Axion Production by Electromagnetic Fields

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(Received 2 March 1987)

By consideration of the conversion of photons into axions in the presence of a classical background magnetic field, the possibility of creating artificial sources of "invisible" axions with a laboratory experiment is stressed. With, in particular, a high-power laser, the attainable axion current density seems to be as high as that expected from the natural astrophysical sources, provided that the axion mass is not much larger than 10^{-5} eV.

PACS numbers: 14.80.Gt

It is well known that, because of the coupling of the axion to the electromagnetic field, it is possible to arrange axion detectors of electromagnetic type, based on the conversion of axions into photons.[1] As discussed recently, in this context one also has the possibility of detecting axions by observing the variation of the polarization state of a light wave interacting with the pseudoscalar field in the presence of a strong background magnetic field.[2]

The object of this paper is to stress that, besides the electromagnetic detectors, it is also possible to produce through the inverse process (i.e., conversion of photons into axions) artificial axionic sources of electromagnetic type. The detectors described by Sikivie[1] and Krauss *et al.*,[3] for example, could be employed then to observe not only an eventual axion background of astrophysical or cosmological origin, but also the axions directly produced in the laboratory.

A coupled system of source and detector could give, even in the absence of positive signals, significant limits on the mass and coupling in the case of generalized axions, i.e., pseudoscalar particles with no *a priori* relation between mass and coupling constant.[4] Even in the case of the "invisible" axions,[5,6] however, the electromagnetic mechanism of production could be interesting because, as will be shown below, for suitable values of the axion mass the axion flux density attainable from a present artificial source seems to be at least as high as the estimated flux density on earth from natural celestial sources.

The total effective Lagrangean density for the interaction of axions and photons can be written (here we follow the conventions of Ref. 2) as

$$\mathcal{L}=\tfrac{1}{2}\,\partial_\mu\phi\,\partial^\mu\phi-\tfrac{1}{2}m\phi^2-\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}+(1/8M)\phi\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}, \quad (1)$$

where M is the dimensionful parameter characterizing the strength of the axion-photon coupling. The classical field equations are then

$$(\Box+m^2)\phi=-M^{-1}\mathbf{E}\cdot\mathbf{B}, \quad \nabla\cdot\mathbf{E}=M^{-1}\mathbf{B}\cdot\nabla\phi,$$
$$\nabla\times\mathbf{B}=\dot{\mathbf{E}}+M^{-1}(E\times\nabla\phi-\mathbf{B}\dot{\phi}) \quad (2)$$

(a dot denotes partial derivative with respect to time), together with the usual sourceless Maxwell equations,

$$\nabla\cdot\mathbf{B}=0, \quad \nabla\times\mathbf{E}=-\dot{\mathbf{B}}. \quad (3)$$

The experimental situation we shall consider is the same as in Ref. 2, that is, a laser beam traveling through a constant magnetic field $\mathbf{B}_0$, orthogonal to the beam axis. Here I suppose that the light waves propagate in the $\hat{\mathbf{x}}$ direction: The electric and magnetic fields $\mathbf{E}_W(x,t)$ and $\mathbf{B}_W(x,t)$ associated with the radiation have their components in the (y,z) plane, and the external magnetic field is constant, uniform, and of strength B_0 between the planes $x=-L$ and $x=0$, while it is vanishing outside this region.

I look for solutions describing an oscillating axion field which propagates along the $\hat{\mathbf{x}}$ direction, $\phi(x,t)$. If we decompose the electric field $\mathbf{E}_W$ into the components $E_\parallel$ and $E_\perp$ parallel and orthogonal to $\mathbf{B}_0$, respectively, and keep only linear terms in ϕ, $\mathbf{E}_W$, and $\mathbf{B}_W$, the combination of the field equations (2) and (3) gives, in the region where B_0 is nonvanishing,

$$(\Box+m^2)\phi=-M^{-1}E_\parallel B_0, \quad (4)$$

$$\Box E_\parallel=M^{-1}B_0\ddot{\phi}, \quad \Box E_\perp=0 \quad (5)$$

(note that $E_\perp$ does not interact with ϕ). Therefore in this situation the axion is coupled to the electromagnetic field only for $-L\le x\le 0$ (region II), while for $x<-L$ (region I) and $x>0$ (region III) we have a free pseudoscalar field satisfying

$$(\Box+m^2)\phi=0. \quad (6)$$

Looking for solutions of the axion equations which represent waves outgoing from the interaction region II, I assume that ϕ in regions I and III is given by

$$\phi_{\rm I}=c_1e^{-i(k_1x+\omega t)}, \quad \phi_{\rm III}=c_2e^{i(k_1x-\omega t)}, \quad (7)$$

where $k_1^2+m^2=\omega^2$, and c_1,c_2 are coefficients to be determined by the continuity conditions at $x=-L$ and $x=0$. A particular solution for ϕ in region II can be obtained by our putting

$$E_\parallel=E_0e^{i(kx-\omega t)}, \quad \phi=\phi_0e^{i(kx-\omega t)}. \quad (8)$$

The coupled equations (4) and (5) then become

$$(k^2+m^2-\omega^2)\phi_0+M^{-1}B_0E_0=0,$$
$$M^{-1}B_0\omega^2\phi_0+(k^2-\omega^2)E_0=0, \qquad (9)$$

and yield the solution

$$\phi_0=-M^{-1}B_0E_0(k^2+m^2-\omega^2)^{-1}, \qquad (10)$$

which obviously exists provided that ω and k are related by the condition

$$(k^2+m^2-\omega^2)(k^2-\omega^2)=M^{-2}B_0^2\omega^2 \qquad (11)$$

(note that since there are in general two roots of this equation,[2] we have two possible values for the oscillation frequency of the produced axion field).

The general solution of Eq. (4) can be expressed by the addition to the particular solution, given by Eqs. (8) and (10), of the general solution of the homogeneous Klein-Gordon equation (6). The axion field in region II is then

$$\phi_{\rm II}=c_3e^{-i(k_1x+\omega t)}+c_4e^{i(k_1x-\omega t)} - M^{-1}B_0E_0(k^2-k_1^2)^{-1}e^{i(kx-\omega t)}. \qquad (12)$$

The four constant coefficients $c_1,\ldots,c_4$ can be uniquely determined by the imposition of the continuity conditions on ϕ and $\partial\phi/\partial x$ at $x=-L$ and $x=0$. The final result for the amplitude of the axionic wave outside the interaction region is the following:

$$c_1=E_0B_0[2k_1(k_1+k)M]^{-1}[e^{-i(k_1+k)L}-1], \qquad (13)$$

$$c_2=E_0B_0[2k_1(k_1-k)M]^{-1}[1-e^{i(k_1-k)L}]. \qquad (14)$$

We should note the possibility of modulating this amplitude by the variation of L. Another modulation of the produced axion field is due to its dependence on $E_\parallel$: This component of the electric field is not constant in time in region II, because even if the beam is linearly polarized at the beginning of this region, the axion-photon interaction described by Eqs. (4) and (5) induces changes in the ellipticity and a rotation of the polarization plane.[2] However, as discussed in Ref. 2, this variation is very small (for example, the rotation angle is not expected to be much larger than 10^{-12} rad in a foreseeable experimental condition[2]).

In order to get an estimate of the axion flux density attainable from an artificial source of this type, we can neglect then the dispersion, so that the initial linear polarization, which we suppose aligned with $\mathbf{B}_0$, is left unchanged. That is, we consider the approximation in which the axion mass is negligible, and the coupled equations (4) and (5) are solved by an iterative procedure, starting from the decoupled equations $\Box\phi=0$, $\Box E_\parallel=0$. To first order in M^{-1} the axion field is then the solution of the equation obtained from (4) if we put $m=0$ and use as source the unperturbed electric field satisfying the free Maxwell equations.

In this approximation the dispersion relation (11) reduces to $k^2=\omega^2$, and we have also $k_1=k$. The axion field in region II can be obtained then simply by consideration of the previous solution in the limit $k_1\to k$. From Eqs. (7) and (14) we find

$$\phi_{\rm III}=(E_0B_0L/2ikM)e^{i(kx-\omega t)}, \qquad (15)$$

and the ratio R of the (time-averaged) energy flux density of the produced axion beam to the electromagnetic flux density thus is given by

$$R=(B_0L/2M)^2. \qquad (16)$$

This expression of course is valid only if $(\omega-k_1)L \simeq m^2L/2\omega \ll 1$, which implies $R<(B_0\omega/Mm^2)^2$. If we consider an incident laser beam with frequency ω and flux density x (given in watts per square centimeter), the maximum attainable axion current density J (in axions/cm^2 sec) then will be

$$J\simeq 2\times10^{16}\frac{xB_0^2\omega}{m^4M^2}, \qquad (17)$$

where ω, m, and M are expressed in electronvolts, and B_0 in gauss. This formula can be applied to estimate the possible production by electromagnetic fields of general pseudoscalar particles, and to obtain information on their masses and coupling constants.

It is interesting, however, to consider also the case of the invisible axion.[5] In such case the axion mass and coupling constant are related to the vacuum expectation value that spontaneously breaks the Peccei-Quinn symmetry,[7] and we have[1,6] $(10^{10}\text{ GeV})/M=\eta[m/(1\text{ eV})]$, where η is a model-dependent number of order unity. Equation (17) becomes then

$$J\simeq 2\times10^{-22}\frac{xB_0\omega\eta^2}{m^2}, \qquad (18)$$

where all quantities are in the same units as in (17).

On the other hand, the solar axion flux density on Earth is approximately[1] $8\times10^{12}[(10^8\text{ GeV})/f_a]^2$ axions/cm^2 sec, where[1,6] $(10^7\text{ GeV})/f_a\simeq\eta[m/(1\text{ eV})]$. The current density of the solar axions (in axions/cm^2 sec) can be expressed then as

$$J_\odot\simeq 8\times10^{14}[m/(1\text{ eV})]^2\eta^2. \qquad (19)$$

The intensity of the laser-generated axion beam is inversely proportional to m^2. Since the axion mass is constrained by the cosmological bound[8] $f_a \lesssim 10^{12}$ GeV (which implies $\eta m \gtrsim 10^{-5}$ eV), the most favorable experimental condition is obtained if $m\simeq10^{-5}$ eV (corresponding to the interesting possibility that the galactic halos are made up of dark axion matter[9]). In that case, by the arrangement of a magnetic field[2] $B_0\simeq10^5$ G, the current density (19) can be reproduced by use of an incident laser beam of frequency $\omega\simeq1$ eV and power per unit area $x \simeq 4\times 10^6$ W/cm^2 (this flux density seems to be easily available even for a continuously operating laser[10]). The energy of the produced axions then would be of order 1 eV, while the typical energy of a solar axion is of order 1 keV. If one considers, however, a short-pulse laser, it would be possible[10] to obtain during the pulse even 10^{14} W/cm^2, with a pulse width of 10^{-3} sec. The response would be then a pulsating axion beam, with an energy current density about 10^4 times higher than the energy flux density of the solar axions (19).

It must be noted, however, that the axion current obtained in this way is concentrated into a very small area (the transverse section of the beam has radius $\sim 10^{-2}$–10^{-3} cm). This considerably reduces the response of detectors of the type considered in Ref. 1, because their sensibility is proportional to the extension of the spatial region crossed by the axion current. It seems possible, however, for one to improve the efficiency of the production mechanism by making the magnetic field inhomogeneous,[1] in order to evade the constraint on L; moreover, in the case of "production plus detection" schemes, the signal-to-noise ratio of the detector can be improved by making the detector selective to the energy of the produced axions.

The last two possibilities are currently under investigation.[11]

Note added.—After this work was completed I learned that the possibility of axion photoproduction was previously considered by Brodsky *et al.*[12] and Tsai.[13] Their works, however, are concerned with the search for particles in the megaelectronvolt mass range.

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