Experimental Tests of the "Invisible" Axion

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Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

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Some time ago, it was shown that the strong CP problem[1] can be solved[2] by the introduction of a light pseudoscalar particle,[3] called the axion a. The properties of the axion depend mainly on the magnitude v of the vacuum expectation value that spontaneously breaks the $U_{PQ}(1)$ quasisymmetry which was postulated by Peccei and Quinn[2] and of which the axion is the pseudo-Goldstone boson. The axion mass and its couplings to ordinary particles are all inversely proportional to v. As far as the solution to the strong CP problem is concerned, the value of v is arbitrary.[4] Past experiments,[5] attempting to produce and detect axions in the laboratory, essentially rule out values of v near 250 GeV. Moreover the range 250 GeV $\lesssim v \lesssim 10^8$ GeV is ruled out by considering the effect axions have on stellar evolution.[6] Stars emit too many axions for those values of v. The axion with $v \gtrsim 10^8$ GeV is so weakly coupled[4] that it has been called "invisible." It was thought, incorrectly I believe, that such an axion solves the strong CP problem in a manner which is free of presently observable consequences.

Actually, the consideration of the cosmological implications[7,8] of axion models has already gone some way towards making a misnomer of the expression "invisible" axion. First, axion models are afflicted with cosmologically unacceptable domain walls[7] unless special precautions are taken to avoid this.[9] Second, it was shown that the present cosmological axion energy density is too large[8] unless $v \lesssim 10^{12}$ GeV. On the other hand, axions may have a useful cosmological role to play with regard to the problem of galaxy formation.[7,10] First, the primordial density perturbations from which galaxies evolved may have been produced by the presence of axionic domain walls for a limited time period in the early universe.[7] Second, axions may be the stuff the dark halos[11] of galaxies are made of.[10] Because of their very large primordial phase-space density, axions cluster easily and if $v \gtrsim 10^{10}$ GeV, axions are abundant enough to provide all the halo matter. In that case, the axion density near the sun's location is about

$$\rho_{a,\text{halo}} \simeq \frac{10^{-24}\text{ g}}{\text{cm}^3} \simeq \frac{0.5\times 10^{12}\text{ axions}}{\text{cm}^3}\left(\frac{v}{10^{10}\text{ GeV}}\right)\frac{1}{r}, \tag{1}$$

where we have used the following expression for the axion mass ($\hbar = c = 1$ everywhere):

$$m_a = 1.24\times 10^{-3}\text{ eV}[(10^{10}\text{ GeV})/v]r = \frac{2\pi}{10^{-1}\text{ cm}}\left(\frac{10^{10}\text{ GeV}}{v}\right)r = \frac{2\pi}{\frac{1}{3}\times 10^{-11}\text{ sec}}\left(\frac{10^{10}\text{ GeV}}{v}\right)r. \tag{2}$$

r is a model dependent number of order $N/6$, where N is the number of vacua of the axion model.[7,9] These halo axions have velocities $\beta \lesssim 10^{-3}$, and thus would form a highly degenerate Bose gas with quantum state occupation numbers averaging $(10^{17}/r^4)[v/(10^{10}\text{ GeV})]^4$. If the cosmological axions did not cluster into galactic halos [possibly because galactic clusters condensed before galaxies did], the axion density on earth should be the average cosmological one which, according to the result of Ref. 8, is about

$$\frac{0.2\times 10^6\text{ axions}}{\text{cm}^3}\left(\frac{v}{10^{10}\text{ GeV}}\right)^{13/6}\frac{1}{r}.$$

If their typical velocity is the virtual velocity in galactic clusters, $\beta \simeq 5\times 10^{-3}$, their average quantum state occupation number is about $0.4(10^9/r^4)[v/(10^{10}\text{ GeV})]^{31/6}$. The first two experiments proposed below would attempt to detect the axions of cosmological origin. The third experiment would attempt to detect the axions emitted by the sun. From the work of Fukugita, Watamura, and Yoshimura,[6] one obtains the following result for the solar axion flux on earth:

$$f_{a,\odot} \simeq \frac{0.8\times 10^{13}\text{ axions}}{\text{sec cm}^2}\left(\frac{10^8\text{ GeV}}{v}\right)^2. \tag{3}$$

The solar axions have energies of order one kiloelectronvolt.

To make the axion visible, we will exploit the coupling of the axion to the electromagnetic field and the fact that we have available in the laboratory large static magnetic or electric fields, or large oscillating ones with frequencies of order the axion mass (2). We also have very sensitive devices to monitor the electromagnetic field. The effective action density of axions and photons is

$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{e^2N}{12\pi^2}\frac{a}{v}F_{\mu\nu}\tilde{F}^{\mu\nu} + \tfrac{1}{2}\partial_\mu a\partial^\mu a - \tfrac{1}{2}m_a{}^2a^2[1+O(a^2/v^2)], \tag{4}$$

where $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$, $F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha$, and where we have assumed grand unification of the strong and electroweak interactions with the unrenormalized $\sin^2\theta_w{}^0 = \frac{3}{8}$. The action density (4) has recently been used to study[12] the long-range interactions $[\sim(\text{distance})^{-2}]$ of electric and magnetic charges with axionic domain walls, which behave towards them like polarizable surfaces. The classical equations of motion derived from (4) are

$$\nabla\cdot\vec{E} = \frac{e^2N}{3\pi^2v}\vec{B}\cdot\nabla a, \quad \nabla\times\vec{B} - \frac{\partial\vec{E}}{\partial t} = \frac{e^2N}{3\pi^2v}\left[\vec{E}\times\nabla a - \vec{B}\frac{\partial a}{\partial t}\right], \quad \Box a = \frac{e^2N}{3\pi^2v}\vec{E}\cdot\vec{B} - m_a{}^2a. \tag{5}$$

The axion haloscope.—According to (4) or (5), axions will convert to photons in a strong inhomogeneous magnetic field $\vec{B}_0(\vec{x})$. The inhomogeneity is necessary because three-momentum must be provided for the transition to occur. We find the following cross section for a detector of volume V:

$$\sigma = \frac{1}{16\pi^2|\vec{\beta}_a|}\left(\frac{e^2N}{3\pi^2v}\right)^2\sum_\lambda\int d^3k_\gamma\delta(E_\gamma - E_a)\left|\int_V d^3x\, e^{i\vec{q}\cdot\vec{x}}\vec{B}_0(\vec{x})\cdot\vec{\epsilon}(\vec{k}_\gamma,\lambda)\right|^2, \tag{6}$$

where $\vec{q} = \vec{k}_\gamma - \vec{k}_a$ and the sum is over the photon polarization. Multiplying (6) by the axion flux of the Milky Way halo, one obtains the rate

$$\frac{\text{No. of photons}}{\text{time}} \simeq \frac{1.6}{10^6\text{ sec}}\frac{V}{1\text{ cm}^3}\left(\frac{B_0}{1\text{ T}}\right)^2 R(m_a)\left(\frac{N}{6r}\right)^2, \tag{7}$$

where $R(m_a)$ is a measure of the detector's response,

$$R = \frac{E_a}{V}\int\frac{d^3k_\gamma}{(2\pi)^3}\delta(k_\gamma - E_a)\sum_\lambda\left|\int_V d^3x\, e^{i\vec{q}\cdot\vec{x}}\vec{b}(\vec{x})\cdot\vec{\epsilon}(\vec{k}_\gamma,\lambda)\right|^2, \tag{8}$$

and $\vec{b}(\vec{x}) = B_0{}^{-1}\vec{B}_0(\vec{x})$. One can choose to have large values of $R(m)$ over a small frequency band near m_0 by making the spatial dependence of $\vec{B}_0(\vec{x})$ periodic over many wavelengths $2\pi/m_0$. If $R = 10$, $B_0 = 10$ T, and $V = (30\text{ cm})^3$, there are about 45 $a\to\gamma$ events in the detector per second. Antennas exist which can detect single microwave quanta. For the signal not to be swamped by thermal noise it will be necessary to cool the volume V to below approximately $\frac{1}{10}m_a \simeq (0.36\text{ K})[(10^{10}\text{ GeV})/v]r$. One way to obtain the desired inhomogeneity of the magnetic field is to embed grains or wires of a superconducting metal in a material transparent to microwave radiation. When the detector is cooled below the critical temperature, the magnetic flux lines will be expelled from the superconducting loci and hence will be made inhomogeneous. If the cosmological axions did not cluster into galactic halos, the rate (7) is reduced by $0.4\times10^{-6}[v/(10^{10}\text{ GeV})]^{7/6}$.

To probe large values of v (small values of the axion mass) it may be advantageous to use a variable-frequency cavity in the axion haloscope experiment. One would attempt to tune the cavity's frequency ω exactly to the energy of the Milky Way axions,

$$m_a < \omega < m_a + \tfrac{1}{2}m_a\beta^2 = m_a[1 + O(10^{-6})]. \tag{9}$$

If Eq. (9) is satisfied, the power due to axion $\to$ photon conversion into the lowest TM mode of a rectangular cavity of length d and square cross section, in which there is a longitudinal static magnetic field B_0, is

$$P = (1.5\times10^{-15}\text{ W})\frac{1}{N^2}\left(\frac{N}{6r}\right)^4\left(\frac{v}{10^{12}\text{ GeV}}\right)^2\left(\frac{B_0}{10\text{ T}}\right)^2 kd, \tag{10}$$

where $k = (\omega^2 - m_a{}^2)^{1/2}$.

Finally, let us take note of the interest of trying to devise an experiment which exploits the very high quantum degeneracy of the axions in the halo of our galaxy. In particular, emission of axions with energies between m_a and $m_a[1+O(10^{-6})]$ is enormously stimulated {the rate is multiplied by a factor $10^{25}[v/(10^{12}\text{ GeV})]^4$}, and hence may become measurable. It is necessary, however, that the emitter does not equally well absorb axions; otherwise, stimulated emission and stimulated absorption will cancel each other, as is the case with a cavity or with any other *harmonic* oscillator coupled to the axion field.

The axion helioscope.—The idea here is the same as the previous one but now applied to the solar axion flux. In a strong magnetic field, solar axions convert to x rays. The change in three-momentum is

$$q_z=\frac{1}{2}\frac{m_a^2}{E_a}\simeq\frac{2\pi}{16\text{ cm}}\left(\frac{10^8\text{ GeV}}{v}\right)^2\left(\frac{1\text{ keV}}{E_a}\right)r^2. \tag{11}$$

Consider a detector of length L in the direction $\vec{n}$ of the sun, inside of which there is a transverse magnetic field $\vec{B}_0=\hat{t}B_0\cos[(2\pi/d)\vec{n}\cdot\vec{x}]$. The response (10) is

$$R=\frac{E_aL}{8\pi}\left[\frac{\sin(2\pi/d-q_z)L/2}{(2\pi/d-q_z)L/2}+\frac{\sin(2\pi/d+q_z)L/2}{(2\pi/d+q_z)L/2}\right]^2. \tag{12}$$

R can be huge and compensate for the smallness of the solar axion flux. (It is of course unessential for this that the spatial dependence of $\vec{B}_0$ is exactly a cosine.) Multiplying (8) by (3) one finds the rate

$$\frac{\text{No. of x rays}}{\text{time}}\simeq\frac{6\times10^{-3}}{\text{sec}}\frac{SL^2}{1\text{ m}^4}\left(\frac{10^8\text{ GeV}}{v}\right)^4\left(\frac{B_0}{10\text{ T}}\right)^2N^2\frac{8\pi R}{E_aL}, \tag{13}$$

where S is the area of the detector perpendicular to $\vec{n}$.

In conclusion, the "invisible" axion hypothesis can be tested experimentally, contrary to what was at first believed. Relatively simple experiments can provide new information about physics at very high energies, near the grand unification mass scale. If the axion exists, we will have new powerful tools to study the sun and the galaxy.

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