Amplitude analysis of the decays $\eta^{'} \rightarrow \pi^+\pi^-\pi^0$ and $\eta^{'} \rightarrow \pi^0\pi^0\pi^0$ postprint

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Abstract

Based on a sample of 1.31×10^9 J/ events collected with the BESIII detector, an amplitude analysis of the isospin violating decays → + − 0 and → 0 0 0 is performed. Significant P-wave contribution from → ± is observed for the first time in → + − 0. The branching fraction is determined to be B(→ ±)=(7.44±0.60±1.26±1.84)×10−4, where the first uncertainty is statistical, the second systematic and the third model dependent. In addition to the non-resonant S-wave component, a contribution from the meson is also essential. The branching fractions of the S-wave components are determined as B(→ + − 0)S=(37.63±0.77±2.22±4.48)×10−4 and B(→ 0 0 0)=(35.22±0.82±2.60)×10−4, respectively. The latter one is consistent with previous BESIII measurements.

Full Text

Preamble

Amplitude analysis of the decays → + − 0 and → 0 0 0

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Abstract

Based on a sample of $1.31 \times 10\hat{}9$ J/ events collected with the BESIII detector, an amplitude analysis of the isospin violating decays $\rightarrow + - 0$ and $\rightarrow 0\ 0\ 0$ is performed. Significant P-wave contribution from $\rightarrow \pm$ is observed for the first time in $\rightarrow + - 0$. The branching fraction is determined to be B($\rightarrow \pm$) = $(7.44 \pm 0.60 \pm 1.26 \pm 1.84) \times 10\hat{}{-4}$, where the first uncertainty is statistical, the second systematic and the third model dependent. In addition to the non-resonant S-wave component, a contribution from the meson is also essential. The branching fractions of the S-wave components are determined as B($\rightarrow + - 0)S = (37.63 \pm 0.77 \pm 2.22 \pm 4.48) \times 10\hat{}{-4}$ and B($\rightarrow 0\ 0\ 0) = (35.22 \pm 0.82 \pm 2.60) \times 10\hat{}{-4}$, respectively. The latter one is consistent with previous BESIII measurements.

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Introduction

The decays $\rightarrow$ are isospin-violating processes. Since the electromagnetic contribution is strongly suppressed [?, ?], they are induced dominantly by the strong interaction via the explicit breaking of chiral symmetry by the light quark mass difference. In recent years, there has been considerable interest in these decays because they allow determination of the light quark mass difference using the ratios of decay widths, $r\pm = \Gamma(\rightarrow + - 0)/\Gamma(\rightarrow + -)$ and $r0 = \Gamma(\rightarrow 0\ 0\ 0)/\Gamma(\rightarrow 0\ 0)$ [?, ?]. Within the framework of chiral effective field theory combined with a relativistic coupled-channels approach, Ref. [?] predicts that the $\pm$ P-wave contribution should be large for $\rightarrow + - 0$. For the channel with three neutral pions, $\rightarrow 0\ 0\ 0$, the P-wave contribution in two-body rescattering is forbidden by Bose symmetry. In general, final state interaction is expected to be very important since it was already found to be essential to explain the decay width of $\rightarrow$ [?, ?]. In the case of decays, final state interaction is further enhanced due to the large phase space and the presence of nearby resonances. It is expected to strongly affect the values of the branching fractions and the Dalitz plot distributions.

So far, there is no direct experimental evidence of the intermediate ± contribution to the decay → + − 0. In 2009, the CLEO-c experiment [?] reported the first observation of → + − 0 with 20.2^{+6.1}_{-4.8} events, corresponding to a branching fraction of (37 ± 8 ± 6) × 10^−4, and a Dalitz plot consistent with a flat distribution. Recently the decay was also observed by the BESIII experiment [?] with a branching fraction consistent with the CLEO-c result; however, no Dalitz plot analysis was presented. Interest in the decay channel → 0 0 0 stems from the observed 4 discrepancy between the recent branching fraction measurement from BESIII [(35.6 ± 0.9 ± 2.6) × 10^−4] [?] and from all previous experiments [?, ?, ?]. The BESIII result indicates a two times larger value for the ratio r0. Furthermore, the recent Dalitz plot slope parameter determination of → 0 0 0, = 0.061 ± 0.014 [?], deviates significantly from phase space (= 0), which implies that final state interactions play an essential role.

In this Letter, we present a model-dependent amplitude analysis combining → + − 0 and → 0 0 0 events originating from J/ radiative decays using 1.31 × 10^9 J/ events (of which 2.25 × 10^8 events [?] were taken in 2009 and 1.09 × 10^9 [?] in 2012) accumulated by the BESIII detector, which is described in detail in Ref. [?].

Event Selection

For J/ → with → + − 0 candidate events, two tracks with opposite charge and at least three photon candidates are required. Each charged track, reconstructed from hits in the main drift chamber (MDC), is required to have a polar angle in the range of |cos | < 0.93 and to cross a region within 10 cm in the beam direction and within 1 cm in the radial direction from the interaction point. Photon candidates are reconstructed using clusters of energy deposited in the electromagnetic calorimeter (EMC) and required to have a minimum energy of 25 MeV in the barrel region (|cos | < 0.80) or 50 MeV in the end cap region (0.86 < |cos | < 0.92). In order to eliminate clusters associated with charged tracks, the angle between the direction of each charged track and any photon candidate must be larger than 10°.

Requirements on the EMC cluster timing with respect to the event start time are used to suppress electronic noise and energy deposits unrelated to the event. Since the radiative photon from the J/ is always more energetic than the photons from the 0 decays, the photon candidate with the maximum energy in the event is taken as the radiative one. For each + − combination, a six-constraint (6C) kinematic fit is performed, and the ^2_6C is required to be less than 25. The fit enforces energy-momentum conservation and constrains the invariant masses of the other photon pair and + − 0 to the nominal 0 and mass, respectively. If there are more than three photon candidates in an event, the combination with the smallest ^2_6C is retained. To reject possible backgrounds with two or four photons in the final states, we further require that the probability of the 4C kinematic fit imposing energy-momentum conservation for the J/ → + − signal hypothesis is larger than those for the J/ → + − and + − background hypotheses. Additionally, events with M(0) < 0.05 GeV/c^2 are rejected to suppress background from J/ → + −.

With the above requirements, a sample of 8267 events is selected, and the corresponding Dalitz plot is shown in Fig. 1 Figure 1: see original paper, where two clusters of events corresponding to the decays of → ± are observed. The possible background events are investigated with an MC sample of 1.2 × 10^9 J/ inclusive decays generated with the Lundcharm or EvtGen model [?, ?]. Using the same selection criteria, the surviving background events mainly originate from the decay → , which accumulate in a peak around the mass region, and the processes with multi-photons in the final states, e.g., J/ → + − 0 0. However, none of these backgrounds contribute to the clusters around the ± mass region. For → , a study with a dedicated MC simulation based on the same BESIII data and Ref. [?] indicates that the number of events from this background is 1362 ± 54, with the branching fractions of J/ → and the cascade decays taken from the Particle Data Group (PDG) [?]. The decay J/ → with → + − 0 0, which is assumed to represent the non-peaking background contribution, is not well known.

In order to estimate the background yield from this source, an alternative data sample is selected by performing a 5C kinematic fit without mass constraint. The resulting + − 0 invariant mass spectrum is shown in Fig. 1(b), where the peak is clearly visible. We then perform an unbinned maximum likelihood fit to M(+ − 0) where the signal is described by the MC simulated shape convoluted with Gaussian resolution function, the peaking background (→) is described by the MC simulated shape and a second order Chebyshev polynomial function for the non-peaking background contribution. The number of → events is fixed to the expected value, while the bump around 1.02 GeV/c^2 from J/ → events is described with a Gaussian function. The number of non-peaking background events in the selected 6C-fitted sample was estimated to be 838 ± 31, using the number of background events from the 5C-fitted sample in signal region (|M(+ − 0) - m_ | < 0.02 GeV/c^2) taking into account the detection efficiency correction.

For J/ → with → 0 0 0, events containing at least seven photon candidates and no charged tracks are selected. The photon selection criteria are the same as those for → + − 0. The photon with the maximum energy in the event is assumed to be the radiative photon originating from the decay of J/ . For the remaining photon candidates, pairs of photons are combined to 0 → candidates which are subjected to a 1C kinematic fit, where the invariant mass of the photon pair is constrained to the nominal 0 mass, and the ^2 value is required to be less than 25. To suppress 0 mis-combinations, the 0 decay angle (_decay), defined as the polar angle of a photon in the corresponding rest frame, is required to satisfy |cos _decay| < 0.95. From the accepted

0 candidates and the corresponding radiative photon, 0 0 0 combinations are formed. A kinematic fit with eight constraints (8C) is performed, imposing energy and momentum conservation and constraining the invariant masses of pairs and 0 0 0 candidates to the nominal 0 and masses, respectively. Events with ^2_8C < 70 are accepted for further analysis. If there is more than one combination, only the one with the smallest ^2_8C is retained. To suppress possible background from J/ → 0 0, a 7C kinematic fit is performed under the J/ → 0 0 hypothesis and events for which the probability of this 7C fit is larger than that of the signal hypothesis are discarded. In addition, events which have at least one pair with invariant mass within the signal region, (0.52, 0.59) GeV/c^2, are rejected. Possible background from J/ → 0 0 is suppressed by vetoing events with M(0) < 0.05 GeV/c^2, where M(0) is the invariant mass of a 0 combination. The background from J/ → 0 0 is estimated to be 46 ± 3, using an MC sample with the decay amplitudes from Ref. [?].

The three 0 selected in the event are ordered as 0_1, 0_2, and 0_3 according to their descending energies in the rest frame. A sample of 2237 events is selected, and the corresponding Dalitz plot is displayed in Fig. 2 Figure 2: see original paper. The analysis of an inclusive MC sample of 1.2 × 10^9 J/ decays indicates a low background level, including peaking background events originating from the decay → 0 0 and the non-peaking background mainly coming from J/ → 0 0 0 0. The number of background events from → 0 0 is estimated to be 3 ± 3, using an MC sample with the decay amplitudes from Ref. [?]. Similarly, we perform a 7C kinematic fit without applying the constraint on the mass to estimate the non-peaking background events. The fit to M(0 0 0) is displayed in Fig. 2(b) using the simulated shape convoluted with Gaussian resolution function for the signal, MC simulated peaking background shape, and a second order polynomial function for non-peaking background events. In this case, the number of the non-peaking background events in the selected → 0 0 0 sample, predominantly originating from J/ → 0 0 0 0, is estimated to be 176 ± 24 after taking into account the detection efficiencies with and without the mass constraint.

Amplitude Analysis

A Dalitz plot analysis based on the formalism of the isobar model [?] is performed. The resonant - S-wave (L = 0 for) and P-wave (L = 1 for ±) amplitudes are described following the formalism from Ref. [?]:

$$W(s) = \frac{1}{\cot \delta_L(s) - i}$$

where

$$\cot \delta_0(s) = \frac{\sqrt{s}}{2k} \left(B_0^S + B_1^S \frac{\sqrt{s} - \sqrt{s_0}}{\sqrt{s} + \sqrt{s_0}} \right)$$

$$\cot \delta_1(s) = \frac{2k}{\sqrt{s}} \left(B_0^P + B_1^P \frac{\sqrt{s} - \sqrt{s_1}}{\sqrt{s} + \sqrt{s_1}} \right)$$

with _L(s) = 2k/√s, √s_0 = 2M_K and √s_1 = 1.05 GeV. Here k = √(s/4 - M_ ^2), M_ is the pion mass; the masses M_ , M_K, and M_ are fixed to the world average values [?]; B_0^S, B_1^S, B_0^P, and B_1^P are the free parameters.

The free parameters of the probability density function (PDF) are optimized with an unbinned maximum likelihood fit using events from both → + − 0 and → 0 0 0 decay channels, where the background contributions are presented as a non-interfering term in the PDF and are fixed according to MC simulation, and the mass resolution and the detection efficiency obtained from the MC simulation are taken into account in the signal PDF. The fit minimizes the negative log-likelihood value:

$$-\ln L = -\sum_{i=1}^{N_{\pi^+\pi^-\pi^0}} \ln P_i - \sum_{j=1}^{N_{\pi^0\pi^0\pi^0}} \ln P_j$$

where P_i and P_j are the PDFs for → + − 0 event i and → 0 0 0 event j, respectively. The sum runs over all accepted events. According to charge conjugation invariance, the magnitude and phase for + and − are the same in the nominal fit.

Projections of the data and the fit results are displayed in Fig. 3 [Figure 3: see original paper]. The data is well described by three components: P-wave (±), resonant S-wave (0), and a phase space S-wave ( ). The interference between and the non-resonant term is large and strongly depends on the parametrization of . Therefore we are unable to determine the single contributions and consider only the sum of the S-wave amplitudes in this analysis.

To estimate the significance of each component, the fit is repeated with the corresponding amplitude excluded and the statistical significance is then determined by the changes of the ^2 value and the number of degrees of freedom. For the signal components described above, the statistical significance are all found to be larger than 25 . To check for additional contributions, we add the an amplitude for the scalar meson f0(980), described by the Flatté function [?] with the parameters fixed using values from Ref. [?]. The corresponding statistical significance is only 0.3 , and the contribution is therefore neglected.

With the fitted values of B_0^P = -39.09 ± 0.006, B_1^P = -39.18 ± 0.2 MeV and B_0^S = 2.69 ± 0.2, B_1^S = 5.66 ± 0.2, the corresponding pole of and are determined as (775.49 ± 0.2) MeV and (512 ± 12) MeV, respectively, and are therefore in reasonable agreement with the ± and values from PDG [?].

The signal yields defined as the integrals over the Dalitz plot of a single decay amplitude squared, the detection efficiencies obtained from the MC sample weighted with each amplitude and the branching fractions for each component are summarized in Table I. In order to compare with the previous measurements without considering P-wave contribution [?, ?], we also provide the branching fraction of $\rightarrow + - 0$ calculated with the number of observed signal events, which is presented in Table I.

To check the charge conjugation process in the P-wave, alternative fits were performed with different magnitudes and phases for $+$ and $-$. The result is consistent with charge symmetry: [B($\rightarrow + -$) - B($\rightarrow - +$)]/[B($\rightarrow + -$) + B($\rightarrow - +$)] = 0.01 ± 0.06(stat) ± 0.01(syst).

Systematic Uncertainties

As an alternative model, the Gounaris-Sakurai parametrization [?] is used to describe the $\pm$ contribution with the mass and width fixed to the world average values [?]. The ^2 value is worsened by 0.9. In another check the - S wave for is replaced with a relativistic Breit-Wigner function. This fit also provides a reasonable description of the data, while the ^2 value only changes by 3.5. The mass and width determined from this fit are (538 ± 12) MeV/c^2 and (363 ± 20) MeV, respectively, which are compatible with the pole position of - elastic scattering amplitude.

Based on the symmetry imposed by Bose-Einstein statistics and isospin [?, ?], the magnitude of the non-resonant S-wave amplitude in $\rightarrow$ 0 0 0 is three times of that in $\rightarrow + - 0$. If this constraint is introduced, the fitted yields are compatible with the unconstrained result, while the change in ^2 is 8.4, corresponding to a statistical significance of 3.7 .

The deviations of the extracted branching fractions for the above tests contribute to the systematic uncertainties, denoted as Model and Constraint, respectively. In addition, the following sources of the systematic uncertainty are considered:

The uncertainties in MDC tracking, photon selection and 0 reconstruction efficiency (including photon detection efficiency) are studied using a high purity control sample of J/ $\rightarrow$. The differences between data and MC simulation are less than 1% per charged track, 1% for the radiative photon and 2% per 0.

The uncertainties associated with the 6C and 8C kinematic fits are studied using the control sample J/ $\rightarrow$. The preliminary selection conditions for good charged tracks, good photons, and 0 candidates are the same as those for J/ $\rightarrow$. The differences between data and MC simulation for the requirements of ^2_6C(+ − 0) < 25 and ^2_8C(0 0 0) < 70 are determined to be 1.7% and 1.6%, respectively.

To investigate the uncertainties of the background determination, alternative fits are performed by inspecting the background components one by one. The peaking backgrounds $\rightarrow$ and $\rightarrow$ 0 0 can vary according to the errors of the branching ratio for J/ → and the cascade decays in PDG [?]. The continuum background can vary according to the uncertainties of the fits to the mass spectra. Different selection criteria for vetoing background are also used. The deviations of the extracted branching fractions with respect to the default values are taken as the uncertainties associated with backgrounds.

All the systematic uncertainties including the uncertainty from the number of J/ events and the branching fraction of J/ → are summarized in Table II, where the total systematic uncertainty is given by the quadratic sum, assuming all sources to be independent.

Summary

In summary, using a combined amplitude analysis of → + − 0 and → 0 0 0 decays, the P-wave contribution from ± is observed for the first time with high statistical significance. The pole position of ±, (775.49 ± 0.2) MeV, is consistent with previous measurements, and the branching fraction B(→ ±) is determined to be (7.44 ± 0.60 ± 1.26 ± 1.84) × 10ˆ−4. In addition to the non-resonant S-wave, the resonant - S-wave with a pole at (512 ± 12) MeV, interpreted as the broad meson, plays an essential role in the → decays. Due to the large interference between non-resonant and resonant S-waves, only the sum is used to describe the S-wave contribution, and the branching fractions are determined to be B(→ + − 0)S = (37.63 ± 0.77 ± 2.22 ± 4.48) × 10ˆ−4 and B(→ 0 0 0) = (35.22 ± 0.82 ± 2.60) × 10ˆ−4, respectively. The branching fractions of → + − 0 and → 0 0 0 are in good agreement with and supersede the previous BESIII measurements [?]. The value for B(→ 0 0 0) is two times larger than that from GAMS [(16 ± 1.6) × 10ˆ−4] [?]. The significant resonant S-wave contribution also provides a reasonable explanation for the negative slope parameter of the → 0 0 0 Dalitz plot [?]. The ratio of the branching fractions between the S-wave components B(→ 0 0 0)/B(→ + − 0)S is determined as 0.94 ± 0.13, where the common systematic uncertainties are cancelled. With the branching fractions of → taken from PDG [?], r± and r0 are now calculated to be (8.8 ± 0.5 ± 0.9) × 10ˆ−3 and (16.9 ± 1.2 ± 1.6) × 10ˆ−3, respectively.

The observed substantial P- and S-wave resonant contributions have to be properly considered by theory before any attempt to extract light quark mass from r± and r0. In particular one of the previous most comprehensive analyses of hadronic decays of and mesons relied on the r0 value which is now two times larger; r± was not known [?]. Further progress will depend on the development of dispersive approaches such as Ref. [?, ?, ?, ?] for hadronic decays.

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References

[1] D. G. Sutherland, Phys. Lett. 23, 384 (1966).
[2] R. Baur, J. Kambor, and D. Wyler, Nucl. Phys. B 460, 127 (1996).
[3] D. J. Gross, S. B. Treiman, and Frank Wilczek, Phys. Rev. D 19, 2188 (1979).
[4] B. Borasoy, Ulf-G. Meißner, and R. Nißler, Phys. Lett. B 643, 41 (2006).
[5] B. Borasoy and R. Nißler, Eur. Phys. J. A 26, 383 (2005).
[6] J. Gasser and H. Leutwyler, Nucl. Phys. B 250, 539 (1985).
[7] J. Bijnens and K. Ghorbani, JHEP, 0711, 030 (2007).
[8] P. Naik et al. (CLEO Collaboration), Phys. Rev. Lett. 102, 061801 (2009).
[9] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 108, 182001 (2012).
[10] F. G. Binon et al. Phys. Lett. B 140, 264, (1984).
[11] D. Alde, F. G. Binon, and C. Bricman, Z. Phys. C 36, 603 (1987).
[12] A. M. Blik et al. (GAMS-4 Collaboration), Phys. Atom. Nucl. 71, 2124 (2008).
[13] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. D 92, 012014 (2015).
[14] M. Ablikim et al. (BESIII Collaboration), Chin. Phys. C 36, 915 (2012).
[15] With the same approach as for J/ events taken in 2009 (see Ref. [?] for more details), the preliminary number of J/ events taken in 2009 and 2012 is determined to be 1310.6 × 10^6 with an uncertainty of 0.8%.
[16] M. Ablikim et al. (BESIII Collaboration), Nucl. Instrum. Meth. A 614, 345 (2010).
[17] J. C. Chen, G. S. Huang, X. R. Qi, D. H. Zhang, and Y. S. Zhu, Phys. Rev. D 62, 034003 (2000).
[18] D. J. Lange, Nucl. Instrum. Methods Phys. A 462, 152 (2001).
[19] G. T. Sanchez, J. L. Garca-Luna, and V. Gonzalez-Enciso, Phys. Rev. D 76, 033001 (2007).

[20] K. A. Olive et al. (Particle Data Group), Chin. Phys. C 38, 090001 (2014).
[21] A. M. Blik et al. (GAMS-4 Collaboration), Phys. Atom. Nucl. 72, 231 (2009).
[22] M. Ablikim et. al. (BESIII Collaboration), Phys. Rev. D 89, 052001 (2014).
[23] R. García-Martín et al., Phys. Rev. D 83, 074004 (2011).
[24] S. M. Flatté, Phys. Lett. B 63, 224 (1976).
[25] M. Ablikim et. al. (BESIII Collaboration), Phys. Lett. B 607, 243 (2005).
[26] G. J. Gounaris, and J. J. Sakurai, Phys. Rev. Lett. 21, 244 (1968).
[27] C. Zemach, Phys. Rev. 133, 1201 (1964).
[28] J. Bijnens and J. Gasser, Phys. Scr. T99, 34 (2002).
[29] G. Colangelo, S. Lanz, and E. Passemar, PoS CD, 09, 047 (2009).
[30] S. P. Schneider, B. Kubis, and C. Ditsche, JHEP, 1102, 028 (2011).
[31] K. Kampf, M. Knecht, J. Novotny, and M. Zdrahal, Phys. Rev. D 84, 114015 (2011).
[32] P. Guo, I. V. Danilkin, D. Schott, C. Fernández-Ramírez, V. Mathieu, and A. P. Szczepaniak, Phys. Rev. D, 92, 054016 (2015).