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Orthopositronium Decay into Axions

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ABSTRACT

We point out that if the mass of the hypothetical particle called the axion is less than $2m_e$, then it can be emitted in the decay of orthopositronium. The lifetime of the decay $1^3S_1 \to \gamma h$ is calculated to be about 8s. We suggest an experiment to look for "single" photons from positronium annihilation. An accurate measurement of the energy E_γ of these photons gives the mass of the axion through the relation $m^2_{axion} = 4m_e(m_e - E_\gamma)$.

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It has been found that, due to pseudoparticle solutions in non-Abelian gauge theories, P and CP are in general violated in the standard theory of quantum chromodynamics.[1] Peccei and Quinn[2] showed that one can naturally avoid such violations by adding a chiral U(1) symmetry to the original Lagrangian with massive quarks. Subsequently S. Weinberg[3] and F. Wilczek[4] pointed out that in unified gauge theories of strong, weak and electromagnetic interactions, imposing a chiral U(1) symmetry leads to a very light neutral pseudoscalar particle (called the axion or Higglet h) which survives the usual Higgs mechanism of providing masses for the $W^{\pm}$ and Z^0 bosons, and which appears as an almost stable particle.

Experiments have been suggested[5,6] to search for axions. Though earlier beam dump and reactor experiments can be interpreted[3,7] to argue against such a particle, its existence is not ruled out because the interaction of axions with hadrons is thought to occur through $h-\pi^0$ and $h-\eta$ mixing which are not well-known.

Analysis of previous experiments and current algebra considerations[8] suggest that $m_h \approx 50-200$ KeV/c^2. We point out that if $m_h < 2m_e$, then electron-positron annihilation from rest into an axion is possible and can be a source of monoenergetic axions. The annihilation is similar to the two and three-photon decays of positronium from the singlet S and triplet S bound states para- and ortho-positronium, respectively. We shall study the reaction

$$e^+ + e^- \to \gamma + h \tag{1}$$

at arbitrary $s=E^2_{c.m.}$, which we later set equal to $4m_e^2$ to calculate the

decay lifetime using

$$\tau^{-1} = \rho\beta\sigma_T(4m_e^2) \tag{2}$$

where $\rho = |\psi(0)|^2$ is the absolute square of the positronium wave function at the origin, $\beta = (1 - 4m_e^2/s)^{\frac{1}{2}}$, and $\sigma_T(s)$ is the total cross section for reaction (1).

Our calculation is based on the two Feynman diagrams shown in Fig. 1. The e - h - e vertex[3,4] is $g\gamma_5$ where $g = 2^{\frac{1}{4}}G_F^{\frac{1}{2}} m_e c_e$ with $c_e \approx 1$. The invariant differential cross section $d\sigma/dt$, where $t = (P_h - P_e)^2$, is found to be

$$\frac{d\sigma}{dt}(e^+e^- \to \gamma h) = \frac{\alpha g^2}{4s^2\beta^2}\Big\{(s+m_h^2)[(t-m_e^2)^{-1} + (u-m_e^2)^{-1}]$$
$$+ 2m_h^2m_e^2[(t-m_e^2)^{-2} + (u-m_e^2)^{-2}] + 2m_h^2(2m_e^2 - m_h^2)(t-m_e^2)^{-1}(u-m_e^2)^{-1}\Big\} \tag{3}$$

where u is given through $s+t+u = 2m_e^2 + m_h^2$. We find that to a very good approximation we can take the limit $m_h \to 0$. The angular distribution in the center of mass, $d\sigma/d\cos\theta$, where θ is the angle between the axion and the electron, is then given by

$$\frac{d\sigma}{d\cos\theta}(e^+e^- \to \gamma h) \approx \frac{\alpha g^2}{2s\beta(1-\beta^2\cos^2\theta)} \quad . \tag{4}$$

Axion production is isotropic near threshold ($\beta\to 0$), but as s increases it soon peaks in the forward and backward direction, i.e., $\theta=0$ and $\theta=\pi$.

The total cross section is obtained by integrating over t in Eq. (3). The result is

$$\sigma(e^+e^- \to \gamma h) = \frac{\alpha g^2}{2s\beta^2}\Big\{[1+m_h^2/s - 2(m_h^2/s)(2m_e^2-m_h^2)/(s-m_h^2)]\ln\left(\frac{1+\beta}{1-\beta}\right)$$
$$- 2m_h^2\beta/(s-m_h^2)\Big\} \tag{5}$$

which again reduces to a very simple expression in the limit $m_h \to 0$:

$$\sigma(e^+e^- \to \gamma h) \simeq \frac{\alpha g^2}{2s\beta^2} \ln\left(\frac{1+\beta}{1-\beta}\right) \quad . \tag{6}$$

We need the total cross section at threshold $s=4m_e^2$. From Eq. (5),

$$\beta\sigma_T(4m_e^2) = \frac{\alpha g^2}{4m_e^2}(1 - m_h^2/4m_e^2) \quad . \tag{7}$$

All the cross sections considered so far have been averaged over the four possible electron-positron spin configurations. Parapositronium decay into γh is forbidden because $J_{Para} = 0$ and $J_{\gamma h} = 1$. Orthopositronium decay is allowed. To calculate its lifetime, we replace the statistical factor 1/4 by 1/3, i.e., multiply Eq. (7) by 4/3. Furthermore,[9]

$$\rho = |\psi(0)|^2 = (\alpha m_e)^3/8\pi n^3 \tag{8}$$

where n=1 for the ground state 1^3S_1. After setting $g=2^{\frac{1}{4}}G_F^{\frac{1}{2}}m_e c_e$, the final result is

$$\tau_{ortho}(\gamma h) = \frac{48\sqrt{2}\,\pi}{\alpha^4 G_F m_e(4m_e^2-m_h^2)c_e^2} = \frac{8s}{c_e^2(1-m_h^2/4m_e^2)} \approx 8s \quad . \tag{9}$$

Such an extremely long lifetime is of course due to the smallness of the coupling $g \approx 2.4\times10^{-6}$ compared to $e = \sqrt{4\pi\alpha} \approx 0.3$. For comparison, the 3γ decay of orthopositronium has a lifetime $\tau_{ortho}(\gamma\gamma\gamma) \approx 1.4\times10^{-7}$s. Earlier experiments[10] on this system are not expected to have seen any effect associated with the γh channel because the branching ratio is so small.

In principle there are two methods of searching for the annihilation of orthopositronium into axions. The first is to detect the axion, far from the source, through its decay $h \to \gamma\gamma$ which has a lifetime between

.01 and 1s (see, e.g., ref. 8). Since the axion is emitted with energy $m_e + m_h^2/4m_e$, its γ factor is $m_e/m_h + m_h/4m_e \approx 2.6 - 10$. Its weak interaction with matter implies that it has a fair chance to decay before being absorbed. To cover a good fraction of the solid angle and to provide space for axion decay, a vast array of photon detectors is needed. The characteristic signal would be about 250 KeV ($\approx m_e/2$) X-rays from axion decay.

The second method is perhaps simpler and more informative. Since the axion from $e^+e^- \to \gamma h$ escapes readily, this reaction would look like a "single photon" decay of positronium. The background consists of two and three photon decays and is easily identifiable. One can therefore use a standard set up around the decay region and look for single photons of about 500 KeV. In fact, an accurate measurement of the energy E_γ of these photons would yield the mass of the unseen axion, because $E_\gamma = m_e - m_h^2/4m_e$.

Obviously very few, only about one in 10^8 annihilations will result in an axion. The system, however, is simple and the interpretation of the experiment is quite straightforward, reaction (1) being a purely leptonic process in which monoenergetic axions and photons are created. If one can measure the lifetime $\tau_{ortho}(\gamma h)$ and E_γ, then one can pin down the values of both c_e and m_h.

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FIGURE CAPTION

Fig. 1 Feynman diagrams for the process $e^+ + e^- \to \gamma + h$.

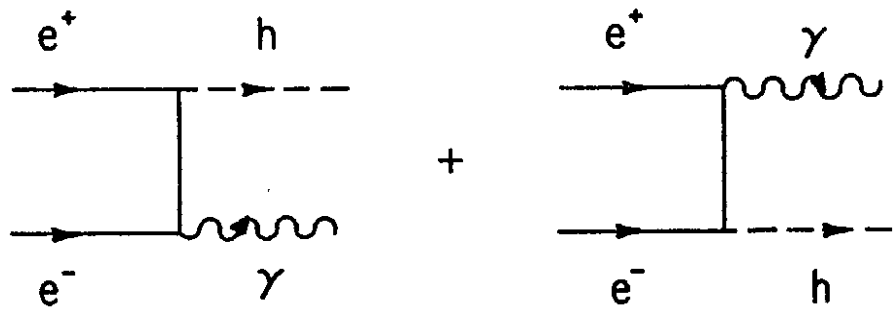

Fig. 1