A Search For Solar Hadronic Axions Using $^{83}$Kr

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Abstract

We introduce a new experimental method for solar hadronic axions search. It is suggested that these axions are created in the Sun during M1 transition between the first thermally excited level at 9.4 keV and the ground state in $^{83}$Kr. Our method is based on axion detection via resonant absorption process by the same nucleus in the laboratory. We use proportional gas counter filled with krypton to detect signals for axions. With this setup, target and detector are the same which increases the efficiency of the experiment. At present, an upper limit on hadronic axion mass of 5.5 keV at the 95% confidence level is obtained.

1 Introduction

Axions, neutral spin-zero pseudoscalar particles, arise from spontaneous breaking of the Peccei-Quinn (PQ) chiral symmetry, the latter being introduced to resolve the strong CP problem. In general, they interact with leptons, photons and hadrons. Axion mass can be interpreted as a mixing of the axion field with pions, and is related to the PQ symmetry breaking scale $f_a$ by $m_a f_a \approx m_\pi f_\pi$ where $f_\pi$ denotes pion decay constant. The original suggestion ($m_a \approx 100$ keV) has not been experimentally confirmed and DFSZ/GUT and KSVZ models of invisible axions have been developed. KSVZ axion coupling to leptons is suppressed. Astrophysical and cosmological considerations predict axion mass window $10^{-5} \text{eV} \leq m_{KSVZ} \leq 10^{-2} \text{eV}$ relating to cold dark matter. Hadronic axion is a class of KSVZ axions which does not couple to photon. Its mass window $10 \text{eV} < m_a < 40 \text{eV}$ relates to hot dark matter. Moriyama was the first to propose the production of monochromatic axions in the solar interior during M1 transitions between first thermally excited 14.4 keV and ground state in $^{57}$Fe. When resonant conditions are fulfilled, the emitted axion could excite same nucleus at long distance. This event could be detected through the subsequent emission of a photon or conversion electron. In our previous experiments we searched for axion-produced M1 electromagnetic transitions in $^{57}$Fe and $^7$Li using Si(Li) and HPGe detectors, respectively. Our experiments yield upper limits on the hadronic axion mass of 745 eV and 32 keV, respectively.

2 Experimental method

In this experiment we were looking for the M1 transitions from the first excited 9.4 keV to the ground state in $^{83}$Kr as possible signals for the resonant absorption of axions emitted from the Sun by the same nucleus. Due to the 1.35 keV thermal motion of $^{83}$Kr nuclei in the Sun core, the extremely narrow natural line width of emitted axions is Doppler broadened to $\approx 2.93 \text{ eV}$. Due to the emission and absorption nuclear recoil, the axion energy shift is $-2 \cdot 0.000572 \text{ eV}$. Gravitational red shift of axions moving from Sun to Earth is $-0.101 \text{ eV}$. Because recoil and gravitational red shifts are much smaller than Doppler broadening in the Sun we conclude that conditions for resonant absorption of axions are fulfilled. The stable isotope of krypton, $^{83}$Kr (with natural abundance 11.5%) is reasonably well abundant in the Sun; from the experimentally determined relative abundance of krypton to hydrogen in meteorites $\approx 1.7 \cdot 10^{-9}$, the solar abundance of $^{83}$Kr by mass fraction is estimated to be $\approx 2 \cdot 10^{-10}$. For detection of 9.4 keV
photons and lower energy conversion electrons we used proportional counter filled with natural krypton. In this arrangement, target and detector are the same which increases the sensitivity of the experiment.

The excitation rate $R$ of the 9.4 keV state in $^{83}Kr$ on Earth was estimated using the KSVZ axion model \[4, 5\]. Nuclear data about M1 transition between ground 9/2+ and first excited 7/2+ state ($T_{1/2} = 154.4$ ns, $\alpha = 17.09$) in $^{83}Kr$ were used from \[6\]. In one-particle approximation the transition is considered as neutron transition which gives nuclear-structure dependent terms $\eta = 0.5$ and $\beta = -1$. With these approximations we obtained

$$R \left[ g^{-1} \text{ day}^{-1} \right] = 7.417 \cdot 10^{-12} \left( \frac{k_a}{k_\gamma} \right)^6 \cdot \left( \frac{m_a}{\text{1 eV}} \right)^4 \cdot (1)$$

where $k_a$ and $k_\gamma$ denote impulses of axions and photons, respectively.

3 Experimental setup

We have used a small proportional gas counter and self-made preamplifier designed for detection of low energy photons and electrons with energies from about 5 keV to about 100 keV. Its cylindrical brass chamber, with effective inner diameter and length of 45 mm and 153 mm, respectively, could be filled by various gases, biased up to 3 kV and could operate at stable pressures from 0.0000001 bar up to 4 bars. Its steel anode with diameter of 50 $\mu$m is connected via its MHV connector to the preamplifier which is supplied with power, signal and test connectors. The chamber is equipped with three apertures for good quality valve, adequate pressure gauge and photon collimator. The valve keeps gas in the chamber at steady pressure up to 4 bars for at least a year. The aperture with diameter of 1 mm for photon collimator is placed perpendicular to the chamber axis and in the middle along the chamber. Thickness of the beryllium window is 5 $\mu$m.

The system was tuned for detection of photons with energies from 5 to 25 keV by applying the anode bias voltage of +1600 V. It was calibrated by the use of $^{55}Fe$ and $^{109}Cd$ X-ray emitters. Energy resolution of proportional counter at 9.4 keV was 4.7 keV.

4 Results and discussion

Expected number of counts $N_c$ in our detector, due to the absorption of axions and subsequent de-excitation of the 9.4 keV state, is

$$N_c = R \left[ g^{-1} \text{ day}^{-1} \right] \cdot M[g] \cdot \Delta T[\text{day}] \cdot \varepsilon \cdot (2)$$

where $M$ is mass of $^{83}Kr$ atoms in the counter, $\Delta T$ is time of data collection, and $\varepsilon$ is detection efficiency. In our experiment we kept the pressure inside the counter at 2 bar and therefore $M = 0.193$ grams. From the tables of electron and photon stopping powers and taking into account small counting rate we estimated $\varepsilon \approx 0.99$.

Data were collected over period of 23.5 days. We did not observe any evidence of statistically significant axion events. Therefore an upper limit on hadronic axion mass was determined from the expression

$$\frac{m_a}{\text{1 eV}} \cdot \left( \frac{k_a}{k_\gamma} \right)^{3/2} < \left( \frac{k' \cdot \sqrt{2 \cdot N_b}}{7.417 \cdot 10^{-12} \cdot M[g] \cdot \Delta T[\text{day}] \cdot \varepsilon} \right)^{1/4} \cdot (3)$$

Here $N_b$ is number of background events in the relevant energy interval. At the 95% CL the recorded number of background events was $N_b \approx 1.73 \cdot 10^8$ cts. Using Eq (3) an upper limit on hadronic axion mass of 5.5 keV is obtained.
5 Conclusion

We have performed an experimental search for solar hadronic axions using a new experimental method in which the target and the detector were the same. In our further research we will try to improve background suppression, energy resolution and detector volume. This could enable us to search for hadronic axion masses in the region $< 100 \text{ eV}$.

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