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## FIRST MEASUREMENT OF THE MAGNETIC BIREFRINGENCE OF HELIUM GAS

# First measurement of the magnetic Birefringence of Helium gas

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## Abstract

Using a sensitive ellipsometer we have measured the Cotton Mouton constant of Helium at 514.5 nm. We have found, at 1 atm and 0 °C that  $C_{CM}(\text{He}) = (3.5 \pm 0.7) 10^{-20} \text{ Gauss}^{-2} \text{ cm}^{-1}$ , in good agreement with theoretical calculations.

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An experiment to detect the production of scalar and pseudoscalar particles, through their coupling to two photon, has recently been conducted [1]. Measurements in high vacuum were taken using a sensitive ellipsometer. To calibrate this apparatus, the Cotton Mouton constant of Nitrogen gas and Neon gas have been measured [2]. In this letter we report the first measurement of the Cotton Mouton constant of Helium gas; to our knowledge previous experiments have only been able to set upper bounds [3].

The Cotton Mouton (CM) effect [4] refers to the birefringence induced in a gas by a magnetic field. The constant  $C_{CM}$  is defined by

$$\Delta n = n_p - n_n = C_{CM} \lambda B^2, \quad (1)$$

where  $n_p$  ( $n_n$ ) is the refractive index for light polarized parallel (normal) to the magnetic field,  $B$  is the component of the magnetic field normal to the direction of propagation of the light of wavelength  $\lambda$ . The difference in the refractive indices can be determined by measuring the ellipticity  $\psi_e$  acquired by linearly polarized light after traversing the medium in the presence of the magnetic field

$$\psi_e = \frac{\pi L}{\lambda} \Delta n = \pi C_{CM} \sin 2\theta \int (\vec{B} \times \vec{k})^2 dx \quad (2)$$

where  $L$  is the total optical path length,  $\vec{k}$  is a unit vector in the direction of light propagation vector, and  $\theta$  is the angle between  $\vec{B} \times \vec{k}$  and the polarization (electric field) vector of the light. The integration is carried over the length of the optical path.

In our set-up we use an Argon ion laser ( $\lambda = 514.5$  nm) and two 4.5 m long superconducting dipoles [5]. The polarization is at  $45^\circ$  with respect to the direction of the magnetic field, which is amplitude modulated from 1.94 T to 2.48 T at a frequency of 30.517 mHz. The induced ellipticity is converted to an optical rotation by a quarter-wave ( $\lambda/4$ ) plate and mixed with the rotation signal of a Faraday cell driven at a frequency of 312.5 Hz. To augment the effect by increasing the optical path  $L$  we used a multipass optical cavity consisting of two dielectric multilayer interferometric mirrors, focal length 950 cm, separated by a distance of 1380 cm. The reflectivity was better than 99.8%. For the measurements reported here the light made 10 passes in the cavity, while for measurements in vacuum [1] we have achieved about 2000 traversals by slightly deforming one of the mirrors [6].

The apparatus and the data acquisition system have been discussed in detail in ref.

2. Fig.1 shows a schematic drawing of the setup. The polarizing prisms P and A are

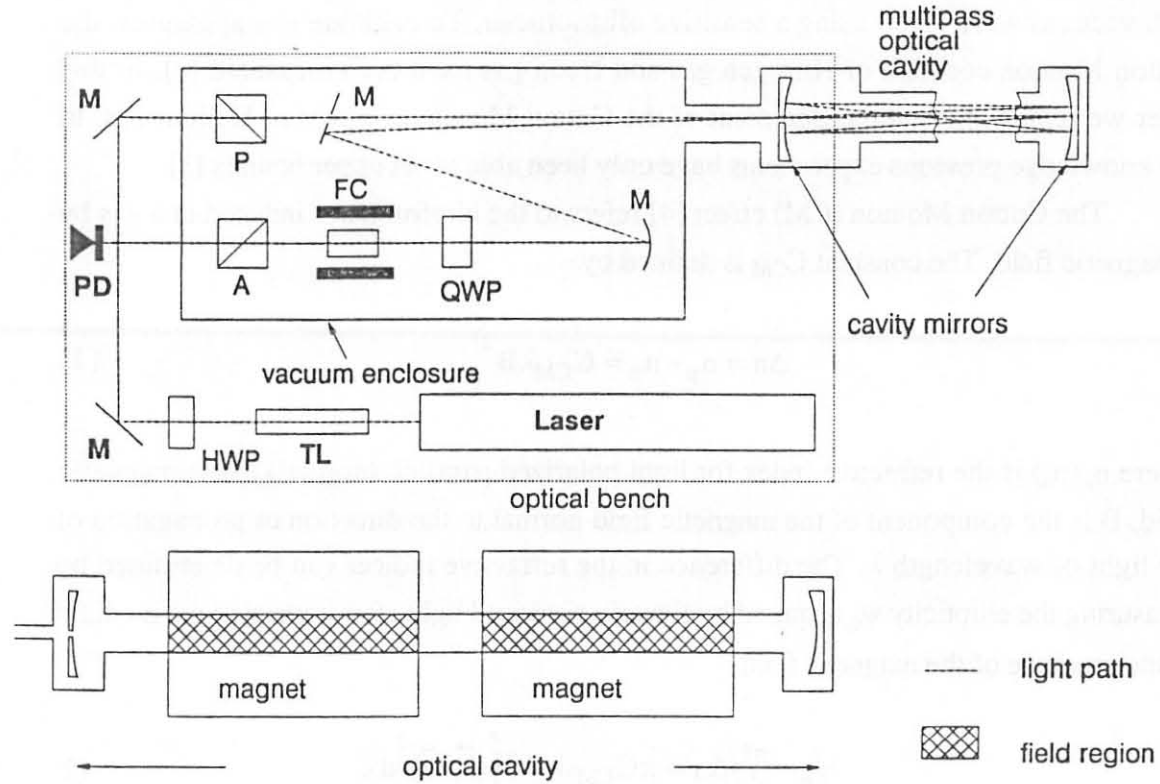


Fig. 1 : Schematic drawing of the sperimental apparatus.

crossed for maximum extinction. In this case the light power incident on the photodiode PD can be written as

$$W(t) = W_0 \left\{ \sigma^2 + [\eta(t) + \psi(t) + \alpha(t)]^2 \right\} \quad (3)$$

where  $W_0$  is the light power before the analyzing prism, typically 10 - 50 mW,  $\sigma^2$  is the extinction factor (typically  $10^{-7}$ ).  $\eta(t) = \eta_0 \cos(2\pi f_F t + \Phi_F)$  is the rotation angle introduced by the Faraday cell (typically  $\eta_0 \approx 10^{-3}$  rad and  $f_F = 312.5$  Hz) and  $\psi(t)$  is the rotation due to eq. (2) after the quarter wave plate QWP. In view of the periodic modulation of the magnetic field,  $\psi(t)$  can be expressed as  $\psi(t) = \psi_0 \cos(2\pi f_M t + \Phi_M)$  with  $f_M = 30.517$  mHz;  $\alpha(t)$  is the residual unavoidable misalignment angle between polarizing and analyzing prisms (typically  $10^{-6}$ ). The amplitude  $\alpha(t)$  drifts slowly over a magnet period

and  $\alpha(t)$ ,  $\psi_0 \ll \eta_0$ , so the signal at the output of the preamplifier can be written to sufficient accuracy as

$$V(t) \propto W_0 \left\{ \sigma^2 + \frac{\eta^2}{2} + 2\alpha\eta_0 \cos(2\pi f_F t + \Phi_F) + \eta_0 \psi_0 \cos[2\pi(f_F - f_M)t + \Phi_{M-}] + \eta_0 \psi_0 \cos[2\pi(f_F + f_M)t + \Phi_{M+}] + \frac{\eta_0^2}{2} \cos[4\pi f_F t + 2\Phi_F] \right\} \quad (4)$$

Table 1 lists the relevant spectral components of the signal indicated by Eq.(4); in this notation the amplitude of the spectral components of  $\psi(t)$  is

$$\psi_0 = \frac{\eta_0 I_{M+}}{2I_{2\omega_F}} = \frac{\eta_0 I_{M-}}{2I_{2\omega_F}} \quad (5)$$

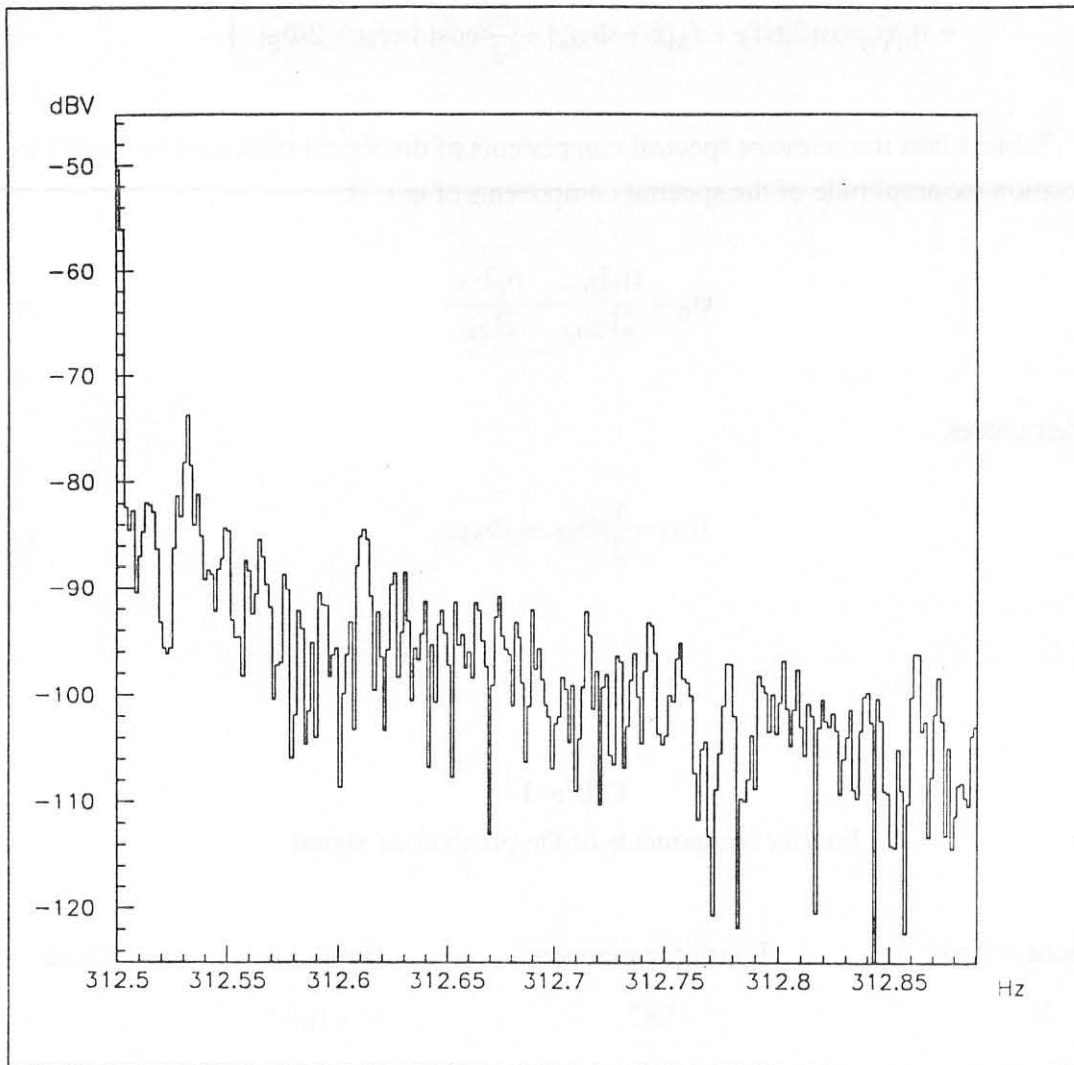
and their phases

$$\Phi_M = \frac{1}{2}(\Phi_{M+} - \Phi_{M-}) \quad (6)$$

**Table 1**  
Fourier components of the photodiode signal

Frequency (Hz)	Fourier component	Amplitude	Phase
0	DC	$\sigma^2 + \eta_0^2/2$	
$f_F$	$I_{\omega_F}$	$2\alpha\eta_0$	$\Phi_F$
$f_F + f_M$	$I_{M+}$	$\psi_0\eta_0$	$\Phi_F + \Phi_M =$ $\Phi_{M+}$
$f_F - f_M$	$I_{M-}$	$\psi_0\eta_0$	$\Phi_F - \Phi_M =$ $\Phi_{M-}$
$2f_F$	$I_{2\omega_F}$	$\eta_0^2/2$	$2\Phi_F$

Fig. 2 shows a typical power spectrum (integration time about 20 min.) of the photodiode signal obtained with He gas in the optical cavity. On the right side of the 312.5 Hz faraday frequency the peak that is proportional to the Cotton Mouton effect is shown.



**Fig. 2 :** Power spectrum obtained with 200 torr of Helium gas in the optical cavity (about 20 minutes integration time).

With the Helium gas in the optical cavity two independent values of the Cotton Mouton constant were obtained : each set of data was taken with pressure values ranging from 250 to 450 torr. The value at 0 torr pressure, coming from vacuum measurements with high statistics, was compatible with zero within the errors. Since the effect is

proportional to pressure a linear fit was performed on the experimental data. The Cotton Mouton constant and its error were obtained from the slope of the curve as shown in ref. 2. We also measured in same conditions and with the same procedure the effect of Nitrogen gas assuming from ref. 4 that the Cotton Mouton constant of Nitrogen gas at 1 atm and 0°C is  $C_{CM}(N_2) = -5.1 \cdot 10^{-17} \text{ Gauss}^{-2} \text{ cm}^{-1}$ . From the effect measured scaled for  $1/T$  temperature behaviour [4] we obtained for the Helium Cotton Mouton constant at 1 atm and 0°C.

- a.  $C_{CM}(\text{He}) = (3.7 \pm 1.0) \cdot 10^{-20} \text{ Gauss}^{-2} \text{ cm}^{-1}$
- b.  $C_{CM}(\text{He}) = (3.2 \pm 1.0) \cdot 10^{-20} \text{ Gauss}^{-2} \text{ cm}^{-1}$

The experimental error is mainly due to low statistics.

Averaging the two results we have

$$C_{CM}(\text{He}) = (3.5 \pm 0.7) \cdot 10^{-20} \text{ Gauss}^{-2} \text{ cm}^{-1}$$

This value is in agreement with an existing theoretical calculation [7] which suggests that, at 1 atm. and 0°C,  $C_{CM}(\text{He}) = 3.57 \cdot 10^{-20} \text{ Gauss}^{-2} \text{ cm}^{-1}$ ; we also found, as expected, that the helium phase  $\Phi_M$  is opposite to that of Nitrogen gas.

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