Photoinduced decay of pseudo-Goldstone bosons and the search for axion emission from the sun

P. V. Vorob'ev

G. I. Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences, 630090 Novosibirsk, Russia[1)]

(Submitted 18 May 1993)
Pis'ma Zh. Eksp. Teor. Fiz. **57**, No. 12, 737–740 (25 June 1993)

The photoinduced decay of axions with a mass of 1–3 eV is discussed. This process might be utilized to develop a new type of detector for searching for axion emission from the sun.

1. *Photoinduced decay of an axion*

Massless or very light pseudo-Goldstone bosons arise in a natural way in supergravity, superstring theory, various versions of supersymmetry, and numerous other such theories. Among these bosons are the axion, the arion, the familon, and the archion; for simplicity we will refer to all these particles here as "axions." These particles and the fields corresponding to them are bound with ordinary matter only extremely weakly.

There are several astrophysical indications that the universe contains a large amount of invisible dark matter. One of the most natural candidates for the role of this dark matter is a nonrelativistic axion gas. Several completely self-consistent cosmological models with an axion dark matter have been worked out.[1,2] There is thus the problem of experimentally searching for axions and an axion dark matter. Several experiments have in fact already been carried out to seek axions from the galactic halo.[3,4] An experiment has recently been carried out at Brookhaven to search for axion emission from the sun.[5] A similar experiment, with a significantly greater sensitivity, is being set up in Novosibirsk.[6] However, the detectors which have been used previously are sensitive to axions with masses less than 0.1 eV.

In this letter we wish to discuss a method for searching for axions with a mass of about 1–3 eV. This interval is a special one in that there are no astrophysical limitations on the existence of an axion with such a mass. A second window for the axion mass which is not "shuttered" by astrophysics or cosmology is 10^{-7}–10^{-4} eV. Such axions can form a condensate. A method for seeking a condensate of light pseudo-Goldstone bosons can be based on the quasimagnetic interaction of an axion with the spin of a fermion (an electron).[7–11] Such methods will be examined in more detail in another paper.[12] Experiments carried out as part of a search for light or strictly massless pseudoscalars and associated interactions are reviewed in Ref. 6. The decay of an axion into two photons, like the decay of a neutral pion, occurs through a triangle diagram with a virtual charged fermion in a loop.

The lifetime of the axion with respect to decay into two photons is given by

$$\tau_a = (m_\pi / m_a)^5 \tau_\pi , \qquad (1)$$

where m_a and m_π are the masses of the axion and the pion, and τ_a and τ_π are the corresponding lifetimes ($\tau_\pi=0.8\times10^{-16}$ s and $m_\pi=135$ MeV). It can be seen from (1) that the lifetime of an axion with a mass of 1 eV is 3.5×10^{24} s, and that of an axion with a mass of 3 eV is 1.5×10^{22} s.

Let us assume a coherent (parallel and monochromatic) beam of axions with a velocity on the order of the velocity of light with respect to the observer. In the comoving frame of reference, an axion decays into two photons with the same energy. They fly off in opposite directions and have orthogonal polarizations. In the comoving frame the decays are isotropic, but when a transformation is made to the laboratory frame of reference, it turns out that the photons are emitted for the most part within an angle on the order of $1/\gamma$ in the direction in which the axion is moving. Decays in which one photon is emitted along the direction in which the axion is moving, while the other is emitted in the opposite direction, lead to the greatest difference in the photon energy as observed in the laboratory frame:

$$E_{\max}=\gamma E_0,\quad E_{\min}=E_0/4\gamma, \tag{2}$$

where $E=m_ac^2$ and $\gamma=[1-(v/c)^2]^{-1/2}$. Such decays are strongly suppressed by the small solid angle, but these are the decays which are of interest here. We now assume that there is an intense, coherent photon beam which coincides with the axion beam. We assume that the photon energy is $E_\gamma=E_{\max}$ if the axion and photon beams are headed in the same direction, while we have $E_\gamma=E_{\min}$ if they are headed in opposite directions. As a result, the axion lifetime decreases in proportion to the number of photons in the photon beam over which the axion interacts with photons:

$$\tau=\tau_a/n_\gamma. \tag{3}$$

Here n_γ is the number of γ rays in the γ-ray beam. The reason for this result is that a very significant Bose-amplification factor arises in the probability for the decay of an axion accompanied by the emission of a γ ray. This effect could be called a "photoinduced decay." Since the decay probability is determined by the number of γ rays in the flux, it is natural to use a y-ray beam with $E_\gamma=E_{\min}$, headed in the direction opposite the axion flux, since the number of photons in it is larger by a factor of γ^2 than that in a beam with $E_\gamma=E_{\max}$ for a given power level.

It is easy to see that the axion decay probability is given by

$$p=(\tau_i/\gamma\tau_a)\tau_i\dot{n}_\gamma \tag{4}$$

in the case of monochromatic parallel axion and photon beams. Here $\tau_i=L/c$ is the duration of the interaction between the axion and photon beams, and $\dot{n}_\gamma$ is the photon flux density, and τ_a is the axion lifetime in the laboratory frame. With $\dot{n}_a$ and $\dot{n}_\gamma$ as the flux densities of axions and photons, respectively, the flux density of γ rays from induced decays is

$$\dot{N}_\gamma=(\tau_i/\gamma\tau_a)\tau_i\dot{n}_\gamma\dot{n}_a. \tag{5}$$

One of the γ rays resulting from the axion decay has a frequency, a polarization, and a direction which are the same as those in the photon beam. The second photon propagates in the opposite direction and has a polarization orthogonal to that of the photon beam. Its frequency is different by twice the Doppler shift. This circumstance raises the hope that an effective detector of axions with masses on the order of 1–5 eV can be developed.

2. *Detection of axion emission from the sun*

Let us examine the possibility of detecting axions from the sun. An axion mass of 1 eV corresponds to an interaction constant $q_{ae}=10^{-7}$ GeV^{-1} or $q_{a\gamma}=10^{-9}$ GeV^{-1}. The flux density of axions from the sun at the earth's orbit should be about 10^{13} cm$^{-2}\cdot$s^{-1}. The energy of an axion leaving the core of the sun is in the interval 1–15 keV. To deal with the energy distribution of the axions and the finite phase volume of the axion beam, we need to modify expression (5):

$$\dot{N}_\gamma=(\tau_i/\gamma\tau_a)\omega^{-1}\dot{n}_a\dot{n}_\gamma \min(1,\Omega_\partial/\Omega_s). \tag{6}$$

Here $\Omega_\partial=4S/L^2$ is the solid angle of the detector, Ω_s is the solid angle of the core of the sun, S and L are the area and length of the detector, and ω is the width of the spectrum of those photons from axion decay which are emitted backward $(E_\gamma E_{\min})$. Let us assume that the mass of the axion is 2.5 eV. We then have $\gamma=2\times10^3$, and γ rays with energies $E_{\max}=5$ keV and $E_{\min}=10^{-4}$ eV are emitted along the direction of motion during the decay. The energy of the photon emitted backward thus falls in the microwave range (the corresponding wavelength is $\lambda\simeq1$ cm). If a microwave beam with a wavelength $\lambda=1$ cm, directed opposite the axion flux, is generated, then the photon flux density at a microwave power $P=10$ MW would be 10^{31} s^{-1}. For an interaction length $L=10$ m, an aperture S$=10$ cm^2, and an axion flux density $\dot{n}_a=10^3$ cm$^{-2}\cdot$s^{-1}, we find the flux density of photons from induced axion decays to be $\dot{N}_\gamma=1.5\times10^{-1}$ s^{-1}. These photons have an energy on the order of 5 keV and could be detected easily by a silicon or gallium arsenide semiconductor detector operating at liquid-helium temperature. The intrinsic noise of a cooled detector with an area of 3–4 cm^2 at energies above 3 keV would be negligible. The x-ray background from the waveguide, which arises in the emission of electrons from microscopic tips in strong fields, is in the low-frequency part of the spectrum and could be suppressed by a filter in front of the detector.

For an axion mass of 1 eV the microwave wavelength should be $\lambda\simeq10$ cm, and the flux of photons with an energy of about 5 keV would be on the order of 3×10^{-3} s^{-1}. Again, this level would present no difficulties for detection.

The detector could be constructed in the following way. The microwave power is built up in a superconducting waveguide whose ends are blocked by cutoff plugs which are transparent to the photons produced during the axion decay. The waveguide is evacuated. Semiconductor counters are mounted at the ends of the waveguide, outside the plugs, to detect decay photons with an energy of a few keV. The waveguide is immersed in liquid helium at 4.2 K. If the waveguide cavity has a quality factor of 10^8, we would need an excitation power of only ~1 W to generate a power of 10 MW. The entire system is mounted on a rotatable platform in order to track the sun.

Our idea is better than that of Ref. 13 since it does not require any fine tuning. In the idea of Ref. 13, axions with a mass on the order of 1–3 eV emitted by the core of the sun are detected through a mixing of states and a resonant axion–photon conversion in a transverse magnetic field. If coherence is to be maintained over the interaction length, the dispersion laws for the mass of axion and the photon must be the same. van Bibber *et al.*[13] suggest that filling the interaction volume with hydrogen would give the photon a mass. For a photon with an energy of a few keV, the electrons of the gas can be regarded as free, and the effective mass of the photon would correspond to the plasma frequency. Detecting an axion with a mass on the order of 1 eV would require that a pressure ~ 200 atm be maintained within an error of 10^{-3} in the interaction volume. Searching for an axion in the interval 1–3 eV would require scanning the pressure over an interval on the order of 200 atm at 0.2-atm steps and building up a large statistical base at each point!

In the detector used by us, the entire mass interval is covered by a set of three waveguides, each excited at its own frequency. There is no need for a magnetic field or for a high gas pressure in the interaction volume.

I am deeply indebted to L. M. Barkov, A. S. Elkhovskiĭ, I. V. Kolokolov, and O. P. Sushkov for interest in this study and for numerous discussions.

1)This work was carried out with partial financial support from the Soros Fund and from the Committee on the Kosmomikrofizika Problem (Kosmion). e-mail: VOROBYOUOINP.NSK.SU.

---

[1] M. S. Turner, Phys. Rep. **197**, 67 (1990)

[2] Z. G. Berezhiani, A. S. Sakharov, and M. Yu. Khlopov, Yad. Fiz. **55**, 1918 (1992) [Sov. J. Nucl. Phys. **55**, 1063 (1992)].

[3] W. U. Wunensch *et al.*, Phys. Rev. D **40**, 3153 (1989).

[4] S. Matsuki, *Proc. of the Fifth Workshop on Elementary Particle Picture of the Universe* (ed. M. Fukugita and A. Suzuki) (KEK, 1990), p. 319.

[5] D. M. Lazarus *et al.*, Phys. Rev. Lett. **69**, 2333 (1992).

[6] P. V. Vorob'ev, *High Energy Physics (Materials of the Twenty-Fourth Winter School of the Leningrad Institute of Nuclear Physics)* (Leningrad, 1989), p. 66.

[7] P. V. Vorobyov and Yu. I. Gitarts, Phys. Lett. B **208**, 146 (1988).

[8] P. V. Vorobyov, I. V. Kolokolov, and V. F. Fogel, Particle World **1**, 163 (1990).

[9] A. I. Kakhidze and I. V. Kolokolov, Zh. Eksp. Teor. Fiz. **99**, 1077 (1991) [Sov. Phys. JETP **72**, 598 (1991)].

[10] D. J. Wineland, J. J. Bollinger *et al.*, Phys. Rev. Lett. **67**, 1735 (1991).

[11] R. C. Ritter *et al.*, Phys. Rev. D **42**, 977 (1990).

[12] P. V. Vorob'ev, A. S. Elkhovskiĭ, A. I. Kakhidze, and I. V. Kolokolov, "The axion wind or possibilities for searching for a cosmological axion condensate" (to be published).

[13] K. van Bibber *et al.*, Phys. Rev D **39**, 2089 (1989).

Translated by D. Parsons