Double Charmonium Production and an X(3940)

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Abstract. Extending a previous analysis [1] the double charmonium production \( e^+e^- \rightarrow J/\Psi (c\bar{c}) \) has been investigated in detail with a data set of 155 fb\(^{-1}\) with the Belle detector. \( J/\Psi \) production and helicity angular distributions are measured and give important information about the production mechanism. Theoretical predictions for the production cross section are one order of magnitude lower than the measurement and this discrepancy is still not understood.

The process \( e^+e^- \rightarrow \Psi(2S) (c\bar{c}) \) has been observed for the first time. The measured cross sections are compatible with \( e^+e^- \rightarrow J/\Psi (c\bar{c}) \) production.

In a very recent update with a dataset of 285 fb\(^{-1}\) strong evidence for a new charmonium state at a mass of 3.940 GeV was found.

1. Analysis of \( e^+e^- \rightarrow J/\Psi (c\bar{c}) \)
Details about the analysis can be found in a previous publication [2]. The \( J/\Psi \) is reconstructed in the leptonic decay channel. QED and \( b\bar{b} \) events are suppressed and the invariant mass of the system recoiling against the \( J/\Psi \) is calculated from the kinematic information of the \( J/\Psi \) solely. The recoil mass \( M_{\text{recoil}} = \sqrt{(E_{\text{CM}} - E_{J/\Psi}^*)^2 - p_{J/\Psi}^*} \) is shown in Fig. 1. Two very distinct peaks are visible around the nominal masses of the \( \eta_c \) and \( \chi_{c0} \). The peak at 3.63 GeV/c\(^2\) is identified as the \( \eta_c(2S) \). The result of the fit, where the cross sections for all the known resonances are free parameters is shown in Table 1. The number of observed events for \( J/\Psi, \chi_{c1}, \chi_{c2} \) and

![Figure 1](image_url)

**Figure 1.** The recoil mass spectrum for the process \( e^+e^- \rightarrow J/\Psi (c\bar{c}) \) with a data set of 155 fb\(^{-1}\). Two fits are shown where the cross section for the \( J/\Psi, \chi_{c1}, \chi_{c2} \) and \( \Psi(2S) \) modes are fixed at zero (solid line) or at their 90% C.L. upper limit (dashed line).
\(\Psi(2S)\) from the fit is compatible with 0 and the extracted upper limits on their cross sections are given. Table 1 shows also the measured cross sections for the other modes, which are one order of magnitude higher than the expectations in single virtual photon production from non-relativistic QCD (NRQCD) calculations [3]. However, theoretical calculations show that the cross section might be significantly increased when 2-virtual photon production is taken into account [4]. In this case also \(J/\Psi\) \(J/\Psi\) production is possible, which is forbidden in single virtual photon production due to C conservation.

Using a control sample of \(e^+e^-\rightarrow \Psi(2S)\gamma\) the bias on the \(M_{\text{recoil}}(J/\Psi)\) spectrum is measured and found to be \(< 3\) MeV for \(J/\Psi\). In addition 3 \(J/\Psi\eta_c\) events were explicitly reconstructed in the data which is compatible with the number of expected events of 2.6 \(\pm\) 0.8 from MC. This corresponds to a significance of more than 4 \(\sigma\). No events were found in a search for fully reconstructed \(J/\Psi\) \(J/\Psi\) events. We conclude that the \(\eta_c\) peak in the \(M_{\text{recoil}}\) spectrum does not include any significant fraction of \(J/\Psi\) \(J/\Psi\) events and the large cross section can not be explained by contributions from 2-virtual-photon production where \(J/\Psi\) \(J/\Psi\) events are misidentified as \(J/\Psi\eta_c\).

For the three observed final states the \(J/\Psi\) production and helicity angles are measured and provide important information about the production process as well as the spin of the final states. The fit results to \(A(1 + \alpha \cos^2 \theta)\) are presented in table 2 together with the expectations for the parameter \(\alpha\) for pure P-wave production of \(J/\Psi\eta_c\) and \(J/\Psi\eta_c(2S)\) and pure S-wave production of \(J/\Psi\chi_{c0}\). The numbers in the 2 left columns show the fit results when production and helicity angles are fitted independently. The right column shows the results of a simultaneous fit to the production and helicity angle distribution where \(\alpha_{\text{prod}} = \alpha_{\text{hel}}\). The fit results are well compatible with the assumption and disfavour NRQCD calculations where \(J/\Psi\chi_{c0}\) is produced in a mixture of a S- and D-wave where \(\alpha_{\text{prod}} = \alpha_{\text{hel}} = +0.25\) is expected.

Associated glueball production [5], [6] was proposed to explain the discrepancy between the calculations and the measurement. In this case \(\alpha_{\text{prod}} = \alpha_{\text{hel}} \approx -0.9\) is expected and associated glueball production unlikely.

| \((c\bar{c})_{\text{res}}\) | N | \(M[\text{GeV}/c^2]\) | Signif. | \(\sigma_{\text{Born}} \times B_{\gamma^2} \, [\text{fb}]\) |
|---|---|---|---|---|
| \(\eta_c\) | 235 \(\pm\) 26 | 2.972 \(\pm\) 0.007 | 10.7 | 25.6 \(\pm\) 2.8 \(\pm\) 3.4 |
| \(J/\Psi\) | -14 \(\pm\) 20 | fixed @ PDG value | — | \(< 9.1\) at 90\% C.L. |
| \(\chi_{c0}\) | 89 \(\pm\) 24 | 3.407 \(\pm\) 0.011 | 3.8 | 6.4 \(\pm\) 1.7 \(\pm\) 1.0 |
| \(\chi_{c1} + \chi_{c2}\) | 10 \(\pm\) 27 | fixed @ PDG value | — | \(< 5.3\) at 90\% C.L. |
| \(\eta_c(2S)\) | 164 \(\pm\) 30 | 3.630 \(\pm\) 0.008 | 6.0 | 16.5 \(\pm\) 3.0 \(\pm\) 2.4 |
| \(\Psi(2S)\) | -26 \(\pm\) 29 | fixed @ PDG value | — | \(< 13.3\) at 90\% C.L. |

Table 1. Summary of the signal yields from the fits to the \(M_{\text{recoil}}\) spectrum for the process \(e^+e^-\rightarrow J/\Psi\ (c\bar{c})\).

The fit results to provide important information about the production process as well as the spin of the final states.

\[ \alpha \] of a S- and D-wave where \(\alpha\) is produced in a mixture of a S- and D-wave where \(\alpha = +0.25\) is expected.

Associated glueball production [5], [6] was proposed to explain the discrepancy between the calculations and the measurement. In this case \(\alpha = -0.9\) is expected and associated glueball production unlikely.

| \((c\bar{c})_{\text{res}}\) | Separate fits | Expectation | Simultaneous fits |
|---|---|---|---|
| \(\eta_c\) | \(+1.4^{+0.8}_{-0.8}\) | \(+0.5^{+0.7}_{-0.5}\) | \(+1\) | \(+0.93^{+0.57}_{-0.47}\) |
| \(\chi_{c0}\) | \(-1.7 \pm 0.5\) | \(-0.7^{+0.5}_{-0.5}\) | \(-1\) | \(-1\) | \(-0.33^{+0.33}_{-0.33}\) |
| \(\eta_c(2S)\) | \(+1.9^{+2.0}_{-1.2}\) | \(+0.3^{+1.0}_{-0.7}\) | \(+1\) | \(+1\) | \(+0.87^{+0.86}_{-0.63}\) |

Table 2. The \(\alpha\) parameter obtained from fits to the \(J/\Psi\) production and helicity angle distributions for \(e^+e^-\rightarrow J/\Psi\ (c\bar{c})\) res.
2. Observation of the process $e^+e^- \rightarrow \Psi(2S) (c\bar{c})$

In this process the $\Psi(2S)$ is reconstructed in the decay channel $J/\Psi \pi^+\pi^-$ where the $J/\Psi$ decays leptonically as above. The $M_{\text{recoil}}(\Psi(2S))$ distribution is shown in Fig. 2. The result of the fit to the $M_{\text{recoil}}$ spectrum is shown in table 3. The significance for $e^+e^- \rightarrow \Psi(2S) (c\bar{c})_{\text{res}}$ where $(c\bar{c})_{\text{res}}$ is the sum over $\eta_c$, $\chi_{c0}$ and $\eta_c(2S)$ is estimated to be 5.3 $\sigma$. This process is observed for the first time. The obtained cross sections have the same order of magnitude as the ones given above for $e^+e^- \rightarrow J/\Psi (c\bar{c})_{\text{res}}$.

3. Evidence for a new charmonium state in $e^+e^- \rightarrow J/\Psi (c\bar{c})_{\text{res}}$

In a very recent update of the analysis on $e^+e^- \rightarrow J/\Psi (c\bar{c})$ the $M_{\text{recoil}}(J/\Psi)$ spectrum shows very clear evidence for a peak at 3.940 $\pm$ 0.011 GeV/$c^2$ with a significance of 4.5 $\sigma$. The $M_{\text{recoil}}$ spectrum is shown in Fig. 3. More detailed studies show that this new state decays primarily into $D^{(*)}D^{(*)}$ final states. Therefore it can be assumed, that the X(3940) is a new charmonium state that has not been observed yet. More statistics is needed for the investigation of angular distributions which are needed to identify the nature of this resonance.

No evidence for the known state X(3872) has been found.

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\begin{array}{cccc}
(c\bar{c})_{\text{res}} & N & \text{Signif.} & \sigma_{\text{Born}} \times B_{>0} [\text{fb}] \\
\hline
\eta_c & 36.7 \pm 10.4 & 4.2 & 16.3 \pm 4.6 \pm 3.9 \\
J/\Psi & 6.9 \pm 8.9 & - & < 16.9 \text{ at 90}\% \text{ C.L.} \\
\chi_{c0} & 35.4 \pm 10.7 & 3.5 & 12.5 \pm 3.8 \pm 3.1 \\
\chi_{c1} + \chi_{c2} & 6.6 \pm 8.0 & - & < 8.6 \text{ at 90}\% \text{ C.L.} \\
\eta_c(2S) & 36.0 \pm 11.4 & 3.4 & 16.0 \pm 5.1 \pm 3.8 \\
\Psi(2S) & -8.3 \pm 8.5 & - & < 5.2 \text{ at 90}\% \text{ C.L.} \\
\end{array}
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Table 3. Summary of the signal yields from the fits to the $M_{\text{recoil}}$ spectrum for the process $e^+e^- \rightarrow \Psi(2S) (c\bar{c})$. 

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**Figure 2.** The recoil mass spectrum for the process $e^+e^- \rightarrow \Psi(2S) (c\bar{c})$ with a data set of 155 fb$^{-1}$. Two fits are shown where the cross section for the $J/\Psi$, $\chi_{c1}$, $\chi_{c2}$ and $\Psi(2S)$ modes are fixed at zero (solid line) or at their 90% C.L. upper limit (dashed line).
4. Summary

The experimental measurement of the cross section for double charmonium production in $e^+e^-$ annihilation is a factor 10 higher than the theoretical calculations and the difference still unexplained. The experimental results favour the single virtual photon production and no evidence for any contribution from neither two virtual photon production nor associated glueball production is found in the data. More input from theory is needed to understand this discrepancy.

The process $e^+e^- \rightarrow \Psi(2S) (c\bar{c})$ was observed for the first time and shows a production cross section that has the same order of magnitude as the $e^+e^- \rightarrow J/\Psi (c\bar{c})$ production.

In a recent update strong evidence for a new charmonium state at a mass of 3.94 GeV/c$^2$ that decays into $D^{(*)}D^{(*)}$ is found. More data is needed for the measurement of angular distributions for this final state. These are needed to obtain the nature of this new charmonium state.

For detailed information on this analysis please refer to [2].

References
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