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Hadron spectroscopy of possible non-standard hadrons and pentaquark search at Belle

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Abstract. The record performance of the KEKB factory is currently supplying Belle with about 1 million $B\overline{B}$ meson pairs per day. The vast amounts of accumulated data have helped Belle Collaboration to discover new particle states in the charm sector. Two years ago a resonance $X(3872)$ was discovered by Belle that does not seem to correspond to any conventional $c\bar{c}$ meson. Current analysis examined possible J^{PC} quantum number assignments for the $X(3872)$. After exhaustive and detailed investigations of its properties, it seems feasible that $X(3872)$ could represent a first known example of a two-meson molecule. This year Belle reported observation of another possible non-conventional hadron, $Y(3940)$. All that is known about it to date hints at the possibility that it may not be a standard quark-antiquark particle, but, instead, an example of a so-called "hybrid meson," which is a particle that is conjectured to be comprised of a quark, an antiquark and a gluon. Search for pentaquarks was also performed at Belle using kaon secondary interactions in the detector material, where the inclusive production of the $\Theta(1540)^+$ was examined. Upper limit was set on the ratio of the $\Theta(1540)^+$ to $\Lambda(1520)$ inclusive production cross-sections.

1 Introduction

The Belle detector [1] is situated at the KEKB e^+e^- collider with asymmetric beam energies tuned to the energy of the $\Upsilon(4S)$ resonance [2]. Its main purpose is to explore CP violation in the decays of B mesons, but its very clean environment with small number of particles in events due to colliding leptons, and specially its record luminosity performance in collecting events, makes it suitable also for other types of analysis.

One of the active sidelines of the Belle detector is also a search for new possible non-standard resonances. Such a search enables us to test the predictions of QCD at low energies (bound states) where the running coupling constant α_s is large and QCD is in its non-perturbative regime.

Search for pentaquarks is also performed with Belle detector data. Since it was argued that the production mechanisms for pentaquark production might be different at different energies, we perform the search both in the B decays and in the events where charged kaons, with typical energies of 0.5 GeV, interacted with the detector material.

1.1 Belle detector

The Belle detector is situated at the interaction region of the e^+e^- beams, covering 92% of the solid angle. Several detector sub-parts enable reconstruction of tracks and identification of particles that were produced in the collision.

The sub-detector closest to the interaction point is the Silicon Vertex Detector (SVD) and it is used to measure the primary and secondary vertices of the produced tracks. The particle momenta are measured using the main tracking device of the detector, the Central Drift Chamber (CDC), which is enclosed in a superconducting solenoid, providing a homogeneous 1.5 T magnetic field. The identification of charged particles is performed with the help of the Time of Flight detector (TOF) and the Aerogel Cherenkov Counter (ACC), where particle velocities are measured through the Cherenkov effect. Combined information on momentum and velocity of the particle determines its mass; the efficiency for identification of charged kaons is about 85%, where the probability of mis-identification of a pion as a kaon is less than 10%, exact performance depending on the momentum and the direction of charged tracks. Electrons and photons are identified in the Electromagnetic Calorimeter (EC), where their energy is measured. Muons and K_L candidates are detected using the K_L and Muon detector (KLM).

1.2 Reconstruction of events with B mesons

The collisions of e^+e^- produce a $q\bar{q}$ meson, where q can be any of the quarks u, d, s, c or b. A smaller sample of data is recorded at about 60 MeV below the mass of the $\Upsilon(4S)$, called continuum data, to study the effect of this continuum (non-$\Upsilon(4S)$) background on the B meson reconstruction.

The reconstruction of B decays needs to differentiate between events where $\Upsilon(4S)$ was produced and events where $q\bar{q}$ mesons with other quarks were produced. This is achieved by combining several observables separating the more spherical B meson decays (B mesons are produced almost at rest in the center-of-mass system of e^+e^-(cms)) from the jet-like annihilation events [3].

The quality of B meson reconstruction is assessed based on the beam-constrained mass, $M_{bc} = \sqrt{E^{*2}_{beam}/c^4 - p^{*2}_B/c^2}$, and the energy difference, $\Delta E = E^*_B - E^*_{beam}$. Here $E^*_{beam} = \sqrt{s}/2 \simeq 5.290\,\mathrm{GeV}$ is the beam energy in the cms, and p^*_B and E^*_B are the cms momentum and energy of the reconstructed B meson. These two variables are used instead of the invariant mass of the B meson, due to better resolution. For genuine decays of the B meson the M_{bc} distribution has a peak at about 5.28 GeV/c^2, the mass of the meson, and ΔE peaks at zero.

To observe a resonance, such as the ones discussed in the following sections, a significant peaking component is searched for in the distributions of the beam-constrained mass near $5.28\,\mathrm{GeV}/c^2$ and energy difference around zero, and the number of events reconstructed in the resonance is obtained by fitting the M_{bc} and ΔE distributions to the sum of an empirical parametrization of the background plus a signal shape.

2 What kind of resonances are X(3872) and Y(3940)?

2.1 X(3872)

The resonance called X(3872) was discovered by the Belle collaboration in 2003 as an enhancement in the $B \to K\pi^+\pi^- J/\psi$ decays [4] and was soon after confirmed by three other experimental groups [5]. It was seen as a narrow peak in decays $B \to \pi^+\pi^- J/\psi K$, where the particle J/ψ is reconstructed in the decays to two leptons: $J/\psi \to \ell^+\ell^-$. There are many difficulties in identifying X(3872) as a $c\bar{c}$ resonance. For example, the distribution of the invariant mass of the pion pair has a broad enhancement near the nominal ρ mass that cannot be described well by the predicted phase space distribution, and seems to be consistent with a ρ meson. The decay of a $c\bar{c}$ meson into $\rho J/\psi$ is isospin-violating and should be highly suppressed, indicating that the resonance X(3872) might not be one of the of the yet unidentified $c\bar{c}$ mesons. Belle collaboration therefore performed several tests [6,7] to determine X(3872) quantum numbers J, P and C, enabling it to make further interpretation. The observation of radiative $X(3872) \to \gamma J/\psi$ decays and

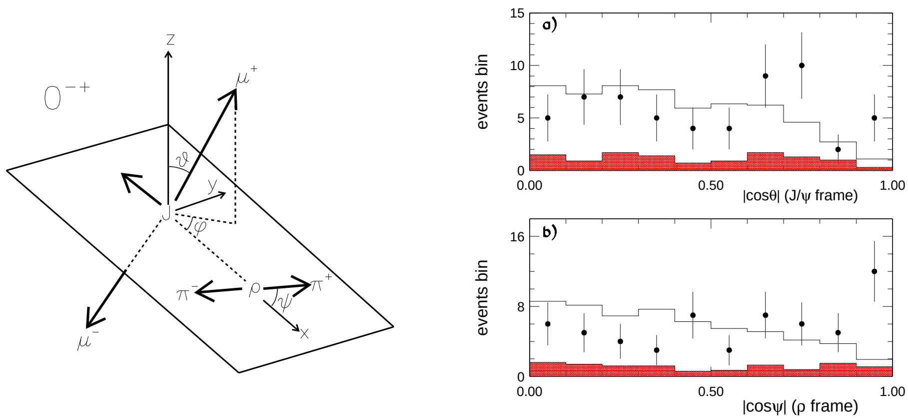

Fig. 1. $X(3872) \to \pi^+\pi^- J/\psi$ angular distributions for data (points), and for the $J^{PC} = 0^{-+}$ hypothesis (histogram), including background estimated from the mass sidebands (shaded). The definition of the angles is shown in the sketch on the left. The χ^2 of the fits are (a) 17.7 and (b) 34.2 for 9 degrees of freedom, disfavoring 0^{-+}. Note the concentration of events in the final bins, contrary to expectation.

subtreshold decays to $\omega^* J/\psi$ in $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$ decays [6] indicate that the C-parity of X(3872) is even.

The analysis of angular correlations of X(3872) decays [7] was used to test different J^{PC} hypotheses, exploiting the comparison of predicted distributions to data in the region where the predicted distribution has zeroes [8] (an example of such analysis is shown in Fig. 1). Such an analysis disfavored 0^{++} and 0^{+-}, while showing good agreement with the 1^{++} assumption. The fits to the invariant mass distribution of the two charged pions in $X(3872) \to \pi^+\pi^- J/\psi$ decays favor J^{++}

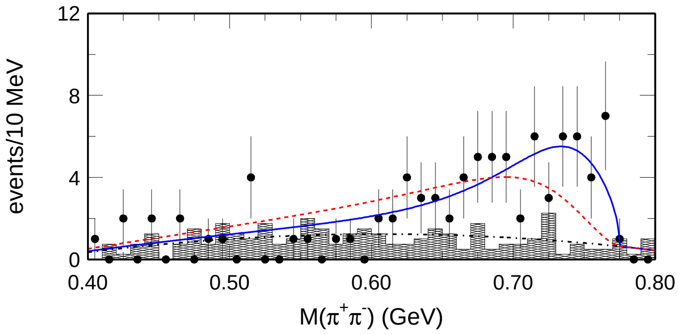

Fig. 2. The distribution of $M(\pi^+\pi^-)$ for events in the $X(3872)$ signal region (points) and sideband (shaded). Fits for S-wave (solid) and P-wave (dashed) hypotheses are also shown, showing the preference for the S-wave hypothesis.

assignment (Fig. 2). The roll-off near the kinematical boundary has a different $q^*_{J/\psi}$ dependence for an S wave ($q^*_{J/\psi}$) compared to a P wave ($(q^*_{J/\psi})^3$), yielding a better agreement for the S wave.

To compare the 1^{++} and 2^{++} assignments, the search of decays $X(3872) \to D^0\overline{D}^0\pi^0$ was performed. The preliminary evidence of such decays disfavors $J^{PC} = 2^{++}$.

We conclude that the assignment for $X(3872)$, corresponding best to our data, is $J^{PC} = 1^{++}$; it is unlikely, though, that $X(3872)$ be the charmonium 1^{++} state χ'_{c1}. Our conclusion rests on the following facts: The χ'_{c1} mass is predicted to be about $100\,\mathrm{MeV}/c^2$ higher than observed, the isospin-violating decays $\chi'_{c1} \to \pi^+\pi^- J/\psi$ should have a very small partial width, contradictory to the measurement, and the low ratio of radiative to dipion partial widths $\Gamma(X \to \gamma J/\psi)/\Gamma(X \to \pi^+\pi^- J/\psi) = 0.14 \pm 0.05$ [6], all disfavoring the χ'_{c1} interpretation.

The observed properties of $X(3872)$ agree well with the molecular $D^0 - \overline{D}^{*0}$ model proposed by Swanson [9]. The mass of the resonance is within errors consistent to the sum of the masses of D^0 and $\overline{D}^{*0}$ mesons: $M(D^0) + M(\overline{D}^{*0}) - M(X) = 0.6 \pm 1.1\,\mathrm{MeV}/c^2$. Since the mass difference of $M(D^+D^{*-}) - M(D^0\overline{D}^{*0}) = 8.1\,\mathrm{MeV}/c^2$ is large compared to it, the isospin violation is natural for such a state, explaining the observation of nearly equally common decays of X to $2\pi J/\psi$ and $3\pi J/\psi$. The small value of $\Gamma(X \to \gamma J/\psi)/\Gamma(X \to \pi^+\pi^- J/\psi)$ is also predicted by the same model.

2.2 Y(3940)

It is natural to ask if the $X(3872)$ resonance is the only non-standard meson candidate in this mass region or is there a new set of resonances with similar non-standard properties like $X(3872)$. A search was performed for enhancements in the spectra of $\rho J/\psi$, $\eta J/\psi$ and $\omega J/\psi$. While the search in the first two modes was unsuccessful, we have observed [10] an enhancement in the spectrum of $\omega J/\psi$ just above the threshold (Fig. 3).

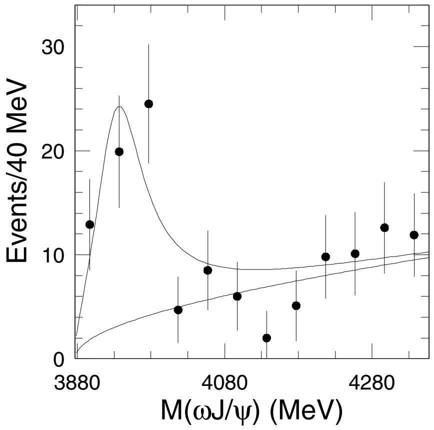

Fig. 3. The invariant mass distribution of $\pi^+\pi^-\pi^0 J/\psi$ just above the threshold for $\omega J/\psi$, from the $B^+ \to K^+\pi^+\pi^-\pi^0 J/\psi$ decays.

The B meson yield was obtained by a simultaneous fit to the M_{bc} and ΔE distributions in bins of $25\,\text{MeV}/c^2$ in $M(\omega J/\psi)$. The obtained yields are plotted in Fig. 3, where the lower curve shows the expectation for the pure phase space distribution, while the enhancement of events, present near the threshold, is fitted using an additional Breit-Wigner function. The Breit-Wigner signal yield is found to be 58 ± 11 events (with statistical significance above 8σ) and was interpreted as a particle ($Y(3940)$) with mass $M = (3943 \pm 11 \pm 13)\,\text{MeV}/c^2$ and decay width $\Gamma = (87 \pm 22 \pm 26)\,\text{MeV}$.

Since the mass of $Y(3940)$ is above the $D\overline{D}^{(*)}$ mass threshold, if this is a standard $c\bar{c}$ resonance, its dominant decay should be to $D\overline{D}^{(*)}$, while the first observation of an enhancement in a decay channel other than $D\overline{D}$ is surprising. While its width makes it unlikely to be a tetraquark, it is a possible candidate for a $c\bar{c} - gluon$ hybrid, for which the decays to open charm are expected to be suppressed or forbidden. Further analysis, determining its quantum numbers, will help resolve its identity.

3 Pentaquark search

Belle has performed dedicated searches of some exotic states interpreted as pentaquarks, that were claimed to be observed in last few years [11,12]. Search was performed in both B decays, and, to mimic the production mechanism of some of the detectors observing pentaquarks [11], in the events where a kaon interacted with detector material.

The search for Θ^+, Θ^{*++}, Θ_c^0 and Θ_c^{*+} was performed [13] in B decays to proton, anti-proton and a D meson or kaon, setting upper limits to ratios of branching fractions for decays proceeding over the searched exotic state to all decays with same decay products.

For example, for the search of $B^0 \to \overline{p}\pi^+\Theta_c^0 \to \overline{p}\pi^+D^-p$ the reconstructed ΔE distribution is shown in Fig.4 (left). For events in the signal region (consisting of 303±21 signal events) the mass of the D^-p is presented in Fig.4 (right). This distribution is fitted with a phenomenological function describing the background and a Gaussian signal, positioned at the mass of 3099 MeV/c^2, corresponding to the mass of the claimed Θ_c^0 pentaquark [12]. Since the peak of the expected pentaquark should be narrower than the detector resolution, the width of the signal part was fixed at 3.5 MeV, the estimated detector resolution. No statistically significant signal was found and the corresponding 90% C.L. upper limit on the production of Θ_c^0 relative to the $B^0 \to \overline{p}\pi^+D^-p$ branching ratio is placed at

$$Br(B^0 \to \Theta_c^0\overline{p}\pi^+) \cdot Br(\Theta_c^0 \to D^-p)/Br(B^0 \to \overline{p}\pi^+D^-p) < 1.2\% \ .$$

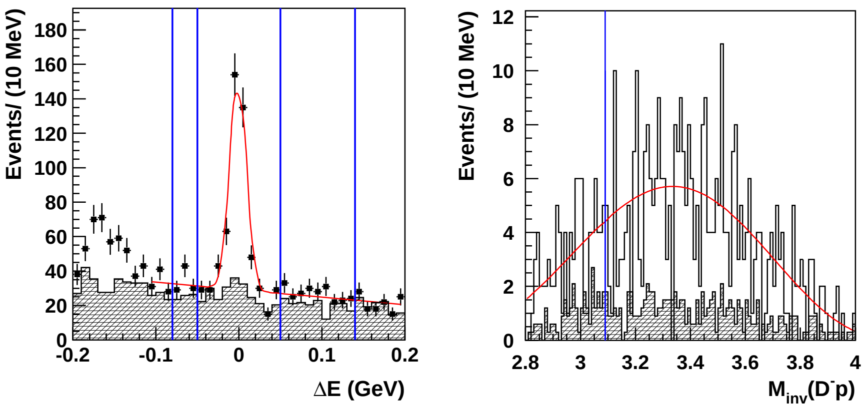

Fig. 4. Left: ΔE distribution of $B^0 \to \overline{p}\pi^+D^-p$ decays, the vertical lines flag the ΔE sideband. Right: Invariant mass of D^-p pairs for events in ΔE signal region, the background (shaded) is estimated from the ΔE sideband. The result of the fit with a phenomenological model function is also shown (dotted/red), while the vertical line indicates 3099 MeV/c^2.

In the search using interactions of charged and neutral kaons in the material of the detector [14] the average energy of kaons is 0.5 GeV, creating "low energy" conditions of pentaquark search similar to that of the HERMES detector [11].

The coordinates of the common vertices of identified K_sp and $K^{\pm}p$ pairs produce a "tomographic" picture of the detector (Fig. 5, left), where the distribution of the material in the beam pipe, ladders of SVD and the support structure of the CDC are clearly visible), showing that such pairs correspond to secondary reactions with the detector material.

The search is performed in $M(pK_S)$, the invariant mass of the pK_S pair, by comparing the possible signal in $M(pK_S)$ to the large signal of $\Lambda(1520)$ in the $M(pK^-)$ distribution (Fig. 5, right).

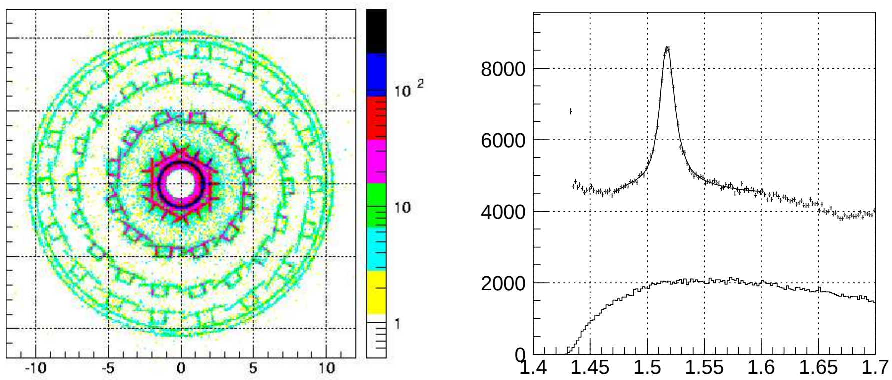

Fig. 5. Left: Scatter plot of pK vertices in the plane perpendicular to the beam, where various elements of the detector can be seen. Right: the invariant mass distributions for the pK^- (top, with $\Lambda(1520)$ peak) and pK_S pairs. (bottom).

In the $M(pK^-)$ distribution the $\Lambda(1520)$ peak in the $M(pK^-)$ is fitted with a threshold function and a D-wave Breit-Wigner term, convolved with the experimental resolution (2 MeV/c^2). The obtained parameters of $\Lambda(1520)$ are in agreement with the world average values [15]. The distribution for the pK_S pairs is fitted with a third order polynomial and a narrow signal, positioned at different values of $M(pK_S)$. For $M(pK_S) = 1540\,\mathrm{MeV}/c^2$, the mass of the claimed Θ^+ pentaquark [11], the resulting signal yield is 58 ± 129 events. Assuming $\mathrm{Br}(\theta^+ \to pK_S) = 25\%$, $\mathrm{Br}(\Lambda(1520) \to pK^-) = 1/2\ \mathrm{Br}(\Lambda(1520) \to N\overline{K})$, and evaluating the ratio of efficiencies for $\theta^+ \to pK_S$ and $\Lambda(1520) \to pK^-$ from MC, one arrives at the upper limit for θ^+ production using Feldman-cousins method [16]:

$$\frac{\sigma(KN \to \theta^+ X)}{\sigma(\overline{K}N \to \Lambda(1520)X)} < 2.5\% \text{ at } 90\%\text{C.L.}$$

This result is two orders of magnitude lower than the value reported by the HERMES Collaboration [11].

4 Conclusion

Recent analyses show that the Belle detector is suitable also for searches of possible new exotic particles, which can test our understanding of QCD. The determination of quantum numbers of $X(3872)$ and the observation $Y(3940)$ opens a new page in exotic particle spectroscopy with exciting possibilities.

The search for pentaquarks puts Belle among the experiments with negative search results, which seem to outnumber those claiming to have detected pentaquarks. The puzzle is nevertheless far from resolved yet, and Belle will try to contribute to increasing the understanding in this field.

References

1. A. Abashian et al. (Belle Collaboration), Nucl. Instrum. Meth. **A 479** (2002) 117.
2. S. Kurokawa, E. Kitakani, Nucl. Instr. Meth. A **A499** (2003) 1.
3. K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **87** (2001) 101801, and references therein.
4. S. K. Choi, S. L. Olsen et al. (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).
5. D. Acosta et al. (CDF-II), Phys. Rev. Lett. **93** (2004) 072001;
   V. M. Abazov et al. (D0), Phys. Rev. Lett. **93** (2004) 162002;
   B. Aubert et al. (BaBar), Phys. Rev. D **71** (2005) 071103.
6. K. Abe et al. (Belle Collaboration), BELLE–CONF–0540, `arXiv:hep-ex/0505037`.
7. K. Abe et al. (Belle Collaboration), BELLE–CONF–0541, `arXiv:hep-ex/0505038`.
8. J. Rosner, Phys. Rev. D **70**, 094023 (2004).
9. E. S. Swanson, Phys. Lett. B **588** (2004) 189; Phys. Lett. B **598** (2004) 197.
10. S. K. Choi, S. L. Olsen et al. (Belle Collaboration), Phys. Rev. Lett. **94** (2005) 182002.
11. HERMES Collaboration, A. Airapetian et al., Phys. Lett. B **585** (2004) 213.
12. H1 Collaboration, A. Aktas et al., Phys. Lett. B **588** (2004) 17.
13. R. Mizuk (for the Belle Collaboration), `arXiv:hep-ex/0411005`.
14. K. Abe et al. (Belle Collaboration), BELLE–CONF–0518, submitted to Phys. Lett. B, `hep-ex/0507014`.
15. S. Eidelman et al. (Particle Data Group), Phys. Lett. B **592** (2004) 1.
16. G. J. Feldman and R. D. Cousins, Phys. Rev. D **57** (1998) 3873.