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 investigate the ηd final state interaction in quasi–free kinematics via the reaction $pd \to p_{\rm sp} d\eta$ at two different beam momenta at ANKE. The angle 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. Both total and differential cross sections will be determined and the requested statistics will allow an investigation of a possible anisotropy in the differential cross sections. According to detailed Monte-Carlo simulations, the size of the scattering length $|a|$ is expected to be reconstructed with a precision in the order of 5%.

1 Introduction – Motivation

The current issue of the Physics and Astronomy Classification Scheme has a section called "21.85.+d Mesic nuclei" and one of the items that fits well in this box is ${}^{3}_{\eta}\mathrm{He}$. The study of the cross section for the $dp \to {}^{3}\mathrm{He}\,\eta$ reaction near threshold [1] showed a surprisingly strong variation with energy and this was taken as evidence for a large final state interaction effect (FSI) between the η and the recoiling ${}^{3}\mathrm{He}$ nucleus. This would correspond to a large scattering length in the $\eta\,{}^{3}\mathrm{He}$ system.

The situation was clarified significantly through two experiments carried out at COSY [2, 3], which measured the differential and total cross sections of the $dp \to {}^{3}\mathrm{He}\,\eta$ reaction in fine energy steps from below threshold up to an excess energy $Q \approx 11$ MeV. The cross section jumped to its plateau value already for $Q < 0.5$ MeV and, after taking the beam momentum spread into account, it was seen that the origin of the large FSI seemed to be a pole in the ${}^{3}_{\eta}\mathrm{He}$ elastic scattering amplitude at $Q = Q_0$, with $|Q_0| \approx 0.2$ MeV.

Further evidence for the pole hypothesis was found from looking at the angular dependence of the cross section, which is biassed towards small $\theta_{p\eta}$ for large Q but has the opposite tendency for $Q \lesssim 1$ MeV [2, 3]. Since this slope arises principally from an interference between the s– and p–waves in the $\eta\,{}^{3}\mathrm{He}$ system, this means that the s–wave amplitude must have a very strong phase variation at low Q, of the type associated with a pole in the $\eta\,{}^{3}\mathrm{He} \to \eta\,{}^{3}\mathrm{He}$ amplitude. The behaviour of the experimental data can be well described by such a hypothesis [4].

However, if the FSI interpretation is correct, then the main features should be largely independent of the particular entrance channel. This has recently been tested by new data from MAMI on the photoproduction of the η on ${}^{3}\mathrm{He}$, $\gamma\,{}^{3}\mathrm{He} \to \eta\,{}^{3}\mathrm{He}$ [5, 6]. The total cross section rises to about one third of its maximum in the first 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. This behaviour can be described with similar s–wave FSI parameters for both hadro– and photoproduction.

Although the case for the existence of ${}^{3}_{\eta}\mathrm{He}$ 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 scattering data, from which 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 [7], the latest photoproduction measurements show no evidence for the decay of ${}^3_\eta$He into $\pi^- ppp$ in the bound–state region [5, 6]. 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 the energy dependence of $|f(dp \to {}^3\text{He}\,\eta)|^2$ [1, 2, 3] is much steeper than that of $|f(dd \to {}^4\text{He}\,\eta)|^2$ [8, 9], 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 radius means that ${}^4_\eta$He should be more bound than ${}^3_\eta$He. Putting these two observations together leads one to think that ${}^4_\eta$He is indeed bound [8], though it says 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 $p^6\text{Li} \to \eta^7\text{B}$ reaction [10, 11]. Apart from the reduced counting rate as the nuclear number A increases, there is a more insidious problem because it seems likely that the binding energy will increase and the resulting η-mesic nuclei will have widths that are larger than the separation between nuclear levels. If this were to happen, the overlapping states would not be identified. Consequently, to study carefully the development with A it would be better to investigate low values, such as the $A = 2$ 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 [12]. However, merely detecting the η did not allow them to separate the quasi–free ηd from the ηnp final state.

In another approach, fast deuterons from proton–deuteron collisions were interpreted as arising from the quasi–free $pn \to d\eta$ reaction. In this case the major problem was in determining the shape of the multipion background sitting under the η signal [13] and it would seem that there could have been some significant misidentification in the analysis.

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 [14] 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. Under quasi–free conditions, the momentum of the

η determines the direction of the deuteron, though this is smeared by the Fermi motion in the target deuteron. It was on the basis of the separation of the deviations between the expected direction and that of the recorded fast particle that the $pn \to d\eta$ reaction was identified. Only in a fraction of the events could the fast charged particle be identified positively as a deuteron. Other events, where the single fast charged particle did not correspond to the expected kinematics, could be classified as arising from $pn \to pn\eta$. The shape of this distribution agreed well with the Monte Carlo simulation and, by extrapolation, allowed one to make a small subtraction from the number of $pn \to d\eta$ candidates. Although it is remarkable that the group were able to extract so much valuable information from this experiment, it has to be stressed that it was a somewhat indirect measurement that provided values of the total cross sections in 10 MeV bins from $Q = 10$ MeV up to 120 MeV.

In a subsequent experiment [15] the Uppsala group detected the η in coincidence with a deuteron that escaped down the CELSIUS beam pipe. This was then identified and measured by adding a small scintillator telescope and using the next bending magnet of CELSIUS as an analysing magnet. [This detection is based on essentially the same principle as that used later very successfully by the COSY–11 collaboration.] Although this technique led to positive identifications of both the η and the deuteron, the fact that the latter had to pass down the beam pipe placed severe constraints on its transverse momentum and hence on the maximum value of the excitation energy that was accessible. In practice the data were reported in six bins up to a maximum of $Q = 10$ MeV. Although these data therefore had no direct overlap with their earlier results [14], the normalisation was determined from this work by measuring in parallel the deuteron in the PROMICE–WASA forward detector. It was estimated that the overall systematic uncertainty was of the order of 30%. The resolution in Q was ≈ 1 MeV (rms) at threshold, decreasing relatively with increasing Q so that at 10 MeV above threshold it was ≈ 2 MeV.

These later CELSIUS data show a clear FSI enhancement, with the $pn \to d\eta$ cross section at low Q being about a factor of five higher than expected on the basis of a phase–space extrapolation to threshold from the higher energy data. This is seen more clearly if we display the ratio of the experimental data to the arbitrarily normalised phase–space dependence, which is done in Fig. 1. Also shown there 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 should be proportional to

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

where $a(d\eta)$ is a complex scattering length and S is a scale factor that depends upon the particular reaction studied and which is assumed to vary slowly with energy. The curves are calculated using estimates where the input ηN interaction is weak, strong, or very strong [16].

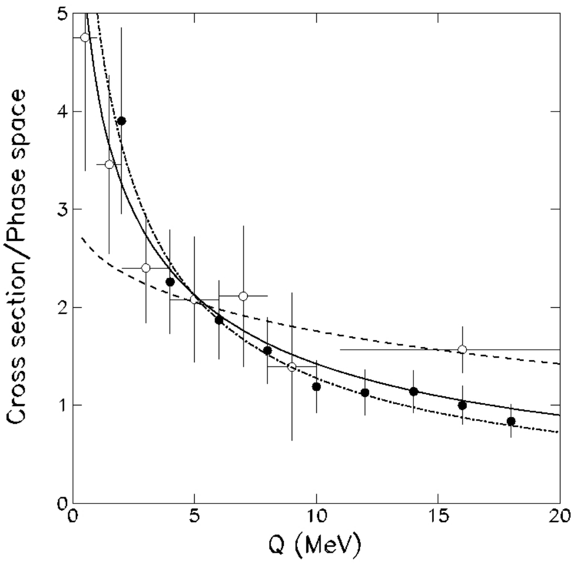

Figure 1: Ratio of the cross section for the production of the $d\,\eta$ system to arbitrarily normalised phase space, as a function of the kinetic energy in the $d\,\eta$ rest frame, for the $pn \to d\,\eta$ total cross section (open circles) [14, 15] and for the $pd \to pd\,\eta$ reaction at 1032 MeV (closed circles) respectively [17]. The broken, solid and chain curves are the predictions of the scattering length formula of Eq. (1), using as input $a(d\,\eta) = (0.73{+}0.56i)$ fm, $(1.64{+}2.99i)$ fm, and $(-4.69{+}1.59i)$ fm respectively [16]. In all cases the overall normalisation is arbitrary.

The two CELSIUS $pn \to d\eta$ experiments [14, 15] were carried out in quasi–free kinematics, where the beam energy was above the η production threshold in nucleon-nucleon collisions. However, the $pd \to pd\eta$ reaction was also studied at CELSIUS well below the free NN threshold by detecting the d and the η and making a full kinematic reconstruction of each event [17]. Whereas the data obtained in this way at 1032 MeV showed ηp and pd invariant–mass distributions that were consistent with phase space, an enhancement was seen for ηd at low invariant mass. The authors divided the latter distribution by phase space and the resulting values are also presented in Fig. 1. Although not inconsistent, given the sizes of the error bars, the low energy data do seem to show a somewhat steeper fall–off with excitation energy than the quasi–free data. However, the division by phase space, even 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 somewhat slower fall–off can be found. Data of this type were also obtained as a by–product of the deuteron charge–exchange programme at ANKE with a deuteron beam of 1.135 GeV per nucleon [18]. These are still under analysis but it seems unlikely that model–independent results will emerge from these data.

Given the importance of getting good and reliable data on the $pn \to d\eta$ reaction, we propose to measure the process in quasi–free kinematics with a deuterium target and study $pd \to p_{\rm sp} d\eta$. The angles and energy of the spectator proton, $p_{\rm sp}$, will be measured in one of the 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 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, the excess energy range $0 < Q < 120$ MeV would be scanned, with a large Q overlap in common between the two settings. A uniform relative normalisation will thus be achieved.
- Information would be obtained on the differential as well as the total cross section, which will help in the identification of the s–wave in the ηd system and hence the study of the s–wave 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 $\cos\theta_\eta$.

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

The proposed experiment is planned to be carried out using the ANKE spectrometer at COSY, which allows an excellent momentum resolution for emitted charged particles, combined with a large acceptance for near-threshold studies. Because of the absence of a free neutron target, the reaction $pn \to d\eta$ will be studied by looking at the quasifree reaction $pd \to p_{\text{spec}} d\eta$, with p_{spec} being a spectator proton. For this purpose COSY will provide a proton beam while the internal cluster-jet target [19] at ANKE will be operated with deuterium as target material. Under the assumption that the proton is a spectator, the beam proton interacts with the neutron of the deuteron and forms the final deuteron. The residual spectator proton of the target deuteron escapes with its Fermi momentum. Through a precise measurement of the four-momentum of the spectator proton using the ANKE spectator detector (STT), it is possible to determine the excess energy of the reaction of interest on an event-by-event basis. The deuteron in the final state will be registered by the ANKE forward system, which in turn allows for a full event reconstruction and the identification of the reaction $pd \to p_{\text{spec}} d\eta$ by the missing-mass method.

It is planned to take data at two different beam momenta, namely $p_1 = 2.03$ GeV/c and $p_2 = 2.20$ GeV/c with a deflection angle of the COSY beam of $\alpha = 9.3^\circ$. According to detailed Monte-Carlo simulations these two beam momenta will allow for the determination of an excitation function ranging from sub-threshold energies up to $Q = 120$ MeV.

For a neutron at rest, the reaction threshold is located at $p_{\text{beam}} = 1.588$ GeV/c, so that these two beam momenta would correspond to excess energies of $Q_1 \approx 19$ MeV and $Q_2 \approx 78$ MeV. However, due to the Fermi motion of the target neutron, the excess energy Q has to be reconstructed on an event-by-event basis. In order to evaluate Q, the spectator proton will be detected in one of the two STTs [20] that are placed to the left and right of the target. The STTs consist each of three double-sided segmented detectors:

- 1^{st} layer: 70 μm thick, 66×52 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, 64×64 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 55.5° and 124.5°. To ensure quasifree conditions, only spectator protons with kinetic energies below 9 MeV will be used in the analysis. There is also a lower bound on the energy of the spectator protons since they have to penetrate the first layer in order to be detected in the second. Due to this constraint, a minimum kinetic energy of 2.5 MeV is required.

The energy/angular acceptance of the STTs is shown in Fig. 2 (black rectangle) for a COSY beam momentum of $p_{\text{beam}} = 2.03$ GeV/c. The beam momentum is chosen so as to allow a large acceptance close to the production threshold and also below threshold for background studies.

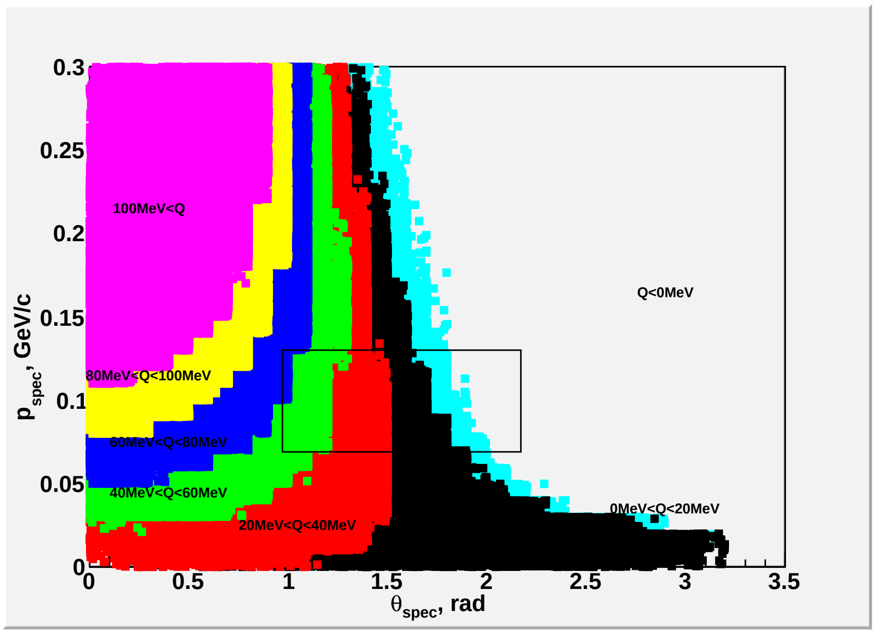

Figure 2: Momentum of the spectator proton versus the angle of the spectator proton for $p_{\text{beam}} = 2.03$ GeV/c. The acceptance of the STTs is shown as a black rectangle. Different colours belong to different intervals of the excess energy Q.

The Q dependence of the acceptance with a proton detected in the STT and a deuteron in the forward system is shown in Fig. 3.

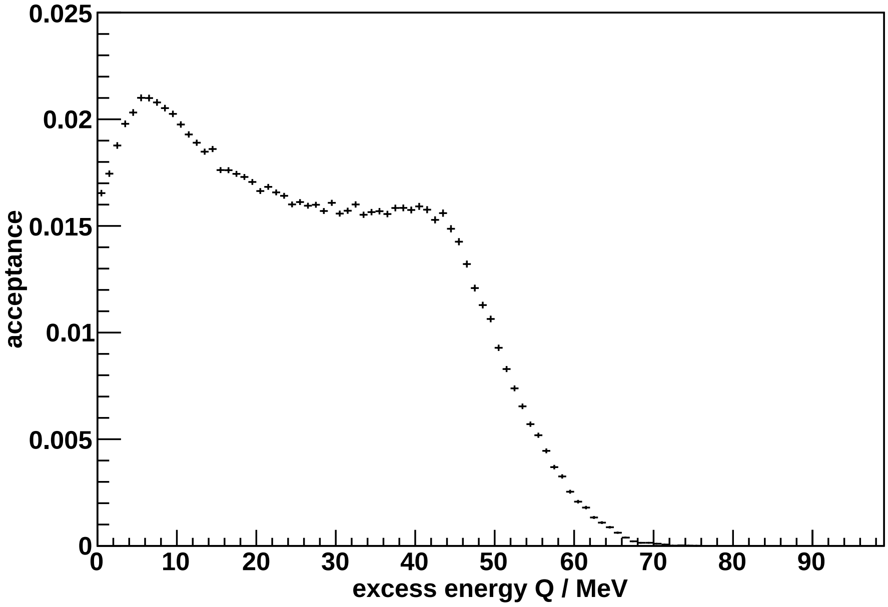

Figure 3: Q dependence of the acceptance of ANKE for $p_{\mathrm{beam}} = 2.03$ GeV/c

Close to the reaction threshold the acceptance distribution is maximal and is in the order of 1.5% for excess energies up to $Q = 45$ MeV. For studies at higher excess energies, i.e. up to $Q = 120$ MeV, a beam momentum of $p_{\mathrm{beam}} = 2.20$ GeV/c will be used. The second momentum is chosen such that the excess energy range will overlap that investigated at the lower beam momentum. This will allow studies on systematic uncertainties to be carried out.

The spectator protons will be identified in the STTs through the $\Delta E/E$-method. The energy resolution has been shown to be in the order of 160 keV FWHM, allowing a good separation of proton and deuteron bands (Fig. 4).

The uncertainty in determining the excess energy is associated mainly with the accuracy of the four-momentum reconstruction of the spectator proton. The most important source of inaccuracy is the uncertainty in the measurement of the polar angle of the proton of approximately $\Delta\theta \approx 3.5^{\circ}$ (σ) caused by small-angle scattering (mostly in the first thin layer) and track recon-

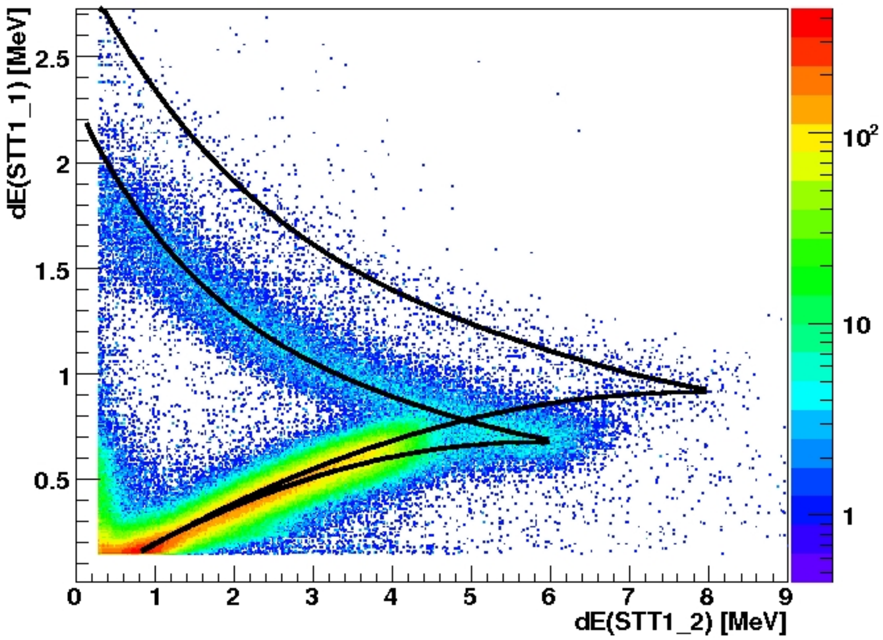

Figure 4: Energy loss correlation for the first and second layers of the STT. The solid lines correspond to the expected $\Delta E/E$ dependence for protons and deuterons

struction. The achievable resolution of the excess energy is about 4.5 MeV (σ).

With this 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), which will allow for detailed studies of the angular dependence of the cross section. This is of great interest for a careful investigation of the final state interaction in the ηd-system since it will allow the determination of a possible anisotropy caused by partial waves higher than s-waves.

According to Monte-Carlo simulations a possible angular anisotropy, which in first order can appear as a $\cos^2\vartheta$ term,

$$\frac{d\sigma}{d\Omega} = a \cdot (1 + b \cdot \cos^2\vartheta) \qquad (2)$$

will be identifiable in the excess energy range from threshold up to $Q = 40$ MeV with an accuracy in the order of $\Delta b \approx 0.05$, assuming $b = 0.1$ and a Q-binning of 5 MeV.

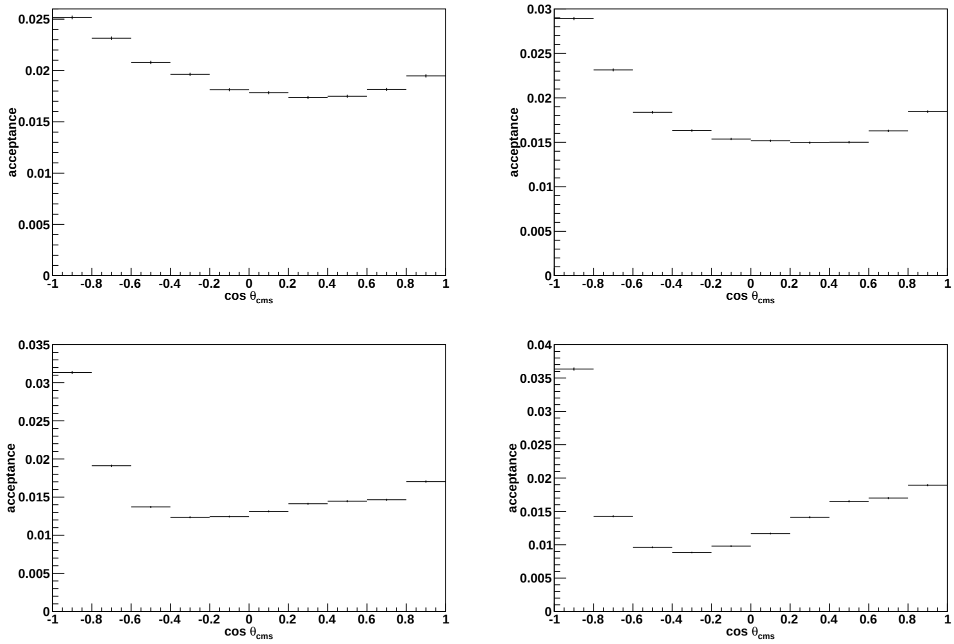

Figure 5: Angular acceptance of ANKE for Q = 0-10 MeV (upper left), Q = 10-20 MeV (upper right),Q = 20-30 MeV (lower left), and Q = 30-40 MeV (lower right), obtained at $p_{\mathrm{beam}} = 2.03$ GeV/c.

By detecting the spectator proton in one of the STTs and a deuteron in the forward detector system, the reaction will be identified by the missing-mass technique. An elegant way to describe and subtract the physical background mainly arising from multi-pion production is a method introduced by the SPESIII group [21]. Here the background of a data set is described by data obtained at a second beam energy, whose reconstructed center of mass momenta are transformed to the laboratory system of the first energy. By this the kinematical 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 ω-meson production in the quasi-free reaction $pn \to d\omega$ [22]. An example is shown in Fig. 6 for the $pn \to d\omega$ reaction at two different beam momenta [23]. The black line indicates experimental data obtained at 2.915 GeV/c whereas the red curved represent the data at the other momentum of 3.015 GeV/c shifted using the SPESIII procedure [21]. In the lower spectra the differences between the two curves are shown, which allow to extract the amount of produced ω-mesons. Due to the larger cross section and smaller mass width this method is expected to work even better in case of the η meson.

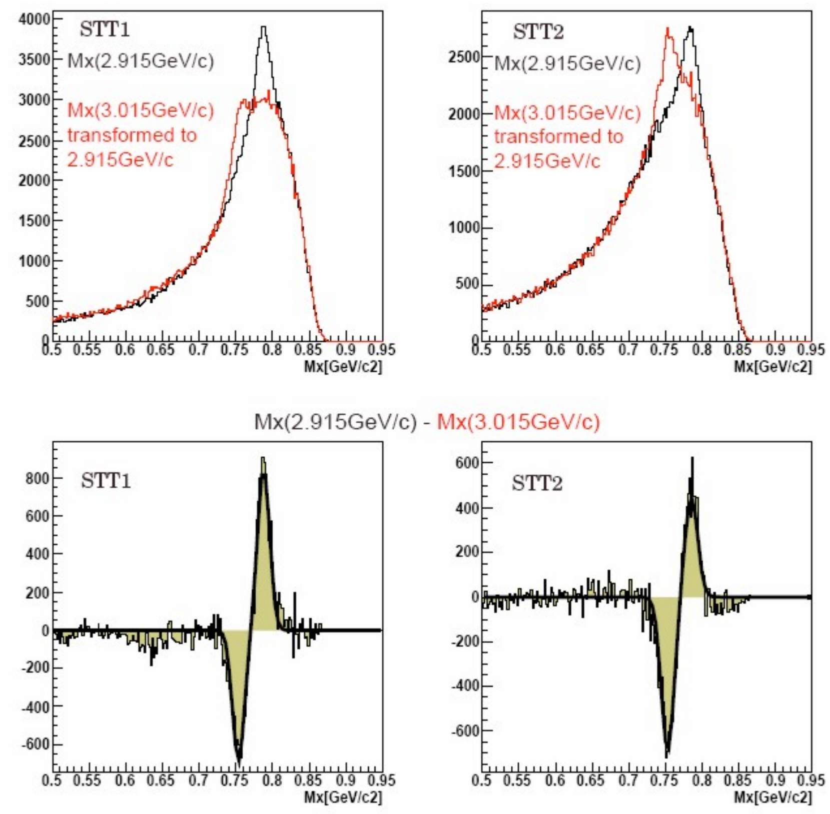

Figure 6: Missing mass spectra for the $pn \to d\omega$ reaction. The black line indicates experimental data obtained at 2.915 GeV/c whereas the red curve represents the data at the other momentum shifted using the SPESIII procedure [21]. In the lower spectra the differences between the two curves are shown.

The quality of the proposed measurement is illustrated in Fig. 7, which shows the assumed input excitation function for the Monte-Carlo simulations based on a scattering length of $a(d\eta) = (1.64 + 2.99i)$ fm by the red curve and the expected reconstructed cross sections by the data points. The black solid line is a fit to these data points using Eq. 1 and this nicely agrees with the input data. Based on Monte-Carlo simulations assuming different scattering lengths it was found that the absolute of the scattering length, $|a|$, can be reconstructed with an accuracy of 5%.

For the detailed investigation of the ηd final state interaction, only the relative shape of the excitation function would be required and no reference reaction is needed. However, in parallel to the reaction of interest, data on proton-deuteron elastic scattering will be recorded, which will enable the de-

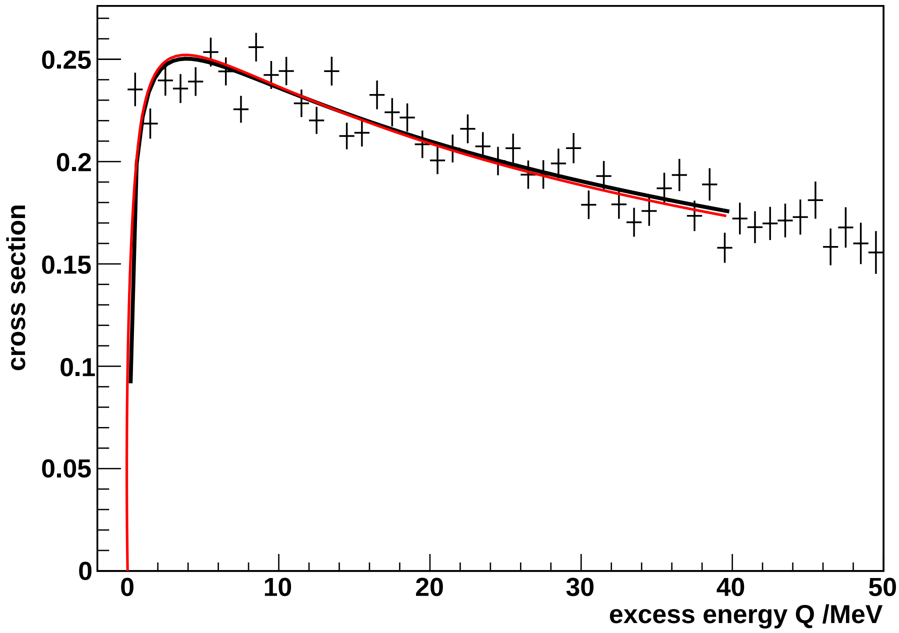

Figure 7: Results of Monte-Carlo simulations with an excitation function based on an assumed scattering length of $a(d\eta) = (1.64 + 2.99i)$ fm (red curve) and expected reconstructed cross sections (data points). The black solid line is a fit to these data points using the scattering length formalism.

termination of the absolute cross sections. In Fig. 8 the acceptance of the ANKE detector system as function of the momentum transfer $|t|$ is shown for events from the *pd* elastic scattering. Here both a hit of the scattered proton in the forward detector and a hit of the deuteron in the spectator detector is requested. For the determination of the integrated luminosity the measured elastic scattering data can be compared to existing data in the same momentum transfer region [24, 25], parametrized by [26]. The precision of the absolute luminosity determination is dominated by the available reference data and will be in the order of 15%.

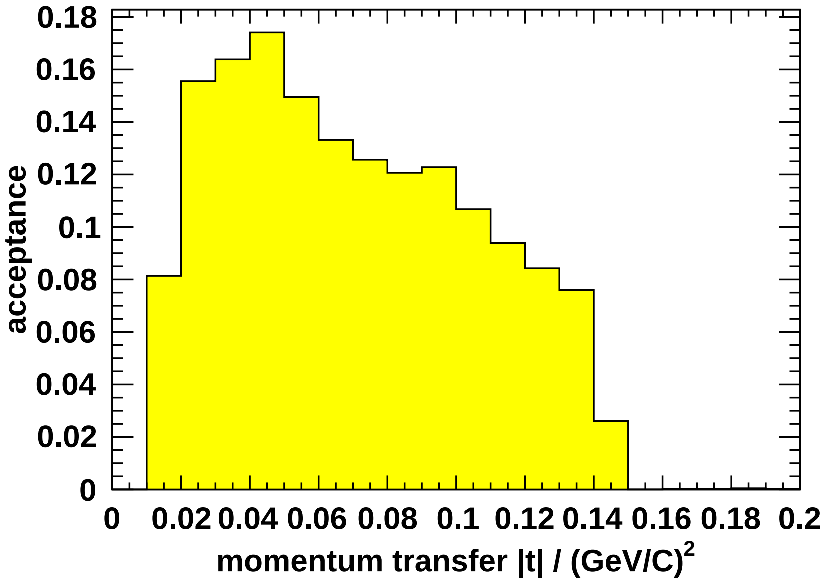

Figure 8: Acceptance of the ANKE detector system for events from the *pd* elastic scattering as function of the momentum transfer $|t|$.

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} and total cross sections reported in [14, 15, 17] (see Fig. 1) are assumed. Under these conditions and considering a dead time in the order of 65% due to the acceptance for the *pd* elastic scattering we expect approximately 4000 events/day (15000 events/day) for $p_{\text{beam}} = 2.03$ GeV/c ($p_{\text{beam}} = 2.20$ GeV/c) in the excess energy range of $Q = 0 - 120$ MeV. The total number of events expected after 18 days of data taking, i.e. 12 days of beam time at a beam momentum of $p = 2.03$ GeV/c and 6 days at $p = 2.20$ GeV/c, is shown in Fig. 9.

In total we ask for **three weeks of beam time**, including 2 days for beam-target overlap studies, installation of the two STTs and trigger adjustment and 1 day for changing the beam momentum from 2.03 GeV/c to 2.20 GeV/c. This will allow us to collect approximatively 48,000 and 90,000 events from the reaction $pd \to p_{\text{spec}} d\eta$ with $p_{\text{beam}} = 2.03$ GeV/c and $p_{\text{beam}} = 2.20$ GeV/c, respectively. This total number of requested events is based on the statistics

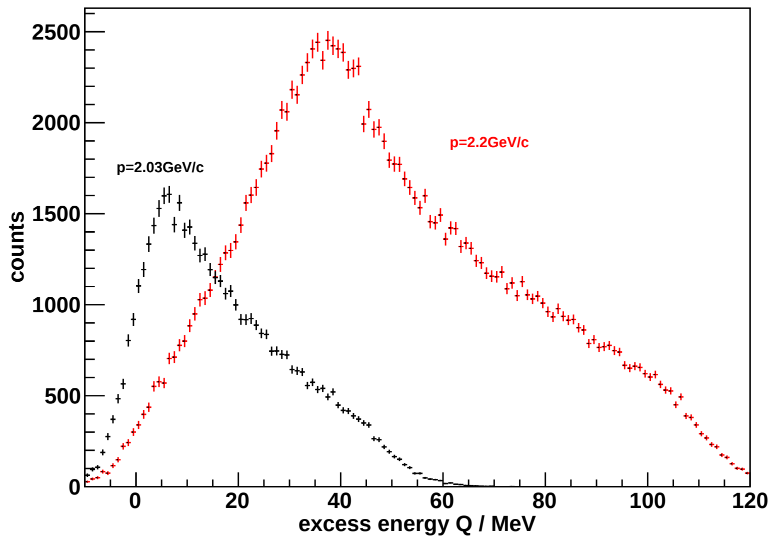

Figure 9: Expected numbers of counts after three weeks of beam time. The black line shows the expected events in each Q bin after 12 days for $p_{\rm beam} = 2.03$ GeV/c and the red line corresponds to 6 days with $p_{\rm beam} = 2.20$ GeV/c.

required to extract angular anisotropies and final state interaction parameters with sufficient accuracy.

The obtained data will allow for the precise determination of the excitation function of the reaction $pd \to p_{\rm spec} d\eta$ from threshold up to $Q \approx 120$ MeV with small systematic uncertainties. Due to the acceptance of the ANKE spectrometer an investigation of differential cross sections with full polar angle coverage will be possible. Finally, the resolution at ANKE will allow us to determine the absolute size of the scattering length, $|a|$, with an accuracy of 5%.

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