Light Meson Decays at BESIII

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The data sample of 1.3×10^9 J/ψ events accumulated at BESIII provides us with a clean environment to study the decay of the η' . In this proceeding, several recent results are reported, including the observation of the doubly radiative decay $\eta' \rightarrow \gamma\gamma\pi^0$, amplitude analysis of the decays $\eta' \rightarrow \pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$, the observation of the Dalitz decay $\eta' \rightarrow \gamma e^+e^-$, and search for the weak decay $\eta' \rightarrow K^\pm\pi^\mp$.

Keywords: Light meson; η' decay; BESIII.

1. Introduction

The decay of η and η' mesons is a field with rich physics. It plays an important role in exploring the effective field theory of Quantum Chromodynamics (QCD) at low energy. It also provides us with a unique stage for understanding the distinct symmetry breaking mechanisms in low-energy QCD, and serves as a probe for the physics beyond the Standard Model (SM). BESIII has accumulated 1.3×10^9 J/ψ events, which is the largest data sample of this resonance all over the world. As a result, 1.4×10^6 (6.8×10^6) η (η') particles could be obtained from the radiative decay of J/ψ mesons, and 5×10^5 (3×10^5) from the hadronic (e.g. $J/\psi \rightarrow \phi\eta$). The large quantities of η and η' particles offer us an ideal environment to investigate their decay. In this proceeding, several recent results related to η' decay are reported.

2. $\eta' \rightarrow \gamma\gamma\pi^0$

The doubly radiative decay of η' meson, which has not been observed yet, could be very useful in testing the QCD calculations on the Transition Form Factor (TFF). The study could also provide valuable inputs to the theoretical understanding of the light meson decay mechanism.

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BESIII reports the first observation of the doubly radiative decay $\eta' \rightarrow \gamma\gamma\pi^0$.¹ Figure 1 (a) shows the results of the fit to $M_{\gamma\gamma\pi^0}$ for the selected inclusive $\eta' \rightarrow \gamma\gamma\pi^0$ signal events, where clear η' peak is observed. Here inclusive means the incoherent sum of ρ , ω and non-resonant contributions. The dotted curve represents the Class I background, which means $J/\psi \rightarrow \gamma\eta'$ component with the η' decaying into other final states ($\eta' \rightarrow \pi^0\pi^0\eta$ and $\eta' \rightarrow \pi^0\pi^0\pi^0$). The dot-dashed curve shows Class II background, which means the J/ψ decaying to final states without the η' ($J/\psi \rightarrow \gamma\pi^0\pi^0$ and $J/\psi \rightarrow \omega\eta$). After the fit, $\mathcal{B}(J/\psi \rightarrow \gamma\gamma\pi^0)_{Incl}$ is determined to be $(32.0 \pm 0.7 \pm 2.3) \times 10^{-4}$.

Figure 1 (b) shows the result of fit to $M_{\gamma\pi^0}$. The ρ - ω interference is considered in the fit. The non-resonant decay $\eta' \rightarrow \gamma\gamma\pi^0$ is observed for the first time, which is shown as the long-dashed curve in this plot, and $\mathcal{B}(\eta' \rightarrow \gamma\gamma\pi^0)_{NR}$ is determined to be $(6.16 \pm 0.64 \pm 0.67) \times 10^{-4}$, which agrees with the upper limit given by GAMS-2000 experiment (8×10^{-4})². In addition, $\mathcal{B}(\eta' \rightarrow \gamma\omega) \times \mathcal{B}(\omega \rightarrow \gamma\pi^0)$ is measured as a validation of the fit and the result is $(23.7 \pm 1.4 \pm 1.8) \times 10^{-4}$, which is consistent with the corresponding product branching ratio from the Particle Data Group $((21.7 \pm 1.3) \times 10^{-4})$ ³. All these measurements could provide valuable inputs to the theoretical understandings of light meson decay mechanisms.

Fig. 1. (a) Results of the fit to $M_{\gamma\gamma\pi^0}$ for the selected inclusive $\eta' \rightarrow \gamma\gamma\pi^0$ signal events. The dots with error bars are the data. (b) Distribution of the invariant mass $M_{\gamma\pi^0}$ and fit results in the η' mass region. The points with error bars are data; the dotted curve is from ω contribution; the long-dashed curve is from the ρ contribution; the short-dashed curve is the contribution of ρ - ω interference; the long-dashed curve is the non-resonance; the histogram is from the class II background; the dot-dashed curve is the combinatorial backgrounds of $\eta' \rightarrow \gamma\omega, \gamma\rho$. The solid line shows the total fit function.

3. $\eta' \rightarrow \pi^+\pi^-\pi^0$ and $\eta' \rightarrow \pi^0\pi^0\pi^0$

The decays of $\eta' \rightarrow \pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$ processes are induced dominantly by the strong interaction via the explicit breaking of chiral symmetry by the $d - u$ quark

mass difference. As a result, the studies of $\eta' \rightarrow \pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$ could help to determine the masses of u and d quarks. The product branching ratios could be related to quark masses through Eqs. (1) ⁴ and (2). In addition, $\eta' \rightarrow \rho^\pm\pi^\mp$ process, which is a P-wave contribution, is predicted to be large for the decay $\eta' \rightarrow \pi^+\pi^-\pi^0$ by chiral effective field theory, but it has not been observed yet. The P-wave contribution is forbidden for $\eta' \rightarrow \pi^0\pi^0\pi^0$ process by Bose symmetry.

$$r_\pm = \frac{\mathcal{B}(\eta' \rightarrow \pi^+\pi^-\pi^0)}{\mathcal{B}(\eta' \rightarrow \pi^+\pi^-\eta)} \approx (16.8) \frac{3}{16} \left(\frac{m_d - m_u}{m_s} \right)^2. \quad (1)$$

$$r_0 = \frac{\mathcal{B}(\eta' \rightarrow \pi^0\pi^0\pi^0)}{\mathcal{B}(\eta' \rightarrow \pi^0\pi^0\eta)}. \quad (2)$$

BESIII reports the amplitude analysis of $\eta' \rightarrow \pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$ processes⁵, and the results are shown in Fig. 2. The P-wave contribution of ρ meson is observed for the first time and the product branching ratio is determined to be $\mathcal{B}(\eta' \rightarrow \rho^\pm\pi^\mp) = (7.44 \pm 0.60 \pm 1.26 \pm 1.84) \times 10^{-4}$. In addition to the non-resonant S-wave contribution, the resonant S-wave contribution of σ meson is also observed. Since the interference between the σ and the non-resonant S-wave contribution is too strong, only the sum is shown in these plots. The corresponding branching ratios for $\eta' \rightarrow \pi^+\pi^-\pi^0$ and $\eta' \rightarrow \pi^0\pi^0\pi^0$ modes are determined to be $\mathcal{B}(\eta' \rightarrow \pi^+\pi^-\pi^0) = (37.63 \pm 0.77 \pm 2.22 \pm 4.48) \times 10^{-4}$ and $\mathcal{B}(\eta' \rightarrow \pi^0\pi^0\pi^0) = (35.22 \pm 0.82 \pm 2.54) \times 10^{-4}$, respectively. The obtained $\mathcal{B}(\eta' \rightarrow \pi^0\pi^0\pi^0)$ is consistent with the previous measurement from BESIII $((35.6 \pm 4.0) \times 10^{-4})$ ⁶, while that is two times larger than the result from GAMS $((16.0 \pm 3.2) \times 10^{-4})$ ⁷. The observed substantial P- and S- wave resonant contributions have to be properly considered by theory before attempting to determine the quark masses from $r_\pm$ and r_0 .

4. $\eta' \rightarrow \gamma e^+ e^-$

The electromagnetic Dalitz decay of light pseudo-scalar mesons, $P \rightarrow \gamma l^+ l^-$ (Here P means π^0 , η and η' ; l means $e^\pm$ and $\mu^\pm$), plays an important role in revealing the structures of hadrons and the interaction mechanism between photons and hadrons. The decay rate of this process could be described by Eq. (3) ⁸.

$$\begin{aligned} \frac{d\Gamma(\eta' \rightarrow \gamma l^+ l^-)}{dq^2 \Gamma(\eta' \rightarrow \gamma\gamma)} &= \frac{2\alpha}{3\pi} \frac{1}{q^2} \sqrt{1 - \frac{4m_l^2}{q^2}} \left(1 + \frac{2m_l^2}{q^2}\right) \left(1 - \frac{q^2}{m_{\eta'}^2}\right)^3 |F(q^2)|^2 \\ &= [\text{QED}(q^2)] \times |F(q^2)|^2. \end{aligned} \quad (3)$$

Here $[\text{QED}(q^2)]$ means the Quantum Electrodynamics (QED) part, which is calculated under the assumption of point-like particles. $|F(q^2)|^2$ stands for TFF, which is used to describe the inner structures of mesons, and this factor could be

calculated by the Vector Meson Dominance (VMD) model. The q^2 represents the square of the invariant mass of lepton pair.

BESIII reports the first observation of the electromagnetic Dalitz decay $\eta' \rightarrow \gamma e^+ e^-$ ⁹. Figure. 3 shows the invariant mass distribution of $\gamma e^+ e^-$, where clear η' signal is observed. The product branching ratio is determined to be $\mathcal{B}(\eta' \rightarrow \gamma e^+ e^-) = (4.69 \pm 0.20(stat) \pm 0.23(sys)) \times 10^{-4}$.

Then the TFF is determined. Fig. 4 (a) shows the signal yields versus $M(e^+ e^-)$ after efficiency correction, where clear deviation between experimental result and QED prediction is observed. Then the experimental result is divided by QED prediction to obtain the TFF shown as the crosses in Fig. 4 (b). In VMD model, assuming the single-pole parametrization, the TFF could be calculated by Eq. (4).

$$|F(q^2)|^2 = \frac{\Lambda^2(\Lambda^2 + \gamma^2)}{(\Lambda^2 - q^2)^2 + \Lambda^2 \gamma^2}. \quad (4)$$

Fig. 2. Comparison of the invariant mass distributions of (a) $\pi^+\pi^-$, (b) $\pi^+\pi^0$, (c) $\pi^-\pi^0$, and (d) $\pi^0\pi^0$ between data (dots with error bars) and the fit result projections (solid histograms). The dotted, dashed, dash-dotted, and dash-dot-dotted histograms show the contributions from background, S wave, ρ^- , and ρ^+ , respectively.

This equation is also used to perform the fit in Fig. 4 (b), and Λ is determined to be $0.79 \pm 0.04 \pm 0.02$ GeV. Then the slope of TFF, which is denoted as b , is calculated by Eq. (5).

$$b = \left. \frac{dF}{dq^2} \right|_{q^2=0} = \Lambda^{-2}. \quad (5)$$

The slope b is determined to be $1.60 \pm 0.17 \pm 0.08$ GeV⁻², which is consistent with the predictions from VMD model (1.45 GeV⁻²)^{10,11}, chiral perturbation theory (1.60 GeV⁻²)¹² and dispersion integral ($1.53^{+0.15}_{-0.08}$ GeV⁻²)¹³.

5. $\eta' \rightarrow K^\pm \pi^\mp$

The decay $\eta' \rightarrow K^\pm \pi^\mp$ is fundamental to understanding the longstanding problem of the $\Delta I = 1/2$ rule, which was first established in $K \rightarrow \pi\pi$ process. A neutral kaon may decay into a two-pion final state with isospin $I = 0$ or $I = 2$ with amplitude A_0 or A_2 , respectively. As the real part of the amplitude, $\text{Re}A_0$ is dominated by

Fig. 3. Invariant $\gamma e^+ e^-$ mass distribution for the selected signal events. The crosses are the data, the dashed line represents the signal, the dot-dashed curve shows the non-peaking background shapes, and the shaded component is the shape of the $J/\psi \rightarrow \gamma \eta', \eta' \rightarrow \gamma \gamma$ peaking background events. The total fit result is shown as the solid line.

Fig. 4. (a) Efficiency-corrected signal yields versus $M(e^+ e^-)$. The crosses are data and the shaded histogram indicates the point-like QED result. (b) Fit to the single-pole form factor $|F|^2$. The crosses are data, where the statistical and systematic uncertainties are combined; the solid curve shows the fit results. The dotted line shows the point-like case (i.e. with $|F|^2 = 1$) for comparison.

$\Delta I = 1/2$ transition and $\text{Re}A_2$ receives the contribution from $\Delta I = 3/2$ transition. $\text{Re}A_0$ is much larger than $\text{Re}A_2$, which expresses the so-called $\Delta I = 1/2$ rule^{14,15}. The decay $\eta' \rightarrow K^\pm \pi^\mp$ receives contributions from both the $\Delta I = 1/2$ and $\Delta I = 3/2$ parts of the weak Hamiltonian. Maybe studying whether the $\Delta I = 1/2$ rule is functional in this decay could shed light on the origin of it.

BESIII reports the search for the weak decay $\eta' \rightarrow K^\pm \pi^\mp$ ¹⁶. Since no significant signal events are observed, the upper limit on $\mathcal{B}(\eta' \rightarrow K^\pm \pi^\mp)$ at 90% C.L. is determined to be 3.8×10^{-5} .

6. Summary

The decay of the η' is a field with rich physics. Based on the large data samples of η' meson obtained from the radiative and hadronic decays of the J/ψ at BESIII, numerous studies of η' decay have been carried out. In this proceeding, some recent results are reported. More exciting results are expected to come with the larger J/ψ data sample that is anticipated in future runs of BESIII.

Acknowledgments

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