Measurement of the quasi-free p+n→d+η reaction near threshold.

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Abstract

The quasi-free p+n→d+η reaction cross section has been measured in the near-threshold region using deuterium from an internal cluster-jet target and 1350 MeV protons in the CELSIUS storage ring. The energy dependence of the cross section is extracted by reconstructing the kinematics on an event-by-event basis and exploiting the Fermi momentum of the target neutron. The data cover centre of mass excess energies from 16 MeV to 113 MeV and show for the first time clearly the influence of the N*(1535) S_{11} resonance for η production in nucleon-nucleon collisions.

As more data are steadily becoming available on η-meson production near the kinematical threshold, the interest in η-meson physics has increased considerably. In particular, attention has been given to the relatively strong and attractive S-wave η-nucleon interaction. The near-threshold region is appropriate for S-wave interaction studies since the final state involves primarily the lowest partial wave. Both the production mechanism and the η-N final state interaction are expected to be dominated by the presence of the $N^*(1535)$ S_{11} resonance.

The strength of the η-N interaction has lead to speculations on the existence of quasi-bound η-nuclear states already in the two-nucleon system [1-3]. Such a quasi-bound state would show up as an enhancement in the meson production amplitude in nucleon-nucleon collisions at threshold.

Precise η cross section data for nucleon-nucleon collisions are available only for the proton-proton reaction channel. It is therefore of interest to get complementary data from the neutron-proton channel. Such data will contribute to the understanding of the h production process, its isospin and spin dependence and the importance of different meson exchanges. Available data for the neutron-proton channel are as yet very limited. Cross sections have been unfolded either from data obtained using the upper energy tail of a neutron beam [4] or from inclusive measurements using a proton beam on a deuterium target [5]. It is evident from these data, however, that the cross section for η production is significantly higher in p+n than in p+p collisions. In this paper we present the first measurement of the cross section for the quasi-free $p+n\to d+\eta$ reaction using a deuterium target. The energy dependence is obtained by utilising the Fermi momentum of the neutron by kinematical reconstruction.

The experiment was carried out at the CELSIUS storage ring of the The Svedberg Laboratory, Uppsala, using the WASA/PROMICE detector set-up [6]. A circulating proton beam with a kinetic energy of $T_p = 1350$ MeV was brought to interact with an internal deuterium cluster-jet target. The integrated luminosity in the experiment was approximately 100 nb^{-1}. Forward-going charged particles are measured in a detector system covering scattering angles between 4^0 and 22^0 with essentially full coverage of the azimuthal angles. This system consists of a tracking detector made from straw chambers, followed by a three-layer scintillator hodoscope and a four-layer calorimeter made from 11 cm thick scintillators. Another scintillator hodoscope is placed at the end of the detector system to register penetrating particles.

An η meson is identified by its 2γ decay (B.R. 38.8 %) recorded in two arrays of CsI(Na) detectors placed at each side of the beam pipe. Each array is made of 56 tapered elements and covers polar angles between approximately 30^0 and 90^0 and azimuthal angles between $\pm 25^0$. Scintillator hodoscopes are placed in front of the arrays to veto charged particles. The 2γ invariant mass resolution obtained at the η-meson mass is 20 MeV (σ). More details about the detector

set-up and its performance can be found in Ref. [6].
There are several reactions that contribute to η production in p+d collisions at the incident proton energy of 1350 MeV:

$$\mathrm{p + d \rightarrow p + p + n_s} + \eta \quad (1)$$

$$\rightarrow \mathrm{p + n + p_s} + \eta \quad (2)$$

$$\rightarrow \mathrm{d + p_s} + \eta \quad (3)$$

$$\rightarrow \mathrm{p + d} + \eta \quad (4)$$

$$\rightarrow {}^3\mathrm{He} + \eta \quad (5)$$

where the s subscript denotes a slow spectator nucleon for the dominant quasi-free reactions. The cross sections for reactions (4) and (5) are small in comparison with reactions (1-3) and can safely be neglected in the analysis at the present level of precision.
Measuring the ηs as well as the other residual particles makes it possible to identify the reactions (1-3) and to measure their cross sections. The Fermi motion of the target nucleon affects the centre of mass (CM) energy of the beam proton and the target nucleon on an event-by-event basis. Thus the CM energy can be extracted for each η event with a topology consistent with one of the reactions (1-3). This allows the energy dependence of the quasi-free p+n cross section to be measured using a fixed beam energy. The selection of η events is made using the information from the CsI(Na) detectors and the reaction channel apportioning is made using the additional information from the forward detectors.
The quasi-free two-body final state, d+η, is separated by kinematic constraints. A kinematical fit (1C) is applied to reconstruct the η energy-momentum 4-vector from the measured directions and energies of its two decay γ's. This information together with the p+n$\rightarrow$d+η two-body kinematics (neglecting the Fermi momentum of target neutron) makes it possible to predict the deuteron emission angle. In Fig. 1a, the differences between the predicted deuteron angle and the measured forward track angle, in spherical co-ordinates are shown. A strong signal from the two-body d+η process is seen in the region where the difference in polar and azimuthal angles is small. The points lying outside this region are compatible with what is expected from the 3-body (pNη) final states. This interpretation is further corroborated by Fig. 1b showing the distance between calculated and measured impact points at the tracker position 90 cm downstream of the target. The data are shown together with distributions from a full Monte Carlo simulation using GEANT3 [7] including the target nucleon Fermi momentum as given by the Paris potential [8].

The dashed and dotted lines correspond to the d+η and the p+N+η reactions respectively and the solid line to the sum of the two reactions. Phase space distributions are used together with the known p+p+η excitation function. The shape of the distribution is well described by these Monte Carlo data.
Events in the d+η region at distances smaller than 5 cm are selected for further analysis. Fig. 2 shows the distributions of the invariant 2γ mass for the selected events and for all events. A clean η peak is seen for the selected events and the region of invariant masses used in the final analysis is indicated. Simulations show that, in this region, the contribution from the p+n+η channel is about 10% whereas the contribution from the p+p+η channel, where one proton escapes undetected in the beam pipe, is negligible (<1%). The background from events with two uncorrelated γ's is 3%.

Knowing the direction of the deuteron together with the energy and direction of the η meson makes it possible to derive the Fermi momentum of the struck target neutron. It is then straightforward to calculate the CM excess energy ($Q_{CM} = \sqrt{s} - (m_d + m_\eta)$), on an event-by-event basis, assuming the spectator proton to be on its mass shell [9]. Simulations show that Q_{CM} can be reconstructed to a precision of 5 MeV (σ) in this way. As a check, a similar procedure has been used on data for the reaction p+p→p+p+η using a H_2 target at the same proton energy with consistent results.
Extensive simulations have been carried out taking into account the geometry and reponse of the detector setup. The normalisation was then established using quasi-elastic p+p scattering data taken in parallel, assuming the quasi-elastic cross section to be equal to the free one [10]. It is assumed that shadowing effects are channel independent when relating the quasi-free elastic and production processes. Any uncertainties are well within the quoted systematic error below. As a cross check of the normalisation procedure, the quasi-free reaction p+p→p+p+η was analysed using events with two charged forward-going tracks. In Fig. 3 the quasi-free and the free reactions [11 - 13] are compared. The agreement is very satisfactory, giving additional confidence in the method used. Fig. 3 also shows the energy dependence of the quasi-free p+n→d+η cross section for Q_{CM} values between 16 MeV and 113 MeV. Only statistical errors are shown. In addition there is an overall uncertainty of 23% in the absolute normalisation. As can be seen the p+n→d+η cross section is substantially larger than the p+p→p+p+η cross section. Numerical values of the cross sections are given in Table 1.
Fig. 4 shows our measured cross section for the quasi-free p+n→d+η reaction on a linear scale. The cross section increases from about 40 μb up to 90 μb at Q_{CM} around 60 MeV. The shape essentially follows phase space in this region (dashed curve) whereas for higher Q_{CM} values data start to deviate substantially from phase space. Also superimposed is a dotted curve which includes in addition to phase space, a Breit-Wigner shape for the $N^*(1535)$ resonance

in the η-N system [14]. The parameters of the resonance were obtained from electro- and photoproduction data near threshold as described in Ref. [15]. The shape of the experimental cross section is well reproduced also for Q_{CM} > 60 MeV where the suppression is governed by the tail of the $N^*(1535)$ resonance. This shows explicitly for the first time the importance of this resonance in nucleon-induced η production.

Fig. 4 also shows the Q_{CM} parameterisation of the p+n$\rightarrow$d+η cross section used in Ref. [4]. It is valid for values of Q_{CM} below our measured range and gives a sharp peak with a substantially larger cross section compared to an extrapolation of our measured values. It would be interesting to have more data in the region below $Q_{CM} < 15$ MeV to see whether or not the cross section increases very close to threshold as suggested by these data. If confirmed, this increase would be an evidence for a bound system between an η and two nucleons.

In conclusion we report on the first measurement of the energy dependence of the quasi-free p+n$\rightarrow$d+η reaction near threshold. This was made possible by analysing η production from quasi-free p+n interactions using a D_2 target and exploiting the Fermi momentum of the target neutron. The shape of the energy dependence is reproduced by a calculation taking into account phase space and the $N^*(1535)$ resonance, showing for the first time explicitly the importance of this S_{11} resonance for nucleon induced reactions. The data presented will constrain existing models [1,15 - 17] and provide new input to theoretical efforts in this field.

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References

[1] T. Ueda, Phys. Rev. Lett. **66** 297 (1991).

[2] S.A. Rakityansky *et al.,* Phys. Rev. C **53** 2043 (1996).

[3] A.M. Green, J.A. Niskanen and S. Wycech. Phys. Lett. **394B** 253 (1966).

[4] F. Plouin, P. Fleury and C. Wilkin, Phys. Rev. Lett. **65** 690 (1990).

[5] E. Chiavassa *et al.*, Phys. Lett. **337B** 192 (1994).

[6] H. Calén *et al.*, Nucl. Instr. Meth. **A379** 57 (1996).

[7] R. Brun *et al.*, GEANT3, CERN Report DD/EE/84-1 (1987).

[8] M. Lacombe *et al.*, Phys. Lett. **101B** 139 (1981).

[9] P. Benz *et al.*, Nucl. Phys. **B65** 158 (1973).

[10] R. A. Arndt, I. I. Strakovskii and R. L. Workman, Phys. Rev. C **50** 2731 (1994).

[11] A.M. Bergdolt *et al.*, Phys. Rev. D **48** 2969 (1993).

[12] E. Chiavassa *et al.*, Phys. Lett. **322B** 270 (1994).

[13] H. Calén *et al.*, Phys. Lett. **366B** 39 (1996).

[14] G. Fäldt and C. Wilkin, Private communication.

[15] G. Fäldt and C. Wilkin, Nucl. Phys. **A587** 769 (1995).

[16] J.M. Laget, F. Wellers and J.F. Lecolley, Phys. Lett. **257B** 254 (1991).

[17] A. Moalem *et al.*, Nucl. Phys. **A600** 445 (1996).

[18] S. Häggström, Ph.D. thesis, Uppsala University, Acta Universitatis Upsaliensis 13, 1997.

Table 1. Total cross sections for the quasi-free reaction p+n→d+η. The errors are statistical and systematical respectively. The energy intervals correspond to the binning and the asymmetry is due to the weighting from the deuteron wave function.

CM excess energy [MeV]	**Equivalent beam energy** [MeV]	σ_{tot} [μb]
16^{+4}_{-6}	1289^{+11}_{-16}	$39 \pm 4 \pm 4$
26^{+4}_{-6}	1315^{+11}_{-15}	$56 \pm 3 \pm 3$
36^{+4}_{-6}	1341^{+11}_{-15}	$64 \pm 3 \pm 2$
47^{+3}_{-7}	1370^{+11}_{-18}	$77 \pm 3 \pm 2$
56^{+4}_{-6}	1394^{+11}_{-16}	$93 \pm 4 \pm 2$
66^{+4}_{-6}	1420^{+11}_{-15}	$94 \pm 5 \pm 2$
76^{+4}_{-6}	1447^{+11}_{-16}	$86 \pm 5 \pm 2$
85^{+5}_{-5}	1471^{+13}_{-13}	$85 \pm 7 \pm 2$
95^{+5}_{-5}	1498^{+13}_{-14}	$85 \pm 9 \pm 3$
103^{+7}_{-3}	1519^{+19}_{-8}	$83 \pm 12 \pm 3$
113^{+7}_{-3}	1546^{+19}_{-8}	$86 \pm 16 \pm 4$

Figure captions

Figure 1.a) Lego plot showing the difference between predicted deuteron track using the measured η and free p+n$\rightarrow$d+η kinematics and measured forward tracks in polar co-ordinates. True two-body events populate the $\Delta\theta = \Delta\phi = 0$ region where a clear signal is seen. The spread is due to the Fermi motion of the target neutron.

b) Distance between the calculated point of impact of a deutron and the measured one for forward particles, at the position of the tracker, 90 cm downstream the target. Superimposed are the results from an analysis using Monte Carlo data from the reactions p+n$\rightarrow$d+η (dashed line), p+N$\rightarrow$p+N+η (dotted line) and the sum of the two (solid line).

Figure 2. Invariant 2γ mass distributions using the information from the two CsI(Na) arrays. The upper histogram corresponds to inclusive events. The lower histogram corresponds to the selected p+n$\rightarrow$d+η candidate events shown in Fig. 1b. The shaded area shows the region of invariant masses selected for the final analysis.

Figure 3. Total cross sections for the quasi-free p+n$\rightarrow$d+η and p+p$\rightarrow$p+p+η reactions (filled symbols) together with previously measured free reaction cross sections (open symbols) [11 - 13].

Figure 4. The measured energy dependence of the quasi-free p+n$\rightarrow$d+η reaction. Also shown is a phase-space curve (dottes line) and curve including from both phase space and a Breit-Wigner shape representing the $N^*(1535)$ [14]. Both curves are arbitrary normalised. Also included is the parameterisation of the cross section from Ref. [4] in the very vicinity of the threshold (solid line).