*, in a space element $d\Omega$.

The orientation function $f(\theta)$ can be expressed according to the Boltzmann distribution formula as:

$$f(\theta) = \frac{\exp[-U/KT]}{\int \exp[-U/KT] d\Omega} , \tag{6}$$

where U is the sum of the energy of interaction between the dipole moments and the field and the energy of dipole–dipole interactions.

For dilute fluids the interaction between the dipole moments and the field is dominant, and consequently the integral in Equation (5) is concentration independent. Therefore, the birefringence, Δn, for dilute fluids is proportional to the concentration of the fluid, and our experimental results are hence in agreement with the theory.

In an anisotropic medium the absorption of light will vary according to the direction of propagation. For a suspension of anisotropic particles, such a phenomenon will appear at the same time as birefringence. In the case of magnetic orientation we consider a uniaxial medium and define dichroism, ΔA, as the difference between the absorbance of light polarized parallel ($A_\parallel$) and perpendicular ($A_\perp$) to the direction of the applied field,

$$\Delta A = A_\parallel - A_\perp . \tag{7}$$

Fredricq and Houssier [14] defined the reduced dichroism A_R, as the ratio of ΔA to the absorbance, A, of the fluid at zero field, *i.e.*,

$$A_R = \frac{\Delta A}{A} . \tag{8}$$

Furthermore, they have shown that the reduced dichroism is independent of concentration. However, since the absorbance, A, at zero field is proportional to the concentration, then the dichroism, ΔA, is proportional to the concentration. Therefore our experimental results are in agreement with the theory.

5. CONCLUSION

The birefringence, Δn, and dichroism, ΔA, have been measured for Fe_3O_4-particle magnetic fluids with concentration ranging between 10^{-3} G to 10 G. Our results show, in this range of concentration, a linear dependence of both birefringence and dichroism on the concentration of magnetic fluids in agreement with the theory.

ACKNOWLEDGEMENTS

I would like to thank Dr. J. P. Llewellyn for very helpful discussions. I also would like to thank the British Council for the award of a British Council Fellowship.

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Paper Received 15 November 1988; Revised 22 February 1989.