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Construction and Operation of an Axion Helioscope

Letter of Intent

to the

Fermi National Accelerator Laboratory

Lawrence Livermore National Laboratory
University of California at Berkeley
Lawrence Berkeley Laboratory
Texas Accelerator Center
Texas A&M University
Ohio State University
CERN

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ABSTRACT

We are preparing and evaluating a design for a detector sensitive to axions and other light particles with a two-photon interaction vertex. Such particles would be produced in the solar interior by Primakoff conversion of blackbody photons and could be detected by their reconversion into x-rays (average energy about 4 keV) in a strong macroscopic magnetic field. The heart of the detector would be the superconducting magnet presently used in the FNAL 15 foot bubble chamber. We envision that the experiment would be sited underground, possibly in the Gran Sasso Laboratory. Assuming the GUT relationship between the axion mass m_a and its two-photon coupling strength, this experiment is sensitive, in principle, to the range $0.1\,\mathrm{eV} < m_a < 5\,\mathrm{eV}$, a regime previously thought to be inaccessible by terrestrial experiments. The range $1\,\mathrm{eV} < m_a$ is excluded by the concordance of calculated and observed lifetimes of helium burning red giants. The observation of the neutrino pulse from the supernova 1987a excludes a range of axion masses between around $10^{-3}\,\mathrm{eV}$ and $1\,\mathrm{eV}$, with considerable uncertainty, however. Thus axions may still exist in the mass range in which our experiment is sensitive. A negative search result would close one of the few remaining windows for axion parameters and thus contribute to an ultimate decision of whether or not the Peccei-Quinn mechanism to solve the CP problem of strong interactions is realized in nature. Considerable work will be required over the next several months to refine background estimates and detection strategies to demonstrate that the necessary signal-to-noise ratio can be achieved over the entire above parameter range. We request assistance from Fermilab to assess the impact of relocation of the bubble chamber magnet and the engineering design required for the proposed use.

TABLE OF CONTENT

1. Introduction

a) Motivation

The conservation of the CP symmetry in strong interactions has been a long standing puzzle of particle physics in view of the CP violating effects observed in the K° meson system. In a compelling theoretical scheme proposed by Peccei and Quinn (1977a,b), the measured absence (or extreme smallness) of the neutron electric dipole moment is linked to the existence of a hitherto undetected particle—the axion (Weinberg 1978, Wilczek 1978). The phenomenological properties of this light, neutral pseudoscalar are mainly determined by the Peccei-Quinn parameter (or axion decay constant) f_a which arises as the scale at which the global chiral $U(1)$ symmetry postulated by Peccei and Quinn is spontaneously broken. Although it was originally thought that f_a should be identified with the electroweak scale $f_{\rm weak} \approx 250\,{\rm GeV}$ ("standard axions"), the axion decay constant can take on, in principle, any value between the GeV range and the Planck scale. Since the interaction strength of axions with matter and radiation scales as $1/f_a$, axion models with $f_a \gg f_{\rm weak}$ are generically referred to as "invisible axions". Depending upon the assumed value for f_a, the existence of axions would lead to a startling variety of phenomenological consequences in particle physics, astrophysics, and cosmology. The compound evidence from these different fields now excludes large ranges of f_a values, leaving open only rather narrow windows in which axions might still exist. Thus it has become a compelling task to attempt the detection of axions in these remaining ranges of parameters, or else to exclude the Peccei-Quinn mechanism once and for all as not being realized in nature.

b) Principle of the detector

We have made a preliminary design of an experiment which relies on the two photon coupling of axions or other light, exotic particles. This vertex allows for the Primakoff conversion (Fig. 1) of photons into axions and vice versa in the presence of external electric or magnetic fields. Thus axions would be produced in the solar interior where blackbody photons (temperature $T = 1.3\,{\rm keV}$ in the solar center) would be converted in the fluctuating electric fields of the charged particles in the hot plasma. These keV axions could be converted into x-rays in the presence of a strong magnetic field in the laboratory ("axion helioscope", Sikivie 1983). We propose to use the FNAL 15 foot bubble chamber magnet for this purpose with a typical magnetic field strength of 3 Tesla and a field volume of about $40\,{\rm m}^3$. Since the magnetic field varies only over macroscopic scales, the axion-photon conversion is best visualized as a mixing phenomenon (Raffelt and Stodolsky 1988) between these states in the presence of the external field: a state initially known to be an axion would subsequently oscillate, in part, into a photon. One easily finds that the transition rate is largest when the axion and photon are "degenerate", i.e., when their dispersion relations are identical so that the axion and photon component of a beam remain in phase for as long a distance as possible. In a medium, the dispersion relation for photons is identical with that of a massive particle if the photon energy is far above all resonances of the constituents of the medium. For x-rays in the keV range and a low-Z gas such as hydrogen or helium, this condition is met with sufficient precision so that one can match the axion mass with an effective photon mass over the whole range of relevant frequencies. Also, the absorption of x-rays by the medium (the imaginary part of the dispersion relation) is then so small that the x-ray component is not strongly damped over meter distances in our detector. The experiment would be operated in a scanning mode where the pressure of the gas is varied in appropriate steps such as to cover an interval of possible axion masses. In summary, the main ingredients of our detection scheme are

- the sun as an axion source,
- a strong magnetic field to mix the axion with the photon for reconversion,
- hydrogen or helium gas at variable pressure to match the axion and photon dispersion relation in order to enhance the transition rate,
- and a large area array of detectors sensitive to single photons in the $1 - 10\,\mathrm{keV}$ range, with a very low background rate.

c) Relevant parameter range

Our experiment would be sensitive to at least one decade of f_a values in a regime that covers one of the remaining parameter ranges in which axions may still exist. It is convenient to discuss the relevant parameter ranges in terms of the axion mass m_a by virtue of a universal relationship between m_a and f_a,

$$m_a = 1.2\,\mathrm{eV}\ N\,(10^7\,\mathrm{GeV}/f_a)\,, \tag{1}$$

where N is a non-zero, model-dependent integer coefficient of the color anomaly of the axion current*. We closely follow the normalization of parameters of Srednicki

* Note that the axion coupling to gluons, which is at the heart of the Peccei-Quinn scheme, is given as $(\alpha_s/4\pi)(N/f_a)G\tilde{G}a$ with the strong fine structure constant α_s and the axion field a. Thus the generic parameter governing different axion models is f_a/N which is uniquely represented by the axion mass.

(1985). The axion photon interaction is given as

$$\begin{aligned}\mathcal{L}_{a\gamma\gamma} &= -\frac{\alpha}{4\pi}\frac{N}{f_a}\,(E/N-1.92)\,a\,F_{\mu\nu}\tilde{F}^{\mu\nu} \\ &= -\frac{(m_a/\mathrm{eV})\,(E/N-1.92)}{2.1\times 10^{10}\,\mathrm{GeV}}\,a\,F_{\mu\nu}\tilde{F}^{\mu\nu}\,,\end{aligned} \tag{2}$$

where E is the coefficient of the electromagnetic anomaly of the axion current. Note that $F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\,\mathbf{E}\cdot\mathbf{B}$ and a is the axion field. In all grand unified axion models $E/N = 8/3$ and we shall refer to this value as the GUT relationship between the axion mass and the photon coupling strength. Other values for E/N are possible, however, and specifically $E/N = 2$ would lead to a large suppression of the photon coupling strength (Kaplan 1985). For GUT axions with $E/N = 8/3$ our range of sensitivity is

$$0.1\,\mathrm{eV} < m_a < 5\,\mathrm{eV}\,. \tag{3}$$

We stress, however, that generally our detection scheme depends on both the axion mass and the axion-photon coupling strength, and that these two parameters are *not* universally related because of the unknown value of E/N. Thus it is frequently convenient to express the axion-photon interaction as

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4M}\,a\,F_{\mu\nu}\tilde{F}^{\mu\nu} = \frac{a\,\mathbf{E}\cdot\mathbf{B}}{M}\,, \tag{4}$$

where M is given by $M^{-1} = |(\alpha/\pi)(N/f_a)(E/N-1.92)|$. Typical values of interest are m_a in the eV range and M in the $10^{10}\,\mathrm{GeV}$ range. With the notation $M_{10} = M/10^{10}\,\mathrm{GeV}$ one finds that

$$\frac{1}{M_{10}} = \frac{E/N-1.92}{8/3-1.92}\times 1.45\,(m_a/\mathrm{eV})\,. \tag{5}$$

For purposes of clarity we shall usually confine our discussion to the case of GUT axions with $E/N = 8/3$ while an ultimate analysis of the experimental results would fully explore the two-dimensional (M, m_a) parameter space. Such a discussion would then also cover more general cases of hypothetical particles besides axions.

d) Competing astrophysical arguments

Our range of sensitivity overlaps, in part, with regimes excluded by astrophysical arguments although we believe that axions can still exist in our parameter range. Raffelt and Dearborn (1987) show in a detailed discussion of stellar evolution that the existence of axions would lead to a severe conflict between calculated and observed lifetimes of helium burning red giants unless $M > 1\times10^{10}$ GeV. It is assumed that axions are lighter than about 10 keV so that their emission from the stellar plasma would not be Boltzmann suppressed. For GUT axions, this excludes the range

$$0.7\,\mathrm{eV} \lesssim m_a \lesssim 10\,\mathrm{keV}\,. \tag{6}$$

It is thought that the uncertainty in this bound—aside from the unknown value of E/N—does not exceed a small factor of order unity. This argument addresses the axion-photon coupling and thus compares most directly with our experiment.

There exist very restrictive constraints on the axion-electron coupling from late neutron star cooling (Iwamoto 1984), from the observed white dwarf cooling time scale (Raffelt 1986), and from the suppression of helium ignition in low mass red giants (Dearborn, Schramm, and Steigman 1986). The translation into axion mass bounds is somewhat model dependent. Typically, the range

$$0.03\,\mathrm{eV} \lesssim m_a \lesssim 10\,\mathrm{keV} \tag{7}$$

would be excluded. However, axions do not need to couple to electrons at tree level ("hadronic axions", Kaplan 1985), and then these results are irrelevant. Thus in our range of interest, only hadronic axions could still be expected to exist. Therefore we shall confine our attention to this type of model with important implications for the calculation of the solar axion spectrum (see Sect. 2 below).

Another argument relevant to our regime arises from late neutron star cooling (Iwamoto 1984, Tsuruta and Nomoto 1986). One finds a bound on the axion-nucleon coupling which translates, somewhat model-dependently, into an excluded regime for the axion mass of about

$$0.01\,\mathrm{eV} \lesssim m_a \lesssim 10\,\mathrm{keV}\,. \tag{8}$$

This result, however, is invalidated if nucleon superfluidity occurs in the interior of neutron stars, as is frequently assumed. Then the emission rate from the relevant nucleon bremsstrahlung processes is strongly suppressed. Other uncertainties associated with this bound arise from the unknown equation of state for dense nuclear matter and from the uncertain determination of the surface temperature of pulsars of known age.

The argument which "competes" most severely with our proposed experiment arises from the observation of a neutrino pulse from the supernova 1987a. This measurement indicates that the gravitational binding energy released in the collapse of the progenitor star was carried away by neutrinos, thus limiting the interaction strength of axions and other weakly interacting, exotic particles (Raffelt and Seckel 1988, Turner 1988, Mayle *et al.* 1988). However, if axions interact too "strongly" they are "trapped" in the hot proto neutron star that has formed after collapse just like neutrinos so that they would be inefficient in carrying away the energy stored in the supernova core. The excluded regime translates, in a model-dependent fashion, into a regime of excluded axion masses,

$$0.001\,\mathrm{eV} \lesssim m_a \lesssim 3\,\mathrm{eV}\,. \tag{9}$$

The upper end of this window where axions would be "strongly" interacting and trapped in the SN core has been estimated by Turner (1988). The uncertainty in this range is rather severe, perhaps as much as an order of magnitude on either end of the window. This means that the actually excluded regime may be much smaller than stated in Eq. (9). Also, however, the regime where axions would be important for SN dynamics could be much larger than the range Eq. (9).

The main uncertainties are: (a) The small number and uncertain energies of the observed neutrinos, the unknown value of the electron neutrino mass, and the uncertain distance to the Large Magellanic Cloud all of which prohibit the precise determination of the time and energy structure as well as the absolute normalization of the neutrino *emission* spectrum at the SN. (b) Uncertainties in the calculation of the axion-nucleon interaction processes in dense nuclear matter. (c) Uncertainties in theoretical SN modelling. (d) The model-dependent translation between the axion-nucleon interaction strength and the axion mass. (e) The lack of a self-consistent treatment of SN models including axions. Note that the (self-consistent) treatment of Mayle *et al.* (1988) only addresses the lower end of the range Eq. (9) in a specific axion model, while only Turner (1988) gives an *estimate* of the upper end which is most relevant for the "competition" with our experiment.

While some of these uncertainties can be removed by a more detailed study of SN models including the effect of axions, it appears that there may well exist a window for the existence of axions between the red giant bound and the SN bound. It is remarkable that our experiment addresses precisely this range where a new and reliable axion search would considerably extend our knowledge about the question of the axion's existence.

e) Other axion experiments

Other experiments that address the question of the axion's existence mainly operate in the regime of f_a values near f_{weak}—for a review see Cheng (1987) and Davier (1987). The experimental exclusion of axions in this regime has lead to the notion that axions must be "invisible" if they exist. For very large values of f_a (very small axion masses), an axion condensate would have formed in the early universe, and unless $f_a/N \lesssim 10^{12}$ GeV, i.e., $m_a \gtrsim 10^{-5}$ eV, the universe would be "overclosed" by axions (Preskill, Wise, and Wilzcek 1983, Abbott and Sikivie 1983, Dine and Fischler 1983). Near saturation of this bound, axions would constitute the "cold dark matter" that is believed to dominate the universe. Then axions clustered in our galaxy could be detected by their magnetic conversion into microwaves in a high-Q cavity (Sikivie 1983). An experiment of this sort is under way and has produced first negative results (DePanfilis *et al.* 1987), at a level, however, not relevant for the relationship between the axion mass and the photon coupling strength Eq. (2). Although this galactic axion search is of paramount importance for particle physics and cosmology, it is not clear at present whether it will be possible to "touch the axion line" Eq. (2) in the near future. For m_a of a few eV, thermally produced axions in the early universe would have survived in large numbers. Their present-day decay would be visible as a "glow" of the night sky (Kephart and Weiler 1987, Turner 1987), and existing measurements of the brightness of the night sky exclude a window of axion masses in the eV range. Another recently proposed experiment (Maiani, Petronzio, and Zavattini 1986, Melissinos *et al.* 1987) which addresses the magnetically induced birefringence of the vacuum will not be able to probe a regime covered by Eq. (2). Aside from measurements of the brightness of the night sky, our experiment is thus the only laboratory method sensitive to realistic axion models in the "far invisible" regime.

f) Summary

We believe, in summary, that the construction and operation of an axion helioscope would substantially extend our knowledge about the existence or non-existence of axions and the realization of the Peccei-Quinn mechanism in nature. The uncertainties of the astrophysical bounds, in conjunction with the freedom of the relevant parameters of the axion models, appear to be sufficiently severe to warrant an independent experimental effort. It is remarkable that our search would be most sensitive in a regime where two very different astrophysical arguments may or may not overlap. A detection of axions in this range—aside from its paramount importance for particle physics—would then be of great importance for astrophysics while a negative search result would allow one close the potential gap between these arguments with confidence. We thus proceed to discuss details of the experiment.

2. The Sun as an axion source

a) The axion spectrum

If we confine our attention to hadronic axion models where these particles do not interact with electrons at tree level, they can be efficiently produced in the Sun only by processes involving their two photon coupling Eq. (4). In the interior of the Sun, blackbody photons can convert into axions in the fluctuating electric fields of the charged particles in the plasma (Raffelt 1988)—see Fig. 1. In the limit of a large momentum transfer, this process can be viewed as the Primakoff effect on isolated charges. For a small momentum transfer, it is better visualized as the interaction with coherent field fluctuations in the plasma (longitudinal plasmons). The total transition rate of a photon (or rather transverse plasmon) of energy ω into axions is found to be

$$\Gamma(\gamma \to a) = \frac{T\,\kappa^2}{(4\pi M)^2}\,\frac{\pi}{2}\left[\left(1+\frac{\kappa^2}{4\omega^2}\right)\,\ln\left(1+\frac{4\omega^2}{\kappa^2}\right)-1\right], \tag{10}$$

where T is the temperature of the plasma. The Debye-Hückel scale κ is given by

$$\kappa^2 = (4\pi\alpha/T)\sum_j Z_j^2 N_j\,, \tag{11}$$

where N_j is the number density of charged particles with charge $Z_j e$. The inverse of κ is the screening scale for charges in a plasma while κ defines the borderline between a "large" and a "small" momentum transfer in the axion production process. The energy of the axion is close to the energy of the original photon because of the non-relativistic motion of the charged particles: the energy is smeared over an interval with a width on the order of the plasma frequency $\omega_{\rm pl}^2 = (4\pi\alpha/m_e)\,N_e$ with the number density N_e of electrons. A detailed result for the energy smearing is given in Raffelt (1988). Numerically, in the solar center one has $T = 1.3\,\text{keV}$, $\omega_{\rm pl} = 0.3\,\text{keV}$, and $\kappa = 9\,\text{keV}$.

The axion luminosity of the Sun is now determined by folding the photon-axion transition rate Eq. (10) with a blackbody photon distribution. To this end we have ignored the small spread of the axion energies for a given photon energy. Then we have integrated over a standard solar model (Bahcall *et al.* 1982) and find the differential axion flux as plotted in Fig. 2 (solid line). The average axion energy is $\langle E_a \rangle = 4.2\,\text{keV}$. With the notation $M_{10} = M/10^{10}\,\text{GeV}$ the total flux at the Earth is found to be

$$F_a = 3.54\times 10^{11}\,\text{cm}^{-2}\,\text{sec}^{-1}/M_{10}^2\,. \tag{12}$$

The total energy flux (luminosity) in axions is

$$L_a = 1.7\times10^{-3}\,L_\odot/M_{10}^2\,, \tag{13}$$

where $L_\odot = 3.86\times10^{33}\,\mathrm{erg\,sec^{-1}}$ is the solar (photon) luminosity. Thus axion production would cause only a very minor perturbation of the sun. The differential axion spectrum at the earth is well approximated by

$$\frac{dF_a}{dE_a} = \frac{1}{M_{10}^2}\,4.02\times10^{10}\,\mathrm{cm^{-2}\,sec^{-1}\,keV^{-1}}\,\frac{(E_a/\mathrm{keV})^3}{e^{E_a/1.08\mathrm{keV}}-1} \tag{14}$$

where E_a is the axion energy—see the dashed line in Fig. 2. Note that this is *not* a thermal spectrum which would vary as $E_a^2/(e^{E_a/T}-1)$. Note also that the difference between the result of our numerical integration and our analytical approximation to this result is negligible in view of the approximations involved in our calculation.

b) The angular divergence of the axion flux at the earth

In our proposed experimental setup the conversion between axions and x-rays would take place in long, relatively thin tubes so that an aperture effect occurs. Thus we need to determine the angular divergence of the axion radiation at the earth which arises because of the spatial extension of the axion source. To this end we have calculated the radial distribution of the axion production rate over the standard solar model of Bahcall *et al.* (1982). In Fig. 3 we show the radial distribution of the axion energy loss rate, dL_a/dr, normalized to unity if integrated from the solar center to the surface. Most axions emerge from a region within $0.2\,R_\odot$ (solar radii) of the solar disk. The average distance beteen the Sun and the earth is $214.9\,R_\odot$, corresponding to one astronomical unit or $1.50\times10^{13}\,\mathrm{cm}$. Thus the angular radius of the axion source region as viewed from the earth is $\delta_a \approx (0.2/214.9)\,\mathrm{rad} = 0.9\times10^{-3}\,\mathrm{rad}$.

3. Axion-photon conversion rate

a) Equation of motion

We now proceed to calculate the axion-photon conversion rate in the presence of a nearly homogeneous magnetic field and a refractive medium. To this end we consider the propagation of a wave ψ, the dispersion relation of which is close to that of a massless particle. Moreover, we consider a definite frequency component ω and plane