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Light Meson Decays at BESIII

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The light pseudoscalar mesons η and η' are central to our understanding of QCD at low energies, and their decays provide important tests of effective field theories. They are also important laboratories for tests of discrete symmetries and searches for beyond Standard model physics. Through its large dataset at the J/ψ resonance, the BESIII experiment has a unique opportunity to study the η' meson and measure its decays with unprecedented precision. Recently, the absolute branching fractions of the five most common decay modes have been determined for the first time, and the rare decays $\eta' \to \pi^+\pi^- e^+e^-, \pi^+\pi^-\mu^+\mu^-, 4\pi^0$, and $\gamma\gamma\eta$ have been studied with high precision.

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1. Introduction

The light pseudoscalar mesons η and η' play a central role in our understanding of QCD at low energies. Precision measurements of their decays provide important tests of effective field theories, such as chiral perturbation theory (ChPT) or the vector meson dominance (VMD) model. Since these mesons are eigenstates of the C, P, CP, and G operators, they provide an important, flavour-conserving laboratory for tests of these fundamental symmetries that complements studies in the kaon sector. Due to P, C, CP and angular momentum conservation, electromagnetic and strong decays of η/η' are forbidden to first order. As a consequence, they are narrow states that are relatively easy to reconstruct in experiment, and low standard model (SM) rates make them an excellent environment for new physics searches.

2. Experimental Prospects at BESIII

The BESIII experiment has collected a total of 10^{10} events at the J/ψ resonance and, via the radiative decay $J/\psi \to \gamma\eta^{(\prime)}$, a sample of 1.1×10^7 η and 5.2×10^7 η'. For η', which is comparatively unexplored, BESIII can measure many decays for the first time and others with unrivaled precision. The results presented in this contribution are based on 1.31×10^9 J/ψ events.

3. Recent Results from BESIII

3.1 Absolute branching fractions of η' decays

Absolute branching fractions are of importance both for tests of theoretical predictions and as a tool for normalizing the branching fractions of rare decay modes. Knowledge of these is furthermore necessary for the study of invisible decays into *e.g.* dark matter particles. It is, however, challenging to estimate the absolute number of η' decays, and only relative measurements of its branching fractions have therefore been performed to date.

At BESIII, a novel method for determining the total number of η' mesons has recently been developed [1]. The radiative photon produced in the $J/\psi \to \gamma\eta'$ decay is monoenergetic, and can therefore be used to tag the production of an η'. By reconstructing these photons through their conversion into an e^+e^--pair in the detector material one can make use of the main drift chamber, rather than the electromagnetic calorimeter , and thereby achieve a considerably better momentum resolution. This leads to a very precise measurement of the photon energy and, in turn, a powerful tool for rejecting non-η' events. Having determined the number of η' mesons produced, the five most common decay modes are studied. In order to improve efficiency, photons are reconstructed with the electromagnetic calorimeter in these studies. The absolute branching fractions can subsequently be determined for the first time as

$$\mathcal{B}(\eta' \to X) = \frac{N_{\eta'\to X}}{\varepsilon_{\eta'\to X}} \frac{\varepsilon_{J/\psi\to\gamma\eta'}}{N_{J/\psi\to\gamma\eta'}} f, \tag{1}$$

where N is the event yield, ε is the corresponding efficiency, and f is a correction factor for differences in the photon conversion probability between data and MC. The values, shown in Table 1, are consistent with relative branching fractions measured by the CLEO experiment [2], but with improved precision.

Mode	N	$\mathcal{B}(\%)$ (this work)	$\mathcal{B}(\%)$ (PDG18 [3])
$\eta' \to \gamma\pi^+\pi^-$	913106 ± 1052	29.90 ± 0.03 ± 0.55	28.9 ± 0.5
$\eta' \to \eta\pi^+\pi^-$	312275 ± 570	41.24 ± 0.08 ± 1.24	42.6 ± 0.7
$\eta' \to \eta\pi^0\pi^0$	51680 ± 238	21.36 ± 0.10 ± 0.92	22.8 ± 0.8
$\eta' \to \gamma\omega$	22749 ± 163	2.489 ± 0.018 ± 0.074	2.62 ± 0.013
$\eta' \to \gamma\gamma$	70669 ± 349	2.331 ± 0.012 ± 0.035	2.22 ± 0.08

Table 1: Number of events and absolute branching fractions measured by BESIII for the five most common decay modes of η' compared to the PDG values [3].

3.2 $\eta' \to \pi^+\pi^-e^+e^-$

The process $\eta' \to \pi^+\pi^-e^+e^-$ is expected to proceed via an intermediate virtual photon $\gamma^* \to e^+e^-$ and the dynamics is similar to the process $\eta' \to \pi^+\pi^-\gamma$ that has previously been studied at BESIII [4]. The dominant contribution is expected to come from $\rho \to \pi^+\pi^-$ alongside a contribution from the Wess-Zumino-Witten box anomaly [5, 6].

In addition, there may be a CP-violating contribution originating from beyond SM electric dipole-type transitions [7, 8] that, in analogy with observations in kaon decays [9, 10], would manifest itself as an asymmetry in the angle between the decay planes of the e^+e^-- and $\pi^+\pi^-$-pairs. This type of asymmetry has been studied by the KLOE [11] and WASA-at-COSY [12] experiments in $\eta \to \pi^+\pi^-e^+e^-$ and found to be consistent with zero, but has never before been measured in the decay $\eta' \to \pi^+\pi^-e^+e^-$.

In the most recent BESIII analysis [13], 2584±52 signal events are observed with a background level of about 2%. The branching fraction is determined to be $\mathcal{B}(\eta' \to \pi^+\pi^-e^+e^-) = (2.42 \pm 0.05_{stat.} \pm 0.08_{syst.}) \times 10^{-3}$ and is in good agreement with predictions from Refs. [14, 15] based on VMD and unitary ChPT. The statistical precision is improved by a factor of two compared to the previous best measurement from BESIII [16]. The CP-asymmetry is measured for the first time, $\mathcal{A}_{CP} = \left(2.9 \pm 3.7_{stat.} \pm 1.1_{syst.}\right)$ %, and found to be consistent with zero and no CP-violation.

3.3 $\eta' \to \pi^+\pi^-\mu^+\mu^-$

Due to the heavier muon mass, the decay $\eta' \to \pi^+\pi^-\mu^+\mu^-$ is suppressed relative to its sibling $\eta' \to \pi^+\pi^-e^+e^-$, but shares the same interesting features. In a recent analysis based on 1.31×10^9 J/ψ events, the BESIII experiment was able to report the first observation of this decay from 53 ± 9 signal events with a significance of 8σ [17]. The measured branching fraction $\mathcal{B}(\eta' \to \pi^+\pi^-\mu^+\mu^-) = (1.97 \pm 0.33_{stat} \pm 0.19_{syst}) \times 10^{-5}$ is in good agreement with predictions from Refs. [14, 15].

3.4 $\eta' \to 4\pi^0$

The S-wave contribution to the decay $\eta' \to 4\pi^0$ violates CP, and is therefore constrained to be vanishingly small by the strong-CP θ term. The leading CP-conserving contribution comes from D-wave pion loops with an expected branching fraction of the order 10^{-8} [18]. Any observation of this process with currently available datasets would therefore be an indication of CP-violation. In the BESIII search for this decay, no significant signal was observed, and an upper limit $\mathcal{B}(\eta' \to 4\pi^0) < 4.94 \times 10^{-5}$ was set at 90 % C.L. [19]. This corresponds to an improvement of a factor 6 compared to the previous best value from the GAMS-4π experiment [20].

3.5 $\eta' \to \gamma\gamma\eta$

An important test for the predictive power of ChPT at higher orders is the decay $\eta' \to \gamma\gamma\eta$ where the first sizeable contribution enters at $O(p^6)$. Phenomenologically, the process is expected to proceed via both intermediate scalar and vector mesons. A recent search for this decay at the BESIII experiment found 25 ± 10 signal events [21]. While encouraging, the statistical significance of 2.6σ is not enough to claim the observation. A new upper limit $\mathcal{B}(\eta' \to \gamma\gamma\eta) < 1.33 \times 10^{-4}$ is set at 90 % C.L, improving upon the previous best limit from the GAMS-4π experiment [22] by a factor of 60. Inspired in part by the BESIII result, the first theoretical prediction for the branching fraction $\mathcal{B}(\eta' \to \gamma\gamma\eta) = 1.17 \pm 0.08 \times 10^{-4}$ was made recently using linear sigma model and VMD [23]. This value is in agreement with the experimental result.

4. Outlook

Many exciting studies can be performed with the full sample of 10^{10} J/ψ events collected at BESIII. Some rare decays, such as $\eta' \to \gamma\gamma\eta$, are expected to be conclusively observed while the dynamics of others will be studied in detail for the first time. For example, a measurement of the doubly off-shell transition form factor in $\eta' \to \pi^+\pi^- e^+e^-$ or a test of lepton flavour universality by comparing the two $\eta' \to \pi^+\pi^- l^+l^-$ decays can be performed. Finally, there is interest in using decays of η' as a hunting ground for the QCD axion [24, 25] or a dark photon [24].

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