Proposal to Search for a Monochromatic Component of Solar Axions Using ^{57}Fe

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(Received 27 March 1995)

A new experimental scheme is proposed to search for almost monochromatic solar axions, whose existence has not been discussed heretofore. The axions would be produced when thermally excited ^{57}Fe in the Sun relaxes to its ground state and could be detected via resonant excitation of the same nuclide in a laboratory. A detailed calculation shows that the rate of the excitation is up to order 1 event/day kg ^{57}Fe. The excitation can be detected efficiently using bolometric techniques.

PACS numbers: 14.80.Mz, 25.40.Ny, 95.30.Cq, 96.60.Vg

The most attractive solution of the strong *CP* problem is to introduce the Peccei-Quinn global symmetry which is spontaneously broken at energy scale f_a [1]. The original axion model assumed that f_a is equal to the electroweak scale. Although it has been experimentally excluded, variant "invisible" axion models are still viable in which f_a is assumed to be very large; since coupling constants of the axion with matter are inversely proportional to f_a, experimental detection becomes very difficult. Such models are referred to as hadronic [2] and Dine-Fischler-Srednicki-Zhitnitskiĭ (DFSZ) [3] axions. At present, these invisible axions are constrained by laboratory searches, and by astrophysical and cosmological arguments. One frequently quoted window for f_a, which escapes all the phenomenological constraints, is $10^{10}-10^{12}$ GeV. Besides this, there is another window around 10^6 GeV for the hadronic axions which have vanishing tree level coupling to the electron. This is usually called the hadronic axion window. Recently, a careful study [4] of the hadronic axion window revealed that f_a in the range 3×10^5 to 3×10^6 GeV cannot be excluded by the existing arguments, because most of them were based on the axion-photon coupling which is the least known parameter among those describing the low energy dynamics of the hadronic axions.

Although several authors [5–7] proposed experimental methods to search for the axions with f_a about 10^6 GeV, all of the methods are clearly based on the axion-photon coupling, both at the source and at the detector. The methods utilize only the Primakoff effect; photons in the Sun are converted into axions, which are commonly called the solar axions, and they are reconverted into x rays in a laboratory. Thus there have been no experimental alternatives to test the hadronic axion window independent of the axion-photon coupling. The only experiment in this region [8], in which an emission line arising from the radiative decay of axions in the halo of our Galaxy is searched for, also proceeded through the axion-photon coupling.

Because of axion coupling to nucleons, there is another component of solar axions. If some nuclides in the Sun have $M1$ transitions and are excited thermally, axion emission from nuclear deexcitation could also be possible. ^{57}Fe can be a suitable axion emitter for the following reasons: (i) ^{57}Fe has an $M1$ transition between the first excited state and the ground state; (ii) the first excitation energy of ^{57}Fe is 14.4 keV, which is not too high compared with the temperature in the center of the Sun (~1.3 keV) [9]; and (iii) ^{57}Fe is one of the stable isotopes of iron (natural abundance 2.2%), which is exceptionally abundant among heavy elements in the Sun [10]. If the axion exists, strong emission of axions is expected from this nuclide.

These monochromatic axions would excite the same nuclide in a laboratory, because the axions are Doppler broadened due to thermal motion of the axion emitter in the Sun, and thus some axions have energy suitable to excite the nuclide.

I propose to search for the axions by detecting this excitation. Since both the emission and absorption occur via the axion-nucleon coupling, but not via the axion-photon coupling, this method is free from the uncertainty of the axion-photon coupling. In addition, this method has the merits that there is no need to tune the detector to a mass of the axions, and the mass can be large far beyond that of the proposed experiment [6] in which it is restricted by the high pressure of buffer gas. In this Letter, the detection rate of the resonant excitation by the monochromatic solar axions is calculated, and experimental realities are briefly discussed.

To estimate axion flux from the Sun, the calculation can be performed as in Ref. [11]. The energy loss due to the axion emission is

$$\delta E(T) = N \frac{2\exp(-\beta_T)}{1 + 2\exp(-\beta_T)} \frac{1}{\tau_\gamma} \frac{\Gamma_a}{\Gamma_\gamma} E_\gamma , \qquad (1)$$

where $N = 2.9 \times 10^{17}$ g^{-1} is the number of ^{57}Fe atoms per 1 g material in the Sun [9], $\beta_T = (14.4\,\mathrm{keV})/kT$, $\tau_\gamma = 1.3 \times 10^{-6}$ s, and $E_\gamma = 14.4$ keV. Γ_a/Γ_γ represents the branching ratio and contains nuclear-structure-dependent terms, which are important to evaluate the flux. It was calculated by Haxton and Lee [11] as

$$\frac{\Gamma_a}{\Gamma_\gamma} = \frac{1}{2\pi\alpha} \frac{1}{1 + \delta^2} \left[\frac{g_0\beta + g_3}{(\mu_0 - 1/2)\beta + \mu_3 - \eta} \right]^2 , \qquad (2)$$

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where $\delta \sim 0$ is the $E2/M1$ mixing ratio. μ_0 and μ_3 are the isoscalar and isovector magnetic moments, respectively: $\mu_0 - 1/2 \sim 0.38$ and $\mu_3 \sim 4.71$. $\beta = -1.19$ and $\eta = 0.80$ are the nuclear-structure-dependent terms. g_0 and g_3 are defined as [12]

$$\mathcal{L} = a\bar{N}i\gamma_5(g_0 + g_3\tau_3)N\,, \tag{3}$$

$$g_0 = -7.8 \times 10^{-8}\left(\frac{6.2 \times 10^6}{f_a/\mathrm{GeV}}\right)\left(\frac{3F - D + 2S}{3}\right), \tag{4}$$

$$g_3 = -7.8 \times 10^{-8}\left(\frac{6.2 \times 10^6}{f_a/\mathrm{GeV}}\right)\left[(D + F)\frac{1 - z}{1 + z}\right], \tag{5}$$

$$m_a = \frac{\sqrt{z}}{1 + z}\frac{f_\pi m_\pi}{f_a} = 1\,\mathrm{eV}\frac{\sqrt{z}}{1 + z}\frac{1.3 \times 10^7}{f_a/\mathrm{GeV}}\,, \tag{6}$$

where D and F denote the reduced matrix elements for the SU(3) octet axial vector currents and S characterizes the flavor singlet coupling. The naive quark model (NQM) predicts $S = 0.68$ [11], but the latest measurement shows that $S = 0.30 \pm 0.06$ [13]. $z = m_u/m_d \sim 0.56$ in the first order calculation. m_a is evaluated to be 1 eV with $z = 0.56$ and $f_a = 6.2 \times 10^6$ GeV. Using Eqs. (2)–(5), Eq. (1) becomes

$$\delta E(T) = 4.6 \times 10^4\ \mathrm{ergs\,g^{-1}\,s^{-1}} \times \left(\frac{10^6\,\mathrm{GeV}}{f_a}\right)^2 C^2 \exp(-\beta_T)\,, \tag{7}$$

$$C(D, F, S, z) \equiv -1.19\left(\frac{3F - D + 2S}{3}\right) + (D + F)\frac{1 - z}{1 + z}\,, \tag{8}$$

where $\beta_T \gg 1$ is assumed in the solar interior. Our estimation differs slightly from that of Ref. [11], because a different value of ^{57}Fe abundance in the Sun is used [9].

Equation (7) provides an estimation of the differential axion flux at the Earth,

$$\frac{d\Phi(E_a)}{dE_a} = \frac{1}{4\pi R_E^2}\int_0^{R_\odot}\frac{1}{\sqrt{2\pi}\sigma(T)}\exp\left[-\frac{(E_a - E_\gamma)^2}{2\sigma(T)^2}\right] \times \frac{\delta E(T)}{E_\gamma}\rho(r)4\pi r^2 dr\,, \tag{9}$$

where R_E is the average distance between the Sun and the Earth. $R_\odot$ denotes the solar radius. $T(r)$ and $\rho(r)$ are the temperature and the mass density at the radius r, respectively. $\sigma(T) = E_\gamma(kT/m)^{1/2}$ represents the Doppler broadening. m is the mass of the ^{57}Fe nucleus. It should be noted that the number of iron atoms per unit mass is assumed to be uniform as in the framework of the standard solar model (SSM) [8], i.e., that N is independent of r. In addition, the SSM provides the mass density and the temperature as a function of the radius r, which are necessary for calculating Eq. (9). The values of the functions are taken from Table XVI in Ref. [8]. Thus Eq. (9) can be evaluated if one fixes D, F, S, z, and f_a. The sharp peak in Fig. 1 corresponds to the axion flux evaluated with $D = 0.77, F = 0.48, S = 0.68, z = 0.56$, and $f_a = 10^6$ GeV . Also shown is the expected axion flux generated through the Primakoff effect [6]. It is a striking fact that substantial axion emission is expected from the nuclear deexcitation. The differential flux at E_γ is obtained to be

$$A = 2.0 \times 10^{13}\ \mathrm{cm^{-2}\,s^{-1}\,keV^{-1}}\left(\frac{10^6\ \mathrm{GeV}}{f_a}\right)^2 C^2, \tag{10}$$

where dependences on D, F, S, and z are included in C. The effects of the nuclear recoil and of the redshift due to the gravitation of the Sun are negligible. The former decreases the axion energy by only about 1.9×10^{-3} eV and the latter about 1.5×10^{-1} eV, which are negligibly small compared with the width of the peak in Fig. 1.

In a laboratory, these axions would resonantly excite ^{57}Fe. The rate of the excitation is calculated as follows. It is a reasonable approximation that $d\Phi(E_a)/dE_a = A$ over the natural width of ^{57}Fe, $\mathcal{O}(10\ \mathrm{neV})$, around 14.4 keV, because the width of the peak in Fig. 1 is extremely broadened to about 5 eV. Hence the rate of the excitation per ^{57}Fe nucleus is

$$R_N = A\sigma_{0,a}\Gamma_{\mathrm{tot}}\pi/2\,, \tag{11}$$

$$\sigma_{0,a} = 2\sigma_{0,\gamma}\Gamma_a/\Gamma_\gamma\,, \tag{12}$$

where $\sigma_{0,\gamma} = 2.6 \times 10^{-18}\ \mathrm{cm}^2$ is the maximum resonant cross section of γ rays [14], and $\Gamma_{\mathrm{tot}} = 4.7 \times 10^{-12}$ keV is the total decay width of the first excited state of ^{57}Fe. The factor 2 in Eq. (12) represents the difference of the spin multiplicity between photons and axions.

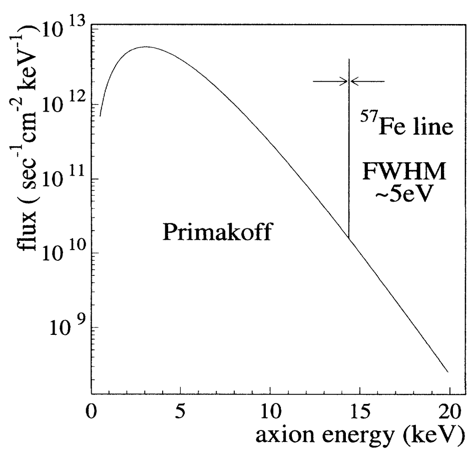

FIG. 1. Differential flux of the axion from the Sun. The sharp peak corresponds to the axion emission from the ^{57}Fe deexcitation. The broad part of the differential flux corresponds to the axion generated through the Primakoff effect.

Equations (10) and (11) now allow us to calculate the total detection rate per unit mass of ^{57}Fe in the laboratory,

$$R = 3.0 \times 10^2 \text{ day}^{-1}\text{kg}^{-1}\left(\frac{10^6 \text{ GeV}}{f_a}\right)^4 C^4, \qquad (13)$$

where C depends on D, F, S, and z as shown in Eq. (8). As for D and F, measurements of the nucleon and hyperon β decays show $D = 0.77$ and $F = 0.48$ [11]. However, the estimations of S and z have large uncertainties and ambiguity [13,15]. In particular, z might suffer large corrections due to instanton effects [15] and be significantly smaller than the value of the first order calculation, 0.56. Therefore the detection rate should be represented as a function of S and z. Figure 2 shows the contours of the calculated detection rate with $f_a = 10^6$ GeV.

The argument of Ref. [11] restricts the excitation rate in Fig. 2. The restriction is obtained from Fig. 2 of Ref. [11] and is shown in Fig. 3. The upper bound is obtained from the argument of red-giant evolution, and the lower bound is given by considering the effect of axion cooling on SN1987A. Since there are both the upper bound and lower bound of the rate, experiments which have adequate sensitivity will definitely determine whether the axion exists with f_a in the window.

In Fig. 3, experimental values of S obtained recently [16] are also shown. The latest experimental result gives $S = 0.30 \pm 0.06$ [13], and an analysis [17] determines $S = 0.31 \pm 0.07$. If the true value of S is around 0.3 as suggested, the expected event rate is restricted between 0.1 and 1 event/kg day.

We now turn to a discussion of experimental realities. After the excitation of the nuclei by the axion, the emission of a γ ray with an energy of 14.4 keV or the emissions of an internal conversion electron with an energy of 7.3 keV and subsequent atomic radiations will occur. Since the attenuation length of the γ ray is 20 μm

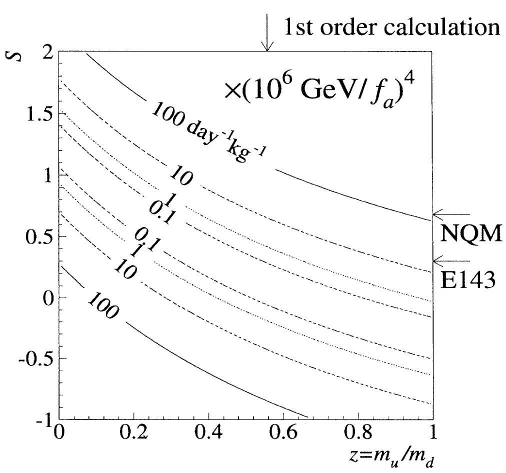

FIG. 2. Contours of the detection rate as a function of S and z. The naive quark model (NQM) predicts $S = 0.68$ [11], but the measurement (E143) [13] obtained $S = 0.30 \pm 0.06$.

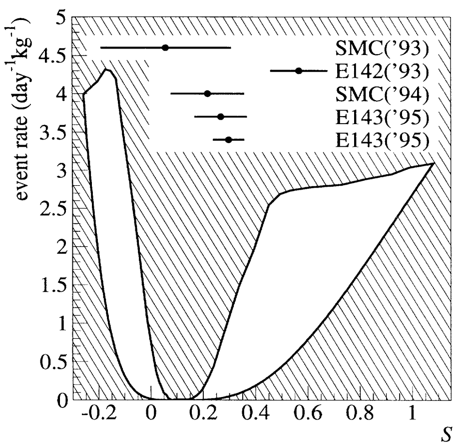

FIG. 3. Bound for the excitation rate with $z = 0.56$. The hatched area is excluded by the argument of red-giant evolution and SN1987A [11]. Also shown is the experimental values of S that were measured recently [13,16].

and the range of the electron is 0.2 μm in iron, it is difficult to detect the γ rays or electrons outside iron. In addition, detectors should have low energy threshold, low background, and high energy resolution. However, these difficulties are possibly overcome by using a bolometric technique with an absorber which contains ^{57}Fe-enriched iron. The technique has many advantages compared with other techniques in these respects. It is generally accepted that a sensitivity down to 0.1 event/kg day is reachable with a bolometer for dark matter search. If we can utilize this technique for the proposed experiment, it is possible to obtain a definite result as discussed above.

In summary, a new scheme to detect almost monochromatic solar axions using resonant excitation of ^{57}Fe is proposed. ^{57}Fe is rich in the Sun, and its first excitation energy is low enough to be excited thermally. Therefore, one can expect the nuclear deexcitation accompanied with the axion emission. Because of the Doppler effect associated with the thermal motion of ^{57}Fe in the Sun, a small portion of the axions from the nuclide can be absorbed by the same nuclide in a laboratory. The nuclide is considered as a well tuned detector of the axions. A detailed calculation shows that the excitation rate is up to order 1 day $^{-1}$kg $^{-1}$. Although it is difficult to detect the excitation outside the iron, this excitation is detected efficiently by a bolometric technique with an absorber which contains ^{57}Fe-enriched iron. I am planning an experiment to search for the monochromatic axions from the Sun in this new scheme.

I am very much indebted to Professor M. Minowa for his many suggestions for improving the manuscript, and for his helpful comments concerning experimental realities. I wish to thank Y. Inoue and Y. Kishimoto for discussions with them and Y. Inagaki, H. Asakawa, and

A. Kawamura for their helpful comments. Discussions with Y. Ito, W. Ootani, and K. Nishigaki helped me to understand the bolometric technique.

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