NEAR THRESHOLD η MESON PRODUCTION
IN THE $dd \rightarrow {}^4\text{He}\,\eta$ REACTION

A. Wrońska[*,†,1]**, V. Hejny**[†] **and C. Wilkin**[‡] **for the ANKE Collaboration**

[*]*Institute of Physics, Jagiellonian University, Reymonta 4, 30-059 Cracow, Poland*
[†]*Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[‡]*Physics & Astronomy Department, UCL, London WC1E 6BT, U.K.*

Investigation of the $dd \rightarrow {}^4\text{He}\,\eta$ reaction has been a part of the experimental programme at the ANKE facility of COSY-Jülich. In a first stage measurements were made at three excess energies: 2.6 MeV, 7.7 MeV as well as one below threshold for physical background studies. The experimental technique and the results are presented. The total cross sections obtained link well with the existing data, though there is some ambiguity at the higher energies, where some earlier data were taken with a polarised beam. Measured angular distributions indicate the onset of higher partial waves at only 7.7 MeV above threshold.

PACS: 13.60.Le, 25.10.+s, 25.45.-z, 11.80.Et

1   Introduction

The physics of the η meson revived when it was discovered, that the η–nucleus interaction is relatively strong and attractive. In the mid-eighties of last century the hypothesis of η–nucleus quasi–bound states was proposed [1–3]. The original predictions concerned heavier nuclei ($A > 11$), but experimental searches for such states were unsuccessful [4, 5]. More recently different theoretical approaches resulted in positive predictions for much lighter nuclei, *e.g.* helium isotopes [6–10]. Indeed, data on the $pd \rightarrow {}^3\text{He}\,\eta$ and $dd \rightarrow {}^4\text{He}\,\eta$ reactions obtained at the SATURNE accelerator [11–14] as well as in other laboratories [15–17] made some authors claim that already η–helium systems are bound [14, 18]. Attempts have also been made to produce the η–${}^3\text{He}$ bound state via the photoproduction reaction [19], though the analysis is not completely unambiguous [20].

It is important to stress that η–nucleus bound states should first occur in the s–wave. Thus, an analysis aiming at the extraction of the η-nucleus s–wave scattering length requires precise information on angular distributions, in particular on the contribution of the s–wave amplitude to the total cross section. For the $pd \rightarrow {}^3\text{He}\,\eta$ reaction, though some differential cross sections for higher Q values ($Q > 21$ MeV) are available, there are still some inconsistencies between

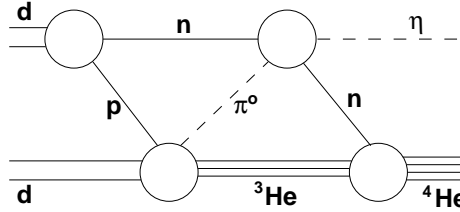---

[1]E-mail address: a.wronska@fz-juelich.de

Fig. 1. Two–step model adopted for the reaction $dd \rightarrow {}^4\text{He}\,\eta$. In fact the calculation comprises eight similar diagrams corresponding to interchanges of neutron and proton, ${}^3\text{He}$ and triton and π^0 and π^+.

various data sets on the total cross section close to threshold [21]. Angular distributions for the η–${}^4\text{He}$ system have never been measured and the existing data on the total cross section [13, 14] cover the energy range only up to $Q = 9$ MeV.

The question of the η–meson production mechanism also remains ambiguous. Simple models where one or more nucleons remain spectators undershoot the cross section due to the very large momentum transfer [22]. A contribution is required where all nucleons are involved in the reaction mechanism. The so–called two–step model has been originally proposed to describe the $pd \rightarrow {}^3\text{He}\,\eta$ process [23]. An extension of this scenario for the $dd \rightarrow {}^4\text{He}\,\eta$ case, depicted in Fig. 1, together with quantum mechanical calculation of the reaction amplitude was presented in Ref. [24]. This model, however, has only been evaluated in the s–wave limit. Extension to higher partial waves is desirable in order to investigate which of these first becomes significant.

2   Experiment with ANKE at COSY

The experiment [25, 26], aiming at the determination of total cross sections and angular distributions for $dd \rightarrow {}^4\text{He}\,\eta$ close to threshold, was performed in the Institut für Kernphysik of the Forschungszentrum Jülich. The measurement was carried out with the use of ANKE – an installation located at the internal target position at the COSY synchrotron [27] at three beam momenta 2.328 GeV/c, 2.343 GeV/c and 2.358 GeV/c. The first of these was a subthreshold measurement undertaken to study the shape of the physical background, considered to be mostly 2π production.

The principle of the measurement was the detection of the ${}^4\text{He}$ particles with, the η being identified through the missing mass technique. At the heart of ANKE are three magnets D1–D3, forming a chicane in the COSY ring, with the one in the middle (D2) being used as a spectrometer. The target is located between D1 and D2. Although ANKE is a rather complex facility, in our measurement only detectors from the forward system were used. These were multiwire drift chambers for track reconstruction and three layers of the scintillation hodoscope allowing time–of–flight and energy–loss determinations. Fig. 2 shows the layout of the detection system.

High count rates from the break–up reactions necessitated the application of a dedicated energy–loss–based trigger, which assured satisfactory background suppression for the data acquisition system. The discrimination threshold was set below the ΔE–p band of the ${}^3\text{He}$.

ANKE provides full acceptance for the $dd \rightarrow {}^4\text{He}\,\eta$ process up to $Q \approx 6.6$ MeV and, with appropriate acceptance corrections, measurement of angular distributions is possible even up to
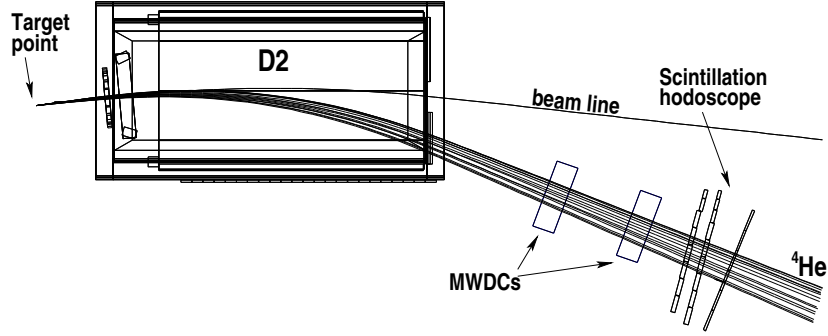
Fig. 2. The floor view of the ANKE forward detection system used in the experiment. Several trajectories of α-particles originating from the $dd \rightarrow {}^4\text{He}\,\eta$ reaction are depicted.
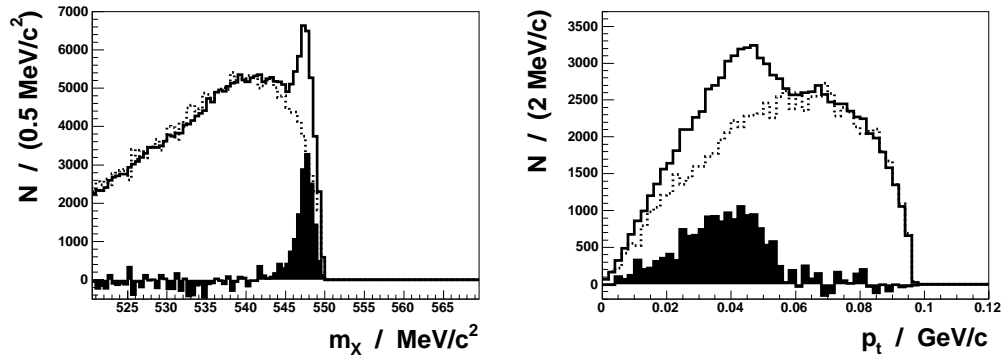

Fig. 3. Missing mass (left) and transverse momentum (right) distributions. Solid line represents data collected at $Q = 2.6$ MeV, dotted line the subthreshold data scaled kinematically to the same energy. Filled histograms, resulting from subtraction of background from signal, correspond to pure η production.

$Q \approx 90$ MeV. The angular resolution (in cms) determined in the simulations was not worse than $19°$ for the lower energy and $11°$ for the higher.

Event selection was accomplished by means of a set of two–dimensional cuts: three ΔE–p and two TOF–p. The overall suppression factor from minimum bias trigger to software ${}^4\text{He}$ selection amounted to about 10^5. The final momentum spectrum exhibited a three-peak structure, similar to those reported in Ref. [28]. In the collected sample of events with ${}^4\text{He}$ detection, the signal of η production was identified as a peak in the missing mass spectra, see left panel of Fig.3. It is also well seen in the transverse momentum distribution (Fig.3, right). As the resolution in the transverse momentum component is about four times better than that of the longitudinal component, the investigation of the transverse momentum spectrum provides direct information on the excess energy.
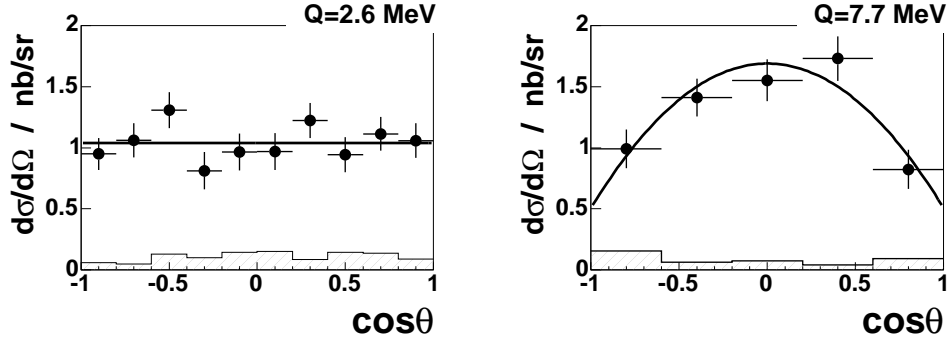
Fig. 4. Experimental angular distributions of the $dd \rightarrow {}^4\mathrm{He}\,\eta$ reaction at the two investigated excess energies. The error bars attached to the points are statistical, while the systematic ones are drawn as histograms. Lines represent the results of constant and quadratic fits.

3   Results and conclusions

To find the angular distributions of the ${}^4\mathrm{He}$ from the $dd \rightarrow {}^4\mathrm{He}\,\eta$ reaction, missing mass spectra were considered separately for each angular bin for both signal and scaled background events. For the lower energy above threshold, the statistics allowed a division into ten angular bins of equal width in $\cos\theta$. For the higher energy, where the statistics and missing mass resolution were worse, the data were divided into five bins. The resulting subtracted spectra, representing pure η signals, were integrated to give the angular distributions. Absolute normalisation was determined by comparing the observed yields for two processes: $dd \rightarrow {}^4\mathrm{He}\,X$ and $dd \rightarrow {}^3\mathrm{He}\,n$ with the data of Refs. [28, 29]. The two results are consistent within the overall uncertainties. However, the $dd \rightarrow {}^4\mathrm{He}\,X$ reaction is preferable for our purposes since it involves the detection of ${}^4\mathrm{He}$ particle with momenta similar to those arising from $dd \rightarrow {}^4\mathrm{He}\,\eta$. Uncertainties originating from the detection setup efficiency cancel completely and those in the acceptance at least partially. The angular distributions obtained are shown in Fig. 4 together with the fit results. At the lower energy the distribution is isotropic, while at the higher it reveals strong anisotropy, which can be described by $a(1 - b\cos^2\theta)$, with $a = 1.69 \pm 0.13$ nb/sr and $b = -0.70 \pm 0.16$ (odd powers of $\cos\theta$ vanish due to having two identical bosons in the entrance channel). The total cross sections at the two energies amounted to:

$$
\begin{aligned}
\sigma_1 &= (13.1 \pm 0.7_{\,\mathrm{stat}} \pm 1.8_{\,\mathrm{syst}})\ \mathrm{nb}\,, \\
\sigma_2 &= (16.4 \pm 1.0_{\,\mathrm{stat}} \pm 2.1_{\,\mathrm{syst}})\ \mathrm{nb}\,.
\end{aligned}
\tag{1}
$$

The systematic errors quoted here have been estimated by varying the conditions of the analysis within their uncertainties and do not include the 15% uncertainty in the luminosity, which does not affect the relative size of the cross section at the two energies.

In Fig. 5 we compare our results with the existing World data on the $dd \rightarrow {}^4\mathrm{He}\,\eta$ total cross section. Of the existing measurements, only one [13] was performed with an unpolarised beam, as in the ANKE experiment. The other [14] exploited a polarised deuteron beam of helicity $m = \pm 1$. Close to threshold, where the η–${}^4\mathrm{He}$ system is in the s–wave, this gives the only
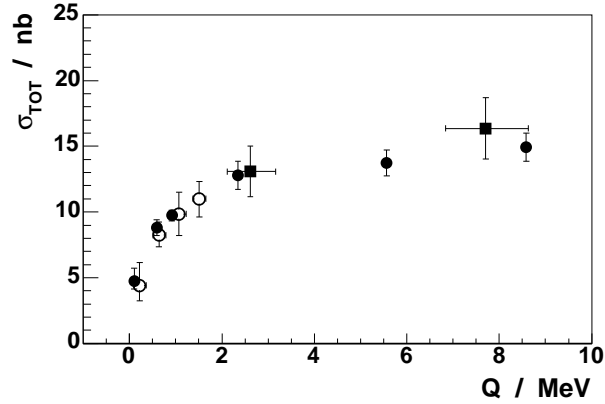
Fig. 5. World data on the unpolarised $dd \rightarrow {}^4\text{He}\,\eta$ cross section. Our results (squares) are compared to the data of Refs. [13] (open circles) and [14] (full circles), the latter being taken with the polarised beam.

non-vanishing cross section. Under the assumption of purely s–wave production the unpolarised cross section equals to 2/3 of $\sigma(m = \pm 1)$, as calculated in the original paper of Willis *et al.* [14]. The group observed no η signal for a beam polarisation $m = 0$ at $p_\eta = 48$ MeV/c, which is in line with the isotropic angular distribution found in our experiment at the lower energy, corresponding to $p_\eta = 50$ MeV/c. Unfortunately, there is no record in the publication of such an absence at higher energies. The evaluation of the unpolarised cross section depends on the partial waves composition assumed and cannot be performed in a completely model–independent way, as long as no additional polarised data are available.

The knowledge of the partial waves composition of the reaction amplitude is also crucial in approaches aiming at the determination of the η–${}^4\text{He}$ s–wave scattering length. For energies $Q > 4$ MeV the "threshold proximity" argument is no longer valid and a proper partial wave analysis is required in order to extract the s–wave reaction amplitude [25].

4 Outlook

The experiment presented here has been continued in a second beam time with measurements at excess energies of 22 MeV and 43 MeV. Due to the wider opening angle of the ${}^4\text{He}$ cone, the small–acceptance multiwire drift chambers were replaced by a larger set of proportional chambers. The data are currently under analysis.

In autumn 2003 another $dd \rightarrow {}^4\text{He}\,\eta$ experiment was proposed by the GEM collaboration [30]. Its main goal is a measurement of the tensor and vector analysing powers t_{20} and t_{11} along with the differential cross sections for several excess energies, starting at 22 MeV. Such data will provide deeper insight into the structure of the $dd \rightarrow {}^4\text{He}\,\eta$ reaction amplitude and will contribute to further studies of the reaction mechanism.

References

[1]   L.C. Liu, Q. Haider: *Phys. Rev.* **C 34** (1986) 1845

[2]   Q. Haider, L.C. Liu: *Phys. Lett.* **B 172** (1986) 257

[3]   H.C. Chiang, E. Oset, L.C. Liu: *Phys. Rev.* **C 44** (1991) 738

[4]   R. Chrien *et al.*: *Phys. Rev. Lett.* **60** (1988) 2595

[5]   B.J. Lieb *et al.*: COSY proposal 50 (2000)   http://www.fz-juelich.de/ikp/gem/Proposals/eta2000.ps

[6]   C. Wilkin: *Phys. Rev.* **C 47** (1993) 938

[7]   S. Wycech, A.M. Green, J.A. Niskanen: *Phys. Rev.* **C 52** (1995) 544

[8]   A. Fix, H. Arenhövel: *Phys. Rev.* **C 66** (2002) 024002

[9]   S.A. Rakityansky *et al.*: *Few Body Syst. Suppl.* **9** (1995) 227

[10] S.A. Rakityansky *et al.*: *Phys. Rev.* **C 53** (1996) 2043

[11] J. Berger *et al.*: *Phys. Rev. Lett.* **61** (1988) 919

[12] B. Mayer *et al.*: *Phys. Rev.* **C 53** (1996) 2068

[13] R. Frascaria *et al.*: *Phys. Rev.* **C 50** (1994) 537

[14] N. Willis *et al.*: *Phys. Lett.* **B 406** (1997) 14

[15] M. Betigeri *et al.*: *Phys. Lett.* **B 472** (2000) 267

[16] R. Bilger *et al.*: *Phys. Rev.* **C 65** (2002) 044608

[17] H.H. Adam *et al.*: *Int. J. Mod. Phys.* **A 20** (2005) 643

[18] V.A. Tryasuchev: *Phys. Atom. Nucl.* **60** (1997) 186

[19] M. Pfeiffer *et al.*: *Phys. Rev. Lett.* **92** (2004) 252001

[20] C. Hanhart: *Phys. Rev. Lett.* **94** (2005) 049101

[21] A. Sibirtsev *et al.*: *Eur. Phys. J.* **A22** (2004) 495

[22] J.-F. Germond, C. Wilkin: *J. Phys.* **G 15** (1989) 437

[23] K. Kilian, H. Nann: *AIP Conf. Proc.* **221** (1990) 185

[24] G. Fäldt, C. Wilkin: *Nucl. Phys.* **A 596** (1996) 488

[25] A. Wrońska *et al.*: submitted to *Eur. Phys. J.*

[26] A. Wrońska: PhD thesis, Jagiellonian University, Cracow (2005)

[27] S. Barsov *et al.*: *Nucl. Inst. Meth.* **A 462** (2001) 364

[28] J. Banaigs *et al.*: *Nucl. Phys.* **B 105** (1976) 52

[29] G. Bizard *et al.*: *Phys. Rev.* **C 22** (1980) 1632

[30] H. Machner *et al.*: COSY proposal 124 (2003) http://www.fz-juelich.de/ikp/gem/Proposals/dd2alphaeta.pdf