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THE η MESON PHYSICS PROGRAM AT GEM[1]

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for the GEM collaboration
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Some experimental studies of η production and η interactions performed or presently under way by the GEM collaboration at COSY Jülich are reviewed.

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1 Introduction

The GEM collaboration operates the GEM detector, i. e. a stack of **Ge**rmanium diodes and a **M**agnetic spectrograph. The germanium wall [1] consists of four annular detectors. The first one is position sensitive with 200 Archimedes spirals on the front and also on the rear side but with

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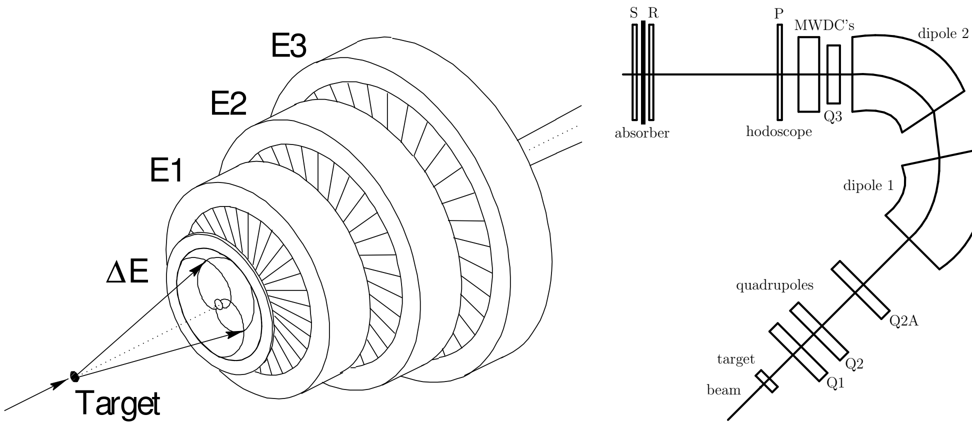

Fig. 1. Left: Perspective view of the germanium wall. An event with two hits is indicated. The diameter of the active area on last diode is 7.7 cm. Right: Cross section of the magnetic spectrograph Big Karl. Note the difference in size to the germanium wall. The flight path from the target to the focal plane is ≈ 15 m long.

opposite orientation. In this way 40000 pixels are defined. It delivers the position (see Fig. 1) and gives a ΔE information. The following thick detectors are segmented into 32 wedges. The total thickness of the germanium wall is ≈ 51 mm. Due to the different topologies one can identify multiple hits. The magnetic spectrograph is schematically also shown in Fig. 1. It is a high resolution device. Reaction products pass through three quadrupole magnets and two dipole magnets. It has point to parallel imaging in the vertical and point to point imaging in the horizontal direction. The last quadrupole magnet $Q3$ is not in use in this operation mode. The direction of the reaction products are measured with MWDC's, twelve layers in two packs. The are followed by scintillator hodoscopes P, R, S which give ΔE information and allow for a time of flight (TOF) measurement. For further particle identification absorber material can be placed between the last two layers. More properties are given in [2]. For the study of the existence of bound η-nuclear states an additional detector ENSTAR around the target was built. It was recently used in a search employing the reaction $p + {}^{27}Al \to {}^{3}He + ({}_{\eta}{}^{25}Mg)$ at recoil free conditions with a second step $\eta + n \to N^{0*} \to \pi^- + p$. The ${}^3He$ was detected in the magnetic spectrograph while the second step was identified in ENSTAR. Details is discussed in the contribution by Gillitzer [3].

2 The reaction $p + d \to {}^3He + \eta$

The reaction $p+d \to {}^3He+\eta$ is of interest to study the η-nucleus scattering length. In Fig. 2 we compare the measurements of different groups on the level of the spin averaged matrix element

$$|f|^2 = \frac{\sigma_{tot}}{4\pi}\frac{p_p}{p_\eta}. \tag{1}$$

as function of the transferred momentum $q = p_p - p_\eta$. The close to threshold data are from

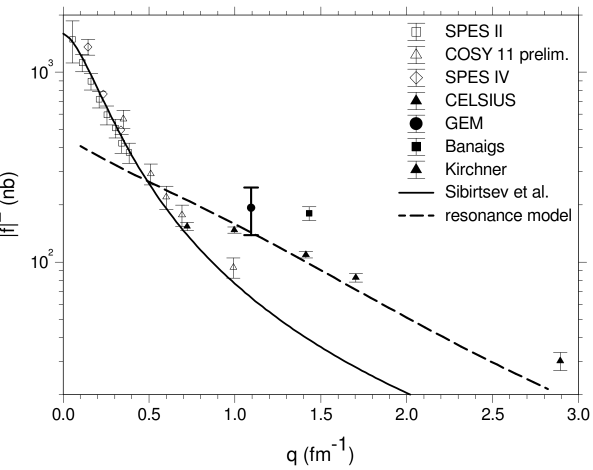

Fig. 2. The spin averaged matrix element for the reaction $pd \to {}^3He\eta$ as function of the transferred momentum. The data are from [4] (open squares), [5] (open triangles), [6] (rhombs), [7] (full triangle), [8] (full dot), [9] (full squares) and [10] (full triangle). The solid curve is a fit [11] and the dashed curve the resonance model calculation [8].

various groups at SATURNE [4,6,9,10] as well as more recent data from GEM [8], CELSIUS [7] and COSY11 [12]. These data seem to be not in agreement to each other. This is especially true if in addition angular distributions are compared. Obviously more data is necessary to clarify the situation. This may come from the newer measurement from COSY11 with inverse kinematics where the detector has a larger acceptance [13]. The solid curve is a fit to the the data assuming s-wave production and final state interaction [11]. The dashed curve assumes the reaction to proceed via a resonance. The matrix element is a Breit-Wigner form

$$|f|^2 = \frac{A\Gamma_r^2}{(\sqrt{s} - \sqrt{s_r})^2 + \Gamma(\sqrt{s})^2} \tag{2}$$

with a momentum dependent width

$$\Gamma(\sqrt{s}) = \Gamma_r(b_\eta \frac{p^*_\eta}{p^*_{\eta,r}} + b_\pi \frac{p^*_\pi}{p^*_{\pi,r}} + b_{\pi\pi}). \tag{3}$$

Here, Γ_r is the width at the resonance $\sqrt{s_r}$. Similar as in photoproduction [14] we assumed $\sqrt{s_r} = 1540$ MeV and $\Gamma_r = 200$ MeV. The branching ratios b_i were taken from the particle data group (PDG) [15]. The absolute normalization A is arbitrary.

3 The reaction $\vec{d} + d \to \eta + \alpha$

Similar as to the case of the previous reaction the study of the $\vec{d} + d \to \eta + \alpha$ reaction is driven by the quest wether a strongly bound η-nucleus system exists. Theory predicts that a heavier

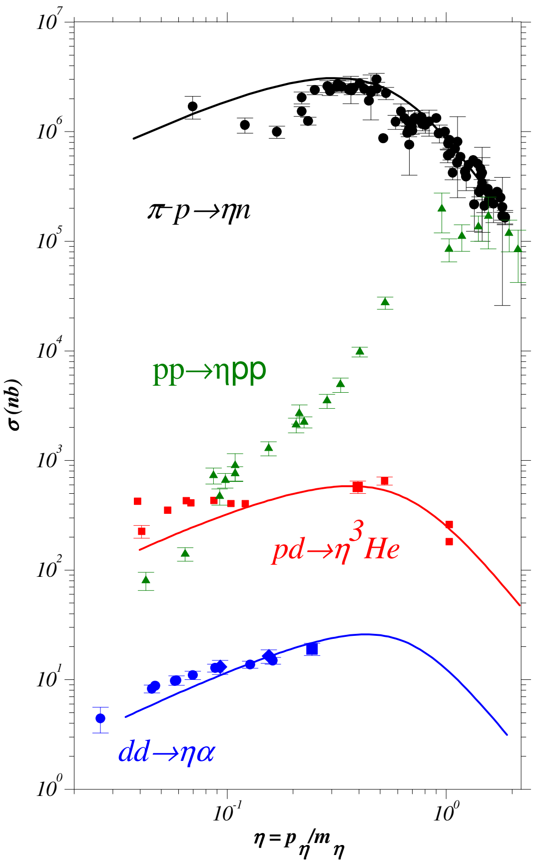

Fig. 3. Excitation functions for the indicated reactions. Points from GEM are always indicated by squares, the new data from ANKE [18] as rhombi. Data for the reaction $pd \to {}^3He\eta$ from Refs. [7] and [5] have been omitted. The solid curves are the predictions of the resonance model discussed in the text.

system should result into a stronger binding. Close to threshold only total cross sections existed so far [16,17]. Only recently the first angular distributions become available [18]. Since they will be discussed within this meeting [19] we will concentrate on the energy dependence of the total cross section. Also GEM has a preliminary value for the total cross section measured at a beam momentum of 2.39 GeV/c. All the known points are included into Fig 3. It is interesting to note that the new data follow the resonance model Eq. 2 together with Eq. 3 prediction which was previously adjusted to the data from Willis et al. [17]. It also accounts for the $\pi^- p \to \eta n$ cross sections. However, the excitation curve for $pp \to \eta pp$ shows a completely different behavior. We can summarize the present observations that reactions with two particles in the final state seem to have a quite similar behavior that reactions with three particles in the final state. The $dd \to \eta\alpha$ reaction allows to extract the real and imaginary parts of the partial wave amplitudes, if one measures the vector and tensor analyzing powers in addition to the differential cross section.

Suppose one is dealing with only s- and p-wave in the initial state. The polarized differential cross section for transversal polarized deuterons is given by

$$\left(\frac{d\sigma}{d\Omega}(\theta,\varphi)\right)_{pol} = \left(\frac{d\sigma}{d\Omega}(\theta)\right)_{unpol.}\left[1-\frac{1}{2}\tau_{20}T_{20}+i\sqrt{2}\tau_{10}T_{11}\cos\varphi-\sqrt{\frac{3}{2}}\tau_{20}T_{22}\cos 2\varphi\right] \tag{4}$$

with τ_{10} and τ_{20} the vector and tensor polarization of the beam. The unpolarized cross section is the sum of the amplitudes squared. The relation between the corresponding analyzing powers T_{ik} and the partial wave amplitude components is then

$$\begin{aligned} T_{11} &= \frac{3}{2\sqrt{10}}\,\mathrm{Im}(a_0 a_1^*)\sin\theta \\ T_{20} &= \frac{1}{3}a_0^2 - \frac{9}{10}a_1^2\sin^2\theta \\ T_{22} &= \frac{9\sqrt{3}}{40}a_1^2\sin^2\theta. \end{aligned} \tag{5}$$

Here a_0 denotes the s-wave and a_1 the p-wave amplitude. From four observables, one can then deduce the two real and two imaginary parts of the amplitudes. The knowledge of the amplitudes is of importance in the context of a bound state. A recent analysis of the scattering length from $pd \to {}^3He\eta$ yielded a very small imaginary part and uncertainty about the sign of the real part [11]. This is surprising since the original pionic inelasticity of ηN scattering is large and seems to decouple in the case of nuclei. This decoupling or very weak absorption was recently attributed to a suppression of the two main inelasticity channels [20]. These are the pion inelasticity due to the process $\eta N \to \pi N$ and the nuclear inelasticity $\eta d \to NN\pi$ with d a quasi deuteron state.

An experiment employing vector and tensor polarized deuteron beams was performed by GEM earlier this year. The data are presently under evaluation. In order to continuously monitor the polarization an additional detector was mounted downstream behind the target consisting of 16 wedge shaped scintillators. The result of such a measurement is shown in Fig. 4 for $p_{zz} = \pm 1$. The curves are fits with the function $\sigma(\varphi) = A(1 + B\cos\varphi + C\cos 2\varphi)$ to the data.

Two open problems remain on the experimental side: the disagreement between different data sets for $pd \to {}^3He\eta$ and missing data for both reactions at higher beam momenta.

4 The reaction $p + {}^6Li \to \eta + {}^7Be$

The reaction $p + {}^6Li \to \eta + {}^7Be$ has a heavier nucleus as target. The study of this reaction may therefore allow to gain insights into the movement of a possible pole position. This reaction was studied earlier at Saclay [21] at a beam energy of 683 MeV. The η was identified via its two photon decay. Eight events were observed within the acceptance of the detector corresponding to a cross section $d\sigma/d\Omega = (4.6 \pm 3.8)$ nb/sr. The error is purely statistical. A systematic error of 20% should be added. With the energy resolution of the set-up it was impossible to distinguish different final states of the residual nucleus. Fig. 5 shows the data together with the kinematical curve for ${}^7Be$ in its ground state and up to 5 MeV excitation. In an accompanying theory paper it was argued that most of the yield is from states close to 10 MeV excitation [22]. At GEM

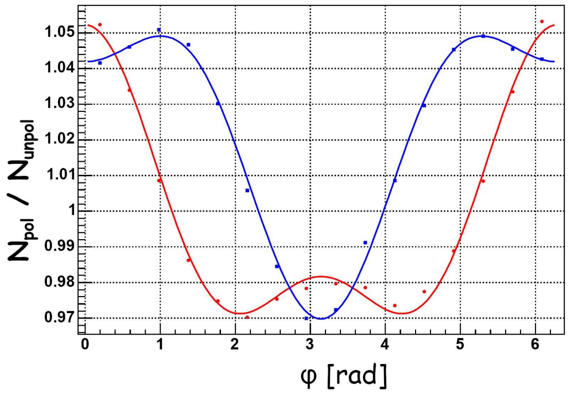

Fig. 4. Ratio of counting rates for polarized to unpolarized deuteron beam as measured with the wedge detector. The curve with the minimum at $\phi = \pi$ is for nominal $p_{zz} = -1$ the other for $p_{zz} = +1$

the investigation of this reaction is planned at an energy closer to threshold. In contrast to the Saclay experiment the detection of the recoiling ^7Be with the magnetic spectrograph is foreseen. The target thickness will limit the resolution to 1 MeV. So the experiment is exclusive since all states above the first excited state at 0.4 MeV are particle unbound. Because of the large stopping power of the recoil in material the present set-up of detectors in the focal plain is not adequate. All detection elements have to operate in vacuum. For this purpose a large vacuum box will host the detectors (see Fig. 5). Particle identification will be performed with a $\Delta E - E$ system of plastic scintillators of 0.5 mm and 2 mm thickness, respectively. Light is read out left and right through windows by fast phototubes. In a test run excellent particle resolution was observed. However, the position resolution was not sufficient to perform missing mass reconstruction. Therefore two packs of multiwire-avalanche chambers with two dimensional position resolution are added in front of the ΔE counter. The run is scheduled for summer 2006.

5 The mass of the η

Compared to other light mesons, the mass of the η is surprisingly poorly known. From 1992 on the Particle Data Group (PDG) ignored the old bubble chamber data since a new measurement with an electronic detector was published [23]. Though PDG quote in their 2004 compilation a value of $m_\eta = 547.75 \pm 0.12$ MeV/c^2 [24], this error hides differences of up to 0.7 MeV/c^2 between the results of some of the modern counter experiments quoted. This new PDG average is in fact dominated by the result of the CERN NA48 experiment, $m_\eta = 547.843 \pm 0.051$ MeV/c^2, which is based upon the study of the kinematics of the six photons from the $3\pi^0$ decay of 110 GeV η-mesons [25]. In the other experiments employing electronic detectors, which typically suggest a mass ≈ 0.5 MeV/c^2 lighter, the η was produced much closer to threshold and its mass primarily determined through a missing-mass technique where, unlike the NA48 experiment, precise knowledge of the beam momentum plays an essential part. The Big Karl spec-

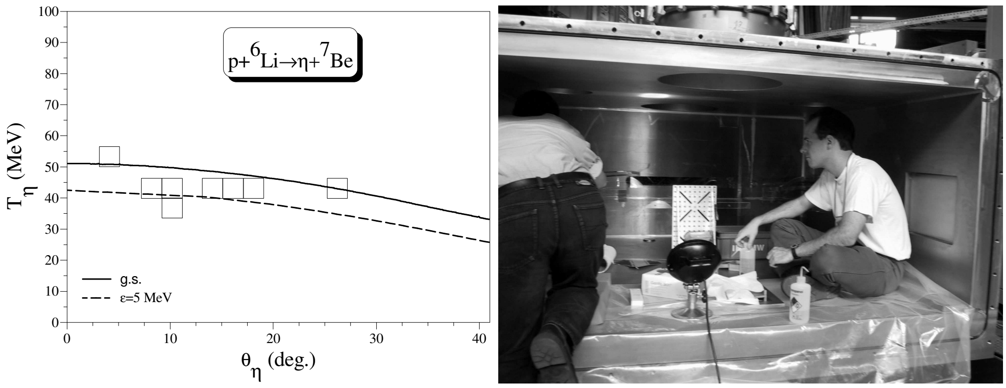

Fig. 5. Left: The data [21] shown as their dependence on kinematics. The kinematical curves are for the ^7Be ground state and an excitation of 5 MeV. Right: Box which contains the detectors in the focal plane in vacuum. See the slit in the backward wall which is the entrance of the spectrograph.

trograph and the high brilliance beam at COSY are ideally suited to perform a high precision experiment. The underlying idea of the study is a self calibrating experiment. Three reaction products were measured at the same time with one setting of the spectrometer and one setting of the beam momentum. The reaction products were

$$\begin{array}{ccccccccc} (1) & + & (2) & \rightarrow & (3) & + & (4) \\ p & + & d & \rightarrow & t & + & \pi^+ \\ p & + & d & \rightarrow & \pi^+ & + & t \\ p & + & d & \rightarrow & ^3He & + & \eta \end{array} \qquad (6)$$

It is always the third particle which was detected. Input are the well known masses of the proton, deuteron, π^+, triton and ^3He. Fig. 6 shows the momenta of the third particle being emitted under zero degree in the laboratory system. Pions and ^3He are being emitted into the forward direction, tritons into the backward direction in the center of mass system. For ^3He the momenta were divided by two in order to account for the double charge. The momentum acceptance of the spectrograph is also shown. Clearly, for a beam momentum close to 1641 MeV/c all three particles are within the acceptance of the spectrograph. The pion is used to deduce the absolute beam momentum. Then the triton will be used to fix the spectrograph setting and finally from the ^3He one obtains the mass of the η meson. So far for the idea. In the analysis the target thickness as measured from the triton momentum was studied as function of measuring time. It was found that it increased with time most probably due to freezing out of air. A thinner target at approximately half of the measuring time coincides with a cleaning of the target windows. In order to fix the investigate the properties of the spectrograph a series of calibration runs were performed. These include sweeping with the primary beam over the focal plane without a target at a beam momentum of 793 MeV/c. This corresponds to a reaction $p + 0 \rightarrow p + 0$. Then the full ellipse of deuterons from the reaction $p + p \rightarrow d + \pi^+$ at the same beam momentum was

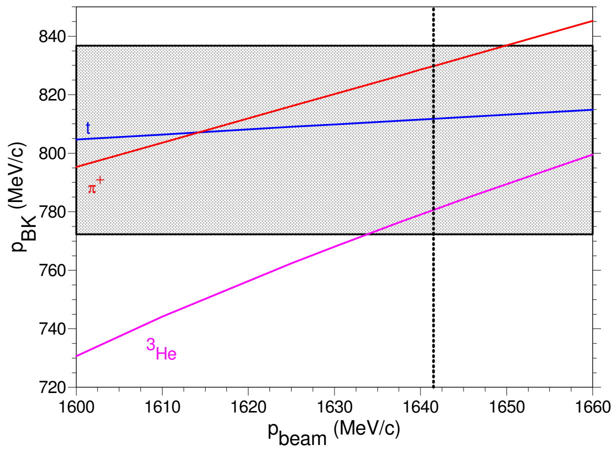

Fig. 6. The momenta of the three particles of interest under zero degree in the laboratory system as function of the beam momentum. The acceptance of the spectrograph for a central momentum of 804.5 MeV/c is shown as shaded area. Also a beam momentum of 1641.4 MeV/c is indicated.

measured. Finally, pions from the reaction $p + p \to \pi^+ + d$ were measured at 1640 MeV/c with again sweeping the deuteron loci over the whole focal plane. The the following procedure was adopted. It is assumed that the spectrograph is known. The three calibration reactions were now used to fix the beam momentum, the target thickness and the η mass. In a second step the assumption (known spectrograph) was studied by determining the missing mass of the unobserved particle in the calibration runs. These are the masses 0, π^+ and d. The result of this exercise is shown in Fig. 7. It shows the deviation of the measured missing mass from its nominal value [24] as function of the relative momentum difference of the central momentum setting of the spectrograph. It is visible that the deviation has an uncertainty of $\sigma = \pm 28$ keV/c^2, which is the main contribution to the systematical error which in total is 32 keV/c^2. The missing mass measurement yields a statistical error of the same order of magnitude. The final result is [28]:

$$m(\eta) = 547.311 \pm 0.028 \,(\text{stat.}) \ \pm 0.032 \,(\text{syst.}) \ \text{MeV/c}^2. \quad (7)$$

Finally this number is compared with the other values presently recognized by the PDG [24] (see Fig. 8).

The present mass is in agreement with the earlier results employing η production. It disagrees with the value from η decay.

6 Summary

GEM has measured a series of differential as well as total cross sections for η production with proton and deuteron projectiles and light nuclei as targets. Obviously the interaction in the final state in these cases is very different from the ηN interaction. The reason might be that the elementary scattering length does not have the same isospin algebraic and spatial properties for

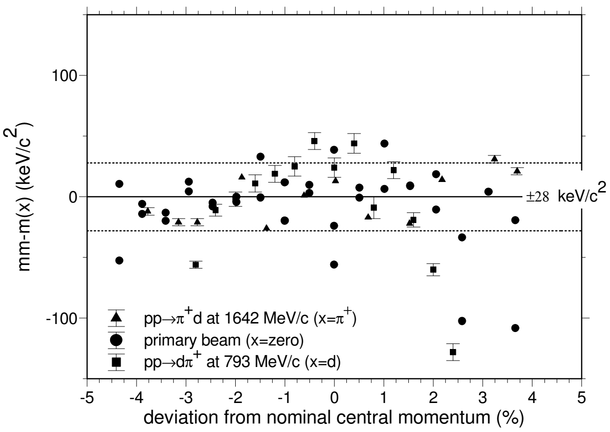

Fig. 7. The deviation of the measured missing mass from its PDG value as function of the deviation from the nominal central value for the momentum of the magnetic spectrograph.

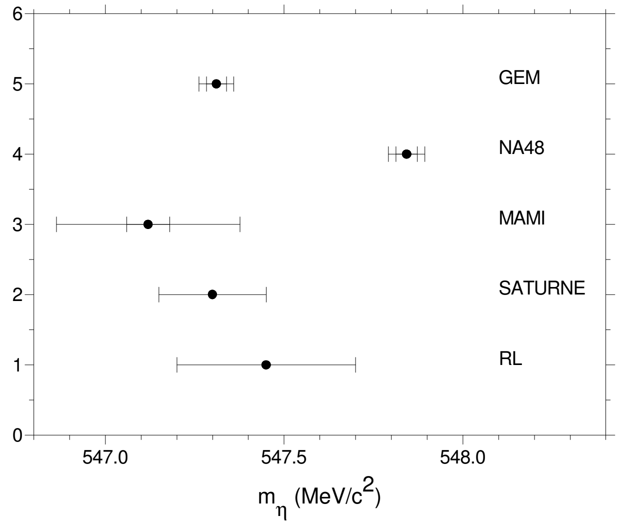

Fig. 8. The results of the η-mass measurements, in order of publication date, taken from the Rutherford Laboratory (RL) [26], SATURNE [23], MAMI [27], NA48 [25], and GEM. When two error bars are shown, the smaller is statistical and the larger total.

the real and imaginary art as in a nuclear medium. A positive value of the real part means a modest attraction while a negative value means repulsion or a bound state. A small imaginary part in the case of nuclei should lead to a more narrow state if a bound η-nuclear state exists [29]. The experiments will allow to fix size and signs of the scattering length components. A dedicated search for a possible bound η-nuclear state has started. Basic properties of the η are its mass and its width. A new value for the mass has been derived with extremely small error bars.

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