Spectroscopy and new particles

Tadeusz Lesiak

Institute of Nuclear Physics PAN
Radzikowskiego 152, 31-142 Kraków, Poland

Abstract. The properties of three new particles: X(3872), Y(3940) and Z(3931), recently discovered by the Belle collaboration, are briefly reviewed. Negative results of the search for the pentaquark Θ(1540)+ are also presented.

INTRODUCTION

In the last two years the Belle collaboration has provided evidence for several new hadrons. This paper presents the observation of three new particles: X(3872), Y(3940) and Z(3931). The other new states discovered recently by Belle were also discussed at this conference in separate talks [1, 2]. The paper also presents the results of searches for the pentaquark state Θ(1540)+. The Belle detector at the KEKB asymmetric e+e− collider [3] is a general purpose spectrometer, described in detail in [4].

PROPERTIES OF THE X(3872)

FIGURE 1. The distribution of π+π− invariant mass for events in the X(3872) → π+π−J=ψ signal region (data points). The shaded histogram corresponds to the background as determined by the X-mass sidebands. The solid (dashed) curve denotes a fit that uses a ρ Breit-Wigner shape with the ρ and J=ψ in a relative S(P)-wave. The dash-dotted curve shows a smooth parametrization of the background that is used in the fit.

The state X(3872) was discovered by the Belle collaboration in 2003 [5] by analyzing exclusive decays B+ → π+π−J=ψK+ (charge conjugate modes are included everywhere, unless otherwise specified). The B mesons were reconstructed using two kine-

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matical variables: the energy offset $\Delta E = \sum E_i - E_{beam}$ and the beam-constrained mass $M_{bc} = \frac{E_{beam}^2 - \sum_i (p_i)^2}{2}$, where $E_i$ and $p_i$ are the center-of-mass (CMS) energies and momenta of the selected $B$ meson decay products and $E_{beam}$ is the CMS beam energy. A very narrow peak in the invariant mass spectrum of the system $\pi^+ \pi^- \ J = \psi$ was observed with a mass of $3872 \pm 0.5 \pm 0.5 \text{ MeV}/c^2$ and a width below $2.3 \text{ MeV} (90\% \text{ C.L.}).$

The observation of $X(3872)$ was very quickly confirmed by the CDF [4], D0 [7] and BaBar [8] experiments. The observed decay mode $X ! \pi^+ \pi^- J = \psi$ seemed to favour the explanation of the $X(3872)$ as an excited charmonium state [9, 10]. However, its properties, in particular the very narrow width, did not allow the identification of the $X(3872)$ with any $c\bar{c}$ state. At the same time the coincidence of the $X$ mass with the $D^0 D^0$ threshold $(3871 \pm 1 \pm 0) \text{ MeV}/c^2$ has prompted many theoretical speculations that $X(3872)$ may be a so-called deuson i.e. a loosely bound molecular state of these two mesons [11, 12]. Moreover, the $\pi^+ \pi^-$ invariant mass distribution (Fig. 1) was found to peak close to the upper kinematical limit of $M(\pi^+ \pi^-)$ as expected for pion-pairs originating from $\rho ! \pi^+ \pi^-$ decays.

Recently, the Belle collaboration, using the $253 \text{ fb}^{-1}$ data sample collected at the $\Upsilon(4S)$ resonance, has provided the first evidence for two new decay modes: $X ! \gamma J=\psi$ and $X ! \pi^+ \pi^- \pi^0 J=\psi$ [13]. They were observed in exclusive $B$ meson decays to the final states $\gamma J=\psi K$ and $\pi^+ \pi^- \pi^0 J=\psi K$, respectively. The yield of the decay $B ! \gamma J=\psi K$ plotted in bins of the $\gamma J=\psi$ invariant mass (Fig. 2a)) exhibits an excess of $13 \pm 4 \pm 4$ events (statistical significance of $4\sigma$). The observation of this decay establishes unambiguously that the charge-conjugation parity of the $X(3872)$ is positive. The partial width ratio $\Gamma(X ! \gamma J=\psi)/\Gamma(X ! \pi^+ \pi^- \pi^0 J=\psi)$ amounts to $0.14 \pm 0.05$. This result is in contradiction with the $X^0(1^+)$ (1$^+$ charmonium) assignment for $X$ as in this case a value around 40 would be expected. The second decay mode $X ! \pi^+ \pi^- \pi^0 J=\psi$ was found to be dominated by the sub-threshold decay $X ! \omega J=\psi$. This is motivated by the fact that the yield of $B$ mesons plotted in bins of the $\pi^+ \pi^- \pi^0 J=\psi$ invariant mass (Fig 2b)) inside of the signal region from the decay $X ! \pi^+ \pi^- \pi^0 J=\psi$ is consistent with zero except for the $M(\pi^+ \pi^- \pi^0) > 750 \text{ MeV}/c^2$. There, the excess of $12 \pm 4 \pm 4$ events (3.5$\sigma$) is observed. The ratio of branching fractions $B(X ! \pi^+ \pi^- \pi^0 J=\psi) / B(X ! \pi^+ \pi^- J=\psi)$ was measured to be $1.0 \pm 0.3 \pm 0.3$, which implies a large violation of isospin symmetry.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{The yield of $B$ mesons from the decay \textbf{a}) $B^0 \to \gamma J=\psi K$, in bins of the $\gamma J=\psi$ invariant mass and \textbf{b}) $B^0 \to \pi^+ \pi^- \pi^0 J=\psi K$, in bins of the $\pi^+ \pi^- \pi^0$ invariant mass, determined from fits to the $\Delta E$ and $M_{bc}$ distributions.}
\end{figure}
The Belle collaboration also attempted to determine the $J^{PC}$ quantum numbers of the X(3872) [14] by studying the angular distributions of the decay $X \to \pi^+ \pi^- J=\psi$, as suggested by Rosner [15]. Among the twelve possible $J^{PC}$ assignments, half (0$^+$, 0$^-$, 1$^-$, 1$^+$, 2$^-$ and 2$^+$) may be discarded due to their negative charge conjugation-parity. The value 1$^+$ is in agreement with the data while the assignments 0$^+$ and 0$^-$ are strongly disfavoured by the analysis of angular distributions [14]. The additional two odd-parity possibilities: 1$^-$ and 2$^+$ are discarded as for them the dipion invariant mass spectrum (Fig. 1) is expected to be much softer to compare with the data. On the other side, the distribution of $M(\pi^+\pi^-)$ is in agreement with the 1$^+$ hypothesis. The assignment 2$^+$ was strongly disfavoured by the recent, preliminary observation by Belle [16] of the decay $B^+ \to K X^0$, $X \to D^0 D^0 \pi^0$, where the 11 $3\sigma$ signal events (5.6$\sigma$) concentrate close to the threshold for the final state $D^0 D^0 \pi^0$. In the 2$^+$ case, the decay of a spin 2 state to three pseudoscalars ($D^0 D^0 \pi^0$) would require at least one pair of them to be in a relative D wave. In such a configuration the near threshold production would be strongly suppressed by a centrifugal barrier.

All the above observations strongly favour the assignment of $J^{PC} = 1^+$ to the X(3872). This matches the expectations of models [11, 12] interpreting the X as a $D^0 D^0$ bound state. This hypothesis also explains the narrow width of the X(3872) and the shape of $\pi^+ \pi^-$ and $\pi^+ \pi^- \pi^0$ spectra in its corresponding decays and leads to the prediction of large isospin violation in the X decays. Among alternative interpretations are: a ‘conventional’ charmonium [9, 10, 17], glueball [18], tetraquark [19] or the so called cusp effect [20].

**EVIDENCE FOR THE Y(3940)**

In 2004 The Belle collaboration provided evidence for another new state, Y(3940), decaying to $\omega J=\psi$ [21]. It was again observed in the $B^+$ meson exclusive decay to the final state $K^+ \pi^+ \pi^- \pi^0 J=\psi$. A fit to the $\omega J=\psi$ invariant-mass distribution (Fig. 3) yielded a signal of 58 $11$ events (8.1$\sigma$) corresponding to a mass of 3943 $11$ 13 MeV/c$^2$ and the width 87 $22$ 26 MeV. The Y mass coincides with that of another

![FIGURE 3](image-url)
FIGURE 4. Invariant mass distribution of $D\bar{D}$ pairs. The solid (dashed) curve shows the fits with (without) a resonance component. The histograms correspond to the distribution of the events from the $D$-mass sidebands.

particle, $X(3940)$, also observed by Belle [1, 2]. However, it is unlikely that these two states are the same, since the $X(3940)$ decays to $D\bar{D}$ and does not decay to $\omega f=\psi$ and the situation is reversed for the $Y(3940)$, as far as the above-mentioned decays are concerned. The properties of $Y(3940)$ are similar to those expected for the $c\bar{c}$ gluon hybrid mesons [22].

DISCOVERY OF THE Z(3931)

A recent search by the Belle collaboration for the production of new resonances in the process $\gamma\gamma \rightarrow D\bar{D}$ [23] yielded evidence for a new state (Fig. 4) at a mass of $3931 \pm 2$ MeV/c$^2$ and a width of $20\pm 8$ MeV. A signal of 41 ± 11 events with a statistical significance of $5.5\sigma$ was observed. The properties of this new state match the expectations [24, 10] for the radially excited states $X^0_{c}$ and $X^2_{c}$. A study of angular distributions of the $D$ mesons in the $\gamma\gamma$ rest frame revealed that the data significantly prefer a spin two assignment over spin zero.

FIGURE 5. Invariant mass spectrum for secondary $pK^0_s$ pairs and expected yield of the charge exchange reaction per 2 MeV/c$^2$ (open dots). A fit to a third order polynomial is represented by the dashed curve. The $\Theta(1540)^+$ contribution expected from the DIANA result [24] is presented with the solid line.
SEARCH FOR THE Θ (1540)⁺

The Belle collaboration has searched for both inclusive and exclusive production of the Θ (1540)⁺ pentaquark using kaon secondary interactions in the material of the detector [25]. An upper limit of 2.5 % (90 % C.L.) was set on the ratio of the Θ (1540)⁺ to Λ (1520) inclusive production cross section. The search for the exclusive production of the Θ (1540)⁺ as an intermediate resonance in the charge exchange reaction $K^+ n \rightarrow p K^0_s$ yielded an upper limit of $\Gamma_{\Theta^+} < 0.64$ MeV (90 % C.L.) at $m_{\Theta^+} = 1539$ MeV/c². This value is below the current Particle Data Group [27] value of 0.9 ± 0.3.

SUMMARY

The properties of three new particles: X(3872), Y(3940) and Z(3931), recently observed by the Belle collaboration, were reviewed. For the X(3872) the observation of new decay modes together with angular analysis of the $\pi^+ \pi^- J=\psi$ favours the assignment $J^{PC} = 1^{++}$ and is in agreement with the deuson hypothesis. The most plausible interpretations of the Y(3940) and Z(3931) are the $c\bar{c}$ gluon and $c\bar{c} \chi_{c2}$, respectively. The search for the Θ (1540)⁺ yielded a null result giving rise to the limit $\Gamma_{\Theta^+} < 0.64$ MeV (90 % C.L.).

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\[ M(\pi^+\pi^- J/\psi) \text{ (MeV)} \]

Events/5 MeV

\[ 3800 \quad 3820 \quad 3840 \quad 3860 \quad 3880 \quad 3900 \quad 3920 \quad 3940 \]

\[ 0 \quad 10 \quad 20 \quad 30 \]
The plot shows the excluded regions for the Higgs mass versus $\tan \beta$ for different experiments:

- **Tevatron Run I (D0) Excluded (95\% C.L.)**
- **LEP Excluded (95\% C.L.)**
- **Belle $2.75 \times 10^6$ BB (90\% C.L.)**
- **BABAR $2.32 \times 10^6$ BB (90\% C.L.)**