η meson physics with WASA-at-COSY

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Abstract. In recent years, the η meson has been a focal point of research for the WASA experiment at the Cooler Synchrotron COSY of the Research Center Jülich. Production experiments using nucleon-nucleon and nucleon-nucleus collisions have been performed, studying the $\eta - N$ interaction in various configurations. A better understanding of this interaction is a key aspect in the ongoing search for η-nuclear bound states. In addition, the η meson itself represents an ideal laboratory for precision studies of the strong and electromagnetic interactions as well as for searches for beyond Standard Model physics. Large datasets were assembled using the WASA experiment to enable studies on rare and forbidden decay modes. An overview over recent highlights of the WASA η meson physics programme was given.

1 Introduction

The η meson has been an integral part of the WASA-at-COSY hadron physics programme over the last decade. Due to its unique properties, it represents an ideal gateway to study two very distinct research areas.

Already in 1985, Haider, Liu and Bhalerao [1, 2] found an attractive interaction between the η meson and nucleons. Although the original model suggested binding between nuclei and the η meson only for mass numbers $A \geq 12$, extensive experimental effort was put into the investigation of η-nucleon and η-nucleus interactions in the search for η-nucleus bound states also in systems as light as the deuteron. While there is, to date, no unequivocal evidence for such a bound state, strong signs of an attractive final state interaction have been found in production experiments off light nuclei such as the deuteron [3–5], ^{3}He [6–13] and ^{4}He [14, 15]. One of the most prominent examples is the $pd \to {}^3\mathrm{He}\eta$ reaction. Here, the total cross section σ rises steeply from zero at threshold to a plateau of around $\sigma = 400$ nb within 1 MeV of excess energy [6–9]. It has been discussed elaborately that such a behaviour can best be explained in the context of a strong final state interaction that might support a (quasi-)bound state below the production threshold [16–18]. While considerable effort was put in the investigation of the near threshold region in the search for potential $\eta - {}^3$He bound state, the main production process of η mesons in the $pd \to {}^3\mathrm{He}\eta$ remains relatively poorly understood. Angular distributions at larger excess energies display strong asymmetries that are not reproduced by any of the available theoretical models. However, a relatively shallow database in combination with large systematic effects between the measurements by different experimental facilities have thus far hindered a detailed study of the importance of higher

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partial waves as a function of the available excess energy. A new, high statistics dataset gathered with the WASA-at-COSY experiment [19] for the first time allows such a detailed study over a large range of excess energies.

For the theoretical interpretation of the η-nucleus interaction in complex systems featuring multiple nucleons it is of great importance to understand the elementary $\eta - N$ interaction. Here, spin can serve as a valuable tool to study both possible mesons in a meson-exchange model and the importance of nucleon resonances in the production process. A new high statistics measurement using a polarised proton beam has recently been made available [20], studying the role of higher partial waves at two different excess energies by determination of the analysing power A_y.

Apart from these production studies, the η meson represents an ideal scenario for various decay studies. It is an eigenstate to the *P*-, *C*- and *G*-parity with an isospin $I = 0$, so that all strong and electromagnetic decays are forbidden to first order. Consequently, there is no strongly dominating decay mode. Thus, the η meson is seen as an excellent gateway to study rare decays or search for symmetry violating forbidden decay modes. Hadronic decays can give access to isospin violation and thus the difference in the up- and down-quark masses, whereas radiative decays can be used to study quantum anomalies. Another major part in the studies of rare and forbidden decays are leptonic and semi-leptonic decays. These give access to the form factor of the η meson, can be used to study symmetry violations and to search for beyond Standard Model physics. Making use of two large, dedicated datasets for decay studies of 30×10^6 η mesons in $pd \to {}^3\mathrm{He}\eta$ and 500×10^6 η mesons in $pp \to pp\eta$, respectively, the search for rare and forbidden η decays is an integral part of the WASA-at-COSY η physics programme.

2 The WASA-at-COSY experiment

The WASA experiment is an internal, fixed target 4π experiment located at the **CO**ooler **SY**nchrotron COSY at Research Center Jülich. The accelerator provides beams of both protons and deuterons in a momentum range of $0.3\ \mathrm{GeV}/c \leq p_{\mathrm{beam}} \leq 3.7\ \mathrm{GeV}/c$ with a momentum resolution of around $\Delta p/p \approx 10^{-3}$ [21]. The beam is brought to collision with a pellet target providing frozen pellets of either hydrogen or deuterium. A Central Detector is built around this interaction point consisting of a drift chamber, a solenoid, a plastic scintillator and a calorimeter.

Due to the fixed target geometry, particles experience a large boost in forward direction. Consequently, a dedicated detection device is used to reconstruct heavy, forward-going ejectiles (mainly protons, deuterons and He-nuclei). This Forward Detector consists of various layers of scintillation detectors and a proportional chamber, which is used to reconstruct the azimuthal and polar scattering angles of charged particles emitted in forward direction.

For more information regarding the WASA detector setup the reader is referred to [22].

3 η meson production

Using the combination of the accelerator COSY and the WASA detector, the production of η mesons can be studied in proton-proton, proton-deuteron (or deuteron-proton) and deuteron-deuteron collisions using either a polarised or an unpolarised beam. During the talk, recent results on η meson production in proton-proton collisions, using a polarised proton beam, and in proton-deuteron fusion were discussed.

3.1 The $\vec{p}p \rightarrow pp\eta$ reaction

The measurement was performed at two different beam momenta of $p_p = 2026$ MeV/c and $p_p = 2188$ MeV/c, corresponding to excess energies of $Q_\eta = 15$ MeV and $Q_\eta = 72$ MeV, respectively. In addition, two different spin orientations were used to be able to better estimate systematic effects related to the beam polarisation. The polarisation was determined by measuring the asymmetry $A(\theta_p, \phi_p) = \frac{N_p(\theta_p,\phi_p)-N_p(\theta_p,\phi_p+\pi)}{N_p(\theta_p,\phi_p)+N_p(\theta_p,\phi_p+\pi)}$ of the number of elastically scattered protons. This asymmetry is related to the analysing power by $A(\theta_p, \phi_p) = P \cdot A_y(\theta_p) cos\phi_p$, where P is the polarisation. For the reaction $\vec{p}p \rightarrow pp$, the analysing power was previously measured [23, 24], so that the polarisation was determined as given in [25].

Similarly, the asymmetry $A(\theta_\eta, \phi_\eta) = \frac{N_\eta(\theta_\eta,\phi_\eta)-N_\eta(\theta_\eta,\phi_\eta+\pi)}{N_\eta(\theta_\eta,\phi_\eta)+N_\eta(\theta_\eta,\phi_\eta+\pi)}$ is measured for both polarisation states and for both beam momenta and, thus, the analysing power is determined. Here, the η meson is reconstructed in its two main decay modes involving neutral particles ($\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^0\pi^0\pi^0$). As is argued in [20], the product of analysing power and differential cross section is given by

$$A_y\left(\theta_\eta\right)\frac{d\sigma}{d\Omega} = 2\pi\left(G_1^{y0}\sin\theta_\eta + \left(H_1^{y0} + I_1^{y0}\right)\sin 2\theta_\eta\right) \quad . \tag{1}$$

According to [20], the coefficients G_1^{y0}, H_1^{y0} and I_1^{y0} can directly be related to the (Ps^*Pp)-, $(Pp)^2$- and $(S s^* S d)$-partial waves, respectively. Using a fit of the type $A_y\left(\theta_\eta\right)\frac{d\sigma}{d\Omega} = C_1 \sin\theta_\eta + C_2 \cos\theta_\eta \sin\theta_\eta$, it was found that the data at $Q_\eta = 15$ MeV are consistent with s-wave production, whereas a clear signal for higher partial waves was observed for $Q_\eta = 72$ MeV. The findings at $Q_\eta = 15$ MeV are in contradiction with earlier predictions from meson exchange models based on pseudo-scalar [26] and vector [27] meson exchange. More detailed information can be found in [20].

3.2 The $pd \rightarrow {}^3\mathrm{He}\eta$ reaction

As previously discussed, the near-threshold region of the $pd \rightarrow {}^3\mathrm{He}\eta$ reaction has been studied in great detail in recent years (see [6–9]). It was found that a strong final state interaction, potentially involving a (quasi-)bound $\eta - {}^3\mathrm{He}$ state, is responsible for the sudden rise of the cross section directly at the production threshold [16–18]. With little knowledge about the production mechanism itself, where thus far two-step models [28–30] and a meson exchange model involving the $S_{11}(1535)$ resonance [31] have been proposed but found little support in higher energy data, strong assumptions on the production amplitude have to be made in order to extract final state interaction parameters.

In 2014, a new measurement was performed using the WASA-at-COSY experimental facility. Data were taken at 15 different beam momenta between $p_p = 1.60$ GeV/c and $p_p = 1.74$ GeV/c with a stepsize of 10 MeV/c, corresponding to an excess energy region of 13.6 MeV $\leq Q_\eta \leq$ 80.9 MeV. Detecting the ^{3}He nuclei in the Forward Detector, a missing mass analysis was performed and both total cross sections and detailed angular distributions could be determined for all 15 excess energies. A large structure was observed in the excess energy range between $Q_\eta \approx 10$ MeV and $Q_\eta \approx 40$ MeV, potentially hinting at a region in which the final state interaction loses its importance and is superseded by the free production amplitude. The strongly forward peaked angular distributions extracted in [19] will for the first time allow to study the behaviour of individual components with rising excess energy, and thus serve as a valuable input to future theoretical model calculations. For more detailed information, we refer to [19].

4 η meson decays

In recent years, two large datasets have been accumulated with the WASA-at-COSY experiment, specifically dedicated to the study of η meson decays, 30×10^6 η mesons in the $pd \rightarrow {}^3\mathrm{He}\eta$ process as well as 500×10^6 η mesons in the reaction $pp \rightarrow pp\eta$. Various analyses have been performed or are ongoing, targeting a wide variety of physics topics (see, e.g., [32]). In all these analyses, the near 4π coverage of the WASA detector in combination with its excellent particle identification capabilities is exploited for a fully exclusive event reconstruction. During the conference, a choice of some recent highlights was presented.

4.1 The $\eta \rightarrow \gamma e^+e^-$ and $\eta \rightarrow e^+e^-e^+e^-$ decays

Dalitz- and double-Dalitz-decays of pseudo-scalar mesons are of high interest as they allow the determination of the electromagnetic form factor $F\left(q_1^2, q_2^2\right)$ for $(q_1^2 > 0, q_2^2 = 0)$ and $(q_1^2 > 0, q_2^2 > 0)$, respectively. These form factors play a key role in the determination of the hadronic light-by-light contribution to the muon anomalous magnetic moment, as it, to date, represents one of the largest contributions to the total uncertainty in the theoretical calculation of $g_\mu - 2$. Using the proton-deuteron fusion dataset containing 30×10^6 reconstructed η mesons, around 14×10^3 $\eta \rightarrow \gamma e^+e^-$ have been observed and a branching ratio of $\mathrm{BR}(\eta \rightarrow \gamma e^+e^-) = (6.72 \pm 0.07_{\mathrm{stat.}} \pm 0.31_{\mathrm{sys.}}) \times 10^{-3}$ [32] was determined. The value obtained in [32] is compatible with the PDG average [33]. In [34], the form factor was extracted and shown to be consistent with other measurements [35, 36]. In addition, a search for the double-Dalitz decay $\eta \rightarrow e^+e^-e^+e^-$ yielded 18.4 ± 4.9 signal events and a branching ratio of $\mathrm{BR}(\eta \rightarrow e^+e^-e^+e^-) = (3.2 \pm 0.9_{\mathrm{stat.}} \pm 0.5_{\mathrm{sys.}}) \times 10^{-5}$. Again, the branching ratio is compatible with the PDG average within the quoted uncertainty. With 18.4 ± 4.9 signal events, a determination of the two-dimensional form factor $F\left(q_1^2, q_2^2\right)$ was not feasible.

The analysis of the $pp \rightarrow pp\eta$ dataset, containing roughly 500×10^6 η mesons is ongoing and was discussed in another contribution.

4.2 The $\eta \rightarrow \pi^+\pi^-e^+e^-$ decay

In the radiative decay $\eta \rightarrow \gamma\pi^+\pi^-$, $M1$ and $E2$ transitions are allowed, whereas the $E1$ transition would be CP-violating. However, in order to distinguish between the different transitions, a measurement of the polarisation of the photon in the final state would be needed. Instead, the decay $\eta \rightarrow \pi^+\pi^-e^+e^-$ with an intermediate virtual photon creating the e^+e^- pair allows the search for CP-violation. If CP-violation were to be found in this η meson decay, an asymmetry in the distribution of the the dihedral angle ϕ, the angle between the decay planes of the $\pi^+\pi^-$ and the e^+e^- pairs, would be seen.

Based on the 30×10^6 $pd \rightarrow {}^3\mathrm{He}\eta$ events, a total of 215 ± 17 $\eta \rightarrow \pi^+\pi^-e^+e^-$ was observed, resulting in a branching ratio of $\mathrm{BR}(\eta \rightarrow \pi^+\pi^-e^+e^-) = (2.7 \pm 0.2_{\mathrm{stat.}} \pm 0.2_{\mathrm{sys.}}) \times 10^{-4}$ [32]. Also here, the resulting branching ratio is consistent with the PDG average within the uncertainties. The asymmetry in the dihedral angle

$$A_\phi = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)} \tag{2}$$

was determined to be $A_\phi = (-1.1 \pm 6.6_{\mathrm{stat.}} \pm 0.2_{\mathrm{sys.}}) \times 10^{-2}$ [32], which is consistent with zero and thus does not signal any CP-violation. For further details, see [32]. In the future, more strict limits on a potential CP-violation in this decay can be set, using the larger dataset in $pp \rightarrow pp\eta$.

4.3 The $\eta \to \pi^0 e^+ e^-$ decay

The semi-leptonic decay of an η meson into a neutral pion and an electron-positron pair created by a single virtual photon is forbidden by C-parity conservation. Standard Model predictions based on a two-virtual-photon exchange range from $\mathrm{BR}(\eta \to \pi^0 e^+ e^-) \approx 10^{-11}$ to $\mathrm{BR}(\eta \to \pi^0 e^+ e^-) \approx 10^{-8}$ [37–39]. Thus, this particular decay channel presents an ideal opportunity to search for C-parity violation in the Standard Model. Also, beyond Standard Model particles, such as the hypothetical *dark photon*, could create the e^+e^- pair in the $\eta \to \pi^0 e^+ e^-$, thus potentially increasing the branching ratio to an observable value. In a recent analysis based on the $pd \to {}^3\mathrm{He}\eta$ dataset no signal was found. A new, world's best upper limit on the branching ratio was determined. Depending on the hypothesis for the e^+e^- invariant mass distribution, the limit is given by [40]

$$\mathrm{BR}_{\mathrm{virtual}}(\eta \to \pi^0 e^+ e^-) < 7.5 \times 10^{-6} \quad , \quad \mathrm{BR}_{\mathrm{PS}}(\eta \to \pi^0 e^+ e^-) < 9.5 \times 10^{-6} \quad . \tag{3}$$

Here, the subscript *virtual* signals the case in which the e^+e^- invariant mass distribution was calculated based on a vector meson dominance model, whereas the subscript *PS* signals the case, where the photon energy distribution and thus also the e^+e^- invariant mass distribution is given by evenly distributed events in three-particle phase-space. In both cases, the limit is a significant improvement over the previous best limit of $\mathrm{BR}_{\mathrm{PDG}}(\eta \to \pi^0 e^+ e^-) < 4 \times 10^{-5}$ [33]. With an order of magnitude more data available in the $pp \to pp\eta$ reaction, a further improvement by a currently ongoing analysis seems feasible.

More detailed information on these decays as well as on further studies that have been performed using the large η meson datasets gathered with the WASA-at-COSY setup can be found in the respective publications [32, 40].

5 Summary

In this contribution, an overview was given over some selected topics within the η meson physics programme with the WASA-at-COSY experiment. In production experiments, the $\eta - N$ interaction is studied. Recent results on the analysing power in the $\vec{p}p \to pp\eta$ reaction were presented. Additionally, a new dataset was presented concerning the $pd \to {}^3\mathrm{He}\eta$ reaction away from the reaction threshold, aiming at a better understanding of the underlying reaction process in a region that is not dominated by the strong final state interaction.

With two large, dedicated datasets a wide variety of η meson decays is studied with WASA-at-COSY. Selected topics included the Dalitz- and double-Dalitz-decays in the quest for the η meson electromagnetic form factor, a search for CP-violation in the decay $\eta \to \pi^+\pi^- e^+ e^-$ and a recent new best upper limit on the C-parity violating decay $\eta \to \pi^0 e^+ e^-$. Results presented during the conference are based on the smaller $pd \to {}^3\mathrm{He}\eta$ dataset containing around 30×10^6 η mesons, while multiple studies on η meson decays in a dataset of 500×10^6 η mesons in the $pp \to pp\eta$ reaction are ongoing.

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