cules—is close to 1 in the isotropic liquid, we have $D \approx D_{\mathrm{NaPal}}$, i.e., the diffusion rate in the isotropic solution is controlled by the mobility of the NaPal groups. This conclusion has been directly verified by a measurement of the self-diffusion coefficient of the NaPal molecules in a 30% NaPal–70% D_2O system, where we found exactly the same D values as in a 30% NaPal–70% H_2O solution at the same temperature in the isotropic phase.

In the mesophase, on the other hand, the translational mobility of the NaPal groups is much lower than in the isotropic liquid, so that $D_{\mathrm{NaPal}} \ll D_{\mathrm{H_2O}}$ and $D \approx (1-p)D_{\mathrm{H_2O}}$. The abrupt decrease in D on going from the mesophase to the isotropic liquid thus seems to reflect a change in p.

The proton spin-lattice relaxation time T_1 of the H_2O molecules in the mesophases is diffusion controlled (Fig. 3). The water molecule spin-spin relaxation time T_2 exhibits an identical temperature dependence to that of T_1. Its value increases for the 30% NaPal–70% H_2O system from 1.6 sec at 320°K to 5.6 sec at 410°K. It abruptly decreases to about 0.5 sec on going to the isotropic-liquid phase. The T_2 measurements were made by a Carr-Purcell sequence and the results were extrapolated to zero pulse spacing.[7] The fact that $(T_2)_{\mathrm{H_2O}}$ differs from $(T_1)_{\mathrm{H_2O}}$ in the liquid-crystalline state ($T_1/T_2 = 2$ in the above system) demonstrates a preferred average orientation of the H_2O molecules in the water channels similarly as this was found for the D_2O molecules.

For the NaPal protons, on the other hand, $T_1/T_2 = 10^2$-10^4 in the liquid crystalline state, demonstrating the much smaller freedom of motion of the backbone molecules as compared with the relatively free H_2O molecules.

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Inverse Faraday Effect in a Plasma

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We have shown experimentally that a magnetic field is created by the electrons of a plasma subjected to high-power pulses of circularly polarized microwaves. The experimental results confirm the predictions concerning this phenomenon, known as the inverse Faraday effect.

The existence in solids of an inverse Faraday effect (IFE) (excitation of a magnetic field by a circularly polarized wave) has been theoretically predicted[1] and experimentally demonstrated.[2] We have studied the same effect in a plasma.

Under the influence of the electric field E_0 of a circularly polarized wave with angular frequency ω, the electrons of a plasma discribe circular orbits with frequency $\omega/2\pi$; each electron thus has a magnetic moment and the sum of these electrons creates an induced magnetic field[3] whose value per unit volume is

$$B = (e/2mc^2)(\omega_p^2/\omega^2)E_0^2 = \alpha E_0^2, \qquad (1)$$

where e and m are, respectively, the electronic charge and mass; c, the speed of light in vacuum; ω_p, the electronic angular plasma frequency ($\omega_p^2 = n_e e^2/m\epsilon_0$); and n_e, the electronic plasma density. This shows that $\partial B/\partial t$ results from the sum of the electronic density variation and the variation of the electric field inside the plasma.

In (1) the effects of the polarization of the plasma have been neglected; when such effects are taken into account one finds[3] that in the limit of small magnetic fields, B is given by

$$B = (\alpha/N)E_0^2, \qquad (2)$$

where $N^2 = 1 - \omega_p^2/\omega^2$ is the refractive index of the medium.

Note that for $\omega \simeq \omega_p$, N goes to zero (neglecting collisions). Thus (2) is not valid when $\omega \simeq \omega_p$ but nevertheless we may expect an enhanced IFE in that case.

The IFE has been demonstrated using a pulsed microwave signal (3000 MHz) supplied by a klystron delivering a few megawatts during 12 μsec with a repetition frequency of 10 Hz. A polarizer[4] transforms the linear polarization of the TE_{11} mode within a circular waveguide (7.5 cm diam) into a circularly polarized wave in the same waveguide. This wave produces a plasma in a Pyrex tube inserted coaxially in the waveguide. This tube, of diameter and length equal to 6.5 cm and 20 cm, respectively, can be thoroughly pumped and filled with neutral gas (helium) at a pressure of the order of 10^{-2} Torr. The section of waveguide surrounding the tube is made of nylon internally coated with a 20-μm layer of copper. The skin depth of the microwave is approximately 0.1 μm, much thinner than the copper layer. A 100-turn coil wound around the wave-guide at the level of the tube detects the variation of the induced magnetic flux and produces a voltage S proportional to the time derivative of B. This coil, together with any stray capacitance, is placed in parallel with a resistance whose magnitude is chosen such that the resultant RLC circuit is critically damped. Signal S is observed on an oscilloscope synchronized with the microwave pulses.

Since the microwave pulses have a rise time and decay time of the order of 0.5 μsec, the variation of S is thus slow enough so that S is not appreciably attenuated by the copper layer. Figure 1 shows the variation of S as a function of time for a pressure of 6×10^{-2} Torr and a microwave power of 1 MW. Note that the two peaks of S have opposite signs and that the first peak corresponds to the beginning of the pulse and the second to the end of the same pulse. Note also that the first peak has a larger amplitude than the second. This may be interpreted as being due to the fact that the first peak results from both the variation of ω_p and the electric field inside the plasma, whereas the second peak results solely from the variation of the electric field, the variation of ω_p at that time being much slower than at the beginning of the microwave pulse. When the winding is inverted, S changes its sign as expected for the effect of a magnetic field.

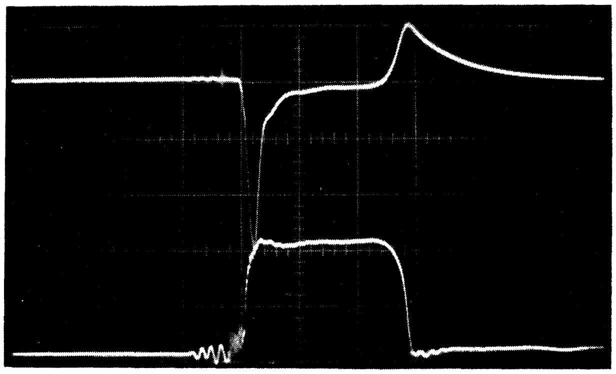

FIG. 1. Top line: signal S detected by the coil; bottom line: microwave pulse. Sweep speed, 4 μsec/cm.

For low pressures of the order of 10^{-5} Torr or for pressures higher than 20 Torr, no plasma is created by the high-frequency field and we observe in this case that $S=0$ at all times. When the polarizer is not inserted in the waveguide the polarization of the wave is linear and, as expected, no signal is detected by the coil.

During the microwave pulse it appears, for pressures higher than about 10^{-2} Torr, that at a time t_0 the plasma becomes less reflective and consequently that a higher high-frequency field develops in it at that time. This last point is confirmed by measurement of the power transmitted by the plasma. One observes that at time t_0 the solenoid detects a variation of magnetic flux.

For pressures of the order of 1 Torr, the signal S becomes very low and goes to zero for increasing pressures. This is due to the fact that for such pressures the collision frequency of electrons with neutrals becomes comparable with, or higher than, the rotation frequency of the electrons.

For circular polarization we measure a maximum amplitude of S of the order of 3 V which, if we suppose that B is produced in a time equal to 0.5 μsec, enables us to calculate the order of magnitude of the induced magnetic field. One finds $B\simeq10^{-2}$ G, i.e., 5×10^{-5} G per cm^3 of plasma. With a microwave power of 1 MW the mean electronic radius is of the order of 0.5 cm, much smaller than the discharge-tube radius.

In order to give an additional proof of the existence of IFE we have studied the influence of wave polarization of the amplitude of S. This polarization can be modified by varying the angle θ_t between the electric field of the TE_{11} mode and a radial direction of the polarizer.

The polarizer is aligned such that for $\theta_t=0$ the wave is right-circularly polarized with respect to the direction of wave propagation. The variation of polarization is thus obtained by varying θ_t. For $\theta_t = \frac{1}{4}\pi$ the wave with linear polarization is not modified by the polarizer and for $\theta_t = \frac{1}{2}\pi$ this wave is left-circularly polarized. A linear polarization results for $\theta_t = 3\pi/4$ and again a right-circular polarization for $\theta_t = \pi$. One observes the same periodicity of polarization values for $\pi \leqslant \theta_t \leqslant 2\pi$.

For an unspecified value of θ_t the wave has an elliptical polarization resulting from the summation of two circularly polarized waves, one of which is left-circularly polarized and the other of which is right-circularly polarized. This may be shown by projecting E_0 on the two directions $\theta_t = 0$ and $\theta_t = \frac{1}{2}\pi$. Each of these waves induces a magnetic field in the plasma and these fields have opposite sign. The sum of these fields is given by

$$B = \alpha E_{01}^2 - \alpha E_{02}^2 = \alpha E_0^2 \cos 2\theta_t,$$

where E_{01} and E_{02} are, respectively, the projections of E_0 on the directions $\theta_T = 0$ and $\theta_t = \frac{1}{2}\pi$.

Thus we wish to relate the amplitude of S to the wave polarization by means of the angle θ_t and we expect a linear variation of S with $\cos 2\theta_t$. However, we have found[4] that the wave polarization depends on the impedance seen by the polarizer which in turn depends upon the plasma density. It is thus essential to know the angles θ_m measured with a plasma-filled waveguide for a given wave polarization, after which θ_m can be related to θ_t. In order to take this perturbation into account we have first simulated the plasma by painting the discharge tube with a silver paint which has a high reflection coefficient for the microwaves. This simulation is a good approximation to the plasma which is almost completely reflecting for the wave. We then measured angle θ_m of the polarizer around its axis. We could thus relate θ_m to the angle θ_t which would have been found for the same ellipticity if the polarizer had been used with a waveguide with no plasma.

Figure 2 shows the variations of the maximum S_M of the first peak of S as a function of $\cos 2\theta_t$. The expected variation law is well observed.

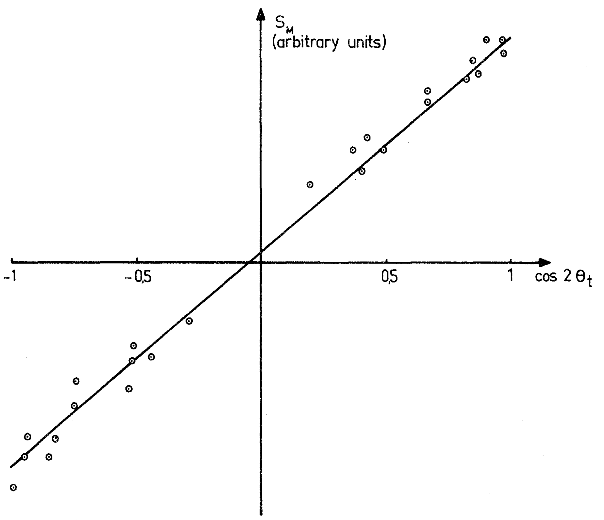

FIG. 2. Maximum amplitude S_M of the first peak of S as a function of $\cos 2\theta_t$, where θ_t is the angle between the electric field of the wave before the polarizer and a radial direction of the polarizer such that, for $\theta_t = \frac{1}{2}\pi$ (π), the wave is right- (left-) circularly polarized and linear for $\theta_t = 0$.

Nevertheless the experimental line does not pass through the origin because of the error introduced into the determination of θ_t as a function of θ_m for large values of the ellipticity. The error thus introduced is of the order of 1.5 deg. To ensure that the measurement of S as a function of θ_m was performed with a fixed value of E_0, independent of the wave ellipticity, we have monitored the microwave power transmitted and reflected by the plasma for each value of θ_m and have observed that it is nearly a constant.

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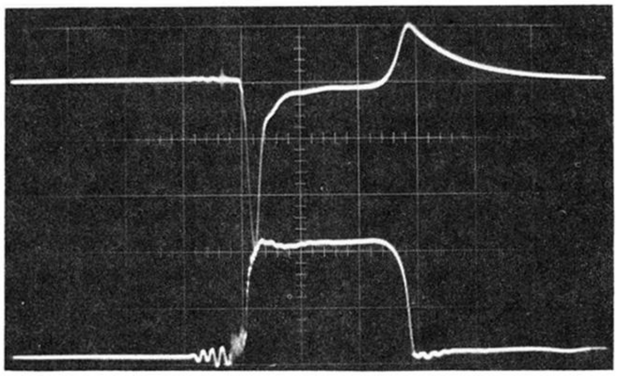

FIG. 1. Top line: signal S detected by the coil; bottom line: microwave pulse. Sweep speed, 4 μsec/cm.