

55

UNIVERSITATEA DIN TIMIȘOARA
FACULTATEA DE FIZICĂ
1900 TIMIȘOARA - ROMÂNIA

UTFT 93-1
SW 9420

V. SOFONEA, L. VEKAS and E. HEGEDŰS

**MAGNETO-OPTICAL EFFECTS INDUCED IN A MAGNETIC
FLUID LAYER BY THERMALLY RELEASED SUPERMASSIVE
MAGNETIC MONOPOLES**

U. T. F. T. 1 | 1993

CERN LIBRARIES, GENEVA



P00023140

**MAGNETO-OPTICAL EFFECTS
INDUCED IN A MAGNETIC FLUID LAYER
BY
THERMALLY RELEASED
SUPERMASSIVE
MAGNETIC MONOPOLES**

V.Sofonea (*), L.Vékás (*) and E.Hegedüs (**)

() Research Center for Hydrodynamics, Cavitation and
Magnetic Fluids, Technical University of Timișoara,
Bd. Mihai Viteazul 1, R-1900 Timișoara, Romania*

*(**) Department of Physics, University of Timișoara,*

Bd. Vasile Pârvan 4, R-1900 Timișoara, Romania

(received Jan.1993)

Abstract

The number of photons in the optical pulse induced via magneto-optical effects by a thermally released (e.g., from old iron ores) supermassive magnetic monopole traversing a thin magnetic fluid layer is evaluated on the basis of phenomenological models. In certain monopole search experiments, these effects could give a detectable signal of the order of tens of photons and thus it may serve as a basis for a new magnetic monopole detection method.

Contents

I	Introduction	3
II	Magnetic monopole induced optical pulse	4
III	Output pulse intensity	5
	A Theoretical model	5
	B Semiempirical model	7
IV	Numerical estimations	8
V	Conclusions	8
VI	Acknowledgements	9
	APPENDIX	10

I. INTRODUCTION

Grand unified theories (GUT's) predict the existence of magnetic monopoles with Dirac magnetic charge $g = hc/4\pi e$ and mass greater than $10^{16} \text{ GeV}/c^2$ [1], whose experimental identification is of principal importance and involves the development of very sensitive techniques [1-4]. In what concerns the possible interactions of monopoles with various materials, the ferro- and ferrimagnetic materials are of great interest because a slowly moving monopole may efficiently align their magnetic domains and consequently, the energy loss connected with this mechanism [5,6] could be relatively large. Monopoles are supposed to be trapped in bulk ferro- or ferrimagnetic materials, e.g., old iron ores [7]. The search for thermally released supermassive magnetic monopoles would be particularly meaningful and could give a sizable signal [1,2,8].

The alignment process may be particularly efficient in the case of magnetic fluids, which are ultrastable colloids of subdomain size ($\simeq 100 \text{ \AA}$) ferro- or ferrimagnetic particles in a carrier liquid [9,10]. This alignment process is characterized by a relaxation time τ_R whose value is mainly determined by the viscosity of the carrier liquid, as well as by the magnetic moment orientation mechanism (Brownian and Néel rotation or linear cluster formation [9-13]).

The stopping power of a magnetic fluid layer should be mainly determined by the energy dissipation due to the alignment of the magnetic moments of the subdomain ferro- or ferrimagnetic particles suspended in the viscous carrier liquid. The transient magnetic field of a passing magnetic monopole could induce also irreversible microstructural processes, e.g., phase transformations [14,15], especially in the case of a highly metastable magnetic fluid.

In this paper, we consider the optical anisotropy of a thin layer of magnetic fluid, induced by the transient field of a very slow supermassive magnetic monopole. Such hypothetical particles are expected to be thermally released from old iron ores [8].

Magnetic fluids are generally opaque but, when diluted or made into a thin layer, they can transmit visible light. The alignment of particles under the action of an applied magnetic field induces the optical anisotropy of the magnetic fluid layer, which gives rise to magneto-optical effects reported experimentally: birefringence, linear dichroism, Faraday rotation and circular dichroism (see [10,12,13,15-19] and references therein). For this reason, when a magnetic fluid layer is placed between crossed polarizer and analyzer and illuminated by a laser beam under normal incidence, the output beam intensity is always controlled by the external magnetic field.

The pulsed magnetic field acting on such an optical magnetic field sensor [18,20], when a magnetic monopole passes through it, could induce magneto-optical effects [21,22]. The aim of this paper is to evaluate the magnitude of the monopole induced output optical pulse on the basis of the available experimental data relative to magneto-optical effects in magnetic fluid layers.

II. MAGNETIC MONOPOLE INDUCED OPTICAL PULSE

Suppose that a magnetic monopole is moving with the velocity \vec{v} along the direction of the laser beam (the z axis), normally to the plane-parallel magnetic fluid layer in Figure 1. The layer is placed between crossed polarizer and analyzer, oriented along the x and y axes, respectively. The magnetic field intensity \vec{H} at a point P of the layer, when the monopole is located at the point M on the z axis, is given by

$$\vec{H} = \frac{g \vec{r}_{MP}}{r_{MP}^3} \quad (1)$$

where \vec{r}_{MP} is the position vector of P relative to M and $g = 32,88 \times 10^{-9}$ CGS_{es} units. This field magnetizes the magnetic fluid which becomes a temporarily anisotropic medium and so, a certain amount of light energy is expected to be registered by a photodetector placed on the beam direction behind the analyzer.

We now consider the point P to be on the incident surface of the layer. When the incident point of the magnetic monopole is chosen to be the origin O of the coordinate system, the point P has the radial coordinate r and the angular coordinate β relative to the x axis. The intensity $I_{out}(r, \beta, t)$ of the laser beam emerging from the analyzer is a function of the point $P(r, \beta)$ and the monopole position (which is a function of t). When the monopole is initially far from the magnetic fluid layer, there is no output beam from the analyzer. As the monopole approaches the magnetic fluid layer, an output beam emerges from the analyzer due to monopole induced magneto-optical effects. The output beam intensity vanishes again after the monopole traversed the magnetic fluid layer since these effects are reversible. To obtain the total energy of the output light pulse generated by the action of the passing monopole, we have to evaluate the integral

$$W = \int_{-\infty}^{+\infty} \int_0^{+\infty} \int_0^{2\pi} I_{out}(r, \beta, t) r d\beta dr dt \quad (2)$$

Since at a certain time t , the magnetic monopole action is significant only in a limited spatial region surrounding its trajectory, the radial integral in (2) is to be cutted at a certain radius R . An appropriate value was found to be $R = 10^{-4}$ cm because the local monopole induced magneto-optical effects become negligible for larger values of r . For a similar reason, also the time integral in (2) is practically restricted to a finite interval. At the beginning of this interval, the monopole position relative to the front of the layer was considered to be $z = z_0 = -0.001$ cm, while at the end of this interval, this position was conventionally considered to be $z = D - z_0$, where D is the layer thickness.

Since at all instants of time the proper magnetic field of the monopole decreases dramatically across the magnetic fluid layer, during the numerical estimations we considered this layer as being structured into N slices having the same thickness $d = D/N$. The value of d must be small enough in order to ensure the accuracy of the time integration in (2), but it must be also sufficiently large in order to ensure the achievement of magneto-optical effects across each individual slice. We adopted here the value $d = 100$ nm which is large enough compared to the diameter of the colloidal particles ($\simeq 10$ nm). The time integration step which we used in subsequent numerical calculations is related to d and v

$$\tau = d/v \quad (3)$$

and so, the monopole position at the n -th time integration step is $z_n = z_0 + nd$, $0 \leq n \leq N + 2|z_0|/d$. For computational purposes, when the monopole position changes from z_n to z_{n+1} , we considered that the magnetic field of the monopole has no variation in the z direction across each individual slice; only the radial dependence was retained. Moreover, all numerical evaluations were performed in such a way to ensure the "most unfavourable case", e.g., for fixed R , the value of the monopole field retained in each slice was the value corresponding to the face of the slice whose distance to the monopole position was greater.

After considering also a discretization $\{R_m\}$, $0 \leq m \leq M$ on the interval $[0, R]$, the integral (2) is approximated by

$$W \simeq \tau \sum_{n=0}^{N+2|z_0|/d} \sum_{m=1}^M \int_0^{2\pi} I_{out}(R, \beta, n\tau) R_m (R_m - R_{m-1}) d\beta \quad (4)$$

Since the proper magnetic field of the monopole decreases very quickly, the discretization $\{R_m\}$ was chosen to be more compact near the monopole trajectory.

III. OUTPUT PULSE INTENSITY

Two expressions for the output laser intensity after traversing a thin magnetic fluid layer placed between crossed polarizer and analyzer were considered for numerical estimations: a general theoretical expression and a semiempirical one.

A. Theoretical model

The general expression for the laser intensity I_{out} transmitted by a diluted magnetic fluid layer placed between crossed polarizer and analyzer, when subjected to an external magnetic field having no radial dependence under static conditions, was derived in [19] within the assumption that each colloidal particle in the base liquid behaves as an anisotropic scatterer:

$$I_{out} = I_0 \left| \frac{1}{2} i D k f [\Delta\alpha \sin \beta \cos \beta F(x) + i\alpha' G(x)] \right|^2 \quad (5)$$

In this relation, $I_0 = \text{constant}$ is the incident laser intensity of wavelength λ , $i^2 = -1$, D is the layer thickness and $k = 2\pi n_0/\lambda$ is the wave number, where n_0 is the refractive index of the carrier liquid. The material constants α' and $\Delta\alpha = \alpha_{\parallel} - \alpha_{\perp}$ are related to the off diagonal (α') and the diagonal ($\alpha_{\parallel}, \alpha_{\perp}$) components of the polarisability tensor in the scatterer coordinate system $x'y'z'$, where the z' axis is an axis of symmetry for the magnetic and optical properties [19]. $F(x)$ and $G(x)$ are thermodynamical averages over all particle orientations. For the simplified case of identical colloidal particles of volume V_p with permanent dipole moment $m = M_s V_p$ and saturation magnetization M_s , we have [18]:

$$\begin{aligned} F(x) &= \sin^2 \gamma (1 - 3L(x)/x) \\ G(x) &= \cos \gamma L(x) \end{aligned} \quad (6)$$

with $L(x)$ the well-known Langevin function of argument

$$x = \frac{\mu_0 M_s V_p H}{k_B T} \quad (7)$$

where μ_0 is the vacuum magnetic permeability, k_B is the Boltzmann constant and T is the temperature of the layer. Here γ is the angle between the z axis and the direction of the magnetic field vector \vec{H} and β is the angle between the polarizer direction and the (\vec{z}, \vec{H}) plane.

For our purposes, the expression (5) needs some generalization in order to take into account the contribution of each individual slice, as well as the radial dependence of the magnetic field (the details are given in the Appendix). Since the magnetic field inside the layer is now dependent on the monopole position, the output laser intensity is now obtained as a function of time and also of the polar coordinates (r, β) of the point P on the incident surface (Figure 1):

$$\begin{aligned} I_{out}(r, \beta, t) &= \\ &= I_0 \left| \frac{1}{2} idkf \left[\Delta\alpha \sin \beta \cos \beta \sum_{j=1}^N F_j(r, t) + i\alpha' \sum_{j=1}^N G_j(r, t) \right] \right|^2 \end{aligned} \quad (8)$$

where $F_j(r, t)$ and $G_j(r, t)$ are the thermodynamical averages (6) at the moment t , at a distance r from the monopole trajectory in the j -th slice.

Taking into account the discretizations introduced above for the r and t variables, introducing Eq.(8) into Eq.(4) and performing the angular integration, we obtain the following approximate expression:

$$\begin{aligned} W &\simeq \frac{1}{4} \tau I_0 (dkf)^2 \sum_{n=1}^{N+2|z_0|/d} \sum_{m=1}^M R_m (R_m - R_{m-1}) \cdot \\ &\cdot \sum_{j=1}^N \left[\frac{1}{4} |\Delta\alpha|^2 F_{jmn}^2 + 2 |\alpha'|^2 G_{jmn}^2 \right] \end{aligned} \quad (9)$$

where F_{jmn} and G_{jmn} are the thermodynamical averages (6) evaluated at the moment $t = n\tau$, $1 \leq j \leq N + 2|z_0|/d$, at a distance R_m , $1 \leq R_m \leq M$ from the monopole trajectory in the j -th slice, $1 \leq j \leq N$. At the beginning, when the monopole is far from the layer, we have $F_{j0} \equiv G_{j0} \equiv 0$ for all j and m .

An estimation of the time evolution of F_{jmn} and G_{jmn} can be adopted as

$$A_{jmn} = A_{jmn}^S + [A_{jm(n-1)} - A_{jmn}^S] e^{-\tau/\tau_R} \quad (10)$$

where the letter A stands for F or G . The A_{jmn}^S value is determined under static conditions according to (6) i.e., when the monopole has the fixed position $z_n = z_0 + nd$ which is reached at the moment $t = n\tau$.

B. Semjempirical model

A general expression for the phase difference θ_S across a thin magnetic fluid layer was derived on the basis of detailed experimental investigations (see [18] and references therein):

$$\theta_S(T, H) = \frac{\theta_a (1 - e^{-\alpha H})}{T/T_a - e^{-\alpha H}} \quad (11)$$

where T is the temperature value and H is the magnetic field intensity. The phenomenological constants θ_a , T_a and α are found to be dependent on the magnetic fluid type and also on the volumic fraction of colloidal particles. When the magnetic field direction is no more perpendicular to the laser beam direction, the original relation (11) is to be modified according to [23]

$$\theta_S(T, H, \gamma) = \sin^2 \gamma \theta_S(T, H) \quad (12)$$

where γ has the same meaning as in Eqs (6).

In the frame of a Ginsburg-Landau model, the temporal evolution of the phase difference θ was found to be described by

$$\theta(t) = \frac{\theta_0 + \int_{t_0}^t p(t') \theta_S(t') \exp\left\{\int_{t_0}^{t'} p(t'') dt''\right\} dt'}{\exp\left\{\int_{t_0}^t p(t') dt'\right\}} \quad (13)$$

where θ_0 is the initial value of θ at $t = t_0$, $\theta_S(t) = \theta_S[H(t)]$ is the static expression (11) of the birefringence, now with H being time-dependent. The relaxation function $p(t)$ is given by

$$p(t) = A \left[T/T_a - e^{-\alpha H(t)} \right] \quad (14)$$

where A is a constant related to the volume of the colloidal particles and the viscosity of the carrier liquid [13,18]. The intensity of the laser beam emerging from the magnetic fluid layer subjected to a constant direction magnetic field is

$$I_{out} = I_0 \sin^2(\theta/2) \approx \frac{1}{4} I_0 \theta^2 \quad (15)$$

As a particular consequence of (13), the phase difference θ is found to decay exponentially when the applied magnetic field is switched off at $t = t_a$ and so, according to (15), I_{out} decays with the relaxation time

$$\tau_R = \left[2 A (T/T_a - 1) \right]^{-1} \quad (16)$$

The typical experimental value of τ_R is found to be of the order of 40 μ sec [13], hence the value of the constant A in (14) can be roughly estimated. Taking into account the temporal and spatial dependence of the magnetic field and introducing the same sliced structure as before, we obtain the results similar to (10).

$$W \simeq \frac{1}{4} \tau I_0 \sum_{n=1}^{N+2|z_0|/d} \sum_{m=1}^M R_m (R_m - R_{m-1}) \cdot \left[\sum_{j=1}^N \sin^2 \gamma_{jmn} \theta_{jmn} \right]^2 \quad (17)$$

where θ_{jmn} is the local birefringence at time $t = n\tau$ at a point in the j -th slice, whose distance from the monopole trajectory is R . The dynamic value of θ_{jmn} is computed from Eqs. (11-13), now with $\theta'_a = \theta_a/N$ instead of θ_a since the birefringence effect is additive. In the frame of this semiempirical model, the other magneto optical effects are not considered to contribute to the output signal.

IV. NUMERICAL ESTIMATIONS

Figure 2 shows the computed number of photons of wavelength $\lambda = 632.8$ nm in the output light pulse, for different monopole velocities. The thickness of the magnetic fluid layer is $D = 2$ mm, divided into $N = 20,000$ slices. All the relevant values for the material constants we used were those reported by several authors and related to the different kinds of diluted magnetic fluids mentioned in Table 1. The relaxation time values τ_R for the samples A, B were calculated according to the well-known Shliomis formula [11], while the corresponding values for the samples C, D were originally reported in [24]. For the sample E, the typical order of magnitude for τ_R was estimated according to the experimental results in [13].

V. CONCLUSIONS

Magnetic fluids form a new class of synthetic magnetic materials, whose interaction with supermassive magnetic monopoles seems to be particularly interesting. The total energy of the transient optical pulse induced via magneto-optical effects by a thermally released very low velocity magnetic monopole traversing a magnetic fluid layer strongly depends on the microstructural properties of the layer, the relaxation time scale of the colloidal particles and also on the monopole velocity. The number of photons in the output pulse was estimated here to be of the order of several tens of photons. Specially tailored magnetic fluids, e.g., those containing iron-nitride colloidal particles with high dipolar magnetic moment [25], or the recently announced optically transparent magnetic fluids [26] (as well as other transparent magnetic materials [27]), could significantly enhance the detectable signal produced by a passing monopole. Moreover, the monopole pulsed field could produce the switching of a magnetic fluid magneto-optical bistable device [18,22] giving rise to a remanent signal keeping its trace.

The very low velocity supermassive magnetic monopoles considered above are not expected in the case of cosmic rays, but they may be encountered when magnetically trapped monopoles are forced to be released from old iron ores, as thought to be the case in the Kobe experiment [8].

VI. ACKNOWLEDGEMENTS

We are indebted to Professor R. Massart, Professor J.C. Bacri and Dr. Régine Perzynski for their kind hospitality during the stay of one of us (L.V.) at the Pierre and Marie Curie University in Paris, France and for providing some recent experimental results on dynamic birefringence effect in magnetic fluids before publication.

APPENDIX

We assume that all slices are identical, but the magnetic field is different across each individual one. If slices are thin enough, as explained above, the z variation of the monopole field across them become negligible and so, we can consider only the radial dependence. For the sake of simplicity, we first consider the case when the layer is structured into two slices only. The magnetic field intensity across each slice is assumed to be $\vec{H}_1(R)$ and $\vec{H}_2(R)$ respectively. These vectors are considered to be in the same plane (\vec{z}, \vec{H}) and their orientation relatively to the z axis are characterized by the angles $\gamma_1(R)$ and $\gamma_2(R)$. The electric field vector of the incident laser beam has the components E_{0X} and E_{0Y} . Following the general theory in [18], at the front of the second slice, these components become (the phase factor $e^{-ikd+i\omega t}$ is omitted here and in all subsequent expressions since the final aim is to evaluate the light intensity):

$$E_{0X_1} = \left[1 - \frac{1}{2} ikdf(\alpha_{\perp} + \Delta\alpha < \sin^2 \zeta \cos^2 \psi >_1)\right] E_{0X} - \frac{1}{2} ikdf\alpha' < \cos \zeta >_1 E_{0Y} \quad (18)$$

$$E_{0Y_1} = \frac{1}{2} ikdf\alpha' < \cos \zeta >_1 E_{0X} + \left[1 - \frac{1}{2} ikdf(\alpha_{\perp} + \Delta\alpha < \sin^2 \zeta \cos^2 \psi >_1)\right] E_{0Y} \quad (19)$$

At the output of the second slice, the corresponding components are obtained in the same manner

$$E_{0X_2} = \left[1 - \frac{1}{2} ikdf(\alpha_{\perp} + \Delta\alpha < \sin^2 \zeta \cos^2 \psi >_2)\right] E_{0X_1} - \frac{1}{2} ikdf\alpha' < \cos \zeta >_2 E_{0Y_1} \quad (20)$$

$$E_{0Y_2} = \frac{1}{2} ikdf\alpha' < \cos \zeta >_2 E_{0X_1} + \left[1 - \frac{1}{2} ikdf(\alpha_{\perp} + \Delta\alpha < \sin^2 \zeta \cos^2 \psi >_2)\right] E_{0Y_1} \quad (21)$$

Introducing (18,19) into (20,21), we have

$$E_{0X_2} \simeq \left\{1 - \frac{1}{2} ikdf[(\alpha_{\perp} + \Delta\alpha < \sin^2 \zeta \cos^2 \psi >_1) - (\alpha_{\perp} + \Delta\alpha < \sin^2 \zeta \cos^2 \psi >_2)]\right\} E_{0X} - \frac{1}{2} kfd\alpha' [< \cos \zeta >_1 + < \cos \zeta >_2] E_{0Y} \quad (22)$$

$$E_{0Y_2} \simeq ikfd\alpha' [< \cos \zeta >_1 + < \cos \zeta >_2] E_{0X} + \left\{1 - \frac{1}{2} ikdf[(\alpha_{\perp} + \Delta\alpha < \sin^2 \zeta \cos^2 \psi >_1) - (\alpha_{\perp} + \Delta\alpha < \sin^2 \zeta \cos^2 \psi >_2)]\right\} E_{0Y} \quad (23)$$

The last expressions are obtained under the assumptions

$$\left| \frac{1}{2} ikdf (\alpha_{\perp} + \Delta\alpha \langle \sin^2 \zeta \cos^2 \psi \rangle_{1,2}) \right| \ll 1 \quad (24)$$

$$\left| \frac{1}{2} ikdf \alpha' \langle \cos \zeta \rangle_{1,2} \right| \ll 1 \quad (25)$$

which are realistic for diluted magnetic fluids ($f \ll 1$) and very thin layers (or slices).

The generalisation of the expressions (22,23) in the case of N slices follows directly:

$$E_X \simeq \left[1 - \frac{1}{2} ikdf \sum_{j=1}^N (\alpha_{\perp} + \Delta\alpha \langle \sin^2 \zeta \cos^2 \psi \rangle_j) \right] E_{0X} - \frac{1}{2} kfd\alpha' \sum_{j=1}^N \langle \cos \zeta \rangle_j E_{0Y} \quad (26)$$

$$E_Y \simeq \frac{1}{2} kfd\alpha' \sum_{j=1}^N \langle \cos \zeta \rangle_j E_{0X} + \left[1 - \frac{1}{2} ikdf \sum_{j=1}^N (\alpha_{\perp} + \Delta\alpha \langle \sin^2 \zeta \sin^2 \psi \rangle_j) \right] E_{0Y} \quad (27)$$

The light emerging from the last slice enters the analyzer and so, the magnitude of the electric field vector E at the analyzer output can be evaluated from (26,27)

$$E = E_X \sin \beta - E_Y \cos \beta = \frac{1}{2} ikdf \Delta\alpha \sum_{j=1}^N \langle \sin^2 \zeta \cos^2 \psi \rangle_j E_0 \sin \beta \cos \beta - \frac{1}{2} kfd\alpha' \sum_{j=1}^N \langle \cos \zeta \rangle_j E_0 \quad (28)$$

Consequently, the expression of the output laser intensity is given by Eq.(8), where the thermodynamical averages $\langle \dots \rangle$ are replaced by their expression (6) in the simpler case considered there.

FIGURE CAPTIONS.

1. Schematic setup for magnetic monopole induced magneto-optical effects in a magnetic fluid thin layer.
2. Computed number of photons of wavelength $\lambda = 632.8$ nm in the output light pulse for several samples and different monopole velocities.

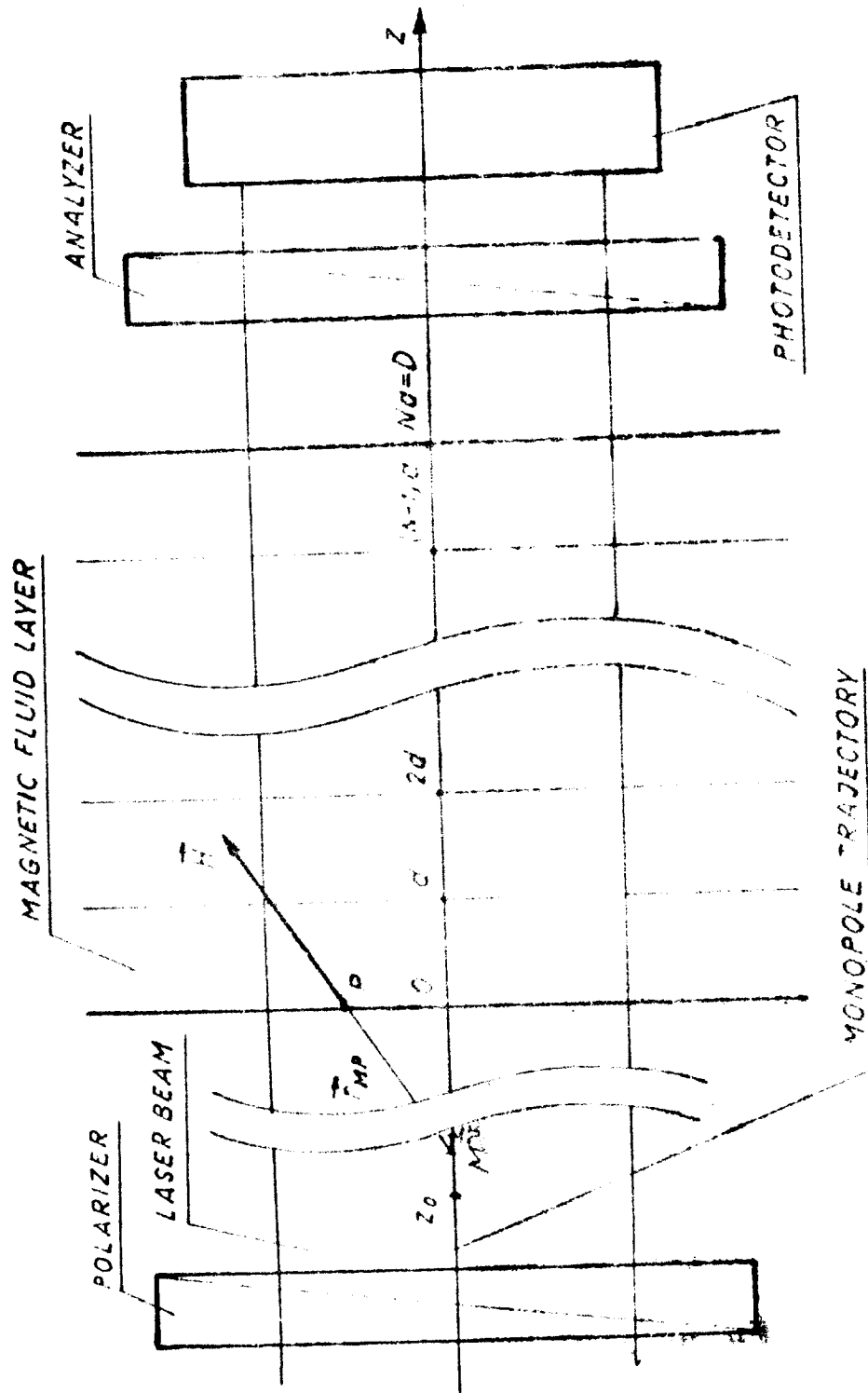


FIGURE 1

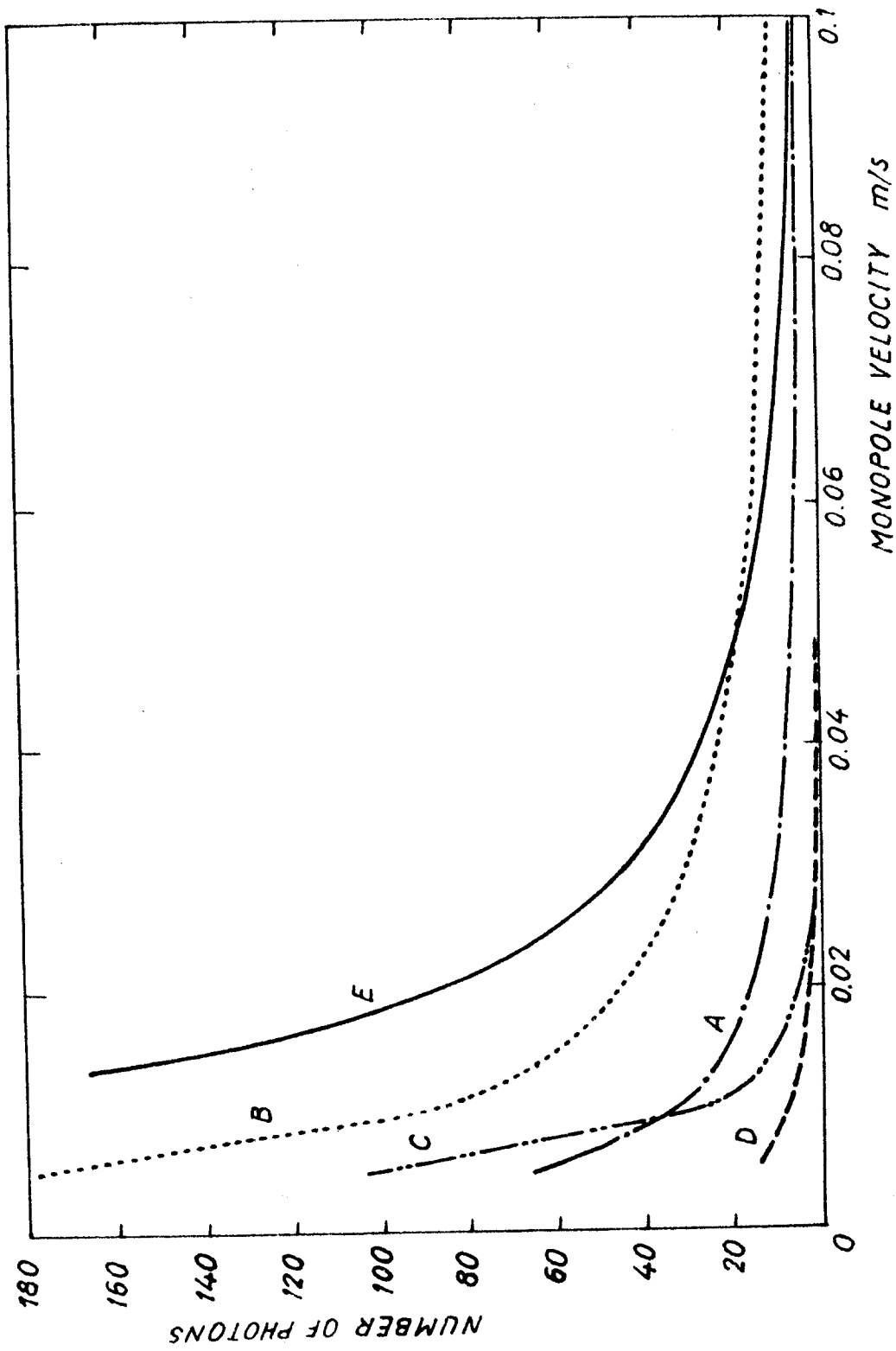


FIGURE 2

TABLES

Table 1.

sample	carrier liquid	colloidal particles	radius nm	τ_R	source
A	toluene	Co	3.3	0.003 μsec	[19]
B	toluene	Fe_3O_4	5.5	0.14 μsec	[19]
C	mixture water-glycerol	$CoFe_2O_4$	7.4	5.3 msec	[25]
D	mixture water-glycerol	$\gamma - Fe_2O_3$	4.25	1.55 msec	[25]
E	alkyl-naphtalene	Fe_3O_4	-	10.0 μsec	[13,18]

REFERENCES

- [1] GIACOMELLI G., *La Rivista del Nuovo Cimento* 7 (1984) No. 12.
- [2] GROOM D.E., *Physics Reports* 140 (1986) 323.
- [3] HUBER M.E., CABRERA B., TABER M.A. and GARDNER R.D., *Phys. Rev. Lett.*, 64 (1990) 835.
- [4] BERMON S., CHI C.C., TSUEI C.C., ROZEN J.R., CHAUDHARI P. and McELFRESH M.W., *Phys. Rev. Lett.*, 64 (1990) 839.
- [5] MARTEMYANOV V.P. and KHAKIMOV S.Kh., *Z. Eksp. Teor. Fiz.* 35 (1972) 20 (in Russian).
- [6] KIRZHNITS D.A., *Z. Eksp. Teor. Fiz.* 98 (1990) 769 (in Russian).
- [7] GOTO E., KOLM H.H. and FORD K.W., *Phys. Rev.*, 132 (1963) 387.
- [8] EBISU T. and WATANABE T., *Phys. Rev. D*, 36 (1987) 3359.
- [9] ROSENSWEIG R.E., *Ferrohydrodynamics* (University Press, Cambridge) 1985.
- [10] BLUMS E.Ya, MAIOROV M.M. and CEBERS A.O., *Magnetic Liquids* (Zinatne, Riga, Latvia) 1989 (in Russian).
- [11] SHLIOMIS M.J., *Sov. Phys. Usp.* 17 (1974) 153.
- [12] TAKETOMI S., *Japanese J. Appl. Phys.*, 22 (1983) 1137.
- [13] TAKETOMI S., OGAWA S., MIYAJIMA H., CHIKAZUMI S., NAKAO K., SAKAKIBARA T., GOTO T. and MIURA N., *J. Appl. Phys.*, 64 (1988) 5846.
- [14] BACRI J.C., PERZYNSKI R., SALIN D., CABUIL V. and MASSART R., *J. Magn. Magn. Mater.* 85 (1990) 27.
- [15] BACRI J.C. and PERZYNSKI R., *Magnetic Fluids in Devices* (European Advanced Short Course "Magnetic Fluids and Powders New Technological Materials", Minsk, Byelorussia, 20-31 May 1991).
- [16] DAVIES H.W. and LLEWELLYN J.P., *J. Phys. D: Appl. Phys.* 13 (1980) 2327.
- [17] SCHOLTEN P.C., *IEEE Transactions on Magnetics*, MAG-16 (1980) 221.
- [18] TAKETOMI S., *The magneto-optics of magnetic fluids: Principles and applications* (European Advanced Short Course "Magnetic Fluids and Powders - New Technological Materials", Minsk, Byelorussia, 20-31 May 1991).
- [19] JANSSEN J.J.M. and PERENBOOM J.A.A.J., *J. Magn. Magn. Mater.* 81 (1989) 14.
- [20] TAKETOMI S., *US Patent* 4,812,767 (1989).
- [21] HEGEDÜS E. and VÉKÁS L., *Possible Magnetic Monopole - Magnetic Fluid Interactions*, University of Timișoara, preprint UTFT 1/1986 (unpublished).
- [22] HEGEDÜS E., SOFONEA V. and VÉKÁS L., *Sixth International Conference on Magnetic Fluids*, July 20-24, 1992, Paris, France. (Book of Abstracts, paper T3/11).
- [23] BORN M., and WOLF E., *Principles of Optics*, 3rd. Edition, (Pergamon Press, Oxford) 1965.
- [24] BACRI J.C., DJERFI K., NEVEU S. and PERZYNSKI R., to appear in *J. Magn. Magn. Mater.* (1993).
- [25] NAKATANI I., HIJIKATA M. and OZAWA K., *Sixth International Conference on Magnetic Fluids*, July 20-24, 1992, Paris, France. (Book of Abstracts, paper T1/4).
- [26] TAKETOMI S., OZAKI Y., KAWASAKI K. and MIYAJIMA H., *Sixth International Conference on Magnetic Fluids*, July 20-24, 1992, Paris, France. (Book of Abstracts, paper T1/5).

- [27] ZIOLO, R., GIANNELIS E.P., WEINSTEIN B., O'HORO M.P., GANGULY B.N., MEHROTRA V., RUSSELL M., HUFFMAN D.R., *Science* 257 (1992) 219.

