On the feasibility of the experimental observation of the interaction of light with a magnetic field

A. M. Fishteĭn

L. V. Kirenskiĭ Institute of Physics, Siberian Division,, Academy of Sciences of the USSR

(Submitted 31 July 1979; resubmitted 12 December 1979)
Zh. Eksp. Teor. Fiz. **78**, 1343–1348 (April 1980)

An experiment is suggested by which the interaction of light with a magnetic field *in vacuo* could be observed, using existing laboratory techniques. In the experiment an intensity-modulated light beam is passed through a region occupied by a static magnetic field and the variations (at the light modulation frequency) of the magnetic flux in the interaction region induced by the interaction of the electric and magnetic fields of the light beam with the static field is detected by a pickup coil. A $\sim 10^3$ W light beam modulated at $\sim 10^8$ Hz traversing path ~ 30 cm long through a $\sim 10^5$ Gs magnetic field would result in a $\sim 10^{-19}$ W signal in the pickup coil.

PACS numbers: 07.55. + x, 41.90. + e

Unlike the classical electrodynamics of the vacuum, the quantum electrodynamics of the vacuum is nonlinear. Electromagnetic fields must therefore interact with one another in vacuo. Such interaction between fields achievable by current laboratory techniques is extremely small, and up to now, as far as we know, it has not been directly observed experimentally. By now a number of schemes for the experimental study of the interaction of light with light,[1] of light with an electric field,[2] and of light with a magnetic field,[3-7] have been analyzed. The interaction effects in these experiments lie at the limits of possible observation by modern laboratory techniques, and some of the proposed experiments are directed toward the improved experimental techniques of the future. In particular, according to Erber,[5] magnetic fields of ~10^8 G would be necessary to observe the conversion of photons into electron-positron pairs under laboratory conditions. Considerably weaker fields, of the order of 10^6 Gs, would suffice for the experiment proposed in Ref. 6, but in that case the path of the light beam in the magnetic field would have to be some tens of meters long.[1)]

In the best case, the results of an experiment whose performance required the utmost possibilities of laboratory techniques could merely provide qualitative confirmation of the theoretical conclusion that the investigated effect exists. If a phenomenon is to be studied, it is not sufficient that the limiting possibilities of the laboratory technique correspond to the first order of the expected effect: they must be better than that. In this paper we suggest an experiment that could be carried through using magnetic fields, light beam intensities, and detector sensitivities considerably lower than have already been achieved in experimental physics.

The nonlinearity of vacuum electrodynamics can be taken formally into account by introducing a field-dependent vacuum permittivity and permeability.[8] If an intensity modulated light beam passes through a region occupied by a static magnetic field $\mathbf{B}_0$, the variations of the vacuum permeability μ_0 caused by the electric and magnetic fields $\mathbf{E}_1$ and $\mathbf{B}_1$ of the modulated light beam must cause the magnetic flux in the interaction region to vary at the light modulation frequency. These oscillations of the magnetic flux will induce an electrical signal into a detecting loop (or coil) surrounding the region in which the fields interact. We shall show that with magnetic fields and light-beam intensities available in a large number of research laboratories, this signal will be strong enough to be detected by an electronic device.

The total energy density of the fields $\mathbf{B}_0, \mathbf{E}_1$, and $\mathbf{B}_1$ is determined by the Lagrangian L (Ref. 8):

$$w=\mathbf{E}\frac{dL}{d\mathbf{E}}-L, \quad L=L_0+L'.$$

For convenience in performing the calculations we write L in the form used in Ref. 9:

$$L_0=\frac{\mathbf{E}^2-\mathbf{B}^2}{8\pi}, \quad L'=\frac{1}{2}\varkappa\{(\mathbf{E}^2-\mathbf{B}^2)^2+7(\mathbf{EB})^2\},$$

$$\varkappa=\frac{\alpha}{180\pi^2 B_c^2}, \quad \alpha=\frac{e^2}{\hbar c}\approx\frac{1}{137}, \quad B_c=\frac{m^2c^3}{e\hbar}\approx 4.4\cdot 10^{13}\text{ G},$$

where c is the velocity of light, $\hbar$ is Planck's constant, and e and m are the electron charge and mass.

The part Δw of the energy density of the field $\mathbf{B}_0$ that depends on $\mathbf{E}_1$ and $\mathbf{B}_1$ vanishes if $\mathbf{S}\equiv\mathbf{E}_1\times\mathbf{B}_1$ is parallel to $\mathbf{B}_0$, while

$$\Delta w_1=0.5\varkappa\mathbf{B}_0^2(2\mathbf{B}_1^2+5\mathbf{E}_1^2) \text{ for } \mathbf{E}_1\|\mathbf{B}_0,\ \mathbf{S}\perp\mathbf{B}_0,$$
$$\Delta w_2=\varkappa\{2\mathbf{B}_1\mathbf{B}_0^3+2\mathbf{B}_1^3\mathbf{B}_0+\mathbf{B}_0^2(3\mathbf{B}_1^2-\mathbf{E}_1^2)\} \text{ for } \mathbf{B}_1\|\mathbf{B}_0,\ \mathbf{S}\perp\mathbf{B}_0.$$

If the power P in the light beam is modulated at the angular frequency Ω, i.e., if

$$P(t)={}^1/_2P_m(1+\sin\Omega t),$$

then Δw will contain a part $\Delta w'$ that varies at the frequency Ω:

$$\Delta w'=0.125\varkappa B_0^2(2B_{1m}^2+5E_{1m}^2)\sin\Omega t \text{ for } \mathbf{E}_1\|\mathbf{B}_0,\ \mathbf{S}\perp\mathbf{B}_0,$$
$$\Delta w'=0.25\varkappa B_0^2(3B_{1m}^2-E_{1m}^2)\sin\Omega t \text{ for } \mathbf{B}_1\|\mathbf{B}_0,\ S\perp\mathbf{B}_0,$$

where B_{1m} and E_{1m} are the maximum values of $\mathbf{B}_1$ and $\mathbf{E}_1$.

The power of the electric signal induced in the coil surrounding the volume v in which the fields interact will be

$$\Delta P=\frac{\partial}{\partial t}(\Delta w' v),$$

so the effective power of the signal in the pickup coil will be

 0038-5646/80/040676-03$02.40

$$\Delta P_1=\frac{7\alpha}{360\pi}\frac{B_0^2}{B_c^2}\Omega P_m\frac{l}{c}\quad \text{for } \mathbf{E}_1\|\mathbf{B}_0,\quad \mathbf{S}\perp\mathbf{B}_0,$$

$$\Delta P_2=\frac{\alpha}{90\pi}\frac{B_0^2}{B_c^2}\Omega P_m\frac{l}{c}\quad \text{for } \mathbf{B}_1\|\mathbf{B}_0,\quad \mathbf{S}\perp\mathbf{B}_0,$$

where P_m is the maximum power of the light beam and l is the length of the light path in the magnetic field. The power will be about the same if the light intensity is square-wave modulated.

In accordance with what was said above, the experiment could be conducted according to the following scheme: an intensity modulated light beam (polarized or unpolarized) propagates perpendicular to the magnetic lines of force; the region in which the light interacts with the field is surrounded by a coil whose plane is perpendicular to the magnetic lines of force (and therefore parallel to the light beam); and the electrical signal at the light modulation frequency induced in the pickup coil is recorded by an electronic device.

It is technically difficult to modulate an intense light beam at a high frequency, so it is advantageous to obtain the modulated light beam by making use of the beats between two light beams whose optical frequencies differ by Ω, e.g. by employing a two-frequency laser. If the lasing action at two frequencies is due to Zeeman splitting, the difference between the optical frequencies will be stable. A signal at the difference frequency Ω for use with a synchronous detector can be obtained from a photodetector. The length l of the light path in the magnetic field can be made greatly to exceed the length d of the region coupled by the field by making use of appropriate reflectors to cause the light beam to traverse the magnetic field many times. If $\Omega \gtrsim c/l$, the traveling-wave principle will obtain in the signal pickup device since in this case the variations of μ_0 along the path l differ substantially in phase. If $d \ll c/\Omega$, this complication of the signal pickup device can be avoided by so choosing the distances between the mirrors and the region occupied by the magnetic field that the light beam will be at the same phase of its modulations each time it enters the magnetic field.

It will be seen on comparing Δw_1 and Δw_2 that a signal of the same order as ΔP_1 and ΔP_2 can be obtained by modulating the polarization of the light beam, rather than its intensity, at the frequency Ω. It is indeed possible to modulate laser light in this manner.[10-12]

If we take $B_0 \sim 10^5$ Gs, $P_m \sim 10^3$ W, $F=\Omega/2\pi \sim 10^8$ Hz, and $l \sim 30$ cm, we obtain[2)] $\Delta P \sim 10^{-19}$ W, several orders of magnitude higher than the limiting power detectable by existing techniques. Such a signal could be detected by an electronic recording device operating at room temperature with a data accumulation time of the order of a few seconds.[13] If cryogenic techniques and a data accumulation time of ~10^5-10^6 sec are used, the limiting detectable power becomes $\Delta P_{\min}=10^{-27}-10^{-28}$ W.[13] Since $\Delta P \gg P_{\min}$, quite accurate measurements can be made.

Since the signal frequency is the same as the light modulation frequency, noise at the signal frequency should arise as a result of nonlinear effects in the interaction of light with matter (when scattered light falls on a part of apparatus, when the light passes through the glass wall of the vacuum chamber, and when the light is reflected from the mirrors). At the limiting sensitivity of the experiment, ΔP is about 30 orders of magnitude below P, so the noise resulting from even a slightly nonlinear effect could turn out to be considerably stronger than the signal, and it would be extremely difficult to reduce it sufficiently by shielding the recording system.

One can reduce the contribution of noise to the results of the measurement not only by shielding, but also by turning the magnetic field on and off periodically at some appropriate frequency, accumulating the sum of the signal and noise with the field on, accumulating the noise (for the same length of time) with the field off, and then subtracting the noise out. If the experiment is done in this manner it is only the difference between the noise levels in the presence and absence of the magnetic field that is not eliminated, and this difference is of course due only to the part of the noise that is generated in the region occupied by the magnetic field. The scattered light propagating within the region occupied by the magnetic field but outside the main beam can be reduced to the necessary minimum by a set of diaphragms mounted within the vacuum chamber but outside the magnetic field; then the main effect of the interaction of light with matter within the magnetic field will come from the interaction of the light with the residual gas.

Since the purpose of the present work is not to plan the experiment in detail, but merely to show that it is feasible, we shall not attempt to determine the contribution of the residual gas to the measured effect but shall merely show that the requirements on the quality of the vacuum in the region in which the light interacts with the magnetic field are not too stringent. By neglecting the decrease of the magnetic susceptibility χ of the residual gas with increasing frequency, i.e., by assuming that χ is the same at optical frequencies as in static fields, we can obtain a reliable estimate of the quality required of the vacuum. Using the formula[14]

$$I=n_0\mu\left(\operatorname{cth}\frac{\mu H}{kT}-\frac{kT}{\mu H}\right),$$

for the magnetization of a paramagnetic gas, in which n_0 is the number of molecules per unit volume, μ is the magnetic moment of a molecule, H is the field strength, k is Boltzmann's constant, and T is the absolute temperature, and retaining only the first nonlinear term, we obtain

$$\chi=\frac{n_0\mu^2}{3kT}-\frac{n_0\mu^4}{45k^3T^3}H^2.$$

The component of the energy density of the fields B_0 and B_1 due to χ has the form

$$\Delta w_\perp=\frac{n_0\mu^4}{45k^3T^3}B_1^2B_0^2\quad \text{for } \mathbf{B}_1\perp\mathbf{B}_0,$$

and

$$\Delta w_\|=\frac{n_0\mu^4}{15k^3T^3}B_1^2B_0^2\quad \text{for } \mathbf{B}_1\|\mathbf{B}_0.$$

If $\Delta w_\perp < \Delta w_1$ and $\Delta w_\| < \Delta w_2$, i.e., if

$$\frac{n_0\mu^4}{k^3T^3}<\frac{\alpha}{6\pi^2B_c^2},$$

the interaction between the fields will obviously be determined mainly by the physical vacuum. Taking $T \sim 300°$ K and μ to be of the order of the Bohr magneton, we find that these inequalities are satisfied when the residual gas pressure is below 10^{-8} Torr. We recall that this estimate is reliable and, in accordance with the initial assumptions, contains a large safety factor.

The interaction between the fields $\mathbf{B}_0$ and $\mathbf{E}_1$ in the residual gas was not taken into account in the above estimate. Any possible change in the estimate on account of this interaction certainly lies within the safety factor resulting from the initial assumption (that χ is the same at optical frequencies as in static fields). Finally, the interaction of the fields $\mathbf{E}_1, \mathbf{B}_1$, and $\mathbf{B}_0$ in the residual gas can be taken into account by making use of the results of recent attempts to detect the birefringence induced in gases by a magnetic field (the Cotton–Mouton effect).[15] According to Ref. 9, the refractive indices of the vacuum in a magnetic field $\mathbf{B}_0$ are

$$n_{B\parallel}=1+\frac{7\alpha}{90\pi}\frac{B_0^2}{B_c^2}, \quad n_{B\perp}=1+\frac{2\alpha}{45\pi}\frac{B_0^2}{B_c^2},$$

where the symbols $\parallel$ and $\perp$ are for light waves polarized with the electric vector parallel and perpendicular, respectively, to $\mathbf{B}_0$. It follows from Ref. 15 that the difference $n_{B\parallel} - n_{B\perp}$ is less than 6×10^{-11} for air and certain other gases at pressures up to 760 Torr and in fields up to 15 kOe. Taking account of the facts that the absolute changes induced by the field $\mathbf{B}_0$ in the refractive indices for light polarized parallel and perpendicular to the field differ by about a factor of two[16-18] and that the Cotton–Mouton effect, like the effect under discussion, is proportional to B_0^2, we find that even if the resolution achieved in the experiment reported in Ref. 15 were such that the difference between $n_{B\parallel}$ and $n_{B\perp}$ could barely be detected, the interaction of the fields with the residual gas could not hide the effect under consideration provided the pressure in the vacuum chamber was below 10^{-9} Torr.

In concluding, we note that the high sensitivity of the proposed experiment is achieved by converting the interaction energy of the fields directly to an electrical signal in the part of the spectrum in which very small energy fluxes can be detected. The following two comparisons may serve to illustrate how small $\Delta P_{\min}$ actually is: for visible light, $\Delta P_{\min}$ corresponds to a "light flux" of about one photon every 10^3 seconds; and the "energy flux" necessary for the production of one electron-positron pair per day exceeds $\Delta P_{\min}$ by ten orders of magnitude.

[1)]Attempts have been made to observe the interaction of light with magnetic fields of the order of 10^4 G (see Ref. 4 and the literature cited there). The estimates presented in Ref. 4 show that in these experiments the sensitivity was more than ten orders of magnitude lower than that required for observing the interaction effects.

[2)]Since ~20-kG fields produced by iron-core electromagnets can be made to fill a very extended space, one can obtain the same power ΔP with them as can be obtained with strong fields by appropriately increasing l. Then, however, complicated signal pickup devices may become necessary (see above).

[1]V. M. Harutyunian, F. R. Harutyunian, K. A. Ispirian, and V. A. Tumanian, Phys. Lett. **6**, 175 (1963).

[2]James D. Talman, Phys. Rev. **139**, B1644 (1965).

[3]R. Kaitna and P. Urban, Nucl. Phys. **56**, 518 (1964).

[4]Thomas Erber, Nature **190**, 25 (1961).

[5]Thomas Erber, in High Magnetic Fields, MIT Press, Cambridge, Mass. and John Wiley, N. Y. and London, 1962, p. 706.

[6]G. K. Oertel, Nature **202**, 684 (1964).

[7]Thomas Erber, Rev. Mod. Phys. **38**, 626 (1964).

[8]A. I. Akhiezer and V. B. Berestetskiĭ, Kvantovaya élektrodinamika (Quantum electrodynamics), Nauka, M., 1969, Section 41. [Interscience].

[9]V. L. Ginzburg and V. N. Tsytovich, Zh. Eksp. Teor. Fiz. **74**, 1621 (1978) [Sov. Phys. JETP **47**, 845 (1978)].

[10]M. B. White, W. D. Gerber, and Walter M. Doyle, IEEE J. Quantum Electron. (QE-6), 457 (1970).

[11]V. N. Parygin and A. S. Lipatov, Radiotekh. Élektron. **20**, 1216 (1975).

[12]A. S. Lipatov and V. N. Parygin, Radiotekh. Élektron. **21**, 209 (1976).

[13]V. B. Braginskiĭ and G. I. Rukman, Vestn. Mosk. Univ. Fiz. No. 3, 3 (1961); Zh. Eksp. Teor. Fiz. **41**, 304 (1961) [Sov. Phys. JETP **14**, 215 (1962)].

[14]S. V. Vonsovskiĭ, Magnetizm (Magnetism), Nauka, M., 1971, Chapter 9 (Engl. Transl. John Wiley, N. Y., 1974).

[15]Wilhelm Schütz, Z. Phys. **38**, 853 (1926).

[16]J. W. Beams, Rev. Mod. Phys. **4**, 133 (1932) [cited in Russian translation, Usp. Fiz. Nauk **13**, 209 (1933)].

[17]M. V. Vol'kenshteĭn, Molekulyarnaya optika (Molecular optics), Gostekhizdat, M.-L., 1951.

[18]Max Born, Optik, J. Springer, Berlin, 1933 (Russ. Transl. Optika, GosNTI, Ukr. SSR, Khar'kov-Kiev, 1937).

Translated by E. Brunner