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Total and Differential Cross Sections of the Reaction pd → ^{3}He + η at 49 and 60 MeV Excess Energy

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Abstract. The p + d → ^{3}He + η reaction has been used recently for various precision experiments at COSY-Jülich, *e.g.* for the investigation of the η-nucleus final state interaction, the search for possible η-mesic nuclei as well as for the η-mass determination with highest accuracy. A remarkable feature of this reaction is the unexpected shape of the excitation function which is strongly influenced by the η-^{3}He final state interaction. While close to threshold ($Q \leq 11$ MeV) a rich data sample has been provided by the ANKE collaboration, only limited information are available at higher excess energies. Therefore, new measurements at $Q = 49$ and 60 MeV with high statistics have been performed at the WASA-at-COSY experiment. Due to the large angular acceptance of the detector detailed investigations on angular distributions as well as their energy dependance have been performed and will be presented and discussed.
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1 Introduction

The production mechanism of the reaction p + d → ^{3}He + η is of high interest, as the cross section for this reaction shows a strong energy dependence within the first MeV excess energy beyond the production threshold. This cannot be described by conventional interaction models, and is a strong evidence for an η^3He bound state. While the development of the cross section σ near the production threshold is well known, especially due to the precise data of the ANKE experiment [1], there are still discrepancies between the data of the different experiments at higher excess energies. Unlike the data from ANKE and WASA/PROMICE, which show a plateau in the energy range between 40 MeV and 120 MeV, the data point of the GEM experiment at 49 MeV indicates an increase of the cross section at this energy [2–4]. Although still consistent with this cross section plateau shown by the neighboring data when considering the statistical and systematic uncertainties, this 49 MeV data point might be a hint for a local increase of the cross section at this energy. A verification of such a possible peak-like structure would be of high interest in the context of the search of possible η-mesic bound states and could give further input for the theoretical understanding of relevant production mechanism, final state interactions and binding effects of the η^3He system.

Thus, the determination of the p + d → ^{3}He + η cross section at 49 MeV excess energy is the main aim of this analysis. For a relative normalization also a sample of the 60 MeV data is analyzed. Besides the total cross sections also the differential cross sections for these energies are determined.

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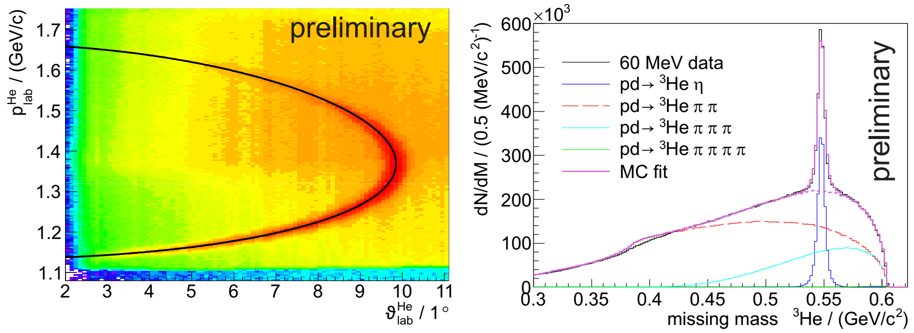

Fig. 1. Left: ^{3}He momenta against the corresponding polar angle for the Q = 60 MeV data compared to a theoretical expectation (black line) after applying the fine calibration. Right: ^{3}He missing mass plot for the 60 MeV data with a Monte Carlo fit.

2 Analysis

The experiment was performed at the COSY storage ring of the Forschungszentrum Jülich, using the WASA-at-COSY experimental setup. A detailed description of the detector system can be found in Ref. [5]. The data were recorded at proton beam energies of 980 MeV (Q = 49 MeV) and 1000 MeV (Q = 60 MeV) and preselected on p + d → ^{3}He + X events using the ΔE-E method. For this purpose one ^{3}He hit in the forward detector was requested. The number of p + d → ^{3}He + η events are extracted from the ^{3}He missing mass spectra of the different angular ranges. For this method it is important that the momenta and scattering angles of the ^{3}He are correctly reconstructed. As the reconstruction of the polar angle of the ^{3}He in the laboratory system is well known with an uncertainty of ±0.2 °, the two dimensional scatter plot of the ^{3}He laboratory momenta versus the corresponding angle ϑ is used to improve the ^{3}He momentum calibaration. Figure 1 (left) shows this plot for the Q = 60 MeV data compared to a theoretical plot after applying the fine calibration.

For each energy the full $\vartheta^{\eta}_{\mathrm{CMS}}$ angular range is divided into 25 equally spaced $\cos\vartheta^{\eta}_{\mathrm{CMS}}$ bins and for each bin the ^{3}He missing mass distribution is created. The different spectra are fitted by a Monte Carlo cocktail, as it is exemplarily shown in Fig. 1 (right) for the 60 MeV data over the whole angular range. It is visible that the background on both sides of the peak can be described well by the Monte Carlo cocktail.

As only those p + d → ^{3}He + η events are counted for which the corresponding ^{3}He nucleus is detected in the forward detector, the determined number of p + d → ^{3}He + η events for each angular bin has to be corrected for the detector acceptance. Since the total cross section of the reaction p + d → ^{3}He + η at 60 MeV excess energy is well known due to the measurement at the ANKE experiment [2], and the main focus of the underlying analysis is the ratio of the cross sections at 49 MeV and 60 MeV excess energy, a relative normalization of the Q = 49 MeV data to the Q = 60 MeV via the direct p + d → ^{3}He + π^0 production is used.

3 Results

Due to the detector design, i.e. openings in the detector for the beam pipe, the acceptance for the 1st and 25th angular bin is much lower than for the other bins. Therefore, in the further analysis the angular ranges $0.92 \leq |\cos\vartheta^{\eta}_{\mathrm{CMS}}| \leq 1.00$ are excluded to avoid systematic uncertainties. Instead the differential cross sections for these angular bins are obtained by fitting the observed differential cross sections for the angular range $-0.92 \leq \cos\vartheta^{\eta}_{\mathrm{CMS}} < 0.92$ with a third order polynomial

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = a_0 \cdot \left[1 + \sum_{n=1}^{3} a_n \left(\cos\vartheta^{\eta}_{\mathrm{CMS}}\right)^n\right] \quad (1)$$

Table 1. Preliminary parameters of the polynomial fits to the differential cross sections determined with WASA-at-COSY.

Q [MeV]	a_0 [nb/sr]	a_1	a_2	a_3	χ^2/ndf
48.8 ± 0.8	30.0 ± 0.3	1.15 ± 0.03	−0.28 ± 0.03	−0.45 ± 0.05	2.48
59.8 ± 0.8	33.8 ± 0.3	1.23 ± 0.02	−0.26 ± 0.02	−0.51 ± 0.03	1.59

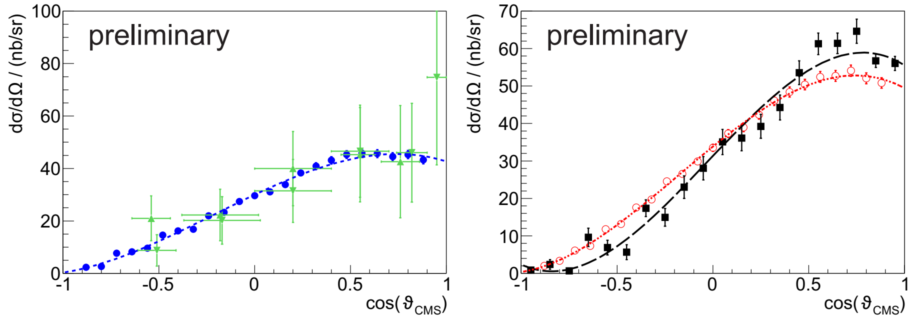

Fig. 2. Differential cross section for the 49 MeV (left) and 60 MeV data (right) with statisitcal uncertainties. The new WASA-at-COSY data (full blue circles and empty red circles) are fitted by a third order polynomial with the parameters shown in Tab. 1. For comparision also the GEM 49 MeV data (full green triangles, Ref. [4]) scaled by a factor of 0.66 and the ANKE 60 MeV data (full black squares, Ref. [2]) are plotted. The later one is fitted by a third order polynomial.

and extracting from this function the values for the two outer angular bins. The parameters of the polynomial fit for both excess energies are given in Tab. 1.

To determine the total 49 MeV cross section, our new 60 MeV data are normalized to the well known ANKE cross section obtained at the same excess energy to $\sigma(60\,\text{MeV}) = (388.1 \pm 7.1 \pm 58)\,\text{nb}$ [2]. Here the latter uncertainty corresponds to a normalization uncertainty of 15 %, which can be ignored when comparing the present data with the ANKE data due to the relative normalization. By this the preliminary cross section for $Q = (48.8 \pm 0.8)\,\text{MeV}$ excess energy results in

$$\sigma_{\text{prel.}}(49\,\text{MeV}) = (342.7 \pm 8.2 \pm 51)\,\text{nb} \tag{2}$$

with the latter uncertainty corresponding to the 15 % normalization uncertainty. Figure 2 shows the differential cross sections after the normalization for both excess energies. For comparison the existing data for these energy ranges are plotted. The vertical error bars include statistical uncertainties as well as systematic contributions arising from the uncertainty in the absolute beam momentum of 0.1 %. The scaled down GEM data and the newly determined WASA-at-COSY data agree well and show the same angular asymmetry. The same holds for the comparison with the ANKE data where slight differences are visible which might be attributed to the statistical uncertainties in the data sets.

Figure 3 shows the parameters of the polynomial fits as function of the excess energy. From these plots it becomes evident that the asymmetry parameter a_1 increases from threshold up to $Q \approx 40\,\text{MeV}$ and remains afterward almost constant. Contrary, both the quadratic and cubic coefficients a_2 and a_3 can be described by a monotonically decreasing linear function. Since one can assume s-wave dominance at threshold it is plausible to assume $a_2(Q = 0\,\text{MeV}) = a_3(Q = 0\,\text{MeV}) = 0$.

The preliminary total cross section for $Q = 49\,\text{MeV}$ is plotted in Fig. 4 together with all existing data for the reaction $\text{p} + \text{d} \to {}^3\text{He} + \eta$ up to $Q = 120\,\text{MeV}$. All data points are presented with their statistical uncertainties, but without normalization uncertainties. It can be seen clearly that the determined preliminary 49 MeV cross section with $\sigma_{\text{prel.}} = (342.7 \pm 8.2 \pm 51)\,\text{nb}$ indicates no evidence for a resonance-like structure in the excitation function. Moreover, the enhancement of the previously available data point is obviously purely an effect of the data normalization.

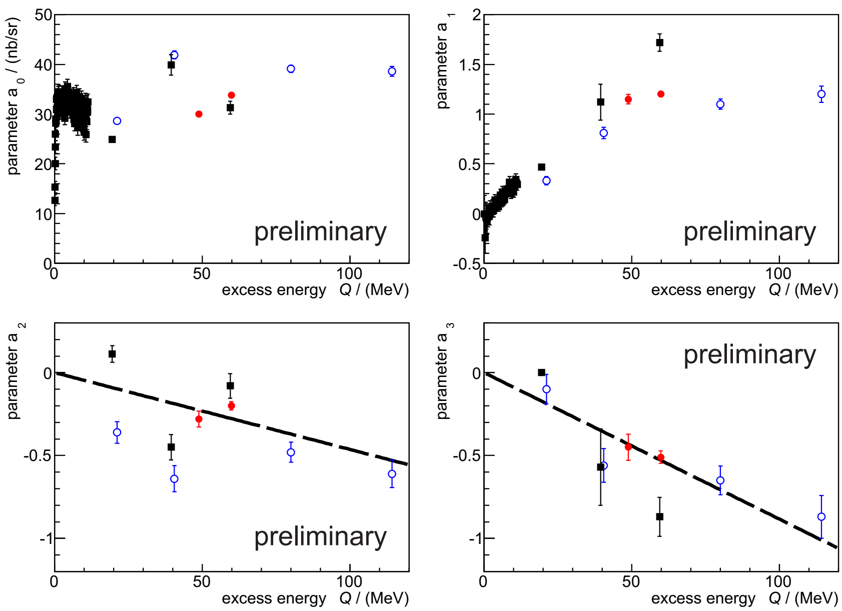

Fig. 3. Polynomial fit parameters for the different excess energies. Besides the parameters of the WASA-at-COSY data (full red circles) the aparameters of the WASA/PROMICE data (empty blue circles, Ref. [3]) and the ANKE data (full black squares, Ref. [1,2]) are plotted. The parameters a_2 and a_3 are fitted by a linear function.

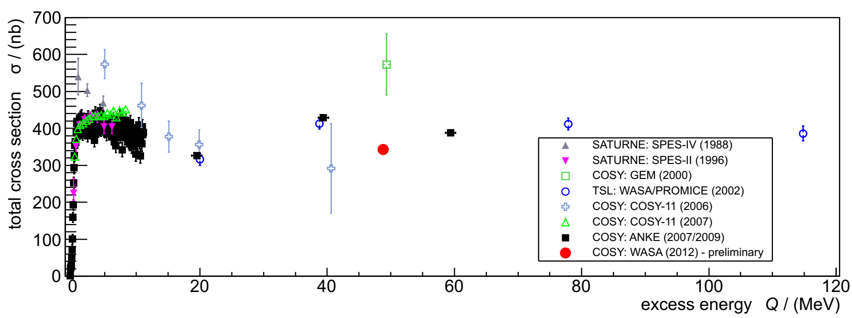

Fig. 4. Total cross sections of the reaction p + d → ^{3}He + η plotted against the excess energy. All data points are given with statistical uncertainties, but without normalization uncertainties. Besides our preliminary result (full red circle) also shown are data from Ref. [6] (full grey triangles), Ref. [7] (inverted full magenta triangles), Ref. [4] (empty green squares), Ref. [3] (empty blue circles), Ref. [8] (empty light blue crosses), Ref. [9] (empty green triangles) and Ref. [1,2] (full black squares).

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