Spectroscopy of Heavy Quarkonia

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In the last few years, the CLEO III experiment has recorded a large collection of data sets at the \( \Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \) and \( \psi(2S) \) resonances. Preliminary results of studies of these data sets are shown here, which include the observation of a new \( \Upsilon(1D) \) state, as well as several hadronic and radiative transitions of \( \Upsilon \) and \( \psi(2S) \) states. In addition, precision branching ratio measurements of charmonium and bottomonium states and recent developments involving the \( \eta_c(2S) \) and \( X(3872) \) states are presented.

1. INTRODUCTION

Heavy quarkonia - \( c\bar{c} \) and \( b\bar{b} \) bound states - are still a very rich exploration ground. For example, no \( b\bar{b} \) singlet states have yet been found, and only a few hadronic and radiative decays are known.

The masses of charm and bottom quarks are relatively large (\( \approx 1.5 \) and \( \approx 4.5 \) GeV). As a consequence, the velocities of these quarks in hadrons are non-relativistic and the strong coupling constant \( \alpha_s \) is quite small (\( \approx 0.3 \) for \( c\bar{c} \) and \( \approx 0.2 \) for \( b\bar{b} \)). Hence, heavy quarkonia provide the best means of testing the theories of strong interaction, i.e. QCD in both pertubative and non-pertubative regimes, QCD inspired purely phenomenological potential models, NRQCD and lattice QCD.

In this paper, the latest results on charmonium and bottomonium spectroscopy from the CLEO III experiment are presented and recent developments of the searches for the \( \eta_c(2S) \) and \( X(3872) \) are discussed.

2. THE CLEO III EXPERIMENT AND DATA SETS

The data used in the presented studies were taken with the CLEO III detector at the CESR \( e^+e^- \) storage ring. The detector includes a silicon microvertex detector, a drift chamber and a ring imaging cerenkov detector (RICH), as well as a crystal calorimeter. On the outside, the detector is surrounded by muon chambers. The tracking volume is placed in a uniform 1.5 T solenoidal magnetic field.

During the last two years, the CLEO III experiment recorded data at the \( \Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \) and \( \psi(2S) \) resonances, resulting in approximately 38 million hadronic events. In addition, data were also recorded below the peak of each resonance for background purposes and for scans across the resonances. Table 1 summarizes the data sets used.

3. BOTTOMONIUM SPECTROSCOPY

3.1. First Observation of \( \Upsilon(13D_2) \) State

CLEO has made the first observation of the bottomonium state \( \Upsilon(13D_2) \). This state was produced in a two-photon cascade via the \( \chi(2P) \) state starting from the \( \Upsilon(3S) \) resonance: \( \Upsilon(3S) \to \gamma\chi(2P) \to \gamma\gamma \Upsilon(13D_2) \)

To suppress photon backgrounds from \( \pi^0 \)s, which are copiously produced in gluonic annihilation of the \( bb \) states, events with two or more subsequent photon transitions were selected via the cascade \( \Upsilon(13D_2) \to \gamma\chi(1P) \to \gamma\gamma \Upsilon(1S) \)

In this four-photon cascade \( 34.5 \pm 6.4 \) signal events were observed which translate into a significance of \( 10.2\sigma \). The \( \Upsilon(13D_2) \) mass was measured to \( M = 10161.1 \pm 0.6(stat) \pm 1.6(syst) \) MeV and the product branching ratio was determined...
Table 1
Summary of the CLEO III data sets used in the studies which are presented in this paper. For comparison, in brackets the number of events recorded with the CLEO II detector are shown.

| \( E_{cm} \) (GeV) | Resonance | # Events (10^6) | Experiment |
|-------------------|-----------|----------------|------------|
| 9.46              | \( \Upsilon(1S) \) | 20 (2)         | CLEO III (CLEO II) |
| 10.02             | \( \Upsilon(2S) \) | 10 (0.5)       | CLEO III (CLEO II) |
| 10.36             | \( \Upsilon(3S) \) | 5 (0.5)        | CLEO III (CLEO II) |
| 3.69              | \( \psi(2S) \) | 3              | CLEO III |
Table 2
Summary of the branching ratio measurements of $B(\Upsilon(nS) \to \mu^+\mu^-)$. For comparison, the world averages (PDG) are given.

|   | $\Upsilon(1S)$ | $\Upsilon(2S)$ | $\Upsilon(3S)$ |
|---|----------------|----------------|----------------|
| CLEO | $2.53 \pm 0.02 \pm 0.05$ | $2.11 \pm 0.03 \pm 0.05$ | $2.44 \pm 0.07 \pm 0.05$ |
| PDG | $2.48 \pm 0.06$ | $1.31 \pm 0.21$ | $1.81 \pm 0.17$ |

excellent place to look for new intermediate resonances, such as $b\bar{b}$ singlet states.

In M1 transitions, CLEO has searched for the states $\eta_b(1S)$ and $\eta_b(2S)$. No significant signals were found and only upper limits for branching ratios as a function of the photon energy were determined.

In E1 transitions, we observed the following three transitions:

- $\Upsilon(3S_1) \to \gamma \chi_b(1P_1)$
- $\chi_b(1P_0) \to \gamma \Upsilon(1S_1)$
- $\chi_b(2P_0) \to \gamma \Upsilon(2S_1)$

No preliminary branching ratios are available at this time. Further precision measurements are in progress.

4. CHARMONIUM SPECTROSCOPY

4.1. Radiative Transitions from $\psi(2S)$

CLEO has measured the branching ratios for the radiative transitions $\psi(2S) \to \gamma \chi_c(1P_1)$ and $\psi(2S) \to \gamma \eta_c(1S)$. Table 3 summarizes the four measurements. The ratios are in good agreement with the Particle Data Group (PDG) averages. CLEO also confirms the M1 transition to $\eta_c(1S)$ made by Crystal Ball. However, we find no indication of the M1 transition to $\eta_c(2S)$ which was reported by the Crystal Ball collaboration 20 years ago.

4.2. Experimental Results on $\eta_c(2S)$

The $\eta_c'$ has a very colorful history with one observation followed by a number of fruitless searches. This situation changed recently with the Belle observation of robust $\eta_c'$ signals in the two channels $B^\pm \to K^\pm \eta_c' \to K^\pm K^\mp K^\pm \pi^\mp$ with $M = 3654 \pm 6(stat) \pm 8(syst)$ MeV and $e^+e^- \to J/\psi \eta_c$ with $M = 3622 \pm 12$ MeV [14,15], quickly followed by BaBar and CLEO observations of $\eta_c'$ signals in two-photon fusion processes. BaBar reported a mass of $M = 3630.8 \pm 3.4(stat) \pm 1.0(syst)$ MeV and a width of $\Gamma = 17.0 \pm 8.3(stat) \pm 2.5(syst)$ MeV [16]. CLEO measured the mass to $M = 3642.9 \pm 3.1(stat) \pm 1.5(syst)$ MeV and the width to $\Gamma < 31$ MeV (90% C.L.) [17]. The CLEO observation was made in two data sets with substantially different detectors and software systems. The results of the three experiments are in reasonable agreement.

Using a combined mass value (Belle, BaBar, CLEO) of $M = 3637 \pm 4.4$ MeV, the value of the hyperfine mass splitting between the $\psi(2S)$ and the $\eta_c'$ can be given as $\Delta M(2S) = 48.6 \pm 4.4$ MeV. This value for $\Delta M(2S)$ is much smaller than most theoretical predictions and should lead to a new insight into coupled channel effects and spin-spin contribution of the confinement part of the $q\bar{q}$ potential.

4.3. Search for the Narrow State $X(3872)$

This new narrow state was first observed by the Belle collaboration in the decay channel $B^\pm \to K^\pm X(3872)$ with $X(3872) \to \pi^+\pi^-J/\psi$ and $J/\psi$ decaying into a lepton pair [18]. The reported mass and width are $M = 3872.0 \pm 0.6(stat) \pm 0.5(syst)$ MeV and $\Gamma < 2.3$ MeV (90% C.L.). The CDF and D0 collaborations have confirmed the $X(3872)$ observation in proton-antiproton annihilation $p\bar{p} \to X(3872) + X$ with $X(3872) \to \pi^+\pi^-J/\psi$ and $J/\psi$ decaying into a muon pair [19,20]. The reported masses are $M = 3871.3 \pm 0.7(stat) \pm 0.4(syst)$ MeV (CDF) and $M = 3871.8 \pm 3.1(stat) \pm 3.0(syst)$ MeV (D0).

CLEO searched for the $X(3872)$ state in untagged two-photon fusion processes and initial-state-radiation production, analyzing the exclusive channels $X(3872) \to \pi^+\pi^-J/\psi$ with $J/\psi$ decaying into a lepton pair. No signal was found,
Table 3
Summary of the branching ratio measurements for $\psi(2S)$ radiative transitions. For comparison, the PDG values are given.

| $B$ (%) | $\psi(2S) \rightarrow \gamma \chi_c(1P_J)$ | $\psi(2S) \rightarrow \gamma \eta_c(1S)$ |
|---------|----------------------------------------|--------------------------------------|
| CLEO    | J = 2 (E1 line) 9.75 ± 0.14 ± 1.17    | J = 0 (E1 line) 9.83 ± 0.13 ± 0.87 |
| PDG     | 7.8 ± 0.8                                  | 0.278 ± 0.033 ± 0.049               |

but upper limits could be set. For untagged two-photon fusion processes, we find

\[(2J + 1)\Gamma_\ell\ell B(X \rightarrow \pi^+\pi^-/\psi) < 16.7 \text{ eV (90\% C.L.)}\]

and for ISR production we report \(\Gamma_{cc} B(X \rightarrow \pi^+\pi^-/\psi) < 6.8 \text{ eV (90\% C.L.)}\).

5. SUMMARY AND CONCLUSION

CLEO is now fully exploiting the world’s largest sample of $\Upsilon$ decays. We have reported on the observation of the $\Upsilon(1^3D_2)$ state and several hadronic and radiative transitions of $\Upsilon$ and $\psi(2S)$ states. We also measured the rate for inclusive $\psi$ production in $\Upsilon(1S)$ decays. In addition, we presented precision branching ratio measurements and searches for $\eta_c(2S)$ and $X(3872)$. All results are preliminary.

As demonstrated above, spectroscopy of heavy quarkonia is a very active field. Collections of large data samples are now available from CLEO III ($b\bar{b}$), BES II ($c\bar{c}$) and CLEO-c ($c\bar{c}$). Many new important experimental observations and measurements have emerged and many more are expected for the near future.

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