Search for solar axions using \(^7\)Li

M. Krčmar\(^1\), Z. Krečak\(^1\), A. Ljubičić\(^1\), M. Stipčević\(^1\), and D. A. Bradley\(^2\)

\(^1\)Rudjer Bošković Institute, POB 180, 10002 Zagreb, Croatia
\(^2\)School of Physics, University of Exeter, Stocker Road, Exeter EX4 4Q1, UK

We describe a novel approach to the search for solar, near–monochromatic hadronic axions, the latter being suggested to be created in the solar core during M1 transitions between the first excited level of \(^7\)Li, at 478 keV, and the ground state. As a result of Doppler broadening, in principle these axions can be detected via resonant absorption by the same nuclide on the Earth. Excited nuclei of \(^7\)Li are produced in the solar interior by \(^7\)Be solar neutrinos of energy 384 keV. An experiment was made which has yielded an upper limit on hadronic axion mass of 32 keV at the 95\% confidence level.

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Axions, neutral, spin–zero pseudoscalar particles that go beyond the Standard Model, arise from spontaneous breaking of the Peccei–Quinn (PQ) chiral symmetry \(^1\), the latter being introduced to resolve the strong CP problem. A non–zero axion mass (\(m_a\)) can be interpreted as a mixing of the axion field with pions, and is related to the PQ symmetry breaking scale (\(f_a\)) by \(m_a f_a \approx m_a f_\pi\), where \(m_\pi = 135\) MeV is the pion mass and \(f_\pi \approx 93\) MeV its decay constant. Generically, all effective coupling constants of axions with ordinary matter and radiation are linear in \(m_a\) or, equivalently, are inversely proportional to \(f_a\). The original suggestion that there existed axions, with \(f_a\) equal to the scale of electroweak symmetry breaking and hence with \(m_a\) of a few hundred keV, was quickly ruled out by experiment. New axion models have subsequently been proposed which de–couple the PQ scale from the electroweak scale, and introduce \(f_a\) at a value much greater than 250 GeV. As such, the axion mass and all couplings become extremely small and therefore axion models of this type are generally referred to as invisible axion models. Two classes of invisible axion models have been developed: KSVZ (Kim, Shifman, Vainshiteit, and Zakharov) models \(^3\) and DFSZ (Dine, Fischler, Srednicki, and Zhitnitskii) or grand unified theory (GUT) models \(^4\). The main difference between KSVZ and DFSZ axions is that the former have no tree–level couplings to ordinary quarks and leptons because new heavy quarks have been introduced that carry the PQ charge while usual quarks and leptons do not. As a result, the interaction of KSVZ–type axions with electrons is strongly suppressed. In spite of this, their coupling to nucleons is not zero due to the generic axion–pion mixing which exists even if the tree–level coupling to ordinary quarks vanishes. Since the KSVZ axions do not couple directly to leptons, they are referred to as hadronic axions. The coupling of invisible axions to photons is described by \(g_a\gamma\gamma \propto m_a\{E/N - 2(4 + z + w)/[3(1 + z + w)]\}\), where the value of the parameter, \(E/N\), is model dependent for hadronic axions, being a function of exotic fermion charges, while the other parameter within the brackets is a function of quark mass ratios \(z = m_u/m_d \approx 0.55\) and \(w = m_u/m_s \approx 0.029\). Note that in a recent review of the Particle Data Group \(z\) was listed to have a value within the conservative range 0.2 to 0.8 \(^5\). It should be mentioned that contrary to the KSVZ models, where \(E/N\) is a model dependent number, in GUT models \(E/N = 8/3\). It was shown by Kaplan \(^6\) that it is possible to construct hadronic axion models with \(E/N = 2\), in which the axion to photons coupling is significantly reduced and may actually vanish because of a cancellation of these two unrelated numbers. As such, the globular–cluster constraints on axion mass \(^7\), which rule out DFSZ-type axions with \(m_a \gtrsim 10^{-2}\) eV, as well as the most sensitive detection techniques for searching for invisible axions \(^8\), based on the axion to photons interaction, have no relevance to hadronic axions which only couple to nucleons. So far the most restrictive boundaries on the mass of the hadronic axion arise from arguments concerning the supernova (SN) 1987A cooling \(^9\) and axion burst \(^10\). This narrow range of allowed axion masses, \(10\) eV \(\lesssim m_a \lesssim 20\) eV, is referred to as the hadronic axion window. Implications of nuclear axion emission in globular–cluster stars on limits for axion mass, involving a metallicity dependent modification of the core mass at helium ignition, have also been considered \(^11\). It should be noted that supernova arguments depend upon axion emission in a hot and dense nuclear medium, one problem being to provide a reliable estimate of the axion emission rate from nucleon–nucleon bremsstrahlung, and on particle physics parameters where there exist large uncertainties and ambiguities. As a result, the SN 1987A limits can be considerably relaxed \(^12\). In addition, the SN 1987A arguments suffer from statistical weakness, with only 19 neutrinos being observed at the Kamiokande II and at the Irvine–Michigan–Brookhaven water Čerenkov detectors. Although supernovae of similar size and distance to that of SN 1987A are very rare events, with only four historical records over the past millennium, verification
of hadronic axion window observations of another supernovae will be required if the uncertainty is to be reduced. In respect of the early universe, axions in the hadronic axion window can reach thermal equilibrium before the QCD phase transition and hence, like neutrinos, they are also candidates for hot dark matter [10].

Because there exists a possibility that hadronic axions can be emitted during magnetic nuclear transition, Moriyama [17] proposed the existence of near-monochromatic axions of energy 14.4 keV, produced by nuclear emission from the first, thermally excited level in $^{57}$Fe in the hot core of the Sun. The proposed axions provide an ability to open a new line of hadronic axion investigations independent of the uncertainties in the axion–nucleon scattering cross section and modeling of supernovae. Contrary to the situation for supernovae, the Sun is the best known star, being well described by the Standard Solar Model (SSM) [18], and the solar axions are continuously available for experiments. The first experiment along this new line of solar axion investigations set an upper limit on hadronic axion mass of 745 eV at the 95% confidence level [19].

Referring to the thermonuclear fusion reactions that produce solar energy, we propose a search for near-monochromatic axions of energy 14.4 keV, produced by magnetic nuclear transition of energy 384 keV. Figure 1 shows the scheme of electron capture decay of $^7$Be [20]. The branching ratio of the electron capture decay to the first excited state of $^7$Li is $\kappa = 0.104$. Note that the decay of the 478-keV excited level proceeds predominantly via $\gamma$-ray emission since the corresponding internal conversion coefficient is $7.3 \times 10^{-7}$. Therefore the $\gamma$-decay width of the first excited to the ground state of $^7$Li ($\Gamma_\gamma = 6.3 \times 10^{-6}$ keV) is a good approximation of the total decay width ($\Gamma$). The high temperatures in the centre of the Sun ($\sim 1.3$ keV) symmetrically broaden the axion line to a full–width at half–maximum (FWHM) of about 0.5 keV owing to the motion of the axion emitter. Since the effects of nuclear recoil ($\approx 1.8 \times 10^{-2}$ keV) and of redshift due to the gravitational of the Sun ($\sim 5 \times 10^{-3}$ keV) are much smaller than Doppler shifts, the axion line is approximately centred at the transition energy $E_\gamma = 478$ keV. Because of thermal broadening the near–monochromatic axions could be resonantly absorbed by the same nucleus in a laboratory on the Earth, and the detection of subsequent emission of $\gamma$ rays of 478 keV would be a sign of axion existence.

As a result of the Doppler effect, the flux of axions accompanying emission of $^7$Be solar neutrinos, differential with respect to axion energy $E_a$, $d\Phi(E_a)/dE_a$, has the particular form [21]

$$\frac{d\Phi(E_a)}{dE_a} = \int_0^{R_\odot} d\Phi(r) \frac{\kappa_2}{\Gamma_\gamma} \frac{1}{\sqrt{2\pi\sigma(T)}} \exp \left[ -\frac{(E_a - E_\gamma)^2}{2\sigma(T)^2} \right], \quad (1)$$

where $R_\odot$ denotes the solar radius, and $d\Phi_B(r)$ is the fraction of the $^7$Be neutrino flux at the Earth, produced in a given spherical shell in the solar interior at radius $r$. The quantity $\sigma(T) = E_\gamma (kT/m)$ represents Doppler broadening of the 478-keV axion line of $^7$Li at the temperature of the Sun ($T$) at the radius $r$, with $k$ and $m$ denoting the Boltzmann constant and the mass of the $^7$Li nucleus, respectively. The branching ratio ($\Gamma_a/\Gamma_\gamma$) of the $M1$ axionic transition relative to the gamma transition is calculated in the long–wavelength limit to be [10]

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

where $k_\gamma$ and $k_\alpha$ are the momenta of the photon and the axion, respectively. $\alpha \approx 1/137$ is the fine structure constant, and $\delta \sim 0$ is the $E2/M1$ mixing ratio. The quantities $\mu_0 \sim 0.88$ and $\mu_3 \sim 4.71$ denote the isoscalar and isovector magnetic moments, respectively. The nuclear–structure–dependent terms $\eta$ and $\beta$ are estimated to have values 0.5 and 1, respectively, since the neutron shell of the $^7$Li is closed, and the present $M1$ transition is considered to be caused predominantly by the proton. The isoscalar ($g_0$) and isovector ($g_3$) axion–nucleon coupling constants as well as the axion mass are related to $f_a$ in the hadronic axion model [22] by expressions

$$g_0 = -\frac{m_N}{f_a} \frac{1}{6} \left[ 2S + (3F - D) \frac{1 + z - 2w}{1 + z + w} \right], \quad (3)$$

![FIG. 1. Decay scheme of $^7$Be.](image-url)
\[ g_1 = -\frac{m_N}{f_a} \frac{1}{2} \left( D + F \right) \frac{1-z}{1+z + w}, \]  

(4)

and

\[ m_a = \frac{f_\pi m_\pi}{f_a} \left[ \frac{z}{(1+z+w)(1+z)} \right]^{1/2} \approx 6 \text{ eV} \frac{10^6 \text{ GeV}}{f_a}, \]  

(5)

where \( m_N \approx 939 \text{ MeV} \) is the nucleon mass. The two axial-coupling parameters \( F = 0.460 \) and \( D = 0.806 \) are determined from hyperon semi-leptonic decays [24]. The flavor-singlet axial-vector matrix element \( S \) is extracted from polarized structure function data, in a scheme dependent way. This is still a poorly constrained parameter because the separation between gluon and quark singlet contributions is, as usual, ambiguous beyond leading order. In our calculations we have used a recently estimated value from experimental data of the scale independent quark spin content of the nucleon \( S \approx 0.4 \) [23].

The rate of excitation per \(^7\text{Li}\) nucleus, which is expected for solar-produced axions incident on a laboratory target of \(^7\text{Li}\) is

\[ R_N = \int_{-\infty}^{+\infty} dE_a \frac{d\Phi(E_a)}{dE_a} \sigma_D(E_a), \]  

(6)

where the effective cross section for resonant absorption of axions is given by [17,21]

\[ \sigma_D(E_a) = \sigma_0 \frac{\Gamma_a}{\Gamma} \frac{\sqrt{\pi} \Gamma}{\sqrt{2} \sigma(T_E)} \exp \left[ -\frac{(E_a - E_\gamma)^2}{2 \sigma(T_E)^2} \right], \]  

(7)

with Doppler broadening effects at room temperature \((T_E \approx 300 \text{ K})\) allowed for, and \( \sigma(T_E) \approx 1 \text{ eV} \gg \Gamma \). The maximum resonant cross section of \( \gamma \) rays is expressed as \( \sigma_0 = 2 \pi g^2 \Gamma \gamma / \Gamma = 5.4 \times 10^{-21} \text{ cm}^2 \), where \( \pi = h c / E_\gamma \), \( E_\gamma \) is the \( \gamma \)-ray energy, and \( h c = 1.973 \times 10^{-8} \text{ keV cm} \).

The statistical weight factor \( g = (2 I_f + 1)/(2 I_i + 1) \) and contains the total angular momenta \( I_f \) of the excited level and \( I_i \) the ground state value.

Using equations (1) for the differential axion flux at the Earth and (6) for the resonant cross section in Eq. (7), the energy integration can be performed explicitly, leading to

\[ R_N = \sqrt{\frac{\pi}{2}} \kappa \sigma_0 \Gamma \left( \frac{\Gamma_a}{\Gamma} \right) \frac{2}{\Gamma} \int_0^{R_\odot} \frac{d\Phi(r)}{\sqrt{\sigma(T)^2 + \sigma(T_E)^2}}. \]  

(8)

Integrating this expression over the BP2000 SSM [18] which predicts a total \(^7\text{Be}\) neutrino flux of \( 4.8 \times 10^9 \text{ cm}^{-2} \text{s}^{-1} \), and translating the rate of axionic excitation per \(^7\text{Li}\) nucleus into the total excitation rate, \( R \), per unit mass of \(^7\text{Li}\) per day, we find

\[ R = 1.3 \times 10^{-17} \left( \frac{m_a}{1 \text{eV}} \right)^4 \text{g}^{-1}\text{day}^{-1}. \]  

(9)

We have searched for a peak corresponding to the 478–keV gamma ray of \(^7\text{Li}\) in a single spectrum measured by a HPGe detector, having a crystal size of about 50 mm\(^2\) \times\) 40 mm, at ground level. By using the veto NaI detector (8HW10/(4)3L, Bicron) and iron–lead shielding the background events are reduced by a factor \( \sim 10 \). We have obtained an energy calibration which identifies the gamma ray peaks that arise from environmental radioactivity present. Energy resolution (FWHM) at the photon energy of 478 keV was estimated to have a value of 1.4 keV. The target of lithium (Aldrich Chemical Company), an ingot with a diameter of 5.7 cm and a thickness of 4.5 cm, was placed 0.5 cm from the window of the detector. The mass of \(^7\text{Li}\) in the target is \( M = 56.72 \text{ g} \). Data and background were both counted for collection times \( t = 111.11 \text{ days} \); gamma ray attenuation due to the lithium ingot was taken into consideration. The detection efficiency of the HPGe detector for 478–keV photons es-
that we have omitted a phase space factor (2); this affects the measured axion mass in our experiment by less than 4\times 10^{-3}. In the frame of SSM (maximal solar abundance of \( ^7\text{Li} \) by mass fraction \( 10^{-5} \)) and by using the expression for the mean free path of the axions from Ref. \[19\], we found solar absorption of axions of mass \( \lesssim 32 \text{ keV} \) to be insignificant (\( <10^{-10} \)), with implication of free escape from the solar interior \[27\].

The obtained limit is about a factor 40 weaker than the only other laboratory–evaluated limit for near–monochromatic solar axions that has been made, the latter measurement concerning nuclear transition in \( ^{57}\text{Fe} \) \[19\]. The present result has demonstrated that the newly–proposed source of solar axions, being that associated with \( ^7\text{Be} \) solar neutrinos, has the potential to provide the parameter space of hadronic axion masses free from the large uncertainties arising from SN 1987A considerations as well as from the uncertainty related to the \( ^{57}\text{Fe}-\)method with respect to determination of the iron abundance in the solar core. Namely, while the flux of \( ^{57}\text{Fe} \) axions is determined, in the frame of SSM, by extrapolation of the iron abundance in the solar photosphere to the iron abundance in the centre of the Sun, the flux of \(^7\text{Li} \) axions is connected with the \(^7\text{Be} \) solar neutrino flux \[25\]. This is to be measured in a new experiment, Borexino \[26\], via \( \nu – e \) scattering in 300 tonnes of liquid scintillator, with a potential detection threshold of as low as 250 keV. In addition, because of the possibility for improvements in detection of 478–keV gamma rays from \(^7\text{Li} \) atoms and further background suppression, solar axion investigations with both, \(^7\text{Li} \) and \(^{57}\text{Fe} \), for probing the hadronic axion window, point towards a variety of data that are independent of supernova models, their statistical weakness and the uncertainties associated with them.

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* Corresponding author.
Email address: mkrmar@rudjer.irb.hr

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