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Observation of Three P States in the Radiative Decay of $\Upsilon(2S)$

R. Nernst, D. Antreasyan, D. Aschman, D. Besset, J. K. Bienlein, E. D. Bloom, I. Brock, R. Cabenda, A. Cartacci, M. Cavalli-Sforza, R. Clare, G. Conforto, S. Cooper, R. Cowan, D. Coyne, D. de Judicibus, C. Edwards, A. Engler, G. Folger, A. Fridman,(a) J. Gaiser, D. Gelphman, G. Godfrey F. H. Heimlich, R. Hofstadter, J. Irion, Z. Jakubowski, S. Keh, H. Kilian, I. Kirkbride, T. Kloiber, W. Koch, A. C. König, K. Königsmann, R. W. Kraemer, R. Lee, S. Leffler, R. Lekebusch, P. Lezoch, A. M. Litke,(b) W. Lockman, S. Lowe, B. Lurz, D. Marlow, W. Maschmann, T. Matsui, F. Messing, W. J. Metzger, B. Monteleoni, C. Newman-Holmes, B. Niczyporuk, G. Nowak, C. Peck, P. G. Pelfer, B. Pollock, F. C. Porter, D. Prindle, P. Ratoff, B. Renger, C. Rippich, M. Scheer, P. Schmitt, M. Schmitz, J. Schotanus, A. Schwarz, D. Sievers, T. Skwarnicki, K. Strauch, U. Strohbusch, J. Tompkins, H.-J. Trost, R. T. Van de Walle, U. Volland, K. Wacker, W. Walk, H. Wegener, D. Williams, and P. Zschorsch

(The Crystal Ball Collaboration)

California Institute of Technology, Pasadena, California 91125
University of Cape Town, Cape Town, South Africa
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
Cracow Institute of Nuclear Physics, Cracow, Poland
Deutsches Elektronen Synchrotron DESY, Hamburg, Germany
Universität Erlangen-Nürnberg, Erlangen, Germany
Instituto Nazionale di Fisica Nucleare and University of Firenze, Italy
Universität Hamburg, I. Institut für Experimentalphysik, Hamburg, Germany
Harvard University, Cambridge, Massachusetts 02138
University of Nijmegen and Nationaal Instituut voor Kernfysica en Hoge-Energiefysica, Nijmegen, The Netherlands
Princeton University, Princeton, New Jersey 08544
Department of Physics, High-Energy Physics Laboratory, and Stanford Linear Accelerator Center, Stanford, California 94305
Universität Wüzrburg, Würzburg, Germany

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The inclusive photon spectrum in hadronic decays of the $\Upsilon(2S)$ is measured with the Crystal Ball detector at DORIS II. Four well separated photon lines, which are consistent with the decay hypothesis $\Upsilon(2S) \rightarrow \gamma + {}^3P_{2,1,0}$ and ${}^3P_{2,1} \rightarrow \gamma\Upsilon(1S)$, are observed. The energies of the lines from the primary transitions are $E_{\gamma 1} = 110.4 \pm 0.8 \pm 2.2$ MeV, $E_{\gamma 2} = 130.6 \pm 0.8 \pm 2.4$ MeV, and $E_{\gamma 3} = 163.8 \pm 1.6 \pm 2.7$ MeV; the branching fractions are $(5.8 \pm 0.7 \pm 1.0)\%$, $(6.5 \pm 0.7 \pm 1.2)\%$, and $(3.6 \pm 0.8 \pm 0.9)\%$, respectively. The secondary transitions center at $\langle E_\gamma \rangle \simeq 430$ MeV with a combined branching fraction of $(3.6 \pm 0.7 \pm 0.5)\%$.

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According to quarkonium potential models, the $\Upsilon(2S)$ $b\bar{b}$ resonance is expected to decay radiatively to three P states: $2^3S_1 \rightarrow \gamma + 1^3P_{2,1,0}$. The P states can decay hadronically or via emission of a second photon to the $\Upsilon(1S)$. The determination of the P-state energies yields insight into some aspects of the interquark potential.[1] Until now only two of the three expected primary photon transitions have been observed with good statistical significance.[2–4]

Here we present an analysis of the inclusive photon spectrum $\Upsilon(2S) \rightarrow \gamma + (\text{hadrons})$ using the Crystal Ball detector at the DORIS II storage ring. This analysis is based on $(193 \pm 15) \times 10^3$ produced $\Upsilon(2S)$ and corresponds to an integrated luminosity of $\int L\,dt \simeq 61\ \text{pb}^{-1}$.

The main Crystal Ball detector consists of a spherical, segmented shell of NaI(Tl) shower counters which cover 93% of the full solid angle. The coverage is increased to 98% of 4π by NaI(Tl) end caps. The thickness of the NaI(Tl) shell corresponds to sixteen radiation lengths and to one nuclear-absorption length. The direction of charged particles is measured by three double layers of proportional tube chambers with charge division readout. The Crystal Ball in its configuration at the SPEAR storage ring has been described in detail elsewhere.[5,6] At DORIS II the end caps and the luminosity monitor system were modified to allow the installation of minibeta quadrupoles.

The energy resolution for photons is measured to be $\sigma(E)/E = (2.7 \pm 0.2)\%/E^{1/4}$ (where E is the energy of the photon in gigaelectronvolts) and the angular resolution is 1°–2° (slightly energy dependent).[7] The distribution of energy deposited by charged hadrons in the NaI(Tl) crystals peaks around 210 MeV due to minimum ionizing charged particles and has a long tail toward higher energies due to nuclear interactions.

The hadronic $\Upsilon(2S)$ event sample is obtained by removing background due to beam-gas interactions, cosmic rays, two-photon events, and QED events. The remaining data sample contains contributions from the resonance and the continuum in a ratio of approximately 1 to 1. The efficiency for the selection of hadronic decays of the $\Upsilon(2S)$ is calculated to be $\epsilon_h = (86 \pm 7)\%$ with use of a Monte Carlo simulation of the properties of the detector. Further details of the event selection and the efficiency determination can be found in Edwards and Nernst.[8]

The photon selection is described next; it is designed to remove charged particles, photons from π^0 decays, and photons whose showers are contaminated by energy depositions of nearby particles. A photon must lie within an angular range defined by $|\cos\theta| \leq 0.75$ (θ is the photon angle with respect to the positron beam). This cut ensures coverage by all three tracking chambers. The photon has to be "neutral" which means that no crystal contributing to the photon shower is correlated with hits in the tracking chambers. To minimize distortion of the photon energy we require that the energy cluster of any photon candidate is well separated from all other clusters by at least 30°. The lateral energy distribution in the crystals must be consistent with the pattern of a single electromagnetic shower, and photon pairs which can be fitted to $\pi^0 \rightarrow \gamma\gamma$ decays are removed.

The photon selection efficiency for these cuts is $\epsilon_\gamma = (15.2 \pm 1.5)\%$, independent of energy for $50 \leq E_\gamma \leq 500$ MeV. It is determined by adding Monte Carlo photons in that energy range into hadronic $\Upsilon(1S)$ events and analyzing these events with the cuts described above. See also Ref. 6 for details on the method.

Figure 1 shows the energy spectrum, with a logarithmic energy scale, of photons satisfying the above requirements. Three clearly separated peaks in the region between 100 to 170 MeV and another around 430 MeV are visible. The shoulder at 210 MeV is due to misidentified charged particles. We fit the spectrum from $E \simeq 50$ to $E \simeq 650$ MeV using the sum of the following terms: (1) A fourth-order Legendre polynomial series representing the photon background. (2) A charged-particle spectrum with variable amplitude to take account of the remaining charged-particle contamination. (The shape of this spectrum is obtained by taking genuine charged particles as defined by the three tracking chambers and applying the photon selection cuts.) (3) Three Gaussian distributions with widths determined by the known energy resolution to describe the signals in the 100–170-MeV region. (4) Two Gaussian distributions to describe the Doppler-broadened secondary lines around 430 MeV, at energies fixed by the two lower energy lines and the known $\Upsilon(2S)$-$\Upsilon(1S)$ mass difference.[9,10] We assume here and below that the line around 430 MeV is due to the secondary transitions ${}^3P_{2,1} \rightarrow \gamma\Upsilon(1S)$, where the ${}^3P_2$ and ${}^3P_1$ are assumed to be the two more massive of the three observed states.[11] The ${}^3P_0 \rightarrow \gamma\Upsilon(1S)$ branching ratio is expected to be small.[12] This is indicated by a previous experiment[13] and our studies[14] of the exclusive channel $\Upsilon(2S) \rightarrow \gamma\gamma\Upsilon(1S) \rightarrow \gamma\gamma l^+ l^-$.

The result of the fit to the inclusive photon spectrum is shown in Fig. 2. The dashed line in Fig. 2(a) represents the smooth polynomial background. The charged-particle "punchthrough" background is given by the difference of the solid line (that excludes the Gaussians) and the dashed line. In Fig. 2(b) this background has been subtracted. The fit has a confidence level of 72%.

The branching ratios for the observed transitions are calculated according to $B = N_\gamma / N_{\text{res}}\epsilon_{\text{tot}}$, where N_γ is the number of photons in a given peak, N_{res} is the

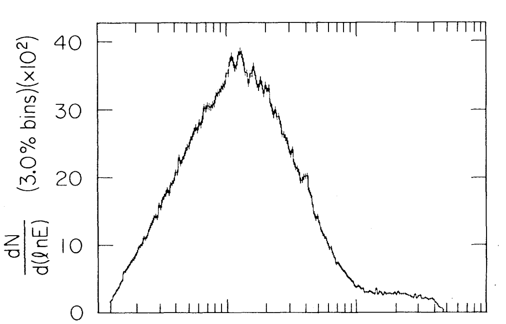

FIG. 1. The inclusive photon spectrum from the $\Upsilon(2S)$ hadronic decay selected with the cuts described in the text.

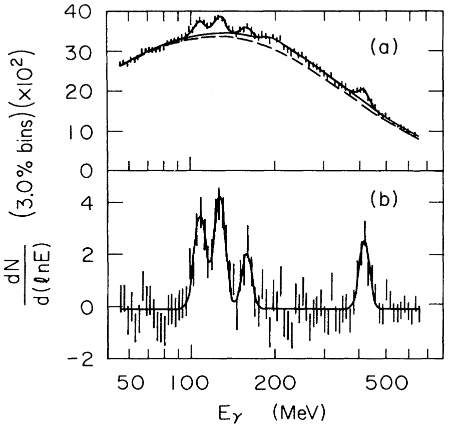

FIG. 2. (a) The fitted part of the photon energy spectrum. As described in the text, the curves represent the result of the fit. (b) The same distribution after background subtraction. Only error bars are shown for clarity. The data points are in the middle of the error bars.

number of $\Upsilon(2S)$ resonance decays, and ϵ_{tot} is the overall detection efficiency for photons of a given energy E. Included in this efficiency is the photon selection efficiency described above, the efficiency to detect the hadronic final state, and losses due to conversion of photons in the beam pipe and the chambers. The energies[9] of the observed lines, and the measured branching ratios are listed in Table I. The systematic error on photon energies is estimated by studying the effect of varying the criteria used in the photon selection, and from effects of small amounts of energy from interacting hadrons contaminating the photon shower. The systematic error in the branching ratio is largely due to uncertainties in estimating the photon detection efficiency, and uncertainties in fitting the shape of the background under the peaks in the photon spectrum. The relative strengths of the two transitions contributing to the secondary line are poorly determined. We therefore give the sum of the individual product branching ratios for the cascades from the transitions proceeding through the $^3P_2$ and $^3P_1$ states.

In Table I we also compare our measurements with the results of recent experiments.[2-4] There is reasonable agreement for the two lower energy lines, but our energy measurement for the line at $E \simeq 164$ MeV disagrees with the result of Ref. 2 and the preliminary result of Ref. 3 by about two standard deviations. This disagreement is surprising given the good agreement among the experiments on the lower energy lines. We know of no effects in our calibration that could produce a difference of this magnitude over this very small range (30 MeV), although the position of this line is somewhat more sensitive to the background assumptions employed as reflected in the larger systematic error assigned.

TABLE I. Photon lines from inclusive $\Upsilon(2S)$ decay.

	Photon energy (MeV)	Branching ratio (%)
This experiment[a]	$110.4 \pm 0.8 \pm 2.2$	$5.8 \pm 0.7 \pm 1.0$
	$130.6 \pm 0.8 \pm 2.4$	$6.5 \pm 0.7 \pm 1.2$
	$163.8 \pm 1.6 \pm 2.7$	$3.6 \pm 0.8 \pm 0.9$
	$\langle 430 \rangle$	$3.6 \pm 0.7 \pm 0.5$
Ref. 2	$108.2 \pm 0.3 \pm 2$	6.1 ± 1.4
	$128.1 \pm 0.4 \pm 3$	5.9 ± 1.4
	$149.4 \pm 0.7 \pm 5$	3.5 ± 1.4
	$427.0 \pm 10 \pm 8$	4.0 ± 1.0
Ref. 3	$109.5 \pm 0.7 \pm 1$	$10.2 \pm 1.8 \pm 2.1$
	$129.0 \pm 0.8 \pm 1$	$8.0 \pm 1.7 \pm 1.6$
	$(158.0 \pm 7.0 \pm 1)$[b]	$(4.4 \pm 2.3 \pm 0.9)$
Ref. 4	$109.0 \pm 1.0 \pm 1.0$	$8.9 \pm 3.0 \pm 1.2$
	$129.8 \pm 0.8 \pm 1.0$	$8.8 \pm 2.2 \pm 1.0$
	$147.2 \pm 1.4 \pm 1.0$	$4.0 \pm 1.8 \pm 1.0$

[a] The first error is statistical and the second is systematic. The angular photon distributions assumed are $1+\frac{1}{13}\cos^2\theta$ for the line at $E_\gamma \simeq 110$ MeV ($^3P_2$ hypothesis), $1-\frac{1}{3}\cos^2\theta$ for the line at $E_\gamma \simeq 131$ MeV ($^3P_1$ hypothesis), $1+\cos^2\theta$ for the line at $E_\gamma \simeq 164$ MeV ($^3P_0$ hypothesis). A flat distribution for the line at $E_\gamma \simeq 164$ MeV would lower the branching ratio by about 10%. For the secondary transitions at $\langle E_\gamma \rangle \simeq 430$ MeV a flat angular distribution is assumed.

[b] The third photon line at $E_\gamma = 158$ MeV is not clearly implied by the data.

With the mass values of the P states, deduced from the energies of the three primary lines, we calculate their center of gravity[15] to be $M_{\text{COG}} = 9899.5 \pm 2.0$ MeV/c^2. In order to further compare the observed masses of the P states to model predictions it has become customary to use the ratio

$$r = \frac{M(^3P_2) - M(^3P_1)}{M(^3P_1) - M(^3P_0)} \equiv \frac{D_2}{D_1}.$$

This ratio has the advantage that the systematic errors of the energy measurements partially cancel. We estimate the errors on the two mass differences D_2, D_1 to be $\sigma(D_2) = 2.5$ MeV/c^2 and $\sigma(D_1) = 3.7$ MeV/c^2, where the statistical and systematic errors have been added linearly. We obtain $r = 0.61 \pm 0.10$. While we lack the accuracy to distinguish between several quarkonium potential models[16] that give r in the range 0.4–0.8, our result disagrees with higher predictions of r (Eichten and Feinberg[17]).

In summary, we observe four photon lines in the inclusive photon spectrum obtained from hadronic decays of the $\Upsilon(2S)$. A coherent picture is obtained when these lines are interpreted as resulting from the $E1$ transitions $\Upsilon(2S) \to \gamma + {}^3P_{2,1,0}$ and ${}^3P_{2,1} \to \gamma\Upsilon(1S)$. By clearly resolving all three low-energy lines in the inclusive photon spectrum and observing the photon line around 164 MeV with a clear statistical significance, we obtain a complete measurement of the fine splitting of the $1^3P_{2,1,0}$ states of the Υ $b\bar{b}$ system.

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[a]Permanent address: Département de Physique de Particules Elémentaires, Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France.

[b]Present address: Institute for Particle Physics, University of California, Santa Cruz, Calif. 95064.

[1] For recent reviews of potential models see, for example, E. Eichten, in Proceedings of the Eleventh SLAC Summer Institute on Particle Physics, Stanford, California, 18–29 July 1983 (unpublished) and J. L. Rosner, Enrico Fermi Institute Report No. EFI 83/17, 1983 (unpublished). For several potential models, see A. Khare, Phys. Lett. **98B**, 385 (1981); S. N. Gupta, Phys. Rev. D **26**, 3305 (1982); W. Buchmüller, Phys. Lett. **112B**, 479 (1982); P. Moxhay and J. L. Rosner, Phys. Rev. D **28**, 1132 (1983); R. McClary and N. Byers, Phys. Rev. D **28**, 1692 (1983); M. Bander *et al.*, Phys. Lett. **134B**, 258 (1984); M. Bander *et al.*, Phys. Rev. D **29**, 2038 (1984); E. Eichten and F. Feinberg, Phys. Rev. D **23**, 2724 (1981).

[2] C. Klopfenstein *et al.*, Phys. Rev. Lett. **51**, 160 (1983).

[3] P. Haas *et al.*, Phys. Rev. Lett. **52**, 799 (1984).

[4] ARGUS Collaboration, in Proceedings of the Twenty Second International Conference of High Energy Physics, Leipzig, 1984, edited by A. Meyer and E. Wieczore (Akademie der Wissenschaften der DDR, Zeuth, to be published).

[5] M. Oreglia *et al.*, Phys. Rev. D **25**, 2259 (1982); M. Oreglia, Stanford Linear Accelerator Center Report No. 236, 1980 (unpublished), and Ph.D. thesis, Stanford University (unpublished).

[6] J. Gaiser, Stanford Linear Accelerator Center Report No. 255, 1982 (unpublished), and Ph.D. thesis, Stanford University (unpublished).

[7] The resolution is determined from Bhabha studies (the basis of our energy calibration), and the exclusive decays $\Upsilon(2S)\rightarrow\pi^0\pi^0\Upsilon(1S)$ and $\Upsilon(2S)\rightarrow\gamma\gamma\Upsilon(1S)$; these confirm our previous resolution values at SPEAR. The effect of the multiparticle hadronic environment is determined by Monte Carlo techniques using real events as background. The final resolution is somewhat sensitive to the cuts applied; with the cuts used for this analysis, we obtain the value given in the text.

[8] C. Edwards *et al.*, Stanford Linear Accelerator Center Report No. SLAC-PUB-3030, 1983 (unpublished); R. Nernst, Ph.D. thesis, Hamburg University, 1985 (unpublished).

[9] D. P. Barber *et al.*, Phys. Lett. **135B**, 498 (1984); A. S. Artamonov *et al.*, Phys. Lett. **137B**, 272 (1984); W. W. McKay *et al.*, Phys. Rev. D **29**, 2483 (1984).

[10] The photon energy scale is fixed by measuring Bhabha scattering events in the detector. Use of a linear relation for the energy calibration (to obtain Fig. 1 and Fig. 2) results in a small ($\simeq 2\%$) energy shift towards lower γ energies as determined from the observed mass values of reconstructed π^0 and η particles, whose decay photons are in the range of $\simeq 70$–300 MeV. The value of the $\Upsilon(2S)$-$\Upsilon(1S)$ mass difference used in the fit takes this shift into account. The final photon energies listed in Table I are corrected for the shift using an empirical correction of the form $E_{\text{cor}}=E'/[1-\alpha\ln(E'/E_{\text{beam}})]$. The parameter $\alpha=0.0137$ is determined from studies of the $\Upsilon(2S)\rightarrow\pi^0\pi^0l^+l^-$ channel; $E'=E_{\text{meas}}-E_{\text{excess}}$ is the measured photon energy after subtracting an average of $E_{\text{excess}}=3.5$ MeV excess energy from hadronic debris of the multihadron environment. E_{excess} is determined from studies with Monte Carlo photons. With this correction applied both π^0 and η masses as well as the $\Upsilon(2S)$-$\Upsilon(1S)$ mass difference assume their correct values. The overall energy scale uncertainty due to shower leakage is estimated to be $\simeq 1\%$. In the range of the measured photon energies (100–170 MeV) the energy dependence of all corrections produces less than a 1% variation in the scale.

[11] The photon energies of the secondary transitions are too closely spaced to be resolved by our detector.

[12] See, for example V. A. Novikov *et al.*, Phys. Rep. **41C**, 1 (1978).

[13] F. Pauss *et al.*, Phys. Lett. **130B**, 439 (1983).

[14] W. Walk *et al.*, Stanford Linear Accelerator Center Report No. SLAC-PUB-3575 and DESY Report No. DESY 85-019, 1985 (to be published).

[15] M_{COG} is defined as $M_{\text{COG}}=\sum(2J+1)M(^3P_J)/\sum(2J+1)$.

[16] Khare, Gupta, Buchmüller, Moxhay and Rosner, McClary and Byers, and Bander *et al.*, Ref. 1.

[17] Eichten and Feinberg, Ref. 1.