Observation of Two New N^* Peaks in $J/\psi \to p\pi^- \bar{n}$ and $\bar{p}\pi^+ n$ Decays

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The decay $J/\psi \to \bar{N}N\pi$ provides an effective isospin $1/2$ filter for the πN system due to isospin conservation. Using 58×10^6 J/ψ decays collected with the Beijing Electromagnetic Spectrometer at the Beijing Electron Positron Collider, more than 100 thousand $J/\psi \to p\pi^- \bar{n}$ + c.c. events are obtained. Besides the two well-known N^* peaks at around 1500 MeV/c^2 and 1670 MeV/c^2, there are two new, clear N^* peaks in the $p\pi$ invariant mass spectrum around 1360 MeV/c^2 and 2030 MeV/c^2 with statistical significance of 11σ and 13σ, respectively. We identify these as the first direct observation of the $N^*(1440)$ peak and a long-sought missing N^* peak above 2 GeV/c^2 in the πN invariant mass spectrum.

The nucleon is the simplest system in which the three colors of QCD can combine to form a colorless object, and the essential non-Abelian character of QCD is manifest. It is necessary to understand the internal quark-gluon structure of the nucleon and its excited N^* states before we can claim to really understand the strong interaction.

A very important source of information for the nucleon internal structure is the N^* mass spectrum as well as its various production and decay rates. Our present knowledge of these comes almost entirely from πN experiments performed more than 20 years ago [1]. Because of its importance for the understanding of nonperturbative QCD, a series of new experiments on N^* physics with electromagnetic probes (real photons and electrons with spacelike virtual photons) have recently been started at JLAB, ELSA at Bonn, GRAAL at Grenoble, and SPRING8 at JASRI [2]. They have already produced some important results [3–6]. Nevertheless, our knowledge of the N^* resonances remains very poor. Even for the well-established lowest excited state, the $N^*(1440)$, properties such as mass, width, and decay branching ratios, etc., still have large experimental uncertainties [1]. Another outstanding problem is that, in many of its forms, the quark model predicts a substantial number of "missing" N^* states around 2 GeV/c^2, which have not so far been observed [7]. The difficulty in extracting information on these high mass N^* resonances from πN and γN experiments is the overlap of many broad resonances with various spin and isospin. Recently J/ψ decays at the BEPC were proposed [8] as an excellent place to study N^* resonances, and N^* production from $J/\psi \to p\bar{p}\eta$ has been studied based on 7.8×10^6 BESI J/ψ events [9].

In this Letter, we report on a study of N^* resonances from $J/\psi \to p\pi^-\bar{n}$ and $\bar{p}\pi^+n$ channels based on 58×10^6 J/ψ events collected with the BESII detector at the BEPC. Because of isospin conservation, the πN system in J/ψ decay is pure isospin 1/2. Compared with πN and γN experiments, which mix isospin 1/2 and 3/2, this is a big advantage.

BESII is a large solid-angle magnetic spectrometer that is described in detail in Ref. [10]. Charged particle momenta are determined with a resolution of $\sigma_p/p = 1.78\%\sqrt{1 + p^2}$ (with p in GeV/c) in a 40-layer cylindrical drift chamber. Particle identification is accomplished using 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 $\sigma_{dE/dx} = 8.0\%$, and the TOF resolution is $\sigma_{\rm TOF} = 180$ ps for the Bhabha events. The combination of dE/dx and TOF information provides efficient identification of the charged pion and proton (or antiproton) for the $J/\psi \to p\pi^-\bar{n}$ and $\bar{p}\pi^+n$ processes.

A GEANT3 based Monte Carlo simulation package (SIMBES)[11] with detailed consideration of real detector performance (such as dead electronic channels) is used for estimating the detection efficiency and background contri-

butions. The consistency between data and Monte Carlo simulations has been carefully checked in many high purity physics channels, and the agreement is quite reasonable.

For the decay $J/\psi \to p\pi^-\bar{n}$, the antineutron is not detected directly. We select the p and π^- from two prong events with oppositely charged tracks and require the missing mass to be consistent with the $\bar{n}$ mass.

In the event selection, we require each charged track to be well fitted to a helix originating near the interaction point and to be within the polar angle region $|\cos\theta| < 0.8$. Both the dE/dx and TOF information are used to form particle identification confidence levels $\wp_{\rm pid}^i$, where i denotes π, K, or p. For the positive charged track, we require $\wp_{\rm pid}^p > \wp_{\rm pid}^K$ and $\wp_{\rm pid}^p > \wp_{\rm pid}^\pi$; for the negative charged track, we require $\wp_{\rm pid}^\pi > \wp_{\rm pid}^K$ and $\wp_{\rm pid}^\pi > \wp_{\rm pid}^p$. After these requirements, the $p\pi^-$ invariant mass spectrum shown in Fig. 1 is obtained. There is a narrow Λ peak at 1.116 GeV due to background channels with Λ's. After imposing a further requirement of $M_{p\pi} > 1.15$ GeV/c^2 to remove this background, the missing mass distribution shown in Fig. 2 is obtained. A clear $\bar{n}$ peak is observed.

A similar selection is used for the charge conjugate channel $J/\psi \to \bar{p}\pi^+n$. The missing mass distribution of $\bar{p}\pi^+$ is almost identical with that for $J/\psi \to p\pi^-\bar{n}$. Fitting the missing mass spectra between 0.60 and 1.15 GeV/c^2 with signal plus background described by a fourth order Chebyshev polynomial and using Monte Carlo determined acceptances for these two channels, branching ratios for these two channels are measured as $(2.36 \pm 0.02 \pm 0.21) \times 10^{-3}$ and $(2.47 \pm 0.02 \pm 0.24) \times 10^{-3}$ for $p\pi^-\bar{n}$ and $\bar{p}\pi^+n$, respectively. The statistical errors are small due to the large data sample. Systematic errors come from several sources. Background uncertainty is about 4%. The difference of particle identification between data and Monte Carlo is about 5%. Uncertainty on the total number of J/ψ events is ~4.7%, and the tracking error is ~4%. Combining these errors in quadrature gives a total systematic error of (9–10)%.
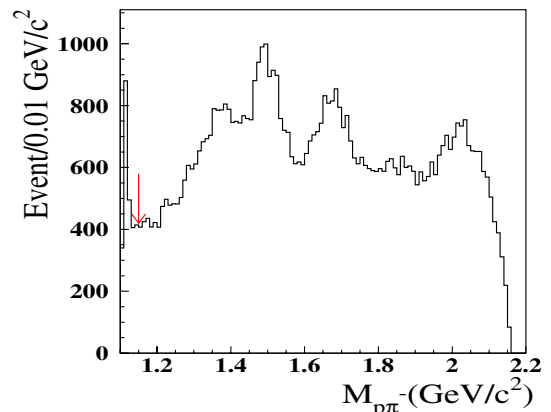

FIG. 1 (color online).   The $p\pi$ invariant mass spectrum before the $M_{p\pi} > 1.15$ GeV/c^2 requirement.
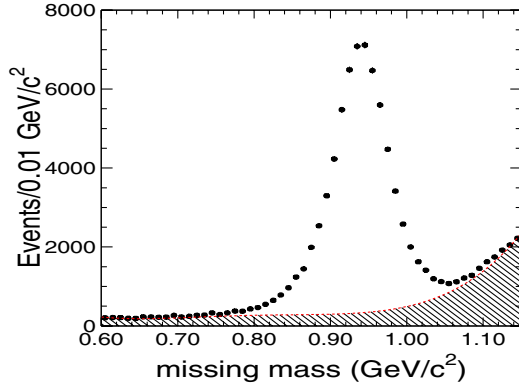
FIG. 2 (color online). The missing mass distribution for $J/\psi \to p\pi^-\bar{n}$ with the fitted background shown by the shaded area.

Taking $\bar{n}/n$ events in the region of the missing mass distribution within 0.94 ± 0.06 GeV/c^2, we get 58 822 and 54 524 events for $J/\psi \to p\pi^-\bar{n}$ and $\bar{p}\pi^+ n$, respectively, including about 6% background. The Dalitz plots for these two channels are shown in Fig. 3, and are very similar. The asymmetry between $p\pi$ and $n\pi$ is partly due to differences in detection efficiency and partly due to isospin symmetry breaking effects from the electromagnetic interaction. The $p\pi$ and $n\pi$ selection efficiencies versus invariant mass in the decay $J/\psi \to p\pi^-\bar{n}$ are shown in Fig. 4. The efficiency has a sharp drop for $\bar{n}\pi^-$ invariant mass above 2 GeV/c^2, where the recoil proton has low momentum and BESII detection efficiency is correspondingly low.

Shown in Fig. 5 are the $p\pi^-$ and $\bar{p}\pi^+$ invariant mass spectra, as well as the phase space distributions (times detection efficiency) obtained with the SIMBES Monte Carlo program. The two invariant mass spectra look very similar.

To investigate the amplitude squared behavior as a function of invariant mass, we remove the phase space factor and efficiency factor from the invariant mass distribution by dividing the data by Monte Carlo phase space times the detection efficiency. The results are shown in Fig. 6 with data and Monte Carlo calculations for the two channels normalized to the same number of events as for $p\pi^-\bar{n}$ data.
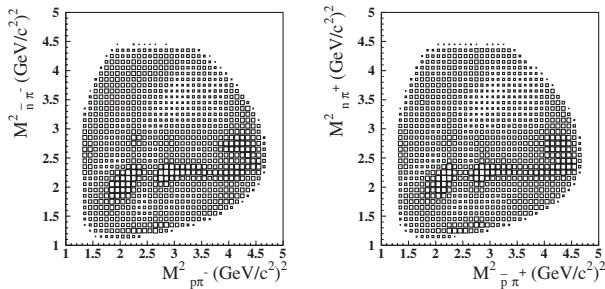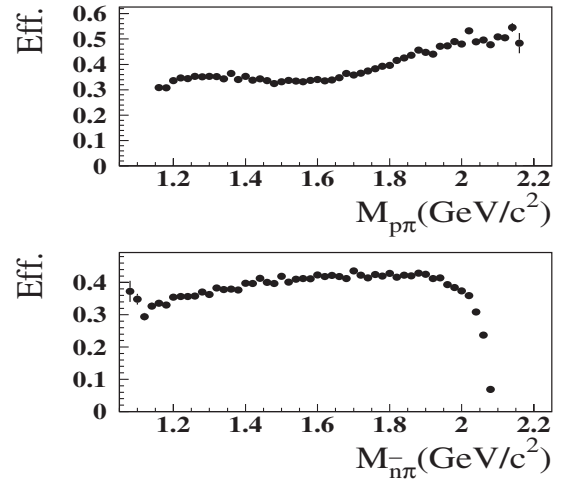

FIG. 4. The selection efficiency versus invariant mass for $p\pi$ (upper plot) and $\bar{n}\pi$ (lower plot) in the decay $J/\psi \to p\pi^-\bar{n}$.

The results for the two charge conjugate channels are consistent. At low $p\pi$ invariant mass, the tail from the nucleon pole term, expected from theoretical considerations [12,13], is clearly seen. There are clearly four peaks around 1360, 1500, 1670, and 2065 MeV/c^2. Note that the well-known first resonance peak [$\Delta(1232)$] in πN and γN scattering data does not show up here due to the J/ψ decay isospin filter. While the two peaks around 1500 MeV/c^2 and 1670 MeV/c^2 correspond to the well-known second resonance peak and the third resonance peak observed in πN and γN scattering data, the two peaks around 1360 MeV/c^2 and 2065 MeV/c^2 have never been observed before in πN invariant mass spectra, although a peak around 1400 MeV was observed in the missing mass spectrum in $pp \to p + X$ reaction [14] with X containing not only πN but also $\pi\pi N$, $3\pi N$, etc. The one around 1360 MeV/c^2 should be from $N^*(1440)$ which has a pole around 1360 MeV/c^2 [1,15,16] and which is usually buried by the strong Δ peak in πN and γN experiments; the other one around 2065 MeV/c^2 may be one or more of the long-sought missing N^* resonance(s).

To estimate the mass and width of these resonance peaks, we use simple relativistic Breit-Wigner functions plus a smooth function to fit the data points of Fig. 6. For
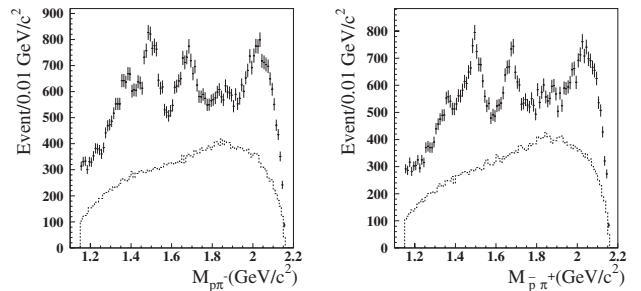

FIG. 3. Dalitz plots of $M^2_{n\pi}$ versus $M^2_{p\pi}$ for $J/\psi \to p\pi^-\bar{n}$ (left) and $\bar{p}\pi^+ n$ (right).

FIG. 5. The $p\pi^-$ and $\bar{p}\pi^+$ invariant mass spectra for $J/\psi \to p\pi^-\bar{n}$ (left) and $\bar{p}\pi^+ n$ (right), compared with phase space.

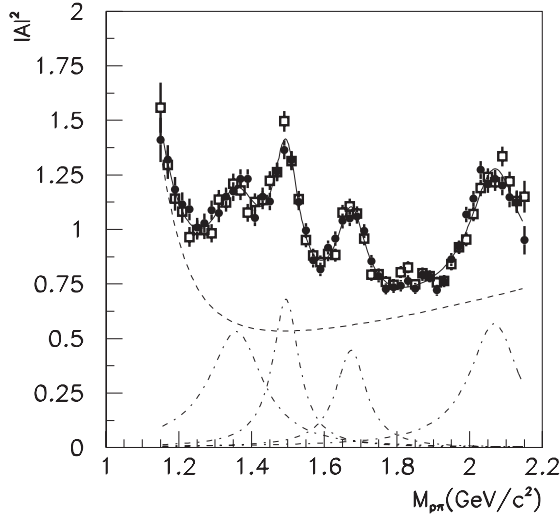FIG. 6. Data divided by Monte Carlo phase space versus $p\pi$ invariant mass for $J/\psi \to p\pi^-\bar{n}$ (solid circles) and $J/\psi \to \bar{p}\pi^+ n$ (open squares), compared with our fit (solid curve). The contributions of each resonance peak are shown by the dot-dashed lines in the same figure. The dashed line is the contribution of background terms including the nucleon pole term.

the final fit we use

$$|A|^2 = |C_0 + C_0' s_{\pi p}| + \sum_{i=1}^{5} \frac{|C_i|}{(s_{\pi p} - M_i^2)^2 + M_i^2 \Gamma_i^2} \quad (1)$$

where $s_{\pi p} = M_{\pi p}^2$ is the invariant mass squared of the $p\pi$ system. Background is described with a constant and $s_{\pi p}$ linear term plus an additional Breit-Wigner function at low energy to simulate the contribution from the nucleon pole term and the Λ and other backgrounds. All parameters are free. The fitted mass and width for the four N^* peaks are listed in Table I. The systematic error in the table is obtained from the variation of fit results when assuming other background functions, such as $|C_0|$, $|C_1 M_{\pi p}|$, $|C_0' s_{\pi p}|$, $|C_0 + C_1 M_{\pi p}|$, $|C_0 + C_1 M_{\pi p} + C_0' s_{\pi p}|$, and adding one more N^* resonance around 1.85 GeV/c^2 or above 2.2 GeV/c^2 in the fitting. The fit to the data is also shown in Fig. 6 with $\chi^2 = 133$ for 102 data points. All four peaks are highly significant. The statistical significance is 11σ for the $N^*(1440)$ peak (the least significant one) and 13σ for the new $N^*(2065)$ peak.

Because we use a constant width for the Breit-Wigner (BW) formulae, the BW mass and width are very close to

TABLE I. The fitted masses and widths for the four N^* peaks shown in Fig. 6.

Mass (MeV/c^2)	Width (MeV/c^2)
$1358 \pm 6 \pm 16$	$179 \pm 26 \pm 50$
$1495 \pm 2 \pm 3$	$87 \pm 7 \pm 10$
$1674 \pm 3 \pm 4$	$100 \pm 9 \pm 15$
$2068 \pm 3^{+15}_{-40}$	$165 \pm 14 \pm 40$

their corresponding pole positions. For the two well-known peaks at 1500 MeV/c^2 and 1670 MeV/c^2, the former contains two well-established N^* resonances, the $N^*(1520)$ and $N^*(1535)$, while the latter contains more than two N^* resonances. Here we only use one BW function to fit each of them.

For the new $N^*(2065)$ peak, orbital angular momentum $L = 0$ is preferred due to the suppression of the centrifugal barrier factor for $L \geq 1$. If we fit the $N^*(2065)$ peak in Fig. 6 with $L = 1$ centrifugal barrier factor instead of Eq. (1), then the χ^2 increases from 133 to 163 for 102 data points. The much worse fit with $L = 1$ compared with $L = 0$ means that there is substantial $L = 0$ component for the new $N^*(2065)$ peak.

For $L = 0$, the spin-parity of $N^*(2065)$ is limited to be $1/2^+$ and $3/2^+$. This may be the reason that the $N^*(2065)$ shows up as a peak in J/ψ decays while no peak shows up in the πN invariant mass spectra in πN and γN production processes which allow all $1/2^\pm$, $3/2^\pm$, $5/2^\pm$, and $7/2^\pm$ N^* resonances and their isospin $3/2$ Δ^* partners around this energy to interfere with each other. In order to determine its spin-parity, a partial wave analysis using an effective Lagrangian approach [9] is tried for the $p\pi^-\bar{n}$ data by including a new $N^*(2065)$ with spin-parity either $1/2^+$ or $3/2^+$ in addition to all well-established N^* resonances below 2 GeV/c^2 with masses and widths fixed to their Particle Data Group values [1]. Comparing with the fit without including any new $N^*(2065)$ resonance, including a $N^*(2065)$ with spin-parity of either $1/2^+$ or $3/2^+$ improves log likelihood value by more than 400. The new $N^*(2065)$ peak cannot be reproduced by reflections of well-established N^* resonances. However, the spin-parity of the new resonance(s) cannot be well determined. The difference of the fits with different spin-parity quantum numbers is small and depends on many fitting details, such as how to treat the background contribution and how large an isospin breaking effect is allowed. Including both $1/2^+$ and $3/2^+$ improves log likelihood value further by more than 60. So it is quite possible that both are needed. There are quark model predictions for the existence of N^* resonances with spin-parity $1/2^+$ and $3/2^+$ in the energy range from 2.0 to 2.1 GeV/c^2 [7,17,18]. The same channel has also been studied in ψ' decays [19]. However, due to lower statistics and the allowance of more partial waves, only a much broader peak was observed above 2 GeV/c^2.

In summary, the $J/\psi \to \bar{N}N\pi$ decay at BEPC provides an excellent place for studying pure isospin $1/2$ excited N^* resonances. Using 58×10^6 J/ψ decays, more than 100 000 $J/\psi \to p\pi^-\bar{n}$ + c.c. events are obtained. The corresponding branching ratios are determined to be $(2.36 \pm 0.02 \pm 0.21) \times 10^{-3}$ and $(2.47 \pm 0.02 \pm 0.24) \times 10^{-3}$ for $p\pi^-\bar{n}$ and $\bar{p}\pi^+ n$, respectively. In the $p\pi$ invariant mass, besides the two well-known peaks around 1500 MeV/c^2 and 1670 MeV/c^2, there are two new clear peaks. The one around 1360 MeV/c^2 with statistical significance of 11σ, identified as due to the $N^*(1440)$ resonance (usually obscured by the strong Δ peak in πN and

γN experiments), has a Breit-Wigner mass and width of $1358 \pm 6 \pm 16$ MeV/c^2 and $179 \pm 26 \pm 50$ MeV/c^2. The other N^* peak around 2065 MeV/c^2 with statistical significance of 13σ is believed to be due to long-sought missing N^* resonance(s) predicted by many theoretical quark models [18] in this energy range. A simple Breit-Wigner fit gives its mass as $2068 \pm 3^{+15}_{-40}$ MeV/c^2 and width as $165 \pm 14 \pm 40$ MeV/c^2. From a partial wave analysis, we conclude that the new $N^*(2065)$ peak cannot be reproduced by reflections of Particle Data Group established N^* resonances and includes at least one new N^* resonance.

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