# 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 $3\leqslant a\leqslant 7$, 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 $B^+\rightarrow K^+\eta_c(\rightarrow K_S K^\pm\pi^\mp)$ [2], the mass and the width of the $\eta_c$ were determined by a 2-dimensional fit of the invariant mass $m(K_S K\pi)$ vs. the angle $\angle(K_S K)$. 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$\pm$1.5$^{+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 $D^0\overline{D}^0$ 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$^{+8.4}_{-5.1}{}^{+2.6}_{-0.9}$ MeV for the fit with interference and $\Gamma$=41.1$\pm$12.0$^{+6.4}_{-10.9}$ MeV for a fit without

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| $\Gamma_{\eta_c}$ | Production Mechanism | Reference |
|---|---|---|
| $35.1\pm3.1^{+1.0}_{-1.6}$ MeV | $B$ decays | [2] and this paper |
| $30.5\pm1.0\pm0.9$ MeV | $\psi'\to\gamma\eta_c$ | [3] |
| $28.1\pm3.2\pm2.2$ MeV | $\gamma\gamma\to\eta_c$ | [4] |
| $31.7\pm1.2\pm0.8$ MeV | $\gamma\gamma\to\eta_c$ | [5] |
| $36.3^{+3.7}_{-3.6}\pm4.4$ MeV | $B$ decays | [6] |

**Table 1:** Width measurements of the $\eta_c$.

interference (i.e. fit of only the invariant mass). The factor $\simeq$5 narrower width of the $\eta_c'$ 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. $\Gamma(^1S_0\to gg)=(32\pi\alpha_S^2/m_c^2)|\psi(r=0)|^2$, 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 $\simeq$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 $B^+\to K^+$X(3872) and $B^0\to K^0(\to\pi^+\pi^-)$X(3872) are based upon the complete Belle data set of 711 fb$^{-1}$ collected at the Υ(4S) resonance [7]. For the determination of the mass and the width of the X(3872) in the decay X(3872)$\to J/\psi\pi^+\pi^-$, a 3-dimensional fit was performed using the three variables beam constraint mass $M_{\rm bc}=\sqrt{(E^{cms}_{beam})^2-(p^{cms}_B)^2}$ (with the energy in the center-of-mass system $E^{cms}_{beam}$ and the momentum of the $B$ meson in the center-of-mass system $p^{cms}_B$), the invariant mass $m(J/\psi\pi^+\pi^-)$ and the energy difference $\Delta E=E^{cms}_B-E^{cms}_{beam}$ (with the energy of the $B$ meson in the center-of-mass system $E^{cms}_B$). In a first step, the fit was performed for the reference channel $\psi'\to J/\psi\pi^+\pi^-$, 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 $D^{*0}\overline{D}^0$ 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 $E_b=-0.12\pm0.35$ 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.

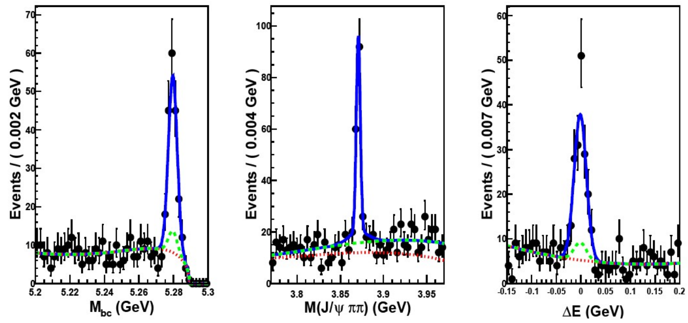


**Figure 1:** Beam constraint mass $M_{\rm bc}$ (left), invariant mass $m(J/\psi\pi^+\pi^-)$ (center) and $\Delta E$ (right) for $B^+ \to K^+$X(3872)($\to J/\psi\pi^+\pi^-$).

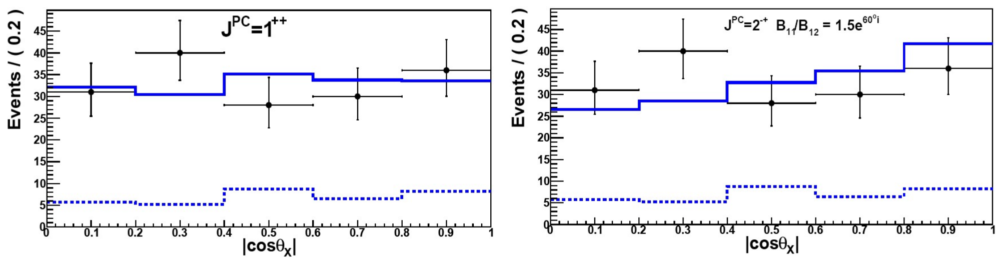


**Figure 2:** Distribution of $|\cos(\theta_X)|$ for $B^+ \to K^+$X(3872)($\to J/\psi\pi^+\pi^-$). The blue line shows the fit for $J^{PC}$=$1^{++}$ (left) and $J^{PC}$=$2^{-+}$ (bottom). For details see text.

*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 $\Gamma_{X3872}$<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 $<\sigma>\simeq 4$ MeV because of the constraints which enter by $M_{\rm bc}$ 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 $\Gamma_{\psi'}^{measured}$=0.52±0.11 MeV. As the world average is $\Gamma_{\psi'}^{PDG}$=0.304±0.009 MeV, this indicates a bias in our measurement of $\Delta\Gamma$=+0.23±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 $w_{90\%}$ for an integral $\int_0^{w_{90\%}} \Gamma d\Gamma$=0.9. This procedure gives $w_{90\%}$=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 $\simeq$2 narrower than the previous upper limit.

| 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 | |

**Table 2:** Mass measurements of the X(3872).

*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 $\chi'_{c1}$, a $^3P_1$ state with $J^{PC}$=$1^{++}$. The predicted mass by potential models is $m$=3953 MeV, thus $\simeq$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 $\eta_{c2}$, a $^1D_2$ state with $J^{PC}$=$2^{-+}$. The predicted mass by potential models is $m$=3837 MeV, thus $\simeq$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 $m_{X(3872)}\simeq m_\rho+m_{J/\psi}$ 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:

$$
\begin{aligned}
(1) \qquad & J^{PC} = 1^{++}, & & \frac{d\Gamma}{dcos\theta_X} \propto const. \\
& J^{PC} = 2^{-+}, & \alpha = 0, \quad & \frac{d\Gamma}{dcos\theta_X} \propto \sin^2\theta_X \\
& J^{PC} = 2^{-+}, & \alpha = 1, \quad & \frac{d\Gamma}{dcos\theta_X} \propto 1 + 3\cos^2\theta_X
\end{aligned}
$$

Two additional angles are defined as follows: the $xy$-plane is spanned by the kaon direction

| Angle | $\chi^2$/n.d.f. | C.L. | $\chi^2$/n.d.f. | C.L. |
|---|---|---|---|---|
| | $J^{PC}$=$1^{++}$ | | $J^{PC}$=$2^{-+}$ | |
| $\chi$ | 1.76/4 | 0.78 | 4.60/4 | 0.33 |
| $\theta_{lepton}$ | 0.56/4 | 0.97 | 5.24/4 | 0.26 |
| $\theta_X$ | 3.82/4 | 0.51 | 4.72/4 | 0.32 |

**Table 3:** $\chi^2$ values for the fit of the angular distributions. See text for the definitions of the angles.

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($i23^o$), which was found in a grid search and which is the only value which gives a confidence level >0.1 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 naïve 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].

## 4 Summary

This paper covered three different topics. At first, the width of the $\eta_c'$ 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

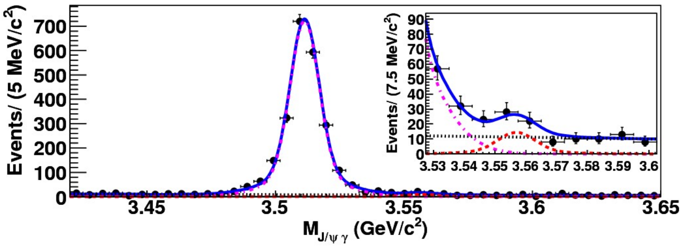


**Figure 3:** Invariant mass $m(J/\psi\gamma)$ for the decay $B^+ \to K^+ \chi_{c1,2}(\to J/\psi\gamma)$. The zoomed region shows the $\chi_{c2}$ signal. See text for details.

resolution to beyond the detector resolution. The new world average mass of the X(3872) is only 120±350 keV below the $D^{*0}\overline{D}^0$ threshold. At third, the production of a $J^P$=2$^+$ charmonium state was observed in $B$ meson decays.

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