Recent results from the CLEO experiment on decays and partial widths of various bottomonium and charmonium resonances are presented. New measurements of $\Gamma_{ee}$ for the 3 bound-state Upsilons and the $J/\psi$ are discussed. A determination of $\sigma(\psi(3770) \rightarrow \text{hadrons})$ is made, which solves a 20-year-old puzzle. The $Y(4260)$ state is confirmed and its decay into 2 new modes is measured.

1 CESR and CLEO

The Cornell electron-positron storage ring (CESR) is a symmetric $e^+e^-$ collider located on the Cornell University campus in Ithaca, NY. For almost 30 years, the accelerator has been running in the Upsilon energy region from $\sqrt{s} = 9-11$ GeV, providing the accompanying detector, CLEO, with data to produce results on $B$, $\Upsilon$, $\tau$, charm, and 2-photon physics. Roughly 2 years ago, the accelerator was modified with the addition of wiggler magnets to allow it to run in the $\sqrt{s} = 3-5$ GeV charmonium energy region.

CLEO\textsuperscript{II} is a standard $4\pi e^+e^-$ magnetic spectrometer. In its latest configuration, called CLEO-c, it consists of inner and main drift chambers for charged particle tracking, a CsI electromagnetic calorimeter, and a Ring-Imaging Cherenkov detector (RICH), all enclosed in a 1 T solenoidal magnetic field. The charged particle momentum resolution is 0.6% at 1.0 GeV/c and the photon energy resolution is 4% at 100 MeV. Particle identification is done using both the RICH and dE/dx measurements in the drift chambers. Muon chambers interspersed in the magnet iron outside the solenoid complete the detector.

2 $\Gamma_{ee}$ of the $Y(1S, 2S, 3S)$

The di-electron partial width, $\Gamma_{ee}$, is one of the basic parameters of any heavy-quark bound system. It is proportional to the square of the state’s wave function at the origin, and is a
number that all heavy-quark theories try to predict. Furthermore, its measurement can provide a stringent test of lattice QCD calculation. However, the present world average precision of \( \Gamma_{ee} \) for the 3 bound-state \( \Upsilon \) resonances\(^2\) is only 2.2%, 4.2%, and 9.4%, respectively. To rectify this situation, CLEO performed scans over the 3 resonances, as well as running below each resonance to constrain the backgrounds.

CLEO uses a standard procedure to measure \( \Gamma_{ee} \) - the total hadronic cross section is measured over each resonance. The integral of this cross section with respect to the center-of-mass energy is proportional to \( \Gamma_{ee} \Gamma_{had}/\Gamma_{tot} \), where \( \Gamma_{had} \) and \( \Gamma_{tot} \) are the resonance’s hadronic and total widths, respectively. If we then assume lepton universality, taking the 3 leptonic branching ratios as equal (\( B_{ee} = B_{\mu\mu} = B_{\tau\tau} \)), we can solve for \( \Gamma_{ee} \) using:

\[
\Gamma_{ee} = \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_{tot}(1 - 3B_{\mu\mu})}.
\]

The main backgrounds include the continuum \( e^+e^- \rightarrow \text{hadrons} \) process with a 1/s energy dependence, two-photon production (\( e^+e^- \rightarrow e^+e^-X \)) with a \( \ln(s) \) dependence, cosmic rays, beam-gas interactions, and events from the high-energy tails of the \( \Upsilon(1S) \) and \( \Upsilon(2S) \). The beam-gas and cosmic ray backgrounds are subtracted using data from special single- and no-beam runs.

The hadronic cross section measurements for each resonance are then fit to a convolution of a Breit-Wigner function, including interference between the resonance and the continuum hadronic production, initial-state radiation, a Gaussian for the 4 MeV CESR beam energy spread, and background terms proportional to 1/s and \( \ln(s) \). The resulting statistical errors on the partial widths are 0.3% (1S), 0.7% (2S), and 1.0% (3S). The main systematic errors are from uncertainties in the luminosity measurement (1.3%) and the hadronic event efficiency (0.5%). The measured parameters, including the total width of each resonance, found from \( \Gamma_{ee} \) by assuming that \( B_{ee} = B_{\mu\mu} \) and using a recent, very precise CLEO measurement of \( B_{\mu\mu} \), are given in Table 1.

Table 1: CLEO measurements of various resonance parameters for the 3 bound-state Upsilons. The first errors are statistical, the second are systematic, and the third for \( \Gamma_{tot} \) are due to the uncertainty on \( B_{\mu\mu} \).

| \( \Upsilon(1S) \) | \( \Upsilon(2S) \) | \( \Upsilon(3S) \) |
|----------------|----------------|----------------|
| \( \Gamma_{ee}\Gamma_{had}/\Gamma_{tot} \) (keV) | 1.252 ± 0.004 ± 0.019 | 0.581 ± 0.004 ± 0.009 | 0.413 ± 0.004 ± 0.006 |
| \( \Gamma_{ee} \) (keV) | 1.354 ± 0.004 ± 0.020 | 0.619 ± 0.004 ± 0.010 | 0.446 ± 0.004 ± 0.007 |
| \( \Gamma_{tot} \) (keV) | 54.4 ± 0.2 ± 0.8 ± 1.6 | 30.5 ± 0.2 ± 0.5 ± 1.3 | 18.6 ± 0.2 ± 0.3 ± 0.9 |
| \( \Upsilon(2S)/\Upsilon(1S) \) | 0.457 ± 0.004 ± 0.004 | 0.329 ± 0.003 ± 0.003 | 0.720 ± 0.009 ± 0.007 |
| \( \Upsilon(3S)/\Upsilon(1S) \) | | | |
| \( \Upsilon(3S)/\Upsilon(2S) \) | | | |

These new measurements of \( \Gamma_{ee} \) have improved on the precision of the previous world averages\(^2\) by factors of 1.5 (1S), 2.5 (2S) and 5.2 (3S). To compare these results to the latest unquenched lattice QCD calculations\(^5\), we use the combination:

\[
\frac{\Gamma_{ee}(2S)M^2(2S)}{\Gamma_{ee}(1S)M^2(1S)}.
\]
Our measured value of $0.517 \pm 0.007$ for this variable is in good agreement with the lattice QCD result, extrapolated to zero lattice spacing, of $0.48 \pm 0.05$. The hope is that the lattice QCD calculations will eventually reach a precision of a few percent for this variable and about a 10% precision for $\Gamma_{ee}$ itself. When this goal is achieved, the experimental measurements will now have the precision needed for a meaningful comparison.

3 $\Gamma_{ee}$ and $\Gamma_{tot}$ of the $J/\psi$

Switching now to the charmonium sector, CLEO has made a new similar measurement of $\Gamma_{ee}$ and $\Gamma_{tot}$ for the $J/\psi$. However, in this case the measurement was not done by scanning over the resonance. Instead, using data taken on the $\psi(3770)$, we look for so-called radiative return events to the $J/\psi$, in which an initial-state photon is radiated, followed by the decay of the $J/\psi$ into $\mu^+\mu^-$. After selecting di-muon events with $M(\mu^+\mu^-) = M(J/\psi)$ and subtracting background from radiative return to the $\psi(2S)$ and QED processes, the resulting signal cross section is proportional to $B_{\mu\mu} \times \Gamma_{ee}(J/\psi)$. Dividing this value by the new CLEO measurement of $B_{\mu\mu}(J/\psi)$, we obtain $\Gamma_{ee}$ for the $J/\psi$. Assuming lepton universality, $B_{ee} = B_{\mu\mu}$, and dividing by $B_{\mu\mu}$ again, then gives $\Gamma_{tot}(J/\psi)$. The results are as follows:

$$B_{\mu\mu} \times \Gamma_{ee}(J/\psi) = 0.3384 \pm 0.0058 \pm 0.0071 \text{ keV},$$

$$\Gamma_{ee}(J/\psi) = 5.68 \pm 0.11 \pm 0.13 \text{ keV},$$

$$\Gamma_{tot}(J/\psi) = 95.5 \pm 2.4 \pm 2.4 \text{ keV},$$

where the first errors are statistical and the second are systematic. Using a recent CLEO measurement of $\Gamma_{ee}(\psi(2S))$ found from an identical technique, we determine the ratio:

$$\frac{\Gamma_{ee}(\psi(2S))}{\Gamma_{ee}(J/\psi)} = 0.45 \pm 0.01 \pm 0.02,$$

in which many of the systematic errors cancel. All of these measurements are more precise than the previous world average values.

4 $\sigma(\psi(3770) \rightarrow \text{hadrons})$ and $\Gamma_{ee}(\psi(3770))$

The $\psi(3770)$, the first $\psi$ resonance above open-charm threshold, has had a long-standing puzzle about it. The Lead-Glass Wall (1977) and Mark II (1981) experiments first measured the total hadronic cross section for the $\psi(3770)$ to be $11.6 \pm 1.8$ nb. Later, the Mark III experiment (1988), using a double-tag technique, found $\sigma(\psi(3770) \rightarrow D\overline{D}) = 5.0 \pm 0.5$ nb. The large difference between these two numbers was a complete surprise and has remained a mystery, since it was believed that above open-charm threshold, $\sigma(\psi(3770) \rightarrow \text{non-}D\overline{D}) \ll \sigma(\psi(3770) \rightarrow D\overline{D})$.

CLEO recently repeated the Mark III measurement, using an identical technique but with much higher statistics (see the write-up by A. Ryd in these proceedings). They found:

$$\sigma(\psi(3770) \rightarrow D\overline{D}) = 6.39 \pm 0.10 \pm 0.17 \text{ nb},$$

which is significantly higher than the Mark III number, but still a long way from the total hadronic cross section value. Thus, it remained to also repeat the measurement of the total hadronic cross section. CLEO measures this cross section using the standard formula:

$$\sigma(\psi(3770) \rightarrow \text{hadrons}) = \frac{N_{\psi(3770)}}{\epsilon_h L},$$

where $N_{\psi(3770)}$ is the observed number of hadronic decays of the $\psi(3770)$, $\epsilon_h$ is the hadronic event efficiency (80%), and $L$ is the total integrated luminosity ($281.3 \pm 2.8 \text{ pb}^{-1}$). To obtain
$N_{\psi(3770)}$, we take the total number of observed hadronic events and subtract off the number of events from the continuum process $e^+e^- \rightarrow \text{hadrons}$, from the tails of the $J/\psi$ and $\psi(2S)$, and from di-lepton events (especially $\tau^+\tau^-$) faking hadrons. The resulting cross section is:

$$\sigma(\psi(3770) \rightarrow \text{hadrons}) = 6.38 \pm 0.08 \pm 0.41 \pm 0.83 \text{ nb},$$

where the first error is statistical and the second is systematic. Subtracting CLEO’s $D\bar{D}$ cross section from this gives:

$$\sigma(\psi(3770) \rightarrow \text{hadrons}) - \sigma(\psi(3770) \rightarrow D\bar{D}) = -0.01 \pm 0.08 \pm 0.04 \pm 0.03 \text{ nb}.$$

This is consistent with a small non-$D\bar{D}$ branching fraction for the $\psi(3770)$, which has been observed, but is much more in line with what was expected theoretically. Thus, the almost 20-year-old puzzle about the $\psi(3770)$ has been solved.

Using the $\sigma(\psi(3770) \rightarrow \text{hadrons})$ measurement and values for the mass and total width of the $\psi(3770)$, we can determine the di-electron partial width:

$$\Gamma_{ee}(\psi(3770)) = 0.204 \pm 0.003 \pm 0.04 \pm 0.02 \text{ keV}.$$

This measurement is in good agreement and as precise as the PDG value of 0.26 ± 0.04, but has quite different sources of systematic error.

5 Charmonium Decays of the $\psi(4040)$, $\psi(4160)$, and $Y(4260)$

Besides the $\psi(3770)$ discussed in the last section, prominent structures in the $e^+e^-$ total hadronic cross section above open-charm threshold are associated with the $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$ resonances. All of these particles can be assigned to specific $c\bar{c}$ states in both non-relativistic and relativistic heavy-quark potential models. They are all characterized by large total widths, weaker couplings to leptons than the bound-state resonances, and with predominant decays to open charm. Over the last few years, though, a number of new states with masses around 4 GeV and with either open- or closed-charm decays have been discovered. The assignments of these particles in the potential model schemes are not so obvious. The latest of these is the $Y(4260)$, discovered by BaBar through its decay to $\pi^+\pi^-J/\psi$, though not yet confirmed by other experiments. With a mass of 4259 MeV and a width of around 90 MeV, this particle does not easily fit into any of the potential models, nor is its large decay to a closed-charm channel what would be expected of a normal $c\bar{c}$ state of this mass. Furthermore, exactly at this energy the $e^+e^-$ total hadronic cross section goes through a local minimum – hardly the normal signal for a $c\bar{c}$ resonance!

Thus, there have been a host of theoretical explanations for this new resonance, including a $(c\bar{g})$ hybrid charmonium state, a $(cs)(\bar{c}\bar{s})$ tetraquark, a $\chi_{cJ}$, or baryonium molecule, and the normal $\psi(4S)$ $c\bar{c}$ state, where interference effects produce the dip in the open-charm cross section. All of these theories have different predictions for the ratios of the state’s branching fractions to $\pi^+\pi^-J/\psi$, $\pi^0\pi^0J/\psi$, and $K^+K^-J/\psi$. For the $\psi(4S)$ possibility, the previously-assigned $\psi(4S)$ state, the $\psi(4040)$, is expected to have an enhanced $\pi^+\pi^-J/\psi$ decay.

To try to confirm and clarify the $Y(4260)$, CLEO performed a scan from $\sqrt{s} = 3.97 - 4.26$ GeV, as well as using data taken at the $\psi(3770)$, looking for decays to 16 different closed-charm final states containing a $J/\psi$, $\psi(2S)$, $\chi_{cJ}$, or $\phi$. The integrated luminosity as a function of $\sqrt{s}$ is shown in Fig. 1(a). We break the scan up into distinct regions, shown by the vertical dotted lines in Fig. 1(b), according to the resonance each scan point is nearest: $\psi(4040)$ for $\sqrt{s} = 3.97 - 4.06$ GeV, $\psi(4160)$ for $\sqrt{s} = 4.12 - 4.20$ GeV, and $Y(4260)$ for $\sqrt{s} = 4.26$ GeV.
Figure 1: (a) Integrated luminosity versus $\sqrt{s}$ for the scan region. (b) The Breit-Wigner cross sections for the resonances in the scan energy region (the $Y(4260)$ vertical scale is arbitrary). The separation between the scan regions is shown by the vertical dotted lines. (c) Radiative-return cross section $e^+e^- \rightarrow \gamma \psi(2S)$ versus $\sqrt{s}$ for the 3 decay modes $\pi^+\pi^- J/\psi$ (circles), $\pi^0\pi^0 J/\psi$ (squares and dashed lines), and $\eta J/\psi$ (triangles), along with the expected values (solid line) from the known $\psi(2S)$ parameters. (d) Cross sections for $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ (circles) and $\pi^0\pi^0 J/\psi$ (squares, dashed lines) versus $\sqrt{s}$. 
As a check on our analysis procedures and efficiencies, we first look for the radiative-return process $e^+e^- \rightarrow \gamma \psi(2S)$, with the $\psi(2S)$ then decaying into $\pi^+\pi^-J/\psi$, $\pi^0\pi^0J/\psi$, or $\eta J/\psi$. These are 3 of the 16 modes searched for in the scan. Given the parameters of the $\psi(2S)$ and its known branching ratios to these 3 modes, one can predict the cross section for the radiative-return process as a function of $\sqrt{s}$. This prediction and our measured cross sections are shown in Fig. 1(c). There is excellent agreement between our measurements and the expected values.

With our analysis technique validated, we now turn to the scan itself. When any of the 16 decay modes is identified, a signal is searched for by requiring that the magnitude of the total missing momentum in the event should be consistent with 0. We observe only 3 statistically significant signals in the modes $\pi^+\pi^-J/\psi$ (11σ), $\pi^0\pi^0J/\psi$ (5.1σ), and $K^+K^-J/\psi$ (3.7σ), all from the $Y(4260)$ scan region. Their corresponding missing-momentum distributions are shown in Fig. 2. The resulting cross sections for the $\pi^+\pi^-J/\psi$, and $\pi^0\pi^0J/\psi$ modes are shown as a function of $\sqrt{s}$ in Fig. 1(d). The signal for the $Y(4260)$ is clear.

Thus, CLEO has confirmed the BaBar discovery of the $Y(4260)$ decaying into $\pi^+\pi^-J/\psi$ and has made the first observation of its decay into $\pi^0\pi^0J/\psi$ and $K^+K^-J/\psi$. We find no evidence for other decays in the 3 resonance regions. In particular, we set upper limits of:

$$B(\psi(4040) \rightarrow \pi^+\pi^-J/\psi) < 0.4\%,$$

$$B(\psi(4160) \rightarrow \pi^+\pi^-J/\psi) < 0.4\%.$$  

The observation of the $\pi^0\pi^0J/\psi$ decay mode disfavors the $\chi_{cJ}\rho$ molecular model. The fact that the $\pi^0\pi^0J/\psi$ rate is consistent with half of the $\pi^+\pi^-J/\psi$ rate disagrees with the prediction of the baryonium model, and the observation of the $K^+K^-J/\psi$ mode is incompatible with the baryonium model.
with both of these models. The lack of an enhancement for $\psi(4040) \rightarrow \pi^+\pi^-J/\psi$ makes the identification of the $Y(4260)$ as the $\psi(4S)^{[21]}$ less attractive. All of our results are compatible with the hybrid-charmonium interpretation $^{[16]}$ of the $Y(4260)$. However, to completely rule-out or verify the remaining theories, searches for the $Y(4260)$ decay to open-charm states will have to be performed. This will be quite difficult, though, given the very small open-charm total cross section at that center-of-mass energy.

6 References

1. D. Peterson et al., Nucl. Instrum. and Meth. A478, 251801 (2005); M. Artuso et al., Nucl. Instrum. and Meth. A502, 91 (2003); Y. Kubota et al. (CLEO Collaboration), Nucl. Instrum. and Meth. A320, 66 (1992).
2. S. Eidelman et al. (Particle Data Group), Phys. Lett. B 592, 1 (2004).
3. G.S. Adams et al. (CLEO Collaboration), Phys. Rev. Lett. 94, 012001 (2005).
4. J.L. Rosner et al. (CLEO Collaboration), Phys. Rev. Lett. 96, 092003 (2006).
5. A. Gray et al., Phys. Rev. D 72, 094507 (2005).
6. G.S. Adams et al. (CLEO Collaboration), Phys. Rev. D 73, 051103 (R) (2006).
7. Z. Li et al. (CLEO Collaboration), Phys. Rev. D 71, 111103 (R) (2005).
8. N.E. Adam et al. (CLEO Collaboration), Phys. Rev. Lett. 96, 082004 (2006).
9. I. Peruzzi et al. (Lead-Glass Wall Collaboration), Phys. Rev. Lett. 39, 1301 (1977).
10. R.H. Schindler et al. (Mark II Collaboration), Phys. Rev. D 24, 78 (1981).
11. J. Adler et al. (Mark III Collaboration), Phys. Rev. Lett. 60, 89 (1988).
12. Q. He et al. (CLEO Collaboration), Phys. Rev. Lett. 95, 121801 (2005).
13. D. Besson et al. (CLEO Collaboration), Phys. Rev. Lett. 96, 092002 (2006).
14. J.Z. Bai et al. (BES Collaboration), Phys. Lett. B 605, 63 (2005).
15. B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 95, 142001 (2005).
16. F.E. Close and P.R. Page, Phys. Lett. B 628, 215 (2005); S.-L. Zhu, Phys. Lett. B 625, 212 (2005); E. Kou and O. Pene, Phys. Lett. B 631, 164 (2005); X.Q. Luo and Y. Liu, hep-lat/0512044 (2005).
17. L. Maiani et al., Phys. Rev. D 72, 031502 (2005).
18. X. Liu, X.-Q Zeng and X.-Q. Li, Phys. Rev. D 72, 054023 (2005).
19. C.Z. Yuan, P. Wang and X.H. Mo, hep-ph/0511107 (2005).
20. C.-F. Qiao, hep-ph/0510228 (2005).
21. F.J. Llanes-Estrada, Phys. Rev. D 72, 031503 (2005).
22. T.E. Coan et al. (CLEO Collaboration), hep-ex/0602034.