# Measurement of the Branching of $\Upsilon(2S) \to \pi^+\pi^- + \Upsilon(1S)$

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We have observed the decay of the $\Upsilon(2S)$ into the $\Upsilon(1S)$, obtaining a branching ratio of $19.1 \pm 3.1 \pm 2.9\%$ for the mode $\Upsilon(2S) \to \pi^+\pi^- + \Upsilon(1S)$. The di-pion mass spectrum peaks at large invariant mass, and the angular distribution of the di-pion system is consistent with $s$-wave production.

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The known members of the $\Upsilon$ family are three narrow states of mass 9.4, 10.0, and 10.3 GeV, and a recently discovered wider resonance at 10.5 GeV.[1,2] The narrow resonances, $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, are interpreted as bound triplet-$S$ states of a $b$ quark-antiquark pair. Observations of hadronic transitions between these states would confirm their relationship as members of the same family and add additional information about the dynamics of bound heavy quarks. The $2\pi$ transition between the $\Upsilon(2S)$ and $\Upsilon(1S)$ should be the most prominent of the hadronic transitions.

We have determined the branching ratio of the cascade decay $\Upsilon(2S) \to \pi^+\pi^- + \Upsilon(1S)$. Other measurements of this decay mode have required the detection of the decay $\Upsilon(1S) \to e^+e^-$ or $\Upsilon(1S) \to \mu^+\mu^-$

and are limited in precision by uncertainty in the leptonic branching ratio of the $\Upsilon(1S)$ and by the small numbers of events.[3,4] Our observation of a peak at the $\Upsilon(1S)$ in the missing mass $M_x$, recoiling against pion pairs detected in the $\Upsilon(2S)$ decays, yields a branching ratio measurement without these limitations. The observation of $\Upsilon(2S) \to \pi^+\pi^- + \Upsilon(1S)$, $\Upsilon(1S) \to e^+e^-$ or $\mu^+\mu^-$ gives the product of the two branching fractions. Combining this with our measurement of the branching fraction of the cascade decay determines the leptonic branching ratio of the $\Upsilon(1S)$.

The CLEO detector[1] at the Cornell Electron Storage Ring (CESR) has been used to detect the particles from the $\Upsilon(2S)$ decays. The momenta of the charged tracks are measured by cylindrical drift chambers in a 4 kG magnetic field. Electrons are identified by proportional tube shower counters that surround the central tracking detector and cover 45% of the total solid angle.[5] Muons are identified as penetrating particles in the outer detector.[6] An event trigger is formed if two or more charged tracks reach the outer detector or if more than 2 GeV of energy is detected in the shower counters.

A sample of hadronic events in the region of the $\Upsilon(2S)$ was obtained after cuts on vertex position, charged energy, and multiplicity, as described in Ref. 1. Within ±10 MeV in center-of-mass energy of the peak of the $\Upsilon(2S)$, we find 10 300 events from an integrated luminosity of 1360 $nb^{-1}$. These data contain a contribution from nonresonant $e^+e^-$ annihilation, which we measure to be 30.3 ± 2.7% of the total, leaving 7200 ± 300 $\Upsilon(2S)$ decays.

The missing mass recoiling against all combinations of opposite-sign pairs of tracks in the $\Upsilon(2S)$ events is shown in Fig. 1. Each track is assumed to be a pion. For comparison we also show in Fig. 1 the missing-mass distribution for like-sign pair combinations. A clear peak is observed at the mass of the $\Upsilon(1S)$, indicating the presence of the decay $\Upsilon(2S) \to \pi^+\pi^- + \Upsilon(1S)$.[7]

In order to extract the number of $\Upsilon(2S) \to \pi^+\pi^- + \Upsilon(1S)$ events, we fit the opposite-sign-pair $M_x$ distribution in Fig. 1. The fitting function is composed of two linear terms joined smoothly by a quadratic and a representation of the peak by two Gaussians of different widths. Two Gaussians are required to adequately fit the $\Upsilon(1S)$ peak region in a Monte Carlo simulation of the $2\pi$ cascade decay. The Monte Carlo simulation accurately reproduces drift-chamber resolution and track finding, multiple scattering, nuclear absorption,

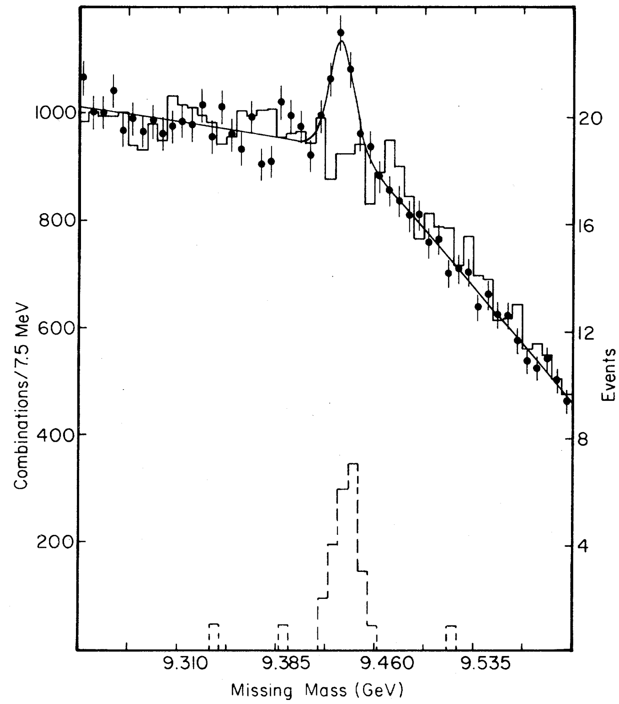


FIG. 1. The missing mass from $\Upsilon(2S) \to \pi\pi X$ recoiling against opposite-sign pions (data points) and same-sign pairs (solid-line histogram) normalized to the same total area. The fit is described in the text. The dashed line histogram represents the missing mass for events of the type $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to e^+e^-$ or $\mu^+\mu^-$ (right-hand scale).

and pion decay. The two pion momenta are generated as predicted by Yan.[8] The widths and relative areas of the two Gaussians are fixed to reduce the number of free parameters.

The fit shown in Fig. 1 has a $\chi^2$ of 36.1 for 43 degrees of freedom and yields 841 ± 130 events in the peak region. We have investigated the sensitivity of this result to different assumptions about the fitting function. A fit to a single unconstrained Gaussian and the same type of background function gives 13% fewer events in the peak region ($\chi^2 = 36.4$ for 42 degrees of freedom). The missing mass for cascade events with a leptonic decay of the $\Upsilon(1S)$ is also shown in Fig. 1 and the peak region may be represented by a single Gaussian of $\sigma = 9.3 \pm 2.1$ MeV. Fixing the width of a Gaussian at this value yields 9% fewer cascade events ($\chi^2 = 36.4$ for 43 degrees of freedom). Requiring the background to be the same shape as the like-sign missing-mass distribution of Fig. 1 gives a value 15% higher with a $\chi^2$ of 113 for 46 degrees of freedom. We conclude that the fit described in the previous paragraph yields a measurement with a systematic error of 15%.

We have also determined the number of $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ events by assuming the $\Upsilon(2S)$ to decay only via $\Upsilon(2S) \to \pi\pi\Upsilon(1S)$, including the $\pi^0\pi^0$-$\Upsilon(1S)$ mode at half the charged-pion rate, and $\Upsilon(2S) \to$ hadrons, where the $\Upsilon(2S) \to$ hadrons distribution was obtained from scaling our $\Upsilon(1S)$ decay spectrum and the $\pi\pi\Upsilon(1S)$ from Monte Carlo and $\Upsilon(1S)$ data. The observed background to either side of the $\Upsilon(1S)$ peak is well fit by this assumption after applying a single normalization factor of 1.05. This procedure gives essentially the same number of events in the $\Upsilon(1S)$ peak as does the fitting procedure described above.

The branching ratio of $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ is calculated from the observed number of cascade events and $\Upsilon(2S)$ decays, after correcting for the detection efficiency of the two pions. The detection efficiency is somewhat model dependent. If the two pions are produced as suggested in Ref. 8 or, equivalently, like the two pions in the analogous charmonium decay[9] $\psi' \to \pi^+\pi^- + \psi$, the di-pion acceptance is 61%. This model is substantially favored by our di-pion mass distribution as shown later. If a phase-space model is used to simulate the two-pion production, the acceptance is 59%. A Monte Carlo simulation also predicts that our detection efficiency for $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ events is essentially the same as for $\Upsilon(2S) \to$ hadrons and no correction is made for a difference in relative acceptance. We use 61% as the di-pion acceptance and find a branching ratio for $\Upsilon(2S) \to \pi^+\pi^- + \Upsilon(1S)$ of $0.191 \pm 0.031 \pm 0.029$. This result has not been corrected for the unknown leptonic branching ratio of the $\Upsilon(2S)$. If the leptonic branching ratio of $\Upsilon(2S)$ were the same as the $\Upsilon(1S)$, then the branching ratio for $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ would decrease to 0.174.

Our measurement of $B[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)]$ is in excellent agreement with the results of Refs. 3 and 4, which determine this branching fraction by measuring the product $B[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)] \times B[\Upsilon(1S) \to e^+e^-$ or $\mu^+\mu^-]$. With $B[\Upsilon(1S) \to e^+e^-] = 0.033 \pm 0.006$, $B[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)]$ is $0.194 \pm 0.054$ from Ref. 3 and $0.188 \pm 0.087$ from Ref. 4. The average value of $B[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)]$, including our measurement, is $0.191 \pm 0.026$.

We also have observed seventeen completely reconstructed events of the type $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to e^+e^-$ and nine events with $\Upsilon(1S) \to \mu^+\mu^-$. They were obtained from a visual scan of all events with six or fewer tracks in the inner detector in conjunction with substantial electromagnetic-shower energy or one or more muon candidates. A similar scan of equivalent integrated luminosity away from the $\Upsilon(2S)$ indicates that these events are free of background. The difference between the number of $e^+e^-$ and $\mu^+\mu^-$ events is the result of a trigger difference which favors showering tracks in our outer detector.

We obtain $B[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)]B[\Upsilon(1S) \to e^+e^-]$ from the seventeen $e^+e^-$ events, excluding the $\mu^+\mu^-$ events because of uncertainties in the triggering acceptance. The efficiency for detecting $\Upsilon(2S) \to \pi^+\pi^-e^+e^-$ is a product of the di-pion and $e^+e^-$ acceptances. We find a combined efficiency of 24% from the Monte Carlo simulation described previously. The total number of $\Upsilon(2S)$ decays is the observed number, $7200 \pm 300$, divided by the acceptance for $\Upsilon(2S) \to$ hadrons. We estimate by Monte Carlo simulation the combined hadronic event selection and triggering efficiency to be 75%. This gives $B[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)]B[\Upsilon(1S) \to e^+e^-] = 0.0074 \pm 0.0018$, again uncorrected for the $\Upsilon(2S)$ leptonic branching ratio.

From this result and $B[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)] = 0.191$, one finds $B[\Upsilon(1S) \to e^+e^-] = 3.9 \pm 1.1\%$. Other measurements of $B[\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)] \times B[\Upsilon(1S) \to e^+e^-]$ are $0.0063 \pm 0.0013$ (Ref. 3) and $0.0061 \pm 0.0026$ (Ref. 4). Combining these three values yields $B[\Upsilon(1S) \to e^+e^-] = 3.5 \pm 0.8\%$, to be compared with $3.0 \pm 0.8\%$, the current world average of direct measurements.[10] The new average for $B[\Upsilon(1S) \to e^+e^-]$ is then $3.3 \pm 0.6\%$.

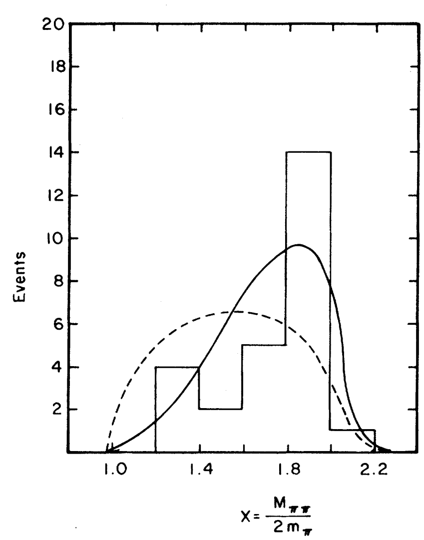


FIG. 2. The two-pion mass distribution from $\Upsilon(2S) \to \pi^+\pi^- + \Upsilon(1S)$. The solid curve is the prediction of Ref. 8 corrected for detector acceptance and the dashed curve is a phase-space model.

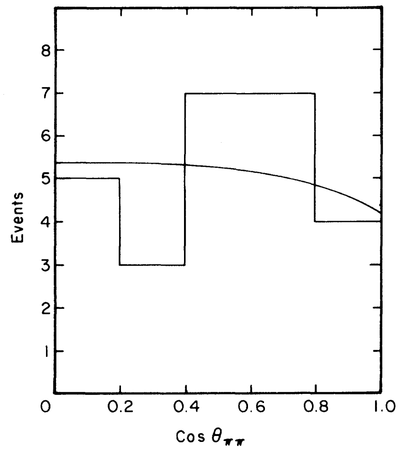


FIG. 3. The angular distribution of the $\pi\pi$ system with respect to the beam direction. The curve is an isotropic distribution corrected for detector acceptance.

The di-pion mass has been observed to peak at large values of $x=M_{\pi\pi}/2m_\pi$ in the decay[9] $\psi' \rightarrow \pi^+\pi^-\psi$. This has been explained by Brown and Cahn[11] and, more recently, by Yan.[8] In Fig. 2 we plot $x$ for the 26 events and observe a similar preference for large $M_{\pi\pi}$. Our acceptance in $M_{\pi\pi}$ is approximately flat and is not responsible for the peaking. The prediction of Ref. 8, corrected for detector acceptance and resolution, is given in Fig. 2 and agrees with the data. The distribution expected for phase space is also shown and clearly disagrees with the data. Similar conclusions have been reached in Ref. 3.

The angular distribution of the $\pi\pi$ system with respect to the beam axis is shown in Fig. 3. The curve is an isotropic angular distribution corrected for detector acceptance. Our data are consistent with $s$-wave production and decay of the $\pi\pi$ system, as has been observed in the analogous charmonium decay.[9]

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[1]D. Andrews *et al.*, Phys. Rev. Lett. 45, 219 (1980), and references therein.

[2]G. Finocchiaro *et al.*, Phys. Rev. Lett. 45, 222 (1980).

[3]G. Mageras *et al.*, to be published.

[4]B. Niczyporuk *et al.*, Phys. Lett. 100B, 95 (1981).

[5]C. Bebek *et al.*, Phys. Rev. Lett. 46, 84 (1981).

[6]K. Chadwick *et al.*, Phys. Rev. Lett. 46, 88 (1981).

[7]The mass of $\Upsilon$(1S) as measured at CESR is 9.433 GeV, with a systematic uncertainty of 0.030 GeV.

[8]T. M. Yan, Phys. Rev. D 22, 1652 (1980).

[9]T. Himel, Ph.D. thesis, SLAC Report No. 223, unpublished. M. Oreglia *et al.*, Phys. Rev. Lett. 45, 959 (1980).

[10]B. Niczyporuk *et al.*, Phys. Rev. Lett. 46, 92 (1981). Lepton universality is assumed.

[11]L. Brown and R. Cahn, Phys. Rev. Lett. 35, 1 (1975).