Identification and Analysis of the $np \rightarrow d\eta$ Cross Section near Threshold

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(Received 12 February 1990)

It is demonstrated that existing $np \rightarrow dX$ data show a strong signal for the two-body reaction $np \rightarrow d\eta$ near its threshold. The cross section is much larger than that for the analogous π^0 threshold production, but is in accord with a model where production is dominated by the S_{11} $N^*(1535)$ resonance. The Abashian-Booth-Crowe enhancement X_{ABC} is a prominent feature of the data. It is shown that the $np \rightarrow dX_{\mathrm{ABC}}$ process at 1.9 GeV/c, which contains most of the 2π production, is almost isotropic, in contrast to theoretical models.

PACS numbers: 25.10.+s, 13.75.−n, 25.40.Ve

Pion absorption and production in nuclei has been extensively investigated and most theoretical models have been tested in the simplest such process $pp \leftrightarrow \pi^+ d$. Though the π is the lightest hadron, πN interactions are rather weak at low energies, only becoming strong as the P-wave Δ resonance is approached. It is therefore of interest to consider another member of the pseudoscalar-meson octet, the η. The field of η-nucleus physics has been opened up at LAMPF using $\pi^- \, {}^3\mathrm{He} \rightarrow \eta \, {}^3\mathrm{H}$.[1] As stressed in Ref. 2, the threshold ηN system is dominated by an inelastic S-wave resonance, the S_{11} $N^*(1535)$.[3] Thus, in contrast to the π case, the low-energy η-nucleus interaction is very strong.

η production via $dp \rightarrow {}^3\mathrm{He}\eta$ has been studied at Saclay with a tensor-polarized deuteron beam.[4] The most remarkable feature found was that the near-threshold amplitude is similar in size to that of the analogous $dp \rightarrow {}^3\mathrm{He}\pi^0$ reaction[5] despite the much greater momentum transfer. Theoretical estimates[6,7] suggest that the η reaction may be dominated by a $3N$ mechanism whose effect is nontrivial to evaluate. The $2N$ sector is naturally much simpler. It is our purpose here to demonstrate that data on $np \rightarrow d\eta$ already exist and to extract the near-threshold cross section.

There is only one threshold $np \rightarrow d\eta$ amplitude

$$f_{np \rightarrow d\eta} = g_0 \mathbf{p}_n^* \cdot \epsilon_d^\dagger \,, \tag{1}$$

where g_0 is the isoscalar threshold amplitude, p_n^* the neutron center-of-mass (c.m.) momentum, and ϵ_d the deuteron polarization vector.[7] The integrated cross section is

$$\sigma_\eta = \sigma_{np \rightarrow d\eta} = \pi p_d^* p_n^* |g_0|^2 \,. \tag{2}$$

Although near threshold the deuteron c.m. momentum p_d^* is small, the laboratory (lab) counting rate is significant as the deuterons are confined to a small cone. This was precisely why $dp \rightarrow {}^3\mathrm{He}\eta$ could be observed under analogous conditions.[4]

Data were taken over ten years ago on the $np \rightarrow dX$ reaction at Saturne I at Saclay[8] with a 1.88-GeV/c neutron beam. Figures 1(a)–1(d) display the deuteron momentum (p_d) spectra at four lab angles, where each spectrum reflects the superposition of eight different magnet settings. The neutron momentum p_n had a FWHM of ≈ 135 MeV/c, mostly induced by the deuteron Fermi motion (neutrons were produced by stripping a primary 3.76-GeV/c deuteron beam on an 18-cm beryllium target).[9] However, the central value is believed to be correct to ± 5 MeV/c. At low p_d the $np \rightarrow d\pi^0$ reaction, with c.m. backward deuterons, is well resolved in spite of the large p_n spread. The peak width is mainly due to the energy loss in the 10-cm liquid-H_2 target. For c.m. forward deuterons, $np \rightarrow d\pi^0$ must contribute to the upper end of the spectrum but the corresponding structure is unresolved, being much more affected by the beam spread. The Abashian-Booth-Crowe (ABC) anomaly, an enhancement in the $\pi\pi$ mass spectrum close to its threshold,[10] is clearly in evidence at both ends of the spectra. Its study was, in fact, the motivation of the experiment.[8]

An even more prominent structure is the sharp central peak at 1.5° [Fig. 1(a)]. We contend that this is due to the $np \rightarrow d\eta$ reaction. The harder part of the neutron spectrum extends[9] beyond the η threshold of 1.976 GeV/c.[11] In the frame of the primary deuteron, this corresponds to a moderate Fermi motion of $\approx 96/\gamma_n \approx 43$ MeV/c, and almost 10% of neutrons should be above it.[9,12]

However, the best evidence for our hypothesis is that the peak is centered close to $p_d = 1533$ MeV/c, correlating with η's produced at rest in the c.m., rather than at $p_d = 1476$ MeV/c, corresponding to the maximum missing mass $m_{\max} \approx 513$ MeV/c^2 for the nominal beam momentum. Furthermore, the peak is quite smoothed out at 6° [Fig. 1(b)], although $m_{\max}$ is only ≈ 30 MeV/c^2 smaller. The only singularity which can induce such a fast variation is that of the η threshold.

An approximate η cross section can be derived analytically from the data assuming c.m. isotropy near threshold. The rate for point counters should be of the form $d\sigma_\eta = (1/4\pi)\sigma_\eta d\Omega^* P_n dp_n$, with P_n the neutron lab

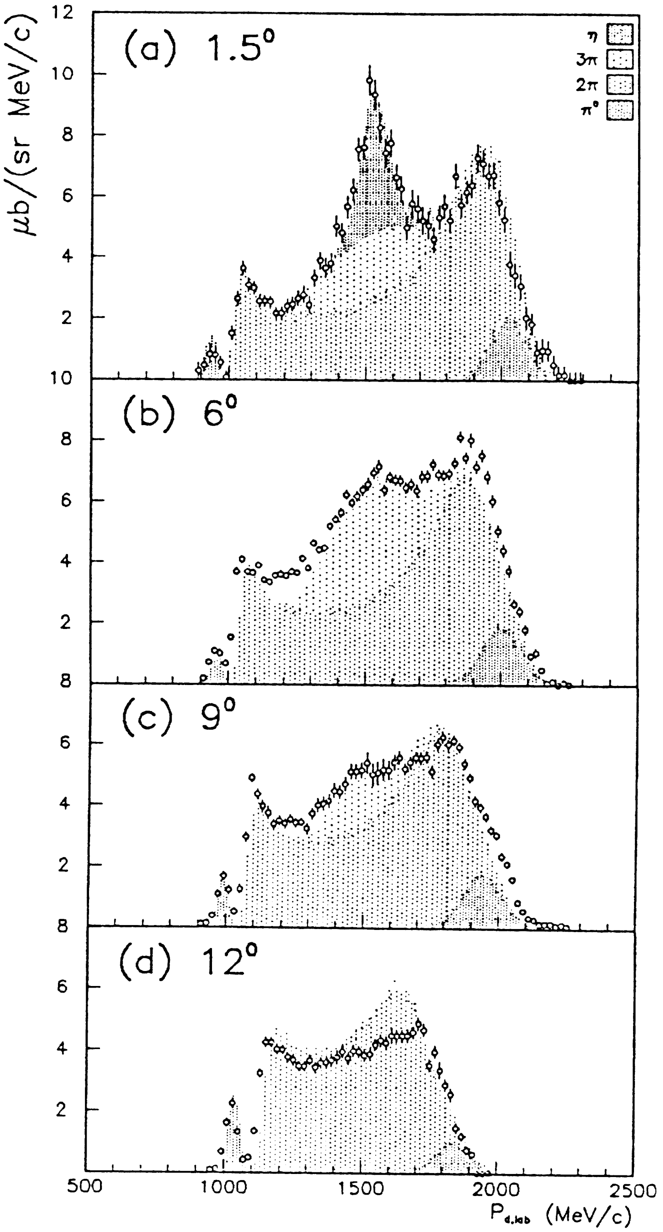

FIG. 1. Differential cross section of $np \rightarrow dX$ at a central neutron momentum of 1.88 GeV/c. The shaded areas correspond to the MC simulations of the η, $\pi\pi$, and $\pi\pi\pi$ contributions according to the parametrizations defined in the text. The π^0 production is taken from the charge-related data of Ref. 13.

momentum probability. Hence

$$d\sigma_\eta = \frac{1}{2\pi} P_n \frac{dp_n}{d(p_d^*)^2} d^3 p_d^* \frac{\sigma_\eta}{p_d^*}\,, \tag{3}$$

and, with the Lorentz factor γ, in the lab

$$\frac{d^2\sigma_\eta}{d\Omega_d\, dp_d} = \frac{1}{2\pi\gamma} P_n p_d^2 \frac{dp_n}{d(p_d^*)^2} \frac{\sigma_\eta}{p_d^*}\,. \tag{4}$$

At the η threshold, $\gamma \approx 1.29$, $p_d \approx 1530$ MeV/c, and $d(p_d^*)^2/dp_n \approx 300$ MeV/c, all with smooth dependences on p_n. Hence, $d^2\sigma_\eta/d\Omega_d\, dp_d \approx 960 P_n(\sigma_\eta/p_d^*)$. If σ_η/p_d^* was constant, the central peak in Fig. 1(a) would merely reflect the neutron Fermi distribution. With $P_n \approx (1.8 \pm 0.2) \times 10^{-3}$ (MeV/c)$^{-1}$ at threshold, the signal height of ≈ 6 μb/sr(MeV/c) [Fig. 1(a)] would correspond to $\sigma_\eta/p_d^* \approx 3$ μb/(MeV/c).

To go further we must model the η, π^0, and multipion contributions and then determine their effect at all four angles simultaneously through a Monte Carlo (MC) simulation. No coherent kinematical description of the total widths of the four spectra seems possible as published.[8] In fact, the p_d values of the raw data for the largest momentum setting at 12° were smaller by ≈ 60 MeV/c. Using the raw data we could restore consistency at the price of a $\approx 1.5°$ angular shift (perhaps due to an error in the stray-field evaluation). For the neutron beam, we used a P_n distribution deduced from the Paris wave function[12] since at high momenta direct measurements are not precise enough.[9]

At all four angles the π^0's and also the 2π threshold are distinctly seen at low p_d. This means that, within a given angular bin for this kinematic region, the correlation between p_d and m_X is not washed out by the measurement errors; the variation of m_X with p_n is, in fact, negligible here. Direct evaluation of the cross section for these low m_X would be possible. However, in order to describe the whole p_d spectra, we choose to postulate empirical production laws, with free parameters to be fitted against the overall data.

For the π^0 we used cross sections deduced from $\pi^+ d \rightarrow pp$.[13] For the ABC anomaly[10] $X_{\rm ABC}$ we used a simple parametrization, hinted at by the data, of the type

$$\frac{d\sigma_{2\pi}}{dm_{2\pi}} = C_{\rm ABC}\Phi_{2\pi}(1 + p_\pi^{*2}/a_{\rm ABC}^2)^{-1}\,, \tag{5}$$

with $\Phi_{2\pi}$ the Lorentz-invariant $\pi\pi d$ phase space, p_π^* the π momentum in the $\pi\pi$ system, and $a_{\rm ABC}$ a free parameter. The MC trial procedure yielded

$$a_{\rm ABC} = 60 \pm 10 \text{ MeV}/c\,. \tag{6}$$

The MC simulation describes the data over a much wider domain than could have been expected on the basis of the *isotropic* ansatz. At all four angles [Figs. 1(a)–1(d)] it reproduces well the heights *and* widths of both the low- *and* high-momentum ABC peaks. At 1.5° the relation between the low- and high-momentum ABC peaks follows mainly from charge symmetry, but this is far less relevant for the larger-angle data. At 12° the ABC c.m. production angle θ^* has typically $\cos^2\theta^* \approx 0.6$ for the slow p_d peak but $\cos^2\theta^* \approx 0.1$ for the fast one. We have therefore very strong evidence, from both the four spectra *and* the relative heights of the slow-to-fast peaks, that *the low-mass $\pi\pi$ production is isotropic to within 10%–20%*. This is compatible with neither the double-baryon-excitation model[14] nor the baryonexchange model[15] and should provide an important clue to the dynamical origin of the effect.

In the simplest final-state interaction model,[16] the above value of a_{ABC} [Eq. (6)] would correspond to the very large $\pi\pi$ scattering length of 3.3 ± 0.6 fm, which is close to that deduced[16] for $pd \rightarrow {}^3\mathrm{He}X_{\mathrm{ABC}}$ from the original work on the ABC anomaly.[10] That is, the shape of the $\pi\pi$ mass spectrum is similar in pd and np reactions. However, there is no sign of a massive $\pi\pi$ scattering length in the extensive data on the peripheral $\pi p \rightarrow \pi\pi p$ reaction.[17] The ABC enhancement must therefore involve the production dynamics, though we not that the $\pi\pi$ decays of the Υ, ψ, and η' also show strong deviations from phase space to low masses.[18]

We turn now to the central p_d region. Even though a bump is observed at 6° and persists at 9°, there exist too few fast neutrons in the beam to give rise to any significant η production at these angles. The lack of fast neutrons also means that the central bump at 1.5° cannot be uniquely identified with η production since the rise begins already at $p_d \approx 1350$ MeV/c [Fig. 1(a)]. Focusing on 1.5°, we have tried different multipion distributions, enriched at high m_X but with no singularity at the η mass. The sharpness of the peak is never reproduced and its position is systematically too low in p_d. Therefore, the only realistic hypothesis is that the central region must be made up of η production plus some multi-π background.

In a form similar to that used in Ref. 4 for $dp \rightarrow {}^3\mathrm{He}\eta$ near threshold, we take σ_η as proportional to p_d^* tempered by a shape factor S_η,

$$\sigma_\eta/p_d^* = C_\eta S_\eta(p_d^*) = C_\eta(1 + p_d^{*2}/a_\eta^2)^{-2} . \tag{7}$$

At 1.5° the multipion effect is well fitted by a straight 3π phase space,

$$\frac{d\sigma_{3\pi}}{dm_{3\pi}} = C_{3\pi}\Phi_{3\pi} , \tag{8}$$

which contributes weakly at other angles. An extra term with a strong angular dependence is required in order to keep the 1.5° accord. We choose a form in terms of the transverse momentum $p_{d\perp} = p_d^* \sin\theta_d^*$:

$$\frac{d^2\sigma'_{3\pi}}{d\Omega_d^*\, dm_{3\pi}} = C'_{3\pi}\Phi_{3\pi}p_{d\perp}^2 . \tag{9}$$

The fit with the two 3π terms is very satisfactory. However, we note that the rise from about $3m_\pi$ is not quite fast enough, as is best demonstrated at 6° by a lack of MC events for $p_d \sim 1200$ MeV/c.

The first merit of the overall fit, performed simultaneously at all four angles, is to show that there exists at least one solution for the deconvolution of the data set in terms of meson production. The corresponding total cross sections $\sigma_{2\pi}$, $\sigma_{3\pi}$, and $\sigma'_{3\pi}$, for neutron momenta around 1.9 GeV/c, are, respectively, 650, 25, and 70 μb. Although the quality of the fit is impressive, there is no direct proof that the 3π terms do correspond purely to 3π production.

Our first attempt at fitting the η on the basis of Eq. (7) with no shape factor resulted in much too broad a central peak. The introduction of S_η leads to a good description of the typical triangular form displayed by the data. The fit gives

$$a_\eta = 60 \pm 20 \text{ MeV}/c , \tag{10}$$

with negligible influence from the shape assumptions made for the continuum productions. This is marginally less than the 80 MeV/c found for $pd \rightarrow {}^3\mathrm{He}\eta$.[4]

For $S_\eta = 1$, the fit leads to $C_\eta \approx 3$ μb/(MeV/c), in agreement with our simplistic estimate. Since p_d^* values higher than a_η are strongly suppressed by S_η, for $a_\eta = 60$ MeV/c the normalization is boosted by ≈ 2. The fit gives

$$C_\eta = 6 \pm 2\ \mu\text{b}/(\text{MeV}/c) . \tag{11}$$

The errors quoted so far are essentially due to the a_η-C_η correlation, marginally to the multipion and P_n assumptions, and negligibly to statistics. However, the maximum η cross section of Eq. (7) (at $p_d^* = a_\eta/\sqrt{3}$) is much less affected by the correlation since it depends upon the product $C_\eta a_\eta$. We find $\sigma_\eta^{\max} = 110 \pm 20$ μb, which is almost big enough to be seen in the np total cross section.

There remains some uncertainty associated with the 1.5° shift introduced into the analysis. Without access to all the original data books, it is impossible to be sure of the validity of the shift. If one insists on the small-angle data being 0°, then this reduces σ_η by a factor of 2 with little change in the other parameters. This ambiguity can only be resolved by further experiments.

From Eqs. (2), (7), and (11) it follows that the isoscalar threshold amplitude

$$|g_0| = 0.10 \pm 0.02 \text{ fm}^2 . \tag{12}$$

Laget and Lecolley[6] considered only one-pion exchange and their estimate for $|g_0|$ falls well below the value of Eq. (12). Germond and Wilkin[7] included ρ exchange and predict $0.06 < |g_0| < 1.4$ fm^2, where the wide range is due to uncertainty of the S_{11} couplings, especially the relative π/ρ sign. Agreement with Eq. (12) is satisfactory even without the 1.5° shift.

Much uncertainty would be removed by measuring the g_1 amplitude in the isospin-1 channel $pp \rightarrow pp\eta$.[19] Despite the π/ρ sign ambiguity in the Germond-Wilkin model,[7] if the amplitudes interfere destructively for $np \rightarrow d\eta$ then they should be constructive for $pp \rightarrow d^*\eta$. Even in this case the cross section is likely to be an order of magnitude smaller.[7]

We have shown that even with a limited neutron beam, a fairly precise $np \rightarrow d\eta$ threshold amplitude could be extracted from the data. A recent precision measurement[20] of $np \rightarrow d\pi^0$ leads to a threshold coefficient $C_\pi = \sigma_\pi/p_d^* = 0.66 \pm 0.02$ μb/(MeV/c). Despite the lower momentum transfer, this is much smaller than our value of C_η and reinforces the argument of the relative strength of low-energy η and π interactions.

Our large value for g_0 is in good agreement with a model where the S_{11} resonance is excited by a combination of ρ and π exchange. Combined with η-π mixing and the final state it could give rise to significant charge-symmetry breaking in reactions such as $np \rightarrow d\pi^0$. Much intermediate-energy nuclear physics may be dominated by this resonance.

The $np \rightarrow d\eta$ reaction could prove to be a source of η's for decay studies. Though the yield is much higher than for $dp \rightarrow {}^3\mathrm{He}\eta$,[4] neutron beams are less intense and the main gain is reduction in uncorrelated noise. Furthermore, it would not have the same precision in tagging the η's.[21] The same drawback exists in quasifree production via dp (or pd) $\rightarrow dp_s\eta$ with a spectator proton, unless the spectator is also detected. A single-arm $dp \rightarrow dp_sX$ experiment was carried out at Saturne I[22] at ≈3.82 GeV/c. Though a fast rise was observed, the investigation was not extended to the top of the η peak.

Another important result is that the reaction $np \rightarrow dX_{\mathrm{ABC}}$ is almost isotropic in the c.m. for $p_n = 1.9$ GeV/c, which is far above threshold. Its cross section between the $\pi\pi$ and $\pi\pi\pi$ thresholds is 500 ± 50 μb, i.e., $\approx \frac{2}{3}$ of the multipion production.

We thank G. Dellacasa, J.-F. Germond, J. M. Laget, and F. Wellers for useful discussions.

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