Near Threshold π Production in $dd \rightarrow {}^3He\,N\pi$ and $dd \rightarrow t\,N\pi$

M.Büscher[1], D.Chiladze[1], C.Hanhart[1], V.Hejny[1], A.Kacharava[2], A.Khoukaz[3], A.Magiera[4], T.Mersmann[3], M.Śmiechowicz[4], H.Ströher[1], A.Wrońska[1,4]

for the ANKE collaboration

[1]Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany
[2]Physikalisches Institut II, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany
[3]Institut für Kernphysik, Universität Münster, 48149 Münster, Germany
[4]Institute of Physics, Jagiellonian University, 30059 Cracow, Poland

Spokespersons: V.Hejny,* A.Magiera†

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*EMail: V.Hejny@fz-juelich.de
†EMail: Magiera@if.uj.edu.pl

Abstract:

It is proposed to measure the excitation functions of the reactions $\mathrm{dd} \to \mathrm{t\,p}\,\pi^0$, $\mathrm{dd} \to {}^3\mathrm{He\,n}\,\pi^0$, $\mathrm{dd} \to {}^3\mathrm{He\,p}\,\pi^-$ and $\mathrm{dd} \to \mathrm{t\,n}\,\pi^+$ at ANKE close to threshold (spanning a range in excess energy of 8 MeV) using a ramped beam.
These data will provide new insights into four nucleon dynamics in large-momentum transfer reactions like the role of 4-body forces. In addition they will allow to better understand the isospin-conserving part of the initial-state interaction relevant for the analysis of the reaction $\mathrm{dd} \to {}^4\mathrm{He}\,\pi^0$ recently measured at IUCF.

Contents

1 Physics Motivation

In the last decades significant progress has been achieved in reformulating low and intermediate energy hadron physics as an effective field theory, namely chiral perturbation theory[1, 2]. The formalism uses the fact that the interaction of pions with matter is largely controlled by the approximate chiral symmetry of *QCD*, for pions are the Goldstone Bosons resulting from the spontaneous breakdown of this symmetry. Up to date most work was done for the two pion system, the πN system and, more recently, the NN system[1, 3]. In addition, a promising scheme was derived to also analyse pion production in nucleon-nucleon collisions[4, 5, 6]. The next step is moving to more complex few nucleon systems. There is already data available for pion production in *pd* collisions that can be analysed within chiral perturbation theory. These studies, together with an analysis for elastic *pd* scattering, will allow a deeper understanding of three body forces. The natural next level of complexity is the four nucleon system, experimentally accessible through the *dd* initial channel. These studies will provide information on 4 body forces and are thus an important guide for the way to complex nuclei.

Since chiral perturbation theory allows a systematic analysis of hadronic reactions, also the breaking of *QCD* symmetries can be addressed quantitatively, one example being the isospin. On the level of *QCD*, isospin is broken by the different (current) masses of the up and the down quark. In addition, the quarks are distinguished through the electromagnetic interaction. Since those contributions can be treated theoretically within the framework of χPT, a study of isospin violation in low energy hadron physics is a unique window to the quark masses and thus to fundamental parameters of the standard model. Isospin breaking effects are typically of the order of a percent and it is difficult to experimentally separate trivial effects due to the different particle masses from those that stem from isospin violating operators. Thus it was a big step forward when recently two null experiments (a measurement of observables that vanish in the absence of isospin violation) for isospin violating quantities were successfully performed. Those are the forward-backward asymmetry in $\mathrm{pn} \to \pi^0\mathrm{d}$ [7] and the total cross section for $\mathrm{dd} \to \alpha\pi^0$ [8]. In order to analyse these reactions theoretically a big theory collaboration was formed (for first results see Ref. [9]). However, to successfully carry out this program and especially to isolate the isospin violating matrix elements of interest more information on the related isospin conserving interactions is needed. For the second reaction close relatives are given by $\mathrm{dd} \to \mathrm{tN}\pi$ and $\mathrm{dd} \to {}^3\mathrm{HeN}\pi$. Especially since the initial states are the same, from these reactions important constraints will follow for the initial state interaction to be used in the analysis of the isospin violating close relative. In addition, experimental information on $\mathrm{dd} \to ({}^3\mathrm{He},\mathrm{t})\,\mathrm{N}\pi$ will at the same time help to show how well we understand in general the isospin conserving part of the 4 N system which is obviously a precondition for a controlled extraction of isospin violating matrix elements.

For the future — continuing the CSB related experiments from IUCF — it is discussed to measure $\mathrm{dd} \to {}^4\mathrm{He}\,\pi^0$ further away from threshold at COSY once the WASA detector is installed. This would provide data on higher partial waves and resonance contributions. However, a crucial point for planning such a program is the precise knowledge of possible background channels. Since no data are available so far, the proposed experiment would also provide indispensable input for these studies.

2 Experimental Details

The ANKE detector system [10] will be used to study the four reactions $\mathrm{dd} \to \mathrm{t p} \pi^0$, $\mathrm{dd} \to \mathrm{t n} \pi^+$, $\mathrm{dd} \to {}^3\mathrm{He\,n}\pi^0$ and $\mathrm{dd} \to {}^3\mathrm{He\,p}\pi^-$ close to threshold. As shown in Fig. 1 the individual detector positions (forward and positive side) ideally fit to the kinematics of the different final states. Each of the four plots correspond to one of the reaction channels at an excess energy of $Q = 1\,\mathrm{MeV}$. Although the distributions become wider at larger Q values, the global pattern will stay the same:

- Tritons with an average momentum of $\bar{p} = 750\,\mathrm{MeV/c}$ are detected in the high momentum part of the forward detector.
- ^{3}He nuclei (having the same momentum, but only half the rigidity) are detected in the sidewall.

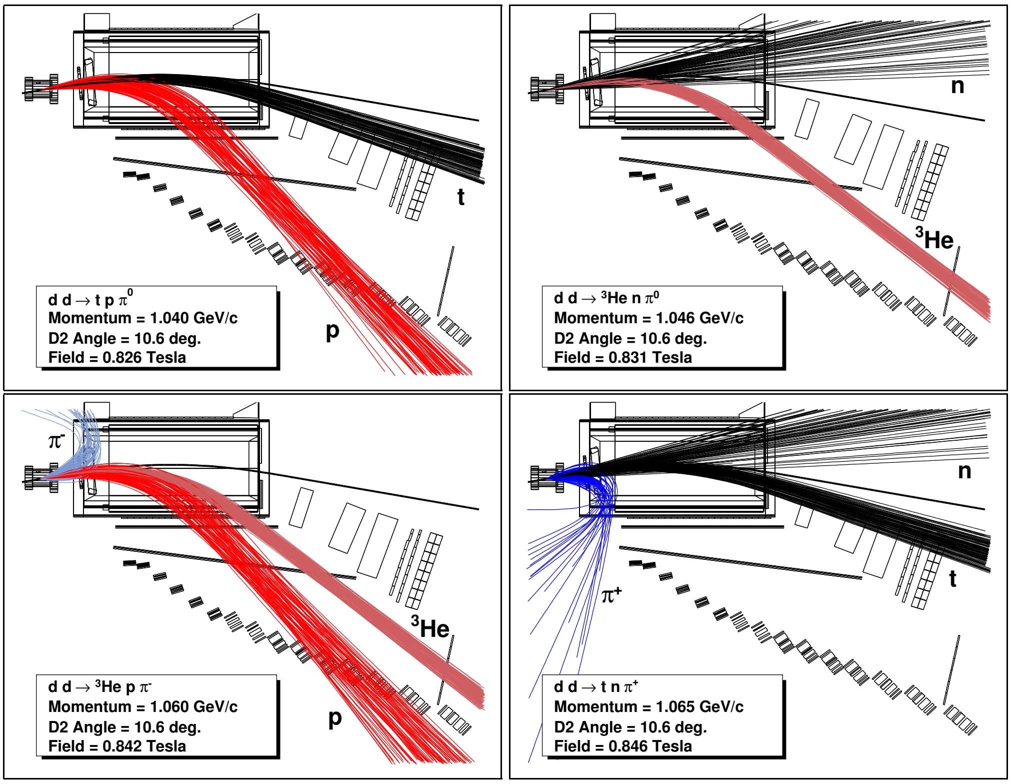

Figure 1: Track pattern in ANKE for all four reactions at an excess energy of $Q = 1\,\mathrm{MeV}$: tritons are detected in the forward detector, ^{3}He in the sidewall and protons in the telescopes. Charged pions are not in the acceptance of ANKE.

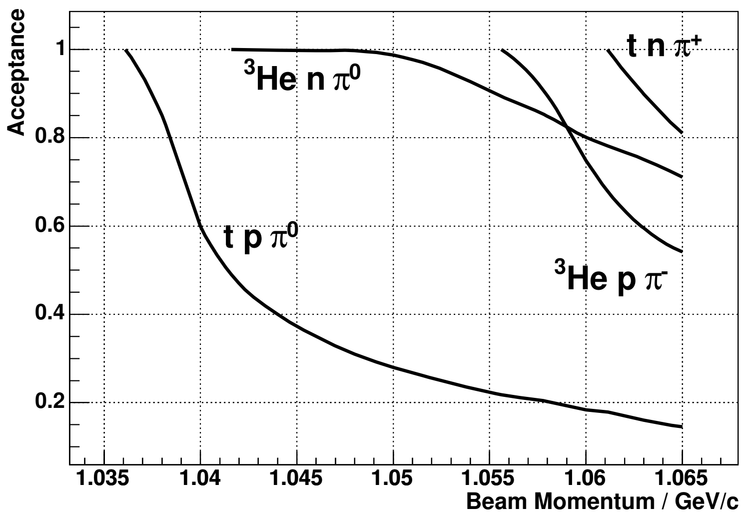

Figure 2: Geometrical acceptance as a function of beam momentum for all four final states.

- Protons ($\bar{p} = 250\,\mathrm{MeV/c}$) are detected in the high momentum part of the telescope array.
- The momentum of the charged pions ($\bar{p} = 50\,\mathrm{MeV/c}$) is too low to fall into the acceptance of ANKE.

At threshold ANKE has full acceptance for all channels. The total acceptance as a function of beam momentum is plotted in Fig. 2. In case of a triton in final state the acceptance drops more rapidly with higher beam momentum, because the centre of the distribution is located close to the edge of the forward detection system. However, for the reaction $\mathrm{dd} \to \mathrm{tp}\pi^0$ the Dalitz plot is fully covered — despite of the low acceptance – even at the highest momentum (see Fig. 3).

2.1 Identification of the reaction channels

Particle identification will be done by means of energy-loss measurements versus momentum in two scintillation layers for tritons in the forward hodoscope and in one scintillation layer (but combined with additional time-of-flight information) for ^{3}He in the sidewall and coincident protons in the telescopes. Due to the lower momentum and the larger separation of tritons and ^{3}He from protons and deuterons (see Fig. 4), the particle discrimination will be even better than in previous ANKE experiments. In these measurements ^{3}He has been identified at a rigidity of about $1\,\mathrm{GeV/c}$.

When analysing the data from $\mathrm{dd} \to {}^4\mathrm{He}\eta$ [11] one major source of background were the break-up or spectator protons originating from quasi-free reactions on the neutron of the beam deuteron. The cross section for these processes is a significant fraction of the total inelastic cross section and the momentum distribution of these protons is centred at half the

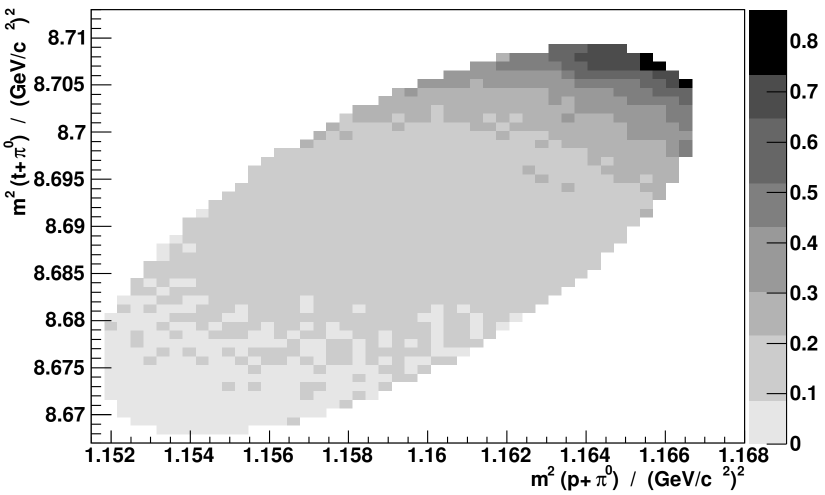

Figure 3: Acceptance distribution within the Dalitz plot for the reaction dd $\rightarrow$ $\mathrm{t p \pi^0}$ at 1.065 GeV/c. The highest acceptance is for tritons and protons both going parallel in c.m. (i.e. small relative momenta) with a π^0 going in the opposite direction.

beam momentum. For dd $\rightarrow$ $^4\mathrm{He}\,\eta$ measured at 2.345 GeV/c the maximum at 1.17 GeV/c was very close to the rigidity of the ^{4}He at $\approx 1.025\,\mathrm{GeV/c}$ and both were located in the forward detector. For the current proposal these break-up protons have a momentum of 500 MeV/c and are located between the forward detector and the sidewall.

The only other channels at this beam momentum containing ^{3}He or tritons are dd $\rightarrow$ $^3\mathrm{He\,n}$ and dd $\rightarrow$ $\mathrm{t\,p}$. In general, the available phase space is larger and the individual particles are not kinematically focussed as in the pion production channels. Therefore, they are already suppressed by trigger (see below). Furthermore, a single detected ^{3}He or triton from these channels will result in a missing mass of a nucleon. The channels to be measured contain an additional pion, which means that the missing mass is at least 135 MeV/c^2 larger (which has to be compared with the typical missing-mass resolution of ANKE of better than 10 MeV/c^2). The same holds for the coincidence measurements of ^{3}He-p and t-p, where the missing mass of a pion has to be requested.

However, as a check a momentum interval of 5 MeV/c below the lowest threshold is foreseen to study the background conditions for these reactions and to allow to subtract the background if necessary.

In two of the four proposed reactions the final state contains a neutron and, thus, two missing particles. Normally, it is not possible to identify this type of reactions using a missing mass analysis. Therefore, a major task will be the discrimination of the channels $^3\mathrm{He\,n}\,\pi^0$ and $^3\mathrm{He\,p}\,\pi^-$ on one hand and $\mathrm{t\,p}\,\pi^0$ and $\mathrm{t\,n}\,\pi^+$ on the other hand. Those with a coincident proton can be identified easily, for the others it is - *a priori* - not clear, whether the proton was missed or the nucleon was a neutron. However, these channels have different thresholds and the aim of this proposal is to measure very close to threshold. This allows the following analysis:

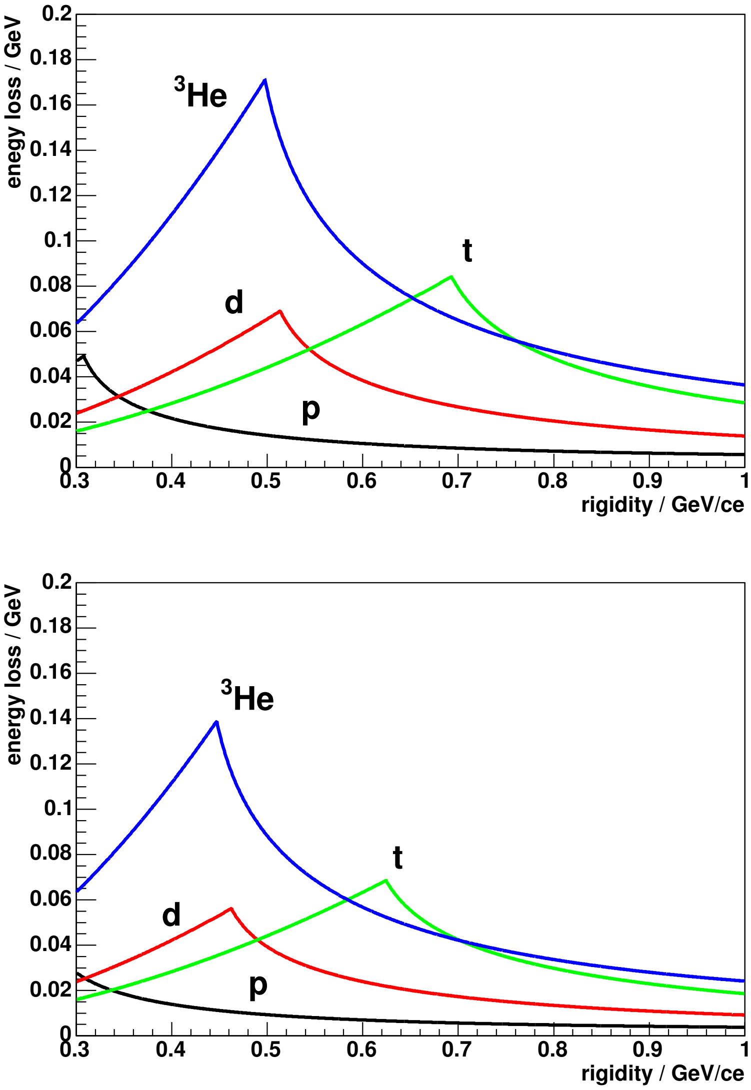

Figure 4: Energy loss in the first layer of the forward hodoscope (upper) and in the side-wall counter (lower) for different types of particles as a function of the rigidity (i.e. momentum per charge). The region of interest for this experiment is between 700 and 800 MeV/c for tritons and between 350 and 400 MeV/c for ^{3}He.

- dd $\longrightarrow$ $^3\mathrm{He}\,\mathrm{n}\,\pi^0$. The threshold of this reaction is lower than for dd $\longrightarrow$ $^3\mathrm{He}\,\mathrm{p}\,\pi^-$. Thus, within the first 3.3 MeV in excess energy a detected ^{3}He with a proper missing mass (see above) can originate only from this reaction. For higher energies the momentum distribution of this final state will be wider as for $^3\mathrm{He}\,\mathrm{p}\,\pi^-$, which will be visible as a peak on the wider distribution. The size of this contribution can be determined, because — as discussed above — the $^3\mathrm{He}\,\mathrm{p}\,\pi^-$ events can be identified unambiguously requiring a coincident proton. The precision for $^3\mathrm{He}\,\mathrm{n}\,\pi^0$ is not affected tremendously, because in this case a small number (^{3}He p π^- events) will be subtracted from a large number (^{3}He n π^0 events). Therefore it should be well possible to identify this channel.

- dd $\rightarrow$ t n π^+. The situation for this final state is worse, because the threshold is higher than the corresponding "charged" final state t p π^0. The argument that one can determine the contribution of t p π^0 to the t n π^+ events is still valid, but in this case one would have to extract a small number by subtraction of two large numbers. How well this will work depends on actual cross sections. Therefore, we will concentrate on the analysis of the other three final states, which is also reflected in the momentum region chosen for the beam request. The highest momentum was selected such that for all four reaction data at $Q = 1\,$MeV will be obtained.

2.2 Trigger

Our recent measurement of η production in dd collisions at higher momenta at ANKE showed how effective and reliable a trigger based on energy loss in the forward hodoscope worked[1]. The rates allowed to run with a trigger open for ^{3}He. For the current proposal the discrimination of ^{3}He from protons and deuterons will be even larger (due to the lower momentum, see above). The same applies for tritons, because their energy loss (see Fig.4) is the same as for ^{3}He with a rigidity lower than measured in η beam time. Furthermore, the expected luminosity is about a factor of 5 lower (see below). Thus, we conclude that the rate using two single-particle triggers for tritons and ^{3}He in the forward hodoscope and the sidewall, respectively, can well be handled by the (currently used) ANKE data acquisition.

2.3 Normalisation

2.3.1 Beam momentum

The goal of the experiment is to provide total cross sections for the discussed final states very close to threshold. We aim at a precision of better than $\pm 30\%$ for excess energies of $Q = 1\,$MeV and above. Since for 3-body final states phase space opens with Q^2, at $Q = 1\,$MeV a change of 30% in cross section corresponds to a change of only 0.15 MeV in Q. Thus, a precise knowledge of the beam momentum is crucial. In our case it has to be known with a precision of better than $\Delta p/p \approx 0.7 \cdot 10^{-3}$.

In order to minimise the systematic error caused by the uncertainty of the absolute beam momentum provided by COSY (at most 10^{-3}), we will use the fact that the four reaction channels t p π^0, ^{3}He n π^0, ^{3}He p π^- and t n π^+ have their thresholds close together at 1.0361 GeV/c, 1.0416 GeV/c, 1.0556 GeV/c and 1.0611 GeV/c, respectively. This spans a range of only 25 MeV/c in momentum and 6 MeV in c.m. energy. COSY offers the possibility of accelerating the beam slowly allowing the experiments to scan a momentum range rather

[1]The scintillators are read out on both sides. Therefore special modules have been built to sum up the two analog signals and to set a threshold on the charge integral.

than measuring at one fixed beam energy. This feature has been used intensively by EDDA [13] and COSY11 [14].

We propose to use this powerful feature also at ANKE in order to cover the full momentum range between 1.030 GeV/c and 1.065 GeV/c, i.e. starting below threshold for dd $\rightarrow \mathrm{tp}\pi^0$ up to $Q = 1\,\mathrm{MeV}$ for dd $\rightarrow \mathrm{tn}\pi^+$. During the ramping (very slow with a speed of a few seconds per MeV/c) we will cross all four reaction threshold and, thus, use them to determine the absolute beam momentum. Aiming at a final binning of 1 MeV/c, this should allow to fix the centre of the bins with a precision of 0.5 MeV/c or better.

Moreover, the spread of the beam momentum has to be taken into account. In earlier deuteron beam times, a spread of $2.5 \cdot 10^{-4}$ at the beginning and $7 \cdot 10^{-4}$ at the end of a 15-minute cycle have been measured. The increased width is due to beam-target interactions. Shortening the cycle to 5 minutes will reduce this effect to a large extent.

Normally, one also has to consider a shift of the beam momentum during the cycle due to energy loss of the beam in the target. This will not take place during ramping. Here, the momentum is defined by the high frequency of COSY.

2.3.2 Luminosity

At this energy no data for dd elastic scattering are available. Instead data for pp and pd elastic scattering can be used by measuring the quasi-elastic scattering in dd. For this purpose the silicon-strip spectator-telescopes will be installed in addition.

However, during recent ANKE beam times a complementary method to determine the target density and — combined with a measurement of the beam current — the luminosity has been developed. It uses the frequency shift (i.e. momentum shift) of the coasting beam due to energy loss in the target. This method has been improved by determining the relevant parameters (especially the η parameter, which correlates frequency and momentum as well as the beam current) with a much higher precision than before. Basic advantages are, that the experiment is not disturbed and that one gets luminosity information for every beam cycle individually. The expected uncertainty of the extracted luminosity is less than 10%.

As already stated above this method cannot be used when the high-frequency is still on during the measurements, which obviously is necessary for ramping. For this reason part of the data-taking cycle will be taken with a fixed beam momentum. A reasonable choice for this is the highest momentum to be measured. At this energy, the available phase space is largest and one has the opportunity to extract differential distributions for the reaction channels with two detected particles ($^3\mathrm{He}\,\mathrm{p}\pi^-$ and $\mathrm{tp}\pi^0$) in final state. These data might provide information on the isospin $I = 1$ ^{3}A-nucleon interaction ($I = 0$ is suppressed due to charge symmetry). Experimental results for this are missing so far.

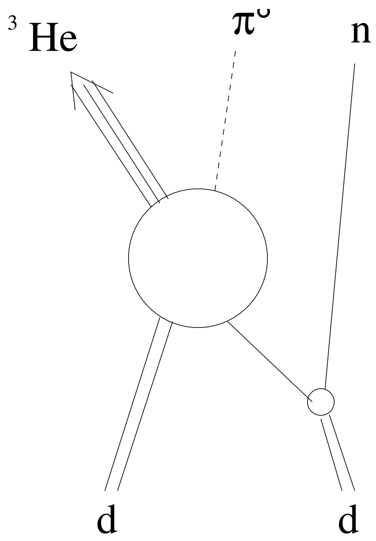

Figure 5: Diagram that contributes to dd $\rightarrow^3$ Heπ^0n and that was used in the cross section estimate.

2.4 Count Rate Estimates

2.4.1 Luminosity

An assumed target thickness of $1 \cdot 10^{14}\,\text{cm}^{-2}$, in average $5 \cdot 10^{10}$ deuterons in COSY at 1.05 GeV/c ($f \approx 0.8\,\text{MHz}$) results in a luminosity of $L = 4 \cdot 10^{30}\text{cm}^{-2}\text{s}^{-1}$. In addition, due to the low momentum the beam diameter is quite large ($\approx 20\,\text{mm}$). In combination with a horizontal target width of $6-7\,\text{mm}$ the beam-target overlap is only 40%. Furthermore, using a 5 minute cycle and allowing 50 seconds between two data-taking blocks (for safety reasons we reduce our high voltage for the wire chambers for injection and initial acceleration) the duty factor will be 85%. For track reconstruction and dead time of the data acquisition another factor of two is taken into account. In total the effective luminosity is $L \approx 7 \cdot 10^{29}\,\text{cm}^{-2}\text{s}^{-1}$, i.e. about 4 counts per 100 nb and minute.

2.4.2 Cross section

Since there is no experimental information available in the literature, estimates are needed. We used the known cross section for pd $\rightarrow^3$ Heπ^0[12] as illustrated in Fig. 5. Using non–relativistic kinematics and estimating the cross section in threshold kinematics lead to the following estimate:

$$\sigma_{\text{tot}} \simeq 0.13 \cdot Q^2_{\text{MeV}} \left(\frac{\sigma_{\text{tot}}(\text{pd} \rightarrow^3 \text{He}\pi^0)[\tilde{p}']}{\tilde{p}'_{\text{MeV}}} \right) ,$$

where Q denotes the excess energy for the complete reaction and $\tilde{p}'$ denotes the outgoing relative cms–momentum of the ^{3}Heπ^0 system where the corresponding total cross section is evaluated. As indicated, both are to be taken in MeV.

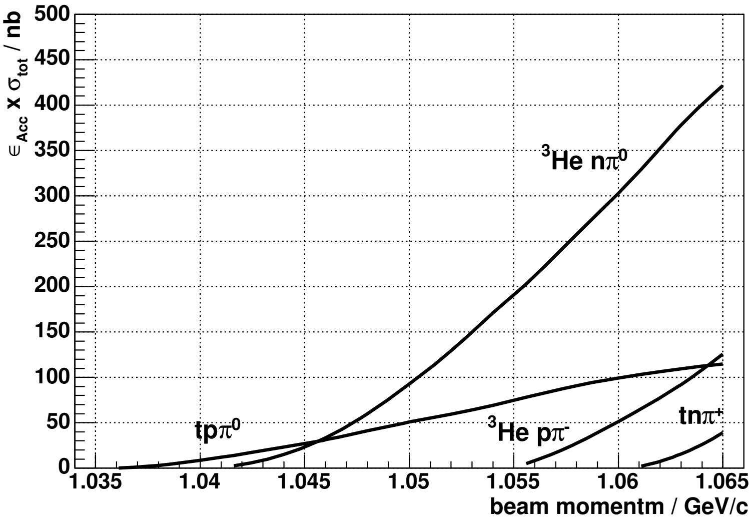

Figure 6: Estimated cross section times geometrical acceptance as a function of beam momentum for the four reaction channels.

Using the results for pd $\rightarrow^3$ Heπ^0 close to threshold one finds the bracket term to be constant (130 nb with $\tilde{p}', Q$ in MeV). Thus, the estimated cross sections are

$$\sigma_{\text{tot}} \simeq 17\,\text{nb} \cdot Q^2_{\text{MeV}}$$

for dd $\rightarrow$ ^{3}He n π^0 and dd $\rightarrow$ t p π^0 and twice larger for dd $\rightarrow$ ^{3}He p π^- and dd $\rightarrow$ t n π^+ (due to the different Clebsch-Gordan coefficients).

Fig. 6 shows these cross sections folded with acceptance.

3 Requested beam time

It is proposed to scan a momentum range between 1.030 GeV/c and 1.065 GeV/c in steps of 1 MeV/c. In order to reach the precision requested by theory (better than 30%) for excess energies of $Q \geq 1\,\text{MeV}$ — taking into account additional systematic errors — the number of events per bin should be about 100 at the lowest cross section (17 nb at $Q = 1\,\text{MeV}$). Folded with acceptance this results in measuring 4 hours per bin resulting in 6 full days.

To measure the luminosity using the energy loss in the target and to take additional data at the highest momentum, a flat top with constant beam momentum for about 1.5 minutes has to be added to each cycle. This will increase the required beam time by 40%.

Since this will be the first time ANKE uses a ramped beam for measurement, further control signals from COSY to ANKE have to be installed and tested. For the same reason additional time for beam preparation should be foreseen. Having a quite large beam diameter at these low beam momenta an optimised COSY setup is also crucial to avoid background from beam losses. In addition, time for calibration runs using a proton target will be necessary as well as for a optimising the trigger setup (e.g. the high voltages have to be properly aligned in order to trigger on the sum of two analog signals).

Thus, in total we ask for two weeks of deuteron beam time during the next period, preferably in one block with other experiments using a deuteron beam at ANKE.

The required beam conditions are:

- $5 \cdot 10^{10}$ deuterons in COSY
- short cycles (5 minutes) consisting of 3.5 minutes ramping from 1.030 GeV/c to 1.065 GeV/c and 1.5 minutes at 1.065 GeV/c.

Cooling is not requested. Although electron cooling at injection would decrease the beam diameter and, thus, increase the beam-target overlap, it is not applicable, because it also worsens the duty-factor and decreases the beam intensity by an order of magnitude.

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