Results on Charmonium and Charmonium-like States at the Belle Experiment

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New results of the Belle experiment at the KEKB asymmetric \(e^+e^-\) collider are presented, in particular (a) measurement of the mass and width of the \(\eta_c\) and \(\eta_c'\) in \(B\) meson decays, (b) measurement of the mass, width and quantum numbers of the \(X(3872)\) and (c) observation of the \(\chi_{c2}\) in \(B\) meson decays.

1 \(\eta_c\) and \(\eta_c'\) in \(B\) meson decays

The \(\eta_c\) is the \(1^1S_0\) ground state of charmonium with quantum numbers \(J^{PC}=0^{-+}\). The \(\eta_c'\) represents the first radial excitation \(2^1S_0\). As a long-standing puzzle the width of the \(\eta_c\) has been determined with large discrepancies between experiments with different production mechanisms: in \(J/\psi\) and \(\psi'\) radiative decays \(\Gamma_{\eta_c} \simeq 15\) MeV, in \(B\) meson decays or \(\gamma\gamma \rightarrow \eta_c\) \(\Gamma_{\eta_c} \simeq 30\) MeV [1]. One possible reason is the fact that in radiative decays the cross section is varying with the photon energy according to \(E_\gamma^a\) with an exponent \(3 \leq a \leq 7\), and thus leading to a distorted line shape of the observed \(\eta_c\) signal. However, in the case of the latter production mechanisms a Breit-Wigner lineshape is considered a valid parametrisation.

In a new analysis of \(B^+ \rightarrow K^+\eta_c(\rightarrow K_SK^\pm\pi^\mp)\) [2], the mass and the width of the \(\eta_c\) were determined by a 2-dimensional fit of the invariant mass \(m(K_SK\pi)\) vs. the angle \(\angle(K_SK)\). As the \(\eta_c\) is a pseudoscalar meson, the angular distribution should be flat. However, \(P\)-wave and \(D\)-wave components by non-resonant charmless \(B\) decays turned out to be non-negligible. By adding the angle into the fit, interference with the background is taken into account. The mass was determined as \(m=2985.4\pm1.5^{+0.2}_{-2.0}\) MeV. The measured width in listed in Tab. 1, in comparison with other recent measurements.

The analysis was repeated for the \(\eta_c'\). The measurement of the width of the \(\eta_c'\) is of high importance, as due to the vicinity to the \(D^0\bar{D}^0\) threshold, potential model predictions are not reliable. In case of the \(\eta_c'\) the interference with the non-resonant background turned out to even have a higher impact for the fit and thus the determination of the width. The result is \(\Gamma=6.6^{+8.4}_{-5.6}\) MeV for the fit with interference and \(\Gamma=41.1\pm12.0^{+6.4}_{-10.3}\) MeV for a fit without interference (i.e. fit of only the invariant mass). The factor \(\simeq 5\) narrower width of the \(\eta_c'\)

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### Table 1: Width measurements of the \( \eta_c \).

| \( \Gamma_{\eta_c} \) (MeV) | Production Mechanism | Reference |
|---|---|---|
| 35.1\( ^{+1.1}_{-1.0} \) | \( B \) decays | [2] and this paper |
| 30.5\( ^{+1.0}_{-0.9} \) | \( \psi' \rightarrow \gamma \eta_c \) | [3] |
| 28.1\( ^{+3.2}_{-2.2} \) | \( \gamma \gamma \rightarrow \eta_c \) | [4] |
| 31.7\( ^{+1.2}_{-1.1} \) | \( \gamma \gamma \rightarrow \eta_c \) | [5] |
| 36.3\( ^{+3.7}_{-3.6} \) | \( B \) decays | [6] |

Compared to the \( \eta_c \) can be explained by the wavefunctions of the states. The hadronic decay of both states proceeds by two gluons; three gluons are forbidden by parity. As the width scales with the wavefunction at the origin, i.e. \( \Gamma(^{1}S_{0} \rightarrow g g) = (32\pi\alpha_{S}^{2}/m_{c}^{2})|\psi(r=0)|^{2} \), and the wavefunction for the \( \eta'_c \) has one node (as it is \( n=1 \) radial excitation), the width at the origin must be narrower. With the new measurement, the error on the previous world average of the width of the \( \eta'_c \) was improved by factor \( \approx 2 \). For additional details of the analysis see [2].

## 2 Mass and Width of X(3872)

New results for the charmonium-like state X(3872) in the decays \( B^{+} \rightarrow K^{+}X(3872) \) and \( B^{0} \rightarrow K^{0}(\rightarrow \pi^{+}\pi^{-})X(3872) \) are based upon the complete Belle data set of 711 fb\(^{-1} \) collected at the \( \Upsilon(4S) \) resonance [7]. For the determination of the mass and the width of the X(3872) in the decay \( X(3872) \rightarrow J/\psi\pi^{+}\pi^{-} \), a 3-dimensional fit was performed using the three variables beam constraint mass \( M_{bc} = \sqrt{(E_{beam}^{\text{cms}})^{2} - (p_{B}^{\text{cm}})^{2}} \) (with the energy in the center-of-mass system \( E_{\text{cms}} \) and the momentum of the \( B \) meson in the center-of-mass system \( p_{B}^{\text{cm}} \)), the invariant mass \( m(J/\psi\pi^{+}\pi^{-}) \) and the energy difference \( \Delta E = E_{B}^{\text{cm}} - E_{\text{beam}}^{\text{cm}} \) (with the energy of the \( B \) meson in the center-of-mass system \( E_{B}^{\text{cm}} \)). In a first step, the fit was performed for the reference channel \( \psi' \rightarrow J/\psi\pi^{+}\pi^{-} \), and the resolution parameters (i.e. the widths of a core Gaussian and a tail Gaussian) were then fixed for the fit of the X(3872). Fig. 1 shows the data and the fits for the X(3872) (blue line: signal, dashed green line: background) in the projections of the three variables as defined above. The yield is 151\( \pm 15 \) events for \( B^{+} \) decays and 21.0\( \pm 5.7 \) events for \( B^{0} \) decays.

**Mass of the X(3872).** The mass, as determined by the fit, is listed in Tab. 2 in comparison to other precise measurements. As the X(3872) does not fit into any potential model prediction, it was discussed as a possible S-wave \( D^{0}\bar{D}^{0} \) molecular state. In this case, the binding energy \( E_b \) would be given by the mass difference \( m(X) - m(D^{0}) - m(D^{0}) \). Including the new Belle result, the new world average mass of the X(3872) is \( m = 3871.67 \pm 0.17 \) MeV. Using the current sum of the masses \( m(D^{0}) + m(D^{0}) = 3871.79 \pm 0.30 \) MeV [1], a binding energy of \( E_b = -0.12 \pm 0.35 \) MeV can be calculated, which is surprisingly small. As \( E_b \) is inverse proportional to the squared scattering length \( a \), and the radius can in first order be approximated by \( <r> = a/2 \) [12], this would indicate a very large radius of the molecular state.
Figure 1: Beam constraint mass $M_{bc}$ (left), invariant mass $m(J/\psi \pi^+ \pi^-)$ (center) and $\Delta E$ (right) for $B^+ \rightarrow K^+ X(3872)(\rightarrow J/\psi \pi^+ \pi^-)$.

Figure 2: Distribution of $|\cos(\theta_X)|$ for $B^+ \rightarrow K^+ X(3872)(\rightarrow J/\psi \pi^+ \pi^-)$. The blue line shows the fit for $J^{PC} = 1^{++}$ (left) and $J^{PC} = 2^{+-}$ (bottom). For details see text.

Width of the $X(3872)$. With the 3-dimensional fit, also a new measurement of the width of the $X(3872)$ was performed. Previously the best upper limit was $\Gamma_{X(3872)} < 2.3$ MeV (90% C.L) [14]. The 3-dimensional fits are more sensitive to the natural width than the resolution provided by the detector $<\sigma> \approx 4$ MeV because of the constraints which enter by $M_{bc}$ and $\Delta E$. As in case of the mass measurement above, the method of determining the width was validated using the $\psi'$ as reference, providing a result of $\Gamma_{\text{measured}} = 0.52 \pm 0.11$ MeV. As the world average is $\Gamma_{PDG}^{\psi'} = 0.304 \pm 0.009$ MeV, this indicates a bias in our measurement of $\Delta \Gamma = 0.23 \pm 0.11$ MeV. The procedure for the determination of the upper limit is as follows: for a given fixed width $\Gamma$ the number of signal events and the number of peaking background events is kept floating in the 3-dim fit, and the likelihood is calculated. Then the 90% likelihood interval is determined by finding $w_{0.90}$ for an integral $\int_0^{w_{0.90}} \Gamma d\Gamma = 0.9$. This procedure gives $w_{0.90} = 0.95$ MeV, for which the bias has to be added, so that $\Gamma_{X(3872)} < 1.2$ MeV at 90% C.L. is the final result. This upper limit is a factor of $\approx 2$ narrower than the previous upper limit.

Quantum numbers of the $X(3872)$. If the $X(3872)$ is a conventional charmonium state, there are two likely assignments. On the one hand there is the $\chi_c'(1)$, a $^3P_1$ state with $J^{PC} = 1^{++}$. The predicted mass by potential models is $m = 3953$ MeV, thus $\approx 70$ MeV higher than the observed $X(3872)$ mass. This would be a $n=2$ radial excitation, and the quantum numbers are favoured by angular analyses [15] [16]. On the other hand there is the $\eta_c$, a $^1D_2$ state
Table 2: Mass measurements of the X(3872).

| Experiment  | Mass of X(3872)                  |
|-------------|---------------------------------|
| CDF2        | 3871.61±0.16±0.19 MeV [8]       |
| BaBar ($B^+$) | 3871.4±0.6±0.1 MeV [9]         |
| BaBar ($B^0$) | 3868.7±1.5±0.4 MeV [9]         |
| D0          | 3871.8±3.1±3.0 MeV [10]        |
| Belle       | 3871.84±0.27±0.19 MeV [7] and this paper |
| LHCb        | 3871.96±0.46±0.10 MeV [11]     |
| New World Average | 3871.67±0.17 MeV              |

with $J^{PC}=2^{-+}$. The predicted mass by potential models is $m=3837$ MeV, thus ≃35 MeV lower than the observed X(3872) mass. This would be a $n=1$ state, and the quantum numbers are favoured by the $3\pi$ mass distribution in the decay $X(3872)\rightarrow J/\psi\omega$ [17]. A new angular analysis was carried out with the new Belle data. For this purpose, it was assumed that the decay $X(3872)\rightarrow J/\psi\pi^+\pi^-$ proceeds via $X(3872)\rightarrow J/\psi\rho(\rightarrow\pi^+\pi^-)$ in the kinematic limit, i.e. both particles are at rest in the $X(3872)$ rest frame. Due to $m_{X(3872)}\approx m_{\rho}+m_{J/\psi}$ this is a valid assumption and it also implies that any higher partial waves can be neglected. For $J^{PC}=1^{++}$, there is only one amplitude with $L=0$ and $S=1$, where $L$ and $S$ are the total orbital angular momentum between and the total spin constructed from the $\rho$ and the $J/\psi$. For $J^{PC}=2^{-+}$, there are two amplitudes with $L=1$ and $S=1$ or $S=2$. These two amplitudes can be mixed with a mixing parameter $\alpha$, which is a complex number. The angular reference frame follows the definition of Rosner [18]. The angle $\theta_X$ is chosen as the angle between the $J/\psi$ and the kaon direction in the $X(3872)$ rest frame. The angular distributions for $\theta_X$ for the different quantum numbers is given by:

\begin{align}
J^{PC} = 1^{++}, & \quad \frac{d\Gamma}{d\cos\theta_X} \propto \text{const.} \\
J^{PC} = 2^{-+}, \quad \alpha = 0, & \quad \frac{d\Gamma}{d\cos\theta_X} \propto \sin^2\theta_X \\
J^{PC} = 2^{-+}, \quad \alpha = 1, & \quad \frac{d\Gamma}{d\cos\theta_X} \propto 1 + 3\cos^2\theta_X
\end{align}

Two additional angles are defined as follows: the $xy$-plane is spanned by the kaon direction and the $\pi^+$ and $\pi^-$ (back-to-back) directions in the $X(3872)$ rest frame. The $x$-axis is chosen to be along the kaon direction. The $z$-axis is constructed perpendicular to the $xy$-plane. The angle $\chi$ is chosen between the $x$-axis and the $\pi^+$ direction. The angle $\theta_\mu$ is chosen between the $\mu^+$ direction and the $z$-axis. A simultaneous fit for all three angles was performed, and the distributions and the fit results for $\theta_X$ are shown in Fig. 2. The $\chi^2$ values are listed in Tab. 3. For the case of $J^{PC}=2^{-+}$, the values in Tab. 3 are given for $\alpha=0.69\exp(i23^\circ)$, which was found in a grid search and which is the only value which gives a confidence level >0.1
Table 3: $\chi^2$ values for the fit of the angular distributions. See text for the definitions of the angles.

for all three angles. Although at the current level of statistical significance, it cannot be distinguished definitely between the two quantum numbers, however $J^{PC}=1^{++}$ seems to be slightly preferable in this analysis. For additional details see [7].

3 $\chi_{c2}$ in $B$ Meson decays

In the decay $B^+\to K^+\chi_{c1,2}(\to J/\psi\gamma)$ for the first time a $\chi_{c2}$ signal could be observed with a statistical significance of 3.6$\sigma$ (Fig. 3). This is the observation of a $J=2$ charmonium state with positive parity in $B$ meson decays and thus very interesting for two reasons: on the one hand, due to the $j_q=1/2$ of the two charm quarks forming the charmonium state, and the $J=0$ in the initial state (i.e. $J^P=0^-$ for the $B$ meson), $J=0$ and $J=1$ are preferred, and $J=2$ is difficult to be generated. One the other hand, this decay $0^-\to 0^- 2^+$ is, because of the positive parity of the charmonium state, forbidden in naive factorization [19]. This implies that at least one additional gluon is required to connect the charmonium and the $K^+$ sides. For additional details of the analysis see [20].

Figure 3: Invariant mass $m(J/\psi\gamma)$ for the decay $B^+\to K^+\chi_{c1,2}(\to J/\psi\gamma)$. The zoomed region shows the $\chi_{c2}$ signal. See text for details.

4 Summary

This paper covered three different topics. At first, the width of the $\eta'$ was determined with a factor $\simeq 2$ smaller error compared to the previous world average. Interference with
non-resonant background turned out to be important and were taken into account. At second, new results on the \(X(3872)\) employed multi-dimensional fits, increasing by constraints the resolution to beyond the detector resolution. The new world average mass of the \(X(3872)\) is only \(120\pm350\) keV below the \(D^*\bar{D}^0\) threshold. At third, the production of a \(J^P=2^+\) charmonium state was observed in \(B\) meson decays.

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