Laboratori Nazionali di Frascati

LNF-69/48

G. Sacerdoti : A TECHNIQUE FOR THE MEASUREMENT OF THE FARADAY EFFECT IN PULSED MAGNETIC FIELDS AT LOW TEMPERATURES

Estratto da : Physics of Solids in Intense Magnetic Fields (Plenum Press, 1969), p. 285

Reprinted from: PHYSICS OF SOLIDS IN INTENSE MAGNETIC FIELDS
(Plenum Press, 1969)

Chapter 12

A TECHNIQUE FOR THE MEASUREMENT OF THE FARADAY EFFECT IN PULSED MAGNETIC FIELDS AT LOW TEMPERATURES

G. Sacerdoti
Comitato Nazionale per l'Energia Nucleare
Roma, Italy

This chapter describes a technique for measuring the spin-lattice relaxation time in paramagnetic crystal and the Faraday effect in different materials. The technique was suggested by Prof. Toraldo di Francia of the University of Florence, and an apparatus based on this technique has been developed for use in the Synchrotron Laboratory at Frascati, Italy. The sample is put in a pulsed magnetic field whose duration is comparable to (or larger than) the relaxation time of the spin-lattice of the crystal. By measuring the magnetic field H versus time and the magnetization of the specimen it is possible to get the value of τ as a function of temperature and magnetic field.

The magnetization M of the specimen is revealed by measuring the angle of Faraday rotation θ that a linearly polarized beam of light undergoes upon passing through the specimen; M is proportional to this angle of rotation at temperatures sufficiently low, on the order of 1 °K (Fig. 1).

The experimental apparatus is shown in Fig. 2. A photograph of the same apparatus is shown in Fig. 3. The light from a laser passes through an orientable glass deflecting system, having all mechanical degrees of freedom, and a diaphram to limit the intensity of the beam; the light then crosses a glass window in the Dewar and a Glan Thompson polarizer at room temperature* in the vacuum chamber of the Dewar; the angular position

* At low temperature both the nicols and the Glan Thomson become opaque.

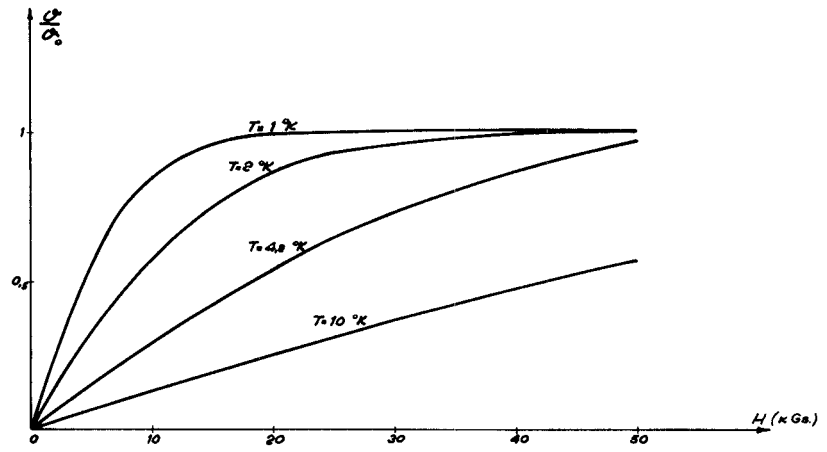

Fig. 1. Behavior of Faraday rotation ϑ versus magnetic field. Curves are relative to the ethyl sulfate hydrate of neodymium.

is easily regulated and read on a circular graduated scale. Then at the temperature of liquid N_2 there is a thermal screen with a small hole. The light enters the liquid helium container through an optically-flat glass window.

After a few millimeters of liquid He there is another window through which the light enters the glass tube containing the specimen; the glass tube is evacuated to avoid too long a path in liquid helium for reasons to be given shortly. From the container of the specimen the light passes through the analyzer (another Glan Thomson polarizer) and then through another window to the photomultiplier tube.

Around the tube that contains the specimen there is a coil of known dimensions for measuring the magnetic field. The magnetic field is obtained by discharging a condenser bank through a multilayer coil immersed in liquid N_2. The energy of the bank is 136 kJ and the maximum voltage is 9 kV. Figure 4 is a photograph of the coil with inner radius $r_i = 38$ mm and with height $h_0 = 180$ mm. The maximum field obtainable is about 100,000 G and the time of discharge is 60 msec. At the maximum field it is necessary to use a crowbar to avoid reversal recharge of condenser bank. The magnet is suspended from the upper plate of the stainless steel Dewar connectors with rubber lining to decrease mechanical vibrations of frequency higher than the frequency of discharge of the condenser bank, but this doesn't become necessary until 60% of the maximum field is reached.

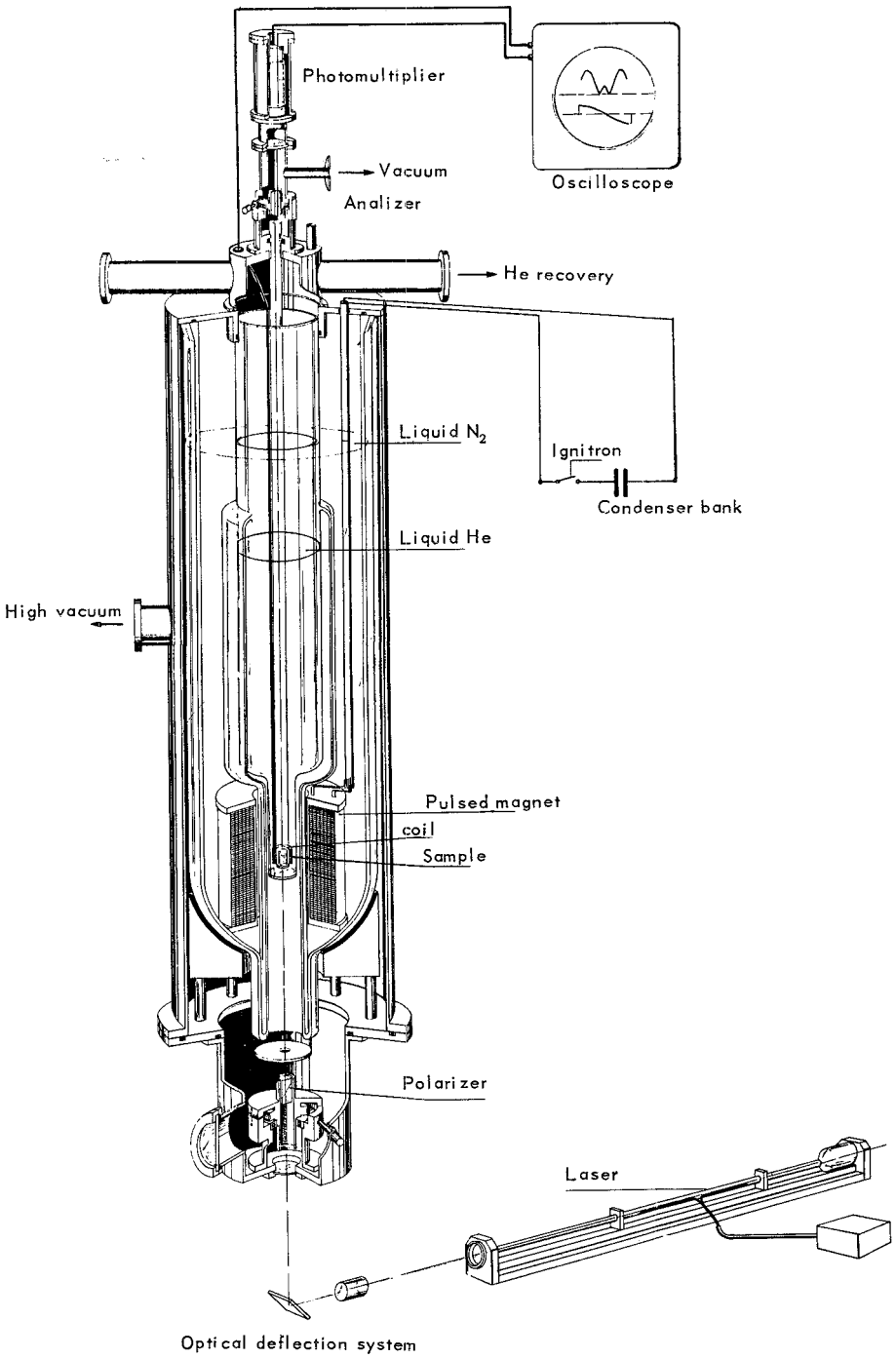

Fig. 2. Schematic of the experimental apparatus (vertical beam).

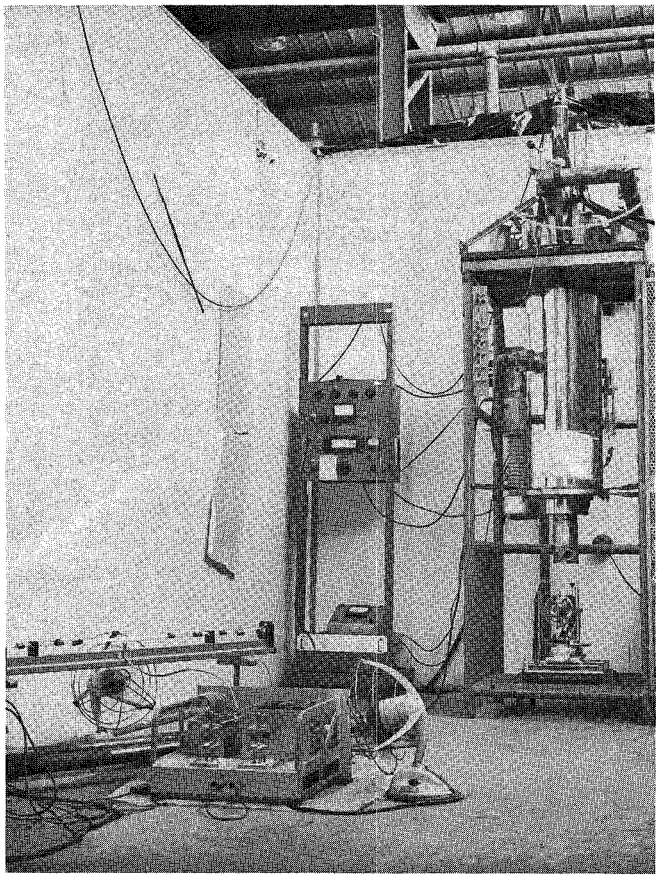

Fig. 3. Photograph of the experimental apparatus.

The following points will be discussed:

1. The reasons we have preferred to work with a vertical rather than with a horizontal light beam.

2. The reasons the specimens are not directly immersed in liquid helium.

3. The best fashion for detecting and measuring the angle of rotation as a function of time and of magnetic field.

4. The main errors in these measurements.

5. The possibility of working at higher fields with a similar apparatus.

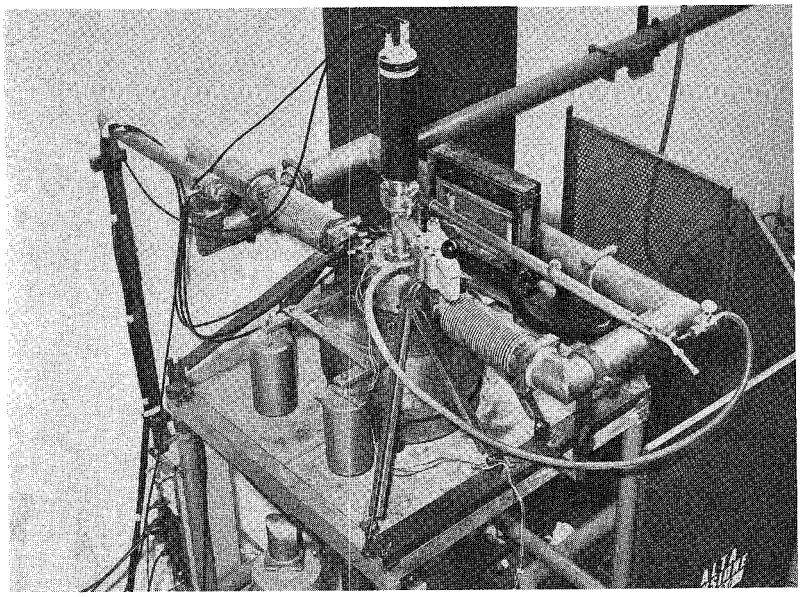

Fig. 4. Photograph of the coil.

1. With a horizontal beam the layout of the apparatus is that shown in Fig. 5. However, the different parts of the apparatus are at different temperatures, and the resulting thermal deformations cause changes in optical alignment, particularly at different levels of liquid He.

To avoid this problem, it is necessary to use the arrangement shown in Fig. 6), where the geometrical position of the different parts of the Dewar are fixed by pyrex supports (Fig. 7); the design is complicated.

2. At first the specimen was immersed in liquid helium, but at temperatures between 4.2° and 2.2 °K (λ point of liquid He) the passage of the beam through the helium caused noise because there was a depolarization of light due to the formation of bubbles when helium passed from liquid to gas. Below $T = 2.2$ °K the noise disappeared, and it was then possible to work with the specimen immersed in liquid He.

With the actual apparatus in use we reduced the path in helium to a few millimeters, and the bubble production did not create detectable disturbances. The thermal conductivity was sufficient to guarantee that the specimen was at the temperature of liquid He.

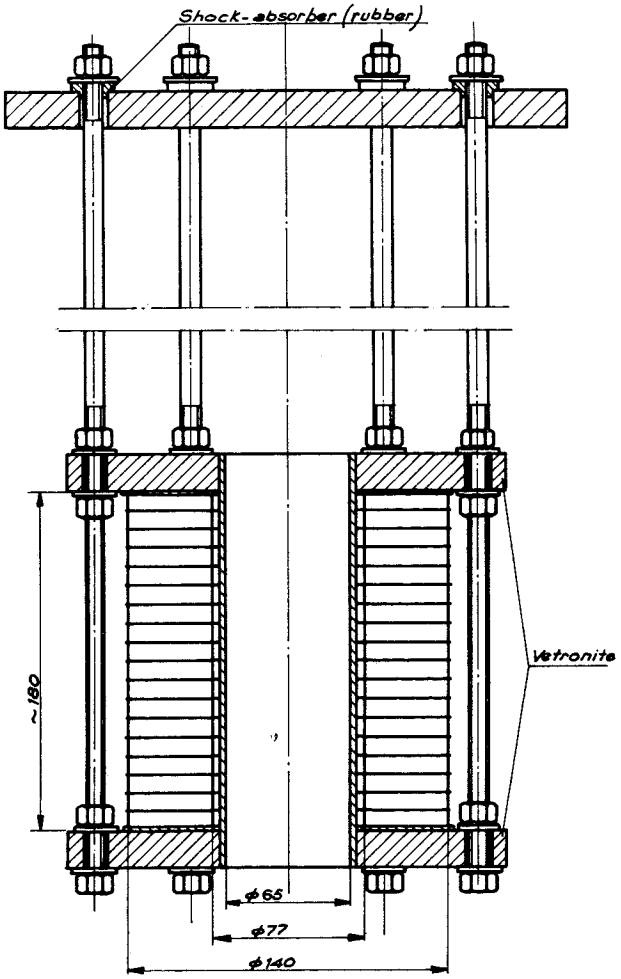

Fig. 5. Scheme of the pulsed coil.

3. Now we describe the measurement of the Faraday rotation, and thus Verdet's constant ($\tau \ll T$, the duration of the pulsed magnetic field). The output signal from a photomultiplier in the case of monocromatic light is (when $\tau_{\text{relaxation}}$ is zero and $M \equiv H$)

$$V_u(t) = K\cos^2\left(\theta_0 + V\int_0^l H\,dl\right) = K\cos^2(\theta_0 + \theta_r) \tag{1}$$

where K is a coefficient proportional to the initial beam intensity and to the sensitivity of the photomultiplier, θ_0 is the angle between the light

polarizer and light analyzer, θ is the Faraday rotation angle, V is the Verdet constant, and l is the length of the specimen. When the light is not monochromatic the signal output is given by

$$V_u(t) = \int_{\lambda_{\min}}^{\lambda_{\max}} I(\lambda)T(\lambda)\delta(\lambda)\cos^2\left[\theta_0 + V(\lambda)\int_0^l H\,dl\right] d\lambda \qquad (2)$$

where $I(\lambda)$ is the intensity of the light source (a function of wavelength), $T(\lambda)$ is the transmissibility of the specimen (a function of wavelength), $\delta(\lambda)$ is the sensitivity of photomultiplier (a function of wavelength), l is the length of specimen, and $V(\lambda)$ is Verdet's constant (a function of wavelength).

We tried to make measurements using a light source from a sodium arc lamp ($\lambda_1 = 5890$ Å, $\lambda_2 = 5896$ Å) using an RCA 6217 photomultiplier, but the influence of the pulsed magnetic field on the source had the effect of changing the emission intensity by a factor of 30% to 50% despite screening by permalloy around the lamps. We also tried using an incandescent lamp and an RCA 6217 tube, but because of the many parameters in Eq. (2) it was very difficult to get noise-free data on the constant $V(\lambda)$. The photomultiplier used had low sensitivity in the red region, at which frequencies our specimens are transparent. As a result we had to use a helium–neon laser with a Philips-type 150CUP photomultiplier with a good sensitivity in red region.

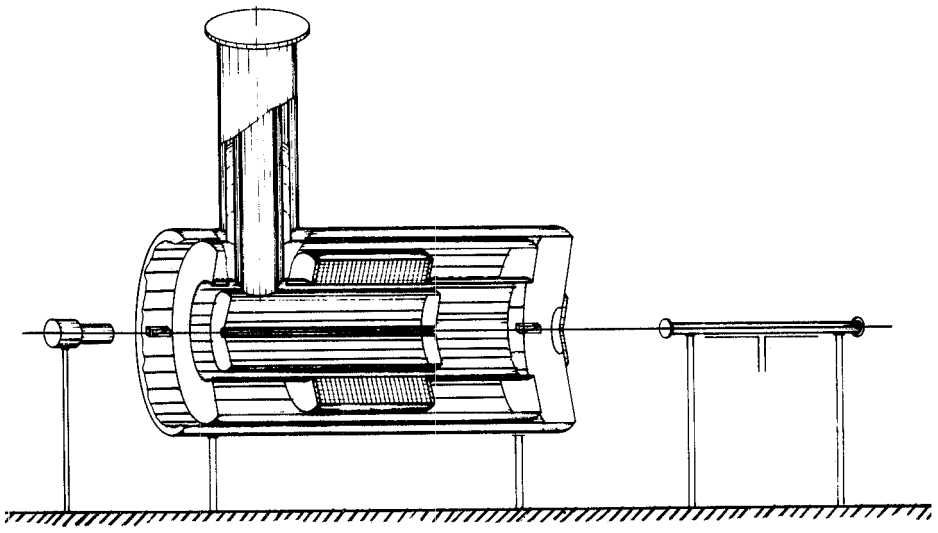

Fig. 6. Scheme of a possible experimental apparatus (horizontal beam).

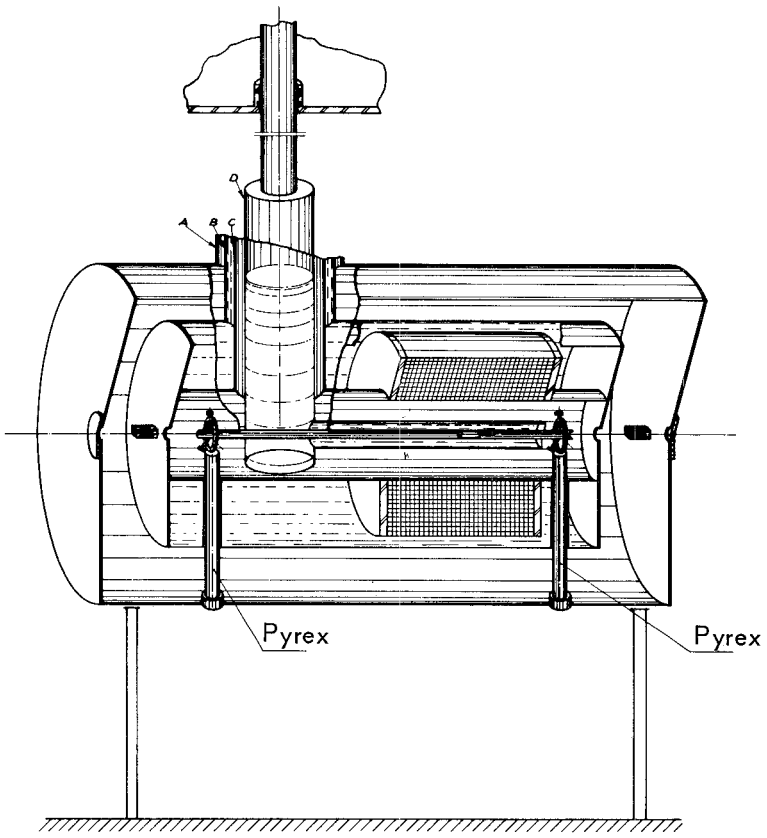

Fig. 7. Detail of the apparatus with horizontal beam.

Equation (1) was used to analyze the results of the measurements, and the coefficient we looked for was Verdet's constant V.

Different methods of data reduction can be used.

(i) We assume *a priori* that during the pulse the value of K remains constant.

The best fit of the curves $V(t) = K\cos^2(\theta_0 + V\int H\,dl)$ taken from a photograph at the oscillograph of the signal $V(t)$ (θ_0 is known) and of the signal proportional to dH/dt (from the pick-up coil of known area) enable one to obtain the values of V and K. We tried this method using a scanning machine and a PDP-8 computer to get the points of the curves $(dH/dt)(t)$ and $V_u(t)$ from the negative of the photograph; to find the best fit it is possible to use a computer or to proceed by manual calculation (Fig. 8).

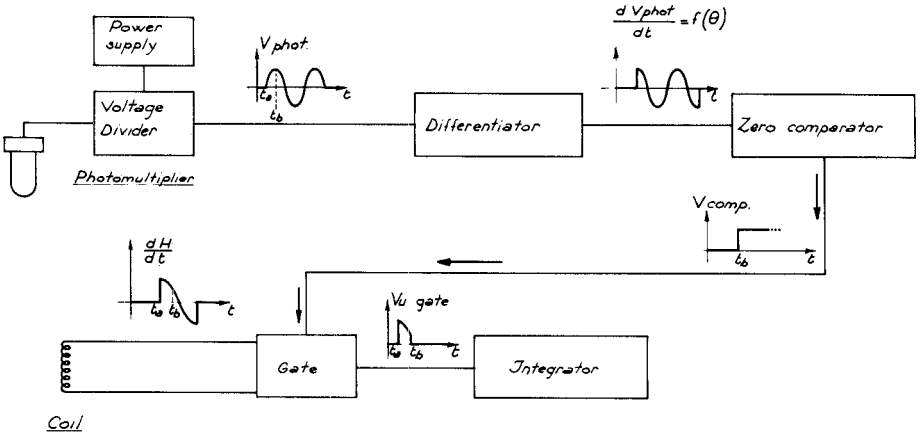

Fig. 8. Circuit of a digital system for detecting $H = H(\frac{1}{2}\pi - \theta_r)$ for Verdet's constant.

In the data reduction one may also try to use the value of $V_{\max}$ obtained when the polarizer and the analyzer are parallel. This value can be found from:

$$\theta_0 + \theta_2 = \arccos\,[V_u(t)/V_{u,\max}]^{1/2} = \theta_0 + V \int H\,dP \tag{3}$$

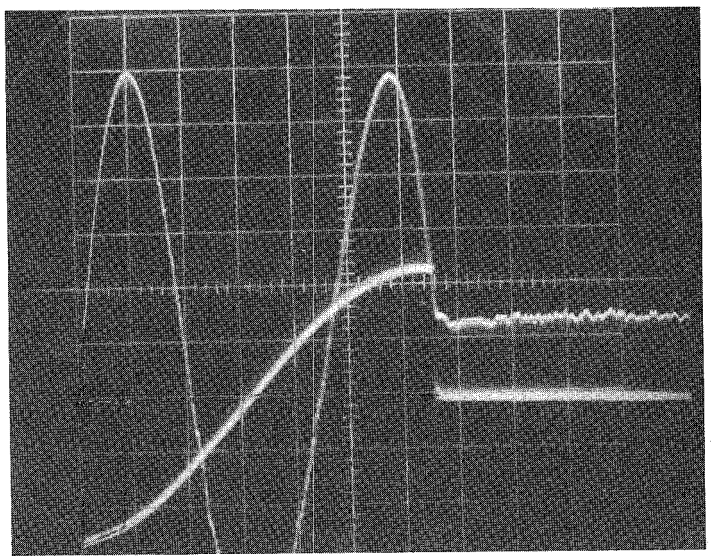

Fig. 9. Oscillograph traces of $V(t)$ and dH/dt.

(ii) To reveal the magnetic field and $V(t)$ on oscillograph changing from a photo to the other the value of θ_0. At the instant where $V(t)$ is minimum (i.e. ~ 0) it results that $\theta_r = (\pi/2) - \theta_0$, and this is determined independently from the fact that K is or is not constant (Fig. 8).

(iii) An integrator can be used to measure magnetic field. The integrator may be digital and the gate may be driven by the derivative of $V_u(t)$. When it changes sign the gate closes, and thus one obtains the value $H = H(\frac{1}{2}\pi - \theta_0)$. At Frascati we are working in this direction.

The first method is obviously less precise than the second. The third should be even more accurate.

Different problems arise when we work on materials that present a relaxation time longer than or of the same order of magnitude as the discharge time of the bank of condensers. In this condition it is better to work without a crowbar, as I will demonstrate.

We know that the following relation between the relaxation time of the magnetic field H and the magnetization M of the specimen is valid:

$$\frac{dM_1}{dt} = \frac{M_0(H_0) - M_1}{\tau(H_0)} \tag{4}$$

where M_1 is the magnetization of the specimen, $M_0(H_0)$ is the equilibrium

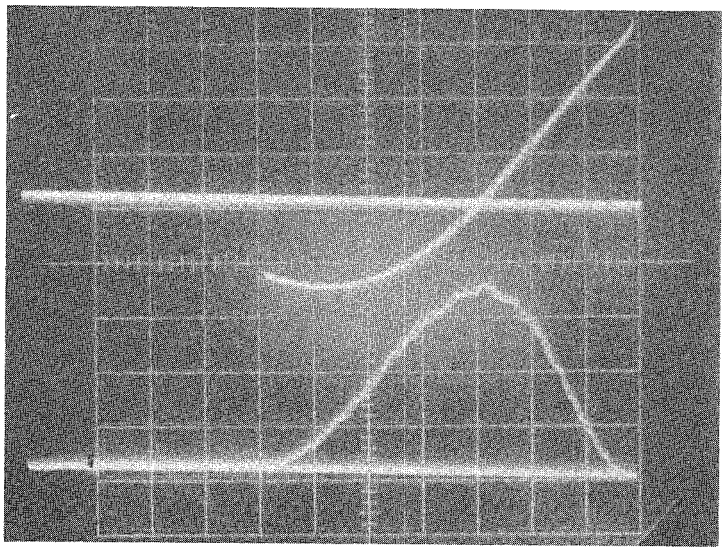

Fig. 10. Oscillographic traces of $V(t)$ and dH/dt with $\theta_0 = 20°$.

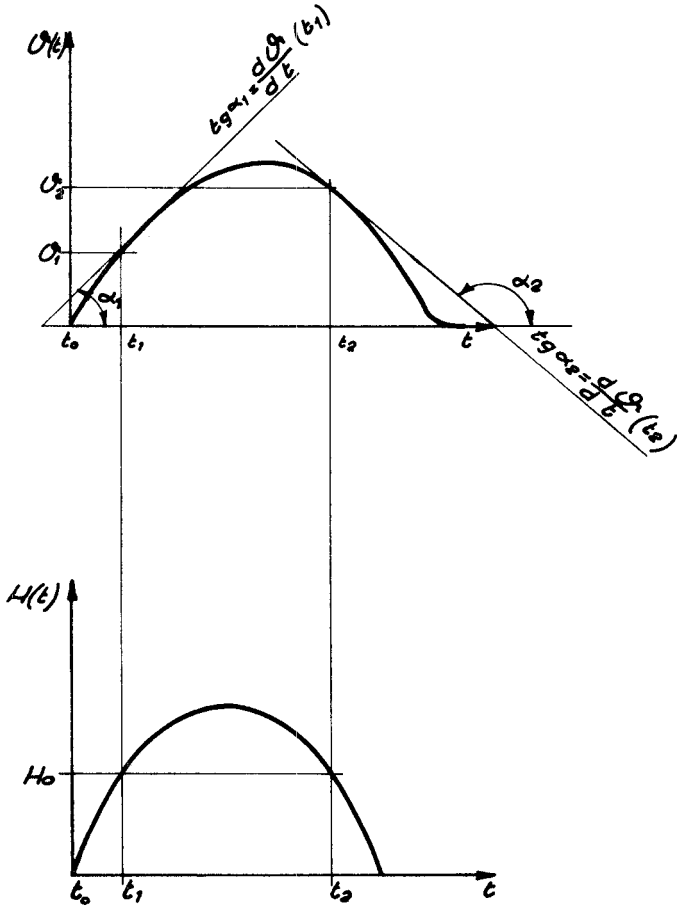

Fig. 11. Scheme for analyzing the output signal from a photomultiplier so as to obtain $\tau(H)$.

magnetization of the specimen at the magnetic field H_0, and $\tau(H_0)$ is the relaxation time.

Consider two points 1 and 2 on the curve $V(t)$ corresponding to the same value of H_0 (i.e., M_0) (see Fig. 11). We may write

$$\frac{dM_1}{dt} = \frac{M_0(H_0) - M_1}{\tau(H_0)} \tag{5}$$

$$\frac{dM_2}{dt} = \frac{M_0(H_0) - M_2}{\tau(H_0)} \tag{6}$$

Taking the difference, we obtain

$$\frac{dM_1}{dt} - \frac{dM_2}{dt} = \frac{M_2 - M_1}{\tau(H_0)} \tag{7}$$

and in the limit of proportionality between M and θ we may write

$$\frac{d\theta_1}{dt} - \frac{d\theta_2}{dt} = \frac{\theta_2 - \theta_1}{\tau(H_0)} \tag{8}$$

If there are many rotations (this may happen only for very long specimens) we obtain

$$\frac{d\theta_1}{dt} = \frac{\pi}{\Delta t_1}, \qquad \frac{d\theta_2}{dt} = \frac{\pi}{\Delta t_2}$$

where Δt_1 and Δt_2 are the time intervals between through the minimum of voltage $V(t)$ and θ_1 and θ_2 are obtained by interpolation. If the rotation is $<2\pi$ it is necessary to get the terms in Eq. (8) by many registrations in which one changes θ_0 ($H_{\max} = \text{const}$). It is thus possible to get terms proportional to $d\theta_1/dt$, $d\theta_2/dt$, θ_1, and θ_2, and so to obtain $\tau(H)$.

It is possible to think of dividing the light in different paths and of analyzing each one with different θ_{0i} (i indicates the path, as shown in Fig. 12) and to obtain sufficient data from the different curves registered simultaneously to obtain the value of $\tau(H)$; this may be a difficult job.

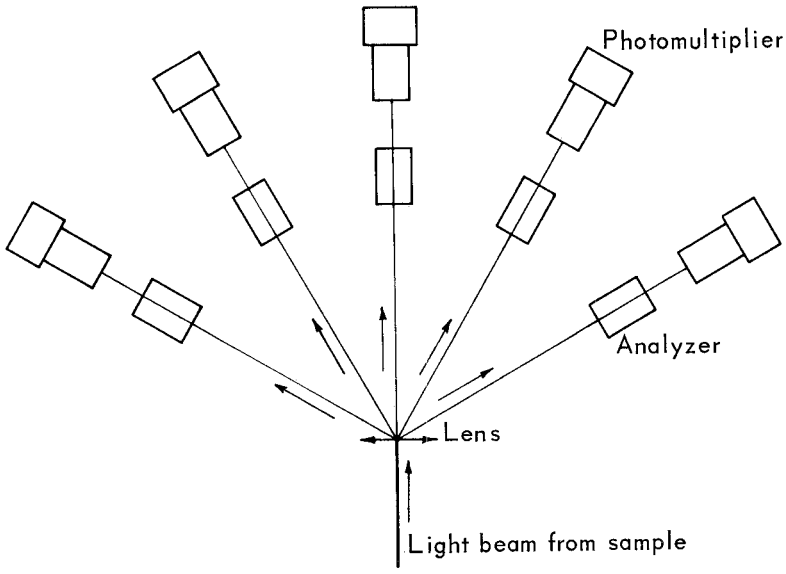

Fig. 12. Scheme of experimental apparatus for obtaining parallel analyses of rotation with different angles.

4. The causes of errors in this kind of measurement are many. Some of the more important error sources are:

(*a*) Depolarization of light due to imperfections and impurities in the specimens and other glass windows. This is not a cause of strong errors if the intensity of the source remains constant. By this assumption the only effect here is to increase the voltage $V_u(t)$ by a constant, and if the experiment works by changing θ_0 this should not introduce errors.

In addition, the bubbles of gas in the liquid helium may cause random depolarization at temperature beyond the λ-point.

(b) Fluctuation in the intensity of the light source due, for example, to the discharge of the condenser bank and noise induced in the photomultiplier and in the wires to the oscillograph.

TABLE I

Faraday Rotation Measurements*

Temperature (°K)	B (Wb/m²)	θ (deg)
77	1.1	7.9
	2	13.1
	3.1	19.8
	4.2	25.3
	5.2	37.1
4.2	10 ± 1	0.55 ± 0.08
	20 ± 1	1.10 ± 0.08
	30 ± 1	1.60 ± 0.09
	40 ± 1	2.12 ± 0.10
	50 ± 1	2.71 ± 0.11
	60 ± 1	3.70 ± 0.11
	70 ± 1	3.69 ± 0.20
1.2	10	0.084
	20	0.139
	40	0.308
	70	0.610
	250	2.105

* Sample: Neodymium glass (length 22.25 mm) plus Pyrex (length 8 mm). Light: He–Ne laser.

In Table I we give some results we obtained. In some cases noise was ± 0.1 V, in other cases ± 0.3 V, compared to 50 V of maximum signal (polarizer and analyzer parallel). It should seem possible in principle to decrease this noise by using filters at frequencies 20–30 times the frequency of discharge of the condenser bank. However, this would decrease the precision in the determination of the point at which the value of $V(t)$ passes through a minimum because the filter itself will produce a delay in the signal of the same order of magnitude as the noise shut down. The noise is often comparable to a rotation of 2°; in the better photographs it corresponds to only 1° ($\theta_0 = 0$).

To reduce the noise of the photomultiplier we also cool it and its voltage divider by liquid nitrogen.

(*c*) The mechanical vibration of the Dewar because of the pulsed magnet. These vibrations are not a problem, because the frequency is much lower than that of the pulsed field. A photograph of the output with $\theta_0 = 20°$ and with the time scale amplified is shown in Fig. 10.

(*d*) Errors in the measurement of the magnetic field. When we obtain the magnetic field by graphical integration of the derivative versus time from the oscillographic record most of the error is due to the scale x, y of the oscilloscope and the precision in the determination of the instant t at which the rotation is equal to $\frac{1}{2}\pi - \theta_0$.

(*e*) Residual rotation in the glass windows. This rotation has been measured at different fields and temperatures, and we have corrected the measurements on the specimen by the corresponding amount.

(*f*) Nonuniformity of the magnetic field in the magnet used. The magnetic field was uniform in the specimen to better than 1%; it is not an important cause of errors.

5. We think that with a larger condenser bank it should be possible to increase the field to 200 kG with the same period of discharge, and to 300 kG with a shorter period of 20-30 μsec. We have already tested pulsed magnets with fields of this order of magnitude.

Using fields of 30 kG preliminary measurements of Verdet's constant have been made on a neodymium-doped glass 2 cm in length. The results obtained are shown in Table II. We have not yet made measurements of spin-lattice relaxation time on the ethyl sulfate hydrate of neodymium because we found many difficulties in preparing specimens and working and polishing their surfaces; only one of the thirty which we prepared seems good enough to be used for our measurements, i.e., it does not depolarize light. We have chosen that "difficult" material (if put in a vacuum

TABLE II

Verdet's Constant as a Function of Temperature in Neodymium Glass

V $\left(\frac{\text{deg}}{\text{cm-Wb/m}^2}\right)$	T (°K)
55.1	1.2
10.8	4.2
3.56	77

at room temperature it becomes opaque to light because the HO crystal ions go to the surface, creating a white layer; thus it is necessary before doing vacuum work to freeze the specimen, avoiding the creation of an opaque layer on the crystal by the residual humidity of air) because it was possible to develop a theory of the phenomenon and to test its validity. Our results [see (6)] change Orbach's results [see (7)] by an order of magnitude and seem to agree better with the few experimental data available on $\tau(H, T)$ at low fields 2 kG. We also calculated the "bottleneck effect," both geometrical and spectral, and the order of magnitude of our approximate calculations indicates that this does not affect our measurements at temperatures greater than 1 °K.

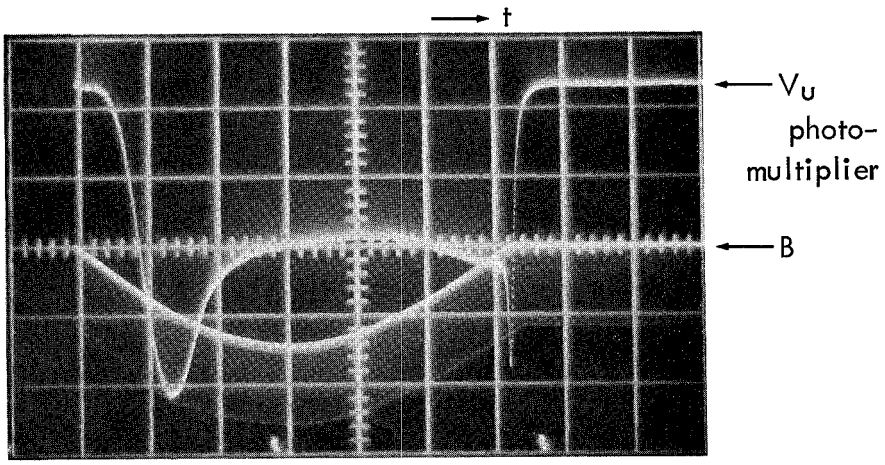

Fig. 13. Experimental result for neodymium ethyl sulfate hydrate. $T_H = 1.0$ °K, the angle between the polarizer and the analyzer is 90°, $B_{\max} \approx 3.9$ Wb/m².

ACKNOWLEDGMENTS

The experimental work reported here has been supported by Consiglio Nazionale delle Ricerche.

REFERENCES

1. C. Faloci, M. Mancini, G. Sacerdoti, G. Toraldo di Francia, and F. Uccelli, INFN/FM - 65/1 (4 January 1965).
2. R. Bruzzese, F. Frazzoli, M. Mancini, G. Sacerdoti, G. Toraldo di Francia, and F. Uccelli, INFN/FM - 65/3 (December 1965).
3. R. Bruzzese, F. Frazzoli, M. Mancini, G. Sacerdoti, G. Toraldo di Francia, and F. Uccelli, INFN/FM - 66/2 (December 1966).
4. C. Faloci, Graduation Thesis, 1964.
5. F. Frazzoli, Graduation Thesis, 1965.
6. F. Frazzoli and M. Mancini, "A Contribution to the Theory of Spin-Lattice Relaxation Time in Rare-Earth Salts," *Nuovo Cimento, Ser. X* **53B**: 471–484 (1968).
7. A. A. Manenkov and R. Orbach (eds.), *Spin-Lattice Relaxation in Ionic Solids*, Harper and Row, New York, 1966.

NOTE ADDED IN PROOF

Following the Crete meeting at which the paper on which this chapter is based was delivered, we experimented on neodymium ethyl sulfate hydrate. A characteristic photograph of the photomultiplier signal and magnetic field versus time is shown in Fig. 13. It is evident that there is a relaxation time and a saturation effect. We are now analyzing data, and our result will be published.