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SEARCH FOR EXOTIC DECAY MODES OF THE $\Upsilon(1S)$

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A search for two exotic decay modes of the $\Upsilon(1S)$ meson has been made using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The first was $\Upsilon(1S)$ decays into weakly interacting particles, for which an upper limit of 2.3% at the 90% CL on the branching ratio is found. The second mode was $\Upsilon(1S)\to\gamma a$, where a is a neutral particle with mass less than 1.5 GeV/c^2, that either decays inside the detector or is sufficiently long-lived to escape detection. For short-lived particles a decaying into an e^+e^- pair, upper limits on the $BR(\Upsilon(1S)\to\gamma a)$ of 3.1×10^{-4} at the 90% CL are found. The upper limit without restriction on the lifetime of a is found to be 1.3×10^{-3}. Limits for other decay modes are also given.

1. Introduction. Limits on decays of the $\Upsilon(1S)$ meson into χ_0, where χ_0 represents weakly interacting particles, put constraints on several interesting theoretical alternatives to the standard model. For example, in supersymmetric models [1], the $\Upsilon(1S)$ can decay into a photino and an antigravitino which escape detection. Another example is the theory of a "mirror universe" [2] proposed to restore P and CP symmetry. Here ordinary particles can, in principle, couple to mirror particles through a new kind of interaction with coupling constant G_X as large as the Fermi constant [3]. Oscillations between the $\Upsilon(1S)$ and its mirror partner the $\Upsilon(1S)_{\mathrm{mirror}}$ are predicted, leading to a decay $\Upsilon(1S)\to$"nothing visible" with a branching ratio [4]

$$BR(\Upsilon(1S)\to\text{"mirror particles"}) = \frac{9G_X^2 M^4_{\Upsilon(1S)}}{64\pi^2\alpha^4 Q_b^4}\times BR^2(\Upsilon(1S)\to\mu^+\mu^-)\,,$$

where Q_b is the charge of the b quark.

Many theories predict massless or very light Nambu–Goldstone bosons, arising from the spontaneous breaking of an underlying symmetry. One such object is the axion [5,6], a light neutral pseudoscalar particle proposed to avoid the problem of P and CP violation in QCD. This has attracted great attention recently due to the observation of correlated and monochromatic e^+ and e^- energy lines in heavy-ion collisions [7] at GSI. The observation can be interpreted as the production of a light neutral particle with mass 1.8 MeV/c^2 decaying into an e^+e^- pair [8]. Several authors have considered the possibility that this particle might be the axion [9].

One of the most promising places to search for the axion and axion-like particles is in radiative $\Upsilon(1S)$ decays. The standard axion model predicts that the $\Upsilon(1S)$ decays into a photon and an axion a with a branching ratio [6] given by

$$BR(\Upsilon(1S)\to\gamma a) = 2.4\times10^{-4}cx^{-2}\,,$$

where x is the ratio of the vacuum expectation values of two Higgs fields and c is a QCD radiative correction [10] of the order 0.5. Short-lived axions correspond to small values of x. For example, a value for x of 0.02, corresponding to an axion with a lifetime of 4×10^{-13} s and a mass of 4 MeV/c^2, leads to a $BR(\Upsilon(1S)\to\gamma a)$ of about 0.3. Previous experiments [11,12] have searched for long-lived axions in radiative $\Upsilon(1S)$ decays. Combined with other searches, they exclude the standard axion model with the exception of lifetimes less than a few $\times10^{-13}$ s [13].

In this paper we report a search for two exotic decay modes of the $\Upsilon(1S)$ meson, namely $\Upsilon(1S)\to\chi_0$ and $\Upsilon(1S)\to\gamma a$, using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. ARGUS is a universal magnetic detector described in detail elsewhere [14]. Besides its excellent momentum resolution and identification capability for charged particles, an important feature for this analysis is the good energy resolution of the ARGUS electromagnetic calorimeter which covers 96% of the full solid angle. The investigation is based on a data set taken on the $\Upsilon(2S)$ corresponding to an integrated luminosity of 38.6

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pb^{-1}. $\Upsilon(1S)$ candidates were tagged by detecting the pions from the transition

$$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)\,. \qquad (1)$$

For normalization, as well as to estimate our trigger efficiency for the two pions of reaction (1), we have used, as a control sample, the exclusive reaction

$$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S),\quad \Upsilon(1S)\to\ell^+\ell^-\,, \qquad (2)$$

where $\ell=\mathrm{e}$ or μ. Events of this type were selected by requiring four charged particles orginating from a common event vertex and no isolated clusters in the calorimeter with energy greater than 50 MeV. We define as isolated a cluster in the calorimeter which is not associated with a charged track. Two of the four particles were required to be collinear with an opening angle θ such that $\cos\theta\leqslant-0.99$, have opposite charge and have momenta greater than 3.5 GeV/c. The other two particles were required to be oppositely charged, have momenta less than 0.5 GeV/c and be identified as pions. The number of events containing $\mathrm{e}^+\mathrm{e}^-$ and $\mu^+\mu^-$ pairs are, within errors, equally divided, where the identity of the two fast tracks is distinguished on the basis of their energy deposition in the calorimeter.

The recoil mass against the two slow pions is shown in fig. 1b. A fit to this spectrum, using a gaussian with mass equal to the $\Upsilon(1S)$ mass and a width given by the mass resolution of 3 MeV/c^2 for the signal, plus a small background, yields 441.6 ± 21.3 events in the peak. The combined acceptance and trigger efficiency for reaction (2) was found by Monte Carlo simulation to be $(33.1\pm1.4)\%$. Combining this with the world average value for $\mathrm{BR}(\Upsilon(1S)\to\mu^+\mu^-)$ of $(2.8\pm0.2)\%$ [15], and assuming lepton universality, we find the total number of transitions (1) in our data sample to be $23\,800\pm2300$. This number has been used to normalize all branching-ratio limits reported here.

2. Search for weakly interacting particles χ_0. Candidate events for the reaction

$$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S),\quad \Upsilon(1S)\to\chi_0 \qquad (3)$$

were selected by requiring exactly two oppositely charged tracks originating from a common event vertex, both identified as pions with momenta below 0.5 GeV/c. In addition, the sum of the transverse momenta of the two particles had to be greater than 50 MeV/c, in order to suppress contributions from two-photon reactions, which nevertheless constitute our main combinatorial background. Finally, no isolated cluster with energy greater than 50 MeV was allowed in the electromagnetic calorimeter.

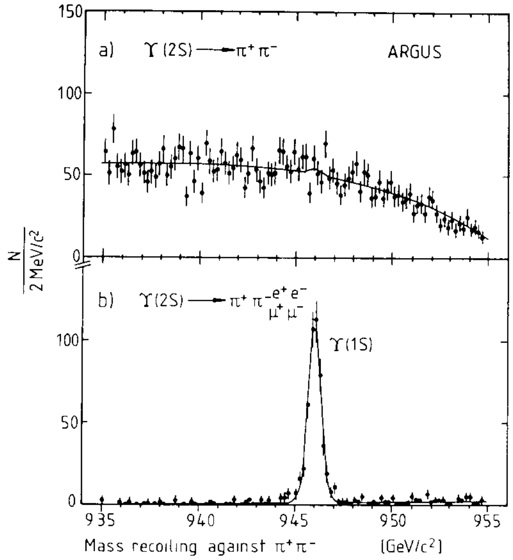

Fig 1 Distribution of mass recoiling against the two pions in the reaction (a) $\Upsilon(2S)\to\pi^+\pi\ \Upsilon(1S)$, $\Upsilon(1S)\to$"nothing visible", (b) $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S)\to\ell^+\ell$ where $\ell=\mathrm{e}$ or μ

The resulting distribution of the recoil mass against the two pions is shown in fig. 1a. A fit to this spectrum yields 10.8 ± 17.8 events for a gaussian signal centered at the $\Upsilon(1S)$ mass with a width equal to the mass resolution of 3 MeV/c^2 superimposed on a polynomial background. A source of background which could simulate reaction (3) comes from reaction (2) where the leptons (e, μ and one-prong decays of τ) are at small polar angles close to the beam pipe and therefore escape detection. A Monte Carlo simulation leads to an estimate of 4.5 ± 1.2 events for this background.

The acceptance for reaction (3) was estimated by a Monte Carlo study. However, the trigger efficiency was determined from the data, using our sample of reaction (2). From this sample we selected those events where the trigger was set by a high-energy deposition in the electromagnetic calorimeter, considerably larger than is possible for a slow pion. Then the fraction of these events, where in addition a charged trigger has been set by the two pions, gives the trigger efficiency of reaction (3) The combined acceptance and trigger efficiency was $(7.2\pm1.6)\%$. This leads to an upper limit of

$$\mathrm{BR}(\Upsilon(1S)\to\chi_0)\leqslant 2.3\% \text{ at the 90\% CL},$$

which is an improvement by a factor of 2 over previous measurements [16]. Our result constrains the coupling constant G_X in the model of mirror particles to be less than $0.3\times G_F$ at the 90% CL, where G_F is the Fermi coupling constant

3 *Search for axion-like particles a*

Candidate events for the reaction

$$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)\,,\quad \Upsilon(1S)\to\gamma a \tag{4}$$

were selected using the same requirements on the two pions as for reaction (2) but with an additional cut on their invariant mass, such that $m_{\pi^+\pi^-}<0.56$ GeV/c^2 The photon was required to have an energy between 4.0 and 5.5 GeV in the electromagnetic calorimeter, resulting in uniform sensitivity for particles a with mass less than about 1.5 GeV/c^2.

Two classes of decays can be distinguished The first represents decays of a short-lived a into two oppositely charged particles seen in the detector. The second class is a long-lived a which escapes without detection For the short-lived class there were two possible topologies considered:

(a) two tracks in the drift chamber opposite the photon γ with a momentum sum greater than 2.5 GeV/c and an angle $\theta_{\gamma a}$ between the photon and the system a such that $\cos\theta_{\gamma a}\leqslant 0.8$. No particle identification requirement was made The acceptance does not depend on the identity of the charged particles but the trigger efficiency is slightly higher for electrons due to their larger energy deposition in the calorimeter.

(b) a single cluster in the electromagnetic calorimeter with total energy greater than 2.5 GeV and in a direction opposite to the photon, with $\cos\theta_{\gamma a}\leqslant -0.8$. In this topology, we are only sensitive to $a\to e^+e^-$ and not to minimum ionizing pairs. However, the decay $a\to\gamma\gamma$ with $m_a<100$ MeV/c^2 would fall into this topology, because the two photons would merge into a single cluster.

In both topologies no other activity was allowed in the detector.

A total of 19 events was found to satify these selection criteria. These events were then visually scanned by physicists The result of the scan for short-lived class (15 events) was: one was found to be a beam-wall interaction, three to be incompletely reconstructed events of reaction (2) with the electrons close to the beampipe, two were identified as reaction (2) with one electron radiating a photon, eight events were doubly radiative Bhabhas (in 5, one photon had converted into an e^+e^- pair), and one had an overlapping charged particle and neutral energy cluster in the calorimeter.

Thus no candidates for the short-lived class remain. The combined detector acceptance and trigger efficiency for these events is $(34.8\pm1.8)\%$ for $a\to e^+e^-$ or $\gamma\gamma$ and $(29.8\pm1.6)\%$ for decays into heavier particles. If we take a to be an unstable object with proper lifetime less than 10^{-13} s decaying into an electron–positron pair, we obtain an upper limit of

$$\mathrm{BR}(\Upsilon(1S)\to\gamma a)\times\mathrm{BR}(a\to e^+e^-)\leqslant 3.1\times10^{-4}$$
at the 90% CL.

The result is more restrictive than the recently reported limits of 5×10^{-4} [17] and of 2.2×10^{-3} [18][‡1]. Our limit is three orders of magnitude below the prediction for short-lived, standard axions. This limit is also valid for the decay $a\to\gamma\gamma$, when $m_a<100$ MeV/c^2 For decays of a into pairs of heavier particles, the limit becomes

$$\mathrm{BR}(\Upsilon(1S)\to\gamma a)$$
$$\times\mathrm{BR}(a\to\mu^+\mu^-,\ \pi^+\pi^- \text{ or } K^+K^-)$$
$$\leqslant 4\times10^{-4} \quad \text{at the 90\% CL}.$$

This is an extension to smaller masses for a than previously published [19]. Two-prong decays constitute the major branching ratio for very light Higgs bosons [20], where one expects $\mathrm{BR}(\Upsilon(1S)\to\mathrm{Higgs})\times\mathrm{BR}(\mathrm{Higgs}\to\text{two-prong})$ to be of the order of 10^{-4} including QCD corrections [10,21].

The result for the scan of the long-lived class (four events) was: one had an overlapping charged particle and neutral energy cluster and two had an electromagnetic cluster with a size much larger than

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[‡1] The upper limit without restriction on the lifetime has been estimated from the figure of ref [18]

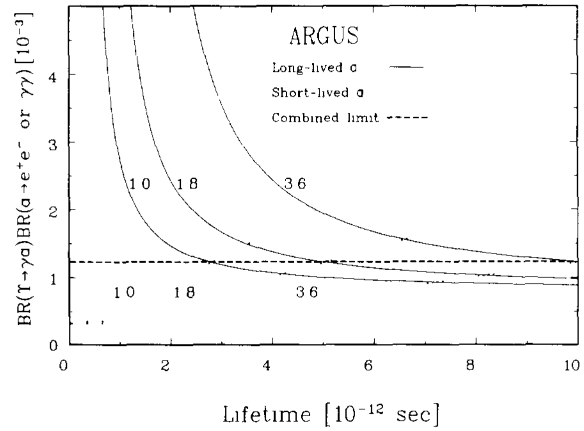

Fig. 2. Upper limits (90% CL) on the branching ratio of $\Upsilon(1S)\to\gamma_a$, where $a\to e^+e^-$ or $\gamma\gamma$, versus the lifetime of a for three masses of a 1.0, 1.8 and 3.6 MeV/c^2. The combined upper limit is also shown.

expected for photons. One event remains for which we have no explanation. The $\pi^+\pi^-$ recoil mass for this event is 9.46 GeV/c^2. The combined detector acceptance and trigger efficiency for the long-lived class is (24.1 ± 1.3)%. This gives an upper limit from 1 event for a with a lifetime greater than 10^{-7} s of

$$BR(\Upsilon(1S)\to\gamma a)\leqslant 8\times10^{-4} \quad \text{at the 90\% CL}$$

independent of the decay mode of a, and in agreement with previously published limits [11,12].

The complementary behaviour of the efficiency for the short- and long-lived particle searches allows one to derive an upper limit which is valid for all lifetimes. As the proper lifetime, τ_0, of the particle a increases, it decays further form the production vertex leading to a decrease of the detection efficiency and hence to a rise of the upper limit as a function of τ_0. On the other hand the efficiency for the search for long-lived particles decaying beyond the active volume of the detector improves with an increase of τ_0 leading to a decrease of the upper limit. For the decay of a into an e^+e^- or photon pair we are sensitive to decay distances less than 1.2 m (short-lived class) and for a escaping detection to decay distances greater than 1.8 m (long-lived class). The upper limits for these two classes are plotted in fig. 2 as a function of τ_a for three choices of m_a. For a given τ_a and m_a the upper limit is represented by the lower of the two curves. The upper limit, valid for all lifetimes τ_a, is given by the intersection of any pair of curves for the same m_a. Thus, the combined upper limit is 1.3×10^{-3}, which is also shown in fig. 2. This is an improvement over recent limits of 2×10^{-3} [17] and 5.5×10^{-3} [18].

4. *Summary.* We have determined upper limits for two exotic decay modes of the $\Upsilon(1S)$ meson. For $\Upsilon(1S)\to\chi_0$, where χ_0 represents weakly interacting particles, we obtain an upper limit on the branching ratio of 2.3% at the 90% CL. For $\Upsilon(1S)\to\gamma_a$, where a is a neutral particle with mass less than 1.5 GeV/c^2 and lifetime less than 10^{-13} s, we find upper limits on the branching ratio for decays of a into e^+e^- pairs of 3.1×10^{-4} at the 90% CL, and for decays into $\mu^+\mu^-$, $\pi^+\pi^-$ or K^+K^- pairs of 4×10^{-4} at the 90% CL. If a is long-lived ($\geqslant 10^{-7}$ s), then the upper limit is found to be 8×10^{-4}, independent of the decay mode. Finally, an upper limit of 1.3×10^{-3} is obtained, without restriction on the lifetime of a for $a\to e^+e^-$ or $\gamma\gamma$.

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