Search for Short Lived Axions Emitted from Neutron Capture on Protons

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Abstract

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We have searched for light neutral particles like the axions which decay rapidly to electron positron pairs produced in the reaction $n + p \rightarrow D + a$. We detect instead the e^+e^- signal expected from direct internal pair conversion. A preliminary analysis gives $(\Gamma_p/\Gamma)_{\text{expt}}/(\Gamma_p/\Gamma)_{\text{theo}} = 1.06 \pm 0.12$. The results exclude existing axion models over the mass range $2 m_e < m_a < 2.22 \text{ MeV}/c^2$. The axion mass would fall in this range if they were responsible for the narrow positron lines observed in recent heavy-ion experiments at the GSI.

1. Introduction

The beautiful explanation of strong CP-conservation based on the Peccei-Quinn [1] symmetry is so appealing that its most dramatic physical consequence, the axion, continues to be the object of experimental search, despite numerous failures. Recently, exciting indications of narrow positron peaks observed in heavy ion collisions at the GSI [2] revived the hope that the axion may indeed exist, but with properties that allow it to evade detection in previous direct searches. The "standard axion model" [3] describes the axion as a pseudoscalar with mass $m_a \approx 0.025 N (1/X + X) \text{ MeV}/c^2$, where N is the number of quark generations and X is a free parameter equal to the ratio of two Higgs field vacuum expectation values. Depending on its mass the axion decays into two gammas or into electron-positron pairs. The coupling strength to quarks and leptons is a function of X , and thus the axions production and decay properties are predicted in a myriad of physical processes. The possibility of discovering the axion has led to a number of negative searches. The most compelling evidence against the standard axion comes from searches for $\psi \rightarrow \gamma + a$ and $T \rightarrow \gamma + a$ [4]. These experiments are complimentary, the rate for $\psi \rightarrow \gamma + a$ goes like X^2 and $T \rightarrow \gamma + a$ like $1/X^2$, and the limits from the two experiments essentially rule out the axion for all X . The interpretation of these experiments is complicated slightly if the lifetime is very short and the axion decays near the interaction point in these high energy e^+e^- annihilation searches [5]. Failure to observe axions coming from nuclear transitions provides additional negative evidence [6]. The nuclear experiments are each sensitive only to limited regions of X , and to relatively long lifetimes, say $\tau > 10^{-10} \text{ sec}$. In addition most nuclear searches concentrate on axions with masses less than $2 m_e$.

If the axion explains the narrow peaks in the GSI experiments it would have a mass around 1.7 MeV. Experiments are compatible with a lifetime in the range 10^{-19} - 10^{-10} sec , but theoretical arguments indicate $\tau \approx 5 \times 10^{-13} \text{ sec}$. The standard axion at $m_a \approx 1.7 \text{ MeV}/c^2$ would have $\tau \approx 5 \times 10^{-12} \text{ sec}$, and this is ruled out by limits on $T \rightarrow \gamma + a$. Motivated by the GSI results and negative axion searches Peccei, Wu and Yanagida [7] and Krauss and Wilczek [8] have considered variations of the standard axion model. Briefly these models have two main characteristics: (1) The axion couples essentially only to light quarks, mitigating the negative evidence from vector meson decay searches; and (2) The axion has a very short lifetime for decay into electron positron pairs, explaining why it was not seen in nuclear decay searches, and making it a candidate for the GSI particle. With these models as a

guide one is lead to search for axion emission from nuclear transitions, for example all the models predict that axion decay will compete favorably with many M1 nuclear γ -ray transitions [3], but in experiments sensitive to axions that decay to e^+e^- with a short lifetime ($\tau < 10^{-10}$ sec). Thus we have searched for axions emitted in the decay of the 2.22 MeV state of the deuteron. This simple isovector M1 transition is an ideal place to search for axion-like particles of the type suggested by the GSI result. The various axion models predict the branching ratio, Γ_a/Γ_γ , for axion decay relative to γ -decay to be at the 10^{-3} level.

2. The Experiment

The experiment is straightforward. We attempt to detect e^+e^- pairs from the sequence of reactions $n + p \rightarrow D$ ($E_x = 2.2245$ MeV) $\rightarrow D + a$ and $a \rightarrow e^+ + e^-$. Figure 1 shows the experimental arrangement. A cold neutron beam from the Institute Laue-Langevin reactor intersects a polyethylene target ($t \approx 0.21$ mm) at the center of 2 m long superconducting solenoidal spectrometer (PERKEO). The spectrometer has previously been used to measure the β -asymmetry of the neutron [9] and more recently to measure the neutron lifetime. In the present experiment e^+e^- pairs are detected in coincidence with plastic scintillator detectors (5 mm thick) at either end of the spectrometer. A ≈ 15 kgauss internal field causes low energy electrons and positrons to move in helical paths with diameters less than 1 cm. Trim coils at the ends of the solenoid pervert the field causing the particle trajectories to intersect the scintillators which are outside of the neutron beam. The system is calibrated with internal conversion sources and the energy resolution corresponds to about 140 photoelectrons/MeV.

Figure 1. Layout of the axion search experiment. The insert shows the details of the inner volume of PERKEO

The expected signal for axion decay is a peak in the two detector sum energy at ≈ 1.2 MeV ($E_x - 2m_e c^2$). The main background in the experiment is direct internal pair conversion. Because of the low transition energy in the deuteron the internal pair conversion probability is small, $\Gamma_{\text{pair}}/\Gamma_\gamma = 3.2 \times 10^{-4}$. Moreover, the rate is reliably predicted, and since $Z = 1$ the Born approximation is adequate [10]. There are three additional sources coincidence background: (1) A cosmic rays striking one scintillator that produce δ -rays that move through spectrometer causing a coincidence; (2) Electron from neutron beta decay that backscatter off a detector; and (3) Background γ -rays that liberate electrons from one detector by Compton scattering. These backgrounds can be partially distinguished by detector timing information but this feature is not used in the present preliminary analysis. Figure 2 is the sum energy spectrum from an 18 hour run of the experiment. The neutron beam capture flux

is $\psi_n = 3.9 \times 10^7$ neutrons/sec, determined by Cobalt activation analysis and observation of the neutron β -decay rate. The peak in Fig. 2 is at the right energy for axion decay and internal pair conversion after accounting for electron (and positron) energy loss in the target foil. The distortion to the peak on the high energy side is also expected. Since one of the detected particles is a positron that annihilates in a detector, one or both annihilation photons can Compton scatter, increasing the observed energy of the event.

Figure 2. Sum energy spectrum for an 18 hour run. The distortion to the high energy side of the peak at 1.2 MeV is from positron annihilation in the detector

At low energy (below $\approx 3/4$ MeV) the background in Fig. 2 is primarily from neutron β -decay backscattering. The background from cosmic rays and γ -rays (mostly from Al capture γ -rays coming from target scattering in the target foil. The effective backscattering coefficient was measured with a ^{207}Bi conversion source. The error from background subtraction, backscattering corrections, and uncertainties about the exact target composition dominates the error the present experiment error. A more elaborate analysis, now underway, and a chemical analysis of the target promises to reduce the error significantly.

Figure 3. The preliminary experimental upper limit on Γ_a/Γ_γ as a function of axion mass. The theoretical curves are obtained from the various axion models: K-W Ref. 8; P-W-Y I-III Ref. 7; and the STANDARD axion with $W=3$ from Ref. 3. There is some loss of experimental sensitivity just above $2 m_e$ because the axion lifetime would be longer than 10^{-10} sec, but this mass region is not significant.

The e^+e^- detection rate we expect for pair decay is given by the expression, $N_p = \psi_n \cdot \sigma_0 \cdot N_H \cdot \epsilon_p$, $\delta n \epsilon \theta \epsilon \sigma_0$ is the thermal capture cross section for $H(n, \gamma)D$, N_H is the number of target hydrogen atoms per cm^2 , and ϵ_p is the calculated detection efficiency which accounts for the angular correlation of the pairs and target backscattering. We obtain $N_p = 2.42 \pm 0.24$; the measured rate is $N_p(\text{expt}) = 2.58 \pm 0.16$. These results are consistent within errors and we construct a 2σ upper limit for the axion emission branching ratio, Γ_a/Γ_γ . Figure 3 shows the experimental limit com-

pared to the various theoretical expectations. The expected rate for axion decay is given by an expression of the form,

$$\Gamma_a/\Gamma_\gamma \approx 1/2 \tilde{\alpha}/\alpha (k_a/k_\gamma)^3 (\rho^{(1)}/4.71)^2 [3] ,$$

where k_i are the momenta, $\tilde{\alpha}$ is the analog of α for the axion, and $\rho^{(1)}$ is a measure of the axions isovector coupling to nucleons which depends on the details of the particular model $N = \phi \cdot \sigma \cdot (\Gamma/\Gamma) \cdot N_H \cdot \epsilon$. The predictions correspond to the models described in Refs. 3,⁷ and ⁸ plotted in Fig. 2 as a function of axion mass. The mass dependence of the experimental limit reflects the kinematic dependence of the acceptance. All the models are ruled out for the range of masses of interest for the GSI experiments. In general the present experiment is sensitive to hypothetical particle emission in the range $2m_e < m_a < Ex/c^2$; we would detect short lived particles with lifetimes up to $\sim 10^{-10}$ sec. Hypothetical particles with longer lifetimes would begin to leave the volume of the spectrometer before decaying.

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