COSY Proposal and Beam Time Request

Measurement of the quasi-free $pn \to d\eta$ cross section at ANKE

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Abstract

We propose to measure the differential and total cross sections for the $pn \to d\eta$ reaction through the investigation of the $pd \to p_{\text{spec}}d\eta$ reaction in quasi-free kinematics at two different beam momenta at ANKE. The angle and energy of the spectator proton, p_{spec}, will be measured in one of the two Silicon Tracking Telescopes and the fast deuteron in the ANKE forward detector. The η meson will then be identified through the missing mass in the reaction.

The data will allow us to follow the development of proton-induced η production on light nuclei, study the influence of the $N^*(1535)$ isobar, and extract information on the contributions of higher partial waves. The size of the scattering length parameter in the ηd final state interaction is expected to be reconstructed with a precision of about 5%.

In total we ask for two weeks of beam with an unpolarized proton beam at two beam energies, i.e. $T = 1.35$ GeV and 1.50 GeV, using the deuterium cluster target at ANKE.

1 Introduction - Motivation

The current issue of the Physics and Astronomy Classification Scheme has a section entitled "21.85.+d Mesic nuclei" and one item that fits well in this box is ${}^{3}_{\eta}$He. The total cross section for the $dp \to {}^{3}\text{He}\,\eta$ reaction near threshold [1, 2] shows a surprisingly strong variation with energy and this is evidence for a significant final state interaction effect (FSI) between the η and the recoiling ^{3}He nucleus, *i.e.*, to a large scattering length in the $\eta\,{}^{3}$He system.

These conclusions were confirmed through two experiments carried out at COSY, where the differential and total cross sections of the $dp \to {}^{3}\text{He}\,\eta$ reaction were measured in fine energy steps from below threshold up to an excess energy $Q \approx 11$ MeV [3, 4]. The cross section jumped from zero to its plateau value already for $Q < 0.5$ MeV. After taking the beam momentum spread into account, it was shown that the large FSI seemed to be associated with a pole in the η^{3}He elastic scattering amplitude at $Q = Q_0$, where $|Q_0| \approx 0.2$ MeV.

Further evidence for the pole hypothesis is to be found in the angular dependence of the $dp \to {}^{3}\text{He}\,\eta$ cross section, which is biassed towards small $\theta_{p\eta}$ for large Q but has the opposite tendency for small Q [2, 3, 4]. Since the slope arises principally from the real part of an interference between s- and p-waves in the $\eta\,{}^{3}$He system, this implies that the s-wave amplitude must have a very strong phase variation at low Q. This would arise if there were a pole in the $\eta\,{}^{3}$He elastic scattering amplitude and the behaviour of the experimental data can be well described by such a hypothesis [5].

If the FSI interpretation is correct, the threshold enhancement should be largely independent of the particular entrance channel. This has been shown to be the case in new data on η photoproduction on ^{3}He from MAMI, $\gamma\,{}^{3}\text{He} \to \eta\,{}^{3}\text{He}$ [6, 7]. Despite the poorer energy binning, the total cross section rises to about one third of its maximum in the first 4 MeV bin above threshold and, moreover, there is an analogous change in the slope of the differential cross section with Q to that seen in the COSY data [3, 4].

Although the evidence for an ${}^{3}_{\eta}$He effect is strong, it is never possible from above-threshold data to ascertain whether the pole is on the bound- or antibound complex sheet. The situation is analogous to the low energy NN case where, from scattering data alone, one could not say if the deuteron were bound or if the S-wave pp in the ${}^{1}S_0$ channel were not. Unfortunately, despite earlier hopes [8], the latest photoproduction measurements show no evidence for the decay of ${}^{3}_{\eta}$He into $\pi^0 pX$ in the bound-state region [6, 7]. Without an η trigger, the background arising from the direct production, *i.e.* not passing through ${}^{3}_{\eta}$He, is presumably too large. One must therefore approach the problem in a different way.

If one divides the differential cross section by the ratio of the final to the initial CM momenta in order to evaluate the absolute square of an amplitude, $|f|^2$, then it is found that $|f(dd \to {}^4\text{He}\,\eta)|^2$ [9, 10, 11, 12] is typically a factor of fifty smaller than that of $|f(dp \to {}^3\text{He}\,\eta)|^2$ [1, 3, 4]. Moreover, the energy dependence in the ^{4}He$\,\eta$ case is much less steep, which means that the FSI pole is at a larger value of $|Q_0|$ for ${}^{4}_{\eta}$He. Now, since the ηN interaction is equally attractive for neutrons and protons, the one extra nucleon in ^{4}He, combined with the smaller nuclear radius, means that ${}^{4}_{\eta}$He should be more bound than ${}^{3}_{\eta}$He. These two observations together imply that ${}^{4}_{\eta}$He is indeed bound [9], though they say nothing at all about the borderline case of ${}^{3}_{\eta}$He.

For heavier nuclei the cross sections for producing η mesons near threshold are very small and the only positive sightings have been two experiments that each captured a few events corresponding to the $p^6\text{Li} \to \eta^7\text{Be}$ reaction [13, 14]. Apart from the reduced counting rate as the nuclear number A increases, there is a more insidious problem because the widths of the η-mesic nuclei become larger than the separation between nuclear levels and individual peaks would not be identified among the overlapping states. In view of the background problems associated with heavier A, or with looking in the bound-state region, it looks more promising to study η production near threshold in the case of $A = 2$ of the deuteron, which is the subject of the present proposal.

The first indication that η production was much stronger in proton-neutron collisions than in proton-proton was provided by the comparison of inclusive production in pd and pp collisions at 1.3 and 1.5 GeV by the PINOT group [15]. However, merely detecting the η did not allow them to separate the quasi-free ηd from the ηnp final state. In an alternative approach, fast deuterons from proton-deuteron collisions were interpreted as arising from the quasi-free $pn \to d\eta$ reaction. The major uncertainty here was in the shape of the multipion background and there could have been some misidentification of the η signal [16].

Two measurements of the quasi-free $pn \to d\eta$ total cross section were carried out at the CELSIUS accelerator using different experimental techniques. In the first [17] the η was detected through its 2γ decay in the PROMICE-WASA central detector and the direction of a coincident fast charged particle in the forward detector. The $pn \to d\eta$ reaction was identified purely on the basis of the separation of the deviations between the expected deuteron direction and that of the recorded fast particle and only in a fraction of the events could this be positively identified as a deuteron. After making small background subtractions, the group obtained values of the total cross sections in 10 MeV bins from $Q = 10$ MeV up to 120 MeV. They noted that the flattening of the cross section for $Q \approx 60$ MeV was to be expected if the production were dominated by the $N^*(1535)$.

The Uppsala group subsequently detected the deuteron that escaped down the CELSIUS beam pipe using a small scintillator telescope in coincidence with the η [18]. Although both the η and deuteron were positively identified, only deuterons with small transverse momenta passed down the beam pipe and data were reported in six bins up to a maximum of $Q = 10$ MeV. The resolution in Q was ≈ 1 MeV (rms) at threshold, and ≈ 2 MeV at $Q =$ 10 MeV. There was no direct overlap with their earlier results [17] but the relative normalisation was determined by measuring in parallel the deuteron direction in the forward detector. The overall systematic uncertainties were of the order of 30%.

The strong FSI enhancement in the later CELSIUS data is seen more clearly in Fig. 1 in the ratio of the experimental data to the arbitrarily normalised phase-space dependence. Also shown are curves evaluated in the s-wave scattering length approximation, where the amplitude squared for the production of a $d\,\eta$ system at low relative momentum k is proportional to

$$|F(k)|^2 = \frac{S}{|\,1 - ik\,a_{\eta d}\,|^2} = \frac{S}{(1 + k\,\mathrm{Im}\{a_{\eta d}\})^2 + (k\,\mathrm{Re}\{a_{\eta d}\})^2}\,, \tag{1}$$

where $a_{\eta d}$ is a complex scattering length and S a scale factor that depends upon the particular reaction studied and which varies slowly with energy. The curves are calculated using estimates where the input ηN interaction is weak, strong, or very strong [19].

The two CELSIUS $pn \to d\eta$ experiments [17, 18] were carried out above the η production threshold in nucleon-nucleon collisions and only events from the quasi-free region were analysed. However, $pd \to pd\eta$ data were also taken at the lower energy of 1032 MeV and these showed an ηd FSI enhancement at low invariant mass [20]. The authors divided the distribution by three-body phase space and the resulting values are also presented in Fig. 1. Although the data are not inconsistent, the division of the low energy data by phase space in conditions that are far from quasi-free is controversial and, if one includes some distortion of the spectrum by the spectator momentum distribution, then a smaller slope is found.

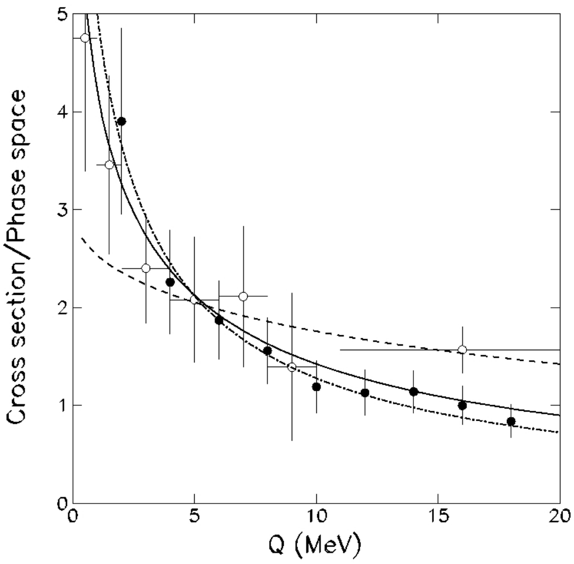

Figure 1: Ratio of the cross section for the production of the $d\,\eta$ system to arbitrarily normalised phase space, as a function of the kinetic energy in the $d\eta$ rest frame, for the $pn \to d\,\eta$ total cross section (open circles) [17, 18] and for the $pd \to pd\,\eta$ reaction at 1032 MeV (closed circles) respectively [20]. The broken, solid and chain curves are the predictions of the scattering length formula of Eq. (2), using as input $a_{\eta d} = (0.73 + 0.56i)$ fm, $(1.64 + 2.99i)$ fm, and $(-4.69+1.59i)$ fm respectively [19]. In all cases the overall normalisation is arbitrary.

Given the importance of getting good and reliable data on the $pn \to d\eta$ reaction, for its own intrinsic interest and to follow the A dependence of η production, we propose to measure the process in quasi-free kinematics with a deuterium target and study $pd \to p_{\rm spec}d\eta$. The angles and energy of the spectator proton, $p_{\rm spec}$, will be measured in one of the two Silicon Tracking Telescopes (STT) and the fast deuteron in the ANKE forward detector. This will allow the η meson to be identified through the missing mass in the reaction. The differences/advantages compared to the previous CELSIUS measurements are:

- Identification of the η from the missing-mass distribution, where the background can be estimated from data taken at another energy.
- By using two beam energies instead of the single one at CELSIUS, the excess energy range $0 < Q < 110$ MeV would be scanned with good acceptance, with a large Q overlap between the two settings. A

uniform relative normalisation will thus be achieved. The region of the maximum in the $N^*(1535)$ contribution would therefore be well covered. This technique also allows a check on the treatment of the Fermi motion inside the target deuteron. Another advantage of using two beam energies is that it enables us to use the data taken at one beam energy to describe the background at the other energy.

- The differential as well as the total cross section would be measured, which will help in the identification of the s-wave contribution and hence in the study of the s-wave ηd FSI.

It is important to note here that there can be no interference between odd and even η partial waves so that the cross section is an even function of $\cos\theta_\eta$. There is, as yet, no evidence for an $N^*(1535)$ contribution to p-wave η production near threshold and higher resonances might prove to be important. In the closely related $pp \to pp\eta$ reaction at $Q = 40$ MeV, strong effects are seen from higher partial waves [22]. Due to the conservation laws, these are ascribed mainly to combined P-wave excitations in the pp and $\eta\{pp\}$ systems. There are data at a similar energy from ANKE [23], where the cut of the final pp excitation energy selects the ${}^1S_0$ final state. This quasi-two-body reaction is then very analogous to the $pn \to d\eta$ reaction proposed here but, unfortunately, the $pp \to \{pp\}_S\,\eta$ data are only available over a very narrow angular range and only at two energies. Nevertheless, the theoretical analysis of a combined data set of $pn \to d\eta$ and $pp \to \{pp\}_S\,\eta$ results could be very informative.

2 The $pn \to d\eta$ reaction at ANKE

The experiment is proposed to be carried out using the ANKE spectrometer at COSY, which offers an excellent momentum resolution for emitted charged particles combined with a large acceptance for near-threshold studies. In the absence of a free neutron target, the quasi-free $pd \to p_{\rm spec}d\eta$ reaction will be studied, with $p_{\rm spec}$ being a spectator proton, using an internal deuterium cluster-jet target [24]. The spectator proton in the target deuteron escapes with its Fermi momentum and, through its precise measurement of the four-momentum of the spectator proton using the ANKE Silicon Tracking Telescopes (STT), the excess energy of the reaction can be evaluated on an event-by-event basis by

$$Q = |P^\mu_{\rm beam} + P^\mu_{\rm target} - P^\mu_{\rm spec}| - m_{\rm d} - m_\eta\,, \qquad (2)$$

with P^μ being the four vector of the corresponding particle and m_d being the mass of the final state deuteron and m_η the mass of the η meson. The deuteron in the final state will be recorded in the ANKE forward system which, in turn, will allow a full event reconstruction and identification of the $pd \to p_\mathrm{spec} d\eta$ reaction by the missing-mass method.

Data will be taken at two different beam momenta, *viz.* $p_1 = 2.09$ GeV/c ($T_1 = 1.35$ GeV) and $p_2 = 2.25$ GeV/c ($T_2 = 1.5$ GeV), with a deflection angle in ANKE of $\alpha = 8.9°$. According to detailed Monte-Carlo simulations these two beam momenta will allow the excitation function to be studied from sub-threshold energies up to $Q = 110$ MeV. For a neutron at rest, these two beam momenta would correspond to excess energies of $Q_1 \approx 40$ MeV and $Q_2 \approx 95$ MeV but these are spread by the neutron Fermi motion. In order to determine the value of Q for each event, the spectator proton will be detected in one of the two STT [25] that are placed to the left and right of the target. These each consist of three double-sided segmented detectors:

- 1^{st} layer: 70 μm thick, $66\times52\,\mathrm{mm}^2$ active area, 151×64 number of segments with 420 μm pitch horizontally and 800 μm pitch vertically.
- 2^{nd} layer: 300 μm thick, identical geometry to 1^{st} layer.
- 3^{rd} layer: 5000 μm thick, $64\times64\,\mathrm{mm}^2$ active area, 64×64 number of segments with 1000 μm pitch.

The different layers will be placed 2.8, 4.8 and 6.2 cm away from the target, covering polar angles θ between 75° and 140°. To emphasise the quasi-free conditions, only spectator protons with kinetic energies below 9 MeV will be used in the analysis. The spectator proton must also have a minimum kinetic energy of 2.5 MeV in order to reach the second layer.

The energy/angular acceptance of an STT is shown by the black rectangle in Fig. 2 for a COSY beam momentum of $p_\mathrm{beam} = 2.09$ GeV/c. This momentum is chosen so as to allow a large acceptance close to the production threshold and also below threshold for background studies.

The Q dependence of the acceptance when a proton is detected in an STT and a deuteron in the forward system is shown in Fig. 3 for a beam momentum of 2.09 GeV/c. The acceptance is maximal for $Q < 10$ MeV but is still on the order of 1% at 40 MeV. For studies at higher excess energies, *i.e.* up to $Q = 110$ MeV, a beam momentum of $p_\mathrm{beam} = 2.25$ GeV/c will be used. This second momentum is chosen such that the two excess energy ranges will overlap, which will allow checks on systematic effects to be undertaken. Additionally, the use of two beam energies will help in the subtraction of the

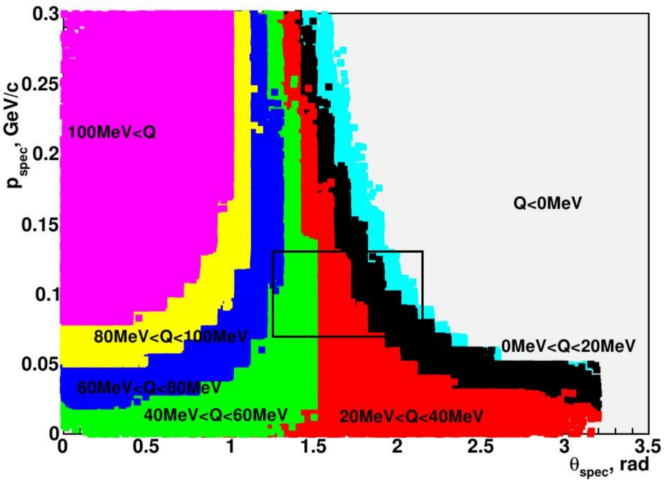

Figure 2: Momentum of the spectator proton versus the angle of the spectator proton for $p_{\text{beam}} = 2.09$ GeV/c. The acceptance of an STT is shown by the black rectangle. The various colours correspond to different intervals in the excess energy Q.

physical background.

Spectator protons will be identified in an STT through the $\Delta E/E$-method. The energy resolution of ≈ 160 keV FWHM, leads to a good separation of proton and deuteron bands, as shown in Fig. 4.

The precision in the excess energy is fixed mainly by the accuracy of the four-momentum reconstruction of the spectator proton. The most important effect here is the uncertainty in the measurement of the proton polar angle, where $\Delta\theta \approx 3.5^\circ$ (σ). This arises mainly from the small-angle scattering (mostly in the first thin layer) and track reconstruction. The resolution achievable in Q is about 4.5 MeV (σ). This uncertainty is taken into account in the simulations.

With the proposed setup and beam momenta, the whole angular range of the deuteron is covered and the angular acceptance shows a smooth behaviour near threshold (Fig. 5). This will allow a detailed study of the angular dependence of the cross section to be made. This is of great interest for the investigation of the final state interaction in the ηd-system since it will allow the determination of possible anisotropies arising from higher partial waves.

Since the $pn \to d\eta$ cross section is a function of $\cos^2\vartheta$, any anisotropy is

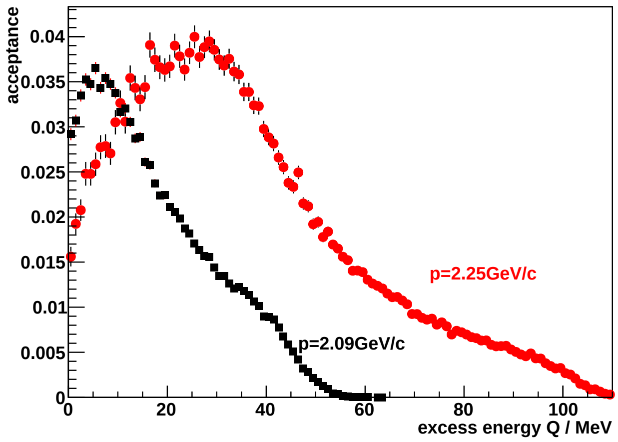

Figure 3: Q dependence of the acceptance of ANKE for $p_{\text{beam}} = 2.09$ GeV/c (black points) and for $p_{\text{beam}} = 2.25$ GeV/c (red points)

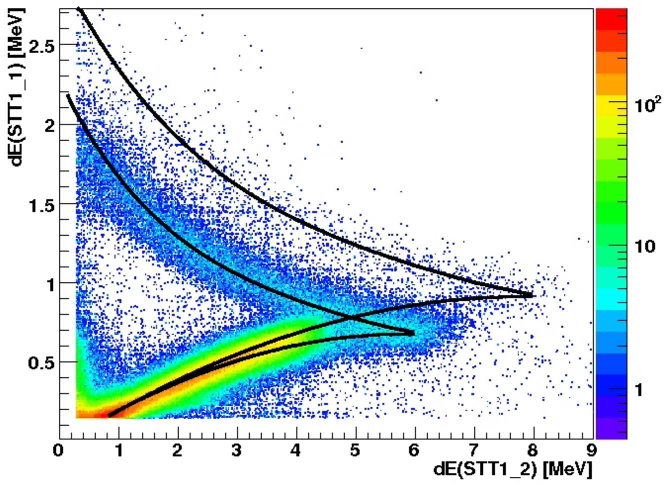

Figure 4: Energy loss correlation for the first and second layers of the STT. The solid lines correspond to the dependence expected for protons and deuterons

expected to be of the form

$$\frac{d\sigma}{d\Omega} = a(1 + b\cos^2\vartheta). \tag{3}$$

Monte-Carlo simulations suggest that, if $b \approx 0.1$ it will be measured to better than $\Delta b \approx 0.05$ in the excess energy range from threshold up to $Q = 50$ MeV

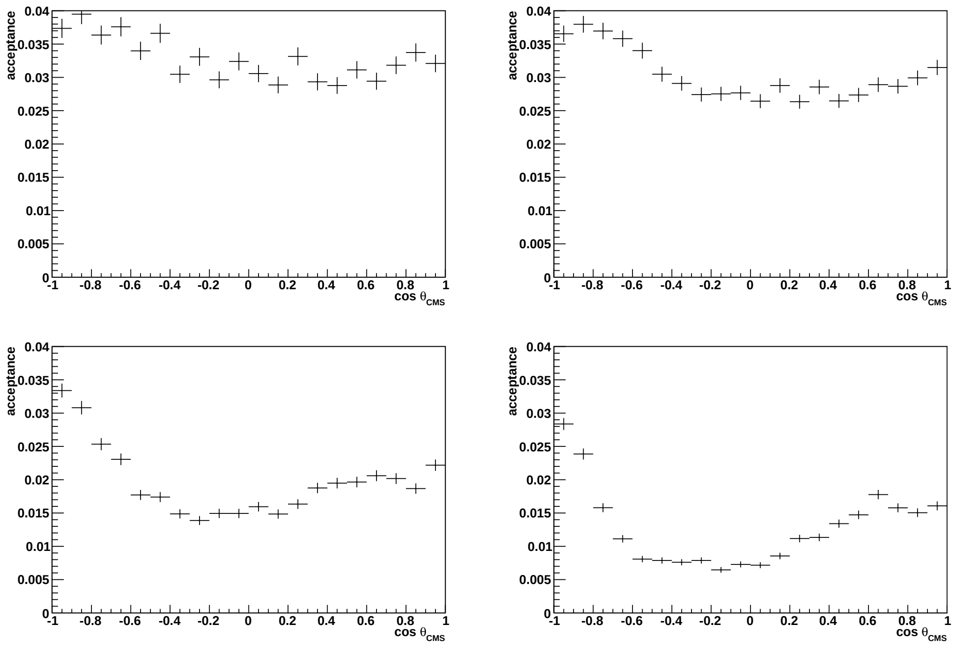

Figure 5: Angular acceptance of ANKE at $p_{\text{beam}} = 2.09$ GeV/c for $Q = 0 - 5$ MeV (upper left), $Q = 10 - 15$ MeV (upper right),$Q = 20 - 25$ MeV (lower left), and $Q = 30 - 35$ MeV (lower right).

for the lower beam energy, assuming a Q-binning of 5 MeV. The measurement at the second energy will allow to determine b with an uncertainty of less than $\Delta b \approx 0.06$ up to an excess energy of $Q = 90$ MeV. The bin width in Q has been chosen so that it will allow to determine the dependence of b on the excess energy Q.

Because the data are taken near the threshold, the peak of the η meson in the missing-mass spectra will be at the kinematic limit. This makes a creative solution for the decription of the background necessary. An elegant way to subtract the physical background, mainly arising from multi-pion production, in a missing-mass experiment was developed by the SPESIII collaboration [26]. The background of a data set is described in terms of data at a second beam energy, whose reconstructed c.m. momenta are transformed to the laboratory system of the first energy. In this way the kinematic limits of both data sets are identical and the spectra can be subtracted from each other, after scaling according to the relative luminosities. This method has been used successfully at ANKE for the quasi-free $pn \to d\omega$ reaction [27] and the procedure is illustrated in Fig. 6 [28].

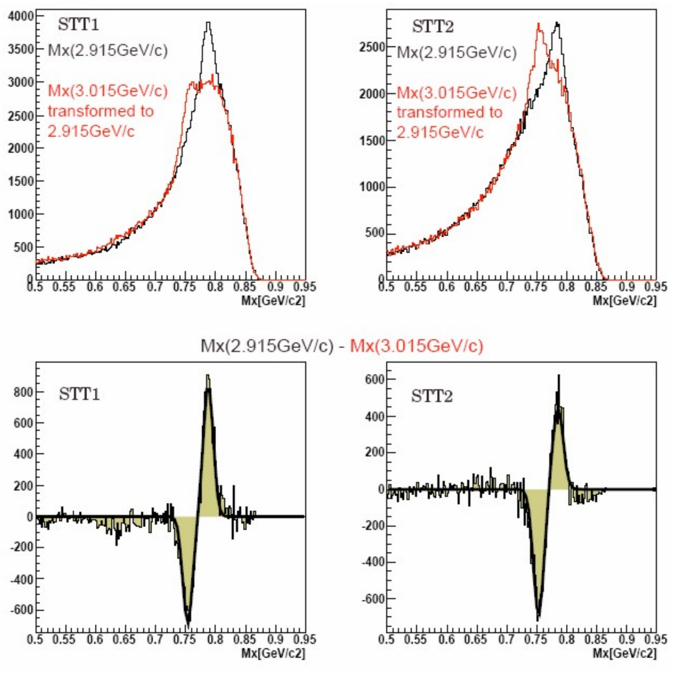

Figure 6: Missing-mass spectra for the $pn \to dX$ reaction. Black lines indicate experimental data at 2.915 GeV/c whereas the red curve represents the data at another momentum, shifted using the SPESIII procedure [26]. The differences between the two spectra are shown in the lower panels.

The black line indicates experimental data at 2.915 GeV/c, whereas the red curve represents the data at 3.015 GeV/c, shifted using the SPESIII procedure [26]. In the lower panels the differences between the two curves are shown, and these allow one to estimate the numbers of ω-mesons produced. Due to the larger cross section and negligible width, the method is expected to work even better for the η meson.

In order to determine the luminosity required to calculate the cross sections, in parallel with the η production reaction, data on proton-deuteron elastic scattering will also be recorded.

The acceptance of the ANKE detector system for pd elastic scattering is shown in Fig. 7 as a function of the square of the momentum transfer $|t|$. Hits from both the scattered proton in the forward detector and the recoil deuteron in the STT are required. The elastic scattering data measured in this way can be compared to existing differential cross sections measured in the same momentum transfer region [29, 30], as parametrized in [31]. The precision achievable in the absolute luminosity in this way is dominated by

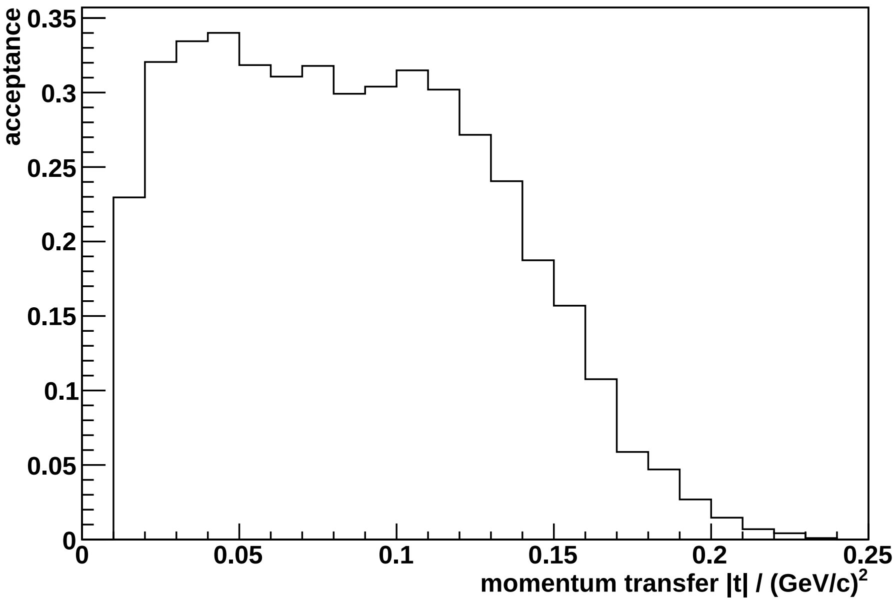

Figure 7: Acceptance of the ANKE detector system for events from pd elastic scattering as a function of the square of the momentum transfer $|t|$.

the available reference data and will be in the order of 15%.
A determination of the luminosity using the Schottky method is not possible, as the η-factor is too close to zero for the chosen beam energies [32].

For the investigation of the ηd final state interaction, only the relative shape of the excitation function is required for which there is no luminosity uncertainty. The quality of the proposed measurement is illustrated in Fig. 8, which shows the assumed input, based on a scattering length of $a_{\eta d} = (1.64 + 2.99i)$ fm (red curve) and the Monte Carlo simulated cross sections (data points). The black line is a fit to these data points using Eq. (2) and this agrees well with the input data. Monte-Carlo simulations with different scattering lengths suggest that the absolute value, $|a_{\eta d}|$, could be reconstructed with a precision of about 5% using the data expected from this experiment.

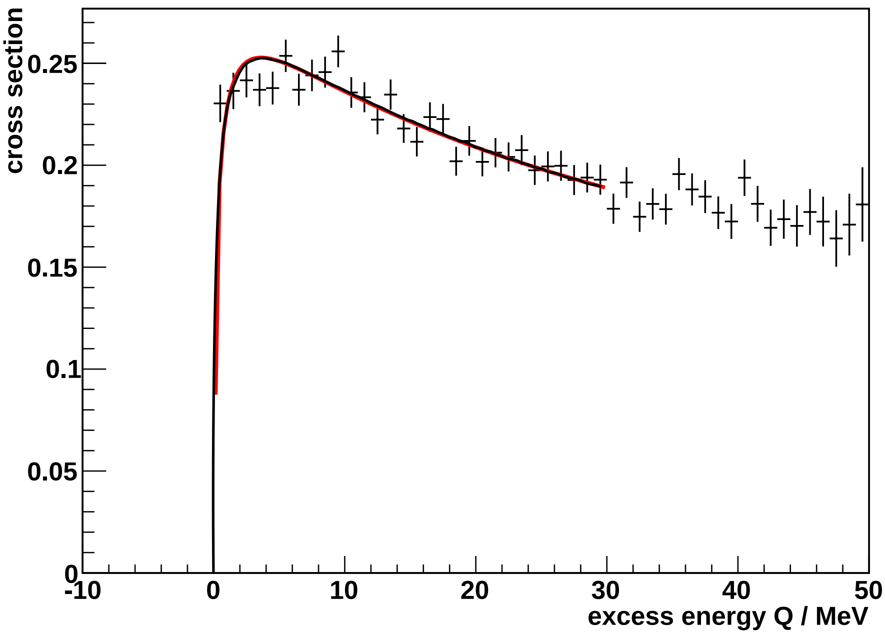

Figure 8: Results of Monte-Carlo simulations with an excitation function based on an assumed scattering length of $a_{\eta d} = (1.64 + 2.99i)$ fm (red curve) and expected reconstructed cross sections (data points). The black solid line is a fit to these data points using the scattering length formalism.

3 Counting rate estimates and beam time request

For a conservative estimation of the expected counting rate, a mean luminosity of 3×10^{30} cm^{-2}s^{-1} is assumed, together with the total cross sections reported in [17, 18, 20]. Under these conditions, and taking into account the dead time, mainly due to the acceptance for the pd elastic scattering, and losses because of the misidentification of the spectator protons, we expect approximately 9,400 events/day (12,800 events/day) for $p_{\text{beam}} = 2.09$ GeV/c ($p_{\text{beam}} = 2.25$ GeV/c) spread over the excess energy range of $Q = 0 - 110$ MeV. The total number of events of the reaction $pn \rightarrow d\eta$ expected after 11 days of data taking, *i.e.* 6 days at $p = 2.09$ GeV/c and 5 days at $p = 2.25$ GeV/c, is shown in Fig. 9. The shown excess energies are the reconstructed ones.

In total we ask for **two weeks of beam time**, including 2 days for beam-

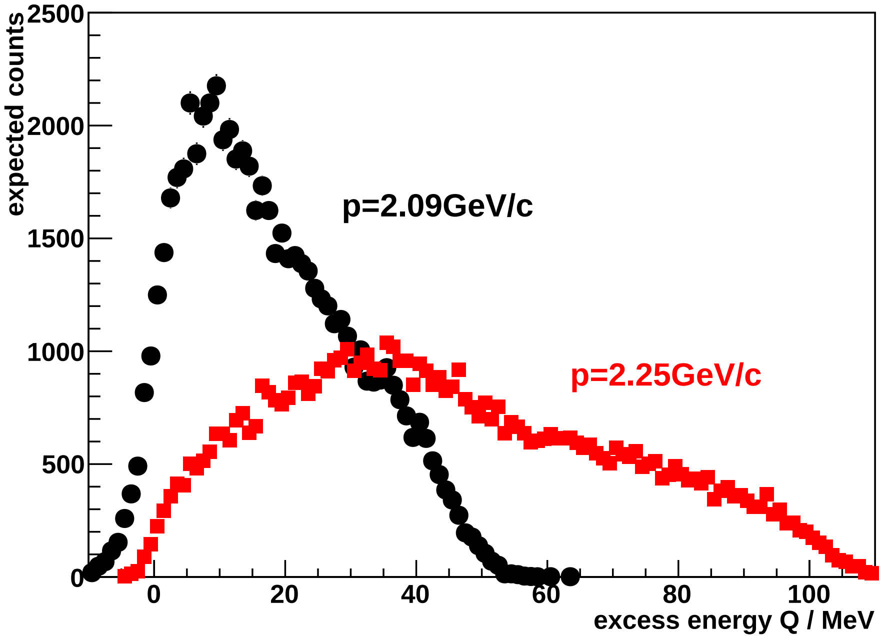

Figure 9: Expected counts after two weeks of beam time. The black points show the expected numbers of events in each Q bin after 6 days for $p_{\text{beam}} = 2.09$ GeV/c and the red points corresponds to 5 days at $p_{\text{beam}} = 2.25$ GeV/c.

target overlap studies, installation of the two STT and trigger adjustment, and 1 day for changing the beam momentum from 2.09 GeV/c to 2.25 GeV/c. This will allow us to collect approximatively 56,000 and 64,000 events of the $pd \to p_{\text{spec}} d\eta$ reaction at $p_{\text{beam}} = 2.09$ GeV/c and $p_{\text{beam}} = 2.25$ GeV/c, respectively. The total number of events requested is based on the statistics required to extract the angular dependence of the reaction as a function of Q up to 110 MeV. The resolution in ANKE will allow us to determine the absolute size of the scattering length, $|a|$, with an accuracy of about 5%.

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