PHYSICAL REVIEW D VOLUME 30, NUMBER 7 1 OCTOBER 1984

High-statistics study of $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$

D. Besson, J. Green, R. G. Hicks,* R. Namjoshi, F. Sannes, P. Skubic,† A. Snyder, and R. Stone
Rutgers University, New Brunswick, New Jersey 08854

A. Chen, M. Goldberg, N. Horwitz, A. Jawahery, P. Lipari, G. C. Moneti, C. G. Trahern, and H. van Hecke
Syracuse University, Syracuse, New York 13210

M. S. Alam, S. E. Csorna, L. Garren, M. D. Mestayer, R. S. Panvini, and Xia Yi
Vanderbilt University, Nashville, Tennessee 37235

P. Avery, C. Bebek, K. Berkelman, D. G. Cassel, J. W. DeWire, R. Ehrlich, T. Ferguson, R. Galik, M. G. D. Gilchriese, B. Gittelman, M. Halling, D. L. Hartill, S. Holzner, M. Ito, J. Kandaswamy, D. L. Kreinick, Y. Kubota, N. B. Mistry, F. Morrow, E. Nordberg, M. Ogg, A. Silverman, P. C. Stein, S. Stone, D. Weber, and R. Wilcke‡
Cornell University, Ithaca, New York 14853

A. J. Sadoff
Ithaca College, Ithaca, New York 14850

R. Giles, J. Hassard, M. Hempstead, K. Kinoshita, W. W. MacKay, F. M. Pipkin, and Richard Wilson
Harvard University, Cambridge, Massachusetts 02138

P. Haas, T. Jensen, H. Kagan, and R. Kass
Ohio State University, Columbus, Ohio 43210

S. Behrends, K. Chadwick, J. Chauveau,§ T. Gentile, Jan M. Guida, Joan A. Guida, A. C. Melissinos, S. L. Olsen, G. Parkhurst, D. Peterson, R. Poling, C. Rosenfeld, E. H. Thorndike, and P. Tipton
University of Rochester, Rochester, New York 14627
(Received 5 March 1984)

A detailed investigation of the decay $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ has been made from 128 000 $\Upsilon(2S)$ decays observed in the CLEO detector at the Cornell Electron Storage Ring (CESR). We find this branching ratio to be $(19.1\pm1.2\pm0.6)\%$. The properties of the $\pi\pi$ system have been studied using 491 exclusive events of the type $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S)\to e^+e^-$ or $\mu^+\mu^-$. Assuming e-μ universality we find $B(\Upsilon(1S)\to\mu^+\mu^-)=(2.84\pm0.18\pm0.20)\%$. A search for $\Upsilon(2S)\to\eta\Upsilon(1S)$ yields an upper limit of 1% at the 90% confidence level for this branching ratio. We have also searched for $[\Upsilon(2S)$ or $\Upsilon(3S)]\to\pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S)\to$noninteracting particles.

I. INTRODUCTION

Within the Υ family of resonances many hadronic transitions ($\pi\pi,\eta,3\pi,\omega$) are possible.[1] Quantum chromodynamics describes these transitions as the emission of soft gluons which subsequently form hadrons. Since the energy available in these transitions is small, perturbative methods are not applicable. Gottfried has suggested that a multipole expansion of the color gauge field for heavy-quark systems such as the Υ family will yield a description of the hadronic transitions.[2,3] Yan[4] and Kuang and Yan[5] have explored this suggestion and have made predictions for the transition rates and properties of some of the hadronic transitions among the Υ states.

Among the many possible hadronic transitions only the following $\pi\pi$ transitions have been observed:

$$\begin{aligned}
\Upsilon(2S)\ &\to\pi^+\pi^-\Upsilon(1S) && \text{(Refs. 6--11)},\\
&\to\pi^0\pi^0\Upsilon(1S) && \text{(Refs. 9,11)},\\
\Upsilon(3S)\ &\to\pi^+\pi^-\Upsilon(1S) && \text{(Refs. 12,13)},\\
&\to\pi^0\pi^0\Upsilon(1S) && \text{(Ref. 13)},\\
\Upsilon(3S)\ &\to\pi^+\pi^-\Upsilon(2S) && \text{(Ref. 13)},\\
&\to\pi^0\pi^0\Upsilon(2S) && \text{(Ref. 13)}.
\end{aligned}$$

The measured branching ratios for these transitions agree with the theoretical predictions. A comparison is given in Sec. IV. In this paper we present a high-statistics study of $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$, including a new measurement of the branching ratio (Sec. IV). Using a large sample (491) of the exclusive events $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S),\Upsilon(1S)\to e^+e^-$ or $\mu^+\mu^-$, we compare the properties of the dipion system to theoretical predictions and to the dipions observed in $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ and $\psi'\to\pi^+\pi^-\psi$ (Sec. V).

We have also searched for $\Upsilon(2S)\to\eta\Upsilon(1S)$ and have determined an upper limit to this branching fraction (Sec. VI). Finally, using the $\pi^+\pi^-$ from $\Upsilon(2S)$ or $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ as a signature, we have searched for $\Upsilon(1S)$ decays to particles which are not visible in our detector, such as neutrinos or supersymmetric[14] particles.

II. THE CLEO DETECTOR

The CLEO detector has been described in detail.[15] We present only a brief summary and describe some special modifications made during the $\Upsilon(2S)$ data-taking period. The charged-particle tracking chambers in the CLEO detector are a three-layer multiwire proportional chamber immediately surrounding the interaction region beam pipe and a 17-layer drift chamber. Both are contained in a superconducting solenoid. During the $\Upsilon(2S)$ running period discussed in this paper a thin (10% of a radiation length) lead photon converter was placed between the proportional chamber and the drift chamber and the solenoid was operated at 0.35 T (the normal field is 1.0 T). The purpose of the converter was to increase the photon conversion probability, and the field was lowered to enhance the detection efficiency of the electron-positron pairs. Surrounding the solenoid are eight identical modules containing drift chambers, dE/dx proportional chambers, time-of-flight scintillation counters, and lead proportional tube shower counters. These modules are in turn enclosed by iron interspersed with drift chambers for muon detection.

An event trigger may be formed from combinations of track information in the inner chambers, hits in the time-of-flight scintillation counters, and energy deposited in the shower counters. A typical hadronic trigger requires three or more tracks in the inner chambers and hits in two modules containing the scintillation counters. Another trigger requires two or more tracks in coincidence with scintillation counters in two modules separated by 180° in azimuth. While one or both of these triggers are highly efficient for most hadronic events they have substantially reduced efficiency for events with only two low-momentum tracks, such as $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$, where the $\Upsilon(1S)$ may decay into particles not observed in our detector. This is discussed in more detail in Sec. VII.

III. THE DATA SAMPLE

Hadronic events were selected by requiring three or more charged tracks with combined energy greater than 30% of the available center-of-mass energy. The reconstructed vertex was also required to be within ±5 cm along the colliding beam direction and ±2 cm in each of the transverse directions.

Data were accumulated at the $\Upsilon(2S)$ [defined to be within ±3.8 MeV/c^2 of the $\Upsilon(2S)$ mass] and in the nearby continuum below the $\Upsilon(2S)$ (see Table I). We have not included a much smaller sample of $\Upsilon(2S)$ data for which results have already been published.[7] The number of observed hadronic $\Upsilon(2S)$ decays is found to be $128\,000\pm1250$ after subtraction of the continuum contribution.

TABLE I. The integrated luminosity, observed number of hadronic events, and the visible hadronic cross sections.

	No. of events	$\int L\,dt$ (pb^{-1})	$\sigma_{\rm vis}$ (nb)
At $\Upsilon(2S)$	200665	22.17	9.051 ± 0.020
Continuum	3924	1.17	3.354 ± 0.054

IV. THE MEASUREMENT OF THE BRANCHING RATIO FOR $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$

The branching ratio for $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ is obtained from the distribution of mass recoiling against oppositely charged tracks, taken to be pion pairs (Fig. 1). A clear peak is visible at the mass[16] of the $\Upsilon(1S)$. In order to extract the signal a least-squares fitting procedure is used. The background is obtained by fitting the distribution with a smooth function excluding the region of the peak. The signal shape is well represented by two superposed Gaussians of different rms resolutions and slightly different mean values. Two Gaussians were necessary because the resolution in missing mass depends on the $\pi\pi$ mass and decay angles. The widths and relative areas of the two Gaussians were determined from a full Monte Carlo simulation of the $\pi\pi$ decay in the CLEO detector. This simulation generated raw data tapes which were analyzed as if they were real data. In Fig. 2 we show the missing-mass distribution after subtracting the background and compare it with our Monte Carlo simulation. The best fit, shown as the solid line in Fig. 1, yields a χ^2 of 124 for 128 degrees of freedom. We have tried variations of the fitting function including a single Gaussian and two Gaussians of different resolutions but the same mean. We have also varied the form of the background function. A simple direct subtraction of the background was also tried. From this study we estimate the error resulting from the form of the fitting function. We have added this error in quadrature with the larger statistical error obtained from the least-squares fit. The final result for the number of observed $\pi^+\pi^-$ decays is $14\,600\pm500$.

The branching ratio is determined from the formula

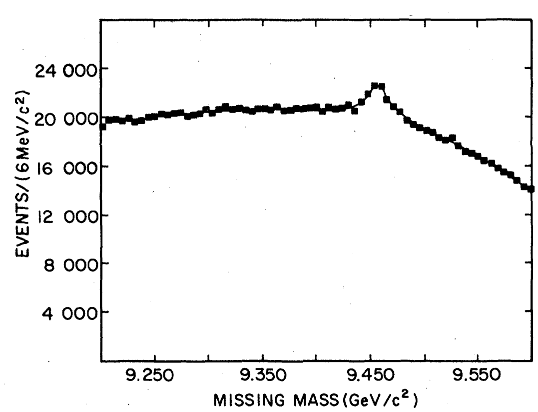

FIG. 1. The missing-mass distribution recoiling against $\pi^+\pi^-$ in $\Upsilon(2S)$ decays.

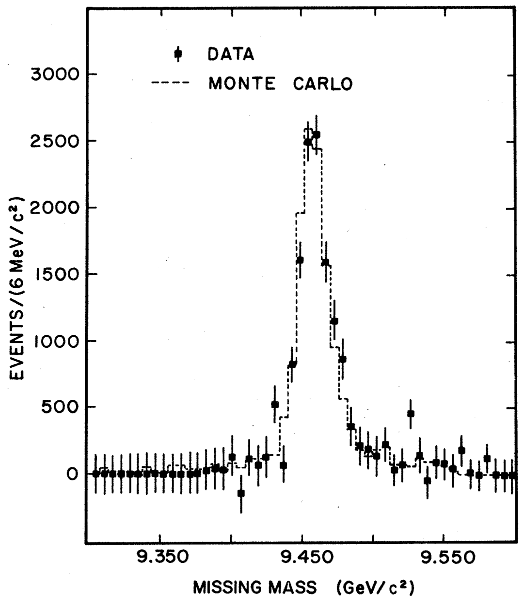

FIG. 2. The missing-mass distribution after subtraction of the background and the comparison with our Monte Carlo simulation.

$$B(\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S))=\frac{N\epsilon_{2S}(1-3B_{2S})}{N_{2S}\epsilon_{1S}},$$

where N_{2S} is the observed number of $\Upsilon(2S)$ decays ($128\,000\pm1250$), N is the number of $\pi^+\pi^-$ events ($14\,600\pm500$), ϵ_{2S} is the acceptance for hadronic $\Upsilon(2S)$ decays (0.87 ± 0.01), ϵ_{1S} is the dipion acceptance for $\pi^+\pi^-\Upsilon(1S)$ decays (0.49 ± 0.01), and B_{2S} is[17] $B(\Upsilon(2S)\to\mu^+\mu^-)=(1.9\pm1.3)\%$.

The acceptances for hadronic decays involving the $\Upsilon(1S)$ and $\Upsilon(2S)$ are obtained from a Monte Carlo simulation.[18] Dipion events are generated using the model described in Sec. V, which agrees with our measurements. The errors shown above for these quantities are statistical only, resulting from a finite sample of Monte Carlo events. In addition there is a systematic error in the acceptance which we estimate to be $\pm5\%$ for the $\Upsilon(1S)$ and $\pm7\%$ for the $\Upsilon(2S)$. The larger error in the case of the $\Upsilon(2S)$ results from uncertainties in the characteristics of those Monte Carlo events which are photon transitions to P states from the $\Upsilon(2S)$. The error in the *ratio* of acceptances which appears in the formula for the branching ratio is $\pm3\%$, which is smaller because the acceptance for the $\pi^+\pi^-\Upsilon(1S)$ events is primarily determined by the decay of the $\Upsilon(1S)$. The factor in the formula involving the leptonic branching ratio of the $\Upsilon(2S)$ corrects for the unobserved leptonic decays of the $\Upsilon(2S)$. Finally, there is a small correction not given in the formula above for the small contribution $[(0.3\pm0.2)\%]$ from $\pi^+\pi^-$ events in the $\Upsilon(2S)$ hadronic sample. The final result is $B(\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S))=(19.1\pm1.2\pm0.6)\%$.

In Table II we have summarized the existing measurements of $\pi^+\pi^-$ transitions. Although $\pi^0\pi^0$ measurements have also been made they are much less precise than the $\pi^+\pi^-$ data. In Table II we also compare the measurements to the predictions of Kuang and Yan.[5] The theoretical predictions depend upon the particular potential model used and hence there is a range of predictions. In general the agreement between data and theory is good, the most striking success being the confirmed prediction of a smaller branching fraction for $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ than for $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$.

TABLE II. A comparison of the different measurements of dipion transitions and theory. A value of $B(\Upsilon(1S)\to\mu^+\mu^0)=3.0\%$ was used to extract the $\pi^+\pi^-$ branching ratios from measurements of product branching ratios. Statistical and systematic errors were added in quadrature.

Reaction	Group	Branching ratio (%)	Reference
$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$	CLEO	$19.1\pm1.2\pm0.6$	This expt.
	CLEO	$21.2\pm2.6\pm2.1$	12
	CUSB	21.0 ± 4.3	6
	CUSB	18.9 ± 2.6	11
	LENA	20.3 ± 8.7	8
	ARGUS	$17.9\pm0.9\pm2.1$	10
	Average	19.1 ± 1.0	
	Theory	16.8–19.4	5
$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$	CLEO	$4.9\pm0.9\pm0.5$	12
	CUSB	4.5 ± 1.5	13
	Average	4.8 ± 0.8	
	Theory	1.3– 3.4	5
$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$	CUSB	3.3 ± 2.1	13
	Theory	1.3– 2.0	5

V. THE EXCLUSIVE EVENTS

Exclusive events of the type $\Upsilon(2S)\to\pi^+\pi^-e^+e^-$ or $\pi^+\pi^-\mu^+\mu^-$ were also extracted from our data sample. We required candidates for these processes to have an observed charged energy greater than 6.0 GeV, a multiplicity of 4 or 5, and a missing mass recoiling against the $\pi\pi$ pair within ±110 MeV/c^2 (about ±11 standard deviations) of the $\Upsilon(1S)$ mass. The angle between each lepton track and the dipion direction was required to be greater than 20 degrees in order to eliminate radiative events which contain a converted photon. Physicists scanned all candidates using a computer-reconstructed picture of the event. Data at the $\Upsilon(2S)$ and on the continuum were both scanned. Events were classified as containing either e^+e^- or $\mu^+\mu^-$ based on information from shower counters and muon chambers in the detector. Table III contains the number of observed events with electrons and muons at the $\Upsilon(2S)$. No events were found on the continuum and we conclude that backgrounds are negligible (less than 40 events at 90% confidence level). In Fig. 3 we show the distribution of mass recoiling against the dipion for these events and compare it to our Monte Carlo simulation. Again the agreement is excellent.

We have used the 491 observed events to study the properties of the $\pi\pi$ system. In particular, we have measured the dipion mass distribution, the angular distribution of the dipion system with respect to the beam direction, and the angular distribution of the π^+ with respect

TABLE III. The number of $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S)\to l^+l^-$ events and the product branching ratios.

	$\pi\pi ee$	$\pi\pi\mu\mu$
Observed number of events	248	243
Number in fiducial region	180	201
Acceptance	0.21	0.23
Corrected number of events	826±68	864±67
$B(\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S))B(\Upsilon(1S)\to l^+l^-)$	$(5.3\pm0.5)\times10^{-3}$	$(5.5\pm0.5)\times10^{-3}$
$B(\Upsilon(1S)\to e^+e^-)$	2.8±0.3	
$B(\Upsilon(1S)\to\mu^+\mu^-)$		2.9±0.3

to the Υ direction in the dipion rest frame. The acceptance-corrected distribution of the dipion invariant mass divided by twice the pion mass is shown in Fig. 4. Previous data had already shown that the mass distribution is strongly peaked at high mass and is similar to that observed[19] in $\psi'\to\pi^+\pi^-\psi$. Brown and Cahn[20] and Morgan and Pennington[21] were the first to use PCAC (partial conservation of the axial-vector current) and current algebra to explain the mass distribution observed in the ψ' decay. By assuming that PCAC and the multipole expansion are compatible, Yan[4,22] has shown that the mass distribution is given by

$$\frac{dN}{dM_{\pi\pi}}=K(M_{\pi\pi}{}^2-4M_\pi{}^2)^{1/2}\left[A^2(M_{\pi\pi}{}^2-2M_\pi{}^2)^2+\tfrac{1}{3}AB(M_{\pi\pi}{}^2-2M_\pi{}^2)\left[(M_{\pi\pi}{}^2-4M_\pi{}^2)+2(M_{\pi\pi}{}^2+2M_\pi{}^2)\frac{K_0{}^2}{M_{\pi\pi}{}^2}\right]\right.$$
$$+\tfrac{1}{20}B^2\left[(M_{\pi\pi}{}^2-4M_\pi{}^2)^2+\tfrac{4}{3}(M_{\pi\pi}{}^2-4M_\pi{}^2)(M_{\pi\pi}{}^2+6M_\pi{}^2)\frac{K_0{}^2}{M_{\pi\pi}{}^2}\right.$$
$$\left.\left.+\tfrac{8}{3}(M_{\pi\pi}{}^4+2M_\pi{}^2M_{\pi\pi}{}^2+6M_\pi{}^4)\frac{K_0{}^4}{M_{\pi\pi}{}^4}\right]\right],$$

where $M_{\pi\pi}$ is the dipion invariant mass, M_π is the pion mass,

$$K_0-(M'^2+M_{\pi\pi}{}^2-M^2)/(2M')\ ,$$

and

$$K=[((M'+M)^2-M_{\pi\pi}{}^2)((M'-M)^2-M_{\pi\pi}{}^2)]^{1/2}\ .$$

M is the mass of the $\Upsilon(1S)$ and M' is the mass of the $\Upsilon(2S)$. A and B are free parameters. The data[25] for $\psi'\to\pi^+\pi^-\psi$ and previous results[6,7,8] on $\Upsilon(2S)$

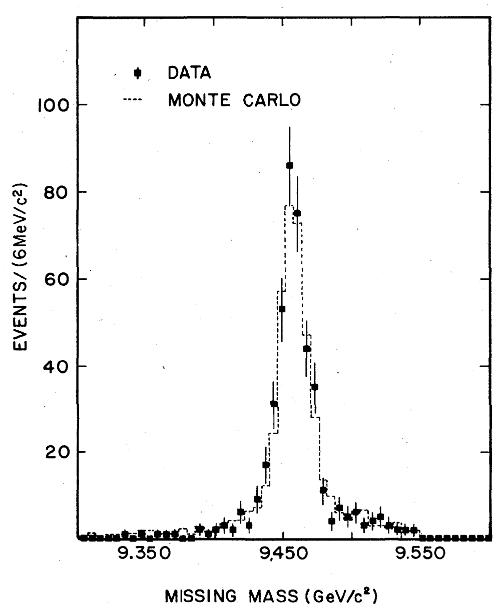

FIG. 3. The missing-mass distribution for exclusive events and the comparison with our Monte Carlo simulation.

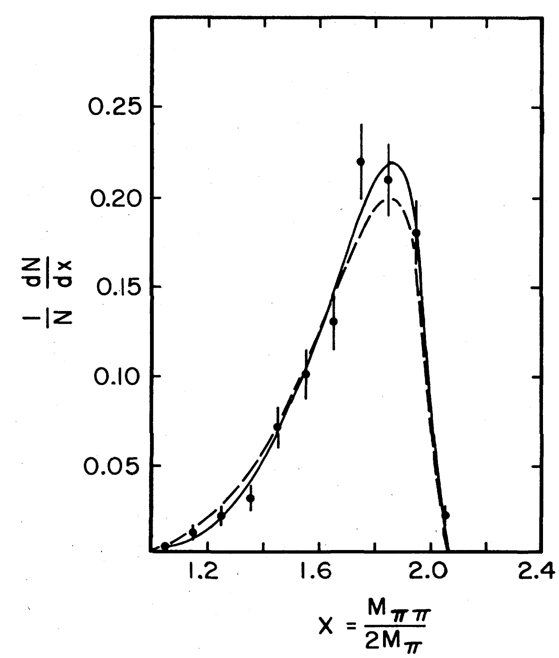

FIG. 4. The dipion invariant-mass distribution for the $\Upsilon(2S)\to\pi^+\pi^-(e^+e^-$ and $\mu^+\mu^-)$ events.

$\to\pi^+\pi^-\Upsilon(1S)$ were consistent with $B=0$ in the above formula. We have determined the ratio B/A from the data shown in Fig. 4 to be -0.18 ± 0.06. The solid line in Fig. 4 is the result of this fit. The dashed line in Fig. 4 represents the $B=0$ case.

Other predictions for the shape of the dipion mass distribution have been made by Voloshin and Zakharov[23] and Novikov and Shifman.[24] The former predicts

$$\frac{dN}{dM_{\pi\pi}}=K(M_{\pi\pi}{}^2-4M_\pi{}^2)^{1/2}(M_{\pi\pi}{}^2-\lambda M_\pi{}^2)^2$$

and the latter

$$\frac{dN}{dM_{\pi\pi}}=K(M_{\pi\pi}{}^2-4M_\pi{}^2)^{1/2}$$
$$\times[M_{\pi\pi}{}^2-\kappa(M'-M)^2(1+2M_\pi{}^2/M_{\pi\pi}{}^2)]^2$$
$$+O(\kappa^2\text{ terms})\,,$$

where κ is expected to be about 0.1. We find $\lambda=3.2\pm0.4$ and $\kappa=0.15\pm0.02$. The ARGUS group finds $\lambda=2.6\pm0.5$ and $\kappa=0.12\pm0.02$, in agreement with our results.[10] The resulting fits to the mass distribution are essentially equivalent to the solid line in Fig. 4 in both cases. The peaking observed at large dipion mass in $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ is in sharp contrast to the mass distribution observed[12,13] in $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$, where[12] B/A is -6.7 indicating an almost uniform mass distribution. As yet there is no adequate explanation for this difference.

In Fig. 5 we show the polar-angle distribution of the dipion momentum vector with respect to the beam (e^+) direction. The polar-angular distribution of the π^+ with respect to the recoil Υ direction in the dipion rest frame is given in Fig. 6. Acceptance corrections have been made in each case. Both distributions are consistent with isotropy, which is expected if the pions are emitted in an S-wave state. Similar results have been obtained in the case

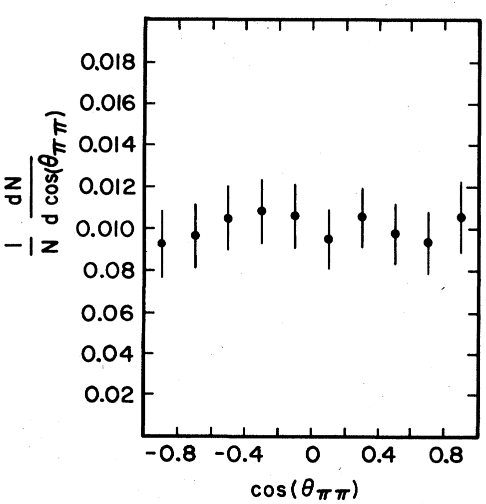

FIG. 5. The polar-angular distribution of the dipion system with respect to the colliding beams axis.

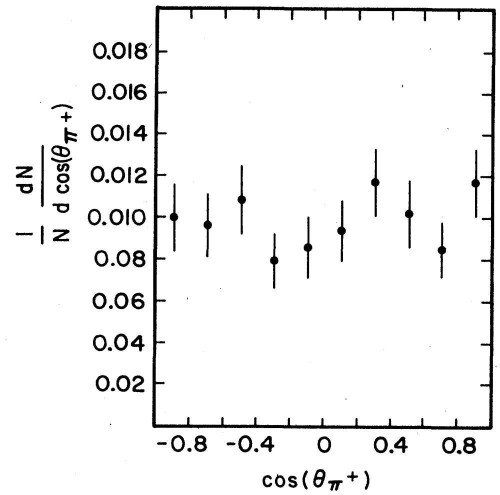

FIG. 6. The polar-angular distribution of the π^+ with respect to the $\Upsilon(1S)$ direction in the dipion rest frame.

of the $\psi'\to\pi^+\pi^-\psi$ decays.

The exclusive events permit the measurement of the leptonic branching ratio of the $\Upsilon(1S)$ and a check of e-μ universality in Υ decay. To control acceptance corrections better, we have restricted the lepton tracks to a fiducial region in the detector. The remaining number of events is also given in Table III. The acceptance is determined separately for the ee and $\mu\mu$ events because of trigger differences between the two kinds of events and the increased probability that ee events will radiate a photon which may convert and be detected in the inner chambers. The acceptances, which include the dipion acceptance, are given in Table III. After acceptance corrections the number of ee and $\mu\mu$ events are the same within the statistical errors, indicating the validity of e-μ universality in Υ decay. The product branching ratios are given in Table III. Using the value of the branching ratio for $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ from Sec. IV and assuming e-μ universality, we find the leptonic branching ratio of the $\Upsilon(1S)$ to be $(2.84\pm0.18\pm0.20)\%$. This result agrees with our recent direct measurement[17] of $(2.7\pm0.3\pm0.3)\%$.

VI. A SEARCH FOR $\Upsilon(2S)\to\eta\Upsilon(1S)$

The decay $\psi'\to\eta\psi$ has been observed with a branching ratio[25] of $(2.8\pm0.6)\%$. The η decay rate from the $\Upsilon(2S)$ is expected to be suppressed because of a smaller matrix element and the reduced phase space available relative to ψ' decay. Yan[4] predicts the branching ratio to be less than 0.1%.

The search consists of looking for $\pi^+\pi^-e^+e^-$ or $\pi^+\pi^-\mu^+\mu^-$ events with a missing mass recoiling against the dipion in the region expected for the decay $\Upsilon(2S)\to\eta\Upsilon(1S)$, $\eta\to\pi^+\pi^-\pi^0$ or $\eta\to\pi^+\pi^-\gamma$ and the $\Upsilon(1S)\to e^+e^-$ or $\mu^+\mu^-$. Two events are found in this region which is consistent with the broad tail expected from $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$. After correcting for acceptance and the unobserved decay modes of the η, we find $B(\Upsilon(2S)\to\eta\Upsilon(1S))<1.0\%$ at the 90% confidence level.

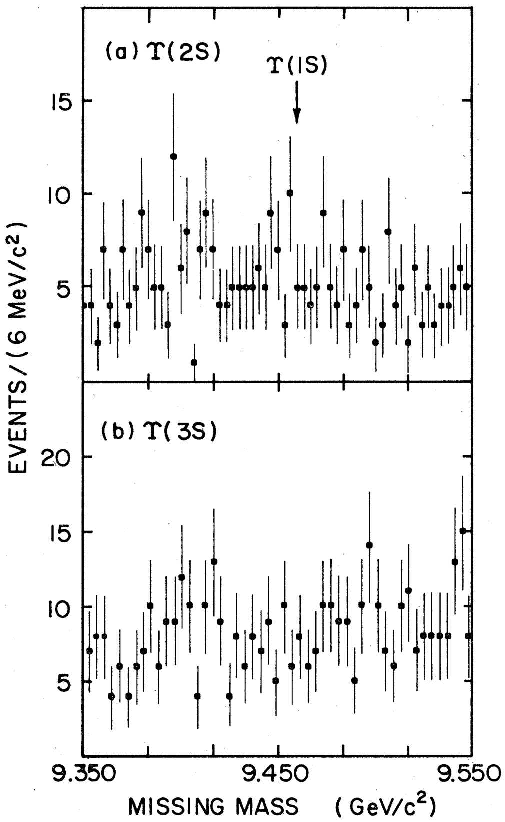

FIG. 7. The missing-mass distribution for (a) $\Upsilon(2S)\to\pi^+\pi^-+$unobserved particles, and (b) $\Upsilon(3S)\to\pi^+\pi^-$ +unobserved particles.

VII. A SEARCH FOR $\Upsilon(1S)$ $\to$ WEAKLY INTERACTING PARTICLES

Supersymmetric theories[14] contain particles which are partners to the known fundamental fermions and bosons. If these theories are correct, the $\Upsilon(1S)$ can decay into a photino and an antigravitino which would not interact in our detector. In order to search for events of this type we use the $\pi^+\pi^-$ from $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ as an identifying signature and require that no other tracks be found. Our detection efficiency for events of this type is very low, primarily because the soft pions are often absorbed in the magnet coil before reaching the scintillation counters required for an event trigger. We have used the pions from the $\pi\pi ee$ and $\pi\pi\mu\mu$ events to determine the trigger efficiency. For this measurement, data previously published at the $\Upsilon(3S)$ were also used,[12] since the pion momentum spectrum is somewhat harder for the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ decays. The overall acceptance including the dipion acceptance (but not the $\pi\pi$ branching fraction) was found to be 0.08 ± 0.035 for the $\Upsilon(3S)$ decays and 0.007 ± 0.004 for the $\Upsilon(2S)$ decays.

Backgrounds to the process of interest include events in which leptons from real $\pi\pi$ transitions are not detected, low-multiplicity events from two-photon collisions, beam-gas interactions, and interactions of the beam with the vacuum chamber. In Figs. 7(a) and 7(b) we show the distribution of mass recoiling against the dipions measured from the $\Upsilon(2S)$ and $\Upsilon(3S)$ decays, respectively. No peak is observed above the background. Using the known resolution, we find 95% confidence level upper limits for the $\Upsilon(1S)\to$ weakly interacting particles of 8% from the $\Upsilon(3S)$ events and 5% from the $\Upsilon(2S)$ events.

These limits may be used to determine a lower limit to the mass of the gravitino using the formula[14]

$$\frac{\Gamma(\Upsilon(1S)\to\text{photino}+\text{antigravitino})}{\Gamma(\Upsilon(1S)\to\mu^+\mu^-)}=\frac{3\kappa^2 M_{1S}{}^4}{2m_{\text{grav}}{}^2}\,,$$

where m_{grav} is the gravitino mass, M_{1S} is the $\Upsilon(1S)$ mass, and κ is 4×10^{-19} $(\text{GeV}/c^2)^{-1}$. Our upper limit implies that the gravitino mass is greater than 3×10^{-8} eV/c^2. The limit obtained from ψ decays[26] is 1.5×10^{-8} eV/c^2.

ACKNOWLEDGMENTS

It is a pleasure to thank the CESR operating staff for their dedicated efforts. Discussions with T.-M. Yan were particularly helpful. One of us (M.G.D.G.) would like to thank the Alfred P. Sloan Foundation for support. This work was supported by the National Science Foundation and the Department of Energy.

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[*] Present address: Singer-Kearfott, Little Falls, NJ 07424.
[†] Present address: University of Oklahoma, Norman, OK 73019.
[‡] Present address: EP division, CERN, CH-1211 Geneva 23, Switzerland.
[§] Permanent address: LPC, College de France, Paris 75231 Cedex 05, France.
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