Upper Limits for the Production of Light Short-Lived Neutral Particles in Radiative Υ Decay

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We have searched for the exclusive decay of the $\Upsilon(1S)$ into a photon and a short-lived spin-0 particle, a, decaying into e^+e^-, using the CLEO detector at the Cornell Electron Storage Ring. Upper limits for the product branching ratio $B(\Upsilon(1S) \to \gamma a)B(a \to e^+e^-)$ are established for a range of masses, $2m_e < m_a < 2m_\mu$.

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Recent observations of narrow structures in electron and positron spectra from heavy-ion collisions[1] have been interpreted[2,3] as evidence for the production of a neutral particle with mass about 1.8 MeV/c^2. We have searched for this particle in radiative $\Upsilon(1S)$ decays. Previous limits on the production of neutral particles in Υ decays[4,5] apply to particles with long lifetimes. Such decays would be characterized by a single high-energy photon, the neutral particle remaining undetected. In this search we have extended existing limits to include short-lived particles decaying within the detector.

We have searched for the decay of the $\Upsilon(1S)$ into a photon and a light particle, a, that decays within the detector to an electron-positron pair. The decay of the Υ at rest would then appear as a monoenergetic photon directly opposite an electron-positron pair from the decay $a \rightarrow e^+e^-$. In this search the $\Upsilon(1S)$ came from the decay of the $\Upsilon(2S)$ resonance which was produced in e^+e^- annihilations. The $\Upsilon(1S)$ events were tagged by the transition $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$.[6] This method avoids the large background contamination inherent in looking at the $\Upsilon(1S)$ resonance produced directly in $e^+e^- \rightarrow \Upsilon(1S)$. This background arises from the nonresonant QED process, $e^+e^- \rightarrow \gamma\gamma$, where one γ converts into an e^+e^- pair, mimicking the process $\Upsilon \rightarrow \gamma a$, $a \rightarrow e^+e^-$.

Data were collected with the CLEO detector[7] at the Cornell Electron Storage Ring. Charged particles were tracked through a uniform magnetic field by means of a three-layer cylindrical multiwire proportional chamber surrounded by a seventeen-layer cylindrical drift chamber inside a superconducting coil. Outside the coil, time-of-flight scintillators and shower counters were used for triggering and photon reconstruction. A 0.1-radiation-length-thick lead converter was placed between the proportional chamber and the drift chamber and the magnet was operated at a low field, 0.35 T, because of a concurrent search for low-energy photon transitions. Event triggers required track information from the drift chamber, two or more hits in the time-of-flight system, and energy deposited in the shower counters. The energy threshold was well below that expected for the two-body decay of the $\Upsilon(1S)$ into a photon and a light particle. Within the fiducial volume covered by the time-of-flight and shower counters the trigger was 99% efficient. We used a sample of $14\,600 \pm 500$ $\Upsilon(1S)$ decays from 22.2 pb^{-1} of luminosity taken on the $\Upsilon(2S)$ resonance.

To identify the decay chain $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow \gamma a$, $a \rightarrow e^+e^-$, we required that an event contain three or four charged tracks and a photon carrying at least 50% of the beam energy. The track requirement allowed for the possibility that the a decay into e^+e^- would produce only one, rather than two, distinguishable tracks. In addition we then demanded that any two oppositely charged tracks, assumed to be pions, be consistent with recoiling against an object of mass lying within 35 MeV/c^2 of the $\Upsilon(1S)$ mass.[6] A detailed Monte Carlo simulation of the process $\Upsilon(1S) \rightarrow \gamma a$ in the CLEO detector was used to estimate the efficiency of our event selection with the assumption that a has spin 0. To remove background including QED processes and beam-gas and cosmic-ray events from our sample, we first calculated the angle, $\theta_{a\Upsilon}$, between a and the direction of the $\Upsilon(2S)$, in the rest frame of the $\Upsilon(1S)$. Decays of the $\Upsilon(1S)$ into a should be isotropically distributed whereas the background peaks at $|\cos\theta_{a\Upsilon}| = 1$ (Fig. 1). The angle $\theta_{a\Upsilon}$ was required to satisfy $|\cos\theta_{a\Upsilon}| < 0.95$. Next, a cut was made on the opening angle, $\theta_{e^+e^-}$, between the daughters of a. If $m_a < 2m_\mu \approx 210$ MeV/c^2, this angle will be small. For this search we demanded $\cos\theta_{e^+e^-} > 0.9$. In addition, to be consistent with a two-body decay hypothesis, the photon and a were required to be in opposite hemispheres.

The 21 events passing these cuts were then scanned to remove events containing additional tracks missed as a result of reconstruction inefficiency and events where the track assumed to be a pion was identified as an electron. Four events remained, each containing only one reconstructed track possibly originating from $a \rightarrow e^+e^-$. These events were scrutinized to determine whether the track was consistent with containing two charged tracks of opposite sign. It was determined from Monte Carlo simulation that 10 ± 1 drift-chamber cylinders would contain "double hits" (hits in azimuthally adjacent cells), for two overlapping oppositely charged tracks with invariant mass 1.8 MeV/c^2 and energy 4.7 GeV. Two of the candidate events contained one double hit and the remainder two double hits. All four were inconsistent with merged tracks

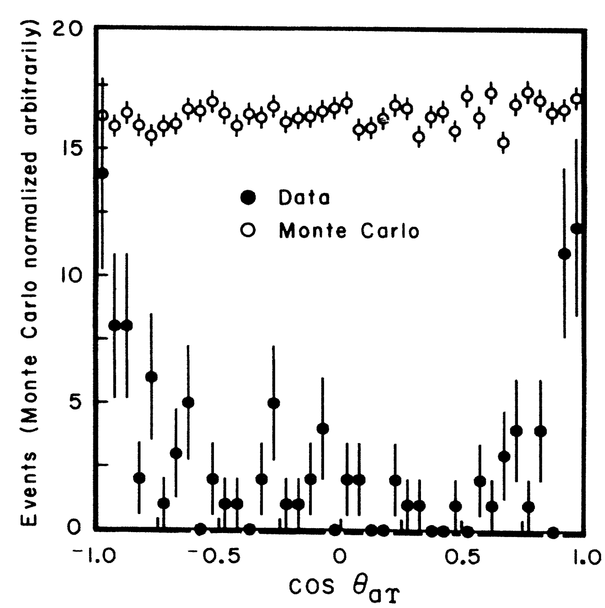

FIG. 1. The distribution of the angle between a and the direction of the $\Upsilon(2S)$ in the rest frame of the $\Upsilon(1S)$. The Monte Carlo simulation shows the isotropic distribution expected for $\Upsilon(1S) \rightarrow \gamma a$. Background events peak in the region $|\cos\theta_{a\Upsilon}| = 1$.

and so we rejected all candidates. Background from the radiative decay $\Upsilon(1S) \rightarrow e^+e^-\gamma$ was estimated to be one event, consistent with our observation of no event.

The detection efficiency, ϵ, varies as a function of mass m_a and proper lifetime τ_0 of the particle. For a spin-0 particle of mass 1.8 MeV/c^2, and $\tau_0 = 10^{-13}$ s (consistent with the data from heavy-ion collisions[1]), $\epsilon = 0.15$. As the lifetime of a increases it decays further from the production vertex, leading to a decrease in the detection efficiency of the daughters and hence to a rise in the upper limit as a function of τ_0. We have established an upper limit at 90% confidence level on $B_a = B(\Upsilon(1S) \rightarrow \gamma a) B(a \rightarrow e^+e^-)$ as a function of τ_0 for different masses, m_a. Our results are shown in Fig. 2. Our previous upper limits[5] on $B(\Upsilon(1S) \rightarrow \gamma a)$, for $m_a = 1.8$ MeV/c^2 and 3.6 MeV/c^2 (where a decays beyond the active volume of our detector), are also shown. The two results together place an upper limit on B_a of 5×10^{-4} at very small lifetimes ($\tau_0 > 5\times10^{-13}$ s) and 3×10^{-4} at large lifetimes ($\tau_0 > 3\times10^{-11}$ s). An overall upper limit of 2×10^{-3} applies to all lifetimes.

Balantekin *et al.*[2] have considered the possibility that the heavy-ion data are evidence for production of the axion, a light neutral pseudoscalar particle proposed[8] to explain the absence of *P* and *CP* nonconservations in gauge theories of the strong interaction.[9] In the standard axion theory[8] the mass, lifetime, and branching ratios from vector meson decays may all be expressed in terms of one free parameter x. In this theory the width for the radiative decay of Υ into an axion relative to the decay into $\mu^+\mu^-$ is given by[8,10]

$$\frac{\Gamma(\Upsilon(1S) \rightarrow \gamma a)}{\Gamma(\Upsilon(1S) \rightarrow \mu^+\mu^-)} = \frac{8.4\times10^{-3}}{x^2}.$$

With the assumption of the standard theory and three quark doublets, an axion with mass 1.8 MeV/c^2 would lead to a value $x = 0.04$ and a proper lifetime, τ_0, of 4×10^{-12} s ($\gamma\beta c\tau_0 = 3.2$ m). The width would be 5 times that for $\Upsilon \rightarrow \mu^+\mu^-$. Such a particle would mostly decay outside our detector and has been excluded by previous measurements.[4,5] Our new measurement (see Fig. 2) applies to particles with shorter lifetimes. The possibility of a short-lived standard axion remaining unobserved in Υ decays, although unlikely because of the large partial width, had not been explicitly ruled out by previous measurements.[11] For example, an axion with $\tau_0 = 3\times10^{-13}$ s would have $x = 0.02$ and mass 3.6 MeV/c^2, and hence $\gamma\beta c\tau_0 = 0.13$ m. The width would be 21 times that for $\Upsilon \rightarrow \mu^+\mu^-$.[12] This is now obviously excluded by our results.

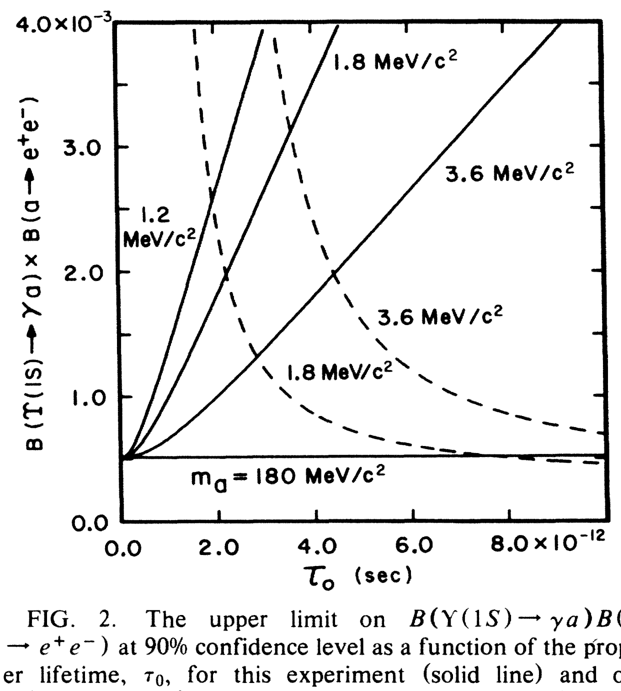

FIG. 2. The upper limit on $B(\Upsilon(1S) \rightarrow \gamma a) B(a \rightarrow e^+e^-)$ at 90% confidence level as a function of the proper lifetime, τ_0, for this experiment (solid line) and on $B(\Upsilon(1S) \rightarrow \gamma a)$ from our previous measurement (Ref. 5) (broken line). At long lifetimes the upper limit from Ref. 5 is 3×10^{-4}.

In conclusion, we have searched for evidence for the production of light, neutral, short-lived, spin-0 particles in radiative $\Upsilon(1S)$ decays. Stringent upper limits are set on the product branching ratio $B(\Upsilon(1S) \rightarrow \gamma a) B(a \rightarrow e^+e^-)$ for masses $2m_e < m_a < 2m_\mu$.

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