PENTAQUARK SEARCH AND OTHER MULTIQUARK CANDIDATES AT BES

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Results are presented on ψ(2S) and J/ψ hadronic decays to $K^0_S p K^- n$ and $K^0_S p K^+ n$ final states from data samples of 14 million ψ(2S) and 58 million J/ψ events accumulated at the BES II detector. No Θ(1540) signal, the pentaquark candidate, is observed, and the upper limits are set. We also present

1 Pentaquark search

In recent years, there have been many experiments claiming a null observation of the Θ(1540). Therefore, further experimental confirmation is required before claiming solid evidence for a $S = +1$ baryon resonance. Compared with the above experiments, the data accumulated at the $e^+e^-$ collision experiment BES are relatively clean and have less background; therefore it is meaningful to investigate the pentaquark state Θ with the hadronic decays of ψ(2S)

and J/ψ. 

The pentaquark state Θ(1540) in ψ(2S) and J/ψ decays to $K^0_S p K^- n$ and $K^0_S p K^+ n$ final states with $K^0_S$ decaying to $\pi^+\pi^-$ is searched for using 14 million ψ(2S) and 58 million J/ψ events taken with the upgraded Beijing Spectrometer (BESII) located at the Beijing Electron Positron Collider (BEPC).

Fig. 1 (left) and Fig. 1 (right) show the scatter plots of $K^- n$ ($K^0_S p$) versus $K^0_S p$ ($K^+ n$) for ψ(2S) and J/ψ → $K^0_S p K^- n$ + $K^0_S p K^+ n$ modes. No clear Θ signal is observed in both ψ(2S) and J/ψ decays. The upper limits are set at the 90% confidence level (C.L.) as:

\[
B(\psi(2S) \rightarrow \Theta K^- n \rightarrow K^0_S p K^- n) < 2.6 \times 10^{-5}
\]

\[
B(\psi(2S) \rightarrow K^0_S p \Theta \rightarrow K^0_S p K^- n) < 0.60 \times 10^{-5}
\]

\[
B(\psi(2S) \rightarrow K^0_S p \Theta \rightarrow K^0_S p K^+ n) < 0.70 \times 10^{-5}
\]

\[
B(J/\psi \rightarrow \Theta K^- n \rightarrow K^0_S p K^- n+c.c.) < 1.1 \times 10^{-5}
\]

\[
B(J/\psi \rightarrow \Theta K^- n \rightarrow K^0_S p K^- n) < 2.1 \times 10^{-5}
\]

\[
B(J/\psi \rightarrow \Theta K^+ n \rightarrow K^0_S p K^+ n) < 5.6 \times 10^{-5}
\]

\[
B(J/\psi \rightarrow K^0_S p \Theta \rightarrow K^0_S p K^- n) < 1.1 \times 10^{-5}
\]

\[
B(J/\psi \rightarrow K^0_S p \Theta \rightarrow K^0_S p K^+ n) < 1.6 \times 10^{-5}
\]

2 Near $p\bar{p}$ threshold enhancement in $J/\psi \rightarrow \gamma p\bar{p}$

There is an accumulation of evidence for anomalous behavior in the proton-antiproton ($p\bar{p}$) system very near the $M_{pp} = 2m_p$ mass...
threshold. Based on a sample of 58 million \( J/\psi \) events accumulated at BES, we report a study of the low mass \( p\bar{p} \) pairs produced via radiative decays.\(^5\)

The events with a high energy gamma ray and two oppositely charged tracks, each of which is well fitted to a helix originating near the interaction point and within the polar angle region \( |\cos \theta| < 0.8 \), are selected. The \( dE/dx \) information is used for the particle identification and both charged tracks should be identified as proton and antiproton. The candidate events are subjected to four-constraint kinematic fits to the hypotheses \( J/\psi \rightarrow \gamma p\bar{p} \) and \( CL_{p\bar{p}} > 0.05 \) is required.

Fig. 2 shows the \( p\bar{p} \) invariant mass distribution for surviving events. Except for a peak near \( M_{p\bar{p}} = 2.98 \text{ GeV}/c^2 \) that is consistent in mass, width, and yield with expectations for \( J/\psi \rightarrow \gamma \eta_c, \eta_c \rightarrow p\bar{p} \)\(^3\) and a broad enhancement around \( M_{p\bar{p}} \sim 2.2 \text{ GeV}/c^2 \), there is a narrow, low-mass peak near the \( p\bar{p} \) mass threshold.

The low mass region of the \( p\bar{p} \) distribution is fitted by an acceptance-weighted \( S \)-wave Breit-Wigner (BW) function to represent the low-mass enhancement and \( f_{\text{bkg}}(\delta) \) to represent the background. The mass and width of the BW signal function are allowed to vary and the shape parameters of \( f_{\text{bkg}}(\delta) \) are fixed at the values derived from the fit to the \( \pi^0 p\bar{p} \) phase-space MC sample. This fit yields 928±57 events in the BW function with a peak mass of \( M = 1859^{+3}_{-10} \mp 5^{+25} \text{ MeV}/c^2 \)

and a full width of \( \Gamma < 30 \text{ MeV}/c^2 \) at a 90% confidence level (CL). Here the first error in the mass is the statistical error and the second is the systematic error which includes changes observed in the fitted values for fits with different bin sizes, with background shape parameters left as free parameters, different shapes for the acceptance variation, different resolutions, and the range of differences between input and output values seen in the MC study. Using a Monte-Carlo determined acceptance of 23%, we determine a product of branching fractions \( B(J/\psi \rightarrow \gamma X(1859))B(X(1859) \rightarrow p\bar{p}) \) = \( (7.0 \pm 0.4(\text{stat})^{+1.9}_{-0.8}(\text{syst})) \times 10^{-5} \), where the systematic error includes uncertainties in the acceptance (10%), the total number of \( J/\psi \) decays in the data sample (5%), and the effects of changing the various inputs to the fit (+24%).

3 The anomalous enhancements near the \( m_p + M_\Lambda \) and \( m_K + M_\Lambda \) mass thresholds in \( J/\psi \rightarrow pK^-\bar{\Lambda} + c.c. \) decays

The results from \( J/\psi \rightarrow pK^-\bar{\Lambda} + c.c. \) decays are presented\(^9\). The \( J/\psi \rightarrow pK^-\bar{\Lambda} \) candidate events are required to have four charged tracks with net charge, each of which is well fitted to a helix within the polar angle region \( |\cos \theta| < 0.8 \) and with a transverse momentum larger than 50 MeV. The combined TOF and \( dE/dx \) information is used for the particle identification. Events where the \( p, K^- \), \( \bar{p} \) and \( \pi^+ \) tracks are all unambiguously identified are subjected to a four-constraint (4C) kinematic fit with the corresponding mass assignments for each track. For events with ambiguous particle identification, all possible 4C combinations are formed, and the combination with the smallest \( \chi^2 \) is chosen. The final \( \chi^2 \) is required to be less than 20. The background events from \( J/\psi \rightarrow pK^\pm\Sigma \) are suppressed by requiring

Figure 2. The \( p\bar{p} \) invariant mass distribution in \( J/\psi \rightarrow \gamma p\bar{p} \) decays.
\[ \xi = E_{\text{miss}} + 1.39M_{pK} \text{ miss} < 1.69 \text{ GeV}, \]

where \( E_{\text{miss}} \) denotes the difference between the center-of-mass energy (3.097 GeV) and the total energy of the four charged tracks, and \( M_{pK} \text{ miss} \) denotes the mass recoiling against the proton-kaon system. The Monte-Carlo studies indicate that the background in the selected event sample is at the 1 ~ 2% level after above criteria.

The \( p\bar{\Lambda} \) invariant mass spectrum for the selected events is shown in Fig. 3(a), where an enhancement is evident near the mass threshold. The \( p\bar{\Lambda} \) Dalitz plot is shown in Fig. 3(b). In addition to bands for the well established \( \Lambda^*(1520) \) and \( \Lambda^*(1690) \), there is a significant \( N^* \) band near the \( K^-\bar{\Lambda} \) mass threshold, and a \( p\bar{\Lambda} \) mass enhancement, isolated from the \( \Lambda^* \) and \( N^* \) bands, in the right-upper part of the Dalitz plot.

This enhancement can be fitted with an acceptance weighted S-wave Breit-Wigner together with a function \( f_{PS}(\delta) \) describing the phase space contribution, as shown in Fig. 3(c), where \( f_{PS}(\delta) = N(\delta^{1/2} + a_1\delta^{3/2} + a_2\delta^{5/2}) \), \( \delta = m_{p\bar{\Lambda}} - m_p - m_{\bar{\Lambda}}, \) and the parameters \( a_1 \) and \( a_2 \) are determined from a fit to the \( p\bar{\Lambda} \) MC sample events generated with a uniform phase-space distribution. The fit gives a peak mass of \( m = 2075 \pm 12 \text{ MeV} \), a width \( \Gamma = 90 \pm 35 \text{ MeV} \) and a branching ratio

\[
\frac{BR(J/\psi \to K^-\bar{\Lambda})BR(X \to p\bar{\Lambda})}{N_{\text{res}}/2\pi BR(\Lambda \to p\bar{\eta})} = (5.9 \pm 1.4) \times 10^{-5}.
\]

Performing the same analysis on the \( \psi' \) data sample, an evidence of a similar enhancement is observed in \( \psi' \to pK^-\bar{\Lambda} \), shown in Fig. 4(a) and (b). If the \( X(2075) \) parameters are fixed to the values obtained from the \( J/\psi \) data, i.e., \( M_X = 2075 \text{ MeV} \) and \( \Gamma_X = 90 \text{ MeV} \), the fit to the \( \psi' \) data sample shows that the enhancement in \( \psi' \) data deviates from the shape of the phase space contribution with a statistical significance of about 4.0\( \sigma \), where the significance is estimated from a comparison of log-likelihood values of the fits with and without the \( X(2075) \) signal function.

As mentioned above, the \( p\bar{\Lambda} \) Dalitz plot, Fig. 3(b), shows a significant \( N^* \) band near the \( K^-\bar{\Lambda} \) mass threshold. This band corresponds to an enhancement near the \( K^-\bar{\Lambda} \) mass threshold in the one dimension projection of \( m_{K^-\bar{\Lambda}} \), shown in Fig. 5(a). The \( m_{K^-\bar{\Lambda}} \) distribution after the effi-

Figure 3. (a) The points with error bars indicate the measured \( p\bar{\Lambda} \) mass spectrum; the shaded histogram indicates phase space MC events (arbitrary normalization). (b) The Dalitz plot for the selected event sample. (c) A fit (solid line) to the data. The dotted curve indicates the Breit-Wigner signal and the dashed curve the phase space Background'. (d) The \( \cos \theta_p \) distribution under the enhancement, the points are data and the histogram is the MC (normalized to data).

Figure 4. Results for \( \psi' \to pK^-\bar{\Lambda} \) events: (a) A fit (solid line) to the data sample (histogram); the dashed line indicates the phase space background contribution. (b) The Dalitz plot.
Figure 5. (a). The $m_{K^{-}\Lambda}$ invariant mass spectrum from $J/\psi \rightarrow pK^{-}\Lambda$. (b). The $m_{K^{-}\Lambda} - m_{K^-} - m_{\Lambda}$ distribution after the efficiency and phase space correction.

...efficiency and phase space correction presents a more obvious peak at the $K^{-}\Lambda$ mass threshold.

The Partial Wave Analysis (PWA) is applied to $J/\psi \rightarrow pK^{-}\Lambda$ to study this near threshold enhancement, denoted as $N_x$. Different combinations of $N^*$ and $\Lambda^*$ states, listed in PDG, are included in $m_{K^{-}\Lambda}$ and $m_{pK^-}$ for the PWA fit. The results show that the mass and width of the enhancement are around 1500 - 1650 MeV and 70 - 110 MeV, respectively, the $J^P$ of 1/2$^-$ is favored and the product branching ratio $Br(J/\psi \rightarrow p\bar{N}_x) \times (\bar{N}_x \rightarrow K^{-}\Lambda)$ is around $2 \times 10^{-4}$. The big product branching ratio indicates a large coupling of $N_x$ to $K\Lambda$.

4 Summary

Based on $5.8 \times 10^7 J/\psi$ and $1.4 \times 10^7 \psi(2S)$ events accumulated at the BESII detector, no $\Theta(1540)$ is observed in both $J/\psi$ and $\psi(2S)$ hadronic decays. From a sample of $5.8 \times 10^7 J/\psi$ events, a narrow enhancement near $2m_p$ in the invariant mass spectrum of $p\bar{p}$ pairs from $J/\psi \rightarrow \gamma p\bar{p}$ decays is observed. In $J/\psi \rightarrow pK^-\Lambda + c.c.$ decays, an enhancement near the $m_p + M_{\Lambda}$ mass threshold is observed in the combined $p\Lambda$ and $\bar{p}\Lambda$ invariant mass spectrum. We also observed an enhancement near the $m_K + M_{\Lambda}$ mass threshold in the same channel. The $J^P$ of this enhancement being 1/2$^-$ is favored and it has a large coupling to $K\Lambda$.

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