

**Precision study of the  $dp \rightarrow {}^3\text{He}\eta$  reaction for excess energies between 20 and 60 MeV**

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The differential and total cross sections for the  $dp \rightarrow {}^3\text{He}\eta$  reaction have been measured at COSY-ANKE at excess energies of 19.5, 39.4, and 59.4 MeV over the full angular range. The results are in line with trends apparent from the detailed near-threshold studies and also largely agree with those from CELSIUS, though the present data have much better angular coverage near the forward and backward directions, thus allowing firmer conclusions to be drawn. While at 19.5 MeV the results can be described in terms of  $s$ - and  $p$ -wave production, by 59.4 MeV higher partial waves are required. Including the 19.5 MeV point together with the near-threshold data in a global  $s$ - and  $p$ -wave fit gives a poorer overall description of the data though the position of the pole in the  $\eta^3\text{He}$  scattering amplitude, corresponding to the quasibound or virtual state, is hardly changed.

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We have recently provided results on the  $dp \rightarrow {}^3\text{He}\eta$  reaction very near threshold in fine energy steps. These show that the total cross section reaches a plateau for an excess energy  $Q$  that is less than 1 MeV [1] and this behavior has been confirmed by an independent measurement [2]. The abrupt variation of the cross section can be understood [3] as being due to a final state interaction (FSI) that is enhanced through the presence of a quasibound or virtual state pole in the  $\eta^3\text{He}$  elastic scattering amplitude for  $|Q| < 1$  MeV, though its location in the complex planes is ambiguous.

Further evidence for the pole hypothesis is to be found from the study of the angular distribution [4]. For  $Q < 11$  MeV a linear dependence on the cosine of the  $\eta$  production angle is seen, which suggests that only the  $\eta$   $s$ -wave and  $s$ - $p$  interference are important in this region. However, the energy dependence of the angular slope shows that the phase of the interference changes rapidly with  $Q$ , presumably because of the pole in the  $s$ -wave production amplitude. It is therefore of interest to investigate how this behavior extends to higher energies and this we have done through measurements at  $Q = 19.5, 39.4, \text{ and } 59.4$  MeV. The first two energies overlap with results obtained by a CELSIUS Collaboration [5] and, while the data sets are largely consistent, the present ones allow firmer conclusions to be drawn. The energy range 10–60 MeV seems to be a transition region going from one

where there is  $s + p$  dominance to a regime where higher partial waves become important.

The experiment was carried out using the ANKE spectrometer [6] in combination with a hydrogen cluster target [7] at an internal station of the Cooler Synchrotron COSY-Jülich. The conditions were identical to those of our near-threshold work [1] with the exception that, instead of using a beam that was continuously ramped in energy, three fixed values of the beam momentum were requested, viz., 3.223, 3.306, and 3.389 GeV/ $c$ . The produced  ${}^3\text{He}$  were detected in the ANKE forward detection system, which consists of one drift chamber, two multiwire proportional chambers, and three layers of scintillation hodoscopes. The trigger used demanded hits in the first two layers. The tracks of charged particles could be traced back through the precisely known magnetic field to the interaction point, leading to a momentum reconstruction for registered particles. The  ${}^3\text{He}$  were then identified by making a cut in the energy loss versus momentum plot using the information from all the hodoscope layers.

The missing-mass distribution for all  $dp \rightarrow {}^3\text{He}X$  events measured at  $Q = 19.5$  MeV is presented in Fig. 1. This shows a prominent  $\eta$  peak sitting on a background that is rather similar to that observed in the below-threshold data taken under conditions identical to the ones used here [1]. The spectrum has been modeled in a phase-space Monte Carlo simulation of two-, three-, and four-pion production plus a small component arising from misidentified protons from the intense deuteron breakup reaction. These simulations were fitted together with that for the  $dp \rightarrow {}^3\text{He}\eta$  reaction to the

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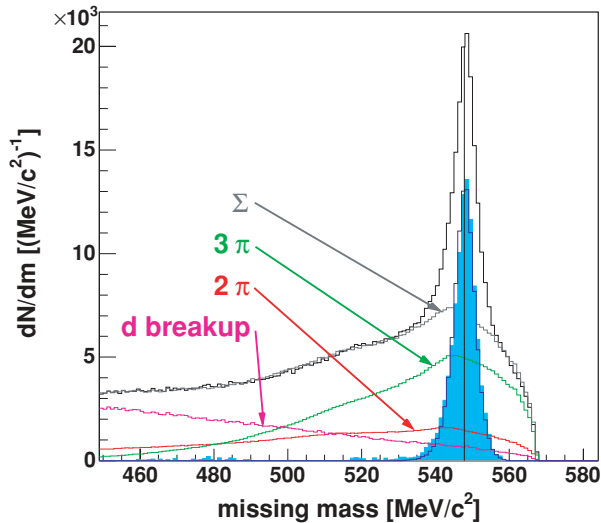


FIG. 1. (Color online) Missing-mass distribution for the  $dp \rightarrow {}^3\text{He}X$  reaction at an excess energy of 19.5 MeV with respect to the  $\eta$  threshold. Contributions of simulated reactions to the background fit and their sum ( $\Sigma$ ) are shown. After subtracting these from the data, the difference histogram shows a clean  $\eta$  peak (shaded) that agrees very well with the simulation (solid histogram) of the  $dp \rightarrow {}^3\text{He}\eta$  reaction.

data. Although a contribution from four-pion production is not visible in Fig. 1, it is needed for certain angular bins of  $\cos(\theta)$ , especially at  $Q = 60$  MeV. After subtracting the sum of the background reactions from the measured points, a clean  $\eta$  peak was found.

To determine the differential cross section for each excess energy, the whole range of the  ${}^3\text{He}$  c.m. production angles was divided into 20 bins and a missing-mass distribution was constructed for each of them. The  $\eta$  content was determined in a manner similar to that shown in Fig. 1.

In the near-threshold experiment  $Q$  could be determined directly from the data by studying the size of the momentum ellipse [1]. This leads to significant errors as  $Q$  gets larger and the ellipse expands. Therefore, the excess energy was calculated from the preset COSY beam momentum. This leads to an uncertainty of 0.8 MeV, which is consistent with the precision of 0.1% in the COSY beam momentum. For excess energies in the 20–60 MeV range this uncertainty is of minor importance.

Just as in the earlier work [1] that was undertaken at the same time, the luminosity  $\mathcal{L}$  needed to convert counts to cross sections was found through the simultaneous measurement in the forward detector of the deuteron from  $dp$  elastic scattering. The cross section varies very fast with the deuteron angle in this region [8] and it is the systematic uncertainty in the determination of this angle that dominates the error in  $\mathcal{L}$  of about  $\pm 15\%$ . However, it is important to stress that this generally affects all three energies in the same way, as it does also the near-threshold data [1].

Figure 2 shows the angular distributions obtained at the three different energies. Also presented are the points measured in a missing-mass experiment by a CELSIUS Collaboration in the vicinity of  $Q = 20$  MeV and 40 MeV, as

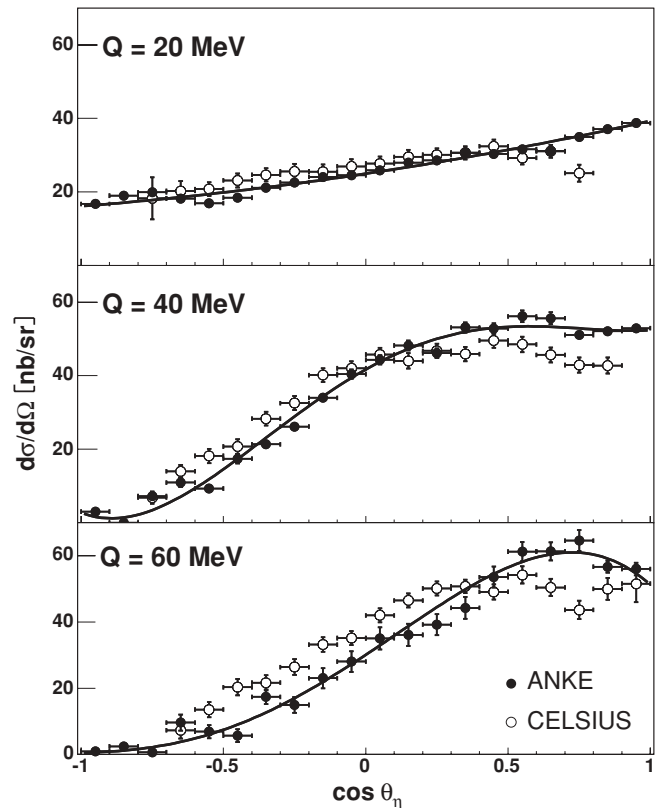


FIG. 2. Differential cross sections for the three excess energies studied at ANKE (solid circles). The CELSIUS data (open circles) shown in the 60 MeV plot were measured at 80 MeV [5]. The solid lines represent fits of Eq. (1) to the ANKE data, with the parameters being given in Table I.

well as those at 80 MeV [5]. These are generally in agreement with the present results, though our data have smaller statistical error bars and cover the complete  $\cos \theta_\eta$  range. There is no sign of a forward dip at 19.5 MeV and that any at 39.4 MeV is much weaker than the one found at CELSIUS. However, although the statistics were poorer and the number of points fewer, the CELSIUS group also measured events where the  $\eta$  meson was detected through its two photon decay in coincidence with the  ${}^3\text{He}$ . These data also seemed to show less of a forward dip at both 20 and 40 MeV [5].

Figure 2 also shows polynomial fits to our points

$$\frac{d\sigma}{d\Omega} = \sum_{n=0}^4 a_n (\cos \theta_\eta)^n, \quad (1)$$

with the values of the parameters  $a_n$  being given in Table I. These prove that, although it might just be sufficient to retain only  $s$  and  $p$  waves for the 19.5 MeV data,  $d$  and higher waves are required to describe the 39.4 and 59.4 MeV data. The negative value of  $a_4$  at 59.4 MeV indicates that at least  $f$  waves are needed here.

The values of the total  $dp \rightarrow {}^3\text{He}\eta$  cross sections are reported in Table I and compared with other published results in Fig. 3. Not shown is the 15% uncertainty in the ANKE data that arises mainly from the luminosity determination. As discussed earlier, this is largely a common factor that does not

TABLE I.  $dp \rightarrow {}^3\text{He}\eta$  differential and total cross sections. In addition to the statistical errors, there is a common systematic uncertainty of 15% in the total cross sections, due mainly to the luminosity determination. The fit parameters  $a_n$  of Eq. (1) are similarly affected by this scale uncertainty.

$Q$ (MeV)	$19.5 \pm 0.8$	$39.4 \pm 0.8$	$59.4 \pm 0.8$
$p_\eta$ (MeV/c)	$134.5 \pm 2.8$	$192.4 \pm 2.0$	$237.7 \pm 1.6$
$a_0$ (nb/sr)	$24.9 \pm 0.3$	$41.7 \pm 0.9$	$30.1 \pm 1.5$
$a_1$ (nb/sr)	$11.6 \pm 0.4$	$43.4 \pm 1.8$	$57.0 \pm 3.2$
$a_2$ (nb/sr)	$2.8 \pm 0.8$	$-36.7 \pm 4.6$	$11.5 \pm 7.4$
$a_3$ (nb/sr)	–	$-18.6 \pm 2.2$	$-31.7 \pm 4.5$
$a_4$ (nb/sr)	–	$22.6 \pm 4.5$	$-15.7 \pm 8.0$
$\sigma_{\text{tot}}$ (nb)	$326.7 \pm 2.0$	$428.8 \pm 3.4$	$388.1 \pm 7.2$

affect the discussion of the energy dependence. Our 20 MeV result seems to join on smoothly to the trends set by our low energy data [1] whereas the COSY11 data [2] would imply a stronger energy variation. The rise apparent between 20 and 40 MeV in both our data and those of CELSIUS [5] possibly reflects the increased influence of the higher partial waves that are needed to describe the angular dependence of Fig. 2.

The strong forward/backward asymmetry shown by the data of Fig. 2 arises from the interference between odd and even partial waves and at low energies this can be summarized by a slope parameter, defined by

$$\alpha = \frac{d}{d(\cos \theta_\eta)} \ln \left( \frac{d\sigma}{d\Omega} \right) \Big|_{\cos \theta_\eta=0}. \quad (2)$$

The values of  $\alpha$  deduced at 19.5 MeV and from our previous measurements are shown in Fig. 4. The results presented in

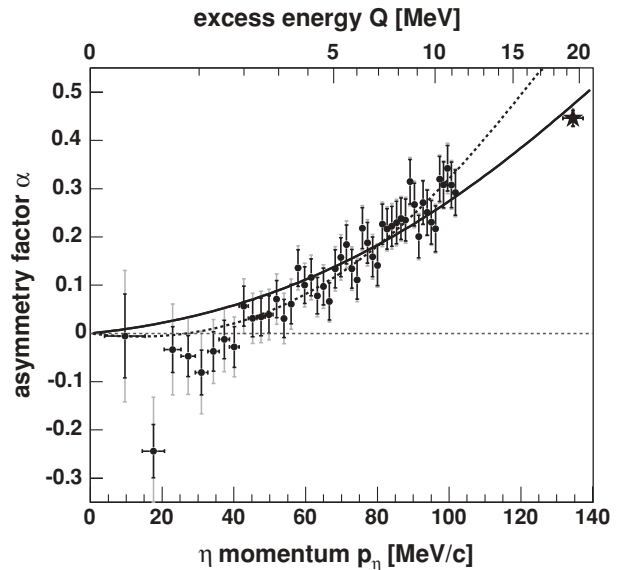


FIG. 4. Slope parameter  $\alpha$  of Eq. (2) as a function of the  $\eta$  c.m. momentum. Bin widths and statistical errors are shown bold; systematic uncertainties are shown with faint lines. The solid and dashed lines show the result of the recursive fit to the data with and without considering the new data point at 19.5 MeV.

Ref. [2] show a very similar behavior, as do those of Ref. [10], though with much lower precision.

Because the 19.5 MeV differential cross section can be fit by a quadratic in  $\cos \theta_\eta$ , these data might be described in terms of  $s$ - and  $p$ -wave production amplitudes. It is therefore of interest to try to include these values together with our near-threshold measurements of the reaction [1] in a global energy-dependent fit to see if the  $s + p$  hypothesis holds up to this energy.

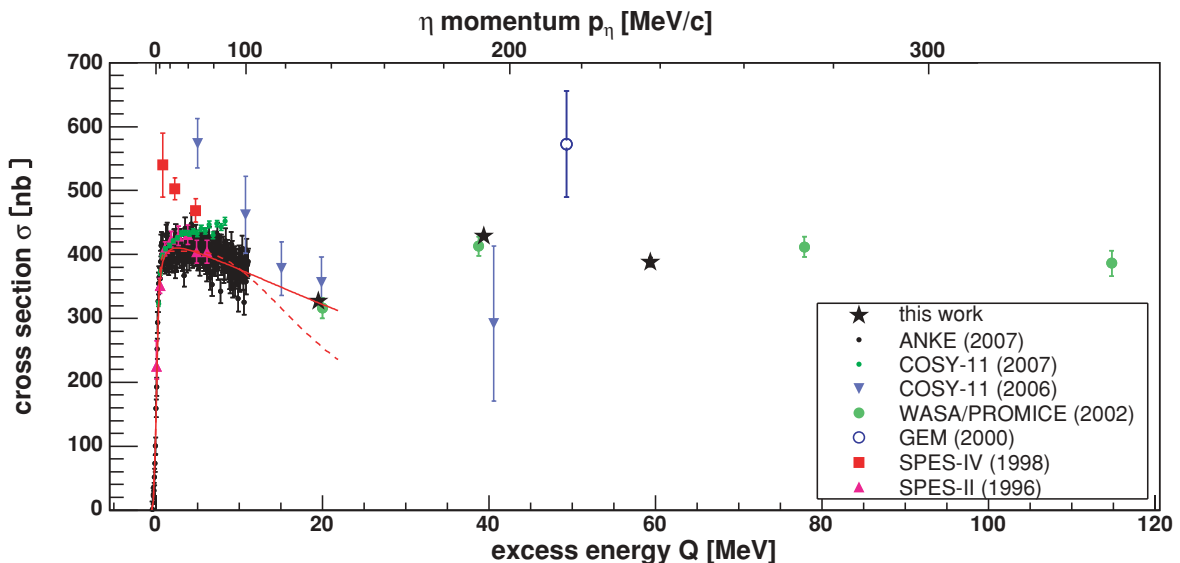


FIG. 3. (Color online) Total cross section for the  $dp \rightarrow {}^3\text{He}\eta$  reaction. The results from this experiment (black stars) have an additional overall 15% systematic uncertainty that is largely common with our previous data [1] (small black circles). Also shown are data from Ref. [2] (small green circles), Ref. [5] (large green circles), Ref. [9] (large red squares), Ref. [10] (magenta triangles), Ref. [11] (open blue circle), and Ref. [12] (inverted blue triangles). The solid and dashed lines show the result of the recursive fit to the data with and without considering the 19.5 MeV point.

As pointed out in Ref. [4], due to the spin complexity, there are two independent  $s$ -wave production amplitudes and five  $p$ -wave terms. The FSI should affect the two  $s$ -wave terms in similar ways and some support for this is to be found in the weak energy dependence of the deuteron tensor analyzing powers of the reaction [9]. The ansatz of Ref. [4] therefore assumes average  $s$ - and  $p$ -wave amplitudes,  $f_s$  and  $p_\eta f_p$ , in terms of which the total cross section and slope parameter are expressed as

$$\sigma_{\text{tot}} = 4\pi \frac{p_\eta}{p_p} [|f_s|^2 + p_\eta^2 |f_p|^2] \quad (3)$$

$$\alpha = 2p_\eta \frac{\text{Re}(f_s^* f_p)}{|f_s|^2 + p_\eta^2 |f_p|^2}, \quad (4)$$

where  $p_p$  is the initial proton c.m. momentum.

The rapid rise in the total cross section from threshold is due to the pole in the  $s$ -wave amplitude  $f_s$  and this is also responsible for the nonlinear behavior of the slope parameter  $\alpha$  with the  $\eta$  c.m. momentum shown in Fig. 4. This comes about because of the variation of the phase of the interference  $\text{Re}(f_s^* f_p)$  with  $p_\eta$  in Eq. (4).

The  $s$ -wave amplitude was taken as the product of a near and distant pole,

$$f_s = \frac{f_B}{(1 - p_\eta/p_1)(1 - p_\eta/p_2)}, \quad (5)$$

where the distant one is an effective pole that absorbs any residual momentum dependence so that  $f_B$  is taken as constant [1], as is the reduced  $p$ -wave amplitude  $f_p$ . This ansatz has to be smeared over the spread in the initial deuteron beam momentum inside COSY [1]. Fitting the resulting formulas to the total cross section and asymmetry data leads to the dashed curves in Figs. 3 and 4 if the 19.5 MeV point is not included in the fit [1]. Including this point leads to the solid curves, which gives a much poorer description of the asymmetry at low  $p_\eta$ , though the differences are much harder to see for the total cross section in the near-threshold region.

Despite the poorer overall description of the low energy data, the position of the nearby pole in the complex energy plane is only changed from  $|Q| \approx 0.4$  MeV to  $|Q| \approx 0.9$  MeV through the inclusion of the 19.5 MeV point. This shows that the position of the  $\eta^3\text{He}$  pole is robustly fixed in magnitude, though the data cannot determine whether it is a quasibound or virtual state. The data also indicate that the  $s$ -wave amplitude continues to decrease with energy until at least 19.5 MeV with the  $p$ -waves becoming steadily more important. However, the higher  $\chi^2/\text{ndf}$  obtained when including the 19.5 MeV point (1.61 versus 1.42) and the systematically poorer description of the asymmetry data in Fig. 4 suggest that the modeling in terms of only spin-averaged  $s$ - and  $p$ -wave amplitudes is insufficient at this energy.

In summary, we have extended the measurements of the  $dp \rightarrow {}^3\text{He}\eta$  differential and total cross sections to higher excess energies. Although the angular distribution at 19.5 MeV might be described in terms of just  $s$  and  $p$  waves, a global fit of the data using the methodology of Ref. [4] gives unsatisfactory results and this suggests that higher partial waves are probably already significant at this energy. The negative value of the  $a_4$  parameter in Table I is a sign that at least  $f$  waves are important at 59.4 MeV. On the other hand, even if the fit is forced to describe a data set that includes the 19.5 MeV point, the position of the  $\eta^3\text{He}$  pole hardly moves.

The analysis of Ref. [4] assumed that the energy dependence of the two  $s$  waves was identical. This can only be tested through precise measurements of the deuteron tensor analyzing powers of the reaction in finer energy steps than are currently available [9]. Data on this observable will be provided by the COSY-ANKE Collaboration [13].

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- [1] T. Mersmann *et al.*, Phys. Rev. Lett. **98**, 242301 (2007).  
 [2] J. Smyrski *et al.*, Phys. Lett. **B649**, 258 (2007).  
 [3] C. Wilkin, Phys. Rev. C **47**, R938 (1993).  
 [4] C. Wilkin *et al.*, Phys. Lett. **B654**, 92 (2007).  
 [5] R. Bilger *et al.*, Phys. Rev. C **65**, 044608 (2002).  
 [6] S. Barsov *et al.*, Nucl. Instrum. Methods A **462**, 364 (2001).  
 [7] A. Khoukaz *et al.*, Eur. Phys. J. D **5**(2), 275 (1999).  
 [8] F. Irom, G. J. Igo, J. B. McClelland, C. A. Whitten, and M. Bleszynski, Phys. Rev. C **28**, 2380 (1983); G. W. Bennett

- et al.*, Phys. Rev. Lett. **19**, 387 (1967); N. Katayama *et al.*, Nucl. Phys. **A438**, 685 (1985).  
 [9] J. Berger *et al.*, Phys. Rev. Lett. **61**, 919 (1988).  
 [10] B. Mayer *et al.*, Phys. Rev. C **53**, 2068 (1996).  
 [11] M. Betigeri *et al.*, Phys. Lett. **B472**, 267 (2000).  
 [12] H.-H. Adam *et al.*, Phys. Rev. C **75**, 014004 (2007).  
 [13] T. Rausmann and A. Khoukaz, COSY Proposal 157 (2006), [www.fz-juelich.de/ikp/anke/en/proposals.shtml](http://www.fz-juelich.de/ikp/anke/en/proposals.shtml).