Investigation of the $^3He\,\eta$ final state in the reaction $dp \rightarrow ^3He\,\eta$ at ANKE

A. Khoukaz, R. Menke, T. Mersmann, N. Lang, J.P. Wessels
Institut für Kernphysik, Universität Münster
Wilhelm-Klemm-Str. 9, D-48149 Münster, Germany

C. Hanhart, A. Sibirtsev
Institut für Theoretische Physik, Forschungszentrum Jülich,
D-52425 Jülich, Germany

C. Wilkin
University College London, London, WC1E 6BT, UK

... to be discussed ...
and the ANKE collaboration

Spokesperson: A. Khoukaz (khoukaz@uni-muenster.de)

March 9, 2004

Abstract

Measurements on the near threshold production of the $^3He\,\eta$ final state in deuteron-proton collisions are of great interest with respect to still open questions concerning the strong attractive η-nucleon and η-nucleus final state interactions and the possible existence of quasi-bound η-nucleus states. To continue and to complete our previous measurements, which have been carried out successfully at the COSY-11 installation, we apply for two weeks of beam time. Although the main focus of our measurements will be the investigation in very near threshold region, we also propose to enlarge our measurements to the range of intermediate excess energies (up to Q = 60 MeV) in order to clarify the indefinite situation concerning the total cross sections.

This will also allow to study the angular distribution of emitted η-mesons in detail, which reveal a transition from isotropic emission at threshold to a highly non-isotropic behavior above Q = 20 MeV. For acceptance reasons the applied measurements will be performed using the ANKE spectrometer in combination with a deuteron beam.

1 Introduction

During the last decade the η interaction with nucleons and nuclei has attracted much attention both experimentally and theoretically. One reason for this excitement is the possibility of the formation of η-nucleus bound states. The existence of such so-called η-mesic nuclei was first predicted by Haider and Liu [1] based on the observation that the elementary ηN interaction is attractive and relatively strong [2]. It is expected that the attraction gets increasingly stronger with increasing mass number of the nuclei and eventually should lead to a bound state. However, so far it is unclear for which mass number that actually happens. For example, in the literature one can find speculations that even the ηd system might already form such a bound state [3] which, however, is disputed by other investigations [4]. More conservative estimations consider the η^4He system as the lightest possible candidate [5, 6, 7]. Heavier nuclei were studied theoretically e.g. in Ref. [8] where it was concluded that although there should be bound states, their width could be of the order of the binding energy making a direct observation of these states very difficult. Experimentally a first indication for the possible existence of a η^3He bound state was reported in Ref. [9].

The occurrence of a bound state near the reaction threshold will be also reflected in the corresponding η–nucleus scattering length [10]. In such a case the (real part of the) scattering length should be relatively large and negative whereas its imaginary part should be small. Studies of the η-nucleus interaction near threshold, as it will show up as final state interaction in production reactions, can be used to determine the η-nucleus scattering length, and then, in principle, would permit conclusions on the existence of such η-nucleus bound states. In order to disentangle the real part and the imaginary part of the scattering length data very close to the production threshold is required [11]. The argument might be made more quantitative by looking directly at the expression for the expected energy dependence. If there is a near by singularity (corresponding to a (quasi–)bound state) in the η^3He system, the effect of the η–nucleus final state interaction on the energy dependence of the production reaction is given by

$$\frac{1}{1+2\cdot\mathrm{Im}(a)k+|a|^2k^2}\ , \tag{1}$$

where k denotes the center–of–mass momentum of the outgoing η. Thus, if we want to disentangle the real and imaginary part of the scattering length, measurements in a regime where $2\cdot\mathrm{Im}(a)k \sim |a|^2k^2$ are necessary. Assuming $\mathrm{Im}(a) \sim 1$ fm and $\mathrm{Re}(a) \sim 4$ fm (this pair of values is in accordance with the existing data base) the above formula would demand a measurement at a few MeV excess energy. In Ref. [11] it was demonstrated that the energy

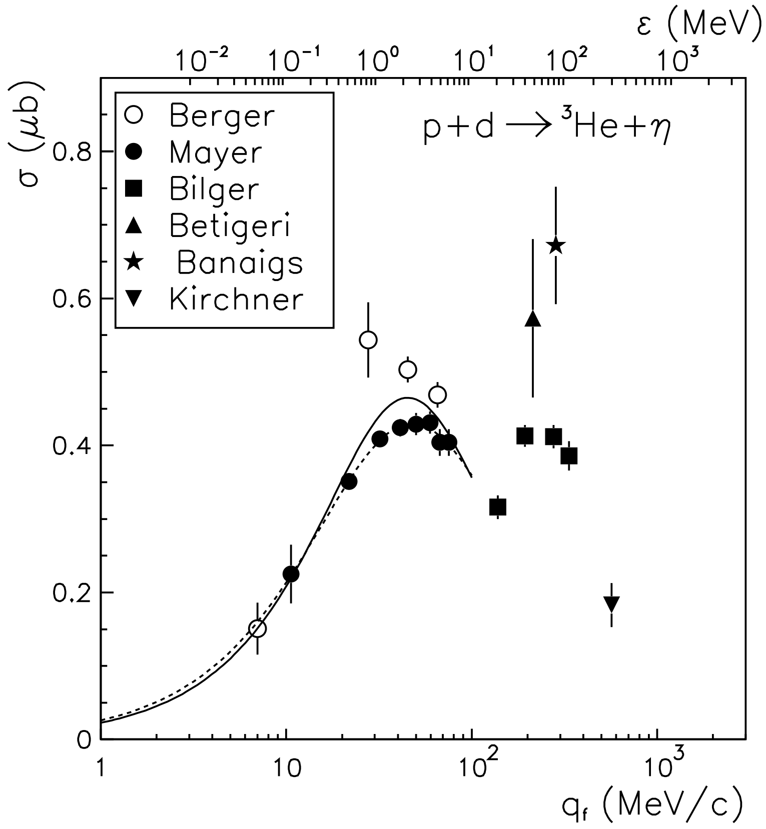

Figure 1: The $pd \rightarrow ^3He\,\eta$ total cross section as a function of the final momentum q in the c.m. system (lower axis) or excess energy ϵ (upper axis). The data are from Refs. [13, 14, 15, 16, 17, 18]. The solid line represents an overall fit by Eq. (1) to low energy data published by Mayer *et al.* [15] and Berger *et al.* [13], while the dashed line represents a fit to the data from Mayer *et al.* [15] alone. The figure is taken from [11].

dependence of currently existing (admittedly conflicting) world data set for $pd \rightarrow ^3He\,\eta$ (Fig.1) seem to be consistent with a quite small imaginary part of the $^3He\,\eta$ scattering length—this imaginary part might be significantly smaller than three times that of ηN scattering. Note, in Ref. [12] it was argued that this can be possibly understood as a consequence of the Pauli principle. In Ref. [7] it was stressed that a necessary condition for the existence of a η^3He bound state is that $|Re(a)| > Im(a)$. All those arguments clearly call for a high quality measurement of the reaction $pd \rightarrow ^3He\,\eta$ close to the production threshold. The existing discrepancies between the available data are also reflected in Fig.1 (figure taken from [11]).

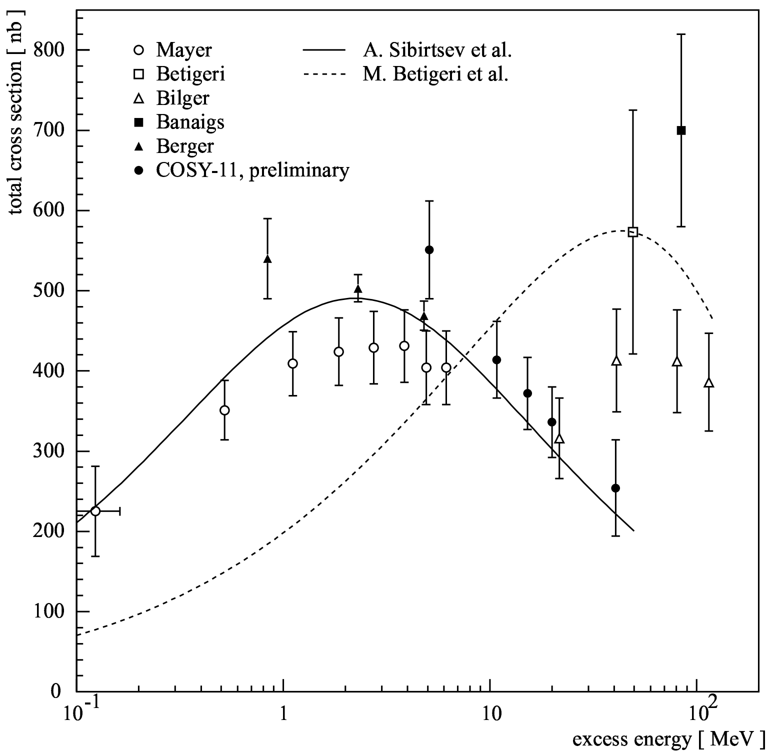

Figure 2: Energy dependence of the total cross section for the $pd \rightarrow ^3He\,\eta$ reaction including preliminary data from COSY-11 [19]. The solid line indicates a fit to the published data based on s-wave final state interaction [11] while the dashed line represents a resonance model calculation employing the matrix element from photoproduction on the proton [17].

A contribution to clarify this situation was made by the COSY-11 collaboration by studying this reaction channel at five different excess energies of Q = 5.1, 10.8, 15.2, 20.0 and 40.6 MeV [19]. These energies have been chosen to fill the open gap between Q = 7 MeV and Q = 49 MeV of the up to that time existing data. The data are currently under final evaluation and are displayed in Fig. 2. Although preliminary, in the studied region of excess energies these data confirm the decrease of the total cross sections as predicted by the model calculations from Wilkin [20, 11]. Here the energy dependence of the cross sections is assumed to be dominated by a strong $^3He\,\eta$ final state interaction. Contrary, predictions by Betigeri et al. [17] (Fig. 2, dashed line), based on resonance model calculation employing the matrix element from photoproduction on the proton, can be excluded.

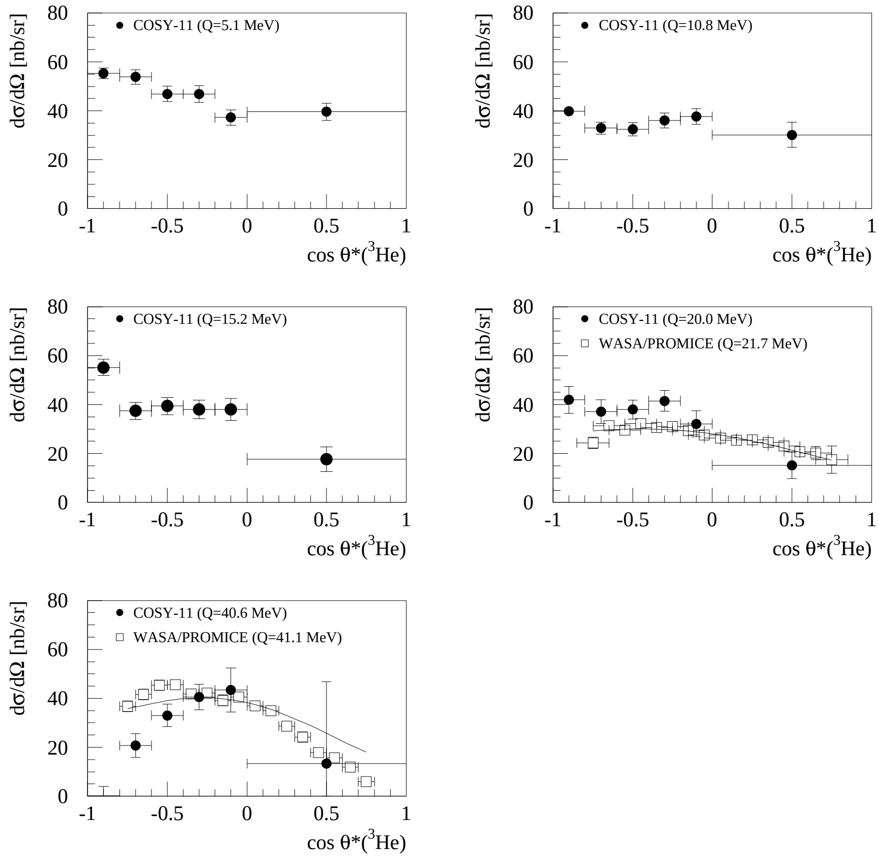

Figure 3: Comparison of angular distributions of emitted ^3He-nuclei in the c.m. system obtained at CELSIUS [16] with preliminary results from COSY-11 [19]. The solid lines represent two-step calculations from Stenmark [21].

Furthermore, the preliminary data from COSY-11 (Fig. 3) indicate a transition of the ^3He c.m.s. angular distributions from s-wave near threshold to distinct contributions from higher partial waves in the regime of intermediate excess energies (Q $\geq$ 20 MeV). This observation is in accordance with measurements from Mayer et al. [15], reporting pure s-wave distributions for Q $\leq$ 7 MeV, and the remaining data sets (above Q = 20 MeV), displaying highly anisotropic emissions. However, the limited statistics of $\sim$ 350-6300 detected events per excess energy limits the quality of the obtained angular spectra. For a more detailed study of the observed transition measurements with high statistics are essential.

2 The reaction $dp \rightarrow ^3He\,\eta$ at ANKE

Monte-Carlo simulations clearly show that the ANKE installation in combination with a deuteron beam is highly suited to study the $dp \rightarrow ^3He\,\eta$ reaction from threshold up to higher excess energies. Fig.4 shows Monte-Carlo generated tracks for this reaction channel at an excess energy of Q = 10 MeV.

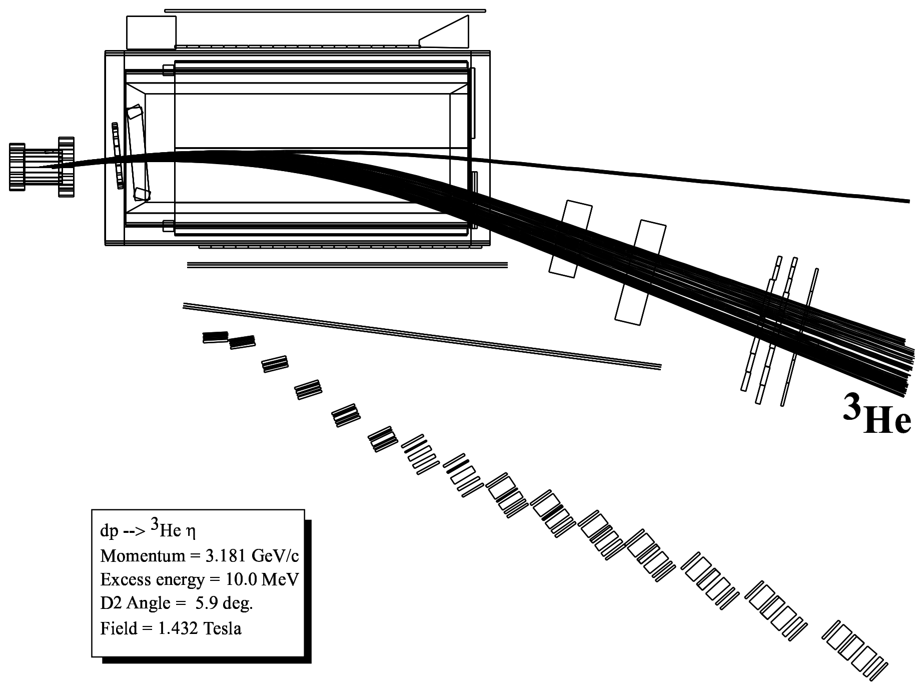

Figure 4: Sketch of the ANKE installation with Monte-Carlo simulated tracks from $dp \rightarrow ^3He\,\eta$ reaction at an excess energy of Q = 10 MeV.

The outgoing ^3He-nuclei can be registered in the forward detection system while the four-momentum components of the produced η-mesons can be reconstructed using the missing mass technique. The main advantage of the ANKE facility is the large acceptance for this reaction channel. As can be seen from Fig.5 the total geometrical acceptance for the detection of ^3He-nuclei amounts to 100% for excess energies of Q $<$ 10 MeV. Therefore, the development of the excitation function and therewith the production amplitude $|f(Q)|^2$ can be studied in the region of interest with minimum systematical errors. Furthermore, even at higher excess energies the total acceptance is comparatively large, which allows to study the $^3He\,\eta$-production effectively.

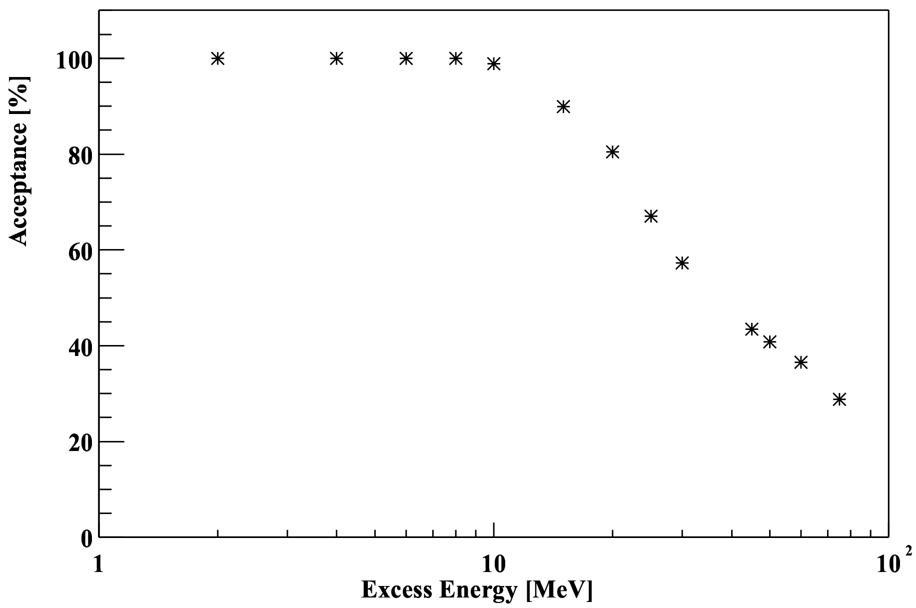

Figure 5: Total geometrical acceptance for the detection of ^3He-nuclei originating from the $dp \rightarrow ^3He\,\eta$ reaction. Note that for excess energies below 10 MeV the geometrical acceptance amounts to 100%.

Important for the interpretation of the obtained data is a reasonable geometrical acceptance of the detection system for the whole range of polar scattering angles θ in the total center of mass system. In Fig.6 a sample of such acceptances is presented for excess energies of Q = 10, 15, 30 and 60 MeV. From the first figure (Q = 10 MeV) the large acceptance for near threshold measurements becomes obvious. At lower excess energies the acceptance amounts to $\epsilon \sim 100\%$ and no corrections have to be considered, which reduces systematical uncertainties. Even at higher excess energies the angular acceptance keeps rather good and presents no gaps. It is worth to note that the ANKE installation provides also large acceptances in the range of $\cos(\theta) = \pm 1$.

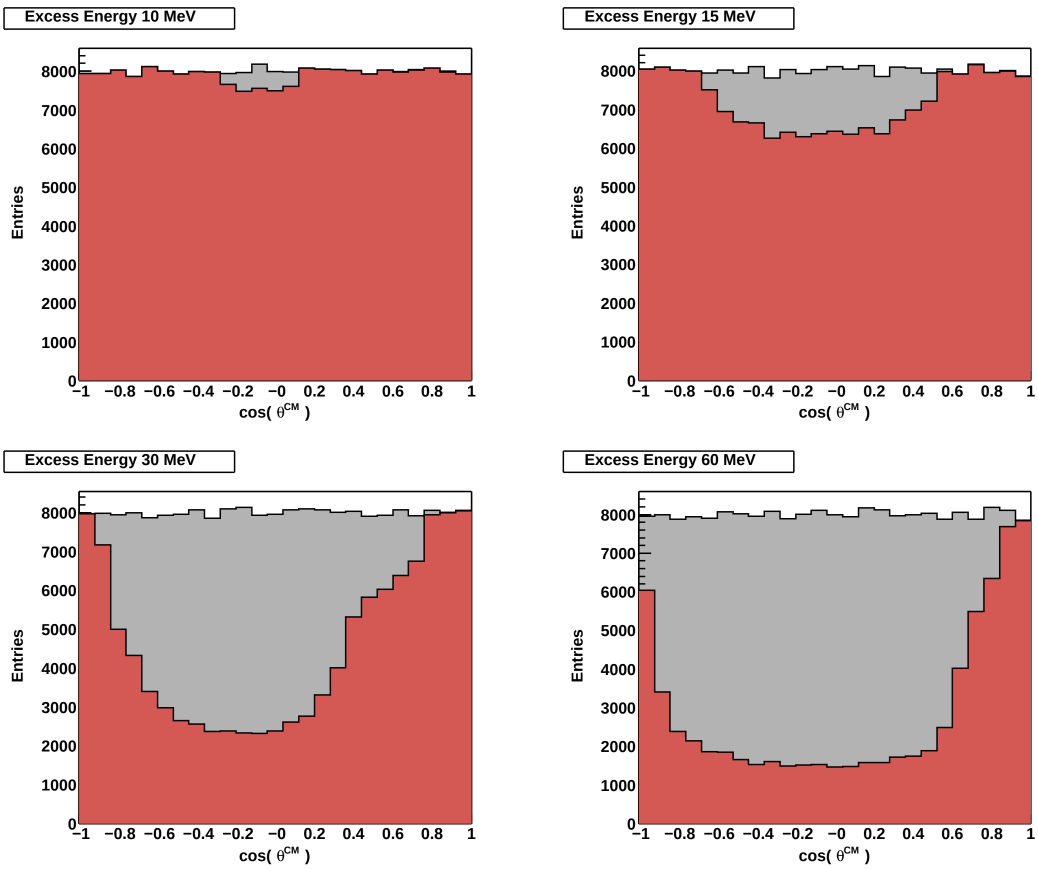

Figure 6: Angular acceptance of the ANKE-spectrometer for the $dp \rightarrow ^3He\,\eta$ reaction for excess energies of Q = 10, 15, 30 and 60 MeV.

The identification of emitted ^3He-nuclei can easily be performed using the energy loss information of the scintillation walls of the forward detection system. In Fig.7 the energy loss of particles detected in the first scintillation hodoscope is presented as function of the corresponding energy loss in the second layer, obtained in dp-collisions at ANKE at an beam momentum of $p_{deut.} = 3.3$ GeV/c [22]. In the region of high energy losses and above the deuteron signal a clear region originating from ^3He-nuclei becomes obvious. Therefore, this information can be used both for trigger purposes and event selection in the offline data analysis.

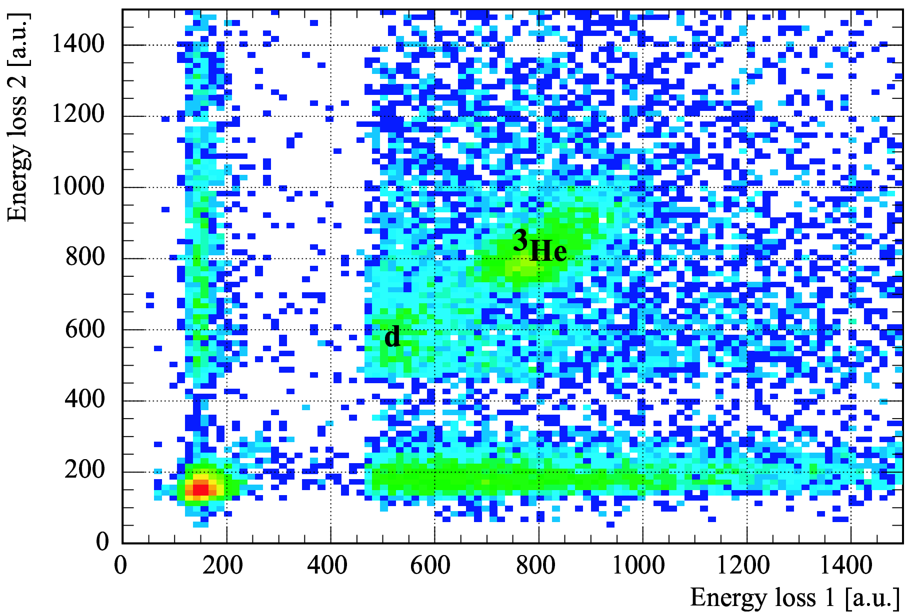

Figure 7: Energy loss information of the second scintillation hodoscope as function of the corresponding information from the first hodoscope.

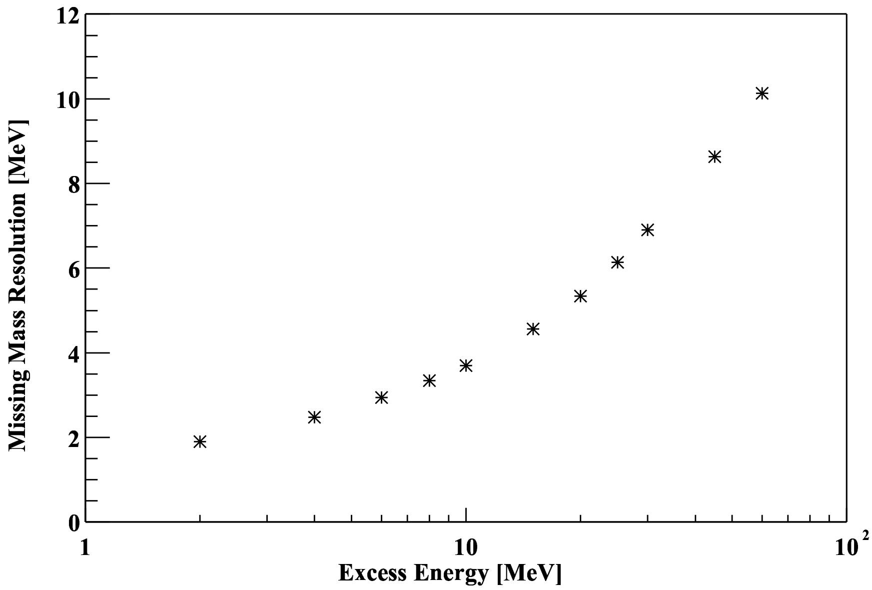

Figure 8: Expected missing mass resolution for the identification of η-mesons at ANKE.

The produced η-mesons will be identified using the missing-mass technique. Based on information from recent measurements and using Monte-Carlo simulations the expected missing-mass resolution as function of the excess energy has been determined and is presented in Fig.8. In the close-to-threshold region a good mass resolution of less than 4 MeV is expected and even at higher excess energies a reasonable mass determination is feasible.

3 Luminosity determination

At all proposed energies the luminosity will be determined by a simultaneous measurement of the dp elastic scattering. Beside a clear identification of this reaction by the detection of the scattered deuterons in the forward detector and the availability of reference data in the region of beam momenta and momentum transfers [23], the only weak energy dependence of the dp elastic cross section over the region of interest guaranties for a high precision in the determination of the relative development of the production amplitude. Detailed information on this topic can be found in the current ANKE beam time request #125 [24].

4 Counting rate estimate and beam time request

We propose to study the $dp \rightarrow^3 He\,\eta$ reaction with minimum statistical and systematical errors from threshold up to higher excess energies (Q = 60 MeV) in order to complete our studies on the $^3He\,\eta$ production in proton-deuteron collisions. One focus of interest will be detailed studies on the close-to-threshold behaviour of the total cross sections in order to extract precise information on the $^3He\,\eta$ final state interaction. For this purpose we propose to take data at excess energies of Q = 1, 2, 4, 6, 8 and 10 MeV. Assuming a mean luminosity of $L = 5 \cdot 10^{30}$ cm^{-2}s^{-1} (proton target density $\rho_{target} = 1.5 \cdot 10^{14}$ atoms/cm^2, number of stored deuterons in COSY $N_{beam} = 5 \cdot 10^{10}$, track reconstruction efficiency of 70% in the forward chambers, DAQ dead time of 20%) and a mean total cross section of $\sigma_{mean} \sim 400$ nb for the $dp \rightarrow^3 He\,\eta$ reaction in this region of excess energies, one expects a mean number of N = 170.000 detected events per day. Thus only one day of beam time per excess energy will be sufficient to extract these events with a low statistical error. However, for this purpose also a precise knowledge of the background situation is necessary. Therefore, it is planned to perform a measurement during one additional day of beam time at an excess energy

below the η-meson threshold (Q = -5 MeV).
The second focus of interest will be the investigation of the development of higher partial waves from threshold up to Q = 60 MeV. Thus, it is planned to take data at four further excess energies of Q = 15, 30, 45 and 60 MeV. Assuming a mean total cross section of $\sigma_{mean} \sim 300$ nb, we expect counting rates between 116.000 (Q = 15 MeV) and 47.300 (Q = 60 MeV) events per day. This expected number of events will allow for a fine segmentation ($\geq$20 bins) of the observed angular distribution with still a sufficiently high precision.

excess energy	**beam momentum**	**requested beam time**
-5 MeV	3.118 GeV/c	1 day
1 MeV	3.144 GeV/c	1 day
2 MeV	3.148 GeV/c	1 day
4 MeV	3.156 GeV/c	1 day
6 MeV	3.164 GeV/c	1 day
8 MeV	3.173 GeV/c	1 day
10 MeV	3.181 GeV/c	1 day
15 MeV	3.202 GeV/c	1 day
30 MeV	3.264 GeV/c	1 day
45 MeV	3.327 GeV/c	2 days
60 MeV	3.389 GeV/c	2 days
trigger and beam adjustment		1 day
total beam time request		**2 weeks**

5 Future plans: Investigation of the $dp \rightarrow {}^3He\,\eta$ at ANKE using a polarized deuteron beam

Since the polarized COSY deuteron-beam is by an order of magnitude less intense than the unpolarized one, the previously described proposal, a high statistic measurement of the ${}^3He\,\eta$ final state from threshold up to high excess energies to complete previous studies with minimum uncertainties, should definitively be performed in one continuous block of beam time using an unpolarized deuteron beam. However, the possibility to utilize a polarized deuteron beam will allow to illuminate the underlying mechanism by a different approach. As discussed above the $pd \rightarrow {}^3He\,\eta$ reaction near threshold shows a very striking energy dependence [13, 15]. Despite the angular distribution remaining essentially isotropic, the square of the amplitude decreases by a factor of three over a few MeV in excess energy. The general feeling is that this is due to a very strong final state interaction between the η and the ^{3}He, which suggests that this system has a nearby pole in the complex momentum plane. It is still a subject of much speculation as to whether this corresponds to a quasi-bound state or not, depending largely upon the sign of the imaginary part of the pole position.

If the FSI interpretation is correct, the effect should depend only weakly upon the characteristics of the entrance channel and it is very important to verify this. Data on $\gamma\,{}^3\mathrm{He} \to \eta\,{}^3\mathrm{He}$ from Mainz [9] seem to show an even stronger energy dependence but these are not as precise as the Saclay $pd \to {}^3\mathrm{He}\,\eta$ results and cannot be used to constrain the pole position.

Now close to threshold there are two independent $\vec{d}p \to {}^3\mathrm{He}\,\eta$ amplitudes and these can be thought of as spin-$\frac{3}{2}$ or spin-$\frac{1}{2}$ combinations of the dp spins coupled with $L_{dp} = 1$ to give the overall $J = \frac{1}{2}^-$ state. An alternative decomposition was given by Germond & Wilkin [25] and used by Kerboul *et al.* [26] to describe the analogous π^0 production amplitudes.

$$f = \bar{u}_\tau \vec{p}_p \cdot \left(A\,\vec{\varepsilon}_d + iB\,\vec{\varepsilon}_d \times \vec{\sigma}\right)\, u_p\,. \tag{2}$$

The moduli-squared of the two amplitudes A and B can be separated by measurements of the differential cross sections and tensor analysing power t_{20}:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \tfrac{1}{6}p_p p_\eta \left[|A|^2 + 2|B|^2\right]\,, \tag{3}$$

$$t_{20} = \sqrt{2}\left[\frac{|B|^2 - |A|^2}{|A|^2 + 2|B|^2}\right]\,. \tag{4}$$

Other analysing powers, such as t_{22} and it_{11} are expected to remain small close to threshold.

Now the pioneering experiment of the SPESIV group [13], where CW took a night shift, showed t_{20} to be small, so that both $|A|^2$ and $|B|^2$ are significant. However, the data were clearly insufficient to determine the energy dependence of the A and B amplitudes separately. This could also not be checked in the SPESII experiment [15] because a proton beam was used there.

Therefore, after the completion of high statistic unpolarized measurements we want to propose in future to extend our experimental program to measurements on the energy variation of $|A|^2$ and $|B|^2$ near threshold in the $\vec{d}p \to {}^3\mathrm{He}\,\eta$ reaction to see whether the striking $\eta\,{}^3$He FSI effect is the same for two different entrance channels. The results should have a significant impact on the ongoing discussions of the possible existence of η-mesic nuclei.

However, before submitting a dedicated experimental proposal we suggest to study the feasibility of such measurements parasitically during one future ANKE beam time on the charge-exchange $np \to pn$ [24] which also will be performed using a polarized deuteron beam in combination with a proton cluster-jet target. For this purpose the charge-exchange reaction will be studied among other beam momenta at one setting corresponding to the $dp \to ^3He\,\eta$ production at an excess energy of Q = 8 MeV.

References

[1] Q. Haider and L.C. Liu, Phys. Lett. B **172**, 257 (1986); **174**, 465 (E) (1986).

[2] R.S. Bhalerao and L.C. Liu, Phys. Rev. Lett. **54**, 865 (1985).

[3] T. Ueda, Phys. Rev. Lett. **66**, 297 (1991); N.V. Shevchenko *et al.*, Eur. Phys. J. A **9**, 143 (2000); S. Wycech and A.M. Green, Phys. Rev. **C 64**, 045206 (2001).

[4] A. Fix and H. Arenhövel, Eur. Phys. J. A **9**, 119 (2000); H. Garcilazo and M.T. Peña, Phys. Rev. **C 63**, 021001 (2001).

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

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

[7] Q. Haider and L.C. Liu, Phys. Rev. **C 66**, 045208 (2002).

[8] C. Garcia-Recio, J. Nieves, T. Inoue and E. Oset, Phys. Lett. B **550** (2002) 47

[9] M. Pfeiffer *et al.*, arXiv:nucl-ex/0312011.

[10] R.G. Newton, *Scattering Theory of Waves and Particles* (Springer-Verlag, New York, 1982).

[11] A. Sibirtsev, J. Haidenbauer, C. Hanhart and J. A. Niskanen, arXiv:nucl-th/0310079.

[12] V. Baru, C. Hanhart, A. E. Kudryavtsev and U. G. Meissner, arXiv:nucl-th/0402027.

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

[14] J. Banaigs *et al.*, Phys. Lett. B **45**, 394 (1973).

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

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

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

[18] T. Kirchner, PhD. Thesis, Institute de Physique Nucleaire, Orsay (1993).

[19] H.-H. Adam, PhD. Thesis (in preparation), Institut für Kernphysik, Universität Münster, Germany (2004).

[20] C. Wilkin, Phys. Rev. C. **47**, R938 (1993).

[21] M. Stenmark, Phys. Rev. C **67**, 034906 (2003).

[22] A. Kacharava et al., COSY-Proposal #125: *The polarized charge exchange reaction d(pol.)+p $\rightarrow$ (pp)$^1S_0$+n*, (2003).

[23] N. Katayama *et al.*, Nucl. Phys. A **438**, 685 (1985).

[24] A. Kacharava et al., COSY Beam Request for the Proposal #125: *First measurement of the Charge-Exchange np $\rightarrow$ pn Reaction with Polarized Deuteron Beam at ANKE*, (2004).

[25] J.-F. Germond & C. Wilkin, J. Phys. **G14**, 181 (1988).

[26] C. Kerboul *et al.*, Phys. Lett. **181B**, 28 (1986).