Search for exotic state 1^{-+} $\pi_1(1400)$ at BESIII*

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Abstract The J/ψ hadronic decays provide good laboratory to search for the hybrid states with exotic quantum numbers. A full Partial Wave Analysis (PWA) is performed to the generated Monte Carlo $J/\psi \to \rho\eta\pi$ data, based on the design of BESIII detector, to study the sensitivity of searching for a possible exotic state at BESIII.

Key words 1^{-+} exotic state, $\pi_1(1400)$, covariant helicity-coupling amplitudes, partial wave analysis

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1 Introduction

Hybrid mesons are color-singlet mixture of constituent quarks and gluons, such as $q\bar{q}g$ bound states. The evidence of the existence of the hybrid mesons is a direct proof of the existence of the gluonic degree of freedom and the validity of QCD. The conventional wisdom is that it would be more fruitful to search for the low lying hybrid mesons with exotic quantum numbers than to search for glueballs. Hybrids have the additional attraction, unlike glueballs, they span complete flavour nonets and hence provide many possibilities for experimental detection. In addition, the lightest hybrid multiplet includes at least one J^{PC} exotic.

In searching for hybrids, there are two ways to distinguish them from the conventional states. One approach is to look for an access of observed states over the number predicted by the quark model. The drawback of this method is that it depends on a good understanding of hadron spectroscopy in a mass region that is still rather murky. At present, the phenomenological models have not been tested to the extent experimentally, so that a given state can be reliably ruled out as a conventional meson. The situation is further muddied by the expected mixing between then conventional $q\bar{q}$ states and the hybrids with the same J^{PC} quantum numbers. The other approach is to search for the states with quantum numbers that cannot be accommodated in the quark model. The discovery of exotic quantum numbers would be definite evidence of something new.

Previous experiments have searched for the isovector 1^{-+} hybrid states, and some of them found the evidence.

The first evidence for an exotic $\pi\eta$ resonance was claimed by the GAMS collaboration[1] in the charge exchange reaction $\pi^-p \to \eta\pi^0 n$, and the findings were, however, ambiguous in later analysis[2]. Contributions from an exotic $\pi\eta$ P-wave were also reported from VES[3]. At KEK[4], observation of a $\pi\eta$ resonance, with the mass and width being coincident with those of $a_2(1320)$, was claimed, however, a feedthrough from the dominant D-wave into the P-wave cannot be excluded. E852 at BNL reported an isovector 1^{-+} state with the mass and width of $(1370 \pm 16^{+50}_{-30})$ MeV/c^2 and $(385 \pm 40^{+65}_{-105})$ MeV/c^2, respectively, in $\pi^-p \to \eta\pi^-p$ at 18 GeV/c[5]. In all these studies, the $\pi\eta$ P-wave was seen in a forward-backward asymmetry of the $\pi\eta$ system produced in $\pi^-p \to \eta\pi^-p$ or $\eta\pi^0 n$ which evidences the interference between the even and the odd $\pi\eta$ partial waves. Later, Crystal Barrel Collaboration found the evidence for an $I^G(J^{PC}) = 1^-(1^{-+})$ exotic state[6] with the mass and width of $(1400 \pm 20 \pm 20)$ MeV/c^2 and $(310 \pm 50^{+50}_{-30})$ MeV/c^2, respectively, in the reaction

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$\bar{\mathrm{p}}\mathrm{n}\to\pi^-\pi^0\eta$ obtained by stopping antiprotons in liquid deuterium. The partial wave analysis of data on $\mathrm{p}\bar{\mathrm{p}}$ annihilation at rest in liquid hydrogen (LH_2) into $\pi^0\pi^0\eta$ by Crystal Barrel shows that the inclusion of a $\pi\eta$ P-wave in the fit gives supportive evidence for the 1^{-+} exotic state with the parameters compatible with the previous findings[7]. Another isovector 1^{-+} meson, $\pi_1(1600)$, was observed in $\rho\pi$[8], $\eta'\pi$[9], and $f_1\pi$[10] decay. The latter experiment also revealed a higher state, $\pi_1(2000)$[10], and the $f_1\pi$ decays of $\pi_1(1600)$ and $\pi_1(2000)$ were measured. This rich spectrum of exotic mesons is somewhat puzzling, since the lattice[11] and flux-tube model[12, 13] calculations predict only one low-mass π_1 meson.

In the flux-tube model the lightest 1^{-+} isovector hybrid is predicted to decay primarily to $b_1\pi$[12]. The $f_1\pi$ branch is also expected to be large and many other decay modes are suppressed. However, few experiments have addressed the $b_1\pi$ and $f_1\pi$ decay channels. The VES collaboration reported a broad 1^{-+} peak in $b_1\pi$ decay[14], and Lee, et al.[15] observed significant 1^{-+} strength in $f_1\pi$ decay. In neither case was a definitive resonance interpretation of the 1^{-+} waves possible. The preliminary results from a later VES analysis show the excitation of $\pi_1(1600)$[16]. E852 experiment at BNL reported the observation of strong excitation of the exotic $\pi_1(1600)$ in the $(b_1\pi)^-$ decay channel and confirmed the exotic $\pi_1(2000)$ in the reaction $\pi^-\mathrm{p}\to\pi^+\pi^-\pi^-\pi^0\pi^0\mathrm{p}$[17].

By simply counting the powers of the electromagnetic and strong coupling constants, one obtains:

$$\Gamma(\mathrm{J}/\psi\to\mathrm{MH}) > \Gamma(\mathrm{J}/\psi\to\mathrm{MM'})\approx\Gamma(\mathrm{J}/\psi\to\mathrm{MG}).$$

Here, M stands for ordinary $q\bar{q}$ meson, G for glueball and H for hybrid state. Therefore, the hadronic decays of J/ψ provide a good place to search for the hybrid states.

In this paper, we present a full Monte Carlo simulation of the decays $\mathrm{J}/\psi\to\rho\eta\pi^0$, with $\rho\to\pi^+\pi^-$ and $\eta\to\gamma\gamma$ and the results from a partial wave analysis, based on GEANT4 and BESIII design.

2 BESIII/BEPCII

The BES is a large general purpose solenoidal detector at the Beijing Electron Positron Collider (BEPC). It is designed to study the exclusive and inclusive e^+e^- annihilations in the τ-charm region. Since 2003, an experimental project of upgrading BES/BEPC to BESIII/BEPCII has been going on. With the double-ring design, the peak luminosity of BEPCII will reach 10^{33} $\mathrm{cm^{-2}\cdot s^{-1}}$ at the center of mass energy around $\psi(3770)$ peak. Then, the luminosity at J/ψ peak will be about 60% of that at $\psi(3770)$ peak. If assuming the average luminosity is half of the peak luminosity and the effective running time for data accumulation is around 10^7 s each year, the expected J/ψ events for one year's running are about 10 billion, taking into account the 3400 nb peak cross section for J/ψ production. This is a huge data sample. On the other hand, the new BESIII detector consists of a drift chamber (MDC) which has a small cell structure filled with helium-based gas, an electromagnetic calorimeter (EMC) made of CsI(Tl) crystals, time-of-flight counters (TOF) for particle identification made of plastic scintillators, a muon system made of Resistive Plate Chambers (RPC) and a super conducting magnet. The designed single wire spatial resolution, $\mathrm{d}E/\mathrm{d}x$ resolution and momentum resolution for the MDC are 130 μm, 6% and 0.5% $\sqrt{1+p^2}$ (p in GeV/c), respectively. The time resolution for TOF is $\sigma_{\mathrm{TOF}}=100$ ps for Bhabha events and the energy resolution for photons is $\sigma_{\mathrm{E}}/E\approx2.5\%/\sqrt{E}$ (E in GeV) in EMC. The huge J/ψ data sample taken with BESIII, a detector having much better performance, makes the systematic study of the light hadron spectroscopy possible and makes the search for the new hadron states, e.g. glueballs, hydrids and multi-quark states possible.

3 Monte Carlo simulation of 1^{-+} exotic state $\pi_1(1400)$ at BESIII/BEPCII

For $\mathrm{J}/\psi\to\rho\eta\pi^0$, we generated possible processes of $\mathrm{J}/\psi\to\rho a_0(980)$, $\rho a_2(1320)$, $\rho\pi_1(1400)$ and $\rho a_2(1700)$, with the fractions listed below,

$$\begin{aligned} Fr(\mathrm{J}/\psi\to\rho a_0(980))&\sim4.4\%,\\ Fr(\mathrm{J}/\psi\to\rho\pi_1(1400))&\sim14.6\%,\\ Fr(\mathrm{J}/\psi\to\rho a_2(1320))&\sim21.4\%,\\ Fr(\mathrm{J}/\psi\to\rho a_2(1700))&\sim41.6\%,\end{aligned}$$

and considered the angular distributions of different spin-parities and the interferences among them. The main background of $\mathrm{J}/\psi\to\rho\eta\pi^0$ comes from $\mathrm{J}/\psi\to\gamma\rho^+\rho^-$ which is also simulated by BESIII Monte Carlo.

For a candidate event, we require two good charged tracks with zero net charge and at least four good photons. A good charged track is one that is within the polar angle region $|\cos\theta|<0.93$ and has the point of the closest approach of the track to the beam axis within 1 cm of the beam axis and 5 cm from the center of the interaction region along the beam line. The two charged tracks are required to consist of an unambiguously identified $\pi^+\pi^-$. Candidate photons are required to have energy deposited in the electromagnetic calorimeter to be greater than

50 MeV and to be isolated from the charged tracks by more than 20° in both x-y and r-z planes; at least four photons are required. A four-constraint (4C) energy-momentum conservation kinematic fit is performed to the $\pi^+\pi^-\gamma\gamma\gamma\gamma$ hypothesis and the $\chi^2_{4\mathrm{C}}$ is required to be less than 15. For events with more than four selected photons, the combination with the smallest χ^2 is chosen. The photons from the decays of π^0 and η are decided by the combination with the smallest δ. Here,

$$\delta = \sqrt{(M_\eta - M\gamma_1\gamma_2)^2 + (M_{\pi^0} - M\gamma_3\gamma_4)^2}.$$

All the generated $J/\psi \to \rho\eta\pi^0$ events are subjected to the selection criteria described above. The error bars in Fig. 1(a) show $\eta\pi^0$ invariant mass spectrum for the surviving events and the shaded area represents the background. The signal and background events are normalized to 1.5×10^8 J/ψ data sample. The mass resolutions and efficiencies in 1.4 GeV/c^2 mass region are about 10 MeV/c^2 and 27.2%, respectively.

All the signal events are added by taking into account the interferences between them, and the backgrounds are included incoherently. A partial wave analysis is performed to these events.

The covariant helicity coupling amplitude method is used[18—21] to construct the amplitudes.

Here we briefly introduce the construction of covariant helicity coupling amplitude. For the decay process $\mathrm{a} \to \mathrm{b}+\mathrm{c}$, the decay amplitude $M^J_{\lambda_\mathrm{b}\lambda_\mathrm{c}}$ of the decay vertex of $\mathrm{a}\to\mathrm{b}+\mathrm{c}$ can be written as:

$$M^J_{\lambda\nu}(\theta,\phi,M) \propto D^J_{M\delta}(\phi,\theta,0)F^J_{\lambda\nu}\ ,$$
$$F^J_{\lambda\nu} = < JM\lambda\nu|\mathcal{M}|JM >,$$

Here, J^{η_J} is the spin-parity of the mother particle a, $S^{\eta_s}, \sigma^{\eta_\sigma}$ are those of the daughter particle b and c, and M, λ, ν are the corresponding helicities, p, q, k and $\phi(\delta)$, $\omega(\lambda)$, $\varepsilon(-\nu)$ are the four momenta and wave functions of particles a, b and c, respectively, with $\delta=\lambda-\nu$, and the θ and ϕ are the polar and azimuthal angles of particle b in the center of mass frame of mother particle a. The parity conservation in the decay leads to the relationship

$$F^J_{\lambda\nu} = \eta_J\eta_s\eta_\sigma(-)^{J-s-\sigma}F^J_{-\lambda-\nu}\ .$$

One may write an explicit covariant expression (Lorentz scalar) for the helicity-coupling amplitudes

$$F^J_{\lambda\nu} = \sum\nolimits_\alpha g_\alpha A_\alpha(\lambda\nu)$$

where

$$A_\alpha(\lambda\nu) = [p^n, r^l, \omega(\lambda), \varepsilon(-\nu), \phi^*(\delta)].$$

Here, the variable α stands for the set $\{l,s\}$, l is the quantum number of relative angular momentum of particles b and c and $r=q-k$ is the relative four-momentum between particles b and c, and g_α is the coefficient to be determined. It is to be noted that $n=1$ is for $s+\sigma+l-J$ odd and $n=0$ for even. The covariant helicity coupling amplitude $F^J_{\lambda\nu}$ which is not the function of the Euler angular included in D-function can then be written. Up to now, the vertex amplitude of single decay process has been obtained.

In the analysis, the constant width Breit-Wigner functions are used for each resonances. The form is described as follows:

$$BW_\mathrm{X} = \frac{m\Gamma}{s-m^2+\mathrm{i}m\Gamma},$$

where s is the square of $\eta\pi^0$ invariant mass, m and Γ are the mass and width of the intermediate resonance X, respectively.

We write down the total covariant helicity coupling amplitude of the sequential decay processes:

$$J/\psi \to \rho^0 + \mathrm{X}, \quad \mathrm{X}\to\eta\pi^0,$$

as

$$A(\mathrm{X_i}) = M^{J_{J/\psi}}_{\lambda_{\rho^0}\lambda_\mathrm{X}} \cdot BW_\mathrm{i}(\mathrm{X}) \cdot M^{J_\mathrm{X}}_{00}\ .$$

The differential cross section, $\mathrm{d}\sigma/\mathrm{d}\Phi$, is given by:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi} = |A_\mathrm{total}|^2 + BG\ . \quad (1)$$

Here, A_total is the total amplitude which is defined as a coherent sum over the amplitudes due to all possible intermediate states, and BG denotes the background contribution.

The magnitudes and relative phases of the amplitudes are determined by an unbinned maximum likelihood fit to the generated data.

The background events from $J/\psi \to \gamma\rho^+\rho^-$ are given the opposite log likelihood in the fit to cancel the background events in the data. The ratio of background of this channel is set to be 10% in the simulation sample. In this analysis, the masses and widths of $a_0(980)$ and $a_2(1700)$ are fixed to PDG values and those for $a_2(1320)$ and $\pi_1(1400)$ are allowed to float.

Figure 1(a) shows the comparison of $\eta\pi^0$ invariant mass spectrum for the generated events and that from PWA projections. The consistency is reasonable. Fig. 1(b) represents the contributions from each component. The angular distributions for the generated events and those from PWA are shown in Fig. 2.

The comparison of the input and output values for the masses, widths and component fractions is shown in Table 1, where the output masses, widths and fractions that are obtained from PWA analysis agree with the input values reasonably.

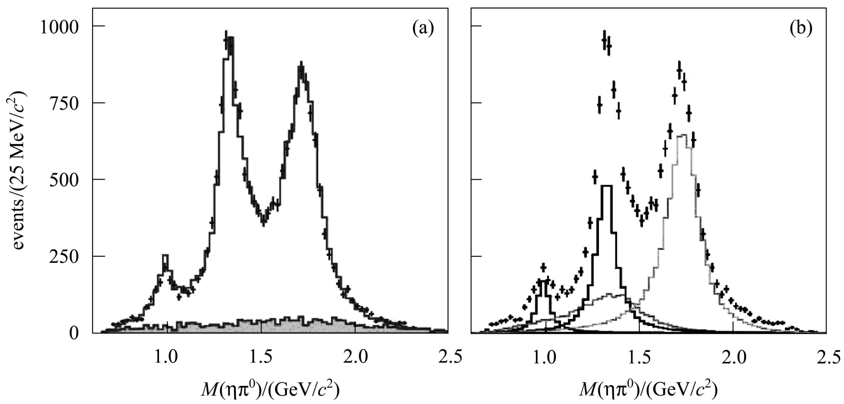

Fig. 1. The $\eta\pi^0$ invariant mass spectrum for $J/\psi \rightarrow \rho\eta\pi^0$. The signals are the Monte Carlo events generated by taking into account the angular distributions of each resonance and the interferences among them, as described in the text, and the backgrounds are added to the signals incoherently. The sum of the signals and backgrounds are shown as the error bars. (a) The comparison of the generated mass spectrum and PWA projection from all contributions. The background is shown as the shaded region; (b) The contribution of PWA projection from different components.

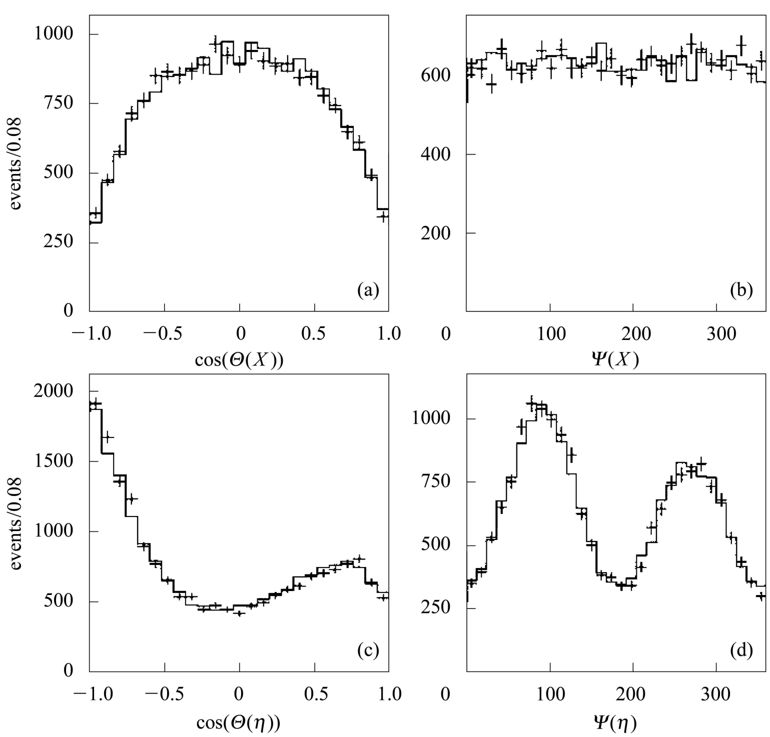

Fig. 2. Angular distributions of $J/\psi \rightarrow \rho\eta\pi^0$. The error bars are the distributions for the signal and background events and the histograms show the results from PWA.

Table 1. Input and output comparison of masses, widths and component fractions. Here the masses and widths of $a_0(980)$ and $a_2(1700)$ are fixed to PDG values.

		$a_0(980)$	$a_2(1320)$	$\pi_1(1400)$	$a_2(1700)$
mass/(GeV/c^2)	input	0.985	1.318	1.376	1.732
	output	fixed	1.320 ± 0.002	1.380 ± 0.008	fixed
width/(MeV/c^2)	input	80	107	360	194
	output	fixed	112 ± 4	376 ± 16	fixed
fraction(%)	input	4.4	21.4	14.6	43.4
	output	4.6 ± 0.3	19.5 ± 0.8	14.5 ± 1.3	41.6 ± 1.7

In order to study the sensibility of the significance for the exotic state $\pi_1(1400)$, we generated another Monte Carlo sample, which contains the same components as the previous one, i.e., $a_0(980)$, $a_2(1320)$, $\pi_1(1400)$, $a_2(1700)$ and their interferences, but has a smaller fraction of $\pi_1(1400)$. Their input fractions are listed below:

$$Fr(J/\psi \to \rho a_0(980)) \sim 4.7\%,$$
$$Fr(J/\psi \to \rho\pi_1(1400)) \sim 8.1\%,$$
$$Fr(J/\psi \to \rho a_2(1320)) \sim 20.4\%,$$
$$Fr(J/\psi \to \rho a_2(1700)) \sim 41.7\%.$$

Following the same steps, we perform a PWA to the second Monte Carlo sample and checked the input and output agreement. Table 2 lists the masses, widths and fractions of the input and output values for each component. They also have a reasonable agreement in the case of smaller fraction of the exotic state $\pi_1(1400)$. In both cases, the $\pi_1(1400)$ is significant.

4 Summary

The Monte Carlo simulation indicates that the partial wave analysis is able to separate the components $a_2(1320)$ and $\pi_1(1400)$ that have different spin-parities but at the same mass, when the statistics is enough and the resolution of the detector is good. With a large statistics, it is also possible to measure the phase motion to give a more convincing evidence for the existence of a resonance.

Table 2. Input and output comparison of masses, widths and branching fractions. Here the masses and widths of $a_0(980)$ and $a_2(1700)$ are fixed to PDG values.

		$a_0(980)$	$a_2(1320)$	$\pi_1(1400)$	$a_2(1700)$
mass/(GeV/c^2)	input	0.985	1.318	1.376	1.732
	output	fixed	1.316 ± 0.002	1.387 ± 0.009	fixed
width/(MeV/c^2)	input	80	107	360	194
	output	fixed	108 ± 4	380 ± 20	fixed
fraction(%)	input	4.73	20.36	8.07	41.67
	output	4.37 ± 0.21	17.68 ± 0.09	9.84 ± 1.07	40.44 ± 0.09

References

1 Alde D. Phys. Lett. B, 1988, **205**: 397
2 Prokoshkin Yu D, Sadovski S A. Phys. Atom. Nucl., 1995, **58**: 606
3 Beladidze G M. Phys. Lett. B, 1993, **313**: 276
4 Aoyagi K. Phys. Lett. B, 1993, **314**: 246
5 Thompson D R. Phys. Rev. Lett., 1997, **79**: 1630
6 Abele A. Phys. Lett. B, 1998, **423**: 175
7 Abele A. Phys. Lett. B, 1999, **446**: 349
8 Adams G et al. Phys. Rev. Lett., 1998, **81**: 5760
9 Ivanov E I et al. Phys. Rev. Lett., 2001, **86**: 3977
10 Kuhn J et al. Phys. Lett. B, 2004, **595**: 109
11 Bernard C et al. Nucl. Phys. B, 1999, **73**(Proc. Suppl.): 264; Lacock P, Schilling K. Nucl. Phys. B, 1999, **73**(Proc. Suppl.): 261
12 Isgur N, Paton J. Phys. Rev. D, 1985, **31**: 2910; Close F E, Page P R. Nucl. Phys. B, 1995, **443**: 233; Page P R, Swanson E S, Szczepaniak A P. Phys. Rev. D, 1999, **59**: 034016-1
13 Barnes T, Close F E, Swanson E S. Phys. Rev. D, 1995, **52**: 5242
14 Amelin D V et al. Yad. Fiz., 1999, **62**: 487; Phys. Atom. Nucl., 1999, **62**: 445
15 Lee J H et al. Phys. Lett. B, 1994, **323**: 227
16 AIP Conf. Proc., 2002, **619**: 143
17 LU M et al. Phys. Rev. Lett., 2005, **94**: 032002
18 Chung S U. Phys. Rev. D, 1998, **57**: 431—442
19 WU Ning et al. Commun. Theor. Phys. (Beijing China), 2001, **35**: 547
20 WU Ning et al. Common. Theor. Phys. (Beijing China), 2002, **37**: 309
21 WU Ning. Helicity Analysis of Relativestic Particles, Ph.D. Thesis, University of Science and Technology of China, 1997