Observation of Two New N^* Resonances in the Decay $\psi(3686) \to p\bar{p}\pi^0$

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Based on $106 \times 10^6\,\psi(3686)$ events collected with the BESIII detector at the BEPCII facility, a partial wave analysis of $\psi(3686) \to p\bar{p}\pi^0$ is performed. The branching fraction of this channel has been determined to be $B(\psi(3686) \to p\bar{p}\pi^0) = (1.65 \pm 0.03 \pm 0.15) \times 10^{-4}$. In this decay, 7 N^* intermediate resonances are observed. Among these, two new resonances, $N(2300)$ and $N(2570)$ are significant, one $1/2^+$ resonance with a mass of $2300^{+40+109}_{-30-0}$ MeV$/c^2$ and width of $340^{+30+110}_{-30-58}$ MeV$/c^2$, and one $5/2^-$ resonance with a mass of 2570^{+19+34}_{-10-10} MeV$/c^2$ and width of 250^{+14+69}_{-24-21} MeV$/c^2$. For the remaining 5 N^* intermediate resonances [$N(1440)$, $N(1520)$, $N(1535)$, $N(1650)$ and $N(1720)$], the analysis yields mass and width values that are consistent with those from established resonances.

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Although symmetric nonrelativistic three-quark models of baryons are quite successful in interpreting low-lying excited baryon resonances, they tend to predict far more excited states than are found experimentally ("missing resonance problem") [1,2]. From the theoretical point of view, this could be due to a wrong choice of the degrees of freedom, and models considering diquarks have been proposed [3]. Experimentally, the situation is very complicated due to the large number of broad and overlapping states that are observed. Moreover, in traditional studies using tagged photons or pion beams [4–11], both isospin 1/2 and isospin 3/2 resonances are excited, further complicating the analysis.

An alternative method to investigate nucleon resonances employs decays of charmonium states such as J/ψ and $\psi(3686)$. By selecting specific decay channels, such as

$\psi(3686) \to p\bar{p}\pi^0$, N^* intermediate resonances coupling to $p\pi^0$ or $\bar{p}\pi^0$ can be studied. Here, Δ resonances are suppressed due to isospin conservation. As a consequence, the reduced number of states greatly facilitates the analysis [12].

N^* production in $J/\psi \to p\bar{p}\eta$ was studied using partial wave analysis at the Beijing Spectrometer (BES) [13], and two N^* resonances were observed. In a recent analysis of $J/\psi \to p\bar{n}\pi^- + \text{c.c.}$ [14], a new N^* resonance around 2000 MeV/c^2 named $N(2065)$ was observed. This $N(2065)$ was also observed in the decay of $J/\psi \to p\bar{p}\pi^0$ [15]. The production of $N(2065)$ in J/ψ decays occurs close to the edge of the phase space. Thus, a similar search for this resonance in the $\psi(3686)$ decays should provide further insight.

In the work of the CLEO Collaboration [16], $\psi(3686) \to p\bar{p}\pi^0$ was studied using $24.5 \times 10^6\,\psi(3686)$ events. With the invariant mass spectra of $p\pi^0$ and $p\bar{p}$, two N^* resonances [$N(1440)$, $N(2300)$] and two $p\bar{p}$ resonances [$R_1(2100)$, $R_2(2900)$] were investigated without taking into account possible interferences between the resonances. The inclusion of R(2100) is suggested by a threshold enhancement in the $p\bar{p}$ mass spectrum. The concentration of events below 1800 MeV/c^2 in the $p\pi^0$ mass spectrum is considered as the contribution of $N(1440)$ alone.

In this Letter, we briefly report a study of N^* resonances from $\psi(3686) \to p\bar{p}\pi^0$ based on a data sample of 160 pb^{-1} corresponding to 106 million $\psi(3686)$ decays collected with the upgraded Beijing Spectrometer (BESIII), located at the Beijing Electron-Positron Collider (BEPCII) [17]. The full details will be published later.

The BESIII detector is composed of a helium-gas-based drift chamber (MDC), a time-of-flight system, a CsI (Tl) electromagnetic calorimeter (EMC), a superconducting solenoid magnet, and a resistive plate chambers-based muon chamber. More detailed information about the detector can be found in Ref. [17].

The final state in this decay is characterized by two charged tracks and two photons. Two charged tracks with opposite charge are required. Each track is required to have its point of closest approach to the beam axis within ± 20 cm of the interaction point in the beam direction and within 2 cm of the beam axis in the plane perpendicular to the beam. The polar angle of the track is required to be within the region of $|\cos(\theta)| < 0.8$.

The time-of-flight and the specific energy loss dE/dx of a particle measured in the MDC are combined to calculate particle identification probabilities for pion, kaon, and proton hypotheses. For each track, the particle type yielding the largest probability is assigned. In this analysis, one charged track is required to be identified as a proton and the other one as an anti-proton.

Photon candidates are selected by requiring a minimum energy deposition of 25 MeV in the barrel EMC or 50 MeV in the end cap EMC. To reject photons due to charged particle radiation production, the angle between the photon candidate and the proton is required to be greater than 10°. A more stringent cut of 30° between the photon candidate and anti-proton is applied to exclude the large number of photons from anti-proton annihilation.

For events with one proton, one anti-proton, and at least two photons, a kinematic fit (4C) with the sum of four-momenta of all particles constrained to the energy and three momentum-components of the initial e^+e^- system is applied. A further kinematic fit (5C) with one more constraint of π^0 mass for the two photons is applied to provide more accurate momentum information on the final states. When more than two photons are found in a candidate event, all possible $p\bar{p}\gamma\gamma$ combinations are considered and the one yielding the smallest χ^2_{5C} is retained for further analysis.

The events passing the above selection criteria are shown in Figs. 1(a) and 1(b), displayed as the Dalitz plot of $\psi(3686) \to p\bar{p}\pi^0$ and the invariant mass of $p\bar{p}$. The $p\bar{p}$ mass spectrum shows a clear J/ψ signal. Due to the detector resolution, the observed width of J/ψ is far larger than its natural width. This width difference causes a problem in the inclusion of J/ψ in partial wave analysis. Thus, a cut of $|MA_{p\bar{p}} - M_{J/\psi}| > 40$ MeV/c^2 is applied to exclude events with $p\bar{p}$ arising from J/ψ decay. A total of 4988 events survive the event selection criteria. The mass spectra of $p\pi^0$ and $\bar{p}\pi^0$ for the surviving events are shown in Figs. 1(c) and 1(d).

For this analysis, two background sources are studied. The first one arises from $\psi(3686)$ decays and has been studied with two methods. In the first method, a sample of 10^8 Monte Carlo- (MC-)simulated $\psi(3686)$ events is used and 40 events survive the event selection, mainly due to misidentified or lost photons. In the second method, the background contribution is estimated using the π^0

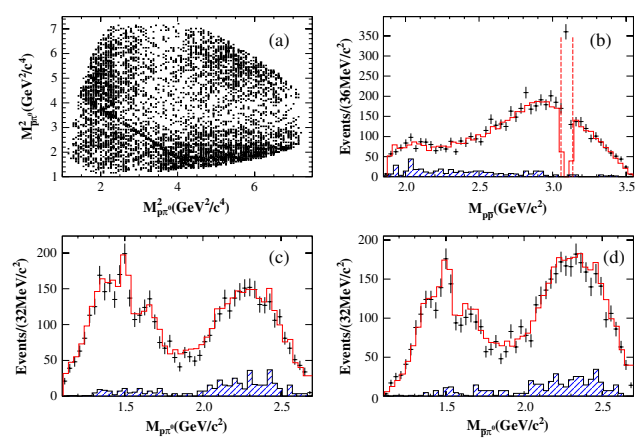

FIG. 1 (color online). (a) Dalitz plot of $\psi(3686) \to p\bar{p}\pi^0$, the invariant mass spectra of (b) $p\bar{p}$, (c) $p\pi^0$, and (d) $\bar{p}\pi^0$. The dashed lines in (b) show the cut at the J/ψ mass region. The crosses represent the experimental data, and the shaded histograms show the background from continuum process and π^0 sideband. The histograms in solid line show the sum of MC prediction and the background.

sideband events, defined by 30 $\mathrm{MeV}/c^2 < |M_{\gamma\gamma} - 135| <$ 45 MeV/c^2. Only 26 events are found in the sideband area. The other background source arises from the continuum process $e^+e^- \to \gamma* \to p\bar{p}\pi^0$. This has been studied using 42 pb^{-1} of continuum data at $\sqrt{s} = 3650$ MeV. After normalizing to the integrated luminosity of $\psi(3686)$, 447 background events are found. In Fig. 1, the shaded histograms show the total background contributions from continuum process and π^0 sideband, in which the continuum contribution accounts for about 95%.

In our present investigation, with larger statistics than at CLEOc, more than one N^* state below 1700 MeV/c^2 is seen in the $p\pi^0$ and $\bar{p}\pi^0$ mass spectra, and the threshold enhancement in the $p\bar{p}$ mass spectrum is also visible. To better understand the components of this decay, a partial wave analysis taking into account the possible interferences is pursued.

The decay of $\psi(3686) \to p\bar{p}\pi^0$ is thought to be dominated by two-body decays involving N^*, $\bar{N}^*$ states [18], which can be described by $\psi(3686) \to p\bar{N}^*(\bar{p}N^*)$, $N^*(\bar{N}^*) \to p\pi^0(\bar{p}\pi^0)$. In addition, a process of the type $\psi(3686) \to R\pi^0$ is considered, where R represents a hypothetical $p\bar{p}$ resonance. The data are fitted applying an unbinned maximum likelihood fit. The amplitudes (A_i) for all possible partial waves are constructed using the relativistic covariant tensor amplitude formalism [15,19,20]. With these amplitudes, the total transition probability for each event is obtained from a linear combination of these partial wave amplitudes as $\omega = |\Sigma_i c_i A_i|^2$. Finally, the likelihood function $\ln(L)$ is constructed as $\sum_{i=1}^{n} \ln(\frac{\omega(\xi_i)\epsilon(\xi_i)}{\int d\xi \omega(\xi_i)\epsilon(\xi_i)})$, where n is the total number of events, ξ is the four-momenta of p, $\bar{p}$, and π^0, $\omega(\xi)$ the probability density for a single event to populate the phase space at ξ, and $\epsilon(\xi)$ is the detection efficiency to detect one event with ξ. The free parameters c_i are determined by maximizing the likelihood function $\ln(L)$. For each N^* state, the amplitude is parameterized with a Breit-Wigner function, in which the mass and width of the resonance are variables, as described in Ref. [15]. The background contributions from π^0 sideband and continuum processes are removed by subtracting the log-likelihood [$\ln(L)$] values, as the log-likelihood value of data is the sum of that of signal and background events. Possible interference between continuum processes and $\psi(3686)$ decays is not considered.

All N^* resonances up to 2200 MeV/c^2 with spin up to $5/2$, listed in the summary tables of the Particle Data Book [21], are considered in this analysis, such as the well-established states, $N(1440)$ and $N(1520)$, and not-well-measured states, $N(2090)$ and $N(2100)$. Phase space decay and two speculative N^* resonances, $N(1885)$ and $N(2065)$, are also considered. According to the framework of soft π meson theory [22], the off-shell decay process is needed in this channel. Thus, $N(940)$ with a mass of 940 MeV/c^2 and zero width is included. The $N(940)$ represents a virtual proton, which could emit a π^0. The Feynman diagram of this process can be found in Ref. [15]. In total, 19 intermediate resonances are considered.

For N^* resonances with spin larger than $5/2$, such as the $N(2190)$, $N(2220)$, $N(2250)$, and $N(2600)$ [23–25], orbital angular momenta $L > 2$ are required, and are not expected to contribute significantly in charmonium decay due to the suppression by the centrifugal barrier. The reason is twofold. At first, the annihilation radius of $c\bar{c}$ is very small, estimated to be in the order of 0.1 fm, due to the large mass of charm quark. This is about one order of magnitude smaller than the interaction radius of πN scattering, which is about several fm. Second, the relative momentum of N^* and $\bar{p}$ is small, especially for large mass N^* resonance. Given the small annihilation radius and the small relative momenta of N^* and $\bar{N}$, orbital angular momenta $L > 2$ should be suppressed. If otherwise high spin states do exist in this decay, this should result in an inconsistency of data and fit, which is not observed. Thus, with the sensitivity of the present experiment, we consider it adequate to include only states with spin up to $5/2$.

In our analysis, the first step is to select the significant resonances among all these resonances. The significance of each resonance is determined from the difference of the likelihood values of fits with and without the given resonance, accounting for the change of the number of parameters. Resonances with significance greater than 5σ are taken as significant ones and include $N(940)$ and seven N^* resonances. The remaining insignificant resonances are removed and only considered when estimating the systematic errors. The mass and width of N^* states are varied, and the values with the best fitting result are taken as the optimized values. Table I lists the optimized values for the seven N^* states. Here, the first errors are statistical and the second ones are systematic. In this table, the first five N^* resonances are consistent with the values in the Particle Data Book [21], while the last two states cannot be identified with $N(2100)$ or $N(2200)$. However, the significance of these two states are 15σ and 11.7σ, respectively. As a consequence, we label these two states as $N(2300)$ and $N(2570)$, with J^P assignment of $1/2^+$ and $5/2^-$, respectively.

Using these eight significant resonances, the fit result agrees well with the data, as shown in Fig. 1. The χ^2 over the number of degree of freedom is 1.12. The contribution of each intermediate resonance including interference effects with other resonances are extracted and shown in Fig. 2. Figure 2(a) shows the contributions of $N(1440)$, $N(1520)$, $N(1535)$, and $N(1650)$ in which we can see clear peaks and also tails at the high mass region from the interference effects. Figure 2(b) shows the contributions of $N(940)$, $N(1720)$, $N(2300)$, and $N(2570)$. For $N(2300)$ and $N(2570)$, their peak positions are below the Breit-Wigner mean values reported in Table I because of the presence of interference contributions, as well as phase space and centrifugal barrier factors.

TABLE I. The optimized mass, width, and significance (Sig.) of the seven significant N^* resonances. ΔS represents the change of the log-likelihood value. $\Delta N_{\rm dof}$ is the change of the number of free parameters in the fit. In the second and third columns, the first error is statistical and the second is systematic. The names of the last two resonances, $N(2100)$ and $N(2200)$, have been changed to $N(2300)$ and $N(2570)$ according to the optimized masses.

Resonance	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	ΔS	$\Delta N_{\rm dof}$	Sig.
$N(1440)$	1390^{+11+21}_{-21-30}	$340^{+46+70}_{-40-156}$	72.5	4	11.5σ
$N(1520)$	1510^{+3+11}_{-7-9}	115^{+20+0}_{-15-40}	19.8	6	5.0σ
$N(1535)$	1535^{+9+15}_{-8-22}	120^{+20+0}_{-20-42}	49.4	4	9.3σ
$N(1650)$	1650^{+5+11}_{-5-30}	150^{+21+14}_{-22-50}	82.1	4	12.2σ
$N(1720)$	1700^{+30+32}_{-28-35}	$450^{+109+149}_{-94-44}$	55.6	6	9.6σ
N(2300)	$\mathbf{2300^{+40+109}_{-30-0}}$	$\mathbf{340^{+30+110}_{-30-58}}$	**120.7**	**4**	$\mathbf{15.0\sigma}$
N(2570)	$\mathbf{2570^{+19+34}_{-10-10}}$	$\mathbf{250^{+14+69}_{-24-21}}$	**78.9**	**6**	$\mathbf{11.7\sigma}$

Various checks have been performed to test the reliability of this analysis. The first one is the spin parity check, in which the spin parity of each state of the optimized solution is changed to other possible values to test the other J^P assignments. For $N(2300)$ and $N(2570)$, $1/2^+$ and $5/2^-$, respectively, are the best J^P values. The significance becomes worse using other J^P assignments. The second one is the input-output check. A MC sample was generated with given components. After the fitting procedure described above, the significant states and their properties (mass, width, branching fraction, and the effect of interference terms) are compared with the input values. The output values agree with the input within $\pm 1\sigma$, corroborating that the analysis procedure is reliable.

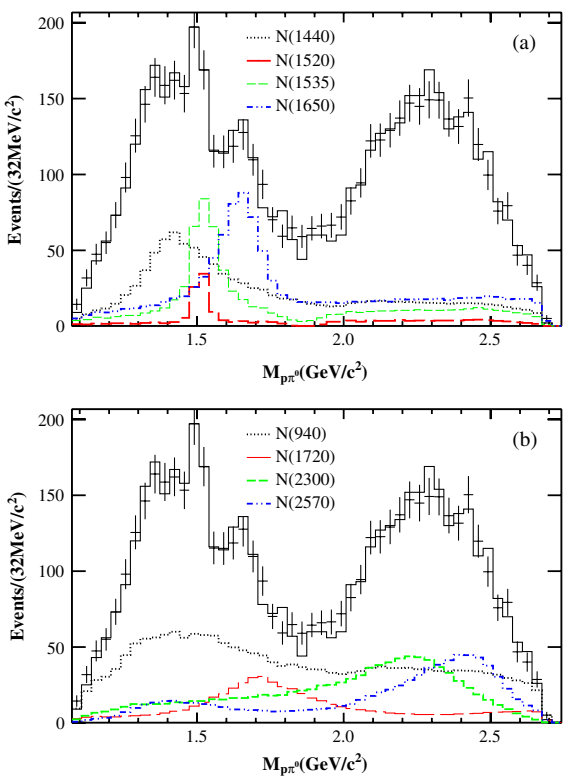

FIG. 2 (color online). The contribution of each intermediate resonance in the $p\pi^0$ mass spectra. The interferences with other resonances are included. (a) contributions of $N(1440)$, $N(1520)$, $N(1535)$, and $N(1650)$; (b) contributions of $N(940)$, $N(1720)$, $N(2300)$, and $N(2570)$.

On the basis of the eight significant states, a scan for additional resonances has been performed with different spin parity, mass, and width combinations. No extra resonance has been found to be significant. For $N(1885)$, the obtained significance ranges from 1σ to 1.2σ depending on the mass and width. The largest significance is obtained at a mass of 1930 MeV/c^2 and width of 150 MeV/c^2. The significance for $N(2065)$ varies between 3.2σ and 4σ, where the maximum is obtained at a mass of 2140 MeV/c^2 and width of 250 MeV/c^2. We consider neither resonance as significant and do not claim any evidence. Besides the known and speculative N^* resonances, a 1^{--} $p\bar{p}$ resonance candidate described by the Breit-Wigner function has been added, as suggested by the near-threshold enhancement in the $p\bar{p}$ mass distribution. Varying the width from 50 MeV/c^2 to 300 MeV/c^2 and mass from 1800 MeV/c^2 to 3000 MeV/c^2 with the step size of 10 MeV/c^2, the largest significance obtained is 4σ at a mass of 2000 MeV/c^2 and width of 50 MeV/c^2, indicating that no $p\bar{p}$ resonance is required to explain the threshold enhancement.

The branching fraction of $\psi(3686) \to p\bar{p}\pi^0$ is determined as follows:

$$B(\psi(3686) \to p\bar{p}\pi^0) = \frac{N - N_{\rm bkg}}{\epsilon \times N_{\psi(3686)} \times B(\pi^0 \to \gamma\gamma)} = (1.65 \pm 0.03 \pm 0.15) \times 10^{-4}.$$

TABLE II. Summary of measurements of the number of events, the MC efficiency (ϵ), and the branching fraction (B.F.) of each intermediate resonance and the whole channel. Here, for the number of events and the branching fraction, the first error is statistical and the second is systematic.

Resonance	N	$\epsilon(\%)$	B.F.$(\times 10^{-5})$
$N(940)$	$1870^{+90+487}_{-90-327}$	27.5 ± 0.4	$6.42^{+0.20+1.78}_{-0.20-1.28}$
$N(1440)$	$1060^{+90+459}_{-90-227}$	27.9 ± 0.4	$3.58^{+0.25+1.59}_{-0.25-0.84}$
$N(1520)$	190^{+14+64}_{-14-48}	28.0 ± 0.4	$0.64^{+0.05+0.22}_{-0.05-0.17}$
$N(1535)$	$673^{+45+263}_{-45-256}$	25.8 ± 0.4	$2.47^{+0.28+0.99}_{-0.28-0.97}$
$N(1650)$	$1080^{+77+382}_{-77-467}$	27.2 ± 0.4	$3.76^{+0.28+1.37}_{-0.28-1.66}$
$N(1720)$	$510^{+27+50}_{-27-197}$	26.9 ± 0.4	$1.79^{+0.10+0.24}_{-0.10-0.71}$
$N(2300)$	$948^{+68+394}_{-68-213}$	34.2 ± 0.4	$2.62^{+0.28+1.12}_{-0.28-0.64}$
$N(2570)$	$795^{+45+127}_{-45-83}$	35.3 ± 0.4	$2.13^{+0.08+0.40}_{-0.08-0.30}$
Total	4515 ± 93	25.8 ± 0.4	$16.5 \pm 0.3 \pm 1.5$

Here, N represents the number of observed events, $N_{\rm bkg}$ stands for the number of estimated background events, and ϵ is the efficiency derived from MC events generated according to the model derived from the partial wave analysis. This result is in agreement with the value of $(1.33 \pm 0.17) \times 10^{-4}$ in the Particle Data Book [21]. The products of the production and decay branching fractions for each N^* intermediate resonance are also determined, as shown in Table II. The sum of the individual branching fractions is larger than the total due to interference effects of the intermediate resonances.

The systematic uncertainty sources are divided into two categories. The first includes the systematic errors from the number of $\psi(3686)$ events (4%), MDC tracking (4% for two charged tracks), particle identification (2% for both proton and anti-proton), photon detection efficiency (2%), and kinematic fit (7%). These uncertainties are applicable to all branching fraction measurements. The total systematic error from these common sources is 9.4%. The second source concerns the fitting procedure, which includes the uncertainties from additional possible resonances, the uncertainties using different Breit-Wigner parameterizations for partial wave amplitude, the uncertainties from background estimation, the uncertainties from the J/ψ exclusion cut, as well as the differences in the input-output check. These sources are applied to the mass, width, and branching fraction measurements of intermediate states. The total systematic errors are the combination of the errors from the common sources and the fitting procedure.

In summary, we studied the intermediate resonances, including their masses, widths, and spin parities, in the decay $\psi(3686) \to p\bar{p}\pi^0$. Two new N^* resonances are observed, in addition to five well-known N^* resonances. The masses and widths as well as the spin parities of the two new N^* states have been measured. The branching fractions of $\psi(3686) \to p\bar{p}\pi^0$ and the product branching fractions through each intermediate N^* state are measured. No clear evidence for $N(1885)$ or $N(2065)$ has been found. The hypothetical $p\bar{p}$ resonance has a significance of less than 4σ, indicating that the threshold enhancement most likely is due to interference of N^* intermediate resonances.

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