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A METHOD TO MEASURE THE AXION MASS

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ABSTRACT

We have calculated the decay rate of the triplet state of positronium into axion + gamma, under the hypothesis that the axion mass is less than 1 MeV. The branching ratio is found to be $\sim 3 \times 10^{-8}$. We describe a possible experiment that could detect the axion and measure its mass.

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Recently it was recognized that the gauge theory of strong interactions allows for violations of the P, C, and CP symmetries [1]. Weinberg [2] and Wilczek [3] suggested that these potential violations could be suppressed in a natural way if a light, long-lived, pseudoscalar boson of zero charge should exist. This hypothetical particle is called an axion (a_0). Its discovery would strongly support the view that gauge theories are really good descriptions of the fundamental interactions.

The theory makes precise statements about the axion [2-4]: in particular, the axion-lepton coupling should have the form

$$\mathcal{L}_{\text{coupl}} = ig_{\ell} \bar{\ell} \gamma_5 \ell \phi, \quad (1)$$

where

$$g_{\ell} = (\sqrt{2}G)^{1/2} m_{\ell} / X, \quad (2)$$

with G being the Fermi constant and m_{ℓ} the lepton mass. The unknown quantity X is commonly estimated to be ≈ 1 [4] and is related to the axion mass through the following equation [4,5]:

$$m_a = 25N \left(X + \frac{1}{X} \right) \quad (\text{keV}), \quad (3)$$

N being the number of quark doublets. Since N is at least two, m_a should be at least 100 keV.

The experimental investigations made so far seem to exclude that m_a is larger than $2m_e$, since otherwise the decay $a_0 \rightarrow e^+ + e^-$ would have been observed [6-12]. Recently, Faissner [13] reported about 14 possible decay events $a_0 \rightarrow 2\gamma$ in a beam-dump experiment at SIN, but evidence for the axion remains scarce.

If we believe that the axion is lighter than two electrons we can use the Lagrangian (1) to calculate the cross-section for the annihilation $e^+ + e^- \rightarrow a_0 + \gamma$ at rest. By applying the result to the positronium system, we find that:

- i) the singlet state ^1S (p-Ps) cannot annihilate into axion + gamma because of angular momentum conservation. The annihilation proceeds through the 2γ channel at a rate $\lambda_{2\gamma} = 7.99 \times 10^9 \text{ s}^{-1}$ [14];

- ii) the triplet state ^3S (o-Ps) still decays into three gammas at the rate $\lambda_{3\gamma} = 7.06 \times 10^6 \text{ s}^{-1}$ [15], but in addition the channel $a_0 + \gamma$ is open, the partial rate being

$$\lambda_{a\gamma} = \lambda_{2\gamma} \frac{2}{3} \frac{\tilde{\alpha}}{\alpha} \left(1 - \frac{1}{4} \frac{m_a^2}{m_e^2} \right). \quad (4)$$

Here $\tilde{\alpha} = g_a^2/4\pi$ and $\tilde{\alpha}/\alpha = 4.5 \times 10^{-11}$ if $X = 1$. From eq. (4) we get the branching ratio (BR) for the axion mode:

$$\text{BR} = \lambda_{a\gamma}/\lambda_{3\gamma} \approx 3 \times 10^{-8}. \quad (5)$$

Since the axion is hardly observable in any detector, the axion decay of positronium will appear as a single-gamma decay event, the gamma spectrum being monochromatic at

$$\omega = m_e \left(1 - \frac{1}{4} \frac{m_a^2}{m_e^2} \right). \quad (6)$$

Thus the axion's existence can be detected by selecting those decays of o-Ps where only one gamma appears, and by looking for a peak in the spectrum. Of course, owing to the smallness of the effect, the anticoincidence system must be very efficient in order to suppress the background from 2γ and 3γ annihilations. In this respect, two items deserve consideration:

- i) The main part of the 2γ background comes from prompt e^+ annihilations and p-Ps decays. This background is greatly reduced by accepting only those events coming ~ 20 ns after the formation of Ps.
- ii) The background from the 3γ decay of o-Ps requires *two* gammas missing the anticoincidence counter. This fact can be exploited to reduce considerably this type of noise.

A possible experimental apparatus to perform a "missing axion" experiment is schematically shown in fig. 1. Positrons from a β^+ source are stopped in a sample of MgO or SiO₂ powder. These positrons form o-Ps with 95% efficiency [16], the atom being substantially free provided the sample is in vacuum [16,17]. A thin plastic scintillator between the source and the powder is used as a trigger counter to signal the formation of Ps. The source and the powder sample are placed

inside a large anticoincidence counter, covering about 85% of the total solid angle. The anticoincidence counter would be made of NaI(Tl) crystals; the efficiency of detecting a 0.5 MeV photon travelling along the axis should be about 99.9%.

An "axion" event would have the trigger counter fired and no signal in the anticoincidence until the arrival of a second trigger pulse. The gamma associated with the axion would be detected in a Ge(Li) detector (resolution 2 keV FWHM), its signal coming in a 200 ns window delayed by about 20 ns with respect to the trigger.

The expected event rate is

$$R_{a\gamma} = A \cdot BR \cdot \epsilon_{\gamma} \cdot \epsilon_T, \quad (7)$$

where A is the source activity, ϵ_{γ} is the detection efficiency of the Ge(Li) detector, ϵ_T is the probability of forming o-Ps, and BR is given above. Assuming $\epsilon_{\gamma} \approx 10^{-2}$, $\epsilon_T \approx 0.3$ [16], and a 25 μ Ci source, we get

$$R_{a\gamma} \approx 10^{-4} \text{ s}^{-1}. \quad (8)$$

The major background sources are the following:

- i) Events from the 3γ decay of o-Ps, two of the gammas having escaped detection by the anticoincidence counter. The more significant losses come from the events where one of the photons misses the NaI crystal, while the other goes through the crystal but is not detected. With the geometry described the signal-to-noise ratio would pass from 1:3 for a 100 keV axion to 1:23 for a 300 keV axion.
- ii) Events due to the quenching of o-Ps: $^3S \rightarrow ^2S + 2\gamma$, one of the gammas remaining undetected by the anticoincidence counter. These events peak at 511 keV, so they only affect the "axion" peak through Compton scattering in the Ge(Li) detector. With a NaI detection efficiency of 99.9% and a 200:1 peak/Compton ratio in the Ge(Li) detector there are 5×10^{-6} background counts per quenched o-Ps. The quenched fraction can probably be kept under 1% by evacuating the powder sample to 10^{-5} Torr and by working at low powder densities [17]. If this can be achieved, this background will be of the same order as or lower than in (i).

Other noise sources are the single counting rate of the Ge(Li) detector and processes involving the loss of more than two photons. These are of the same order as or smaller than in (i).

With the signal-to-noise ratios given above, ~ 250 events are required in order to overcome three times the fluctuations of the background in the case of a 300 keV axion; this would require about one month of data taking. The axion mass would be measured with a precision of 6 keV even with low statistics.

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Figure caption

Fig. 1 : Schematic view of the apparatus.

- 1) Ge(Li) detector;
- 2) Positron source;
- 3) Plastic scintillator;
- 4) Powder sample;
- 5) NaI(Tl) crystals.

fig. 1