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Precision Study of the η^3He System Using the $dp \to {}^3\mathrm{He}\eta$ Reaction

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The differential and total cross sections for the $dp \to {}^3\mathrm{He}\eta$ reaction have been measured in a high precision high statistics COSY-ANKE experiment near threshold using a continuous beam energy ramp up to an excess energy Q of 11.3 MeV with essentially 100% acceptance. The kinematics allowed the mean value of Q to be determined to about 9 keV. Evidence is found for the effects of higher partial waves for $Q \gtrsim 4$ MeV. The very rapid rise of the total cross section to its maximum value within 0.5 MeV of threshold implies a very large η^3He scattering length and hence the presence of a quasibound state extremely close to threshold.

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The low energy η^3He system has been investigated in both the $dp(pd) \to {}^3\mathrm{He}\eta$ reactions [1,2] as well as in photoproduction [3]. The anomalous energy dependence found there suggests that the strong η^3He final state interaction (fsi) might lead to the formation of a new state of matter in the form of an η^3He quasibound state [4] for nuclei much lighter than originally postulated [5]. This question is far from being settled and further high quality data are required to inform the debate.

The SPESII measurements [2] show that the absolute square of the production amplitude $|f|^2$ falls by a factor of 3 between threshold and an excess energy $Q = \sqrt{s} - m_\eta - m_{^3\mathrm{He}}$ of about 6 MeV and the conclusion drawn was that the η^3He scattering length a is very large. However, in order to distinguish between the effects of the real and imaginary parts of a, one needs data with a good knowledge of the absolute value of Q and with a very small energy spread. These conditions are hard to meet in the interesting near-threshold region when using a liquid hydrogen target and an extracted proton beam because of the energy losses in the target. On the other hand, they can be overcome by using a thin windowless gas target placed inside a storage ring, and we have taken advantage of these features in a measurement of the $dp \to {}^3\mathrm{He}\eta$ reaction near threshold.

The experiment was performed with a hydrogen cluster-jet target [6] using the ANKE spectrometer [7] placed at an internal station of the COoler SYnchrotron COSY-Jülich. During each of the beam cycles of 277 s, the deuteron beam energy was ramped slowly and linearly in time, from an excess energy of $Q = -5.05$ MeV to $Q = +11.33$ MeV. The ^{3}He produced were detected in the ANKE forward detection system, which consists of two multiwire proportional chambers, one drift chamber, and three layers of scintillation hodoscopes. The geometrical acceptance for the ^{3}He of interest was ~100%, so that systematic uncertainties from acceptance corrections are negligible. The tracks of charged particles could be traced back through the precisely known magnetic field to the known interaction point, leading to a momentum reconstruction for registered particles. The luminosity required to determine cross sections was found by simultaneously measuring dp elastic scattering, with the scattered deuterons being registered in the forward detector and the proton reconstructed from the missing mass. Data in this region show that $d\sigma/dt$ changes little with beam energy, though the dependence on the four-momentum transfer in our available range of $0.08 < |t| < 0.20$ $(\mathrm{GeV}/c)^2$ is very strong [8]. The systematic uncertainty in the measurement of the deuteron angle thus dominates the error of about ±15% in the luminosity determination. However, the relative luminosity over the ramp is known much better and its effects are included in the point-by-point errors.

The ^{3}He were selected by the $\Delta E/E$ method, with the η meson being subsequently identified through a peak in the missing-mass distribution [9]. The distribution for the

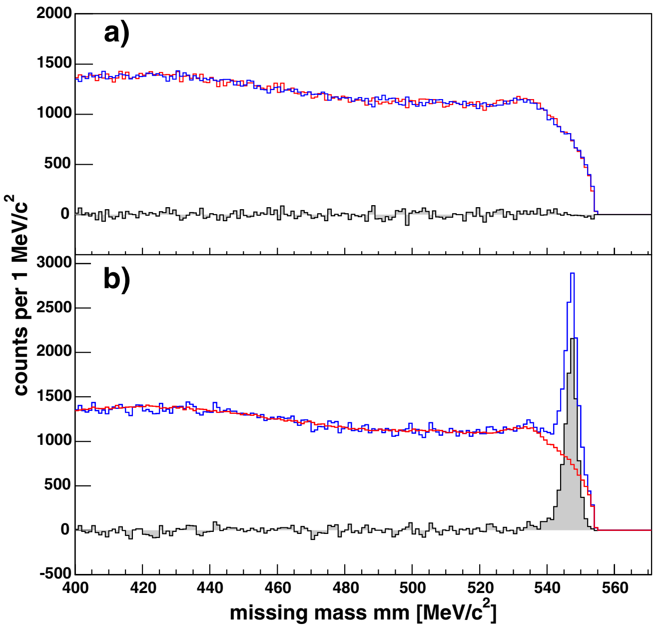

FIG. 1 (color online). Missing-mass distributions of detected ^{3}He nuclei. (a) Measurements at the subthreshold energies of $Q = -(4.75 \pm 0.30)$ MeV and $Q = -(0.60 \pm 0.30)$ MeV were analyzed as if they were both taken at $Q = +6.95$ MeV. After correcting for luminosity, the two distributions look identical and the difference shown is consistent with zero. (b) The $Q = 6.95$ MeV distribution is compared with the background description derived from all the subthreshold data which is smooth in the η region. The only nonzero signal in the difference spectrum is the very clean η peak (shaded) with $\sigma_{\mathrm{mm}} = 2.0$ MeV$/c^2$.

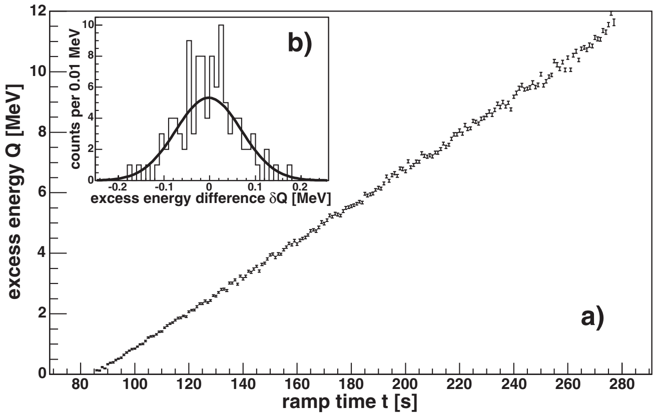

FIG. 2. (a) Reconstructed excess energy Q as a function of the timing information of the linearly ramped beam. (b) Distribution of the deviations from a linear fit to the time dependence for different bins in excess energy compared to a Gaussian curve of width 72 keV.

interval $Q = 6.95 \pm 0.12$ MeV is presented in Fig. 1(b). In order to extract the total number of η events, the background below the η peak, originating mainly from multipion production, has to be subtracted. For this purpose, measurements performed below the η threshold were analyzed as if they were made above [9]. The reliability of this approach is made clear in Fig. 1(a), where events obtained at $Q = -(4.75 \pm 0.30)$ MeV and $Q = -(0.60 \pm 0.30)$ MeV were both analyzed assuming a value of $Q = +6.95$ MeV. After correcting for luminosity, the two distributions coincide perfectly and their difference is consistent with zero. This technique is applied above threshold in Fig. 1(b), where the distribution corresponding to all the measurements with $Q < -0.3$ MeV has been subtracted from the $Q = 6.95$ MeV missing-mass spectrum. All that remains in the difference spectrum is an η meson peak with a width of $\sigma_{\mathrm{mm}} = 2.0$ MeV$/c^2$ sitting on a vanishingly small background.

The η c.m. momentum p_η at a particular time during the ramp was found from the size of the ^{3}He momentum locus in the c.m. frame and comparing it with analytic formulas and simulations. It is demonstrated in Fig. 2(a) that the values of $Q = p_\eta^2/2m_{\mathrm{red}}$, where m_{red} is the η^3He reduced mass, follow the expected linear variation of the beam energy with ramp time. The deviations from the linear fit presented in panel 2(b) are consistent with a statistical distribution of width $\sigma_{\delta Q} = 72 \pm 11$ keV. The mean value could therefore be determined to 9 keV and this becomes even more precise as one approaches threshold. Since, due to the uncertainty in the orbit length, the absolute beam momentum is not known to better than about 3 MeV$/c$, this excellent measurement of Q cannot be translated into an accurate value of the η mass.

In order to determine the differential cross section for each excess energy bin, missing-mass distributions were analyzed for different ^{3}He c.m. production angles $\theta_{\mathrm{c.m.}}$ in a similar manner to that shown in Fig. 1. The asymmetry in the angular distribution of Fig. 3(a) implies that there are higher partial wave contributions even in this very near-threshold region. Defining an asymmetry parameter α through $(d\sigma/d\Omega)_{\mathrm{c.m.}} = \sigma_{\mathrm{tot}}(1 + \alpha \cos\theta_{\mathrm{c.m.}})/4\pi$, it is seen from Fig. 3(b) that above an η c.m. momentum p_η of 40 MeV$/c$ ($Q = 1.7$ MeV), α is positive and increases monotonically with p_η but with a magnitude much larger than that found at SPESII [2]. At low momentum, both data sets show a tendency for α to go negative but the systematic uncertainties here are large. The slope of the cross section at $\cos\theta_{\mathrm{c.m.}} = 0$ has the same sign as that found at higher excess energies, though the data there do not remain linear over the whole angular range [10–12].

The $dp \to {}^3\mathrm{He}\eta$ total cross sections obtained at 195 bins in excess energy Q are displayed in Fig. 4. The minimal relative systematic errors resulting from the measurement of the excitation function in a single experiment form a robust data set for any phenomenological analysis. Our data are broadly compatible with those of SPESII [2] and any global difference is within our overall normalization uncertainty. However, in contrast to our data presented in Fig. 4(b), the SPESII results do not define firmly the

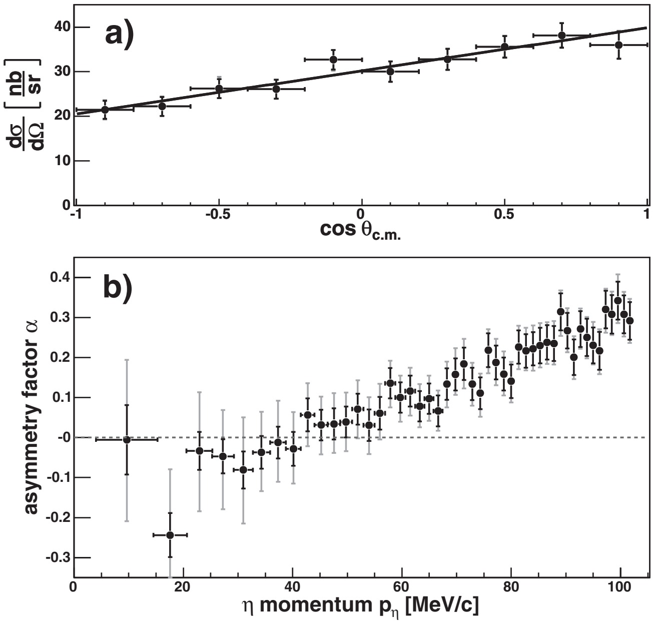

FIG. 3. (a) $dp \rightarrow {}^3\mathrm{He}\eta$ differential cross section at $Q = 10.27 \pm 0.12$ MeV [$p_\eta = 97.0 \pm 0.6$ MeV/c] compared to a linear fit in the cosine of the ^{3}He c.m. angle. (b) Asymmetry parameter α for different values of the η c.m. momentum p_η. The bin widths and point-to-point statistical errors are shown bold; correlated systematic uncertainties are shown with faint lines.

energy dependence in the near-threshold region. The total cross section reaches its maximum within 0.5 MeV of threshold and hardly decreases after that. This behavior is in complete contrast to phase-space expectations and indicates a very strong final state interaction [4].

The angular average of the amplitude squared is derived from the total cross section σ_{tot} through $\overline{|f|^2} = p_d\sigma_{\mathrm{tot}}/4\pi p_\eta$, where p_d is the initial c.m. momentum. We parametrize the s-wave component f_s in the form

$$f_s = \frac{f_B}{(1 - p_\eta/p_1)(1 - p_\eta/p_2)}. \tag{1}$$

In the presence of a strongly attractive final state interaction, there should be a pole of f_s, where $|p_1|$ is very small. The second singularity of Eq. (1) has no direct physical meaning since it represents an attempt to reproduce the rest of the energy dependence, including that residing in the reaction mechanism f_B, in terms of a simple pole. In the scattering-length fit of SPESII [2], $p_2 = \infty$ and $p_1 = -i/a$.

The shape of the η production below the nominal threshold shown in Fig. 4 is a very sensitive measure of the momentum width of the COSY beam, and this resolution has to be taken into account in any phenomenological analysis. The excitation function $\sigma_{\mathrm{exp}}(Q)$ visible in the experiment is the convolution of the true one $\sigma_{\mathrm{true}}(Q)$ with a smearing function $w_g(Q)$, taken to be Gaussian, which is then grouped in finite bins of $Q \pm \Delta Q/2$:

$$\sigma_{\mathrm{exp}}(Q) = \frac{1}{\Delta Q}\int_{Q-\Delta Q/2}^{Q+\Delta Q/2} dQ_1 \int_{-\infty}^{+\infty} dQ_2 w_g(Q_1, Q_2) \times \sigma_{\mathrm{true}}(Q_2), \tag{2}$$

where the luminosity is assumed constant over each bin of a typical $\Delta Q = 0.06$ MeV width. Fits to the data show that the resolution in Q is $\sigma_Q = 171 \pm 15$ keV. If this arises purely from the momentum spread of the beam it would correspond to $(\delta p/p)_{\mathrm{beam}} \approx 2.2 \times 10^{-4}$. The effect of the smearing in Q is illustrated in Fig. 4(b), where the unsmeared parametrization, σ_{true}, is shown by the dotted curve.

The gray line in Fig. 4(a) shows the published single-pole fit of Eq. (1) to the SPESII results [2] without smearing over the effective beam energy. Although this parametrizes these data very well, it underestimates the rapid rise from threshold in our more extensive data set. In fact, any fit of Eq. (1), smeared according to Eq. (2), to the present data that neglects p_2, fails to satisfy simultaneously the data in the proximity of threshold ($Q \leq 1$ MeV) and at the higher energies ($Q \geq 3$ MeV). This effect becomes visible here for the first time because of the quality and extent of the data.

The retention of the p_2 term in Eq. (1) results in the significantly better description of the whole data set shown by the solid line in Fig. 4(a). The higher Q data might be contaminated by non-s-wave contributions. Their presence is obvious from the angular distributions of Fig. 3, but an unambiguous isolation requires experiments with a polarized deuteron beam [13]. However, these have only a small effect on the value extracted for p_1 though they would influence the position of the effective pole p_2.

The fit for $Q \leq 11$ MeV shown in Fig. 4(a) gave

$$\begin{aligned} p_1 &= [(-5 \pm 7^{+2}_{-1}) \pm i(19 \pm 2 \pm 1)]\ \mathrm{MeV}/c, \\ p_2 &= [(106 \pm 5) \pm i(76 \pm 13^{+1}_{-2})]\ \mathrm{MeV}/c, \end{aligned} \tag{3}$$

with the resulting scattering length of

$$\begin{aligned} a &= -i(p_1 + p_2)/p_1 p_2 \\ &= [\pm(10.7 \pm 0.8^{+0.1}_{-0.5}) + i(1.5 \pm 2.6^{+1.0}_{-0.9})]\ \mathrm{fm}, \end{aligned} \tag{4}$$

where the first errors are statistical and the second (where given) systematic, including effects associated with the fitting range assumed. Note that the signs of Im$\{p_i\}$ and Re$\{a\}$ are not fixed by the data.

The results show that a is dominantly real with large errors on the imaginary part, though unitarity requires Im$\{a\} \geq 0$. The value of $|a|$ is much larger than that found in earlier work [2,12] or in the later COSY-11 experiment [14]. This is due, in part, to the treatment of energy-smearing effects, whose need is very evident in our data with the fine energy steps near threshold.

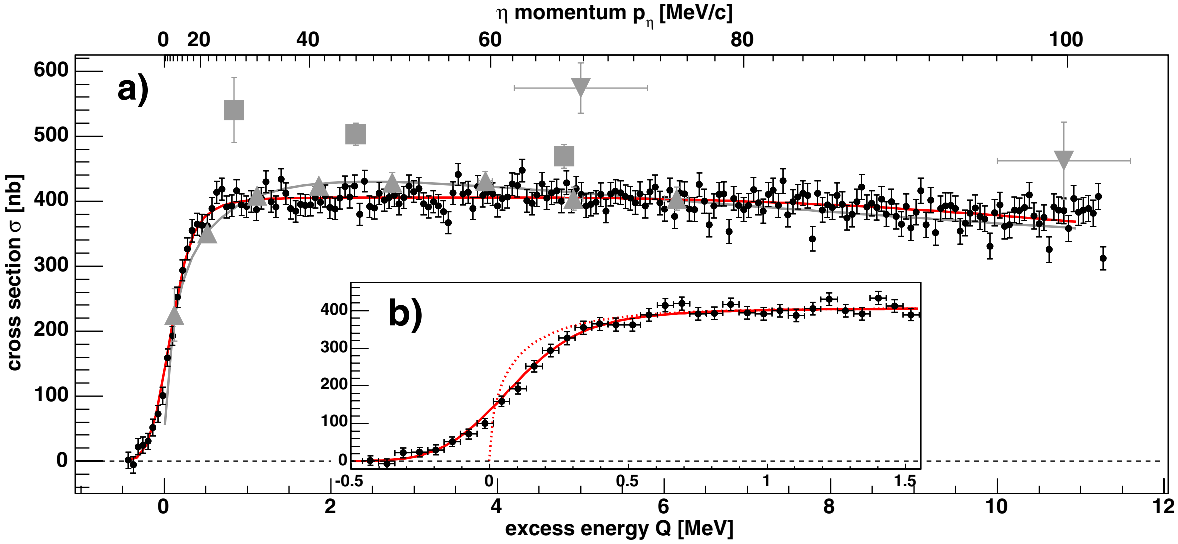

FIG. 4 (color online). Comparison of the extracted total cross sections (circles) with previous data drawn in gray: Ref. [1] (squares), Ref. [2] (triangles), and Ref. [12] (inverted triangles). Equation (1) with the parameters given in Eqs. (3) and (4) represents well all our results. The gray curve is the SPESII fit to their own data [2]. Our near-threshold data and fitted curve are shown in the inset, while the dotted curve is the result to be expected without the 171 keV smearing in Q.

In order to affect the cross section variation over a scale of less than 1 MeV, there must be a pole of the production amplitude in the complex plane that is typically only 1 MeV away from $Q = 0$. From our fit values we find a stable pole at $Q_0 = p_1^2/2m_{\rm red} = [(-0.30 \pm 0.15 \pm 0.04) \pm i(0.21 \pm 0.29 \pm 0.06)]$ MeV.

In summary, we have performed measurements of the differential and total cross sections for the $dp \rightarrow {}^3\mathrm{He}\eta$ reaction near threshold where the spectrometer acceptance is close to 100%. The use of a beam whose energy varies linearly with time ensured that point-to-point systematic errors were under control. It also allowed us to determine the mean value of the excess energy with unparalleled accuracy. It was shown that the large physics background could be eliminated essentially completely through the subtraction of data taken below threshold. Although there is a 15% uncertainty in the luminosity, and hence in the values of the cross sections, this is a global feature that affects all our data in the same way and so will not change any of our principal conclusions.

It is remarkable that already for $Q \gtrsim 4$ MeV the angular distributions are no longer isotropic and this must be an important clue to the dynamics. Effects of p waves might become clearer when data are available on the angular dependence of the deuteron analyzing powers [13].

The consistent set of total cross section measurements with high statistics at closely spaced values of Q should allow theoretical models to be tested in a rigorous manner. The very rapid rise and leveling-off indicates the existence of a pole in the production amplitude within 1 MeV of $Q = 0$. Fits on the basis of Eq. (1) suggest that the scattering length has an enormous real part that largely masks any effects arising from the imaginary part. The steep variation of $\overline{|f|}^2$ with p_η may bring the results closer to those of photoproduction of the η^3He state [3].

Our experiment was only possible because of the high quality of the ramped deuteron beam and for this we are indebted to the COSY accelerator crew. We would also like to thank Ch. Hanhart for many valuable discussions. The support from FFE grants of the Jülich Research Center is gratefully acknowledged.

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