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Experimental Upper Limits for Hadronic and Axion Decays of the $\Upsilon(1S)$

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Abstract. A search for the decays $\Upsilon \to \rho\pi$, $\Upsilon \to J/\psi X$ and $\Upsilon \to \gamma a$ (where X is undetermined and a is an axion) has been completed using the LENA detector at the DORIS storage ring. No evidence for any of these processes was found. For these decay modes we set branching fraction upper limits (90% C.L.) of 2.1×10^{-3}, 2.0×10^{-2} and 9.1×10^{-4}, respectively.

1. Introduction

We report on a search for three channels in the decay of the $\Upsilon(1S)$ using the non-magnetic LENA detector at the e^+e^- storage ring DORIS. The $\Upsilon(1S)$ and $\Upsilon(2S)$ were discovered in proton nucleon interactions [1]. Further information regarding the Υ family has been obtained from measurements at the e^+e^- storage rings DORIS [2] and CESR [3] where Υ states have been observed as peaks in the total hadronic cross section. We have previously reported global properties of the final states occurring in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays in terms of the sphericity [4], the thrust [5] and the charged multiplicity [5] and the angular distribution of the thrust axis [5]. In this work we present the results of a search for the decays $\Upsilon(1S) \to \rho^0\pi^0$, $\Upsilon(1S) \to \gamma a$ (where a is an axion) and the inclusive decay $\Upsilon(1S) \to J/\psi X$ where X is undetermined. We have seen no conclusive evidence for any of these processes, but are able to place 90% confidence level upper limits on their branching fractions.

We proceed in the following way. In Sect. 2 we describe our apparatus and data samples. Section 3

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deals with the $\rho\pi$ decay. We discuss in Sect. 4 the search for inclusive J/ψ decay of the $\Upsilon(1S)$ and in Sect. 5 the search for $\Upsilon(1S)$ decay into a single photon plus an axion. We will use the symbol Υ to denote the $\Upsilon(1S)$ state throughout the remainder of this text.

2. Apparatus and Data Samples

The LENA detector has been described in detail in previous publications [6, 7]. In short, it consists of an inner track detector to measure the direction of charged particles and a segmented shower detector which allows the measurement of the energy of electrons and photons as well as their direction.

Data relevant to this experiment were taken at DORIS in 1979–1980. The integrated luminosity was determined from Bhabha scattering events. We accumulated $701 \pm 6\,\mathrm{nb}^{-1}$ at center of mass energies between 9.45 and 9.47 GeV and $1{,}199 \pm 7\,\mathrm{nb}^{-1}$ between 7.35 and 9.43 GeV. We have used the latter to investigate background processes.

We previously determined the total number of Υ mesons produced in this experiment when we measured the leptonic and total widths [8] of the Υ. In this work we modify the number of Υ produced by using the world average value of $B(\Upsilon \to \mu^+\mu^-) = 0.033 \pm 0.005$ [8]. Our Υ sample then contains $(7{,}100 \pm 210)$ decays.

3. $\Upsilon \to \rho^0 \pi^0$

Our motivation in searching for the process $\Upsilon \to \rho^0 \pi^0$ is due to the fact that $\rho\pi$ is one of the largest branching fractions in the hadronic decay of the J/ψ ($\mathrm{BR} = (1.2 \pm 0.1)\%$) [9]. We expect that the branching fraction $B(\Upsilon \to \rho\pi)$ is smaller than $B(J/\psi \to \rho\pi)$ because of the greater phase space available in Υ decay. The decay $\Upsilon \to \rho^0\pi^0$ should appear in our detector as two charged tracks opposite a cluster of neutral energy roughly equal to the beam energy. Due to the angular resolution of our energy detector we cannot resolve the π^0 decay into two separate photons. The opening angle of the $\pi^+\pi^-$ pair is kinematically restricted to be less than approximately 50° and the distribution of opening angles peaks sharply near 20° [10].

The following selections were made to our data. Each event was required to have exactly two charged particles reconstructed in the inner detector. The opening angle between the charged particles was required to be less than 30°. The total energy deposited in the energy detector was required to be greater than 2.5 GeV and less than 5 energy clusters were required. We also required that the cluster with the maximum energy contain at least 2 GeV and that it be collinear with the average direction of the two charged particles within approximately 70°. (This very wide cut is due, in part, to the poor angular segmentation of the energy detector. It is also a consequence of the fact that we measure only the directions of the charged pions and not their momenta. This introduces an uncertainty in the momentum direction of the ρ). In addition, because edge blocks of the detector do not completely contain showers of this energy, we required that at least one half of the energy of the shower be in interior blocks. Finally, we required that there be no signal in the muon detector correlated with either charged track.

In $701\,\mathrm{nb}^{-1}$ of data taken at the Υ resonance, we observed 5 events consistent with these selection criteria. We also observed 5 events in the $1{,}199\,\mathrm{nb}^{-1}$ of data taken in the continuum which we use here as a background sample. The distribution of the opening angle between the charged particles for both the Υ and background data are shown in Figs. 1a, b. We obtained a background substracted distribution by normalizing the luminosity of the continuum data to that of the data taken at the Υ and then subtracting. The result of this procedure is shown in Fig. 1c. We observe an excess of three events with opening angle cosines between 0.98 and 1.0. In Fig. 1d we show the distribution of the cosine of the opening angle produced by our Monte Carlo program which simulates the angular resolution of the drift chambers. The three events are consistent with originating from the process $\Upsilon \to \rho^0\pi^0$, but this is unlikely since each event is observed to have an opening angle which should be seen in our detector only 4% of the time. Since the probability that all three events are due to Υ decay is less than 10^{-4}, we reject them from further consideration.

We estimated an upper limit on the branching fraction for $\Upsilon \to \rho^0\pi^0$ by considering the events with opening angle cosines less than 0.98. In this region we observe -1.4 ± 2.0 events. If we assume a Gaussian probability distribution of events and normalize the positive part of the probability distribution to unity, we obtain a 90% confidence level estimate that less than 2.6 events should have this opening angle. By Monte Carlo simulation we determined the efficiency for detection of the $\rho^0\pi^0$ to be 52%. Thus, we determine that the $\Upsilon \to \pi^0\rho^0$ branching fraction is less than 6.9×10^{-4} and from isospin conservation we deduce that the $\Upsilon \to \rho\pi$ branching fraction is less than 2.1×10^{-3} (90% C.L.) where we have included allowances for systematic uncertain-

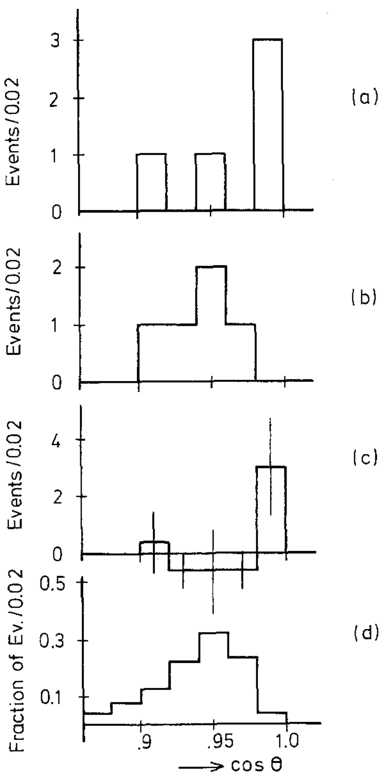

Fig. 1a–d. Search for the exclusive channel $\rho^0\pi^0$, $\rho^0\to\pi^+\pi^-$ in events with 2 charged tracks and 1 opposite neutral energy cluster. ϑ is the opening angle of the 2 charged tracks. **a** The $\cos\vartheta$ distribution observed in the data taken at the $\Upsilon(1S)$ resonance. **b** The $\cos\vartheta$ distribution observed in the data taken at CM energies below the $\Upsilon(1S)$. **c** The background subtracted $\cos\vartheta$ distribution. The background events from (b) have been weighted by the ratio of the luminosities of the signal and background data samples. **d** The expected $\cos\vartheta$ distribution including the effects of detector resolution determined by Monte Carlo simulation

ties in the luminosity and the total number of Υ mesons produced.

The quantity $Z\equiv\Gamma(\Upsilon\to\rho\pi)\Gamma(J/\psi\to 3g)/\Gamma(\Upsilon\to 3g)\cdot\Gamma(J/\psi\to\rho\pi)$, where $3g$ is a final state mediated by three gluons, has been predicted theoretically [11] using dimensional counting rules [12] to be on the order of $(M_{J/\psi}/M_\Upsilon)^6\sim 1.2\times 10^{-3}$. Using the world average values of $B(\Upsilon\to\mu^+\mu^-)=0.033\pm0.005$ [8], $B(J/\psi\to\mu^+\mu^-)=0.07\pm0.01$ [13], taking R (the ratio of the total hadronic cross section to the $\mu^+\mu^-$ cross section) to be 3.5 ± 0.4 (world average) at 9.46 GeV [7] and 2.5 ± 0.25 at 3.1 GeV [14], we determine $Z\leqq 0.16$ (90% C.L.) This upper limit is well above theoretical expectations.

4. $\Upsilon\to J/\psi X$

We have searched for inclusive J/ψ production in Υ decay by looking for hadronic events containing e^+e^- pairs having an invariant mass equal to that of the J/ψ. Our data sample consists of the same 701 nb^{-1} of data taken on the Υ resonance that were used in the search for the $\rho^0\pi^0$ decay channel.

The sample of hadronic events was selected with the following requirements [5]:

- Three or more charged tracks were reconstructed using the drift chamber information of the inner detector.
- At least 1.8 GeV was deposited in the energy detector.
- Not all the energy was deposited in one half of the detector.

The events which met these criteria were all visually scanned by physicists to remove any obvious beam gas, Bhabha scattering, or cosmic ray events.

All two particle invariant masses were formed for events within the hadronic data sample if the energy deposited in the energy detector correlated with a drift chamber track and exceeded 400 MeV. The invariant masses were calculated using the energy information and treating all tracks as due to electrons or positrons. Because of the finite thickness of our energy detector, we adjusted the measured energy of each cluster by estimating that fraction of the cluster energy which was not contained in our NaI and leads glass blocks. A shower normally extends into two or three counters of the energy detector. We made use of the universal transition curve of Nagel [15]:

$$\frac{1}{E_0}\frac{dE}{dX}=\frac{4.21}{\ln E_0}\exp(-1.89\,X/\ln E_0)$$

where E_0 (in MeV) is the incident energy of the showering particle and X is the thickness of the absorber measured in radiation lengths. We integrated this formula from X_T (the thickness of the energy detector along the line of flight of the particle) to infinity to obtain the cluster energy not contained as a function of the incident particle energy. We then iterated this formula to determine a mean estimate of the true incident energy of the particle since we knew only the measured energy.

The resultant invariant mass distribution is shown in Fig. 2. There is no apparent structure visible at the J/ψ mass. We have subtracted the background by forming invariant mass combinations using pairs of tracks which come from different events. The background subtracted invariant mass distribution is shown in Fig. 2.

To determine an upper limit on the number of J/ψ's detected, we fit the background subtracted invariant mass spectrum to a Gaussian distribution

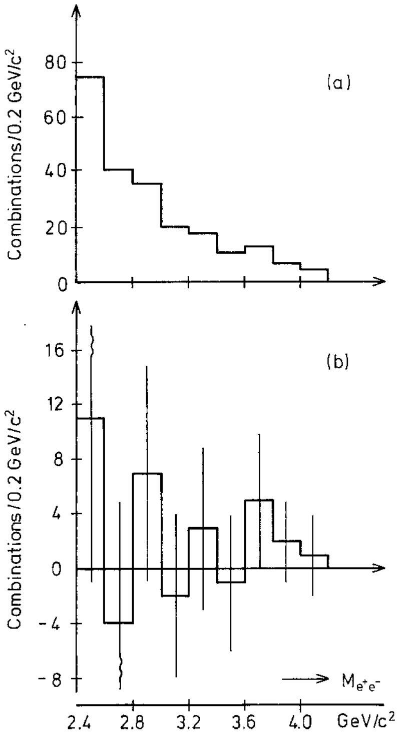

Fig. 2. **a** The two particle invariant mass distribution. Each particle was assigned the mass of an electron. **b** The two particle invariant mass distribution after background subtraction. The errors shown are statistical

with a center fixed at the J/ψ mass plus a constant background. The width was determined by Monte Carlo simulation. We normalized to the sum of all the events in the background subtracted invariant mass spectrum. The result of this fit was that less than 5 events were observed (90% C.L.). Through Monte Carlo simulation we also determined our detection efficiency to be $(50 \pm 10)\%$. The uncertainty is due to the dependence of the detection efficiency on the invariant mass of the system recoiling against the J/ψ. If we consider the most conservative case where the detection efficiency is 0.4, we obtain 2.0% as upper limit for the branching fraction of for $\Upsilon \to J/\psi X$.

By making a model dependent assumption about the nature of the Υ decay we are able to determine a more restrictive upper limit on this branching fraction. It has been proposed by Fritzsch and Streng [16] that the recoil system opposite the J/ψ should be predominantly of low invariant mass. We have fit all two particle invariant masses to the J/ψ mass using a χ^2 minimization technique which assumes that the production angles of the two tracks are well known, so that the error in the invariant mass is entirely due to mismeasurement of the lepton energy alone. In calculating the χ^2 we assumed that the energy resolution in our detector varies as $\sqrt{E}$ where E is the energy of the incident particle. Using the recoil mass distribution of Fritzsch and Streng and requiring that the recoil mass observed be less than 5.5 GeV/c² and that the χ^2 per degree of freedom of the fit to the J/ψ be less than 10, we exclude all our data from the possibility of Υ decay into a J/ψ. We therefore determine the upper limit (90% C.L.) for the branching fraction for $\Upsilon \to J/\psi X$ to be less than 1.2%. This result can be compared to theoretical predictions [16, 17] which estimate that $B(\Upsilon \to J/\psi X) \sim (1\text{-}2)\%$. Theoretical calculations contain a substantial uncertainty arising from a lack of knowledge of what proportion of the $c\bar{c}$ quark pairs produced are in resonant states such as the J/ψ. Our result does not invalidate these calculations, but it does place a constraint on the amount of J/ψ formation within the $c\bar{c}$ system.

5. $\Upsilon \to \gamma +$ Axion

The axion is a neutral pseudo-scalar boson which has been postulated [18, 19] as a result of the Peccei-Quinn solution [20] to the problem [21] of parity conservation and time reversal invariance in strong interactions. The axion is expected [19, 22–25] to have a mass on the order of a few hundred keV, and it should couple weakly [18] to quarks and charged leptons with a coupling constant of $2^{1/4} G_F^{1/2} m\lambda$ for u, c, and t quarks, and $2^{1/4} G_F^{1/2} m/\lambda$ for d, s, and b quarks and charged leptons. Here, m is the mass of the quark or lepton and the parameter λ is the ratio of the vacuum expectation values acquired by the two Higgs doublets in the standard axion theory.

One of the least model dependent ways to search for axions is in the decay of the J/ψ or Υ to an axion plus a photon. The axion is expected to decay primarily into two photons [22] and to have a lifetime on the order of $(100\,\mathrm{keV}/m_a)^5$ s. Therefore, we have searched for events in the LENA detector where we observe only the photon from the direct decay of the Υ while the axion escapes unobserved. We required the events to have no cosmic or muon counter signal, no drift chamber signals, and exactly one photon which had a measured energy close to the beam energy. This photon was required to deposit at least one half of its energy in blocks other than those which are on the edges of the detector.

To determine the range of energies allowed for the observed photon, we used electrons and positrons from Bhabha events produced on the Υ resonance and we determined the mean energy deposition per particle and the variance of the energy deposition as a function of solid angle in our detector. We were then able to calculate the probability that a photon of a given measured energy actually had an energy equal to one half the Υ mass. We required that this probability be greater than 5%.

No events were observed which satisfied these selection criteria. We determined the detection efficiency [26] for the process $\Upsilon \to \gamma a$ by Monte Carlo simulation to be 56%. The trigger efficiency was determined by comparing our observed yield of $e^+e^- \to \gamma\gamma$ events in the same data sample with the number of events predicted by QED. After correcting for the detection efficiency of the two photon events, we conclude that the probability that a single photon with an energy equal to one half the Υ mass triggers the detector is 65%. Since we have found no evidence for $\Upsilon \to \gamma a$, we calculate a 90% confidence level upper limit for the branching ratio to be $B(\Upsilon \to \gamma a) < 9.3 \times 10^{-4}$.

It has recently been reported [27] by the Crystal Ball Collaboration that $B(J/\psi \to \gamma a) < 1.4 \times 10^{-5}$ (90% C.L.). This result puts a lower bound on $B(\Upsilon \to \gamma a)$. Following the suggestion of Porter and Königsmann [28] we determine the unexcluded range of $B(\Upsilon \to \gamma a)$. In the standard model [19] the axion and μ pair branching fractions in Υ decay are related by:

$$\frac{B(\Upsilon \to \gamma a)}{B(\Upsilon \to \mu^+\mu^-)} = \frac{G_F m_b^2}{\sqrt{2}\pi\alpha\lambda^2}$$

where m_b is the b quark mass and α is 1/137. A similar expression describes the ratio of axion to μ pair production in J/ψ production when m_c is substituted for m_b and $1/\lambda^2$ is replaced by λ^2. Multiplying these two expressions and evaluating them using $m_c = 1.5$ GeV/c^2, $m_b = 4.7$ GeV/c^2, $B(J/\psi \to \mu^+\mu^-) = 0.07 \pm 0.01$ [13] and $B(\Upsilon \to \mu^+\mu^-) = 0.033 \pm 0.005$ [8] imposes the lower limit on $B(\Upsilon \to \gamma a)$ of 9.2×10^{-4}. If we ignore uncertainties due to quark masses and uncertainties in the $J/\psi \to \mu^+\mu^-$ and $\Upsilon \to \mu^+\mu^-$ branching fractions, the Crystal Ball and LENA results together exclude the existence of an axion within the standard model [29].

6. Conclusions

Table 1 summarizes the results of our search for specific decay modes of the Υ. It lists the 90% confidence level upper limits for Υ decays into the three decay modes we have investigated, the detector acceptance for each decay mode, and the 90% confidence level upper limit on the number of events observed in each individual mode.

Table 1. Branching Fraction Upper Limits for $\Upsilon \to \rho\pi$, $J/\psi X$, and γa

Decay mode	Limit on number events observed (90%C.L.)	Detector acceptance	Branching fraction upper limit (90%C.L.)
$\Upsilon \to \rho\pi$	2.6	52%	2.1×10^{-3}
$\Upsilon \to J/\psi X$	5.0	50%	2.0×10^{-2}
$\Upsilon \to \gamma a$	2.3	36%	9.3×10^{-4}
Integrated luminosity		$701 \pm 6\,\text{nb}^{-1}$	
Total number of Υ produced		$7{,}100 \pm 210$	

The existence of the axion is almost ruled out within the standard model due to the complementary nature of our data and that from the Crystal Ball experiment. The upper limit we determine on the $\Upsilon \to J/\psi X$ branching fraction approximately equals theoretical expectations, and if these estimates are correct we expect that inclusive production of the J/ψ in Υ decays should soon be visible in experiments at the DORIS and CESR e^+e^- storage rings. The $\Upsilon \to \rho\pi$ branching fraction is at least a factor of 10 smaller in Υ decays than the corresponding fraction in J/ψ decays. The upper limit we have determined is well above theoretical expectations.

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