Search for Solar Axions Using $^{57}$Fe

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We have made a search for $^{57}$Fe gamma rays of energy 14.4 keV induced by resonant absorption of monochromatic solar axions, as proposed by Moriyama. The proposed axions are suggested to be emitted from the Sun, in M1 transitions between the first, thermally excited state and the ground state of $^{57}$Fe. An upper limit on hadronic axion mass of 745 eV is obtained at the 95% confidence level, it being assumed that $z = 0.56$ and $S = 0.5$.

24.80.-y, 14.80.Mz, 23.20.Lv, 96.60.Vg

The existence of axions, proposed as very light neutral pseudoscalar bosons which couple weakly to stable matter, would solve the strong CP problem associated with the $\Theta$–vacuum structure of QCD. The effects of $\Theta$–vacuum lead to an effective interaction which violates CP invariance in strong interactions, the magnitude of the interaction being proportional to the parameter $\Theta$. A limit on $\Theta$ of less than (or of an order of) $10^{-5}$ follows from present experimental bounds upon the electric dipole moment of the neutron. In an attempt to guarantee strong CP invariance automatically, Peccei and Quinn have introduced an additional global chiral symmetry, spontaneously broken at an energy scale $f_a$, yielding $\Theta=0$ dynamically [1]. This solution predicts the existence of a pseudo Nambu–Goldstone boson, called the axion, whose mass ($m_a$) is inversely proportional to $f_a$ [2]. Axions also arise in supersymmetric and superstring theories and are candidates for dark matter in the universe. In the standard axion model [1,2] the Peccei–Quinn (PQ) symmetry breaking scale is assumed to be equal to the scale of electroweak symmetry breaking. The axion mass would be roughly of the order of 100 keV to 1 MeV and has been experimentally excluded [3]. Variant axion models keep $f_a \sim 250$ GeV, but drop the constraints of tree–level flavor conservation and predict an axion mass near to 1.7 MeV [4]. The existence of variant axions has similarly been ruled out by experiment [5]. In efforts to retain the PQ idea, new axion models have been proposed which decouple the scale of PQ symmetry breaking from the electroweak scale and introduce $f_a$ at a value much greater than 250 GeV. Because coupling constants of axions with matter and radiation are inversely proportional to $f_a$, axion models of this type are generically referred to as invisible axions. The two classes of invisible axion models which have been proposed are referred to as KSVZ or hadronic axions [6] and DFSZ or “GUT” axions [7]. While astrophysical and cosmological considerations constrain the mass of these invisible axions to a rather narrow range of $10^{-5}$ eV $\leq m_a \leq 10^{-2}$ eV, but with large uncertainties on either side, less model-dependent laboratory experiments have excluded masses greater than about 10 keV [8–10]. However, it should be noted that for hadronic axions there exists a small window $10$ eV $\leq m_a \leq 20$ eV, between the supernova (SN) 1987A cooling and axion burst arguments [9–11], as long as the axion–photon coupling is sufficiently small $(E/N \approx 2)$.

Because of axion coupling to the nucleus, Moriyama [12] has proposed the existence of almost monochromatic axions produced in the solar interior during M1 transitions between the first, thermally excited state of 14.4 keV and the ground state of $^{57}$Fe. The stable isotope of iron, $^{57}$Fe (with natural abundance 2.2%), is exceptionally abundant among the heavy elements in the Sun (solar abundance by mass fraction 2.7×10$^{-5}$). The axions are Doppler broadened due to thermal motion of the axion emitter in the Sun and therefore they are able to excite the same nuclide. In the laboratory it is possible that this effect could be measured by absorption of solar axions in a $^{57}$Fe target. The possibility of decay of the axion into two photons during their traversal from the Sun to the Earth is insignificant. The resonant excitation of $^{57}$Fe by axions would be accompanied by subsequent decays of excited nuclei, either through emission of a gamma ray with an energy of 14.4 keV, or through emission of an internal conversion electron. By detecting these decay products one could make conclusions about the mass of the axion. This makes possible an experimental test of the hadronic axion window, independent of the axion–photon coupling. Experiments based on the axion–photon coupling have been proposed and results were reported by several authors [13].

Following the calculations in Ref. [12], one can express the total rate of excitation per unit mass of $^{57}$Fe in the laboratory as

$$R_{\text{exc}} = 1.65 \times 10^{24} \frac{(\Gamma_a/\Gamma_\gamma)^2}{\Gamma_\gamma} \text{ day}^{-1} \text{ g}^{-1},$$

where $\Gamma_a/\Gamma_\gamma$ represents the branching ratio of the M1 axionic transition, relative to the gamma transition [14] and contains the nuclear–structure–dependent terms $\beta$ and $\eta$. 


as well as the isoscalar and isovector axion–nucleon coupling constants $g_0$ and $g_3$.

$$\frac{\Gamma_a}{\Gamma_\gamma} = \left( \frac{k_b}{k} \right)^3 \frac{1}{2\pi \alpha} \frac{1}{1 + \delta^2} \left[ \frac{g_0\beta + g_3}{(\mu_0 - \frac{1}{2})\beta + \mu_3 - \eta} \right]^2,$$

where $k_b$ and $k$ are the momenta of the photon and the axion, respectively, $\alpha \approx 1/137$ is the fine structure constant, $\delta = 0$ is the E2/M1 mixing ratio, $\mu_0 - 1/2 \approx 0.38$, $\mu_3 \approx 4.71$, $\beta = -1.19$ and $\eta = 0.80$. The quantities $\mu_0$ and $\mu_3$ denote the isoscalar and isovector magnetic moments, respectively, while $g_0$ and $g_3$ are related to the axion mass in the hadronic axion model [15] as follows:

$$g_0 = -7.8 \times 10^{-8} \left( \frac{m_a}{1 \text{ eV}} \right) \left( \frac{3F - D + 2S}{3} \right)$$

and

$$g_3 = -7.8 \times 10^{-8} \left( \frac{m_a}{1 \text{ eV}} \right) \left( \frac{F + D}{1 + z} \right) \frac{1 - z}{1 + z}.$$

The mass of the axion is related to $f_a$ by

$$m_a = 1 \text{ eV} \sqrt{\frac{z}{1 + z}} \frac{1.3 \times 10^{30}}{f_a/\text{GeV}}.$$

The constants $F$ and $D$ are the invariant matrix elements of the axial current, determined from semileptonic decays, $S$ is the flavor–singlet axial–vector matrix element, and $z = m_a/m_d \approx 0.56$ is obtained in a first order calculation of the quark mass ratio. The naive quark model gives $S = 3F - D = 0.58$. However, the estimation of $z$ and $S$ suffer from large uncertainties and ambiguity, and are still poorly constrained parameters. The error on $z$ is of the magnitude of a second–order correction [9], while the experimental value of $S$, extracted from the polarized structure function data, ranges from $-0.09$ to $0.57$ [16]. Combined reanalyses have been carried out, from recent data taken using different targets, including NLO perturbative QCD [17,18]. A value $S \simeq 0.5$ was estimated, with $F + D = 1.257$ and $F/D = 0.575$.

We have searched for a peak corresponding to the 14.4 keV gamma ray of $^{57}$Fe in a single spectrum measured by a Si(Li) detector (SLP–10180–P, ORTEC). The energy resolution at this photon energy is 235 eV for presently used facilities. The total internal conversion coefficient for nuclear deexcitation of the first excited state of $^{57}$Fe is 8.56 [19], and thus the corresponding probability for emission of 14.4 keV gamma rays is $\gamma = 0.105$. We have obtained an energy calibration using the radioactive sources $^{55}$Fe, $^{57}$Co and $^{241}$Am (IAEA) with a diameter of about 7 mm. The target of $^{57}$Fe was a Mössbauer absorber, 95% enriched (WISSEL), with a diameter of 10 mm and a thickness of about 53 $\mu$m. A disc of natural iron with the same dimensions was used for background measurement. The mass of $^{57}$Fe in the enriched target is $M = 31.53 \times 10^{-3}$ g, and a distance between the target and beryllium window of the detector of 3 mm was used. Since the attenuation length of the 14.4 keV gamma ray is 20 $\mu$m in iron, the average escape probability from the target is $\xi = 0.35$. We have estimated a total efficiency for detection of 14.4 keV gamma rays using the 13.9 keV gamma ray emission from the $^{241}$Am source (activity $2.05 \times 10^3$ Bq) and obtained $\varepsilon = (1.6 \pm 0.1) \times 10^{-2}$.

![Figure 1](image-url)

**FIG. 1.** (a) The 14.4 keV gamma ray peak from the $^{57}$Co source. (b) Energy spectra measured with the enriched $^{57}$Fe (run) and with the natural iron (background) targets, accumulated for time periods of $5.3 \times 10^6$ s. (c) Net number of counts in the region of the 14.4 keV gamma ray peak in an effort to detect axionic excitation of $^{57}$Fe.

The position and width of the peak have been estimated by measuring the 14.4 keV gamma ray peak from the $^{57}$Co Mössbauer source, Fig. 1(a). Energy spectra
have been measured with the enriched $^{57}$Fe target, providing sensitivity to monochromatic solar axions, and with the natural iron target, Fig. 1(b). The difference between these two spectra is shown in Fig. 1(c). Data and background were both accumulated for time periods $\Delta t = 61.343$ days. We have detected $N_\gamma = 56 \pm 201$ gamma ray events in the energy interval of 481 eV. Equations (1)–(4) allow us to relate the axion mass to the measured value of $N_\gamma$,

$$\left( \frac{m_a}{\text{eV}} \right)^4 = \frac{4.9 \times 10^3}{C^4} \frac{N_\gamma}{M \cdot \Delta t \cdot \gamma \cdot \xi \cdot \varepsilon},$$

(5)

where $C = \beta(3F - D + 2S)/3 + (F + D)(1 - z)/(1 + z)$. If the value of $S$ is 0.5, as suggested by recent analyses [17,18], we obtain $m_a^4 = (4.5 \pm 16.0) \times 10^{10}$ eV$^4$. To determine an upper limit to the invisible hadronic axion mass, we have multiplied our statistical error by 1.645 and added in the value of $m_a^4$ to obtain $m_a < 745$ eV at the 95% confidence level. It can be noted that in Eq. (5) we have omitted a phase space factor $(k_a/k)^3$. The effect of this on the measured axion mass in our experiment is estimated to be less than $2 \times 10^{-3}$. We have also considered self absorption of monochromatic axions with $m_a \leq 1$ keV in the solar interior, in addition to the effect of absorption by the Earth (day/night modulation). The mean free path of the axions has been calculated to be $(2\pi)^{1/2}(\sigma_{\text{em}} + \sigma_{\text{ab}})^{1/2}/\gamma n$, the effects of nuclear recoil $(1.9 \times 10^{-6}$ keV) and the redshift due to the gravitation of the Sun $(1.5 \times 10^{-4}$ keV) being considered negligible. The quantities $\sigma_{\text{em}}$ and $\sigma_{\text{ab}}$ represent Doppler broadening of the 14.4 keV line of $^{57}$Fe at the temperature of the emitter and the absorber, respectively, while $n$ is the average density of $^{57}$Fe atoms in the absorber. The integrated cross section for axion resonant absorption is $\sigma = \frac{\pi \sigma_0 \Gamma a}{\Gamma_{\gamma}}$, where $\sigma_0 = 2.6 \times 10^{-18}$ cm$^2$ is the maximum resonant cross section of $\gamma$ rays and $\Gamma = 4.7 \times 10^{-12}$ keV is the total decay width of the first excited state of $^{57}$Fe. From the above, it is indicated that axions of mass $m_a \leq 1$ keV would escape from the Sun with insignificant absorption $(<10^{-7})$. The day/night modulation is less than $10^{-5}$.

We have performed the first measurement of nuclear axion emission from the Sun, deriving an upper limit to the hadronic axion mass of 745 eV. The SN 1987A bound for hadronic axion mass is 20 eV [11]. Note however that both limits depend upon astrophysical and particle physics parameters. Solar axion emission has been estimated using temperature and $^{57}$Fe density distributions, obtained within the framework of the standard solar model [20]. SN 1987A axion emission was estimated, identifying absorption probability for a given coupling to nucleons $(g_{aN})$ within a simplified model of the supernova density and temperature profile. However, statistics dominate the uncertainties associated with the axion burst argument, with only 19 neutrinos being observed from SN 1987A. Observations of other supernovae will be required if the uncertainty is to be reduced. Recent measurements of the particle physics parameters, used in obtaining the SN 1987A upper mass bound, allow estimation of expected events in the Kamiokande II study. From Fig. 1 in Ref. [11] we have scaled the events, expected due to absorption of 10.96 MeV axions into the $0^-$ state of $^{16}$O, using $c_6^2$, where $c_6 = (3F - D + 2S)/6$ is the dimensionless isoscalar coefficient. From the derived value of $g_{aN} \approx 2 \times 10^{-6}$ and the recent value of $g_{aN} = 5 \times 10^{-8}$ eV/fm$^3$ we have recalculated the upper limit of hadronic axion mass from the axion burst argument to be $m_a \leq 40$ eV.

We conclude, by noting that improvements in detection of 14.4 keV gamma rays from $^{57}$Fe atoms are possible, by seeking increase in the value of the factor $M \cdot \xi \cdot \varepsilon$ in Eq. (5) and by further suppressing the background. This new method of investigation appears very promising in determining the hadronic axion window, being independent of supernova models and the uncertainties associated with them.

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