

Studies on η meson production and the C -parity violating decay $\eta \rightarrow \pi^0 e^+ e^-$ with WASA-at-COSY

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Abstract. The WASA-at-COSY experiment is a near 4π detector, located at the Forschungszentrum Jülich (Germany). It is highly suited to study both the production of light mesons in hadron collisions and their subsequent decays. Current investigations include a study on the energy dependence of the production cross section and angular distributions of the η meson in the proton-deuteron fusion reaction $pd \rightarrow {}^3\text{He}\eta$, as well as a search for beyond standard model physics in the C -parity violating decay $\eta \rightarrow \pi^0 e^+ e^-$. The status of both these analyses and preliminary results are presented.

1 Introduction

In the very near threshold region, the $pd \rightarrow {}^3\text{He}\eta$ reaction has been studied in great detail [1–5], whereas at higher excess energies Q the amount of available data is limited [6–9]. Moreover, while the data from ANKE [6] and WASA/PROMICE [7, 8] suggest a plateau in the total cross section for higher Q -values, recent results from the WASA-at-COSY experiment [10] suggest an unexpected narrow variation of the total cross section at $Q = 48.8$ MeV as can be seen in Fig.1. Furthermore, theoretical model calculations available in the literature [11–13] based on either one- or two-step models fail to describe the strongly forward peaked angular distributions and total cross section in parallel. While new calculations based on a boson exchange model look promising [13], more high quality data at intermediate excess energies is needed to support and test new calculations in order to deepen our understanding of the underlying production mechanism.

Due to the rather large production cross section of η mesons in both pp - and pd -collisions, data taken with the WASA-at-COSY experiment also present a nice opportunity to investigate rare η meson decays. A first dataset consisting of approximately 3×10^7 $pd \rightarrow {}^3\text{He}\eta$ events is being used for the search of the C -parity violating decay $\eta \rightarrow \pi^0 e^+ e^-$ among others. The current experimental upper limit for this decay is $\text{BR}(\eta \rightarrow \pi^0 e^+ e^-) < 4 \times 10^{-5}$ (90% CL), whereas the standard model expectation for the C -parity conserving fourth order process $\eta \rightarrow \pi^0 \gamma^* \gamma^* \rightarrow \pi^0 e^+ e^-$ is of the order of 10^{-9} [14]. An observation of a significantly higher branching ratio would therefore indicate beyond standard model physics being involved in the decay chain, like for example a Z -like dark boson.

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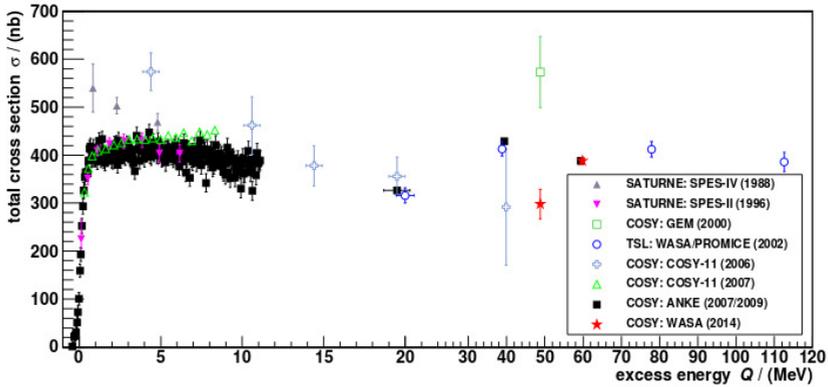


Figure 1. Total cross section data for the reaction $pd \rightarrow {}^3\text{He}\eta$ obtained by Ref. [1–9] as a function of the excess energy Q . The uncertainties shown do not include systematic uncertainties resulting from an absolute normalization. The data from WASA- at-COSY (red stars) are scaled to the ANKE data point at $Q = 59.4$ MeV. Figure taken from Ref. [10].

2 The WASA-at-COSY experiment

The WASA-at-COSY experiment is a fixed target experiment located at the COoler SYnchrotron (COSY). With COSY providing either polarized or unpolarized protons or deuterons with beam momenta of up to $p = 3.7$ GeV/ c and a frozen hydrogen or deuterium pellet-target, it is possible to investigate pp -, pd - and dd -collisions with WASA-at-COSY. The Central Detector system, consisting of a solenoid magnet, a drift chamber, a plastic scintillator barrel and an electromagnetic calorimeter, is used for the identification and reconstruction of light mesons and their decay particles, like pions, electrons and photons. Due to the fixed target geometry, all ejectiles experience a large boost in forward direction, so that heavier particles like protons, deuterons or helium nuclei are scattered under small polar angles and therefore measured in the Forward Detector system. The FD consists of various layers of thin scintillators, a proportional chamber and five layers of a thick scintillator hodoscope. This experimental setup offers the possibility to precisely reconstruct both the azimuthal and the polar scattering angles of forward going particles, as well as their energy. With its near 4π coverage and excellent detector systems, the WASA-at-COSY experiment allows for both inclusive and exclusive measurements.

3 η meson production in pd fusion to ${}^3\text{He}\eta$

In May 2014, a beam time was conducted with the COSY storage ring providing unpolarized protons at 15 different beam momenta between $p_p = 1.60$ GeV/ c and $p_p = 1.74$ GeV/ c , that were brought to collision with the deuterium pellet-target. With this new dataset, covering an excess energy range relative to the ${}^3\text{He}\eta$ threshold from $Q \approx 13.6$ MeV to $Q \approx 80.9$ MeV with a step size of $\Delta Q \approx 4.8$ MeV, it is possible to extract precise total and differential cross sections of the $pd \rightarrow {}^3\text{He}\eta$ reaction.

The ${}^3\text{He}$ -nuclei can be identified in the forward detector due to their energy loss ΔE by use of the ΔE - E technique. Combining the energy loss information with a measurement of both the azimuthal and the polar scattering angles φ and ϑ , the full four-momenta of the ${}^3\text{He}$ -nuclei can be reconstructed, so that the missing mass technique can be applied. Such a missing mass distribution is shown in

Fig.2. Performing a simultaneous fit of a polynomial for the background and a gaussian for the signal, the background can be subtracted to get a first estimate of more than 1.2×10^5 η mesons per excess energy. Applying the same background subtraction technique to missing mass spectra binned in $\cos \vartheta_{\eta}^{\text{cm}}$, first raw angular distributions can be extracted (see Fig.2). These distributions have yet to be corrected for the detector acceptance and cut efficiencies. Due to a full angular coverage and good statistics, the angular distributions can be examined in great detail in the future. The reaction $pd \rightarrow {}^3\text{He}\pi^0$ will be used for normalization purposes, so that ultimately total and differential cross sections can be determined with an estimated point-to-point uncertainty of $\sim 8\%$, mainly resulting from the normalization procedure, over the whole excess energy range from $Q \approx 13.6$ MeV to $Q \approx 80.9$ MeV. This will present a considerable extension of the current database, allowing a detailed investigation of theoretical models describing the underlying production mechanism of η mesons in pd fusion to ${}^3\text{He}\eta$.

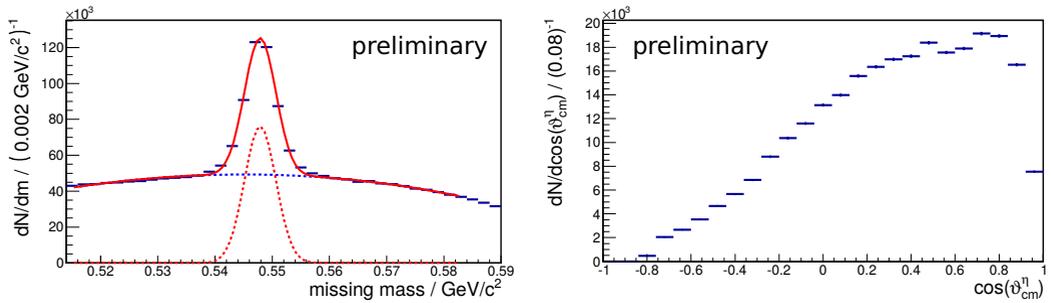


Figure 2. Left: Missing mass of $pd \rightarrow {}^3\text{He} X$ for ${}^3\text{He}$ -nuclei stopped in the first layer of the Forward Range Hodoscope. The solid red line is a combined fit of a signal gaussian (dotted red line) and a background polynomial (dotted blue line). **Right:** Raw angular distribution of ${}^3\text{He}\eta$ events. No geometrical acceptance and efficiency correction have been applied so far. Both spectra show data for $p_p = 1.70 \text{ GeV}/c$ ($Q \approx 61.7$ MeV).

4 The C -parity violating decay $\eta \rightarrow \pi^0 e^+ e^-$

A huge dataset of approximately 3×10^7 $pd \rightarrow {}^3\text{He}\eta$ events allows the search for (very) rare and forbidden η meson decays with the WASA-at-COSY experiment. The decay $\eta \rightarrow \pi^0 e^+ e^-$ is of particular interest, as the decay via a virtual photon would violate C -parity and is therefore forbidden. In the standard model, a fourth order process involving two virtual photons exists, that does not violate C -parity. However, the estimated branching ratio of this process is in the order of 10^{-9} [14]. With the current experimental upper limit at $\text{BR}(\eta \rightarrow \pi^0 e^+ e^-) < 4 \times 10^{-5}$ (90% CL), there remain four orders of magnitude that can be probed for beyond standard model physics. To significantly reduce the existing upper limit, it is highly important to gain a very good understanding of the contributing background processes. Knowing these, cuts can be optimized in a way that the signal-to-background ratio is maximized. This procedure is applied to cuts on particle identification, the invariant mass of two neutral particles ($\pi^0 \rightarrow \gamma\gamma$), the invariant mass of two neutral and two oppositely charged particles ($\eta \rightarrow \pi^0 e^+ e^-$), a kinematic fit probability for the hypothesis of a ${}^3\text{He}\gamma\gamma e^+ e^-$ final state and finally a cut on the missing mass of the ${}^3\text{He}$ -nucleus in a blind analysis. An eventual signal of BSM physics could appear in the invariant mass distribution of the lepton pair, for example, in the case that the decay is mediated by a Z -like dark photon. Preliminary results of this analysis of roughly one third of the whole dataset can be seen in Fig.3. The observed distributions of both missing mass

of ${}^3\text{He}$ and invariant mass of the lepton pair are consistent with the expectation from Monte-Carlo simulations for direct ${}^3\text{He}\pi^0\pi^0$ production with one of the two pions performing a Dalitz decay and one photon escaping the detector.

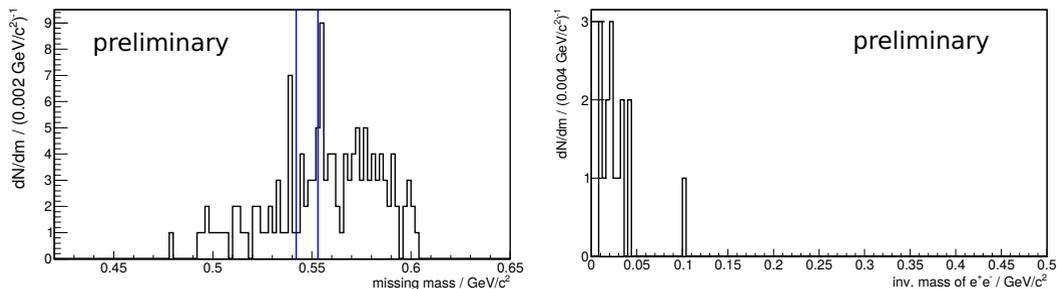


Figure 3. Left: Missing mass of ${}^3\text{He}$ after all cuts were applied. The blue lines represent the cut conditions on the missing mass of ${}^3\text{He}$ used for the invariant mass spectrum of the lepton pair. **Right:** Invariant mass of the lepton pair after all cuts were applied. Both distributions are consistent with direct $\pi^0\pi^0$ production with one pion performing a Dalitz decay. A sample of the whole dataset (from [16]) is displayed here.

The ongoing analysis of the full dataset will significantly reduce the existing upper limit for the C-parity violating η meson decay $\eta \rightarrow \pi^0 e^+ e^-$ and will therefore reduce the available parameter space for BSM physics in the near future.

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