CLEO Results on Quarkonium Transitions

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Abstract. This note presents new preliminary CLEO measurements on \( \psi(2S) \rightarrow X + J/\psi \) transitions and reviews final CLEO results on \( n^3S_1 \rightarrow n^3P_J, n^1S_1 \) in charmonium and bottomonium.

1. Introduction
Charmonium and bottomonium, both consisting a bound heavy quark-antiquark pair, are similar in many aspects such as mass splittings or transition mechanisms. Differences between \( b \bar{b} \) and \( c \bar{c} \) arise e.g. from the different quark masses, making charmonium slightly less non-relativistic (\( \beta_{c \bar{c}} \sim 0.25 \) vs. \( \beta_{b \bar{b}} \sim 0.08 \)). Given the low-energy regime, calculation of decay rates and spacings must resort to special non-perturbative techniques or models. The results will have to be compared against experimental data. With the data samples at hand, relative accuracies at the percent level can be reached for many important reactions.

This note describes three analyses of quarkonium transitions: \( \psi(2S) \rightarrow \gamma c \bar{c}, \psi(2S) \rightarrow \gamma b \bar{b}, \) and \( \Upsilon(2S) \rightarrow \gamma b \bar{b} \). All three use data delivered by the CESR e+e− accelerator and collected with the CLEO detector \[1\], which features an angular coverage of 93%, a track momentum resolution of 0.6% at \( p = 1 \text{ GeV}/c \), and a photon energy resolution of 2.2% (5%) at \( E_\gamma = 1 \text{ GeV} \) (\( E_\gamma = 100 \text{ MeV} \)). Besides updating previously measured results with increased precision, several new aspects are studied.

2. \( \psi(2S) \) hadronic transitions to \( J/\psi \)
Transitions to the \( J/\psi \) under emission of hadrons constitute the most copious decays of the \( \psi(2S) \), at 54% of the total width. Its dominant contribution comes from \( \psi(2S) \rightarrow \pi^+ \pi^- J/\psi \) and \( \psi(2S) \rightarrow \pi^0 \pi^0 J/\psi \), related by isospin with a small correction for phase space. Other observed hadronic transitions are \( X = \eta, \pi^0 \) at much smaller absolute branching fractions. Many analyses used \( \psi(2S) \rightarrow \pi^+ \pi^- J/\psi \) or \( J/\psi + \text{anything} \) as normalizing modes to circumvent the problem of not knowing the number of \( \psi(2S) \) decays precisely enough. The PDG performs a global fit to all available data to come up with an optimized set of exclusive branching fractions; \( B(\psi(2S) \rightarrow \pi^0 \pi^0 J/\psi) \) has not yet been measured before at all with full final state reconstruction.

The analysis presented here addresses the aforementioned hadronic transition branching fractions simultaneously, thereby also facilitating the correct treatment of correlated uncertainties for all deduced ratios.

We investigate \( \pi^+ \pi^- J/\psi, \pi^0 \pi^0 J/\psi, \psi(2S) \rightarrow \eta J/\psi (\eta \rightarrow \gamma \gamma \text{ and } \eta \rightarrow \pi^+ \pi^- \pi^0), \pi^0 J/\psi \), and the inclusive channel \( XJ/\psi \) in 3.08M \( \psi(2S) \) decays. The exclusive modes are fully reconstructed. The \( J/\psi \) is identified through \( J/\psi \rightarrow \mu^+ \mu^- \) or \( J/\psi \rightarrow e^+ e^- \). Requirements are placed on the
total energy and total momentum in the event. The selection is as loose as possible to minimize the impact of systematic uncertainties. Bremsstrahlung shower candidates are added to the track. The event samples are found to be very clean, and excellent agreement between Monte Carlo (MC) simulation and data is observed. This is demonstrated in Figure 1.

The detection efficiency is estimated from signal MC. A combination of signal MC, weighted by branching fraction, is used to arrive at a detection efficiency for $X J/\psi$. Event topology dependent sources of systematic uncertainty are: modelling of tracking, $\pi^0/\eta$ finding, and decay radiation; cross-feed between the modes; lepton identification; continuum background subtraction; detection efficiency precision. Their relative importance varies by channel. Uncertainties common to all are the accuracy of the number of $\psi(2S)$ decays (3%) and the error of the $J/\psi \rightarrow \ell^+\ell^-$ branching fraction (1.7%). The total systematic error spreads a range of $3-7\%$ and, except for $\pi^0 J/\psi$, is the dominant portion of the total error.

Table 1 shows the CLEO preliminary branching fraction. They are competitive with or more precise than previous measurements and constitute a big step forward in terms of a systematic way of surveying the $\psi(2S)$ transitions. Some noteworthy conclusions:

- The branching fraction ratio $\pi^+\pi^- J/\psi/\pi^0 \pi^0 J/\psi$ is found to fulfill the isospin based prediction.
- The difference between $B(\psi(2S) \rightarrow X J/\psi)$ and the sum of all exclusive hadronic transitions, attributable to the doubly radiative decays, $\psi(2S) \rightarrow \gamma \chi_{cJ}$, $\chi_{cJ} \rightarrow \gamma J/\psi$, is found to be about $(6.2 \pm 1.1)\%$. This is about $1.5\sigma$ above a recent direct measurement of these decay chains, $(4.5 \pm 0.2)\%$ [3], and $2.0\sigma$ above the PDG [2] result of $(3.9 \pm 0.2)\%$, dominated by a CBAL measurement [5].
- Using $\Sigma J B(\psi(2S) \rightarrow \chi_{cJ}) = (27.6 \pm 0.3 \pm 2.0)\%$ and $B(\psi(2S) \rightarrow \gamma \eta(1S)) = (0.32 \pm 0.04 \pm 0.06)\%$ [6] as well as $\Sigma J B(\psi(2S) \rightarrow \ell\ell) = (1.77 \pm 0.11)\%$ [2], together with the exclusive branching fractions, one obtains $B(\psi(2S) \rightarrow \text{light hadrons}) = (17.2 \pm 3.6)\%$. In comparison with the corresponding number for the $J/\psi$, one finds $B(\psi(2S)_{\ell\ell})/B(\psi(2S)_{\ell\ell}) = (19.8 \pm 4.1)\%$, or about $2\sigma$ above $B(\psi(2S)_{\ell\ell})/B(\psi(2S)_{\ell\ell}) \sim 13\%$ [2].

**Figure 1.** $\psi(2S) \rightarrow X J/\psi$ (inclusive selection); for dimuon (left) and dielectron (right) events in the $\psi(2S)$ data (open circles), scaled continuum data (blue), and MC (red): distributions of the dilepton mass before (top) and after (bottom) subtraction of the scaled continuum from the $\psi(2S)$ distributions. Arrows indicate cut limits. The MC is the branching fraction weighted sum of all contributing signal modes. The small peak at $m(J/\psi)$ in the continuum data is due to the BW tail of the $\psi(2S)$. The two peaks above 3.2 GeV in the dimuon plots correspond to backgrounds from $\chi_{c0} \rightarrow K^+K^-$, $\chi_{c0} \rightarrow \pi^+\pi^-$, and $\chi_{c2} \rightarrow K^+K^-$. The detection efficiency is estimated from signal MC. A combination of signal MC, weighted by branching fraction, is used to arrive at a detection efficiency for $X J/\psi$. Event topology dependent sources of systematic uncertainty are: modelling of tracking, $\pi^0/\eta$ finding, and decay radiation; cross-feed between the modes; lepton identification; continuum background subtraction; detection efficiency precision. Their relative importance varies by channel. Uncertainties common to all are the accuracy of the number of $\psi(2S)$ decays (3%) and the error of the $J/\psi \rightarrow \ell^+\ell^-$ branching fraction (1.7%). The total systematic error spreads a range of $3-7\%$ and, except for $\pi^0 J/\psi$, is the dominant portion of the total error.

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Table 1. Branching fractions for \( \psi(2S) \to XJ/\psi \) transitions. For each channel, the first line indicates the CLEO measurement (preliminary). Entries in the second line with one error shown are the PDG average (not fit) [2]; the others are BES results [3, 4].

| Channel        | \( \mathcal{B} \)     | \( \mathcal{B}/\mathcal{B}_{\chi J/\psi} \) | \( \mathcal{B}/\mathcal{B}_{\pi^+\pi^-J/\psi} \) |
|----------------|------------------------|-----------------------------------------------|-----------------------------------------------|
| \( XJ/\psi \)  | 56.9 ± 0.2 ± 2.4       | –                                             | –                                             |
| \( \eta J/\psi \) | 55 ± 7                 | –                                             | –                                             |
| \( \pi^+\pi^- J/\psi \) | 33.3 ± 0.1 ± 1.8       | 55.8 ± 0.3 ± 1.1                              | –                                             |
|               | 32.3 ± 1.4             | 53.5 ± 0.7 ± 1.6                              | –                                             |
| \( \pi^0\pi^0 J/\psi \) | 16.9 ± 0.2 ± 0.8       | 28.3 ± 0.3 ± 0.6                              | 50.7 ± 0.5 ± 1.5                              |
| \( \eta J/\psi, \eta \to \gamma \gamma \) | 3.3 ± 0.1 ± 0.1       | 5.5 ± 0.1 ± 0.1                              | 9.9 ± 0.2 ± 0.2                              |
|               | 3.0 ± 0.1 ± 0.2       | 6.9 ± 0.8                                    | 9.8 ± 0.5 ± 0.1                              |
| \( \eta J/\psi, \eta \to \pi^+\pi^-\pi^0 \) | 3.0 ± 0.1 ± 0.2       | 5.5 ± 0.2 ± 0.1                              | 9.9 ± 0.4 ± 0.2                              |
| \( \pi^0 J/\psi \)  | 0.15 ± 0.02 ± 0.01    | 0.26 ± 0.03 ± 0.01                           | 0.46 ± 0.05 ± 0.03                           |
|               | 0.143 ± 0.013 ± 0.011 | –                                             | –                                             |

3. Radiative transitions in charmonium and bottomonium

Radiative charmonium transitions from the \( \psi(2S) \) have been analyzed in an inclusive photon study using 1.5\( M \) \( \psi(2S) \) decays [6]. The analysis selects hadronic events with a photon. Background from \( e^+e^- \to e^+e^- \), \( \mu^+\mu^- \) is suppressed. The dominant source of background for the photon selection is from \( \pi^0 \) decays, against which a restriction on the opening angle between any two photons that form an acceptable \( \pi^0 \) candidate is imposed.

The resulting photon energy spectrum exhibits three well-separated peaks for the \( \psi(2S) \to \gamma \chi_{cJ} \) transitions, a broader peak corresponding to the overlap of \( \chi_{cJ} \to \gamma J/\psi \), and a small elevation for \( \psi(2S) \to \gamma \eta(1S) \), which, being a hindered M1 transition, is suppressed relative to the E1 transitions. In a fit, each photon line is represented by a non-relativistic Breit-Wigner curve convoluted with a Crystal Ball line shape to extract the peak position and yield, leading to measurements of the photon energy and branching fraction. The natural widths of the \( \chi_{cJ} \) states contribute only for \( J = 0 \) significantly; in all other cases, detector resolution dominates. The measured masses of the states are in good agreement with the very precise world averages determined in recent measurements. The measured M1 branching fractions confirm and improve upon previous measurements. CLEO observes significantly larger branching fractions for the E1 transitions than the PDG average. A search for a line corresponding to the previously observed \( \eta_c(2S) \) Crystal Ball candidate resulted in an upper limit below the quoted branching fraction, in accordance with recent measurements of \( m(\eta(2S)) \) that implies a photon energy and a width below the present CLEO reach. The reader is referred to Ref. [6] for more detail.

A similar study is performed using CLEO’s 9.3\( M \) \( \Upsilon(2S) \) \( (\Upsilon(3S)) \) data [7]. The experimental situation is less favorable in \( b\bar{b} \) than in \( c\bar{c} \): The \( n^3P_J \) splittings are smaller due to the lower value of \( \beta \), and in addition, higher multiplicity and continuum production contribute more background. The increase in data sample size over previous measurements by a factor of ten and the CLEO photon energy resolution allows to perform the most precise measurement to date of \( \Upsilon(2S) \to \gamma \chi_{bJ}(2S) \) and \( \Upsilon(3S) \to \gamma \chi_{bJ}(1S) \) transition photon energies and branching fractions. The analysis strategy is similar as above, except that below-resonance data and 1.06\( fb^{-1} \) of \( \Upsilon(1S) \) data are relied on for background subtraction. The measured \( \chi_{bJ} \) peak positions were used to correct the CLEO calorimeter energy scale, a 0.5% change. The resulting \( \chi_{bJ}(1S) \) masses and branching fractions are in excellent agreement with present world averages,
but pose an improvement in precision. The same is true for the $\chi_{bJ}(2S)$ results, except that the $\Upsilon(3S)$ $\rightarrow \chi_{bJ}(2S)$ are found to be significantly higher than previous measurements (complete set of numerical results in Ref. [7]). The systematic errors, the largest of which is related to the absolute calibration of photon energies, dominate the total uncertainty. The hindered transition $\Upsilon(3S)$ $\rightarrow \gamma \chi_{b0}(1S)$ is observed for the first time at $B = (0.30 \pm 0.04 \pm 0.10)\%$ ($\Upsilon(3S)$ $\rightarrow \gamma \chi_{b1,2}(1S)$ cannot be resolved), and upper limits are placed on the M1 transitions, $\Upsilon(2,3S)$ $\rightarrow \eta_b(1,2S)$ at roughly $0.5 \times 10^{-3}$ level (90% CL), or about a factor of six below the observed corresponding rate of $\psi(2S)$ $\rightarrow \gamma \eta_c(1S)$. With these results, a number of potential models can be ruled out.

Finally, one can compare the E1 transition rates for different $J$. In the non-relativistic limit, the rates should be independent of $J$ apart from a kinematic factor, $(2J + 1)E_3^3$. While the $J=2/J=1$ ratios comply with this prediction, the $J=0/J=1,2$ rates show the need for relativistic corrections at the 20% level. As expected, the deviations from unity are significant for all three ratios in charmonium.

4. Summary
Recent CLEO results on hadronic charmonium transitions and radiative charmonium and bottomonium transitions have been presented, showing an increase in precision that should prove useful to theory.

References
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