Abstract

The cross section and tensor analysing power $t_{20}$ of the $\vec{d}d \to \eta^4\text{He}$ reaction have been measured at six c.m. momenta, $10 \leq p_\eta \leq 90$ MeV/c. The threshold value of $t_{20}$ is consistent with $1/\sqrt{2}$, which follows from parity conservation and Bose symmetry. The much slower momentum variation observed for the reaction amplitude, as compared to that for the analogous $p\,d \to \eta^3\text{He}$ case, suggests strongly the existence of a quasi-bound state in the $\eta^4\text{He}$ system and optical model fits indicate that this probably also the case for $\eta^3\text{He}$.

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The near-threshold data on the $p\,d \to \eta^3\text{He}$ reaction [1,2] are remarkable for both their overall strength and energy variation. To quantify this, let us define a spin-averaged amplitude squared in terms of the unpolarised c.m. cross section by

$$|f|^2 = \frac{p_d}{p_\eta} \left( \frac{d\sigma}{d\Omega} \right),$$

(1)

where $p_d$ and $p_\eta$ are the initial and final c.m. momenta respectively. The threshold value for $\eta$ production is as big as that for $\pi$ production at its threshold, despite the much larger momentum transfer [1,2]. This has been interpreted as evidence for two-step processes with intermediate virtual pions [3]. Furthermore, while remaining essentially isotropic, $|f|^2$ falls by over a factor of three.
from threshold up to $p_\eta \approx 0.35$ fm$^{-1}$ [2]. As this corresponds to the change of only a few MeV in the incident beam energy, it must be associated with an interaction in the final state between the $\eta$ and $^3\text{He}$ [4]. Parametrising this interaction by an $S$–wave scattering length formula,

$$f = \frac{f_B}{1 - i\alpha p_\eta}, \quad (2)$$

where $f_B$ is slowly varying, the best fit is obtained with a scattering length [2]

$$a = \pm (3.8 \pm 0.6) + i(1.6 \pm 1.1) \text{ fm}. \quad (3)$$

It should be noted that the data are completely insensitive to the sign of $\text{Re}\{a\}$ and moreover that the errors on the real and imaginary parts of the scattering length are strongly correlated in the fit.

Such a large scattering length raises the question [4] of whether the $\eta$ meson can form quasi-bound states with nuclei much lighter than those originally suggested [5]. The existence of such states depends critically upon the sign of the real part of the scattering length, with $\text{Re}\{a\} < 0$ corresponding to ‘binding’; (c.f. the spin-triplet and singlet nucleon–nucleon systems where the negative value of $a_t$ corresponds to the existence of the deuteron). This quantity is difficult to estimate ab initio, due to both uncertainty in the form of the multiple scattering schemes to be used [6] and incomplete knowledge of the basic $\eta$–nucleon input [7].

The analogous $\eta^4\text{He}$ channel is most easily accessed through the $d\,d \rightarrow ^4\text{He}\,\eta$ reaction though, since the cross section is much smaller, the signal-to-background ratio is less favourable than for the $\eta^3\text{He}$ case. The signal can be enhanced by using a tensor polarised deuteron beam since parity conservation for a system of two identical deuterons ensures that at threshold or in the forward direction only deuterons with helicity $m = \pm 1$ can initiate the reaction [8], leading to a tensor analysing power of $t_{20} = 1/\sqrt{2}$. Constructing cross sections with different helicities through

$$\sigma_0 = (1 - t_{20}\sqrt{2}) \sigma, \quad \sigma_{\pm 1} = (1 + t_{20}/\sqrt{2}) \sigma, \quad (4)$$

where $\sigma$ is the unpolarised cross section, any $\eta$ signal near threshold should be observed only in $\sigma_{\pm 1}$.

Unpolarised $d\,d \rightarrow ^4\text{He}\,\eta$ data have been published from the SPES IV spectrometer at the Laboratoire National SATURNE (LNS) [9] for $p_\eta$ between 14 and 40 MeV/c. The present experiment used the large acceptance spectrometer SPES III at LNS. The $\bar{d}\,d \rightarrow ^4\text{He}\,\eta$ reaction was measured over a wider
range of $p_\eta$, at six different beam energies $T_d$ above threshold between 1121 and 1139 MeV ($10 < p_\eta < 90 \text{ MeV/c}$) with a tensor polarised deuteron beam. Two additional measurements were performed below the $\eta$ threshold to study background contributions. The SPES III magnetic spectrometer is sensitive to particles produced in a forward laboratory cone of $\pm 3^\circ$, giving a large solid angle of $\Delta \Omega \approx 10 \text{ msr}$. The momentum acceptance in $p/Z$ of $600 - 1400 \text{ MeV/c}$ covers the whole possible range of the $\vec{d}d \to ^4\text{He}X$ reaction and allows a full phase space acceptance ($4\pi$) for $\eta$ production from threshold up to 1139 MeV. This is a clear advantage over the SPES IV experiment where, even close to threshold, only $5 - 18\%$ of events could be seen [9].

A cryogenic deuterium target of 169 mg/cm$^2$ thickness was used. Empty-target measurements showed a flat background contribution of the order of 10%. The deuteron beam flux was monitored with an ionisation chamber in the beam and two scintillator telescopes viewing the target. Absolute normalisation of this monitoring system was established through the carbon activation method [10]. After also taking into account uncertainties in the target thickness, angular acceptance, corrections for detection efficiency and dead-time, an overall accuracy in the cross section normalisation of $\pm 12\%$ was achieved. The beam tensor polarisation is known to be very stable with a value of $\rho_{20} = 0.649 \pm 0.011$ [11].

Phase space varies as $\sqrt{T_d - T_d^{\text{thresh}}}$ so that a good knowledge of the beam energy is vital in evaluating the cross section very close to the production threshold energy $T_d^{\text{thresh}}$. The nominal beam energy delivered by the SATURNE synchrotron is subject to slight offsets of up to $1 - 2$ MeV, though changes of up to 20 MeV required in this experiment can be controlled to better than $\pm 0.1$ MeV. We observed both the forward and backward c.m. $\alpha$ peaks and close to the threshold of $\eta$ production their separation is a very sensitive determination of $p_\eta$. Taking the value of the $\eta$ mass as $m_\eta = 547.45 \text{ MeV/c}^2$ [12] and introducing it into a two-body Monte Carlo program, the beam energy is the only free parameter. Comparing data with the simulation fixes the deviation from the nominal central beam energy to be $(-1.2 \pm 0.1)$ MeV. A slightly different assumption for $m_\eta$ would give a modified energy shift, but this would be of no consequence when looking at the cross section as a function of $p_\eta$. A spread in beam energy arises mainly from the synchrotron ($\sigma_p/p \approx 2.5 \times 10^{-4}$) with smaller contributions coming from energy loss in the target, leading to an energy width of $\sigma \approx 250 \text{ keV}$.

The $\alpha$ particles were identified by time-of-flight and energy loss measurements between two scintillator hodoscopes placed 3 m apart. The electronics were tuned such as to suppress online most of the other particles produced, so that about 20% of the events written on tape contained $\alpha$ particles. The position measurement and trajectory reconstruction back to the target, and hence the evaluation of the momentum of the $\alpha$ particles, were carried out using the
information from two multiwire drift chambers. Further experimental details on the SPES III set-up can be found in ref. [13].

Fig. 1 shows the $\alpha$ particle laboratory momentum spectrum for the $d d \rightarrow ^4$He $X$ reaction at $T_d = 1125.8$ MeV without using the polarisation information of the beam. This is 5.5 MeV above the $\eta$ production threshold of $T_d^{\text{thresh}} = 1120.3$ MeV. The most prominent feature of the data are the so-called ABC enhancements [14,15] of the two-pion spectrum at $p/Z \approx 780$ and 1260 MeV/c, corresponding to a missing mass $m_{ABC} \approx 310$ MeV/c$^2$ produced in the forward and backward directions in the c.m. system. The maximum possible missing mass of the unobserved particle $X$ is detected near the centre of the spectrum in fig. 1, where a third broader peak is apparent.

The central peak contains events from two different reactions. There is first a ‘bump’, whose shape was fitted by a simple fourth order polynomial that is shown in the figure as a broken line. This ‘bump’ is also present below the $\eta$ threshold and its shape does not change significantly throughout the kinematic conditions of this experiment. Secondly, situated upon the central ‘bump’ is an almost rectangularly shaped peak which shows up for all measurements above the $\eta$ threshold. The shape is typical of an $S$–wave two-body reaction near threshold measured with complete spectrometer acceptance. It can be unambiguously associated with the $d d \rightarrow ^4$He $\eta$ reaction. The width of the peak is a direct measure of $T_d - T_d^{\text{thresh}}$, the rise on either side reflecting the resolution of beam and spectrometer.

To evaluate the number of $d d \rightarrow ^4$He $\eta$ counts one could simply apply the fitting method shown in fig. 1. Though all the $\eta$ events are contained within the central rectangle, it would be hard to evaluate the two-body cross section with precision without a detailed understanding of the central ‘bump’. There are however two important pieces of experimental information which can improve significantly the signal-to-background ratio and reduce the model dependence.

Transformation of the data in fig. 1 into the c.m. system makes use of the experimental knowledge of the scattering angle $\theta_{cm}^\alpha$. The peak for the two-body $\alpha\eta$ production will therefore be narrow as compared to the slowly varying $\alpha\pi\pi$ three-body reaction which dominates the background. In an attempt to eliminate non-$\eta$ background, data taken just below threshold were subtracted from above-threshold results. In the central region this could be done at fixed values of $p_\alpha$ but, by introducing a scaling variable

$$x = p_\alpha/p_\alpha^{\text{max}}, \quad (5)$$

it is possible to extend this comparison even into the ABC regions. Here $p_\alpha^{\text{max}}$ is the maximum possible value of the $\alpha$ particle momentum, corresponding to the production of a system with $m_x = 2m_\pi$. 4
The other important information to be used is the beam polarisation. The data transformed into the c.m. system are shown for helicities $m = 0$ and $m = \pm 1$ in fig. 2. The two upper plots show data for a beam energy below the $\eta$ threshold, $T_d = 1116.7$ (figs. 2a$_0$ and 2a$_1$). The central ‘bump’ is now divided into two sharper structures with a central dip dictated by phase space. Events where the $\alpha$ particle goes in the forward c.m. hemisphere are plotted with positive $x$. It should be noted that in general the polarised cross section for two-pion production need not to be symmetric around $\theta^{cm} = 90^\circ$. Analogous data above threshold at $T_d = 1125.8$ MeV, shown in figs. 2b$_0$ and 2b$_1$, look very similar apart from the presence of two narrow peaks in fig. 2b$_1$ corresponding to forward and backward going $\eta$ mesons. Using the beam intensity monitors to renormalise the below-threshold data to the same beam luminosity, it is possible to subtract the spectra from the above-threshold data, and these are shown in figs. 2c$_0$ and 2c$_1$. For helicity $m = 0$ there is no sign of any visible $\eta$ signal so that $t_{20}$ for $\eta$ production is consistent with a value of $+1/\sqrt{2}$. This provides a quantitative test of our subtraction procedure since conservation laws forbid such contributions. The two $\eta$ peaks for $m = \pm 1$ sit on a random background which on average vanishes. The number of good $\eta^4$He events is obtained by integrating the counts in the peaks and this leads to statistical errors of the order of 2%. The systematic error of the method has been carefully evaluated from the fluctuations outside the $\eta$ peaks and found to be between 3.5 and 8.3% of the counting rate in the peak, depending on the accumulated statistics.

The same procedure has been carried out on data from all the above-threshold measurements. Since there is full phase space acceptance for $\eta$ events up to $T_d = 1139$ MeV, no assumptions have to be made regarding the angular distribution of the reaction in order to extract the total production cross sections, whose values are given in table 1. In addition to the systematic errors discussed earlier, it must be noted that the lowest energy point involves an extra uncertainty due to an imprecision of 0.1 MeV in the central value of the beam energy and uncertainty in the shape of the energy spread. There is therefore significant model dependence for this point, especially in the value of the effective target thickness, induced through the energy loss in the target.

The spin-averaged $|f|^2$ are evaluated assuming the angular distribution to be isotropic, as is the case for $pd \rightarrow ^4$He$\eta$ up to quite high $\eta$ momenta [2], and which is consistent with our limited angular information. The values given in table 1 take into account that no $S$-wave $\eta$ production is possible for $m = 0$. The results of this and the SPES IV experiment [9], shown in fig. 3, are completely consistent though it must be borne in mind that the lowest points of both our and the SPES IV data have large error bars since the two experiments are subject to similar beam momentum resolution problems and hence effective target thickness uncertainties.
The variation of $|f|^2$ with $p_\eta$ is markedly less steep than that found for the $\eta^3$He system [2] and whose data, also illustrated in fig. 3, have suggested the existence of a quasi-bound $\eta^3$He state.

Direct fitting of the data with the scattering length formula of eq. (2) leads to large correlations between the real and imaginary parts and it is therefore appealing to fit both the $\eta^3$He and $\eta^4$He data simultaneously using a lowest order optical potential [4], for which

$$2m_R V_{opt}(r) = -4\pi A \rho(r) a(\eta N), \quad (6)$$

where $m_R$ is the $\eta$–nucleon reduced mass and $A$ the mass number of the residual nucleus. Gaussian nuclear densities $\rho(r)$ with rms radii of 1.9 fm and 1.63 fm were assumed for the $\eta^3$He and $\eta^4$He systems respectively. The best overall agreement is found with an $\eta$–nucleon scattering length of $a(\eta N) \approx (0.52 + 0.25i)$ fm. This is not dissimilar to the value deduced from $\pi^- p \rightarrow n \eta$ [7], but second order effects in the optical potential must be taken into account before a quantitative comparison is made.

This input $a(\eta N)$ scattering length leads to

$$a(\eta^3\text{He}) \approx (-2.3 + 3.2i) \text{ fm},$$
$$a(\eta^4\text{He}) \approx (-2.2 + 1.1i) \text{ fm}, \quad (7)$$

and the resulting curves are shown in fig. 3 (full lines). The negative signs on the real parts indicate that both systems are ‘bound’, though the imaginary parts give widths overlapping the thresholds. The difference to the fit given in eq.(3) reflects the error correlation between the real and imaginary parts of $a(\eta^3\text{He})$ which makes it hard to fix both parameters purely from the $\eta^3$He production data.

In fact, independent of any details of the $\eta$–nucleus scattering scheme, the $\eta^4$He system is expected to be more bound than $\eta^3$He due to the smaller radius of the $^4$He nucleus and the presence of one extra nucleon. This implies that in any scattering length fit

$$|Re \left\{ 1/a \left( \eta^4\text{He} \right) \right\}| > |Re \left\{ 1/a \left( \eta^3\text{He} \right) \right\}|, \quad (8)$$

and this is valid for the parameters derived above (0.36 versus 0.15 fm$^{-1}$).

Also shown in fig. 3 is the prediction of the two-step model with an intermediate virtual pion (broken curve) [8]. It is in reasonable agreement with the overall normalisation of the data, though the momentum dependence is too sharp, due to the form of the final state interaction assumed.
We have clearly shown that the momentum dependence is significantly flatter in the $\eta^4$He as compared to the $\eta^3$He case and this must arise because this system is more ‘bound’ and the pole pushed further away from the physical region. This argument depends weakly on any reaction mechanism but does not itself prove that $\eta^3$He is ‘bound’, though this is suggested strongly by the optical potential analysis taken in conjunction with the $\eta^4$He data. This indicates that further studies should be carried out on the $\eta$–deuteron channel to seek an exotic dibaryon at the $\eta$ threshold [16]. On the other hand any $\eta$ interaction with a heavier nucleus is likely to give too much binding to be seen in threshold production.

This was the last experiment carried out before the closure of the SPES III spectrometer. We should like to thank E. Tomasi-Gustafson for helping us in the beam polarisation measurements. We also greatly acknowledge the SAT-URNE accelerator crew for the excellent beam quality and the technical support.

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Fig. 1. Unpolarised momentum spectrum from the $d d \to ^4\text{He} X$ reaction at $T_d = 1125.8$ MeV. Due to the large acceptance of SPES III, events corresponding to $d d \to ^4\text{He} \eta$ fall in the rectangular-shaped peak lying on top of the dashed central ‘bump’, whose shape is consistent with the data taken below the $\eta$ threshold. The large enhancements at $p/Z = 800$ and 1250 MeV/c are known as the ABC effect [14,15]. The missing mass scale [MeV/c$^2$] in the top part of the figure is only valid for events with $\theta_{\text{cm}} = 0^\circ$ or $\theta_{\text{cm}} = 180^\circ$. $\pi^0$ and $\eta$ masses are indicated. While in the centre of the spectrum full phase space acceptance (4$\pi$) is provided, this no longer holds in the region of the ABC peaks.

Fig. 2. Spectra of the $\vec{d} d \to ^4\text{He} X$ reaction with helicities $m = 0$ ($a_0, b_0, c_0$) and $m = \pm 1$ ($a_1, b_1, c_1$), in terms of the c.m. scaling variable $x = p_\alpha/p_{\alpha}^{\text{max}}$. The correctly normalised data at $T_d = 1116.7$ MeV (a) are subtracted from those at $T_d = 1125.8$ MeV (b) to reveal two narrow peaks in (c$^1$) corresponding to forward and backward $\eta$ production in the c.m. system for helicities $m = \pm 1$. The $m = 0$ subtracted spectrum shown in (c$^0$) is consistent with random background with zero mean in the $\eta$ region.

Fig. 3. Averaged squared amplitudes of the $d d \to ^4\text{He} \eta$ reaction as functions of the $\eta$ c.m. momentum. Closed circles represent the results of this work; open circles are from ref. [9]. Error bars shown represent the systematic errors, including those arising from eq. (1) due to the imprecision in $p_\eta$. The data of ref. [2] on the $p d \to ^3\text{He} \eta$ reaction (crosses) vary markedly faster with $p_\eta$. Both shapes are well reproduced with the scattering length formula of eq. (2) (solid curves) using the optical potential fit values of eq. (7), as explained in the text. The broken curves are predictions in the two-step model of ref. [8], including a normalisation factor of 2.5 in the $\eta^3\text{He}$ case.
Total cross section for the $\vec{d}d \rightarrow ^4\text{He} \eta$ with helicities $m = \pm 1$ as functions of the c.m. momentum $p_\eta$ and the mean deuteron laboratory beam energy $T_d$, the scale for the latter being set using $m_\eta = 547.45$ MeV/$c^2$ [14]. Since our data are consistent with the result that only deuterons with $m = \pm 1$ can produce $S$–wave $\eta$ mesons, the unpolarised cross section $\sigma = \frac{2}{3} \sigma_{\pm 1}$. The spin-averaged amplitudes squared $|f|^2$ are obtained by assuming the angular distributions to be isotropic. The statistical errors of about 2% are added quadratically to the systematic error of the subtraction method. The lowest momentum point is subject to an additional systematic error due to the imprecision in the beam energy of 0.1 MeV causing an uncertainty in the effective target thickness. Note that, following eq.(1), the error in $|f|^2$ includes a contribution from $\Delta p_\eta$. Not shown in the table is the overall uncertainty of $\pm 12\%$ in absolute normalisation.

| $T_d$ (MeV) | $p_\eta$ (fm$^{-1}$) | $\Delta p_\eta$ (fm$^{-1}$) | $\sigma_{\pm 1}$ (nb) | $\Delta \sigma_{\pm 1}$ (nb) | $|f|^2$ (nb) | $\Delta |f|^2$ (nb/sr) |
|------------|-------------------|---------------------|------------------|-----------------|-------------|------------------|
| 1120.7     | 0.05              | 0.005               | 7.1              | $^{+1.5}_{-0.9}$ | 39.7        | $^{+15.3}_{-7.8}$ |
| 1121.8     | 0.12              | 0.008               | 13.2             | 0.9             | 31.2        | 3.0              |
| 1122.6     | 0.15              | 0.006               | 14.6             | 0.6             | 27.0        | 1.5              |
| 1125.8     | 0.24              | 0.004               | 19.2             | 1.6             | 22.3        | 1.9              |
| 1131.8     | 0.37              | 0.002               | 20.6             | 1.5             | 15.6        | 1.1              |
| 1138.8     | 0.46              | 0.002               | 22.4             | 1.6             | 13.6        | 1.0              |
$m=0$

$a_0 \quad 1116.7$

$b_0 \quad 1125.8$

$c_0$

$m=\pm 1$

$a_1 \quad 1116.7$

$b_1 \quad 1125.8$

$c_1$

$x = p/p_{\text{max}}$
