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Light meson decays at BESIII

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Charmonia decays provide a clean method to study properties of light mesons. In particular with 6.7×10^6 η' mesons from the radiative J/ψ decay, BESIII is the world leading facility for η' decay studies. For many η' decay channels the low background data samples are up to three orders of magnitude larger than collected in any previous experiment. The analyses range from detailed studies of the common decays dynamics, observations of new radiative and Dalitz decays with branching fractions $\mathscr{B} \sim 10^{-4}$ and search for rare/forbidden decays with sensitivity up to $\mathscr{B} \sim 10^{-5}$. The most recent results include precision studies of $\eta' \to \pi^+\pi^-\gamma$, $\eta' \to 3\pi$ and $\eta' \to \eta\pi\pi$ dynamics. The highlights are:

- observation of $\rho^0 - \omega$ interference and the need of a additional contribution such as box anomaly or other intermediate states in $\eta' \to \pi^+\pi^-\gamma$
- observation of $\eta' \to \rho^\pm\pi^\mp$ contribution in $\eta' \to \pi^+\pi^-\pi^0$.

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1. Introduction

The η' meson is heavier than the Goldstone bosons of broken chiral symmetry and is predominantly the singlet state arising from the strong axial $U(1)$ anomaly. Decays of the η' probe a wide variety of physics issues *e.g.* $\pi^0-\eta$ mixing, light quark masses and pion-pion scattering. In addition decays are used to search for processes beyond any considered extension of the Standard Model (SM) and to test fundamental discrete symmetries. The main decays are hadronic and radiative processes. Alternatively one can divide the decays into two following classes. The first class consists of hadronic decays into three pseudoscalar mesons, such as $\eta' \to \eta\pi\pi$. Those processes are already included in the lowest order, $\mathcal{O}(p^2)$, of chiral perturbation theory (ChPT) [1]. The second class includes anomalous processes involving odd number of pseudoscalar mesons, such as $\eta' \to \pi^+\pi^-\gamma$. They are driven by the Wess-Zumino-Witten (WZW) term [2, 3] which enters at $\mathcal{O}(p^4)$ order [4]. Description of η' decays requires extensions of ChPT (such as large number of colors, N_C [5]) together with dispersive methods for treatment of final state interactions or model-dependent approaches for describing low energy meson interactions, such as Vector Meson Dominance (VMD) [6, 7].

A sample of 1.31×10^9 J/ψ events (2.25×10^8 events in 2009 and 1.09×10^9 in 2012) [8, 9] has been collected with the BESIII detector [10] and offers a unique opportunity to investigate η' decays via $J/\psi\to\gamma\eta'$. The present contribution focuses on the most recent results from precision studies of $\eta'\to\pi^+\pi^-\gamma$, $\eta'\to3\pi$ and $\eta'\to\eta\pi\pi$ dynamics. Ref. [11] gives a recent more complete review of η/η' decays studies at BESIII. Table 1 summarizes some of the BESIII results on η' branching fractions.

Table 1: Some of the BESIII results on η' branching fractions, $\mathscr{B}$, based on 1.31×10^9 J/ψ. Extracted yields with statistical errors, detection efficiency and branching fractions for the studied η' decay modes, where the first error is statistical, the second systematic, and the third from model dependence. The last column gives the status before BESIII experiment.

Decay Mode	Yield	ε (%)	$\mathscr{B}$ ($\times10^{-4}$)	Ref.	Comment
$\eta'\to\pi^+\pi^-\pi^0$	6067 ± 91	25.3	$35.91\pm0.54\pm1.74$	[12]	20 events
$(\pi^+\pi^-\pi^0)_S$	6580 ± 130	26.2	$37.63\pm0.77\pm2.22\pm4.48$	[12]	first
$\rho^\pm\pi^\mp$	1231 ± 98	24.8	$7.44\pm0.60\pm1.26\pm1.84$	[12]	first
$\eta'\to\pi^0\pi^0\pi^0$	2015 ± 47	8.8	$35.22\pm0.82\pm2.60$	[12]	235 events
$\eta'\to e^+e^-\gamma$	864 ± 36	24.5	$4.69\pm0.20\pm0.23$	[13]	first
$\eta'\to e^+e^-\omega$	66 ± 11	5.45	$1.97\pm0.34\pm0.17$	[14]	first
$\eta'\to\gamma\omega$	33187 ± 351	21.9	$255.00\pm3.00\pm16.00$	[14]	
$\eta'\to\gamma\gamma\pi^0$	655 ± 68	15.9	$6.16\pm0.64\pm0.67$	[15]	first
$\eta'\to\pi^+\pi^-\pi^+\pi^-$	199 ± 16	34.5	$0.853\pm0.069\pm0.069$	[16]	first
$\eta'\to\pi^+\pi^-\pi^0\pi^0$	84 ± 16	7.0	$1.82\pm0.35\pm0.18$	[16]	first

2. Study of $\eta'\to\pi^+\pi^-\gamma$ decay dynamics (prel.)

The anomalous process $\eta'\to\gamma\pi^+\pi^-$ is the second most probable decay of the η' meson ($\mathscr{B}\approx30\%$) and frequently used for η' tagging. In the VMD model the main contribution to the

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decay comes from $\eta' \to \gamma\rho^0$ [17]. In the past the di-pion mass distribution was studied by several experiments with conclusion that ρ^0 contribution is not sufficient to describe the di-pion mass spectrum. This discrepancy could be attributed to the WZW box anomaly contribution which should be included as an extra non resonant term in the decay amplitude. It was suggested that the fits to the shape of the di-pion distribution will allow to determine the ratio of the two contributions [18]. The evidence for the box anomaly with a significance of 4σ was reported in 1997 by the Crystal Barrel experiment [19] using a sample of 7490±180 η' events but this observation was not confirmed by the subsequent measurement by the L3 Collaboration [20] using 2123±53 events. Recently proposed model-independent approach, based on ChPT and a dispersion theory, describes the $\eta/\eta' \to \pi^+\pi^-\gamma$ decay amplitudes as a product of a universal and a reaction specific part [21]. The universal part could be extracted from the pion vector form factor measured in $e^+e^- \to \pi^+\pi^-$.

For BESIII analysis a low background data sample of 9.7×10^5 $\eta' \to \gamma\pi^+\pi^-$ decays candidates is selected. The distribution of the $\pi^+\pi^-$ invariant mass, $M(\pi^+\pi^-)$, shows $\rho^0 - \omega$ interference for first time in this decay. In the model-dependent approach the data can not be described with Gounaris-Sakurai parameterisation [22] of the ρ^0 and the ω contributions including the interference. The fit performance gets much better after including the box anomaly with a statistical significance larger than 37σ. An alternative fit was performed by replacing the box anomaly with $\rho^0(1450)$ by fixing its mass and the width to the world average values. The fit is slightly worse but it still provides a reasonable description of the data.

Using model-independent approach of Ref. [21] and including $\rho^0 - \omega$ mixing the pion vector form factor $F_V(s)$ (where $s = M^2(\pi^+\pi^-)$) and amplitudes for $\eta/\eta' \to \gamma\pi^+\pi^-$ decays are proportional to $P(s)\cdot\Omega(s)$ where $P(s)$ is a reaction specific term, $P(s) = 1 + \kappa s + \lambda s^2 + \xi \cdot BW_\omega + \mathscr{O}(s^4)$, $\Omega(s)$ is the Omnes function describing $\pi - \pi$ interactions with $L = 1$ [23, 24]. The fit to the BESIII $M(\pi^+\pi^-)$ distribution gives $\kappa = 0.992 \pm 0.039$ GeV^{-2}, $\lambda = -0.523 \pm 0.039$GeV^{-4}, $\xi = 0.199 \pm 0.006$ with the fit goodness χ^2/ndf=145/109. The presence of the quadratic term is consistent with recent calculations including intermediate $\pi^\pm a_2^\mp$ state [25].

3. $\eta' \to \pi^{+(0)}\pi^{-(0)}\eta$ [26]

The combined branching fraction of the two main hadronic decays of η': $\eta' \to \pi^+\pi^-\eta$ and $\eta' \to \pi^0\pi^0\eta$ is nearly 2/3. The ratio $\mathscr{B}(\eta' \to \pi^+\pi^-\eta)/\mathscr{B}(\eta' \to \pi^0\pi^0\eta)$ should be exactly two in the isospin limit. The decays involve both η and pions in the final state and therefore allows to extract information about $\pi\eta$ interactions. However, the excess energy of the processes is relatively small: 130 MeV and 140 MeV for $\pi^+\pi^-\eta$ and $\pi^0\pi^0\eta$ respectively. This means precision high statistics experimental studies of the Dalitz plots together with an appropriate theory framework for extraction of the $\pi\eta$ phase shifts are needed.

The two Dalitz plot variables, X and Y, are usually defined as $X = \frac{\sqrt{3}}{Q}(T_{\pi^+} - T_{\pi^-})$ and $Y = \frac{m_\eta + 2m_\pi}{m_\pi}\frac{T_\eta}{Q} - 1$, where $T_{\pi,\eta}$ denote the kinetic energies of the mesons in the η' rest frame and $Q = T_\eta + T_{\pi^+} + T_{\pi^-} = m_{\eta'} - m_\eta - 2m_\pi$. Two different parametrizations of the Dalitz plot distribution are used. The historically first one assumes a linear amplitude in Y variable: $|A(X,Y)|^2 \propto |1 + \alpha Y|^2 + cX + dX^2$, the other representation is just a general polynomial expansion: $|A(X,Y)|^2 \propto 1 + aY + bY^2 + cX + dX^2$, where, α is complex and a, b, c, d are real parameters. These two representations are equivalent in case of $b > a^2/4$.

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The most recent BESIII analysis uses nearly background free samples of 3.5×10^5 $\eta'\to\eta\pi^+\pi^-$ events and 5.6×10^4 $\eta'\to\eta\pi^0\pi^0$ events from 1.31×10^9 J/ψ. For the $\eta'\to\eta\pi^+\pi^-$ decay, the results are not consistent with the measurement from VES [27]. In particular for the cofficient a, the discrepancy is nearly 4σ. For the charge conjugation violating cofficient c, the fitted value is consistent with zero within one standard deviation. The $\eta'\to\eta\pi^0\pi^0$ results are consistent with other recent measurements [28, 29] and theoretical predictions within the uncertainties. We note a 2.6σ tension for parameter a between $\eta'\to\eta\pi^+\pi^-$ and $\eta'\to\eta\pi^0\pi^0$ modes in our data. Additional effects like radiative corrections [30] and π^+/π^0 mass difference should be considered in the future experimental and theoretical studies. The determined b parameters are significantly less than zero: $-0.049\pm0.006\pm0.006$ and $-0.073\pm0.014\pm0.005$ for $\eta'\to\eta\pi^+\pi^-$ and $\eta'\to\eta\pi^0\pi^0$ modes respectively. Therefore the linear representation could not describe data. A search for the cusp in $\eta'\to\eta\pi^0\pi^0$ performed by inspecting the $\pi^0\pi^0$ mass spectrum close to $\pi^+\pi^-$ mass threshold, reveals no statistically significant effect. Most recent theoretical dispersive analysis of the cusp in the $\eta'\to\eta\pi^0\pi^0$ [31] uses Dalitz plot parameters from VES and 2009 BESIII [32] $\eta'\to\eta\pi^+\pi^-$ data. However, the amplitudes from Ref. [31] should be preferably fitted directly to the Dalitz plot data for the two decay modes.

3.1 Amplitude analysis of $\eta'\to\pi^{+(0)}\pi^{-(0)}\pi^0$ [12]

At first, the low intensity process $\eta'\to\pi^+\pi^-\pi^0$ may be considered to come from $\pi^0-\eta$ mixing in the dominating decay $\eta'\to\pi^+\pi^-\eta$ [33]. This would offer a possibility to determine precisely $d-u$ quark mass difference from the branching fraction ratio of the two processes. However, a recent analysis shows that even at tree level other terms are needed [34]. In addition the decay amplitudes are strongly affected by resonances in the final state. The decay $\eta'\to\pi^+\pi^-\pi^0$ was first observed in 2008 in CLEO experiment [35] and BESIII has reported branching fraction measurements using 2009 J/ψ data set [36].

The common amplitude analysis of the decays $\eta'\to\pi^+\pi^-\pi^0$ and $\eta'\to\pi^0\pi^0\pi^0$ is performed using the full data set. In addition to the non-resonant S-wave, the resonant π-π S-wave with a pole at $(512\pm15)-i(188\pm12)$ MeV, interpreted as the $f_0(500)$ meson, plays essential role in the $\eta'\to\pi\pi\pi$ 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 determined branching fraction $\mathscr{B}(\eta'\to\pi^+\pi^-\pi^0)_S$ is reported in Table 1. For $\eta'\to\pi^0\pi^0\pi^0$, only S-wave contribution in two-body rescattering is included since the S-wave is forbidden by the Bose symmetry. The fit results show significant P-wave contribution from $\eta'\to\rho^\pm\pi^\mp$ in $\eta'\to\pi^+\pi^-\pi^0$ and the determined branching fraction is reported in Table 1.

The branching fractions of $\eta'\to\pi^+\pi^-\pi^0$ and $\eta'\to\pi^0\pi^0\pi^0$ are in good agreement with and supersede the previous BESIII measurements [36]. The value for $\mathscr{B}(\eta'\to\pi^0\pi^0\pi^0)$ is two times larger than GAMS measurement of $(16\pm3.2)\times10^{-4}$ [37]. The significant resonant S-wave contribution also explains the negative slope parameter of the $\eta'\to\pi^0\pi^0\pi^0$ Dalitz plot [38]. The ratio between the S-wave components of the two decay modes, $\mathscr{B}(\eta'\to\pi^0\pi^0\pi^0)/\mathscr{B}(\eta'\to\pi^+\pi^-\pi^0)_S$, is determined to be $0.94\pm0.029\pm0.13$, where the common systematic cancels.

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