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Total $d+d \rightarrow \alpha+\eta$ cross sections near threshold

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The total cross section for η production in deuteron-deuteron interactions has been measured at four different kinetic energies, from 0.7 MeV to 3.7 MeV above threshold. The squared amplitude is consistent with a constant value of $|f|^2=(24.6\pm1.2\pm1.7)$ nb/sr close to threshold ($14<p_\eta<40$ MeV/c). Assuming that the π^0-η mixing reaction mechanism is dominant, this result allows a prediction of $(d\sigma/d\Omega)_{\pi^0}=(8.3\pm0.5\pm0.6)$ pb/sr for the cross section of the isospin-forbidden reaction $d+d\rightarrow\alpha+\pi^0$ at the η-threshold energy.

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A precise determination of the $d+d\rightarrow\alpha+\eta$ total cross sections near threshold is of great interest for at least two reasons:

(i) The first observation of a positive signal in the $d+d\rightarrow\alpha+\pi^0$ reaction was made a few years ago [1] at the French National Laboratory Saturne (LNS). The measured cross section close to the η threshold at a deuteron kinetic energy (T_d) of 1100 MeV and a c.m. angle of 107° is $(0.97\pm0.20\pm0.15)$ pb/sr. This value seems high and well above the upper limit of 0.003 pb/sr at 600 MeV expected from a purely electromagnetic process emphasized by a Δ excitation in an intermediate state [2]. Charge symmetry breaking (CSB) is necessarily concerned with the small u-d quark mass difference which is responsible for the well-known ρ-ω and π^0-η mixing. Charge symmetry (CS) holds in strong interaction in the limit where the u-d quark mass difference is neglected. In this case CS forbidden transitions like $d+d\rightarrow\alpha+\pi^0$ are strongly suppressed [3]. Coon and Preedom [4] predicted a CSB in $d+d\rightarrow\alpha+\pi^0$ via external π^0-η mixing but with a weak signal of 0.12 pb/sr at 1.95 GeV. The possibility that the production could be enhanced in the vicinity of the η production threshold, $T_d=1120.3$ MeV, was proposed by Wilkin [5]. This idea is based on the comparison of π^0 and η production close to the η threshold in proton-deuteron interactions also studied at LNS [6], where it was found that the η-production amplitude is much greater than that for backward π^0 production in the η-threshold region. This was explained as being due to the excitation of the S_{11} (1520) resonance in intermediate states in three-body mechanisms [7,8].

(ii) Information on the η-nucleus interaction at low relative energies can help to test the Haider and Liu ideas [9] about the possible existence of a bound η-nucleus state, especially for light nuclei. For that purpose a measurement of the η-^{4}He production cross sections close to the production threshold compared to that for η-^{3}He in terms of scattering lengths would emphasize the atomic number dependance of a possible binding of the η to nuclei [10].

The $d+d\rightarrow\alpha+\eta$ reaction was observed for the first time some years ago at the LNS [11] well above threshold at an incident kinetic energy of 1.95 GeV and an α-particle detection angle of 6° in the laboratory. The c.m. differential cross section was found to be (0.25 ± 0.10) nb/sr. This value has been used as an input in the calculation of Coon and Preedom [4], yielding their prediction of (0.12 ± 0.05) pb/sr for the π^0 production, well below the observation of Ref. [1].

Taking advantage of the SPES4 experimental setup at the LNS, we have measured the $d+d\rightarrow\alpha+\eta$ total cross section near threshold. The experimental conditions are here described succinctly; a more detailed description of the beam line and the detectors can be found in Ref. [12].

The high intensity deuteron beam, about 2×10^{11} per cycle, provided by the Mimas-Saturne accelerating complex, was focused on a 160 mg/cm^2 thick liquid deuterium target. The thickness was chosen on the basis of a Monte Carlo simulation to get the narrowest width for the two-body η-production signal over a continuum multipion production. This choice is compatible with a reasonable counting rate based on the expected $1-10$ nb cross section deduced from previous inclusive $d+d\rightarrow\alpha+X$ experiments [13].

The SPES4 beam line is a 32 meter long spectrometer which allows the momentum analysis of particles up to 4 GeV/c. The acceptance of SPES4 is determined in this experiment by a circular collimator defining a solid angle $\Delta\Omega$ of 10^{-4} sr. The Monte Carlo simulation takes into account the beam emittance, the target thickness, the collimator acceptance, the transmission of the spectrometer and finally the energy losses of beam and α particles in different materials and in particular in scintillators located 16 meters away from the target in the intermediate focal plane of the spectrometer. The start signals for time-of-flight measurements are given by these scintillators and the stop signals by a row of scintillators placed 16 meters behind in the final focal plane of the spectrometer. In front of these last scintillators, two multidrift chambers allow the reconstruction of particle trajectories in the focal plane where momentum spectra can be achieved after discrimination of particles other than α particles. The rejection of these particles, mainly pions, protons, and deuterons, was obtained by time-of-flight and energy loss measurements in the scintillator hodoscopes. A clear and

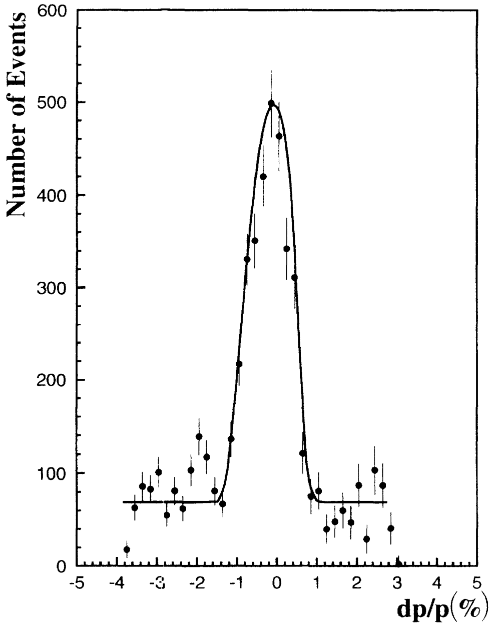

FIG. 1. Experimental results for $d + d \rightarrow \alpha + \eta$ at $T_d = 1121$ MeV as a function of the α-particle momentum relative to the central value of 2030 MeV/c (dots) and Monte Carlo simulation with the same experimental conditions (continuous line).

efficient selection of the α particles was finally obtained either by electronic cuts with a fast trigger of 5 ns width or by software analysis on individual spectra.

The threshold energy for η production in the $d+d \rightarrow \alpha+\eta$ reaction is at an incident kinetic energy of 1120.3 MeV (using the 1992 PDG value of 547.45 MeV/c^2 for the η mass [14]). Four different beam energies were selected, 1121, 1122, 1123, and 1124 MeV, corresponding to η c.m. momenta of $p_\eta = 14.4$, 24.7, 32.0, and 38.0 MeV/c. The SPES4 beam line was set as close as possible to 0° for the outgoing α particles and, for each chosen energy, tuned to a central magnetic field value corresponding to the α-particle momentum associated with the two-body production of η mesons. The angular position of the spectrometer was determined by two movable wire chambers which are located at the target position and 40 cm downstream. The momentum acceptance of the SPES4 spectrometer is only $\pm$ 3%, but the proximity of the η threshold means that this corresponds to a large fraction of the total cross section.

The beam monitoring system consists of two scintillator telescopes viewing a thin mylar film positioned upstream and two other telescopes viewing the deuterium target at different angles. The absolute measurement of the beam intensity was obtained by a carbon activation method [15]. Empty target measurements were performed to determine the contribution of the target windows to the counting rates.

A typical momentum spectrum in the final focal plane of the spectrometer is shown in Fig. 1. It corresponds to the measurement closest to threshold (T_{thr}) with $\Delta T = T_d - T_{\text{thr}} = 0.7$ MeV. The error bars are only statistical ($\pm\sigma$). A constant ratio of about 10% between empty target and full target in the multipion continuum is observed. The peak corresponding to the two-body α-η channel being about five times higher than this continuum, the empty target contribution, is always weak and has already been subtracted in Fig. 1. The physical background comes from multipion events.

The Monte Carlo simulation for the $d+d \rightarrow \alpha+\eta$ reaction plus a flat multipion continuum in the same experimental conditions are shown in the same figure as a solid line and this reproduces fairly well the observation both in position and width. Similar agreement is found at all four incident energies. The contributions to the width of the peaks come mainly from the energy beam spread ($\sigma \approx 100$ keV) and energy losses in the different materials (target and scintillators).

From these simulations, two fundamental experimental parameters conditions can be obtained. A few MeV above threshold, the peaks corresponding to forward and backward η production are well separated in the momentum spectra. Their relative distance in momentum is independent of the absolute α momentum calibration and is strictly related to kinematics. From the observed forward and backward peak positions at 1122 and 1124 MeV compared to the Monte Carlo simulations it is possible to check the absolute value of the incident deuteron energy. The result of this study shows that the energies delivered by Saturne during this experiment were known to ± 100 keV in absolute value. Steps in energy of a few MeV can be well controlled by the Saturne accelerator tuning procedure. The second parameter given by the simulations is the acceptance of the detector, defined as the ratio between the number of α particles analyzed by the spectrometer to those produced. It ranges from 14% near threshold to 6% a few MeV above.

It is then possible to obtain the total cross sections for η production by

$$\sigma_T = \frac{1}{\mathcal{A}} \times \frac{N_\eta}{N_d} \times \frac{A}{N_A \rho\, t}, \tag{1}$$

where $\mathcal{A}$ is the acceptance discussed above and ρ, t, N_A, and A are respectively the density and thickness of the deuteron liquid target, and the Avogadro and atomic numbers. N_η is the number of η mesons produced corrected by analysis and detection efficiencies, the main correction coming from the multidrift chambers. N_d is the number of incident particles. Dead-times corrections, less than 2%, are controlled and taken into account.

The total cross sections as well as the uncertainties on their measurements are given in Table I. These uncertainties are dominated by the error in the accuracy of $\mathcal{A}$, which arises principally from the knowledge of the accuracy of the angular setting of the spectrometer, which is estimated to be $\pm 0.05°$. This leads to an error of $\pm 20\%$ near threshold down to $\pm 4\%$ a few MeV above. The other contributions to the errors are given in Table I. In the same table, the c.m. η momenta deduced from the Monte Carlo simulations are also given. The uncertainty Δp_η in p_η comes from the spreading due to energy losses (first number) and from the absolute beam energy determination (second number).

The resulting total cross sections are shown on Fig. 2, where they are compared with other few-body measurements near threshold [16–23]. One should note the five orders of magnitude difference between the $d+d \rightarrow \alpha+\eta$ and

TABLE I. Total cross sections σ_T for η production in the $d+d\rightarrow\alpha+\eta$ reaction as a function of the c.m. η momenta p_η. In the last column, the uncertainties on σ_T are given. The first contribution is the result of statistical uncertainties on incident deuterons and detected α-particle counting rates added quadratically to the acceptance and detection efficiency uncertainties. For the α-particle counting rates a flat physical background has been assumed. The last number in this column is the systematic error due to the absolute beam calibration.

p_η (MeV/c)	Δp_η (MeV/c)	σ_T (nb)	$\Delta\sigma_T$ (nb)
14.4	$\pm3.2\pm1.1$	4.42	$^{+1.41}_{-0.84}\pm0.33$
24.7	$\pm2.0\pm0.8$	8.25	$^{+0.41}_{-0.33}\pm0.58$
32.0	$\pm1.6\pm0.7$	9.85	$^{+0.97}_{+0.95}\pm0.69$
38.0	$\pm1.3\pm0.5$	11.0	$^{+0.57}_{-0.61}\pm0.77$

$\pi^-+p\rightarrow\eta+n$ total cross sections, stressing the achievement of the present experiment.

The spin-averaged squared amplitude $|f|^2$ is extracted from the total cross sections, through

$$|f|^2=\frac{p_d}{p_\eta}\times\frac{\sigma_T}{4\pi}, \qquad (2)$$

where p_d is the c.m. momentum of the incident deuteron. An S-wave production has been assumed near threshold. The values are presented in Fig. 3(a) as a function of p_η. The horizontal line shown on the same figure corresponds to $|f|^2=(24.6\pm1.2\pm1.7)$ nb/sr and results from a χ^2 test with a confidence level of 75%. The systematic error on $|f|^2$ corresponds to the $\pm7\%$ uncertainty due to the absolute monitor calibration.

The calculated total cross sections depend on the generator of α particles used in the simulations. In the above, the α particles have been generated in proportion to their momenta, as expected in a S-wave production, with an energy dependence only from the phase space factor.

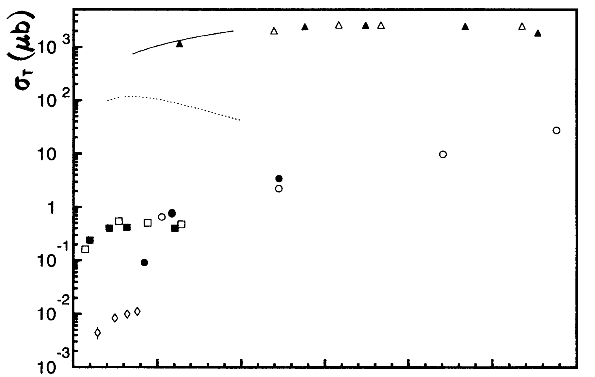

FIG. 2. Comparison of η production in different reactions near threshold. Total cross sections for the elementary process $\pi^-+p\rightarrow\eta+n$ (full triangles) [16], (empty triangles) [17], (solid line) [18]; $p+p\rightarrow p+p+\eta$ (full circle) [19], (empty circles) [20]; $n+p\rightarrow d+\eta$ (dashed curve) [21]; $p+d\rightarrow{}^3\mathrm{He}+\eta$ (full squares) [22], (empty squares) [23]; and this $d+d\rightarrow\alpha+\eta$ experiment (diamonds).

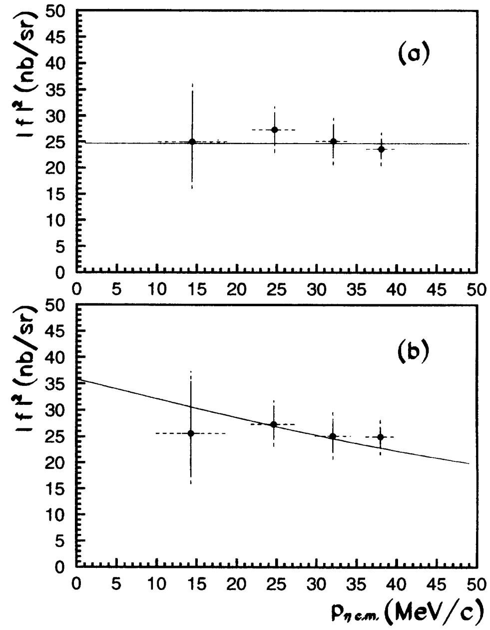

FIG. 3. (a) Squared amplitude $|f|^2$, defined by Eq. (2), as a function of the η c.m. momentum and fit by a constant value. (b) Squared amplitude $|f|^2$ and its corresponding theoretical calculation based on a model described by Eq. (3). Error bars on $|f|^2$ include statistical and systematic errors. Error bars on p_η come mainly from energy losses in the target and the absolute energy beam uncertainty.

Following a suggestion by Wilkin [10], a generator of events has also been built using the Goldberger and Watson [24] approximation, valid in the case of a weak transition to a channel with a strong final-state interaction at low energies. This model yields an amplitude f proportional to $(1-iap_\eta)^{-1}$, where a is the complex scattering length in the exit channel. With a scattering length $a=(-2+i)$ fm, obtained in Ref [10], from an optical potential model, the new generator produces events proportional to $p_\eta/|1-iap_\eta|^2$. The resulting amplitudes presented in Fig. 3(b) are close to those previously obtained.

The calculated squared matrix elements

$$|f|^2=\frac{|f_B|^2}{|1-iap_\eta|^2}, \qquad (3)$$

where f_B is a Born factor, are represented on the same figure [Fig. 3(b)] by the continuous line. The extrapolated value of these squared matrix elements at $p_\eta=0$ is $|f|^2=(35.9\pm1.3\pm2.5)$ nb/sr, with a confidence level of 45%.

With the value of $|f|^2=(24.6\pm1.2\pm1.7)$ nb/sr extracted from the first model, it is possible to make an estimation for the isospin-forbidden $d+d\rightarrow\alpha+\pi^0$ differential cross section using the Coon and Preedom external mixing model [4]. Through virtual η-production and π^0-η mixing Coon and Preedom deduce that

$$\left(\frac{d\sigma}{d\Omega}\right)_{\pi^0}=\frac{p_{\pi^0}}{p_\eta}\times\lambda_\eta^2\times\left[1+\frac{\lambda_{\eta'}}{\lambda_\eta}\tan\phi\right]^2\times\left(\frac{d\sigma}{d\Omega}\right)_\eta . \quad (4)$$

Using Ref. [25] parameter values of $\tan\phi=0.95$, $\lambda_\eta=0.021$, $\lambda_{\eta'}=0.006$, we find at a deuteron energy of 1120.3 MeV (the η-meson threshold energy, where $p_\pi=488$ MeV/c)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\pi^0}=(8.3\pm0.5\pm0.6)\ \text{pb/sr}. \quad (5)$$

This suggests that π^0-η mixing is mainly responsible for the isospin-forbidden $d+d\rightarrow\alpha+\pi^0$ near the η threshold and could explain the observation of a π^0 signal found in Ref. [1]. It would clearly be interesting to study the $d+d\rightarrow\alpha+\pi^0$ reaction not only below the η threshold but also slightly above.

In summary, total cross sections for η production near threshold in deuteron-deuteron interactions have been measured for the first time. The comparison between these results and the two models describing the resulting amplitudes favors an independent energy amplitude near threshold. Further experimental developments are possible, in particular in measuring the deuteron tensor analyzing power T_{20} close to threshold. Measurement at higher p_η should be done but this needs theoretical development, in particular to take into account other partial waves.

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