RADIATIVE DECAYS OF THE Υ(2S) INTO THE THREE χ_b STATES

The ARGUS collaboration

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The ARGUS detector at the e^+e^- storage ring DORIS II has been used as a pair spectrometer to study the photon transitions in the reaction $\Upsilon(2S) \to \gamma\chi_b(1^3P_{2,1,0})$. Three photon lines were observed with energies $(110.6 \pm 0.3 \pm 0.9)$ MeV, $(131.7 \pm 0.3 \pm 1.1)$ MeV and $(162.1 \pm 0.5 \pm 1.4)$ MeV, respectively. The corresponding branching ratios were found to be $(9.8 \pm 2.1 \pm 2.4)\%$, $(9.1 \pm 1.8 \pm 2.2)\%$ and $(6.4 \pm 1.4 \pm 1.6)\%$. Upper limits for full widths at the 90% confidence limit are 1.0 MeV for the $\chi_b(1^3P_2)$ and 2.6 MeV for the other two states.

For footnotes see next page.

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The bound states of a b- and $\bar{b}$-quark form a sequence of levels analogous to the spectroscopy of positronium. A measurement of the masses of the various states provides information on the details of the quark–antiquark interaction. In particular, for heavy quarks the interaction has been successfully described by potential models and properties of the $b\bar{b}$ system have been predicted by extrapolations from the charmonium system or from QCD sum rules ‡1. The predictions, however, vary substantially between models. The triplet P states are characterized by parallel quark spins and an orbital angular momentum of $l = 1$, leading to total spins $J = 0,1,2$. The three $1\ ^3P_{0,1,2}$ states of the $b\bar{b}$ system can be reached by e^+e^- annihilations through photon transitions from the $\Upsilon(2S)$ state:

$$e^+e^- \to \Upsilon(2S) \to \gamma\chi_b(1\ ^3P_J)\,. \qquad (1)$$

The potential models predict electric dipole transition rates proportional to $(2J+1)E_\gamma^3$, where E_γ denotes the photon energy. These transitions have already been investigated by the CUSB [3], CLEO [4] and Crystal Ball [5] Collaborations.

We report here on a high resolution measurement of the three photon transitions using the ARGUS detector at the e^+e^- storage ring DORIS II. An integrated luminosity of 38.6 pb^{-1} accumulated on the $\Upsilon(2S)$ resonance was used for this investigation. The inclusive photon spectrum from the reaction

$$\Upsilon(2S) \to \gamma X$$

was studied using the ARGUS detector as a pair spectrometer, by measuring the energy of electron–positron pairs from photons which convert in the beam vacuum pipe, in the inner wall of the drift chamber or within the drift chamber volume out to a radius of 50 cm. These materials comprise 2.2%, 1.3% and 0.3% of a radiation length respectively. Fig. 1 shows an example of such an event.

For the purposes of this study, no extra converter material was added, nor was the magnet run at reduced field. Thus very asymmetric pairs were lost, and the detection efficiency was only 0.3–1.2% in the photon energy range 100–200 MeV. Nevertheless, this method provides optimal precision in the photon energy range investigated, once a sufficient statistical significance is reached to separate the photon lines of reaction (1) from the substantial background of photons from π^0 decay.

The event selection started with multihadron events obtained by the standard ARGUS procedure [6]. These represent a complete inclusive data set for events with three or more charged tracks. Beam–gas, two-photon and radiative Bhabha reactions in this sample were suppressed by requiring for each event a sphericity, $S > 0.1$, a total shower counter energy, $E_{SH} > 2.2$ GeV and for the sum of all charged track momenta and shower energy, $\Sigma_j p_j + E_{SH} < 14.0$ GeV. To ensure that the events have a well measured primary vertex, only those were accepted which contain four or more detected charged tracks originating from the annihilation point. This vertex had to lie within ±2.5 cm of the centre of the interaction region along the beam direction. A total of 125 000 $\Upsilon(2S)$ decays survived these cuts.

Pairs of oppositely charged tracks which come close to intersecting and have equal polar angles were selected as photon candidates. Both tracks were required to be consistent with an electron assignment based on energy loss measurements in the drift chamber. Tracks with a polar angle θ such that $|\cos\theta| < 0.9$ were used, to ensure good acceptance. Finally, the photon candidates were selected by a 5-C fit, which accounted for the effects of multiple scattering and energy loss, and adjusted the momenta and positions of the electrons by minimizing χ^2 subject to the following constraints:

(1) The invariant mass of the pair must be small (1-C).

(2) The momentum vector of the pair must point backwards to the reconstructed primary vertex (2-C).

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‡1 For a recent review of the potential model, see ref. [1]; for several theoretical predictions, see ref. [2].

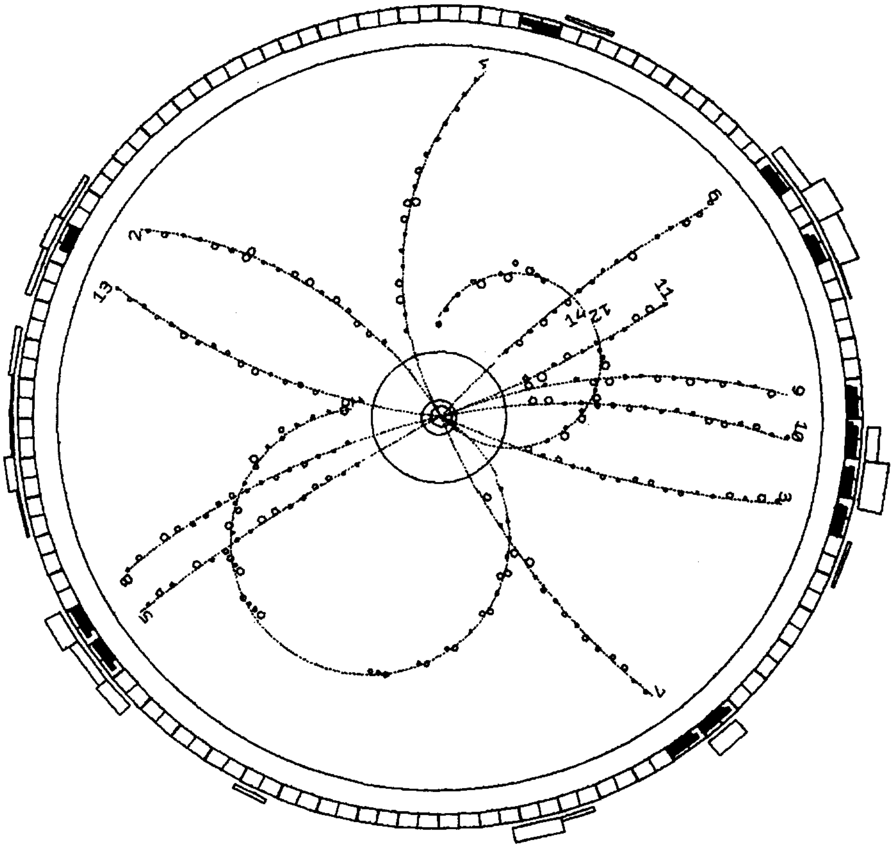

Fig. 1. Example of an event with a photon of 130 MeV energy, which converted into an e^+e^- pair in the beam pipe.

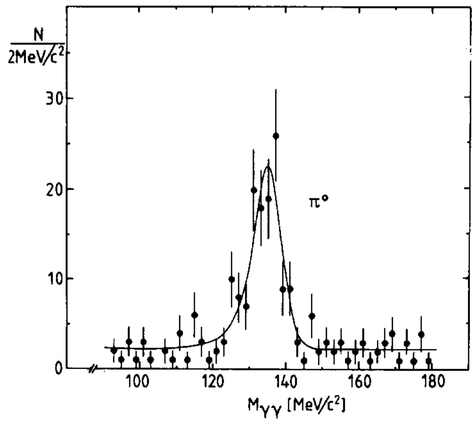

Fig. 2. Distribution of invariant masses of pairs of converted photons showing a clear π^0 signal, used to check the photon energy calibration.

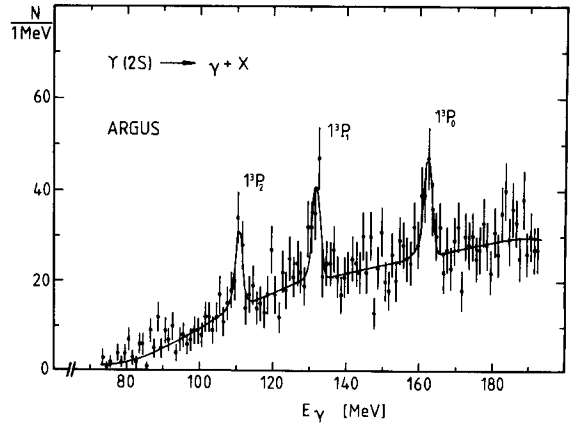

Fig. 3. Inclusive photon spectrum from the ϒ(2S) resonance and the underlying continuum. The curve shows the best fit to the three photon lines with shape given by the detector energy resolution for converted photons, plus a smooth fifth-order Legendre polynomial series for the background.

(3) The pair must intersect in either the vacuum pipe or drift chamber wall or, for conversions in the drift chamber volume, in the drift cell containing the point of closest approach (2-C).

Details of this procedure can be found in ref. [7].

The photon energy calibration and energy loss corrections applied were checked using events with two converted photons. The distribution of the invariant mass of such photon pairs is shown in fig. 2. The π^0 peak appears at 134.8 ± 0.5 MeV/c^2, consistent with the accepted value for the π^0 mass.

The resulting photon energy spectrum is shown in fig. 3. The three photon lines from the transitions $\Upsilon(2S) \to \gamma\chi_b(1\ ^3P_{0,1,2})$ are clearly visible. The fitted curve is a fifth-order Legendre polynomial series for the background plus gaussians with radiative tails to represent the three lines. The parametrization of the line shape was obtained from Monte Carlo simulation which included energy loss by ionization and radiation of the e^+e^- pair. The observed line widths are consistent with the detector energy resolution of $\sigma_E = 1.1$ MeV. Upper limits for the full widths of the χ_b states were obtained by fitting a Breit–Wigner distribution folded with the detector resolution function to the lines.

The photon detection efficiency was determined by a Monte Carlo simulation. A check of this calculation was made by comparing the observed background with that predicted by assuming the converted photon spectrum to be entirely due to π^0 production originating from the $\Upsilon(2S)$ and underlying continuum, and that the π^0 momentum distribution is the same as that measured for charged pions [8]. The photon angular distributions used in the acceptance calculation were based on the assumption that the masses of the three P states are ordered as follows:

$$m(1\ ^3P_0) < m(1\ ^3P_1) < m(1\ ^3P_2)\ ,$$

and that the transitions were purely dipole (E1). The ordering of the states has been recently confirmed by the Crystal Ball Collaboration [9].

The results obtained from the photon energy spectrum are summarized in table 1. A comparison with previously reported results is given in table 2. There is good overall agreement on the energy of the photon transitions to be $\chi_b(1\ ^3P_{2,1})$ states. The energy of the third line reported here agrees well with the result of the Crystal Ball Collaboration [5]; the existence of

Table 1
Measured properties of the 1 ^3P_J states.

Assumed transition	Photon energy a) [MeV]	Efficiency [%]	Assumed angular distribution	Branching ratio [%]	Branching ratio relative to $^3P_1$	$(2J+1)E_\gamma^3$ relative to $^3P_1$	Upper limit for Γ (90% CL) [MeV]	$M(1\ ^3P_J)$ b) [MeV/c^2]	$M(1\ ^3P_J)-M_{COG}$ c) [MeV/c^2]
$2\ ^3S_1 \to 1\ ^3P_2$	110.6 ± 0.3 ± 0.9	0.41	$1+(1/13)\cos^2\theta$	9.8 ± 2.1 ± 2.4	1.08 ± 0.30	0.99 ± 0.05	1.0	9911.9 ± 1.5	12.9 ± 0.9
$2\ ^3S_1 \to 1\ ^3P_1$	131.7 ± 0.3 ± 1.1	0.59	$1+(1/3)\cos^2\theta$	9.1 ± 1.8 ± 2.2	(1.00)	(1.00)	2.6	9890.5 ± 1.7	−8.4 ± 1.4
$2\ ^3S_1 \to 1\ ^3P_0$	162.1 ± 0.5 ± 1.4	0.86	$1+\cos^2\theta$	6.4 ± 1.4 ± 1.6	0.70 ± 0.21	0.62 ± 0.03	2.6	9859.6 ± 2.1	−39.3 ± 2.1

a) $R = [E_\gamma(^3P_1) - E_\gamma(^3P_2)]/[E_\gamma(^3P_0) - E_\gamma(^3P_1)] = 0.69 \pm 0.04$.
b) $\Upsilon(2S)$ mass of (10023.1 ± 0.04 ± 0.05) MeV/c^2 taken from ref. [10].
c) $M_{COG} = [\Sigma_J(2J+1)M(^3P_J)/\Sigma_J(2J+1)] = 9898.9 \pm 1.0$ MeV/c^2.

Table 2
Comparison of results for photon lines from inclusive $\Upsilon(2S)$ decays.

Collaboration	Reference	Photon energy [MeV]	Branching ratio [%]
ARGUS	this experiment	110.6 ± 0.3 ± 0.9	9.8 ± 2.1 ± 2.4
		131.7 ± 0.3 ± 1.1	9.1 ± 1.8 ± 2.2
		162.1 ± 0.5 ± 1.4	6.4 ± 1.4 ± 1.6
CLEO	[4]	109.5 ± 0.7 ± 1	10.2 ± 1.8 ± 2.1
		129.0 ± 0.8 ± 1	8.0 ± 1.7 ± 1.6
		(158.0 ± 7.0 ± 1)	(4.4 ± 2.3 ± 0.9)
CUSB	[3]	108.2 ± 0.3 ± 2	6.1 ± 1.4
		128.1 ± 0.4 ± 3	5.9 ± 1.4
		149.4 ± 0.7 ± 5	3.5 ± 1.4
Crystal Ball	[5]	110.4 ± 0.8 ± 2.2	5.8 ± 0.7 ± 1.0
		130.6 ± 0.8 ± 2.4	6.5 ± 0.7 ± 1.2
		163.8 ± 1.6 ± 2.7	3.6 ± 0.8 ± 0.9

this transition is thus well established. The branching ratios obtained by this experiment are in good agreement with those reported by the CLEO Collaboration [4], also obtained using e^+e^- pairs from converted photons. However, our results appear to be systematically higher than those obtained with the CUSB and Crystal Ball detectors using electromagnetic shower counters [3,5]. The expected proportionality of the branching ratios to

$$(2J+1)\,E_\gamma^3$$

is well satisfied, supporting the assumed spin assignment. The absence of Doppler broadening of the photon lines excludes the possibility that they are due to the reaction $\chi_b(1\,^3P_{2,1,0}) \to \gamma\Upsilon(1S)$. Comparison of recent results with theoretical predictions can be found in ref. [2]. There is qualitative agreement with most approaches, but none of the calculations reproduces in detail the observations presented here. The precision with which we have determined both the centre-of-gravity mass and the mass splitting of the χ_b states provides new constraints for adjusting the parameters of these models.

In summary, we have observed the three photon transitions $\Upsilon(2S) \to \gamma\chi_b(1\,^3P_{0,1,2})$. We have measured the branching ratios, determined the mass of the three χ_b states with high precision and obtained upper limits for their widths.

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