Improved Measurement of Branching Fractions for $\pi\pi$ Transitions among $\Upsilon(nS)$ States

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(Dated: September 6, 2008)

Abstract

Using samples of \((5.93 \pm 0.10) \times 10^6\) \(\Upsilon(3S)\) decays and \((9.11 \pm 0.14) \times 10^6\) \(\Upsilon(2S)\) decays collected with the CLEO detector, we report improved measurements of the branching fractions for the following five transitions: 

\[
\begin{align*}
B(\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-) &= (4.46 \pm 0.01 \pm 0.13)\%, \\
B(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-) &= (18.02 \pm 0.02 \pm 0.61)\%, \\
B(\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^0\pi^0) &= (2.24 \pm 0.09 \pm 0.11)\%, \\
B(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^0\pi^0) &= (8.43 \pm 0.16 \pm 0.42)\% \\
B(\Upsilon(3S) \rightarrow \Upsilon(2S)\pi^0\pi^0) &= (1.82 \pm 0.09 \pm 0.12)\%.
\end{align*}
\]

In each case the first uncertainty reported is statistical, while the second is systematic.

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Hadronic transitions among heavy quarkonium states provide an excellent testing ground for non-perturbative Quantum Chromodynamics (QCD) [1]. They are generally understood to proceed by the emission and hadronization of low momentum gluons [2], and their investigation is one of few possible laboratories for the study of the low-\(q^2\) hadronization process. The study of such transitions in the bottomonium \((bb)\) system is particularly advantageous because of the non-relativistic nature of the system and the richness of the spectrum of states below open-bottom threshold. (See Figure 1.)

For the first 22 years after the observation of hadronic transitions among bottomonium states by LENA [3] and CUSB [4], only the six \(\pi\pi\) transitions among the vector \(\Upsilon(nS)\) bottomonia were known. CLEO has recently observed three other examples of hadronic transitions in bottomonium: \(\chi_{b1,2}(2P \rightarrow \omega \Upsilon(1S))\) [5], \(\chi_b(2P) \rightarrow \pi\pi \chi_b(1P)\) [6] and \(\Upsilon(2S) \rightarrow \eta \Upsilon(1S)\) [7]. Very recently, the BaBar Collaboration has reported new measurements of several hadronic transitions in the bottomonium system using bottomonium states produced in ISR while running at the \(\Upsilon(4S)\) resonance [8].

In this Article we report improved measurements of the branching fractions for \(\pi\pi\) transitions among the vector states of the bottomonium system. Dipion transitions from \(\Upsilon(3S)\) to the lower vector states (\(\Upsilon(2S)\), \(\Upsilon(1S)\)) and from \(\Upsilon(2S)\) to \(\Upsilon(1S)\) have been of interest ever since their first observation in 1982 [9]. There has recently been a resurgence of interest in dipion transitions following the observation by Belle [11] and BaBar [12] of dipion transitions from the bottomonium resonances \(\Upsilon(4S)\) and \(\Upsilon(5S)\) to lower bottomonium states, of the new state \(\Upsilon(4260)\) [13] to \(J/\psi\), and also the observation by BES and CLEO of similar transitions of \(\psi(3770)\) [14, 15]. Additional motivation to update measurements of the branching fractions for dipion transitions among bottomonium states below open-bottom threshold is presented by the prospects of using \(\Upsilon(3S), \Upsilon(2S) \rightarrow \pi\pi \Upsilon(1S)\) as a clean source of tagged \(\Upsilon(1S)\) decays, including searches for invisible decay modes [16].

A well-known feature of the \(\pi\pi\) transitions in bottomonium is that the invariant mass of the dipion system in \(\Upsilon(3S) \rightarrow \pi\pi \Upsilon(1S)\) differs greatly from that produced in other known dipion transitions in bottomonium and in charmonium [9]. Theoretical interest in these invariant mass distributions has been substantial, and several attempts to describe them have been made since the first observation of dipion transitions [10]. Analysis of the dipion invariant mass shapes in transitions from bottomonium states above open-bottom threshold show similar interesting features [11, 12]. A detailed analysis of the dipion invariant mass shapes including the extraction of the matrix elements for the transitions considered in this Article was performed using the most recent CLEO data and appears in Ref. [17]. The results of that matrix element determination are used in the present analysis to properly determine the detection efficiency.

For this work, data samples were collected using the CLEO III [18] detector at the Cornell Electron Storage Ring. These samples included \((5.93 \pm 0.10) \times 10^6 \Upsilon(3S)\) collected on the \(\Upsilon(3S)\) resonance, at \(\sqrt{s} = 10.355\) GeV and \((9.11 \pm 0.14) \times 10^6 \Upsilon(2S)\) decays collected on the \(\Upsilon(2S)\) resonance, at \(\sqrt{s} = 10.025\) GeV. Charged particle tracking is done by a 47-layer drift chamber and a four-layer silicon tracker immersed in a 1.5 T solenoidal magnetic field. Photons are detected using an electromagnetic calorimeter consisting of 7784 CsI(Tl) crystals in a projective barrel geometry.

In this analysis, we study the transitions both inclusively (in which case we detect only the pair of charged pions) and exclusively (in which case we detect, in addition to the charged or neutral pair of pions, the decay of the daughter \(\Upsilon(nS)\) state to either \(\mu^+\mu^-\) or \(e^+e^-\)). In each case, the primary quantity used to identify our observation of the dipion transition...
FIG. 1: The spectrum of bottomonium states below $B\bar{B}$ threshold for different $J^{PC}$ combinations. Established bottomonium states are indicated by the solid horizontal lines, while those indicated by dashed horizontal lines have never been observed. Arrows connecting various bottomonium states represent hadronic transitions that have been observed.

Transitions of interest is the mass recoiling against the dipion system. This may be most simply defined in terms of the formula $M_{\text{recoil}} = \sqrt{(E_{\text{cm}} - E_{\pi\pi})^2 - (p_{\pi\pi})^2}$, where $E_{\text{cm}}$ is the energy in the center-of-mass system, $E_{\pi\pi}$ and $p_{\pi\pi}$ are the energy and three-momentum of the dipion system, respectively. For a dipion system produced in the transition from $\Upsilon(nS)$ to $\Upsilon(1S)$ ($\Upsilon(2S)$), $M_{\text{recoil}}$ will be equal, within detector resolution, to the $\Upsilon(1S)$ ($\Upsilon(2S)$) mass, 9.460 (10.023) GeV/$c^2$ \cite{19}. Randomly selected pion pairs from hadronic events do not peak at all, but form a smooth combinatoric background.

In the inclusive analysis, we select two charged tracks that originate within 5 cm in the beam direction and 5 mm in the transverse direction from the center of the interaction region. The vertex requirements drastically reduce the likelihood that the $\pi$ candidate tracks were produced in interactions between the $e^+$ or $e^-$ beams and the beampipe, residual gas, or other material. Monte Carlo studies show that low momentum kaon or muon pairs arising
from generic Υ\((nS)\) or QED processes do not produce peaking backgrounds in the recoil mass spectrum. Therefore, we did not require positive identification of these tracks as pions. The mass recoiling against the two tracks, assumed to be pions, was required to be greater than 9.0 GeV/c^2.

In the exclusive analysis we require events to have two high momentum tracks with an invariant mass of 9.2 – 9.7 GeV/c^2, consistent with \(M(\Upsilon(1S))\), or greater than 9.9 GeV/c^2, consistent with \(M(\Upsilon(2S))\). These tracks must have an angle with respect to the beam direction, \(\theta_\ell\), which satisfies \(|\cos \theta_\ell| < 0.82\), a region in which the acceptance is relatively uniform. We apply no further track quality criteria for the lepton candidates, and we do not attempt to distinguish to which dilepton final state (electron or muon) the \(\Upsilon(1S)\) candidate has decayed. Since in the exclusive analysis we reconstruct the full event, we require the sum of energies of all final state particles to be greater than \(\sqrt{s} - 200\text{ MeV}\)\((\sim 300\text{ MeV})\) for the \(\Upsilon(3S)\)\((\Upsilon(2S))\) analyses. The more stringent requirement on the \(\Upsilon(3S)\) energy conservation was necessary to remove possible contamination in the signal sample due to cascades through the \(\Upsilon(2S)\).

In the charged exclusive case, we require that in addition to the dilepton candidate, events have a pair of low momentum tracks that satisfy the same requirements as the pion candidates in the inclusive analysis. The dilepton invariant mass requirement alone provides a nearly background-free sample, and imposition of additional criteria in order to identify the tracks as leptons only leads to larger systematic uncertainties and reduced signal efficiency without much improvement in signal quality. An additional requirement is imposed to remove radiative Bhabha events \((e^+e^-\rightarrow e^+e^-\gamma)\) in which the \(\gamma\) converts in the inner material of the detector or the beampipe, producing an \(e^+e^-\) pair that can fake the transition \(\pi^+\pi^-\). In such events a small angle between momentum of the conversion pair and one of the two high-momentum leptons is favored. Essentially all of this background is removed by the requirement that this angle be greater than 0.15 radians. Finally, in addition to the four tracks (two \(\pi^\pm\) candidates, two \(\ell^\pm\) candidates) we allow events to have one additional track, which prevents the loss of otherwise good events due to failures in pattern recognition or to other spurious track candidates. Monte Carlo (MC) studies show that this allowance does not contribute any peaking background in the region of interest.

In the neutral dipion analysis, we require that in addition to the dilepton candidate, events contain four or five showers in the calorimeter. Each of these showers must have an energy of at least 50 MeV and have angles relative to the beam axis such that \(|\cos(\theta_\gamma)| \leq 0.804\), where \(\gamma\) reconstruction is best. None of these showers may be matched to either charged track in the event. Showers satisfying these criteria are then paired to produce \(\pi^0\) candidates. Pairs with invariant masses within 50 MeV/c^2 of the nominal \(\pi^0\) mass must further satisfy the requirement that the mass pull - the normalized deviation from the nominal \(\pi^0\) mass, \(\frac{(M_{\gamma\gamma} - M_{\pi^0})}{\sigma_{\gamma\gamma}}\) - be in the range (-4.0,2.5) for \(\Upsilon(nS)\rightarrow\Upsilon(1S)\pi^0\pi^0\) and (-5.0,3.0) for \(\Upsilon(3S)\rightarrow\pi^0\pi^0\Upsilon(2S)\). The pair-mass resolution, \(\sigma_{\gamma\gamma}\), which is calculated event by event based on the calorimeter energy deposits, is typically between 5 and 7 MeV/c^2. The \(\pi^0\) candidates satisfying this condition are then subject to a mass-constrained fit in order to improve the \(\pi^0\pi^0\) recoil mass resolution.

We have also allowed one additional spurious shower to be present in the calorimeter, in order that we do not needlessly remove events due to spurious signals in the calorimeter. Because we allow up to five showers in the calorimeter it is possible for an event to have more than two combinations of showers that satisfy the \(\pi^0\) candidate requirements. In such cases, the combination of \(\pi^0\) pairings having the smallest sum of squared mass pulls.
In order to evaluate detector acceptances and efficiencies and to study backgrounds to the signal processes, MC samples were generated for several different event types. Generic \( \Upsilon(3S) \) and \( \Upsilon(2S) \) decays and continuum processes (such as \( e^+e^-\to\tau\tau \)) at center of mass energies equal to the masses of the two states were simulated using the routine \( QQ \) [20]. MC samples were also generated for the signal dipion transitions and for individual background channels using EvtGen [21]. Each sample was then passed through a GEANT-based [22] detector simulation. Generic and continuum MC samples contained approximately one and five times the actual integrated luminosity taken at each of the resonances, respectively.

For the study of acceptance and efficiency, separate signal MC samples for inclusive and exclusive analyses were created. In order to take advantage of the matrix element analysis previously performed by CLEO [17], the signal MC samples were generated according to phase space and then weighted according to the square of the matrix elements. In the exclusive analyses, a further weighting factor of \( 1 + \cos^2 \theta^*_\ell \) (where \( \theta^*_\ell \) is the lepton angle relative to the beamline in the rest frame of the daughter \( \Upsilon \)) was applied. This assumes a negligible \( D \)-wave component in the \( \pi\pi \) transition. For the inclusive analyses, 200,000 events were generated for each of \( \Upsilon(3S) \) and \( \Upsilon(2S) \) decaying by \( \pi^+\pi^-\Upsilon(1S) \), where \( \Upsilon(1S) \) was decayed generically. For the exclusive analyses, 500,000 events were generated for each of the five transitions, with the daughter \( \Upsilon(1S) \) or \( \Upsilon(2S) \) decaying equally to \( e^+e^- \) and \( \mu^+\mu^- \).

In all analyses, the distribution of the mass recoiling against the \( \pi\pi \) pair for accepted data and MC events is used to evaluate signal yield and efficiency, respectively. Recoil mass distributions for all the transitions observed in our data are shown in Figs. 2 and 3.

For the inclusive analysis, there is a large combinatoric background because the analysis involves only combining pairs of charged pions, which are prolifically produced in \( \Upsilon \) decays. The background due to these is smooth and has been fitted to a third-order polynomial, and then subtracted in order to evaluate the yield for the signal process of interest. A study of continuum data taken below the \( \Upsilon(3S) \) and \( \Upsilon(2S) \) resonances, and both continuum and generic \( \Upsilon(3S) \) and \( \Upsilon(2S) \) MC simulations (which include decays of daughter \( \Upsilon(1S) \) states) reveal no peaking background in \( \pi^+\pi^- \) recoil mass.

For the exclusive charged analysis, background events arise either from non-\( \pi\pi \) hadronic transitions to the daughter \( \Upsilon \) state in which the hadrons involved in the transition fake the signal due to poor reconstruction or noise in the detectors, or from \( udsc \) quark pair production from the continuum. Backgrounds arising from these process should be negligible, because of the lack of significant non-\( \pi\pi \) hadronic transitions in the bottomonium system, and because of the required detection of a high mass dilepton. Continuum data taken below \( \Upsilon(3S) \) and \( \Upsilon(2S) \) resonances and both continuum and generic MC simulations (with simulated \( \pi^+\pi^- \) transitions removed) have been analyzed, and this expectation is confirmed.

For the neutral analysis, there are also a number of possible background processes to consider. One such process is the decay chain \( \Upsilon(3S)\to\gamma\chi_b(2P), \chi_b(2P)\to\gamma\Upsilon(2S), \Upsilon(2S)\to\gamma\chi_b(1P), \chi_b(1P)\to\gamma\Upsilon(1S), \Upsilon(1S)\to\ell^+\ell^- \). The resulting \( 4\gamma+\ell^+\ell^- \) final state has an overall branching fraction of approximately 0.2%, while the branching fractions of the signal processes are of order several percent [19]. Such a process is furthermore unlikely to produce a fake signal because the four photons produced in the cascade would need to combine to produce two good \( \pi^0 \) candidates. Similarly, the two-photon cascades \( \Upsilon(3S)\to\gamma\chi_b(2P,1P) \), followed by \( \chi_b(2P,1P)\to\gamma\Upsilon(1S) \), and \( \Upsilon(1S)\to\ell^+\ell^- \) could potentially fake the \( \pi^0\pi^0 \) signal with the addition of two spurious clusters in the calorimeter. To evaluate these small but possibly pernicious backgrounds, special MC samples, each of 50,000 events, were produced.
FIG. 2: $\pi^+\pi^-$ recoil mass distributions for the four charged dipion transition analyses, (a) $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ inclusive, (b) $\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ inclusive, (c) $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ exclusive and (d) $\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ exclusive. The data are represented by symbols with uncertainty, while the histograms overlaid in each inclusive plot represents background-subtracted data. Note the logarithmic scale for the exclusive analyses.

for both the four and two photon cascade processes described above. Analysis of these samples show that such processes contribute negligible background. Finally, transitions involving $\eta$ could as well, but because of the tiny branching fraction for $\eta$ transitions, they have been assumed to produce no background.

To determine the branching fractions for the charged exclusive analyses, we used a cut-and-count method in which the background underneath the peak in the recoil mass distribution was subtracted by means of 20 MeV wide sidebands separated by 15 MeV from the 40 MeV wide signal region. We analyzed the inclusive recoil mass distributions similarly, first subtracting the smooth combinatoric background followed by cut-and-count using the same signal and sidebands as in the exclusive analysis. This method minimizes the systematic uncertainties associated with the MC signal shape, and corrects for any inaccuracies resulting from the use of the background function in the vicinity of the signal peak. Finally, from the
\[ \pi^0 \pi^0 \text{ recoil mass distributions in the neutral dipion transition analyses, (a)} \ \Upsilon(3S) \rightarrow \pi^0 \pi^0 \Upsilon(1S), \ (b) \ \Upsilon(3S) \rightarrow \pi^0 \pi^0 \Upsilon(2S) \ \text{and (c)} \ \Upsilon(2S) \rightarrow \pi^0 \pi^0 \Upsilon(1S). \] The data are represented by the symbols with errors, while the histograms represent the result of the fit using the MC shape and a linear background function. Note the logarithmic scale.

resulting data recoil mass histograms, we obtain the data yield, and from the signal MC, we obtain the efficiency by dividing the MC yield by the amount of MC generated.

For the neutral analyses we instead obtained the efficiency-corrected data yield directly by fitting the data recoil mass histogram using the recoil mass histogram shape found from neutral signal MC samples, allowing for a first degree polynomial background contribution.

From the data yields and MC efficiencies, we then calculate the branching fraction, using

\[ \mathcal{B}(\Upsilon(nS) \rightarrow \Upsilon(mS) \pi\pi) = \frac{N_{\text{exc}}/\epsilon_{\text{exc}}}{[N(\Upsilon(nS))]2\mathcal{B}(\Upsilon(mS) \rightarrow \mu^+\mu^-)], \quad (1) \]

in the case of the exclusive analyses and

\[ \mathcal{B}(\Upsilon(nS) \rightarrow \Upsilon(1S) \pi^+\pi^-) = \frac{N_{\text{inc}}/\epsilon_{\text{inc}}}{[N(\Upsilon(nS))]}, \quad (2) \]

in the case of inclusive studies.

The branching fractions obtained are summarized in Tables I and II. In order to evaluate the exclusively-measured branching fraction, we have assumed lepton universality. We have therefore used twice the PDG average value of \( \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-) = 2.48 \pm 0.05% \) to normalize our results for the transitions terminating in \( \Upsilon(1S) \), and twice the recent CLEO measurement of \( \mathcal{B}(\Upsilon(2S) \rightarrow \mu^+\mu^-) = 2.03 \pm 0.08% \) [23] for the one terminating in \( \Upsilon(2S) \).

Systematic error contributions are summarized in Table III. For event reconstruction in the exclusive analyses, a systematic uncertainty of 1.2% per pair of charged pions and 3.2% per pair of neutral pions was assessed. These systematic uncertainties were evaluated by comparing the ratio of event yield in the standard exclusive analysis to the yield obtained using an analysis that depends on the reconstruction of only one \( \pi^\pm \) or \( \pi^0 \). From this ratio a per-\( \pi^\pm \) or \( \pi^0 \) uncertainty was obtained, and doubled to give the relative uncertainty for finding the pair. For the exclusive analyses, a systematic uncertainty of 1.0% per lepton pair was similarly obtained. For the inclusive analyses, based on tracking studies in a variety
TABLE I: Results of the branching fraction measurements for charged dipion transitions $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$. The first uncertainty in the branching fraction is the statistical uncertainty, while the second is systematic. The averages listed are weighted averages of the inclusive and exclusive measurements which take into account correlation of systematic uncertainties between them.

| Analysis  | Data Yield   | Efficiency (%) | $B$ (%)   |
|-----------|--------------|----------------|-----------|
| 3S Excl.  | 5215 ± 72    | 39.7 ± 0.1     | 4.47 ± 0.06 ± 0.18 |
| 3S Incl.  | 184760 ± 430 | 69.9 ± 0.2     | 4.46 ± 0.01 ± 0.14 |
| Average   |              |                | 4.46 ± 0.01 ± 0.13 |
| 2S Excl.  | 26417 ± 163  | 32.0 ± 0.1     | 18.26 ± 0.11 ± 0.81 |
| 2S Incl.  | 824418 ± 908 | 50.3 ± 0.1     | 17.99 ± 0.02 ± 0.59 |
| Average   |              |                | 18.02 ± 0.02 ± 0.61 |

TABLE II: Results of measurements of the branching fractions for neutral dipion transitions. The middle column lists the efficiency-corrected data yield, which is obtained as described in the text. The statistical uncertainty presented accounts for both the data and finite MC statistics, and the second uncertainty reflects the remaining systematic contributions.

| Analysis  | Efficiency-corrected Yield | $B$ (%)   |
|-----------|----------------------------|-----------|
| $3S \to 1S\pi^0\pi^0$ | 6584 ± 274                | 2.24 ± 0.09 ± 0.11 |
| $3S \to 2S\pi^0\pi^0$ | 4391 ± 207                | 1.82 ± 0.09 ± 0.12 |
| $2S \to 1S\pi^0\pi^0$ | 38069 ± 727               | 8.43 ± 0.16 ± 0.42 |

of neutral and charged multiplicity environments, we conservatively assign a systematic uncertainty of 2.4% per pair of charged pions.

For the $\Upsilon(3S)$ analyses, a common relative uncertainty of 1.7% due to the uncertainty in the number of $\Upsilon(3S)$ produced; for $\Upsilon(2S)$, the corresponding uncertainty was 1.5%. This class of systematic uncertainty derives primarily from the uncertainty in the knowledge of the integrated luminosity accumulated at each of the resonances.

Three sources of systematic uncertainty produce relatively large contributions in some cases. Uncertainties due to modelling of the dipion dynamics were studied by varying the MC weighting according to the uncertainties of the matrix elements reported in Ref. [17], and by studying the resulting reproduction of the dipion invariant mass. In the case of the $\Upsilon(3S) \to \Upsilon(2S)\pi^0\pi^0$ and both analyses of $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ estimated systematic contributions of $1.4 - 2.3\%$ were obtained. For the other transitions, the systematic uncertainty due to modelling was much smaller.

The exclusive samples were all divided into $\mu^+\mu^-$ and $e^+e^-$ subsamples for the purpose of studying the difference between reconstruction of these two leptonic channels. From the difference in branching fractions obtained from the two subsamples, a relative systematic uncertainty of 2.5% due to lepton type was obtained. The exclusive analyses carry an additional systematic uncertainty from the branching fractions for the decays of $\Upsilon(1S)$ and $\Upsilon(2S)$ to dileptons.
TABLE III: Summary of relative systematic uncertainties on the measurement of the branching fractions, expressed in percent. Systematic uncertainties for the inclusive and exclusive analyses of charged dipion transitions are separately listed in the table.

| Contribution | $\Upsilon(3S)\rightarrow\pi^+\pi^-$ | $\Upsilon(3S)\rightarrow\pi^0\pi^0$ | $\Upsilon(2S)\rightarrow\pi^+\pi^-$ | $\Upsilon(2S)\rightarrow\pi^0\pi^0$ |
|--------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
|              | Excl. | Incl. | Excl. | Incl. | Excl. | Incl. | Excl. | Incl. |
| $\pi^\pm/\pi^0$ | 1.2   | 2.4   | 3.2   | 3.2   | 1.2   | 2.4   | 3.2   | 3.2   |
| $\ell$ Tracks | 1.0   | N/A   | 1.0   | 1.0   | 1.0   | N/A   | 1.0   | N/A   |
| Luminosity   | 1.7   | 1.7   | 1.7   | 1.7   | 1.5   | 1.5   | 1.5   | 1.5   |
| $\ell$ Type  | 2.5   | N/A   | 2.5   | 2.5   | 2.5   | N/A   | 2.5   | N/A   |
| MC Modelling | 0.2   | 0.4   | 0.5   | 2.2   | 2.3   | 1.4   | 0.2   | 0.2   |
| $\ell\ell$ BR | 2.0   | N/A   | 2.0   | 4.2   | 2.0   | N/A   | 2.0   | N/A   |
| Other Sources | 0.35  | 0.8   | 1.0   | 1.0   | 0.1   | 0.8   | 1.0   | 1.0   |
| Total        | 4.0   | 3.1   | 5.1   | 6.6   | 4.5   | 3.3   | 5.0   | 5.0   |

Uncertainties due to the choice of analysis requirements, MC statistics, side band range choices, etc., were all much smaller in each case compared to the other systematic uncertainties. The overall relative systematic uncertainty is obtained by adding all contributions in quadrature. The complete array of systematic uncertainties for all seven analyses appears in Table III.

We have measured the charged dipion branching fractions both inclusively and exclusively. Our final result for the measurement of each of these branching fractions is a weighted average of the two independent results, which we have calculated using a toy Monte Carlo method [24] in which we have properly accounted for the correlation between the various contributions to the systematic uncertainties that are applied to the two analyses. That is, the luminosity uncertainties on the exclusive and inclusive results are fully correlated, while the statistical uncertainties are uncorrelated, as are any uncertainties unique to either the exclusive or the inclusive analysis. These average values are $B(\Upsilon(3S)\rightarrow\Upsilon(1S)\pi^+\pi^-) = (4.46 \pm 0.01 \pm 0.13)\%$ and $B(\Upsilon(2S)\rightarrow\Upsilon(1S)\pi^+\pi^-) = (18.02 \pm 0.02 \pm 0.61)\%$.

It is interesting to compare the branching fractions for the $\pi^0\pi^0$ transitions to those for the corresponding $\pi^+\pi^-$ branching fractions that we have measured. Isospin conservation requires that the square of the matrix elements for the $\pi^0\pi^0$ transitions be half that of the $\pi^+\pi^-$ transitions. Phase space for the two types of transitions also differs slightly and modifies this expectation, such that the expected ratio $B(\pi^0\pi^0\Upsilon(1S))/B(\pi^+\pi^-\Upsilon(1S))$ is $0.53$ for the transitions from $\Upsilon(2S)$ and $0.51$ for transitions from $\Upsilon(3S)$. Combining our neutral and charged results, and taking into proper account correlations and cancellations among individual systematic errors, we obtain ratios of $0.462 \pm 0.037$ for $\Upsilon(2S)$ transitions and $0.501 \pm 0.043$ for the transitions from $\Upsilon(3S)$.

In summary, we have reported improved measurements of five of the six dipion transitions among the lower-lying bottomonium vector states $\Upsilon(3S)$, $\Upsilon(2S)$ and $\Upsilon(1S)$. Each of the measurements is more precise than those made by any previous experiment, and also more precise than the current PDG world average [19].

We gratefully acknowledge the effort of the CESR staff in providing us with excellent
luminosity and running conditions. This work was supported by the A. P. Sloan Foundation, the National Science Foundation, the U.S. Department of Energy, the Natural Sciences and Engineering Research Council of Canada, and the U. K. Science and Technology Facilities Council.

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