Threshold Structure of the Quasifree $p + n \rightarrow d + \eta$ Reaction

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The quasifree $p + n \rightarrow d + \eta$ reaction cross section has been measured at the threshold using 1295 MeV protons in the CELSIUS storage ring and an internal cluster-jet deuterium target. The kinematics is chosen such that the target proton can be assumed to be a spectator. The Fermi momentum of the target neutron is used to extract the energy dependence of the cross section by reconstructing the kinematics on an event-by-event basis. The data cover excess energies from threshold to 10 MeV in the center of mass of the final $d\eta$ system. Approaching the threshold the cross section is enhanced compared to what is expected from phase space. This behavior is typical for a strong final-state interaction. [S0031-9007(98)05507-0]

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Over the last few years, the interest in η-meson physics has increased considerably. The strength of the η-N interaction has led to speculations on the existence of a quasibound η-nuclear state even in the two-nucleon system [1–3]. Such a quasibound state would be a new phenomenon and should show up as a threshold enhancement of η-meson production in nucleon-nucleon collisions. A first indication of such an enhancement at threshold came from a Saclay study of the $n + p \rightarrow d + \eta$ reaction [4]. However, in that experiment, only the deuteron was measured and, furthermore, the cross section had to be unfolded from the high-energy tail of a wide band neutron beam. Another indication of an anomalous threshold behavior comes from the comparison between the measurements of the $p + p \rightarrow p + p + \eta$ and the $p + p \rightarrow p + p + \pi^0$ reactions [5].

An exclusive measurement of the quasifree $p + n \rightarrow d + \eta$ reaction has previously been done at the The Svedberg Laboratory, Uppsala, using a deuterium internal cluster-jet target and a 1350 MeV proton beam circulating in the CELSIUS storage ring [6]. The energy dependence of the cross section was measured by utilizing the Fermi momentum of the interacting neutron and assuming that the constituent proton acts as a spectator. The center-of-mass (c.m.) energy of the initial interacting $p + n$ system was calculated by kinematical reconstruction on an

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event-by-event basis. Since deuterons escaping down the accelerator beam pipe could not be detected, the measurements covered c.m. excess energies starting slightly above the Saclay data. The lowest point from the published Uppsala data [6], at 15 MeV above threshold, has a cross section of 40 μb which is significantly below the value of 110 μb deduced a few MeV above threshold in Saclay.

In order to explore the region of very low c.m. excess energies, we modified the WASA/PROMICE detector setup [7], so that deuterons going forward inside the beam pipe could be detected. Charged particles scattered at angles below 1°, and with a magnetic rigidity in the range 0.71–0.91 of the beam momentum, were detected in a telescope placed in the third bending magnet of CELSIUS, 7.6 m downstream of the target region (Fig. 1). This telescope is made of three planes of 2 cm thick plastic scintillators. With this arrangement, deuterons from threshold pn production of η mesons can be extracted from the beam region and measured.

In this paper we present the first exclusive cross section data for the quasifree $p + n \rightarrow d + \eta$ reaction at threshold (0–10 MeV in c.m. excess energies). The proton beam energy was 1295 MeV, the target gas deuterium and the integrated luminosity approximately 100 nb^{-1}. As in the earlier Uppsala studies [6], an η meson is identified by its 2γ decay ($B = 39.25\%$ [8]) recorded in two 7×8 arrays of CsI(Na) crystals placed on either side of the scattering chamber (Fig. 1).

In this energy region, η production in pd collisions is known to be dominated by the two quasifree reaction channels [6]:

$$p + d \rightarrow p + n + p_s + \eta\,, \quad (1)$$

$$p + d \rightarrow d + p_s + \eta\,. \quad (2)$$

The subscript s denotes a slow spectator proton. A possible contribution from the coherent $p + d \rightarrow p + d + \eta$ reaction was investigated and found to be below a few percent [6].

The decay γ's from the η in reaction (2) are selected by means of the hit pattern in the CsI(Na) arrays, and an associated deuteron is identified by means of the signals from the three planes in the downstream scintillator telescope. The 2γ invariant-mass distribution around the η mass for inclusive events is shown by the solid curve in Fig. 2(a). The invariant-mass resolution obtained is 20 MeV/c^2 (rms). The other curves show the distributions for those events with (dashed) and without (dotted) a charged particle in the angular range 4°–20° in the forward detector [7]. Events with hits in the downstream telescope give a clear enhancement at the η mass in the 2γ invariant-mass distribution [Fig. 2(b)].

The downstream telescope allows a separation of deuterons from protons by using the different energy depositions in the three scintillator planes. Figure 3(a) shows the energy deposited in the plane with the smallest deposited energy with two peaks due to protons and deuterons. The same distribution for those events with the 2γ invariant mass in the η region is given in Fig. 3(b) and then only the deuteron peak remains. This shows that $p + n \rightarrow d + \eta$ events are cleanly identified and that the background from reaction (1) is negligible.

Simulations using GEANT3 [9] have been carried out taking into account the geometry and response of the detector setup and including an accurate tracking of the particles in the magnetic field of CELSIUS. The acceptance for the deuteron to hit the downstream telescope is around 10% at threshold. It decreases rapidly with energy and is practically zero for c.m. excess energies above 20 MeV. This variation of the acceptance is well understood and is corrected for.

The events selected for the final analysis are those consistent with the $p + n \rightarrow d + \eta$ two-body reaction kinematics and having a 2γ invariant mass in the range 525–575 MeV/c^2. This sample is assumed to consist of η mesons of known mass, 547.45 MeV/c^2 [8]. Knowing the direction of the deuteron together with the energy and

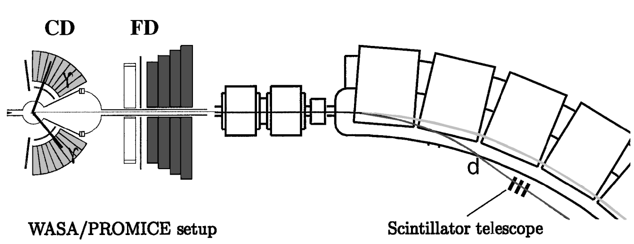

FIG. 1. Layout of the experiment at CELSIUS. To the left is shown the WASA/PROMICE setup at the cluster-jet target [7]. It consists of a central part (CD), used for the detection of η decay γ's and a forward part (FD) for charged particles. The scintillator telescope for detection of zero-degree deuterons is situated outside the beam vacuum chamber at the third of the CELSIUS bending magnets downstream of the target.

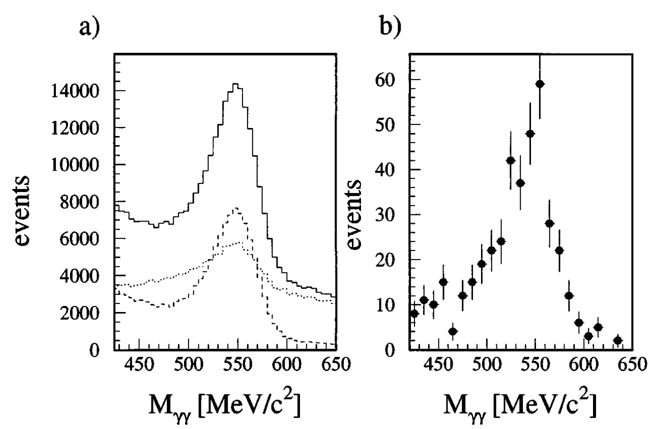

FIG. 2. (a) Invariant 2γ mass distributions using the information from the two CsI(Na) arrays. The upper solid line corresponds to all events. The lower dashed and dotted lines correspond to events with and without a charged particle detected at a scattering angle in the range between 4° and 20°, respectively. (b) Invariant 2γ mass distribution for the events with a signal in the downstream scintillator telescope.

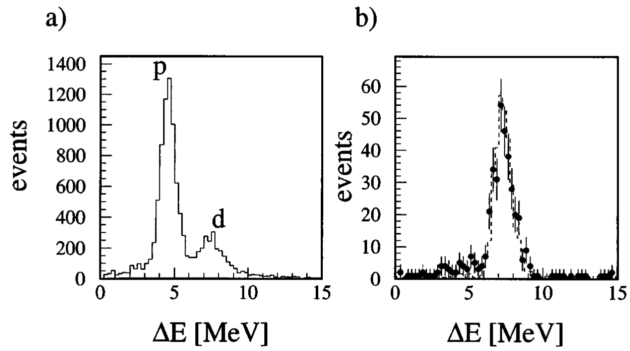

FIG. 3. (a) Energy deposition distribution (ΔE) in that of the downstream telescope planes having the lowest deposition. The plot contains all events with hits in the downstream telescope. The two peaks correspond to the expected energy depositions of protons and deuterons. (b) The ΔE distribution for events where in addition, 2γ having an invariant mass in the η region as shown in Fig. 2(b), are detected in the CsI(Na) arrays. Monte Carlo data for the $p + n \to d + \eta$ events are shown by the dashed histogram.

direction of the η meson makes it possible to derive the Fermi momentum of the struck target neutron within the impulse approximation. It is then straightforward to calculate, on an event-by-event basis, the c.m. excess energy ($Q_{\mathrm{CM}} = \sqrt{s} - (m_d + m_\eta)c^2$, $\sqrt{s}$ being the c.m. energy of the $d\eta$ system), assuming that the spectator proton is on the mass shell. Having selected events that are kinematically consistent with this reaction (an identified deuteron and the two γ's constrained to have an invariant mass equal to the η mass), there is no possibility of events to be reconstructed so as to appear at negative Q_{CM} values. In the presented data, the Fermi momenta are below 100 MeV/c, where quasifree η production should be comparatively clean [6].

There could still be some background, mainly from events with two uncorrelated γ's from $2\pi^0$ production. By cutting on the 2γ invariant-mass distribution, this background is reduced to a level below 5% and is evenly distributed in the measured Q_{CM} range.

Figure 4(a) shows the cross section dependence on Q_{CM} for the quasifree $p + n \to d + \eta$ reaction at threshold together with our earlier result at higher Q_{CM} [6]; numerical values of the cross section are given in Table I. The normalization of our new data is obtained from data simultaneously acquired at higher Q_{CM} [the deuteron measured in the forward detector (FD) in Fig. 1] where the cross section has been determined in the earlier measurement [6]. The overall systematic error, including a 20% uncertainty in the relative normalization, is estimated to be around 30%. The main contributions to the error come from uncertainties in the alignment and in the absolute beam energy ($\approx \pm 3$ MeV). The error from the assumption that the spectator proton is on the shell is less than 10%, a figure obtained from analyzing the kinematics under the assumption that the participating

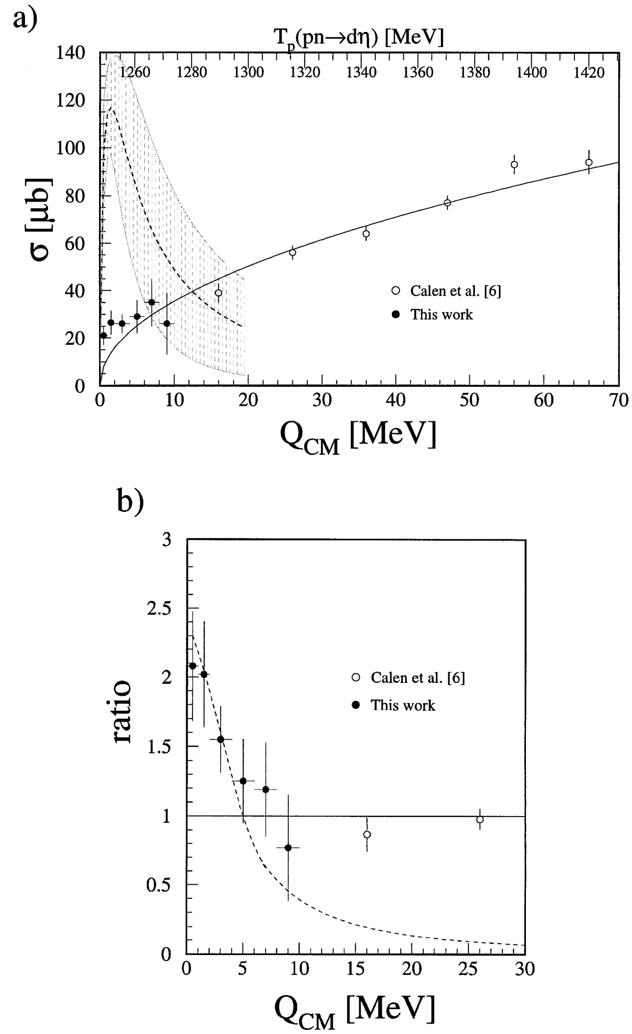

FIG. 4. (a) The measured energy dependence of the cross section for the quasifree $p + n \to d + \eta$ reaction at threshold together with the earlier results at higher c.m. energies from our experiment [6]. The statistical errors are indicated by the vertical bars and the bin width by the horizontal bars. Also shown is an arbitrarily normalized phase-space curve (solid line), and the parametrization of the cross section from Ref. [4] (dashed line). The dashed area corresponds to the quoted errors (1σ) in the parameters. The scale on top gives the corresponding beam energy for a fixed-target experiment. (b) The ratio of the measured cross section and the expectation for a two-body phase-space behavior (shown by the solid line in Fig. 4(a). The dashed curve gives the expectations for a cross section behavior according to the parametrization of Ref. [4] (arbitrarily normalized).

neutron is on the shell. The analysis of our data together with acceptance calculations show that, at threshold, the contribution from coherent $p + d \to p + d + \eta$ events is well below the per mille level. The cross section is fairly constant, about 30 μb, in the whole range from threshold to 10 MeV. The resolution in Q_{CM} is 1 MeV (rms) at threshold and it decreases with increasing Q_{CM}, and at 10 MeV above threshold it is 2 MeV. Therefore, the result implies a rapid increase of the cross section

TABLE I. Total cross section values for the quasifree reaction $p + n \rightarrow d + \eta$. The errors are statistical and systematical, respectively. In addition, there is an uncertainty of 20% in the normalization to the earlier measured higher Q_{CM} data [6]. The energy intervals correspond to the binning.

c.m. Excess energy (MeV)	σ_{tot} (μb)
0–1	$21 \pm 4 \pm 4$
1–2	$26.5 \pm 5 \pm 5$
2–4	$26 \pm 4 \pm 5$
4–6	$29 \pm 7 \pm 6$
6–8	$35 \pm 10 \pm 7$
8–10	$26 \pm 13 \pm 5$

from zero to around 30 μb very close to threshold. Our cross section close to threshold is clearly much below the curve representing the earlier Saclay measurements.

Figure 4(b) shows the ratio of the measured cross section relative to what is expected from phase space. Below $Q_{CM} = 3$ MeV there is a significant deviation from phase space which is typical for a strong final-state interaction and could be consistent with the existence of a quasibound state or a resonance in the ηd system [1–3]. The observed signal agrees in magnitude and shape with predictions of such effects [1] which correspond to ηd scattering lengths of a few fermi.

We note that the same final state has been studied by the coherent photoproduction of η on deuterium, $\gamma + d \rightarrow X + \eta$. However, the $\gamma + d \rightarrow d + \eta$ process is highly suppressed due to its isoscalar nature, and measurements [10,11] are not yet accurate enough to be sensitive to a threshold structure of the predicted magnitude, although interesting fluctuations are observed.

In conclusion, we report on the first exclusive measurement of the energy dependence of the quasifree $p + n \rightarrow d + \eta$ reaction at threshold. This was made possible by analyzing η production from quasifree pn interactions using a deuterium target and exploiting the Fermi momentum of the target neutron at a fixed beam energy, 1295 MeV. The cross section rises to about 30 μb already at 1 MeV above threshold and is constant within errors in the range up to 10 MeV. This is clearly at variance with a pure phase-space behavior and is most likely explained by a strong final-state interaction. Whether this is strong enough to make possible the formation of an $NN\eta$ resonance or a quasibound state remains to be seen.

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