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Studies of Light Pseudoscalar Mesons at BESIII

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Abstract. Studies of light pseudoscalar mesons are an important aspect of the physics program pursued at BESIII. In this presentation recent results from η and η' decays and the current status of the $\gamma\gamma$ physics program will be discussed.

1 Introduction

Even decades after their discovery light pseudoscalar mesons are still a vivid field in hadron physics research. The recent progresses of chiral perturbation theory, the effective field theory of strong interactions at low energies, and the appearance of so-called meson factories allowed for significant improvements in the understanding of low-energy hadron physics. Two aspects of the investigations at BESIII involving light pseudoscalar mesons are discussed in this presentation.

The decays of η and η' mesons offer a unique laboratory to test symmetries and symmetry breaking mechanisms of QCD at low energies. A special feature of the η meson is that all electromagnetic and strong decays are forbidden at lowest order. It is thus possible not only to test the conservation laws, which forbid the decays, but also to access rare, higher order processes experimentally. In this way it is also possible to search for physics beyond the Standard Model. The same holds for the decays of the η' meson, except for the fact that it has an allowed hadronic decay mode $\eta' \to \eta\pi\pi$, which involves in turn the η meson.

Another aspect discussed here is the production of light pseudoscalar mesons in two-photon collisions. The production cross sections are proportional to the space-like electromagnetic transition form factors of the mesons. The form factor does not only describe the interaction of mesons and (virtual) photons, but it also gives information on the meson structure and in the case of η and η' mesons it can be related to their mixing. The main motivation for the current studies performed at BESIII, however, is the fact that the electromagnetic transition form factors of light pseudoscalar mesons are an important input to the calculation of the contribution of hadronic light-by-light scattering to the anomalous magnetic moment of the muon $a_\mu = \frac{1}{2}(g_\mu - 2)$.

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2 BESIII at BEPCII

The BESIII experiment [1] is located at the double-ring e^+e^- collider BEPCII, which is operated at the IHEP in Beijing (China). Data can be collected in a center-of-mass energy range from 2.0 GeV to 4.6 GeV with a peak luminosity of 10^{33} cm^{-2}s^{-1} at a beam current of 0.93 A. The BESIII detector setup consist of a helium-based drift chamber surrounding the Beryllium beam pipe, a plastic scintillator time-of-flight system, and a CsI(Tl) electromagnetic calorimeter, which are placed inside the bore of a superconducting solenoidal magnet providing a 1.0 T magnetic field. The flux-return yoke is instrumented with resistive plate counters and serves as muon chamber. The detector covers 93% of the solid angle. Momenta of charged particles and photon energies are measured with a resolution of 0.5% and 2.5% at 1 GeV, respectively.

Data taking is routinely performed since 2009. In the recent data taking campaigns BESIII has collected $1.25 \times 10^9 J/\psi$ decays, more than $500 \times 10^6 \psi(2S)$ decays, 2.9 fb^{-1} at the $\psi(3770)$ peak, and more than 2.8 fb^{-1} in the center-of-mass region above 4 GeV, which are devoted to studies of the XYZ states [2]. This data set comprises the world's largest samples of J/ψ, $\psi(2S)$, and $\psi(3770)$ mesons. It is used to pursue the BESIII physics program [3], which focuses on charmonium spectroscopy, charm physics, light hadron spectroscopy, τ physics, and R-measurements.

3 η and η' decays

At BESIII η and η' mesons are produced the decays of J/ψ. The radiative decays $J/\psi \to \gamma\eta/\eta'$ or the hadronic decays $J/\psi \to \phi\eta/\eta'$ are used to tag the mesons. The branching ratios of these decay modes and the number of decays expected from the 225×10^6 reconstructed J/ψ events of the first data taking at the J/ψ peak are listed in Tab. 1. The choice of the tagging channel depends on the physics case under study. The radiative decay can be tagged by the monochromatic photon of 1.5 GeV and 1.4 GeV for

	BR	mesons produced
$J/\psi \to \gamma\eta$	$(1.104 \pm 0.034) \times 10^{-3}$	2.8×10^5
$J/\psi \to \gamma\eta'$	$(5.15 \pm 0.16) \times 10^{-3}$	1.2×10^6
$J/\psi \to \phi\eta$	$(7.5 \pm 0.8) \times 10^{-4}$	1.7×10^5
$J/\psi \to \phi\eta'$	$(4.0 \pm 0.7) \times 10^{-4}$	0.9×10^5

Table 1. Branching ratios of the radiative and hadronic J/ψ decays [4] used to tag η and η' meson production at BESIII, and the number of produced mesons in a data sample of 225.3×10^6 reconstructed J/ψ mesons.

the η and η' mesons, respectively. The branching ratios are larger compared to the hadronic modes, however, the tagging accuracy is limited by the energy resolution of the calorimeter. In the case of the hadronic J/ψ decays, the ϕ meson is reconstructed by its decay into K^+K^- pairs. This method of tagging η and η' mesons benefits not only from the good resolution of the drift chamber, but also from the fact that the ϕ meson is a narrow resonance. Additionally, the η and η' mesons are given a stronger boost compared to the radiative decays, which limits the phase space for their decay product in the lab frame.

Using η' mesons tagged in radiative J/ψ decays a Dalitz plot analysis of the decay $\eta' \to \pi^+\pi^-\eta$ has been performed [5]. Precise knowledge of the decay dynamics can provide tests for chiral perturbation theory and its extensions, such as Large N_C ChPT or resonance chiral theory [6]. It can also be used to study effects of the gluon component [7] or contributions of a possible light scalar nonet [8]. With 44000 $\eta' \to \pi^+\pi^-\eta$ events in the Dalitz plot, the Dalitz plot parameters have been determined with a new level of precision in a generalized and a linear representation. The results are found to be in agreement with previous measurements [9]. However, the statistical errors are still to large to allow for compelling tests of theory predictions.

The same data set has been used to study the rare hadronic decay modes of η' into three pions [10]. The decay width of these isospin violating decays is connected with the light quark mass difference. The branching ratios have been extracted as $BR(\eta' \to \pi^0\pi^0\pi^0) = (3.83 \pm 0.15 \pm 0.39) \times 10^{-3}$ and $BR(\eta' \to \pi^+\pi^-\pi^0) = (3.56 \pm 0.22 \pm 0.34) \times 10^{-3}$, respectively. Compared to previous measurements [11, 12], the statistical accuracy has been significantly improved. However, the resulting branching ratio of the neutral channel exceeds the PDG average [4] by a factor of two, while the result of the charged channel is in good agreement.

Also the semi-leptonic decay modes $\eta' \to \pi^+\pi^-e^+e^-$ and $\eta' \to \pi^+\pi^-\mu^+\mu^-$ have been investigated [13]. A clear η' signal has been observed in the invariant mass distribution of the $\pi^+\pi^-e^+e^-$ system. The branching ratio was determined as $B(\eta' \to \pi^+\pi^-e^+e^-) = (2.11 \pm 0.12 \pm 0.14) \times 10^{-3}$. It is in good agreement with previous measurements [15] as well as theoretical predictions [14]. The latter also holds for the differential mass distributions of the di-pion and the di-lepton systems.

A signal from the η' decay involving muons was not observed. An improved upper limit for the branching ratio has been determined as $B(\eta' \to \pi^+\pi^-\mu^+\mu^-) < 2,9 \times 10^{-5}$ at 90% confidence level.

As a test of the fundamental symmetries C and CP in the decay of η and η' into two pions were studied. In the Standard Model the process is only possible in weak interaction with branching rations in the order of 10^{-15} to 10^{-27}. An observation of these decays at the level accessible today would hint at sources of CP violation beyond the Standard Model. Evident signals for any of the processes $\eta/\eta' \to \pi^0\pi^0/\pi^+\pi^-$ were not observed in the $225.3 \times 10^6 J\psi$ events under study. Improved upper limits of the branching ratios have been determined as $B(\eta \to \pi^+\pi^-) < 3.9 \times 10^{-4}, B(\eta \to \pi^0\pi^0) < 6.9 \times 10^{-4}, B(\eta' \to \pi^+\pi^-) < 5.5 \times 10^{-5}$, and $B(\eta' \to \pi^0\pi^0) < 4.5 \times 10^{-4}$, at 90% confidence level [16].

An attempt was made to search for invisible and weak decays of η and η' based on the hadronic J/ψ decays. In the Standard Model the only invisible decay channel is $\eta/\eta' \to \nu\bar{\nu}$. It is helicity suppressed and would not occur if neutrinos are massless. But there are also possibilities for physics beyond the Standard Model, where the mesons decay into light dark matter. The branching ratios for such processes have been estimated as $B(\eta \to \chi\chi) \sim 7.4 \times 10^{-5}$ and $B(\eta' \to \chi\chi) \sim 8.1 \times 10^{-7}$ [17]. The recoiling mass of the K^+K^- pairs, used to tag on the production of η and η' mesons, has been investigated. Signals above background, which would hint at invisible decays were not observed. Upper limits for the branching ratios have been determined relatively to the decays into two photons as $\frac{B(\eta \to \text{invisible})}{B(\eta \to \gamma\gamma)} < 2.6 \times 10^{-4}$ and $\frac{B(\eta' \to \text{invisible})}{B(\eta' \to \gamma\gamma)} < 2.4 \times 10^{-2}$ at 90% confidence level. The ratio of the upper limit reduces the systematic uncertainty of the results, as most of the systematics cancel out. Upper limits for the absolute branching ratios are determined by using the branching fractions of $\eta/\eta' \to \gamma\gamma$ as $B(\eta \to \text{invisible}) < 1.0 \times 10^{-4}$ and $B(\eta \to \text{invisible}) < 5.3 \times 10^{-4}$ at 90% confidence level [18].

The same analysis strategy has been applied to search for the first time for the weak decays $\eta/\eta' \to \pi^-e^+\nu_e + c.c.$. The Standard Model prediction for the branching ratio of the decay is $B(\eta/\eta' \to \pi^-e^+\nu_e + c.c.) \sim 2 \times 10^{-13}$ [19]. Considering contributions of scalar or vector type interactions in the process the branching ratio can be of the order of $\sim 10^{-8}$ to $\sim 10^{-9}$ [20]. In the data set under study signals of weak leptonic decays were not observed. The upper limits of the branching ratios were determine as $B(\eta \to \pi^-e^+\nu_e + c.c.) < 1.7 \times 10^{-4}$ and $B(\eta' \to \pi^-e^+\nu_e + c.c.) < 2.2 \times 10^{-4}$ at 90% confidence level [21].

4 $\gamma\gamma$ physics

Studies of the production of pseudoscalar mesons in two-photon collisions is a new aspect, which has recently been added to the BESIII physics program. The aim is to measure the electromagnetic transition form factors (TFF) of pseudoscalar, scalar and tensor mesons in the space-like regime. The TFF provide information on the electromagnetic structure of the mesons, but precise knowledge of the pseudoscalar TFF is also of vital importance for the Standard Model calculations of the muon anomaly $a_\mu = \frac{1}{1}(g_\mu - 2)$ [22]. The muon anomaly is one of the most precisely measured quantity in particle physics [23], but there is a difference of approximately three standard deviations between the experimental measurement and the theory prediction. This deviation, if confirmed and found with larger significance, could hint at a new physics. Thus, it has motivated numerous theoretical and experimental efforts, which is also reflected in the program of this symposium.

Currently, the theoretical prediction of a_μ is completely limited by the uncertainties of the hadronic contributions. In contrast to the QED and weak contributions to the muon anomaly, the hadronic contributions cannot be determined perturbatively, due to the nature of QCD at the relevant energy scales. One of the hadronic contributions is due to the effects of the hadronic vacuum polarization. It can be related to hadronic cross sections, which are currently measured at e^+e^- colliders world wide with highest precision [24], via a dispersion integral. Another hadronic contribution to a_μ is the hadronic light-by-light scattering. It describes the interaction of virtual light pseudoscalar mesons with real and virtual photons. Thus, it cannot be directly related to exprimental data, but it has to be modeled. Here, the TFF, describing the interaction of real mesons with real and virtual photons, which will be measured at BESIII, are needed as experimental input for the calculations.

The feasibility of the TFF measurements at BESIII has been studied [25] using the Ekhara [26, 27] event generator. It was found that using data taken at the $\psi(3770)$ peak the TFF's of π^0, η and η' mesons can be extracted at momentum transfers in the range of $0.3 \le Q^2[GeV^2] \le 10$. Assuming a total integrated luminosity of 10 fb^{-1}, the statistical accuracy would be unprecedented for momentum transfers of $Q^2 \le 4$ GeV^2, a region of special relevance for the hadronic light-by-light scattering [28, 29]. At higher momentum transfers the precision is compatible with the CLEO [30] result, allowing for cross checks also with other previous measurements of TFF's [31].

The analysis of the currently available $\psi(3770)$ data is based on a single-tag technique: Only the decay products of the produced meson and one of the two scattered leptons are measured in the detector. The other lepton is reconstructed from four-momentum conservation and it is required to have a small scattering angle. The corresponding momentum transfer is small and the exchanged photon is quasi-real. Thus, the form factor $F(Q_1^2, Q_2^2)$ depends only on a single momentum transfer $F(Q^2)$. In most advanced analyses π^0 and η mesons are reconstructed via their main decay modes into two photons. A major source of background in the event selection are QED processes, such as radiative Bhabha scattering. The hard photon from the radiative process, in combination with a soft photon from any secondary process, easily results in a photon pair with an invariant mass compatible with the mass of the meson under investigation. Conditions to successfully suppress this background involve the helicity angle of π^0 and η, the scattering angle of the mesons, and the relative scattering angle of the photons from which the mesons have been reconstructed. Finally, a condition based on energy and momentum conservation is applied, to reject background from hadronic sources and other two-photon production channels, including initial state radiation in the signal channels. Remaining background is subtracted bin-by-bin from the differential distribution of momentum transfer. Due to a lack of suitable Monte Carlo generators, background is removed by fitting the continuous background in the invariant mass spectrum of the two photon system and counting the π^0 and η signals above background.

The currently available data at the $\psi(3770)$ peak statistically only allow for a measurement of the transition form factor of the π^0 at momentum transfers of $0.3 \le$ Q^2 [GeV]^2 ≤ 3.1. However, this region is of special relevance for the hadronic light-by-light scattering [28, 29]. The statistical accuracy obtained with the analysis scheme described above is unprecedented for Q^2 ≤ 1.5 [GeV]^2 for larger momentum transfers it is still compatible with the CLEO [30] result. The systematics are still under study, but first results are expected soon.

5 Outlook

The results of the investigation of η and η' decays presented in this contribution are only based on $225.3 \times 10^6 J/\psi$ events. A total amount of more than 1.2 billion recorded J/ψ events is now available at BESIII. The analysis of the full data set will allow for higher precision in updated studies of decays of pseudoscalar mesons and thus for more stringent tests of predictions from chiral perturbation theory and its extensions, in the tests of fundamental symmetries, and in the search for very rare decays, which might contain hints for new physics.

In parallel to the studies presented in this contribution, the measurement of space-like transition form factors of pseudoscalar mesons is complemented by analyses tagging the production of η and η' with additional, mainly hadronic, decay modes. The statistical limitation of the $\psi(3770)$ data can be overcome by including the large data set, taken in order to study the investigate the XYZ states (see Sec.2). The higher center-of-mass energies allow not only to access to larger momentum transfers, but also to benefit from higher cross sections of the two-photon processes.

Future prospects of the $\gamma\gamma$ physics program at BESIII comprise the investigation of multi-meson final states to study scalar and tensor meson production, the measurement of polarization observables, and double tagged measurements of $\gamma\gamma$ processes. As a first step the investigation of the two-photon production of $\pi^+\pi^-$ pairs has been started.

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