Search for the Pentaquark State in $\psi(2S)$ and $J/\psi$ Decays to $K^0_S p K^- \bar{n}$ and $K^0_S \bar{p} K^+ n$

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Abstract

Results are presented on $\psi(2S)$ and $J/\psi$ hadronic decays to $K_S^0 p K^- n$ and $K_S^0 \bar{p} K^+ n$ final states from data samples of 14 million $\psi(2S)$ and 58 million $J/\psi$ events accumulated at the BES II detector. No $\Theta(1540)$ signal, the pentaquark candidate, is observed, and upper limits for $\mathcal{B}(\psi(2S) \to \Theta \bar{\Theta} \to K_0^S p K^- n + K_0^S \bar{p} K^+ n) < 0.84 \times 10^{-5}$ and $\mathcal{B}(J/\psi \to \Theta \bar{\Theta} \to K_0^S p K^- n + K_0^S \bar{p} K^+ n) < 1.1 \times 10^{-5}$ at the 90% confidence level are set. For single $\Theta(1540)$ production, the upper limits determined by our analysis are also on the order of $10^{-5}$ in both $\psi(2S)$ and $J/\psi$ decays.

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I. INTRODUCTION

Recently the LEPS Collaboration at Spring-8 reported the 4.6 $\sigma$ discovery of a new $S = +1$ state, the $\Theta(1540)$, with a mass of 1.54 ± 0.01 GeV/$c^2$ and a width of less than 25 MeV/$c^2$, close to $NK$ threshold in the reaction $\gamma^{12}C \rightarrow K^+K^-X$ [1]. Subsequently, the DIANA Collaboration at ITEP, CLAS at Jefferson Lab, and SAPHIR at ELSA claimed this narrow state, the candidate for a pentaquark state ($uudd\bar{s}$), in $n + K^+$ or $p + K^0$ decay configurations - all published in 2003 [2-4].

The work of LEPS was motivated, in part, by the work by Diakonov, Petrov and Polyakov who studied anti-decuplet baryons using the chiral soliton model [5]. In their model, the anti-decuplet was anchored to the mass of the $P_{11}(1710)$ nucleon resonance, giving the pentaquark state $\Theta^+$ (spin 1/2, isospin 0, and $S = +1$) a mass of $\sim 1530$ MeV/$c^2$ and a total width of less than 15 MeV/$c^2$. In particular, it is predicted to be an isoscalar.

There are many other theoretical works to try to explain the properties of the $\Theta(1540)$ with various quark models [6-9] or alternative approaches [10]. Isospins 0 and 1 are both possible; isospin 1 would lead to three charge states $\Theta^0, \Theta^+, \Theta^{++}$. A reanalysis [11] of older experimental data on the $K^+$-nucleon elastic scattering put a more stringent constraint on the width to be $\Gamma_\Theta < 1$ MeV. Since the mass of the $\Theta$ is larger than the sum of the masses of the nucleon and kaon, it is not easy to understand why its width should be so narrow, unless it has very special quantum numbers. Capstick, Page and Roberts point out that the $\Theta^+$ could be a member of an isospin quintet with charges from $-1$ to $+3$ where the $Q = +3$ state has a ($uuuu\bar{s}$) quark-model configuration. Decays of an isotensor $\Theta^+$ into $pK^0$ and $pK^+$ are isospin violating; hence an isotensor $\Theta^+$ is expected to be narrow [6].

The analyses of CLAS and SAPHIR support that the $\Theta^+$ is isoscalar, but the statistics of present experiments are limited.

There are experimental questions concerning the $\Theta(1540)$. For the four experiments [1-4], the exact shape of the background is very difficult to estimate since the $\Theta^+$ is close to $NK$ threshold, and strong cuts have been applied to the event samples in all cases. The calculation of Dzierba et al. [12] shows that kinematic reflections of meson resonances could well account for the enhancement observed in the $K^+n$ effective mass distribution at the mass of the purported $\Theta^+$. They suggest that further experimental studies will be required with higher statistics, including varying the incident beam momentum and establishing
the spin and parity, before claiming solid evidence for a $S = +1$ baryon resonance. It is important to understand the properties of the $\Theta$ through systematic studies by different experiments. 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 $\Theta$ with the hadronic decays of the charmonium states $\psi(2S)$ and $J/\psi$.

In this work, we search for the pentaquark state $\Theta(1540)$ in $\psi(2S)$ and $J/\psi$ decays to $K^0_spK^−n$ and $K^0_s\bar{p}K^+n$ final states using samples of 14 million $\psi(2S)$ and 58 million $J/\psi$ events taken with the upgraded Beijing Spectrometer (BESII) located at the Beijing Electron Positron Collider (BEPC). These processes could contain $\Theta$ decays to $K^0_sp$, $K^+n$ ($uudd\bar{s}$) and $\bar{\Theta}$ decays to $K^0_s\bar{p}$, $K^−n$ ($\bar{u}\bar{u}\bar{d}\bar{s}$).

II. BES DETECTOR

BES II is a large solid-angle magnetic spectrometer that is described in detail in Ref. [13]. Charged particle momenta are determined with a resolution of $\sigma_p/p = 1.78\%\sqrt{1 + p^2(\text{GeV})^2}$ in a 40-layer cylindrical drift chamber. Particle identification is accomplished by specific ionization ($dE/dx$) measurements in the drift chamber and time-of-flight (TOF) measurements in a barrel-like array of 48 scintillation counters. The $dE/dx$ resolution is $\sigma_{dE/dx} = 8.0\%$; the TOF resolution is $\sigma_{\text{TOF}} = 180$ ps for Bhabha events. Outside of the time-of-flight counters is a 12-radiation-length barrel shower counter (BSC) comprised of gas proportional tubes interleaved with lead sheets. The BSC measures the energies of photons with a resolution of $\sigma_E/E \approx 21\%/\sqrt{E(\text{GeV})}$. Outside the solenoidal coil, which provides a 0.4 Tesla magnetic field over the tracking volume, is an iron flux return that is instrumented with three double layers of counters that are used to identify muons.

In this analysis, a GEANT3 based Monte Carlo simulation package (SIMBES) with detailed consideration of detector performance (such as dead electronic channels) is used. The consistency between data and Monte Carlo has been checked in many high purity physics channels, and the agreement is quite reasonable.
III. EVENT SELECTION

In \(\psi(2S)\) or \(J/\psi\) decays to \(K_S^0 p K^- \bar{n}\) and \(K_S^0 \bar{p} K^+ n\), the anti-neutron and neutron are not detected. The first step in the analysis is to select in four prong events the \(\pi^+ \pi^-\) pair, which composes the \(K_0^0\). Next the missing mass is calculated according to energy-momentum conservation. The events with missing mass close to the \(\bar{n}(n)\)'s mass are selected. We use the same criteria and treatment for both \(\psi(2S)\) and \(J/\psi\) data.

The first level of event selection requires two positively and two negatively charged tracks with less than ten neutral tracks. The charged particles are each required to lie within the acceptance of the detector and to have a good helix fit.

The \(K_S^0\) meson in the event is identified through the decay \(K_S^0 \rightarrow \pi^+ \pi^-\). For the selection of the \(K_S^0\), both the \(\pi^+\) and \(\pi^-\) are required to be consistent with being pions, namely, \(\text{Prob}_{\text{pid}}(\pi) > 0.01\). The definition of \(\text{Prob}_{\text{pid}}\) is

\[
\chi^2_{\text{com}} = \chi^2_{\text{TOF}} + \chi^2_{dE/dx}
\]

\[
\text{Prob}_{\text{pid}} = \text{Prob}(\chi^2_{\text{com}}, 2),
\]

where \(\chi^2_{\text{TOF}}\) and \(\chi^2_{dE/dx}\) are determined from the measured and expected TOF times and ionization information for the particle hypothesis of interest. If only TOF or \(dE/dx\) information is available, \(\text{Prob}_{\text{pid}} = \text{Prob}(\chi^2, 1)\). The four charged tracks can be grouped into a maximum of four possible \(\pi^+ \pi^-\) combinations. The combination with the invariant mass closest to the mass of \(K_S^0\) is chosen as the \(K_S^0\) candidate, and the intersection point of the two tracks is regarded as the secondary vertex. Candidate events are required to satisfy \(|M_{\pi^+ \pi^-} - M_{K_S^0}| < 15 \text{ MeV}/c^2\), where \(M_{\pi^+ \pi^-}\) is calculated at the \(K_S^0\) decay vertex. For the proton (or anti-proton) and kaon, we require \(\text{Prob}_{\text{pid}}(p) > 0.01\) and \(\text{Prob}_{\text{pid}}(K) > 0.01\), respectively.

Candidate events are kinematically fitted (one constraint fit) under the assumption of a missing \(\bar{n}(n)\) to obtain better mass resolution and to suppress the backgrounds. As an example, Fig. 1 shows the \(\chi^2_{K_S^0 p K^- \bar{n}}\) distribution of \(\psi(2S) \rightarrow K_S^0 p K^- \bar{n}\) candidate events after particle identification. We require \(\chi^2_{K_S^0 p K^- \bar{n}} < 5\) and use a further cut on the \(K_S^0\) decay length, \(L_{xy} > 3 \text{ mm}\), to remove remaining backgrounds.

Fig. 2 shows the \(\bar{n}\) missing mass distributions of data and Monte Carlo for \(\psi(2S) \rightarrow K_S^0 p K^- \bar{n}\) after the above cuts. The surviving events fall mostly within the range 0.9 - 1.0
FIG. 1: \( \chi^2 \) distribution of \( \psi(2S) \rightarrow K^0_S p K^- \bar{n} \) candidate events after requiring particle identification. The solid histogram is for data, and the dashed histogram for Monte Carlo simulation (phase space), where the Monte Carlo is normalized to the data in the first bin.

GeV/\( c^2 \), and we further require 0.9 GeV/\( c^2 \) < \( m_{\text{missing}} \) < 1.0 GeV/\( c^2 \). The missing mass distributions for the other modes \( \psi(2S) \rightarrow K^0_S p K^- n \) and \( J/\psi \rightarrow K^0_S p K^- \bar{n} \), \( K^0_S p K^+ n \) are similar to those of Fig. 2.

IV. ANALYSIS RESULTS

After the above requirements, the individual mass distributions of \( \psi(2S) \rightarrow K^0_S p K^- \bar{n} \) and \( K^0_S p K^+ n \) are shown in Fig. 3, and the scatter plot of \( K^- n \) (\( K^0_S p \)) versus \( K^0_S p \) (\( K^+ n \)) for \( \psi(2S) \rightarrow K^0_S p K^- \bar{n} + K^0_S p K^+ n \) modes is shown in Fig. 4. No clear \( \Theta \) signal is observed in Fig. 3, which contains 19 (\( K^0_S p K^- \bar{n} \)) and 10 (\( K^0_S p K^+ n \)) events, or Fig. 4. We determine an upper limit for \( B(\psi(2S) \rightarrow \Theta \bar{\Theta} \rightarrow K^0_S p K^- \bar{n} + K^0_S p K^+ n) \). The signal region is shown as a square centered at (1.540, 1.540) GeV/\( c^2 \) in Fig. 4. Zero events fall within the signal region defined as \( \pm 20 \) MeV from the central value [14]. We set an upper limit of 2.30 events in the absence of background at the 90% confidence level (C.L.) for \( N_{\Theta \bar{\Theta}} \) and

\[
B(\psi(2S) \rightarrow \Theta \bar{\Theta} \rightarrow K^0_S p K^- \bar{n} + K^0_S p K^+ n) < \frac{2.30}{0.686 \times (2.85 \pm 0.08)\% \times (14.0 \times 10^6)} = 0.84 \times 10^{-5},
\]
where 0.686 is the decay ratio of $K_S^0$ to $\pi^+\pi^-$; (2.85 $\pm$ 0.08)% is the detection efficiency and the uncertainty is statistical error of the Monte Carlo sample, and 14.0 $\times$ 10$^6$ is the total number of BES II $\psi(2S)$ events [16].

Another possibility is that the $\psi(2S)$ decays to only one $\Theta$ or $\bar{\Theta}$ state. To determine the number of $\Theta(1540)$ events from single $\Theta$ or $\bar{\Theta}$ production, we count the number of events within regions of 1.52 - 1.56 GeV/$c^2$, shown by the arrows in Fig. 3 and set upper limits on the branching fractions at the 90% C.L.

\[
\mathcal{B}(\psi(2S) \rightarrow \Theta K^+\bar{n} \rightarrow K^0_S p K^-\bar{n}) < 1.0 \times 10^{-5}
\]
\[
\mathcal{B}(\psi(2S) \rightarrow \bar{\Theta} K^+ n \rightarrow K^0_S \bar{p} K^+ n) < 2.6 \times 10^{-5}
\]
\[
\mathcal{B}(\psi(2S) \rightarrow K^0_S p \Theta \rightarrow K^0_S p K^-\bar{n}) < 0.60 \times 10^{-5}
\]
\[
\mathcal{B}(\psi(2S) \rightarrow K^0_S \bar{p} \Theta \rightarrow K^0_S \bar{p} K^+ n) < 0.70 \times 10^{-5}.
\]

Backgrounds are not subtracted in the calculation of the upper limits. The numbers used to determine the upper limits are summarized in Table I.

For the decays of $J/\psi \rightarrow K^0_S p K^-\bar{n} \text{ and } K^0_S \bar{p} K^+ n$, we just use the same criteria and analysis method as those used for the $\psi(2S)$ data to study possible $\Theta(1540)$ production. The scatter plot of $K^- n (K^0_S \bar{p}) \text{ versus } K^0_S p (K^+ n)$ is shown in Fig. 5. The individual mass distributions of $J/\psi$ data are shown in Fig. 6, which contains 25 $K^0_S p K^-\bar{n}$ events.
FIG. 3: Mass distributions of $\psi(2S) \rightarrow K_S^0 p K^- \bar{n}$ and $K_S^0 \bar{p} K^+ n$ modes.

FIG. 4: Scatter plot of $K^- n (K_S^0 \bar{p})$ versus $K_S^0 p (K^+ n)$ for $\psi(2S) \rightarrow K_S^0 p K^- \bar{n} + K_S^0 \bar{p} K^+ n$ modes.
### Table I: Summary of numbers used in the determination of upper limits for the $\psi(2S)$ data.

| Decay mode | $N_{\text{obs}}$ | Efficiency | Upper limit |
|------------|-----------------|------------|-------------|
| $\psi(2S) \rightarrow \Theta \bar{\Theta} \rightarrow K_{S}^{0}pK^{-}\bar{n}$ | 0 | $(2.85 \pm 0.08)\%$ | $0.88 \times 10^{-5}$ |
| + $K_{S}^{0}pK^{+}n$ | 1 | $(4.07 \pm 0.09)\%$ | $1.0 \times 10^{-5}$ |
| $\psi(2S) \rightarrow \Theta K^{-}\bar{n} \rightarrow K_{S}^{0}pK^{-}\bar{n}$ | 4 | $(3.17 \pm 0.08)\%$ | $2.6 \times 10^{-5}$ |
| $\psi(2S) \rightarrow \bar{\Theta}K^+n \rightarrow K_{S}^{0}\bar{p}K^{+}n$ | 0 | $(3.99 \pm 0.09)\%$ | $0.60 \times 10^{-5}$ |
| $\psi(2S) \rightarrow K_{S}^{0}p\bar{\Theta} \rightarrow K_{S}^{0}pK^{-}\bar{n}$ | 0 | $(3.42 \pm 0.08)\%$ | $0.70 \times 10^{-5}$ |

and 21 $K_{S}^{0}\bar{p}K^{+}n$ events. There is no $\Theta(1540)$ signal, and we determine upper limits on the branching fractions at the 90% C.L.

\[
\mathcal{B}(J/\psi \rightarrow \Theta \bar{\Theta} \rightarrow K_{S}^{0}pK^{-}\bar{n} + K_{S}^{0}pK^{+}n) < 1.1 \times 10^{-5}
\]

\[
\mathcal{B}(J/\psi \rightarrow \Theta K^{-}\bar{n} \rightarrow K_{S}^{0}pK^{-}\bar{n}) < 2.1 \times 10^{-5}
\]

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

\[
\mathcal{B}(J/\psi \rightarrow K_{S}^{0}p\bar{\Theta} \rightarrow K_{S}^{0}pK^{-}\bar{n}) < 1.1 \times 10^{-5}
\]

**FIG. 5:** Scatter plot of $K^{-}n$ ($K_{S}^{0}\bar{p}$) versus $K_{S}^{0}p$ ($K^{+}n$) for $J/\psi \rightarrow K_{S}^{0}pK^{-}\bar{n} + K_{S}^{0}pK^{+}n$ modes.
These results along with the numbers used to determine them are summarized in Table II.

V. SUMMARY

In this work, we studied \( \psi(2S) \) and \( J/\psi \) hadronic decays to \( K_S^0 p K^- \bar{n} \) and \( K_S^0 \bar{p} K^+ n \) using 14M \( \psi(2S) \) and 58M \( J/\psi \) events. No \( \Theta(1540) \) signal is observed. We set upper limits for \( \mathcal{B}(\psi(2S) \to \Theta \bar{\Theta} \to K_S^0 p K^- \bar{n} + K_S^0 \bar{p} K^+ n) < 0.84 \times 10^{-5} \), \( \mathcal{B}(J/\psi \to \Theta \bar{\Theta} \to K_S^0 p K^- \bar{n} + K_S^0 \bar{p} K^+ n) < 1.1 \times 10^{-5} \) at 90% confidence level (C.L.). For the case of single \( \Theta(1540) \) production, the upper limits determined are also on the order of \( 10^{-5} \) for both \( \psi(2S) \) and \( J/\psi \) data.
| Decay mode | $N_{\text{obs}}$ | Efficiency | Upper limit |
|------------|------------------|------------|-------------|
| $J/\psi \rightarrow \Theta \Theta \rightarrow K_S^0 p K^- \bar{n}$ | 1 | (0.88 ± 0.04)% | $1.1 \times 10^{-5}$ |
| $J/\psi \rightarrow \Theta K^- \bar{n} \rightarrow K_S^0 p K^- \bar{n}$ | 4 | (0.96 ± 0.04)% | $2.1 \times 10^{-5}$ |
| $J/\psi \rightarrow \Theta K^+ n \rightarrow K_S^0 p K^+ n$ | 8 | (0.59 ± 0.03)% | $5.6 \times 10^{-5}$ |
| $J/\psi \rightarrow K_S^0 p \Theta \rightarrow K_S^0 p K^- \bar{n}$ | 2 | (1.19 ± 0.05)% | $1.1 \times 10^{-5}$ |
| $J/\psi \rightarrow K_S^0 p \bar{\Theta} \rightarrow K_S^0 p K^+ n$ | 2 | (0.86 ± 0.04)% | $1.6 \times 10^{-5}$ |

TABLE II: Summary of numbers used in the determination of upper limits for the $J/\psi$ data.

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