MESON PHYSICS AT GEM.

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representing the GEM collaboration

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

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1 Introduction

The collaboration operates the GEM detector, which is a combination of a stack of GErmium diodes and a Magnetic spectrograph. The germanium wall \cite{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 opposite orientation. In this way 40000 pixels are defined. It provides position

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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 differences in scale of the two drawings. The flight path from the target to the focal plane is ≈ 15 m long.

(see Fig.1) and ΔE information. The thick detectors that follow 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 in which 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 is measured with MWDC’s, twelve layers in two packs. They are followed by scintillator hodoscopes P, R and 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. Additional details of the detector are given in [2]. For a search for the existence of bound η-nuclear states an additional detector ENSTAR was added surrounding the target. It was recently used in a search employing the reaction $p + ^{27}Al \rightarrow ^3He + (\eta ^{25}Mg)$ at recoil-free conditions followed by a second step $\eta + n \rightarrow N^{0*} \rightarrow \pi^- + p$. The $^3He$ was detected in the magnetic spectrograph while the second step was identified in ENSTAR. Details are discussed in the contribution by Gillitzer [3].

2 The reaction $p + d \rightarrow ^3He + \eta$

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

$$|f|^2 = \frac{\sigma_{tot} p_p}{4\pi p_\eta}$$  \hspace{1cm} (1)$$
as function of the transferred momentum $q = p_p - p_\eta$. The close to threshold data are from various groups at SATURNE [4, 6, 9, 10] as well as more recent data from GEM [8], WASA [7].
Fig. 2. The spin averaged matrix element for the reaction $pd \rightarrow ^3H\eta$ 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].

and COSY11 [12]. These latter data are not in agreement with each other. This is especially true if in addition angular distributions are compared. Obviously more insight 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 interactions [11]. The dashed curve assumes the reaction to proceed via a resonance. The matrix element is a Breit-Wigner form

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

with a momentum dependent width

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

$\Gamma_r$ is the width at the resonance $\sqrt{s_r}$. 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 is arbitrary.

3 The reaction $d^3 + d \rightarrow \eta + \alpha$

Similar to the case of the previous reaction, the study of this reaction is driven by the question whether a strong bound $\eta$-nucleus system exists. Theory predicts that a heavier system should result in stronger binding. Close to threshold only total cross sections exist so far [16, 17] and
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 in Fig. 3. It is interesting to note that the new data follow the resonance model prediction (Eq. (2) together with Eq. (3)) which was previously adjusted to the data from Willis et al. [17]. It also accounts for the $\pi^- p \rightarrow \eta n$ cross sections, however, the excitation curve for $pp \rightarrow \eta pp$ 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 is different from reactions with three particles in the final state. The $dd \rightarrow \eta \alpha$ reaction allows the extraction of 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. If we assume that there is only s- and p-wave in the initial state, the polarized
The differential cross section for transversely polarized deuterons is given by

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

(4)

with \( \tau_{10} \) and \( \tau_{20} \) 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 amplitude components is then

\[ T_{11} = \frac{3}{2\sqrt{10}} \text{Im}(a_0 a_1^*) \sin \theta \]
\[ T_{20} = \frac{1}{3} a_0^2 - \frac{9}{10} a_1^2 \sin^2 \theta \]
\[ T_{22} = \frac{9\sqrt{3}}{40} a_1^2 \sin^2 \theta. \]

(5)

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 \( pd \rightarrow ^3He\eta \) yielded a very small imaginary part and uncertainty about the sign of the real part \cite{11}. This is surprising since the free pionic inelasticity of \( \eta N \) 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 \cite{20}. This is the pion inelasticity due to the process \( \eta N \rightarrow \pi N \) and the nuclear inelasticity \( \eta d \rightarrow NN\pi \) with \( d \) a quasi deuteron state.

![Ratio of counting rates for polarized to unpolarized deuteron beam as measured with the wedge detector.](image)

**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 \( p_{z\bar{z}} = -1 \) the other for \( p_{z\bar{z}} = +1 \)

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 the function \( \sigma(\phi) = A(1 + B \cos \phi + C \cos 2\phi) \) with fitted constants \( A, B \) and \( C \) to the data.

Two open problems remain on the experimental side: the disagreement between different data sets for \( pd \to ^3He\eta \) and the lack of data for both reactions at higher beam momenta.

4 The reaction \( p + ^6Li \to \eta + ^7Be \)

This reaction has a heavier nucleus as target and thus the study of this reaction may yield insight into the movement of a possible pole position. The reaction was studied earlier at Saclay \[21\] at a beam energy of 683 MeV. The \( \eta \) was identified via its two-photon decay. Eight events were observed. Taking the acceptance of the detector into account a cross section \( d\sigma/d\Omega = (4.6 \pm 3.8) \) nb/sr is obtained. The quoted error is purely statistical and 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

![Figure 5](image)

Fig. 5. Left: The kinematic dependence of the data [21]. 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.

that most of the yield is from states close to 10 MeV excitation [22]. At GEM 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 a magnetic spectrograph is planned. 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 \(^7Be\) in material, (or in air,) 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 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 have been added in front of the $\Delta E$ counter. The run is scheduled for summer 2006.

5 The mass of the $\eta$

Compared to other light mesons, the mass of the $\eta$ is surprisingly poorly known. From 1992 on the PDG ignored the old bubble chamber data since a new measurement with an electronic detector was published [23]. Though the PDG quote in their 2004 compilation a value of $m_\eta = 547.75 \pm 0.12 \text{ MeV/c}^2$ [24], this error hides differences of up to 0.7 MeV/c$^2$ between the results of some of the modern counter experiments. This new PDG average is in fact dominated by the result of the CERN NA48 experiment, $m_\eta = 547.843 \pm 0.051 \text{ MeV/c}^2$, which is based upon the study of the kinematics of the six photons from the $3\pi^0$ decay of 110 GeV $\eta$-mesons [25]. In the other experiments employing electronic detectors, which typically suggest a mass $\approx 0.5 \text{ MeV/c}^2$ lighter, the $\eta$ 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 spectrograph 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 simultaneously with one
Fig. 6 shows the momenta of the third particle being emitted at zero degree in the laboratory system. Pions and \( ^3\text{He} \) are emitted in the forward direction, tritons in the backward direction in the center of mass system. For \( ^3\text{He} \) 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 \( ^3\text{He} \) one obtains the mass of the \( \eta \) meson.

In order to fix the properties of the spectrograph a series of calibration runs were performed. These include sweeping 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 kinematical ellipse of deuterons from the reaction \( p + p \rightarrow d + \pi^+ \) at the same beam momentum was measured. Finally, pions from the reaction \( p + p \rightarrow \pi^+ + d \) were measured at \( \approx 1640 \text{ MeV/c} \) while again sweeping the deuteron loci over the whole focal plane. 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. Evidence for a thinner target at the midpoint of the measurement corresponds with a cleaning of the target windows. Then the following procedure was adopted. It is assumed that the properties of the spectrograph are known. The three calibration reactions were now used to fix the beam momentum, the target
Fig. 8. The results of the $\eta$-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.

GEM has measured a series of differential as well as total cross sections for proton and deuteron projectiles and light nuclei as targets. Obviously the interaction in the final state in these cases is very different from the $\eta N$ interaction. The reason might be that the elementary scattering length does not have the same isospin algebraic and spatial properties for the real and imaginary part 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 $\eta$-nuclear state exists [29]. The experiments will allow the determination of size and signs of the scattering length components. A dedicated search for a possible bound $\eta$-nuclear state has started. Basic properties of the $\eta$ such as its mass and width were poorly known. A new value for the mass has been derived with extremely small error bars. The width is only known up to 50% [24] and needs further measurements.

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