Identification of the $d + p \rightarrow {}^3\mathrm{He} + \eta$ Reaction Very Near Threshold: Cross Section and Deuteron Tensor Analyzing Power

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From the interactions of a deuteron beam in a liquid-hydrogen target at energies near the $d+p \rightarrow {}^3\mathrm{He}+\eta$ threshold, η events were selected on the basis of the momentum-analyzed ${}^3\mathrm{He}$ with a background of less than 2%. This opens the way to a ${}^3\mathrm{He}$-tagged η beam at Saturne, with a possible flux of 10^4–10^5 η's per pulse. The present data allow an evaluation of the cross section down to less than 0.5 MeV above threshold. The deuteron tensor analyzing power t_{20} has also been measured: The small negative value found at threshold (-0.15 ± 0.05) seems incompatible with models based on one-pion exchange.

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It has recently been observed at Saclay that the tensor analyzing power (t_{20}) in the $d+p \rightarrow {}^3\mathrm{He}+\pi^0$ reaction close to the production threshold is large and negative.[1] This is consistent with a one-pion-exchange model where the pion is emitted by one nucleon and scattered by a second before emerging. The η meson has the same spin-parity as the pion so that the amplitude spin structure of $d+p \rightarrow {}^3\mathrm{He}+\eta$ is the same as that for pion production. Despite the difference in the η and pion isospins, if the η production mechanism is dominated by an intermediate pion which converts into an η on a second nucleon before emerging, then the t_{20} for this reaction should also be large and negative near threshold.[2] While investigating this, it became apparent that the high efficiency for selecting events near threshold, based upon ${}^3\mathrm{He}$ detection, was a matter of great practical interest in its own right. Also of unforeseen importance is the method of intrinsic incident-energy determination which was hinted at by the data themselves.

The experiment was carried out with the primary polarized deuteron beam of the Saturne synchrotron,[3] colliding with a 3.9-cm liquid-hydrogen target under conditions similar to those of the π^0 experiment.[2] The beam was monitored with a low-energy polarimeter, based upon $d+d \rightarrow p+{}^3\mathrm{H}$, prior to injection in Saturne. The mean tensor polarization, $\rho_{20}=0.637 \pm 0.025$, was found to be stable throughout the period of data taking. The beam intensity ($\simeq 10^{10}$ d/pulse) was monitored by an ionization chamber whose response is independent of the beam polarization. The SPES4 spectrometer and its associated scintillator hodoscope ($\Delta P/P=0.2\%$ per element) were used for the momentum analysis of the ${}^3\mathrm{He}$'s produced at around 0° with respect to the beam.

Data were taken at five incident energies above the $d+p \rightarrow {}^3\mathrm{He}+\eta$ threshold which is expected to be at $T_d=1786.7$ MeV. We refer to these energies by their fitted values ΔT_d with respect to threshold, according to a procedure explained later, namely, $\Delta T_d=0.2$, 3.0, 7.9, 16.6, and 71.7 MeV. At the highest ΔT_d, only the ${}^3\mathrm{He}$'s emitted backward in the center-of-mass system have been investigated. At 16.6 MeV, two separate runs were done, with a 4% difference in the SPES4 central momenta, in order to cover the complete ${}^3\mathrm{He}$ spectrum. For the three lowest energies, the momenta of ${}^3\mathrm{He}$'s are fully contained within the SPES4 momentum acceptance.

The detected ${}^3\mathrm{He}$ momentum distributions, shown in Fig. 1, tend to define a *double-peak structure*. This corresponds to forward and backward center-of-mass emissions; the depletion in between the two peaks is accounted for by the cutoff of about 5 mrad imposed by the collimator placed downstream of the hydrogen target. The separation between the two peaks is a direct measure of p^*, the center-of-mass momentum of the ${}^3\mathrm{He}$ in the final state. Along the beam line the relative separation is given by

$$\Delta P/\langle P\rangle = 2p^*/\beta_{\mathrm{c.m.}}E_{\mathrm{c.m.}}({}^3\mathrm{He}), \tag{1}$$

where $\beta_{\mathrm{c.m.}}$ is the velocity of the center of mass. Since $\beta_{\mathrm{c.m.}}$ and $E_{\mathrm{c.m.}}({}^3\mathrm{He})$ are slowly varying functions of p^* in the region of interest, we find that

$$\Delta P/\langle P\rangle \simeq 1.04\times 10^{-3}p^*, \tag{2}$$

where p^* is measured in MeV/c.

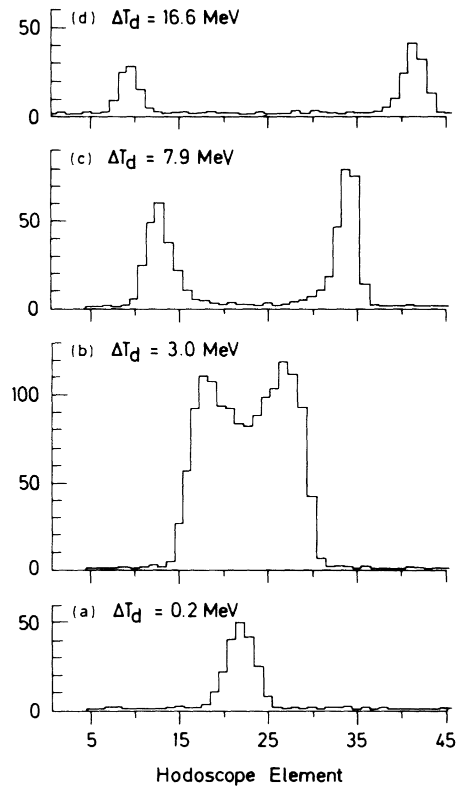

FIG. 1. Number of events per machine burst (10^{10} d) for individual hodoscope elements of the SPES4 focal plane of about 5 MeV/c, the center of the 25th element corresponding to $p/Z = 1.317$ GeV/c.

A more detailed analysis of the data, with Monte Carlo simulations, led to p^* evaluations accurate to ± 0.2 MeV/c when the two peaks were observed, i.e., at $\Delta T_d = 3.0$, 7.9, and 16.6 MeV [Figs. 1(b) to 1(d)]; a systematic error of less than 1% on p^* could arise from the uncertainty in the dispersion coefficient of the spectrometer, but its absolute calibration plays no role. The incident energy with respect to threshold ΔT_d is then readily determined. Since the threshold energy is just a function of the masses, the incident energy itself, T_d, is thus measured independently of the nominal values given by the accelerator. This would then constitute an absolute determination of the machine energy to within $\simeq \pm 0.1$ MeV, if the mass of the η meson were better known! With $m_\eta = 548.8 \pm 0.6$ MeV, the nominal energy of Saturne appears as 9 ± 2 MeV (i.e., $0.5\% \pm 0.1\%$ too low in this region).

However, from the consistency of the above results on the three fitted energies, it can be inferred that during the runs of about an hour each the stability of the Saturne energy was better than 0.1 MeV and that energy steps of a few MeV could be controlled by the Saturne operators with about the same accuracy. Consequently Saturne, after correct calibration, would be well suited for experiments requiring a precise mean energy of the extracted beam. Already in the present study, the consistency of the energy determination was used to obtain the ΔT_d values of 0.2 and 71.7 MeV where the double-peak method is not possible.

For the sake of the present study, p^* is, in fact, a more relevant variable than, say, T_d to express the dynamics of threshold production. Furthermore, to evaluate $d\sigma/d\Omega_{\text{c.m.}}$ in terms of $d\sigma/d\Omega_{\text{lab}}$, p^* is again the most relevant parameter since, near threshold, the Jacobian of the c.m.-to-laboratory transformation has a $1/(p^*)^2$ divergence. For the present study, the high stability of Saturne was necessary, but an absolute incident-energy measurement was not required, since its determination is best obtained, *a posteriori*, from the data via p^*.

From the observation of Fig. 1, *the very low level of the background*, less than 1% under the peaks, was quite a surprise. This is related to the large values of the Jacobian for two-body reactions at small p^*. This acts as a focusing effect for η events on small P intervals along the SPES4 focal plane, while the competitive multipion production spreads over a much broader P band. Indeed, the allowed bandwidth, in terms of $\Delta P/\langle P \rangle$, increases linearly with $\Delta m/m$; typically the production of mesonic masses m within 0.5% of the η mass would result in a full coverage of the SPES4 momentum acceptance. The intense two-pion production in this energy region, known as the *ABC* effect,[4] is mostly associated with low $m(\pi\pi)$ values and is drastically suppressed in the present data.

The center-of-mass cross sections, determined by the direct method outlined above, should be relatively free from systematic errors at $\Delta T_d = 7.9$, 16.6, and 71.7 MeV. This is not the case for the two lowest-energy points. There, the maximum ^{3}He production angle happened to be comparable to the collimator aperture, so that the acceptance factor depends critically on the beam divergence evaluation and/or on a collimator misalignment. This could have been avoided by our choosing a collimator of a larger size. Furthermore, at the lowest energy η production can only occur in about the first half of the hydrogen target, not enough energy being available afterwards because of the ionization losses of the primary deuterons. This limited efficient length of the production target has been taken into account in the simulations, by the assumption of a cross section that decreases as p^* as the energy approaches threshold. All quoted ΔT_d values are defined as $[(\Delta T_d)_{\text{in}} + (\Delta T_d)_{\text{out}}]/2$, where $(\Delta T_d)_{\text{in}}$ refers to the value at the target entrance and $(\Delta T_d)_{\text{out}}$ to that at the target exit (except at the lowest energy where it is taken as zero). The associated p^* values correspond directly to these ΔT_d.

The results on the $d + p \to {}^3\text{He} + \eta$ cross section, shown in Fig. 2, are in qualitative agreement with the expected behavior of vanishing at threshold, although direct evidence for this only arises from the lowest-energy point. More data would be welcome for the rise in the 0–30-MeV/c p^* region. Up to $p^* \simeq 50$ MeV/c,

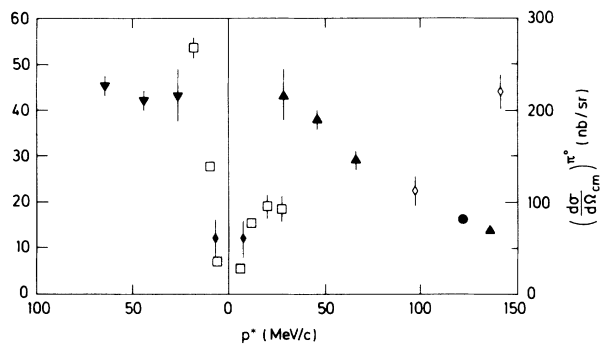

FIG. 2. Center-of-mass cross section for $d+p \rightarrow {}^3\mathrm{He}+\eta$ as a function of the ^{3}He center-of-mass momentum p^*. The filled symbols refer to η data: backward angles (triangles), forward angles (inverted triangles), average over all angles (lozenges), backward point of Ref. 5 corrected for the 10-MeV shift (circle). On a compressed scale, the analogous π^0 data are shown with open symbols: data are from Ref. 6 (squares) and Ref. 2 (lozenge).

the forward-backward cross-section ratio remains close to 1, whereas the $d+p \rightarrow {}^3\mathrm{He}+\pi^0$ data[6] soon display a very asymmetric behavior. Note that, in Fig. 2, the two lowest-energy points correspond to an average over all angles; higher-energy data are given as forward and backward values integrated over intervals of about 19° and 13° in $\theta_{\mathrm{c.m.}}$ at $\Delta T_d = 7.9$ and 16.6 MeV, respectively.

To eliminate phase-space factors, the cross section may be written in terms of a spin-averaged amplitude f as

$$d\sigma/d\Omega_{\mathrm{c.m.}} = [p^*/p_{\mathrm{c.m.}}(d)]\,|f|^2. \quad (3)$$

Our data on $|f|^2$ join well to the earlier backward-angle results taken at Saclay at higher energies[5] and shown in Fig. 3. A combined fit of all the data shows a sharp falloff with momentum:

$$|f|^2 = a/[1 - bp^* \cos(\theta_{\mathrm{c.m.}}) + c(p^*)^2]^2, \quad (4)$$

with $a = 1.37 \pm 0.05$ μb/sr and, for p^* in MeV/c, $b = (1.6 \pm 0.2) \times 10^{-3}$ (MeV/c)$^{-1}$ and $c = (1.53 \pm 0.05) \times 10^{-4}$ (MeV/c)$^{-2}$.

The threshold value, a, is also affected by beam calibration uncertainties of about 7%, resulting in $a = 1.4 \pm 0.1$ μb/sr. It is striking that this value is very close to the 3.1 ± 0.2 μb/sr extracted[7] from the analogous π^0 production reaction.[3]

Turning to the deuteron tensor analyzing power, Fig. 4 shows the values of t_{20} for the different incident energies. The forward and backward values are averaged over rather large angular domains whose widths vary with energy. This does not, however, affect the extrapolation to threshold where we find $t_{20} = -0.15 \pm 0.05$. This error bar takes into account systematic effects such as the uncertainty in the beam polarization.

Thus the analyzing power for η production is much smaller than that found for the π^0 case[2] (-1.32 ± 0.03).

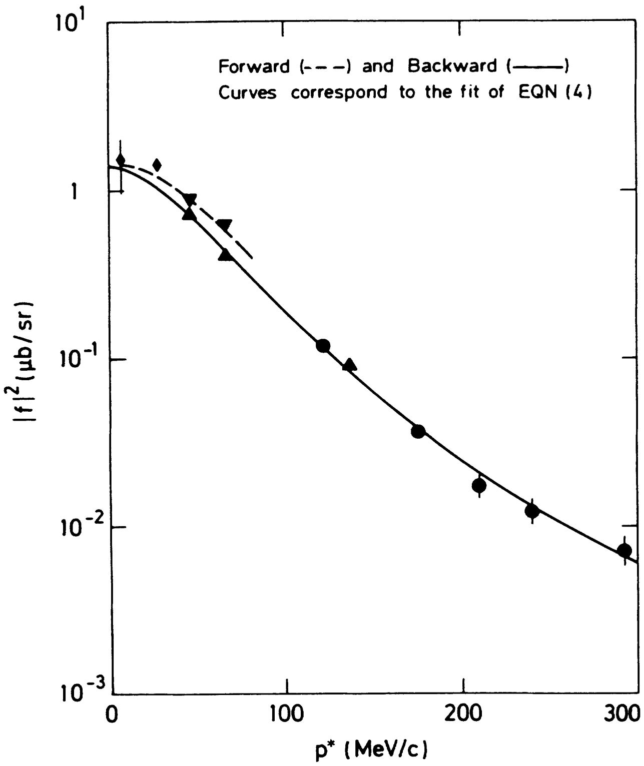

FIG. 3. Values of the spin-averaged $|f|^2$ of Eq. (3) taken from the present experiment and Ref. 5, with the same conventions as for Fig. 2 (at $p^* \simeq 27$ MeV/c, the about equal forward and backward values are here averaged into a single data point).

In the conventional model for pion production, the pion is emitted by one nucleon and then rescattered by a second before emerging. A model of this type reproduces well the threshold value of t_{20} and the cross section provided that nuclear D states are included.[8] For η production the dominant mechanism should again involve

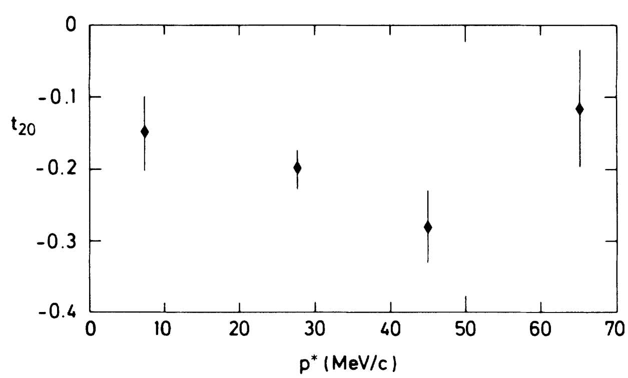

FIG. 4. The deuteron tensor analyzing power t_{20} for $d+p \rightarrow {}^3\mathrm{He}+\eta$ as a function of the average value of p^*. The forward and backward values never differ by more than half a standard deviation and only their average is shown.

an intermediate pion and this leads to the production of $-\sqrt{2}$ for a pure S-state nuclear wave function and -1.3 when D states are incorporated. The discrepancy with experiment may be associated with the large η mass which engenders high-momentum transfer so that a genuine three-nucleon process might become important.

The kinematical separation effect between the η and the background, which we have exploited here, could be of more dramatic interest for the study of rare decay modes of the η. Indeed, the production of η's by the $d+p \rightarrow {}^3\text{He}+\eta$ reaction near threshold, detected through the momentum selection of the ^{3}He's, could lead to a tagged-η-beam facility. The idea of a tagged η beam was already advocated,[9-11] and it is now clear that the threshold production permits higher fluxes with less background. We estimate that with 5×10^{11} d/cycle and realistic increases in target length and collimator aperture, up to 10^5 η/cycle could be obtained keeping the 1% background.

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[1]C. Kerboul *et al.*, Phys. Lett. B **181**, 28 (1986); C. Kerboul, thesis, University of Strasbourg, France, Commissariat à l'Energie Atomique Report No. CEA N-2539, 1987 (unpublished), and to be published.

[2]C. Wilkin, in Quatrièmes Journées d'Etudes Saturne—La Physique avec Mimas, Gif-sur-Yvette, France, 10–14 November 1986, edited by the Commissariat à l'Energie Atomique [Centre d'Etudes Nucléaires de Saclay Report No. 86-0066, 1987 (unpublished), p. 103].

[3]J. Arvieux *et al.*, Nucl. Phys. **A431**, 613 (1984).

[4]J. Banaigs *et al.*, Nucl. Phys. **B67**, 1 (1973).

[5]P. Berthet *et al.*, Nucl. Phys. **A443**, 589 (1985).

[6]M. A. Pickar, in *Pion Production and Absorption in Nuclei—1981,* edited by R. D. Bent, AIP Conference Proceedings No. 79 (American Institute of Physics, New York, 1982).

[7]J. F. Germond and C. Wilkin, J. Phys. G **12**, 1379 (1986).

[8]J. F. Germond and C. Wilkin, J. Phys. G **14**, 181 (1988).

[9]O. Piccioni, private communication; tagged η beam with the $d+p \rightarrow d+p+\eta$ reaction.

[10]L. Goldzahl and F. Plouin, presented at Journées de Physique Nucléaire, Lyon, France, 10–11 May 1984 (unpublished).

[11]L. Satta *et al.*, presented at the Workshop on Nuclear Physics at Intermediate Energies with Hadrons, Miramare-Trieste, Italy, 1–3 April 1985; quoted by R. Bertini, in *Nuclear and Particle Physics at Intermediate Energies with Hadrons,* edited by T. Bressani and G. Pauli (Societa Italiana di Fisica, Bologna, Italy, 1986), p. 249.