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LIMIT ON EXOTIC TWO-BODY DECAYS OF ORTHOPOSITRONIUM ^{*)}

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ABSTRACT

We have searched for the exotic annihilation of orthopositronium, $e^+e^-(^3S_1) \rightarrow a^0\gamma$, where a^0 denotes a neutral particle of mass $m_a < 2m_e$. The negative results of our search allow us to derive an upper limit on the coupling constant $\tilde{\alpha}$ of the hypothetical a^0 in the mass range $150 < m_a < 900$ keV. Our bound is about 10 times lower than the one derived from the $(g-2)$ measurements.

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1. INTRODUCTION

In this paper we describe the results of a study of the annihilation spectrum of the orthopositronium $e^+e^-({}^3S_1)$ system (o-Ps).

The purpose of this experiment was to establish an upper limit for the decay

$$e^+e^-({}^3S_1) \rightarrow a^0\gamma, \quad (1)$$

where a^0 denotes an hypothetical neutral particle of mass $m_a < 2m_e$, coupling to the electron with a strength $\tilde{\alpha} = g^2/4\pi$.

The axion, the pseudoscalar first postulated some years ago [1], is a possible candidate [2,3] for this process. Other particles, e.g. those introduced by supersymmetric theories, could also, in principle, participate in this type of decay [4]. At present, the most stringent limit on the coupling of a light neutral particle to the electron comes from the $(g-2)$ experiment. The exchange of a neutral pseudoscalar will contribute to the electron anomaly a factor of

$$\Delta a_e = (\tilde{\alpha}/2\pi) \int_0^1 dx \, x^3/[x^2 + (m_a^2/m_e^2)(1-x)], \quad (2a)$$

and the comparison between theory and experiment [5] implies that $\Delta a_e < 5 \times 10^{-7} (\alpha/2\pi) (99.7\% \text{ CL})$. For $m_a \rightarrow 0$ we have for the coupling $\tilde{\alpha}$:

$$\tilde{\alpha} < 7 \times 10^{-9}. \quad (2b)$$

The relative probability of process (1), compared with the normal 3γ decay is, in the case of a pseudoscalar a^0 [3]:

$$R = \Gamma[e^+e^-({}^3S_1) \rightarrow a^0\gamma]/\Gamma[e^+e^-({}^3S_1) \rightarrow 3\gamma] = \\ \cong (\tilde{\alpha}/\alpha) 754 (1 - m_a^2/4m_e^2). \quad (3)$$

From formula (2) we obtain $R < 8 \times 10^{-4}$. The exotic decay (1) will show up as a peak at $\omega = m_e(1 - m_a^2/4m_e^2)$ in the delayed annihilation spectrum of positronium, over a continuous background due mainly to 3γ annihilations.

The recoiling a^0 will in turn decay into $\nu\bar{\nu}$ or $\gamma\gamma$ pairs, depending on its spin. In the first case ($S = 1$) the particle could decay quickly but would be virtually undetectable. For $S = 0$ the $\gamma\gamma$ decay occurs via the virtual creation of e^+e^- pairs. Rescaling the $\pi^0 \rightarrow \gamma\gamma$ calculation [6], we have

$$\Gamma(a^0 \rightarrow \gamma\gamma) = (1/16\pi^2)\alpha^2\tilde{\alpha}m_a^3/m_e^2 \quad (4)$$

and, because of formula (2), $\Gamma \lesssim 10^6 \text{ s}^{-1}$ can be expected.

In both cases, therefore, the decay of the a^0 would be difficult to observe in a small detector, and process (1) would appear as the emission of a *single monochromatic* γ . Good energy resolution and an efficient anticoincidence for rejecting the dominant electromagnetic decay mode are crucial for enhancing the signal-to-noise ratio.

2. EXPERIMENTAL METHOD

The positrons from a ${}^{22}\text{Na}$ source were stopped in Freon-12 gas to form positronium. The energy of the γ -rays emitted in the annihilation of the 3S_1 state was recorded in delayed coincidence with respect to the 1274 keV photon emitted by ${}^{22}\text{Na}$ simultaneously with the positron. A system of NaI counters was arranged in such a way as to reject most of the 3γ and 2γ annihilations.

The apparatus is shown schematically in fig. 1. The ${}^{22}\text{Na}$ source, 5.1 μCi strong, was sandwiched between two 0.1 mm thick mylar disks, and was placed inside a small stainless-steel vessel (T). The vessel had thin walls (0.2 mm) and was filled with 5 atm Freon-12, so as to stop almost all the emitted positrons. In these conditions about 18% of the emitted positrons formed orthopositronium, giving rise to the characteristic continuum in the annihilation energy spectrum. Since collisions with gas atoms quench orthopositronium [7], a 511 keV line due to 2γ annihilations was also present, its intensity rising linearly with the gas pressure. Because of this effect, at 5 atm 29% of the o-Ps atoms annihilated into 2γ , and the lifetime was reduced to about 100 ns from the 140 ns value found in vacuum.

The vessel T was surrounded by a set of γ -ray detectors. A 44 cm^3 Ge(Li) detector (G) was used to measure the annihilation spectrum (resolution $\approx 0.6\%$ FWHM at 511 keV). Four NaI crystals, $X_1, \dots, X_4$, 10 cm dia. $\times$ 7.5 cm high, provided the trigger signal by detecting in a suitable window the 1274 keV prompt γ . The main anticoincidence AX was a NaI crystal, 27 cm dia. $\times$ 34 cm high, seen by seven photomultipliers. The geometry was such that for 2γ annihilations, when one of the photons was seen in G the other one had necessarily to enter the anticoincidence AX.

To measure the anticoincidence efficiency, we compared the counting rates of the prompt 2γ annihilations with and without the anticoincidence requirement. It was found that 98.3% of the γ 's were in fact seen in the anticoincidence. The

loss was mainly due to Compton back-scattering in the Freon gas, in the vessel walls, and in the AX entrance window. The AX efficiency in detecting the 3γ annihilations was not much higher. In fact, the incomplete coverage of the solid angle often caused one of the two recoiling γ 's to miss the anticoincidence. This loss increased with the opening angle of the recoiling γ pair, i.e. when the energy of the photon detected in the Ge(Li) decreased.

The data acquisition was started by the 1274 keV trigger pulse (p_{trig}) in one of the $X_1, \dots, X_4$ crystals. Only one of the four crystals was required to generate the trigger pulse, in order to reduce the background caused by Compton scattering inside the crystals and also to anticoincide part of those γ 's missing the main anticoincidence AX. In this way we had 18 prompt annihilations per second, yielding a pulse in the 511 keV photopeak of the Ge(Li) detector.

The trigger pulse opened a 200 ns wide gate, delayed by 50 ns with respect to p_{trig} , to reject the tails of the prompt annihilations. This value of the delay was dictated by the relatively poor NaI-Ge(Li) time resolution.

A pulse from the Ge(Li) detector falling inside the gate was accepted provided no signal was present in the large anticoincidence crystal. Then the amplitude signal from the Ge(Li) was stored on a 512-channel pulse-height analyser.

Typical runs lasted about one week. Thresholds, gains, and stability were checked periodically. Data were accumulated over a 9.2×10^6 s live time, roughly corresponding to four months of data taking. Comparison runs without anticoincidence and prompt annihilation runs were also recorded.

3. RESULTS

Figure 2 shows the spectra recorded without the anticoincidence requirement in 5 abs atm Freon-12. Figure 2a is the energy spectrum of the delayed annihilation events. In comparison with the prompt 2γ annihilations (Fig. 2b), the characteristic continuum of the 3γ annihilation is clearly visible. The 511 keV peak in Fig. 2a is partly due to the already mentioned orthopositronium quenching and partly to the tail of the prompt annihilations. A very small peak (seen more clearly in fig. 2b) around channel 145 (corresponding to a photon energy $= m_e/3 \approx 170$ keV) is due to 180° back-scattering of 511 keV photons.

The spectrum of the delayed annihilations recorded with the anticoincidence request is shown in fig. 3. The broad bump is due to the aforementioned anticoincidence efficiency which varies with the energy of the detected γ . The anticoincidence requirement also enhances the back-scatter peak, which was barely visible in fig. 2a. The spectrum does not show other statistically significant peaks, except perhaps for a small enhancement, about 2.5σ above the background, centred around channel 390 ($\omega = 454$ keV), whose nature we are still investigating.

From the spectrum of fig. 3 and knowing the prompt annihilation rate, the probability to form o-Ps, and the detection efficiency, a 3σ bound (99.7% CL) on $\tilde{\alpha}$ can be established. The limit, shown in fig. 4 versus the mass m_a , is about one order of magnitude lower than the $(g-2)$ result also shown in the figure, except in the case of very small masses.

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Figure captions

- Fig. 1 : Schematic view of the apparatus. AX: anticoincidence NaI crystal; T: stainless-steel vessel; $X_1, \dots, X_4$: NaI crystals for the trigger; G: Ge(Li) detector; P: Ge(Li) preamplifier; D: liquid-air dewar.
- Fig. 2a : Energy spectrum of the delayed annihilation γ 's from o-Ps measured without anticoincidence requirement (live time 4.2×10^5 s). The continuum due to the 3γ decay is clearly visible. The 2γ annihilation line at 511 keV is discussed in the text.
- Fig. 2b : Energy spectrum of the prompt annihilation into 2γ 's, without anticoincidence requirement (live time 2×10^4 s).
- Fig. 3 : Energy spectrum of the delayed annihilation γ 's from o-Ps measured with the anticoincidence requirement (live time 9.2×10^6 s). The peak due to the 511 keV back-scatter is indicated.
- Fig. 4 : The bound (99.7% CL) obtained in this experiment on the coupling $\tilde{\alpha}$ of the hypothetical a^0 versus the a^0 mass m_a . The dashed line gives the upper bound derived from the $(g-2)$ experiments using eq. (2a) of the text.

Fig. 1

Fig. 2

Fig. 3

Fig. 4