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Measurement of the quasifree $pn \rightarrow pn\eta$ reaction

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The first measurement of the cross section of the quasifree $pn \rightarrow pn\eta$ reaction has been carried out at the CELSIUS storage ring using a deuterium internal cluster jet target. The energy dependence of the cross section is extracted using a fixed incident proton energy of $T_p = 1350$ MeV and exploiting the Fermi momentum of the struck neutron. The data cover a range of center-of-mass excess energies from 16 to 109 MeV. The shape of the excitation function is broadly similar to that of the $pp \rightarrow pp\eta$ reaction, though with a cross section about a factor of 6.5 larger. [S0556-2813(98)02811-8]

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It is generally believed that the production of η mesons in nucleon-nucleon collisions proceeds mainly via the excitation of intermediate nucleon isobars, dominantly the $N^*(1535)$ S_{11}, which subsequently decays into the nucleon-η channel. The importance of this resonance has been demonstrated directly in a measurement of the $pn \rightarrow d\eta$ channel in the threshold region [1]. Theoretical calculations for these processes are generally based on the one-boson-exchange model [2–6] and, although all similar in spirit, they differ significantly in their assumptions of the relative importance of different meson exchanges. Therefore good experimental data from different channels are needed in order to restrict these models. There are two independent $NN \rightarrow NN\eta$ total cross sections, σ_0 and σ_1, where the subscript refers to the total isospin of the two nucleons (0 or 1) in the initial state. The $pp \rightarrow pp\eta$ reaction, which corresponds to a pure σ_1 cross section, has been reasonably well measured in the threshold region [7–9] and it is these data which have provided the primary tests of the calculations. To measure the isospin-zero cross section, and thereby learn more about different meson exchanges, one has to study pn interactions for which data are much more scarce. Inclusive measurements of η production in proton-deuteron scattering clearly show that the production on the neutron is much stronger than on the proton [10], but these data sum together both $pn\eta$ and $d\eta$ final states and average over a wide range of excess energies. We have recently given results on the pure isospin-zero quasifree $pn \rightarrow d\eta$ reaction [1,11] but no measurements have yet been published isolating the $pn \rightarrow pn\eta$ reaction, which would allow the extraction of a pure isospin-zero cross section through $\sigma(pn \rightarrow pn\eta) = (\sigma_1 + \sigma_0)/2$. We make good this deficiency by presenting the

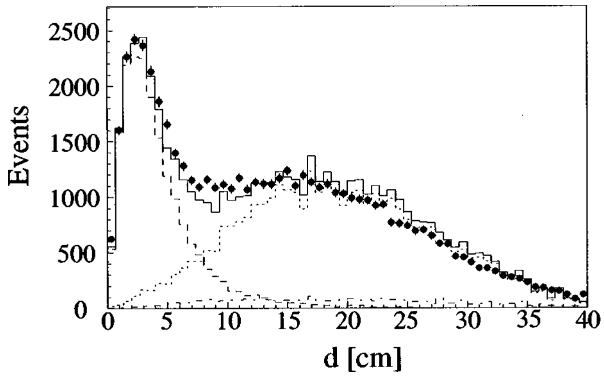

FIG. 1. Distance d between the calculated point of impact of a deuteron and a forward-going track at the position of the tracker 90 cm downstream of the target (solid points). Superimposed are the results from an analysis using Monte Carlo data from the reactions $pn \rightarrow pn\eta$ (dotted line), $pp \rightarrow pp\eta$ (dashed-dotted line), $pn \rightarrow d\eta$ (dashed line), and the sum of the three (solid line).

first determination of the energy dependence of the quasifree $pn \rightarrow pn\eta$ total cross section using a deuterium target. A rather large energy interval in the center-of-mass system could be covered by working at fixed beam energy and identifying and exploiting the neutron Fermi momentum. It should be stressed that, in addition to providing tests of basic models, the pn cross sections are also of great relevance in the modeling of η production in heavy ion collisions where the η has been advanced as a probe of the high-density region [4].

The experiment was carried out using the WASA/PROMICE apparatus at the CELSIUS storage ring at the Svedberg Laboratory, Uppsala, with a beam of protons of energy $T_p = 1350$ MeV incident on an internal deuterium cluster jet target. The integrated luminosity was approximately 100 nb^{-1}. The η's are identified from their 2γ decay channel, where the γ's are detected in two CsI(Na) arrays placed at either side of the scattering chamber. Each array is made of 56 tapered elements and covers polar angles between approximately 30° and 90° and $\pm 25°$ in azimuth. Thin 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 (rms). Forward-going charged particles are measured in a detector system covering polar angles between 4° and 22° with respect to the beam direction. It consists of a tracking detector, made from straw chambers, followed by a three-layer scintillator hodoscope and a four-layer scintillator calorimeter. A second hodoscope is placed at the end of the detector system to register penetrating particles. The angles and energies of the forward-going protons are reconstructed to a precision of better than 1° and 4% [full width at half maximum (FWHM)], respectively. More details about the detector setup and its performance are given in Ref. [12].

The production of η mesons in pd collision at an incident proton energy of 1350 MeV is dominated, in our region of acceptance, by quasifree reaction channels [1,13]. We therefore assign all events, with an η identified from the CsI information, to one of the reactions

$$pd \rightarrow pp\eta + n_s, \tag{1}$$

$$\rightarrow pn\eta + p_s, \tag{2}$$

$$\rightarrow d\eta + p_s, \tag{3}$$

where the subscript s denotes a slow spectator nucleon. This assumption is checked further in the analysis. In a previous paper we reported the extraction of cross sections for the reaction channels (1) and (3) [1]. The quasifree channel (1) was compared with the truly free $pp \rightarrow pp\eta$ reaction measured with a H_2 target and the consistent results found served as an important control of the analysis method employed (see also Fig. 3). Since the scattered proton and deuteron energy losses overlap in the energy region considered, we used the two-body kinematics to separate out channel (3) from the other two. This was achieved by calculating the expected deuteron emission angle from the reconstructed energy-momentum four-vector of the η. The latter is obtained from a kinematical fit (1C) using the measured directions and energies of the two decay γ's. For events with one charged particle detected, the distance between the predicted and measured point of impact in a tracking detector plane placed 90 cm downstream of the target is then calculated. From the results shown in Fig. 1, a strong enhancement is seen at small distances and this is a clear signal for the two-body $pn \rightarrow d\eta$ process. Events with larger distances are found to be dominated by channel (2), which is the one of interest in the present study. In the analysis we classify events with a distance $d < 5$ cm as candidates for the $d\eta$ channel, whereas events with $d > 10$ cm are used in the $pn\eta$ analysis.

The Fermi motion of the target nucleons affects the c.m. energy of the system, consisting of the beam proton and the target nucleon, on an event-by-event basis. Thus the c.m. energy of the final state can be reconstructed for each event with a topology consistent with one of the reactions (1)–(3), provided that enough information is available. The energy and direction of the η meson, together with the direction of the deuteron, or alternatively the direction plus energy of the two protons, make it possible to determine the Fermi

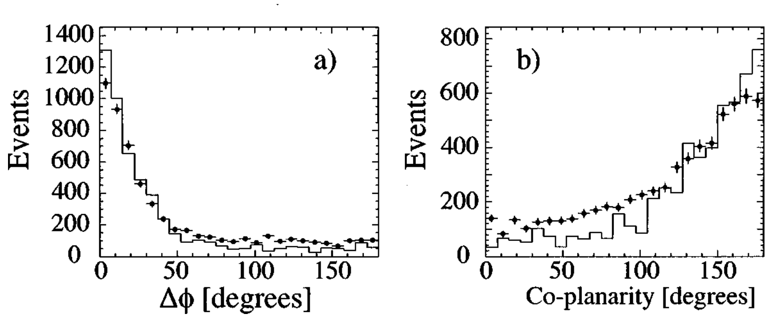

FIG. 2. Difference between measured and reconstructed (a) azimuthal angle for the neutron, $\Delta\phi$ and (b) coplanarity between the neutron and the charged particle track for events identified as $pn \rightarrow pn\eta$. The solid points are experimental data and the line is the result from the Monte Carlo simulation.

momentum for channels (1) and (3). It is then straightforward to calculate the excess energy in c.m. system, $Q_{\mathrm{c.m.}}=\sqrt{s}-m_{\mathrm{final}}$, on an event-by-event basis, assuming the spectator nucleon to be on its mass shell. The $pnp_s\eta$ final state involves two undetected particles and it is therefore not possible to reconstruct the spectator momentum from the measured quantities. However, it is principally the longitudinal component of the Fermi momentum which determines the extracted c.m. energy of the quasifree collision. Therefore, by neglecting the transverse component, we have enough information to reconstruct the c.m. energy. Simulations show that, under these conditions, $Q_{\mathrm{c.m.}}$ can be reconstructed to a precision of about 8 MeV (rms) for the $pn\eta$ channel as compared to 5 MeV in the $d\eta$ and $pp\eta$ cases.

The relative contributions of the different reaction channels to the distribution in Fig. 1 were checked using Monte Carlo simulated events from GEANT3 [14], including the target nucleon Fermi momentum, as given by the Paris potential [15]. For the apportioning of events between the $pn\eta$ and $pp\eta$ channels, we use the known experimental acceptance and excitation function of the latter. For $pn\eta$ events, we assume S-wave behavior, which reproduces the proton and η energy and scattering angle distributions over the kinematically covered region. Figure 1 shows the result of this analysis for the $pn\eta$, $pp\eta$, $d\eta$ contributions and their sum. The agreement between the experimental and MC data demonstrates that, within experimental errors, all the η events can be attributed to the three quasifree channels. To check further the $pn\eta$ hypothesis, we searched for signals from the final state neutron in the forward detector. Such neutrons have a probability of around 40% of interacting in the 44 cm thick plastic scintillator material [16]. By using the three layers of the forward hodoscope as a charged particle veto, we find a consistent number of detector hits. For these events, both the neutron azimuthal angular distribution and the neutron-proton coplanarity distribution agree reasonably well with expectations, as shown in Fig. 2.

To extract the total cross section, we use the normalization from Ref. [1], which was established using quasielastic proton-proton scattering data recorded in parallel. By using the free pp elastic cross section as normalization, effects from shadowing will be largely compensated. Figure 3 shows the extracted energy dependence of the quasifree $pn\rightarrow pn\eta$ cross sections, together with data on the other η channels, both free and quasifree, as a function of $Q_{\mathrm{c.m.}}$. In addition to the statistical errors and the individual systematic errors for each data point, there is an overall uncertainty of about 23% in the absolute normalization [1]. Numerical values of the cross sections are given in Table I.

With the three quasifree reaction channels (1)–(3) having been measured, it is possible to make a final consistency check. The total number of η's seen in the invariant mass distribution of the two γ's detected in the CsI calorimeters agree, to within 5%, with what is expected from the quasifree channels alone. Also the apportioning of events with 0, 1, and 2 charged particle tracks in the forward detector agrees very well with what is expected from the simulations. This once more justifies the assumption of the dominance of the quasifree channels in the region of acceptance covered by this experiment.

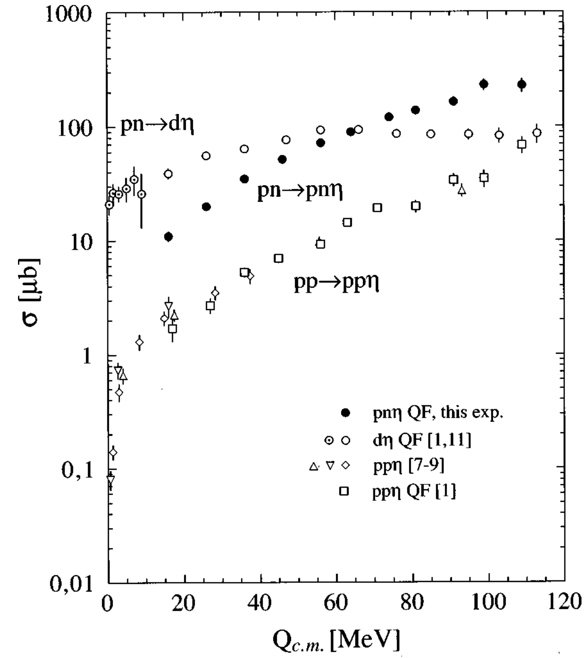

FIG. 3. Total cross sections for the quasifree $pn\rightarrow pn\eta$ reaction (solid points) together with other free and quasifree pN reactions (open symbols) (Refs. [1,7–9,11]) as a function of $Q_{\mathrm{c.m.}}$. The errors shown are statistical only.

As expected, the η production in pn collisions dominates over that in pp in this region [1,10]. The $pn\rightarrow d\eta$ cross section is larger than $pn\rightarrow pn\eta$ one at c.m. excess energies below 70 MeV. Such a behavior can be understood in terms of phase space arguments, since the two body phase space opens up more rapidly close to threshold, and can be predicted quantitatively in terms of final-state-interaction theory [17]. Figure 4 shows the cross section ratio between the quasifree $pn\rightarrow pn\eta$ and $pp\rightarrow pp\eta$ reactions, which is fairly constant at approximately 6.5 over the whole range of $Q_{\mathrm{c.m.}}$ covered. The similarity in the energy dependence of the two cross sections is expected in most theoretical models; it is the magnitude rather than the shape of the excitation curve that

TABLE I. Total cross sections for the quasifree $pn\rightarrow pn\eta$ reaction. The errors shown are statistical and systematic, respectively. In addition there is a 23% uncertainty in the overall normalization [1].

Excess energy $Q_{\mathrm{c.m.}}$ [MeV]	Equivalent beam energy [MeV]	σ_{tot} [μb]
16	1295	$11\pm1\pm0.6$
26	1321	$20\pm1\pm0.9$
36	1347	$35\pm2\pm1$
46	1374	$52\pm2\pm2$
56	1400	$72\pm3\pm2$
64	1421	$90\pm5\pm3$
74	1448	$121\pm7\pm4$
81	1466	$138\pm10\pm6$
91	1492	$165\pm14\pm7$
99	1514	$232\pm26\pm10$
109	1541	$229\pm31\pm12$

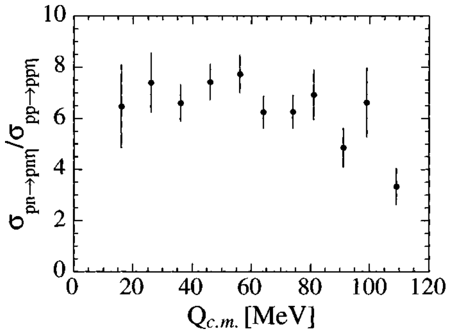

FIG. 4. The ratio between the measured quasifree $pn \to pn\eta$ and $pp \to pp\eta$ cross sections as a function of $Q_{\mathrm{c.m.}}$.

changes with the different assumptions about the meson exchanges. This can be quantified using the short range approximation where the *S*-wave cross sections are given by [18]

$$\sigma(pp\to pp\eta) = \sigma_1(pn\to pn\eta) = C|t_\pi + t_\eta + t_\rho + t_\omega|^2 \, |\psi^{T=1}(0)|^2$$

and

$$\sigma_0(pn\to pn\eta) = C|-3t_\pi + t_\eta + 3t_\rho - t_\omega|^2 \, |\psi^{T=0}(0)|^2,$$

where t_i represents the strength of the different meson exchanges and their relative phases are taken to be real. The factor C, which includes the phase space, distortion, etc., should be essentially the same for the two isospins. The squared ratio between the $T=0$ and 1 wave functions $\psi(r)$ at zero distance has been taken from the *S*-wave solutions to the Paris nucleon-nucleon potential and this accounts for the difference between the nucleon-nucleon final state interactions. This ratio is practically constant at approximately 0.8 in the energy region of interest. These considerations, together with the experimental information that $\sigma(pn\to pn\eta)/\sigma(pp\to pp\eta) \approx 6.5$, gives the ratio

$$\frac{|-3t_\pi + t_\eta + 3t_\rho - t_\omega|^2}{|t_\pi + t_\eta + t_\rho + t_\omega|^2} \approx 15$$

between the squares of the $T=0$ and 1 amplitudes, noting that $\sigma(pn\to pn\eta) = (\sigma_1 + \sigma_0)/2$. The main uncertainties in calculating those amplitudes comes from the unknown phase between the meson exchanges and the lack of detailed knowledge about the coupling of the ρ and ω mesons to the N^* resonance. The relatively large measured ratio demonstrates the dominance of isovector meson (π and ρ) exchange for these reactions and will be useful to constrain the theoretical models.

In conclusion, we report on the first measurement of the energy dependence of the cross section for the quasifree $pn\to pn\eta$ reaction near 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. The shape of the energy dependence is similar to that of $pp\to pp\eta$, although the cross section is approximately 6.5 times larger in magnitude. This information constrains theoretical models for these reactions and provides an input to calculations on η production in heavy ion collisions. This measurement completes the measurements of all isospin channels for η production in nucleon-nucleon scattering that are relevant in the threshold region.

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