COSY Proposal and Beam Request

Measurement of nucleon-nucleon elastic scattering at small angles up to the maximum COSY energy

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Abstract

Adding to the nucleon-nucleon (NN) scattering database is one of the major priorities of the ANKE collaboration. Such data are necessary ingredients, not only for the understanding of nuclear forces, but also for the description of meson production and other nuclear reactions at intermediate energies. Any facility that can make significant and new contributions in this field should do so. This was the philosophy of very successful COSY-EDDA collaboration, which produced a wealth of data on proton-proton elastic scattering that completely revolutionised the isospin-one NN phase-shift analysis.

The relevance of this field was already emphasised in the 2005 spin document (COSY proposal #152) and since then the ANKE collaboration has made significant progress. By measuring the cross section, deuteron analysing powers, and spin-correlation parameters in the $dp \to \{pp\}_s n$ reaction, where $\{pp\}_s$ represents the $^1S_0$ state, information has been obtained on small-angle neutron-proton spin-flip charge-exchange amplitudes. Although very successful, the basic limitation in this approach is set by the maximum deuteron energy that can be achieved in COSY, which means that the np interaction could only be studied up to a neutron kinetic energy of about 1.15 GeV. It was therefore always envisaged that continuation of the programme would be in inverse kinematics, with a proton beam incident on a polarised deuterium gas cell.

Since the two weeks of beam time granted for the initial research with the polarised internal deuterium gas target (COSY proposal #201) will be conducted only in June 2012, it will soon be time to consider production runs using such a polarised deuterium target in conjunction with a polarised proton beam. However, as shown in detail in the current document, in the energy domain between 1.15 and 2.9 GeV relatively little is known about small-angle neutron-proton scattering. A major contribution would already be achieved by using a polarised proton beam together with an unpolarised deuterium cluster-jet target. Therefore, as a first phase of the np programme (with proton beam), we propose to measure small-angle proton-neutron scattering in a centre-of-mass angular domain that is typically $5^\circ < \theta_{cm} < 40^\circ$. This will be the main thrust of the present deuterium-target proposal, but data will be taken in parallel on the backward (charge-exchange) neutron-proton differential cross section and analysing power by measuring two slow protons in the Silicon Tracking Telescopes at ANKE.

Furthermore, the unpolarised differential cross sections for pp elastic scattering have been measured at ANKE over this angular region at eight energies between 1.0 and 2.8 GeV (COSY proposal #200). Since the apparatus will be in place, we will measure also the proton analysing powers using again the cluster-jet target (but filled with hydrogen) at the same set of proton energies.

Although our main aim is the investigation of proton-proton and proton-neutron elastic scattering, valuable data will also be accumulated on a variety of other reactions, especially when the deuterium target is being used.

In the framework of the PRESENT proposal and beam request, based on past experience and the first results from the unpolarised pp elastic scattering measurements, the collaboration asks for the allocation of **five weeks of beam time at 8 different energies of polarised proton beam** (including the polarimetry energy of 796 MeV) in the range $T_p = 1.6 - 2.8$ GeV (in 200 MeV steps) to advance the NN experimental programme at ANKE/COSY. After these measurements are completed, we intend to come to the next PAC with a proposal for a double-polarised experiment.

Contents

1 Introduction

Data on nucleon-nucleon (NN) scattering are necessary ingredients, not only for the understanding of nuclear forces, but also for the description of meson production and other nuclear reactions at intermediate energies. It must be a priority at any facility to try to fill any gaps in our knowledge in the area. The COSY–EDDA collaboration [1] produced a wealth of data on proton-proton elastic scattering that has completely revolutionised the isospin $I = 1$ NN phase-shift analysis up to about 2.1 GeV [2]. The relevance of this field was already emphasised in the 2005 spin document [3] and since then the ANKE collaboration has made significant progress in two distinct areas.

By measuring the cross section and deuteron tensor analysing powers in the $\vec{d}p \to \{pp\}_s n$ reaction, information has been obtained on the small-angle neutron-proton spin-flip charge-exchange amplitudes [4, 5, 6]. The $\{pp\}_s$ notation here represents a two-proton system at such low excitation energy that it is overwhelmingly in the $^1S_0$ state with antiparallel spins (though contamination from spin-triplet P-waves is accounted for in the subsequent analysis). The phases between the np amplitudes were also studied by measuring the spin-correlation parameter with a polarised hydrogen gas cell rather than the cluster-jet employed in the initial experiments.

Although very successful, the basic limitation in the deuteron beam approach is dictated by the maximum deuteron energy that can be achieved in COSY, which means that the np interaction could only be studied up to about a neutron kinetic energy of $T_n \approx 1.15$ GeV. Furthermore, the range in the three-momentum transfers that were accessible, $q \lesssim 200$ MeV/c, was constrained by the spectrometer design. It was therefore always envisaged that the continuation of the programme would be in inverse kinematics with a proton beam incident on a polarised deuterium gas cell [3]. The protons from the charge exchange on the deuteron can be detected in one or both of the Silicon Tracking Telescopes (STTs) that form part of the ANKE facility. This will allow us to study np observables up to the maximum COSY beam energy of ≈ 2.9 GeV.

However, as is shown in detail later, in the energy domain between 1.15 and 2.9 GeV relatively little is known about small-angle neutron-proton scattering [2] so that a major contribution would already be achieved by using a polarised proton beam together with an (unpolarised) deuterium cluster-jet target. We therefore would like to exploit these possibilities before completing the programme with the polarised gas target. By detecting a fast proton in ANKE and a slow one in an STT, it is possible to measure small-angle proton-neutron scattering in a centre-of-mass angular domain that is typically $5^\circ < \theta_{cm} < 40^\circ$. This will be the main thrust of the current deuterium-target proposal but data will be taken in parallel on the backward (charge-exchange) neutron-proton differential cross section and analysing power by measuring two slow protons in the STTs. At the smaller momentum transfers, corrections need to be made in both cases for final state interactions between slow nucleons.

It may seem surprising that proton-proton elastic scattering was little investigated at small angles for proton energies between about 1.0 to 3.0 GeV. Furthermore, what cross sections that did exist seemed to differ systematically from the predictions of a standard phase-shift analysis [2], where the input is dominated by the highly precise COSY-EDDA data [1]. However, these systematic results are restricted to centre-of-mass angles $\theta_{cm} \gtrsim 35^\circ$. Unpolarised differential cross sections for pp elastic scattering have been measured at ANKE over the missing angular region at eight energies between 1.0 and 2.8 GeV. The data, which were obtained by detecting the fast proton in ANKE or the slow one in an STT (or both), are currently being analysed [7]. As was stressed in the original experimental proposal, the big advantage at COSY is that the absolute value of the beam-target luminosity can be measured independently by studying the energy loss as the beam passes repeatedly through the target. This changes the revolution frequency, which can be detected by examining the Schottky spectrum [8]. It was also made clear in the proposal that it was our intention to fill a similar hole in the proton-proton database by measuring the proton analysing power A_{000n} at similar energies, using again the cluster-jet target and that this theme would be pursued eventually through the measurement of the transverse spin correlation parameter A_{00nn} [7].

The nucleon-nucleon elastic cross sections are quite large and so the beam time required to accumulate the significant statistics required at a single energy for a high precision experiment is relatively modest. This means that a large fraction of the total time is involved with the development by the COSY crew of the polarised proton beam at the eight individual energies. To minimise this effort and the resulting loss of time, we propose to measure proton-proton and proton-neutron scattering at the same eight energies merely by interchanging the two targets. This will avoid having to perform very complicated beam developments twice, separately for each target. It also has the added advantage that information will be obtained in *pp* and *pn* elastic scattering at the same energies, which is helpful in the subsequent amplitude analysis.

As already indicated, the luminosity for both targets will be measured using the Schottky technique which, for technical reasons, cannot be employed with much precision in the 1.0–1.6 GeV interval [8]. The *pp* elastic differential cross sections were measured at the seven energies 1.6, 1.8, 2.0, 2.2, 2.4, and 2.8 GeV, with the methodology being tested at 1.0 GeV [7], where reliable data exist [2]. These energies will also be used in the current proposal but, to take advantage of the precise measurement of the proton-deuteron analysing power at 796 MeV [9], this will replace the 1.0 GeV as the calibration energy. At this energy the analysing power in *pp* elastic scattering can be confidently taken from the phase shift predictions [2]. The polarisations at higher energies will be determined using the well-tried polarisation-export technique.

Although the main thrust of this proposal is the investigation of *pp* and *pn* elastic scattering, valuable data will also be accumulated on a variety of other reactions, especially when the deuterium target is being used. These include the cross sections and analysing powers for

- Charge exchange in $pd \to \{pp\}_s n$, where two protons are detected in the STT at small E_{pp}, gives information on the sum of the charge-exchange spin-flip contributions;
- Proton-deuteron small-angle scattering with the deuteron being detected in an STT;
- Proton-deuteron large-angle scattering with the deuteron being detected in ANKE;
- Single pion production in $pp \to d\pi^+$. The analysing power at 796 MeV will also provide a check on the value assumed for the beam polarisation [10];
- Single pion production in quasi-free $pd \to p_{\rm spec} d\pi^0$. The cross section for $pn \to d\pi^0$ should be half that for $pp \to d\pi^+$ but the analysing powers should be identical. This gives a valuable check on the relative beam polarisations in the experiments with the two targets;
- Isobar excitation in $pd \to \{pp\}_s \Delta(N^*)$, where the two protons are detected in the STT with the possibility of measuring a p or π^- from the $\Delta(N^*)$ decay in ANKE;
- Quasi-free $pd \to p_{\rm spec} dX$, with the fast deuteron being detected in ANKE, allows one to study the small angle $pn \to dX$ reaction. By putting a cut on the missing mass at say $m_X \lesssim 320$ MeV/c^2, the development of the $I = 0$ cross section with energy can be studied;
- Diproton production in $pd \to p_{\rm spec}\{pp\}_s \pi^-$, with two fast protons being detected in ANKE;
- $pd \to {}^3{\rm He}\,\pi^0$, with the ^{3}He being detected in ANKE, though the cross section falls fast at large momentum transfers.

After these measurements with a cluster target are completed, we intend to come to the next PAC with a proposal for double-polarised experiments to measure tensor and spin-correlation observables.

2 The database of elastic nucleon-nucleon scattering

The existing database of elastic pp and pn differential cross sections is shown in the abundance plots of Fig. 1 (taken from Ref. [2]). Note that in the pp case the cross section is symmetric about 90° and so few points are plotted in the backward hemisphere. There is a heavy concentration of pp points for $40^\circ < \theta_{cm} < 90^\circ$, corresponding to the EDDA measurements [1], but there are very few at smaller angles, though this will be changed when the ANKE data are finalised [7]. On the other hand, it is seen that the pn database is even more sparse above 1.15 GeV (the maximum energy of the SATURNE "monochromatic" neutron beam).

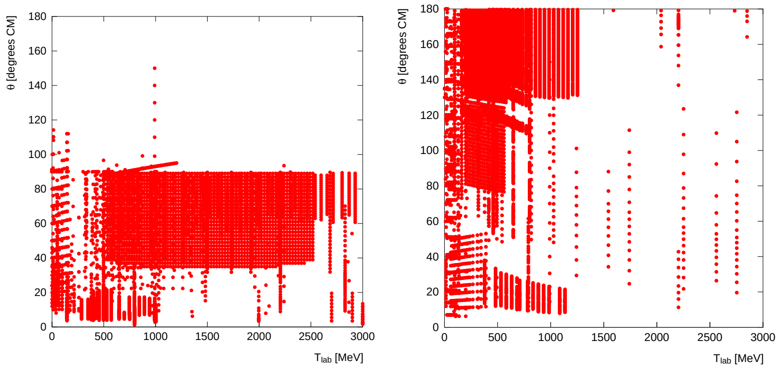

Figure 1: Abundance plots of c.m. scattering angle versus beam energy for elastic differential cross section experiments for pp (Left) and np (Right), taken from the SAID compilation [2].

The situation is broadly similar in the A_y measurements summarised in Fig. 2. For pp elastic scattering this parameter is antisymmetric around 90° but is seen from the figure that there have been relatively few measurements for $\theta_{cm} < 30^\circ$ for beam energies above 1.0 GeV. In the case of np scattering, there is no longer this antisymmetry but there are even fewer measurements above 1.15 GeV. It is important to note that isospin invariance requires the analysing powers for polarised protons and neutrons shown in panels (b) and (c) should be the same, though we will only be able to test this at ANKE with the polarised deuterium target at a subsequent stage. It is in the context of these gaping holes in the nucleon-nucleon database that our proposal should be judged.

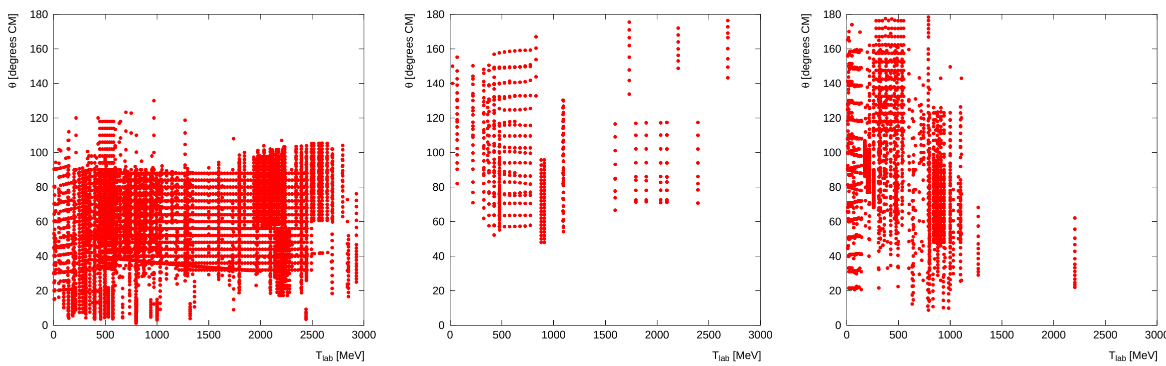

Figure 2: Abundance plots of c.m. scattering angle versus beam energy for experiments on the analysing power of (left) pp elastic scattering, (middle) the proton in pn elastic scattering, and (right) the neutron in pn elastic scattering.

3 Experimental facilities

The procedure to measure pp elastic scattering was described in some detail in our earlier proposal [7] and the only difference is associated with the use of the polarised proton beam where the procedures are the same for both hydrogen and deuterium targets. We will therefore concentrate here on describing the methodology to be employed in the case of pn quasi-elastic scattering. For this we plan to use polarised and unpolarised proton beams hitting the deuterium cluster-jet target placed at the ANKE position. Two STTs will be positioned inside the target chamber, very close to the target, symmetrically to the left and right of the beam direction. The $pd \to p_{\rm spec}pn$ reaction will be identified by detecting a spectator proton $p_{\rm spec}$ in one of the STTs, while the scattered proton is identified in either the ANKE Forward Detector (FD) or in an STT. The Schottky spectra will be recorded with a dedicated frequency analyser in order to determine the luminosity. The polarimetry of the beam at energies higher than the calibration point at 796 MeV will be done using the polarisation export technique. The relevant details of each element in this procedure are described below.

3.1 The ANKE detection system

The ANKE spectrometer is fully described in Ref. [11] and, for the pn studies, mostly the FD system will be used. This comprises one drift chamber, two multi-wire proportional chambers and a three-plane scintillation hodoscope, consisting of vertically oriented counters (eight in the first plane, nine in the second, and six in the third). The ANKE side detection systems (positive and negative) will be also switched on in order to collect by-products from other pd breakup reactions.

3.2 Silicon Tracking Telescopes

For the identification and tracking of slow recoil deuterons and protons, including spectator protons, silicon tracking telescopes have been developed at ANKE that can be operated inside the ultra-high vacuum of the accelerator. The basic detection concept of the STT combines proton and deuteron identification with tracking over a wide range in energy. The tracking is accomplished by three layers of double-sided micro-structured silicon strip detectors that can be placed close to the target inside the vacuum chamber (Fig. 3).

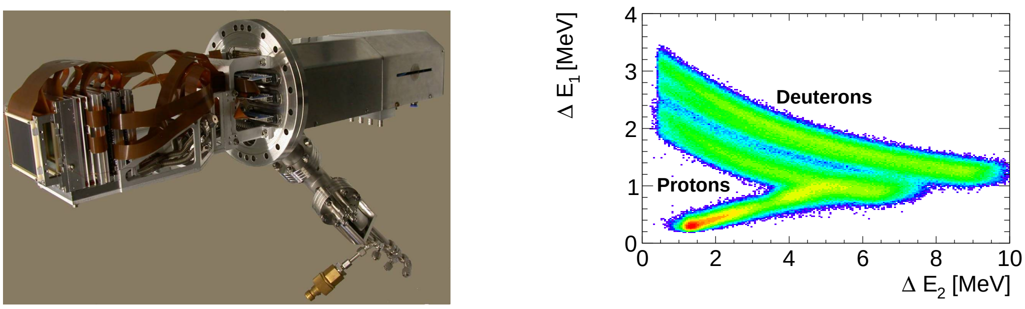

Figure 3: Left: Silicon Tracking Telescope consisting of three detector layers of different thickness. Right: Energy loss correlation for the first and second layers of the STT showing the separation of protons from deuterons in a logarithmic z-scale.

Measuring the energy loss in the different layers allows stopped particles to be identified by the $\Delta E/E$ method (Fig. 3). A particle is registered when it passes through the inner layer and is stopped in the second or third layer, so that the minimum energy of a proton that can be tracked is determined by the thickness of the innermost layer. The maximum energy of tracked protons is given by the range within the telescope and hence by the total thickness of all detection layers. Therefore, the primary design goal in the development of the STT was to combine the thinnest possible first layer with the thickest available final one. In the current experiment the following settings will be used:

- 1^{st} layer: 70 μm thick, $66{\times}52\,\mathrm{mm}^2$ active area, $151{\times}64$ segments with 420 μm pitch horizontally and 800 μm pitch vertically,
- 2^{nd} layer: 300 μm thick with a geometry identical to that of the 1^{st} layer,
- 3^{rd} layer: 5000 μm thick, $64{\times}64\,\mathrm{mm}^2$ active area, $64{\times}64$ segments with 1000 μm pitch,

so that a particle must have a minimum kinetic energy of 2.5 MeV in order to reach the second layer, which is a necessary condition for track reconstruction.

The three layers will be placed 2.8, 4.8 and 6.2 cm away from the target, covering laboratory polar angles $75^\circ < \theta_{\mathrm{lab}} < 140^\circ$. The energy resolution of ≈ 160 keV FWHM leads to a good separation of proton and deuteron bands, as shown in Fig. 3. Being positioned so close to the COSY beam, STT detectors can only be installed after the beam development is finalised.

3.3 Luminosity determination

The ANKE collaboration and the COSY machine crew have jointly developed a very accurate method for determining the absolute luminosity $L = n_B n_T$ in an experiment at an internal target position. The measurement of the beam intensity (n_B) is a routine procedure at any accelerator and is performed at COSY via a high precision Beam Current Transformer (BCT). The BCT signal is introduced directly into the data stream and recorded together with the

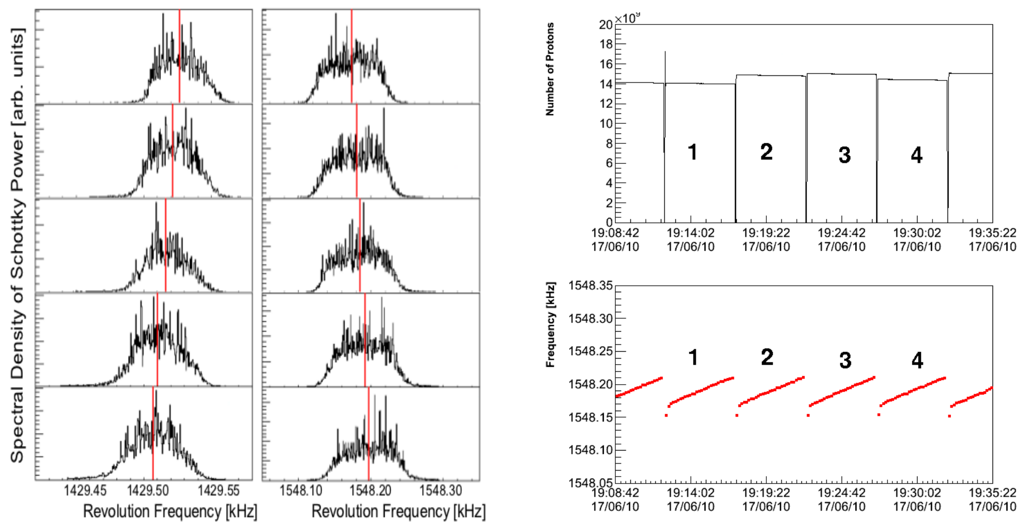

Figure 4: Left: Schottky power spectra obtained during one 300 s cycle and scaled to harmonic number 1 for 1.0 and 2.0 GeV energy (left and right column, respectively). Although the data were recorded every 10 seconds, for ease of presentation, only the results from every 70 s are shown, starting from top to bottom. The mean frequencies are indicated by the vertical lines. For a positive η parameter the frequency increases through the cycle and *vice versa*. Right: The BCT particle current n_B, and mean revolution frequency f for a typical machine cycle.

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detector information, thus providing the value of the actual beam intensity at any given moment. The target density n_T determination relies on measuring the energy losses due to the electromagnetic interactions of the beam as it passes repeatedly through the thin target. This shift can be measured by studying the Schottky spectrum of the beam [8].

The use of this technique to determine the luminosity puts some demands on the parameters of the accelerator to guarantee the intended accuracy. It also requires additional beam development of dedicated cycles to measure the frequency-slip parameter η and determine the residual gas effect for each energy. To be able to measure the frequency shift sufficiently well, the luminosity should not be very high, so that the beam intensity should be $1-2\times10^{10}$ protons with a target thickness of $2-4\times10^{14}$ atoms/cm^2. To minimise the frequency shift arising from the residual gas in the ring, the vacuum away from the target section should be better than 10^{-9} mbar and air leakages must be avoided. Finally, the frequency shift may deviate from linearity over a long cycle and this complicates the determination of the target thickness and thus reduces the accuracy [8]. Cycles with a length of ≈ 300 s seem to be optimal for the proposed study.

The Schottky luminosity technique was already used in the measurement of the differential cross section for elastic pp scattering during the June 2010 beam time at eight different beam energies between 1.0 GeV and 2.8 GeV. Due to the structure of the COSY lattice, η changes sign for $T_p \approx 1.3$ GeV, so that the Schottky method cannot be used reliably in the beam energy interval 1.0 GeV $< T_p <$ 1.6 GeV. For a positive η parameter the distribution shifts to lower values and moves to higher values when η is negative. The observed frequency shifts at 1.0 GeV and 2.0 GeV during typical cycles are presented on Fig. 4. The figure also shows a typical picture of beam intensity and beam frequency during data taking. Measurements of the corresponding frequency shift and target density are presented in Table 1. The total accuracy in the luminosity determination is roughly 2%, which is mainly defined by the error in the measurement of the η parameter. Preliminary values of differential cross-sections for some selected energies will be presented at the PAC meeting.

Cycle	df/dt	Target Density
1	0.152	2.75×10^{14} cm^{-2}
2	0.151	2.74×10^{14} cm^{-2}
3	0.154	2.79×10^{14} cm^{-2}
4	0.149	2.70×10^{14} cm^{-2}

Table 1: Results of the frequency shift and target density measurements for the cycles presented on the right panel of Figure 4.

3.4 Polarisation export

The beam polarisation is usually determined from the scattering asymmetry in a suitable nuclear reaction for which the analysing power is already known. Calibration standards are few and only exist at discrete energies and so it is of great practical importance to be able extend their application to arbitrary energies where standards are not yet available.

If care is taken to avoid depolarising resonances in the machine, the beam polarisation should in general be conserved during the ramping of the beam energy up or down [12] and this has been tested at COSY for beams of both polarised protons and deuterons. For the proposed experiment, polarisation export can be implemented by setting up a cycle with a flat top at $T_p = 0.796$ GeV (I), followed by acceleration to a flat top at the required energy (II), and subsequent deceleration to the 0.796 GeV flat top (III). Agreement in the measurement of the beam polarisations at (I) and (III) will guarantee that depolarising resonances have been

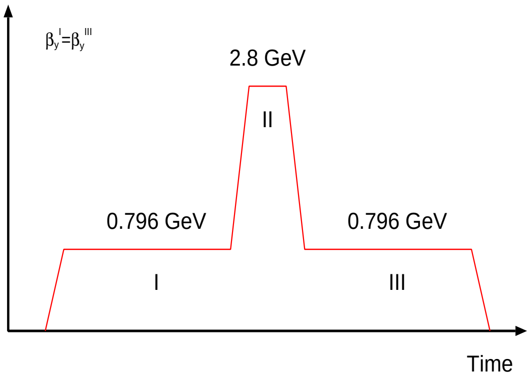

Figure 5: Schematic picture of three different flat-top regions. If the proton polarisations were identical in regions I and III it would mean that there was no loss of polarisation so the value at 0.796 GeV could be “exported” to 2.8 GeV.

successfully avoided (Fig. 5).

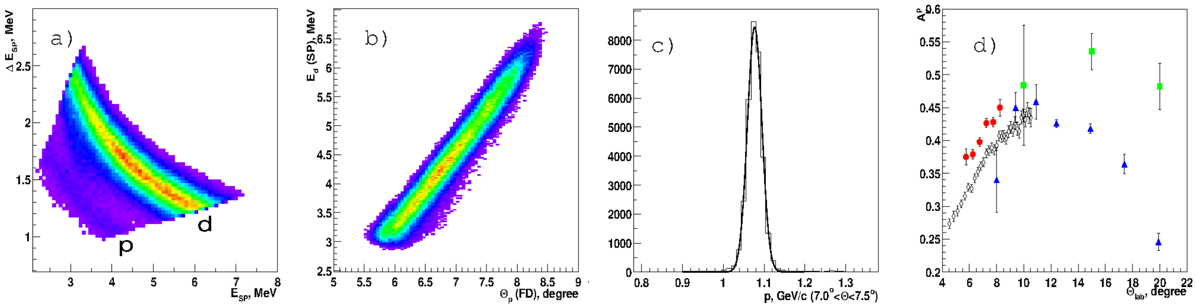

Figure 6: a) Energy loss *versus* the energy of particles stopped in the second layer of the STT. b) Energy of deuterons stopped in the second layer of the STT *versus* the polar angle of forward protons. c) Proton momenta registered in the FD in coincidence with deuterons stopped in the second layer of the STT. d) Angular dependence of A_y for $\vec{p}d$ elastic scattering at 796 MeV [9] (open diamonds), together with data at other energies.

The proton polarisation export method has already been successfully used at ANKE in experiments with the deuterium cluster-jet target [13]. The beam polarisation was determined at $T_p = 0.796$ GeV by measuring pd elastic scattering, where there are very good analysing power data [9]. Recoil deuterons are identified in the silicon telescopes while the fast scattered protons are registered in the forward detector. The results from Ref. [13] presented in Fig. 6 demonstrate that clean identification and precise polarimetry are possible.

The same technique can be exploited in the case of the hydrogen target by measuring pp elastic scattering, also at $T_p = 0.796$ GeV. Although there are no analysing power measurements over the angular region covered by ANKE, at these low energies the phase shift analysis is reliable and the necessary values of A_y can be obtained from the SAID predictions [2].

It should be stressed that the preparation of polarisation export requires extra measurements with the EDDA detector. This is standard procedure when preparing polarised proton beams at COSY. It is aimed to overcome depolarising resonances during the acceleration and requires additional time and effort of the COSY crew.

4 Measurements at ANKE

As already mentioned, the measurement of quasi-free pn elastic scattering requires mainly the use of the forward detector system and the silicon tracking telescopes. The ANKE collaboration has considerable experience in isolating the required reactions from the background using these detection systems. To have a better understanding of the acceptance, Monte Carlo simulations were performed using the GEANT4 software package at all the requested energies.

4.1 Acceptance

To isolate the quasi-free pn elastic process, it is necessary to stop the slow spectator proton in one of the STTs and identify the fast scattered proton in the FD system. The angular acceptance for the reaction was estimated, including a Fermi momentum distribution for the proton spectator in the MC simulations. These show that the detected angular range changes little with beam energy and c.m. angles from 5° to 40° in the pn system will be covered (Fig. 7).

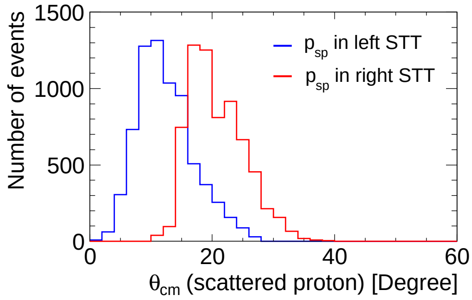

Figure 7: Angular distribution in the pn c.m. frame for the scattered protons detected in FD system, with spectator protons being stopped in $\theta_{\text{lab}} > 100°$. Left panel: $T_p = 1.6$ GeV. Right panel: $T_p = 2.8$ GeV.

The fact that neutrons are moving in the deuteron means that, at any fixed beam energy, a certain energy range defined by the Fermi distribution is covered. Figure 8 shows the energy spread of the beam in the neutron rest frame. Depending on the beam energy, this range varies from 200 up to 400 MeV.

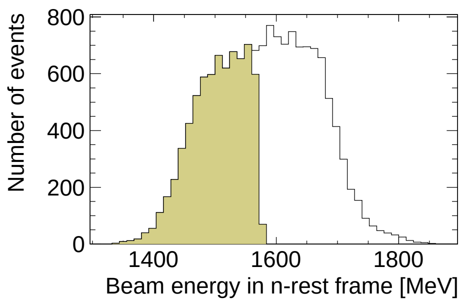

Figure 8: Beam energy distribution in the neutron rest frame when the scattered proton is detected in the Fd and the spectator in STT. Empty histograms correspond to the spectator protons detected in the right STT, while the filled areas represent the distribution in the left detector with angular cut of $\theta_{\text{lab}}^{\text{spec}} > 100°$. Left panel: $T_p = 1.6$ GeV. Right panel: $T_p = 2.8$ GeV.

One problem that may arise during the identification of this process is that a spectator proton coming from quasi-free pn scattering cannot be distinguished in the left STT from low energy protons from quasi-free pp elastic scattering or pd elastic processes. To reduce the background and identify clean quasi-free pn scattering an angular cut of $\theta_{\rm lab}^{\rm spec} > 100°$ is applied, which halves the beam energy spread covered by left STT. Fortunately this is not the case for the right detector and it can be used without additional cuts (Fig. 8) . If enough statistics are collected, we will produce at least three data sets at each beam energy by dividing the energy spread into 20 MeV bins. The accuracy with which this can be done is defined by the precision of the spectator proton momentum reconstruction, which introduces the uncertainty of the centre-of-mass energy of the (9–10) MeV (FWHM).

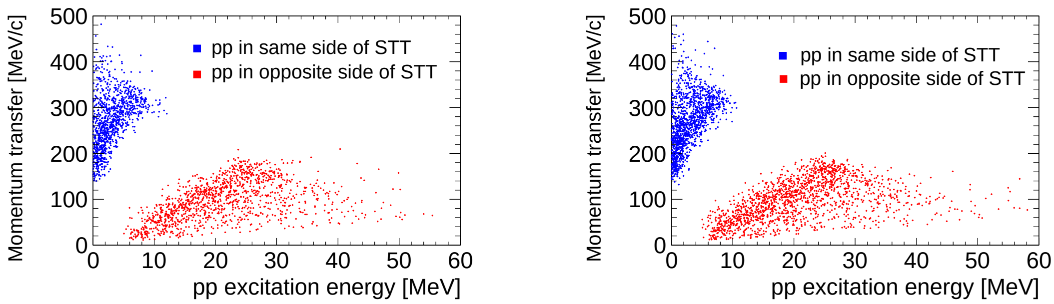

Figure 9: Three-momentum transfer q versus the pp excitation energy for $pd \to ppn$ when both slow protons are detected in the STTs. Left panel: $T_p = 1.6$ GeV. Right panel: $T_p = 2.8$ GeV.

As mentioned in the introduction, another reaction of great interest for pn studies is the $pd \to \{pp\}_s n$ process, where both slow protons are detected in the STTs. The results of the MC simulations show that acceptance for this reaction changes little with beam energy (Fig. 9). Unfortunately the current silicon tracking telescopes do not allow one to access simultaneously the region of small E_{pp} and small three–momentum transfer q. The STT have three layers and, in order to get a good kinematic determination, the proton has to pass through the first. This requires a minimum energy of ≈ 2.5 MeV, i.e. a momentum of ≈ 70 MeV/c. If the protons are detected in the same STT, then E_{pp} can be small but the momentum transfer must be at least twice the 70 MeV/c.

The angular acceptance expected for pp elastic scattering using the hydrogen cluster target is reported in Table 2. The details are discussed in COSY proposal #200 [7].

Energy [GeV]	θ_{cm} (FD)	θ_{cm} (STT)	θ_{cm} (STT tracks)
1.0	$5° - 28°$	$5° - 21°$	$21° - 70°$
1.6	$5° - 28°$	$5° - 17°$	$17° - 60°$
2.8	$5° - 32°$	$5° - 13°$	$13° - 50°$
Resolution	$0.5° - 0.8°$	$0.05°$	$2.7° - 5.7°$

Table 2: Angular acceptance and resolution of the FD and STT for pp elastic scattering.

4.2 Reaction identification

To show the feasibility of the programme, we present the results from the 2008 beam time (COSY proposal #175.1). The experiment was carried out with a proton beam of energy $T_p \approx 2.1$ GeV interacting with a deuterium cluster target. Two STTs were installed inside the target chamber symmetrically to the left and right of the COSY beam. This is very similar to the settings we are proposing and it can therefore give valuable information on the expected conditions. Figure 10 shows the experimental angular distribution of quasi-free pn elastic scattering. The angular range is similar to that of the simulation. There is a relative difference between the numbers of events for spectator protons detected in the left and right STTs. This is due to the behaviour of the *pn* differential cross-section, which is not included in the simulations.

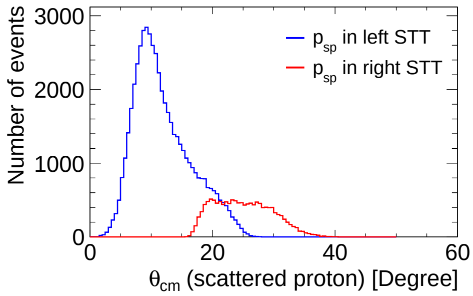

Figure 10: Experimental angular distribution in the *pn* c.m. at $T_p = 2.1$ GeV for scattered protons detected in FD system when spectator protons are detected in the STT at $\theta_{\text{lab}}^{\text{spec}} > 100°$.

One of the main challenges of the proposed experiment will be to identify quasi-free *pn* elastic scattering without significant background. Figure 11 (left panel) shows the reconstructed missing mass for different kinetic energies of the spectator proton detected in an STT when the scattered proton is identified in the FD. For the investigation of charge exchange $pd \to \{pp\}_s n$ break-up, we are also interested in the events where both protons are detected in STTs. An experimental missing mass distribution of such *pp* pairs, which was taken for the proton beam energy $T_p = 353$ MeV (COSY proposal #192), is presented in the right panel of the Figure 11.

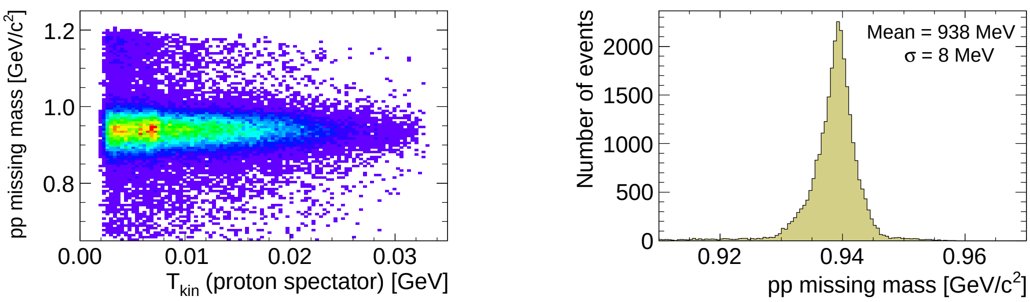

Figure 11: Left: Experimental distribution at $T_p \approx 2.1$ GeV of *pp* missing mass *versus* the kinetic energy of the spectator proton where fast protons are detected in the FD. Right: Experimental missing mass distribution of *pp* pair at $T_p = 353$ MeV, where both protons are detected in the STTs.

Significant progress has been made in the analysis of the *pp* elastic differential cross section, which was measured at 8 different energies during the 2010 beam time. Experience in this experiment shows that we are able to cleanly identify *pp* scattering with the STT and FD systems. Preliminary results were already presented at several conferences [14] and updated versions will be shown at the PAC session.

The estimations of the systematic uncertainties for the angular range $5° < \theta_{cm} < 40°$ are shown in Table 3. This is a region where the momentum of the scattered proton is reconstructed using the FD or STT detectors. The precision of the analysing power measurement will be defined by the accuracy of the polarisation export and angular resolution of the detection system. It is expected to be $\sim 5\%$

Uncertainty	[%]
Track reconstruction efficiency	$\lesssim 3$
Acceptance correction	$\lesssim 4$
Momentum reconstruction	1
Data-taking efficiency	1
Background subtraction	1
Luminosity	3
Total	$\lesssim 6.1$

Table 3: Estimations of systematic uncertainties in the measurement of the cross section for pn elastic scattering in the angular range $5^\circ < \theta_{cm} < 40^\circ$.

5 Beam-time request

To carry out the programme presented here we request beam time with the polarised proton beam, with "spin-up" and "spin-down" polarisation of $\sim 60\%$ for the measurement of the analysing powers and the unpolarised proton beam for the determination of differential cross–sections. We assume a luminosity on the order of $L = 1 \times 10^{30}$ s^{-1}cm^{-2} ($\approx 5 \times 10^9$ stored polarised protons, $f_{\rm rev} \sim 1.2 - 1.6$ MHz, and $n_T = 2 \times 10^{14}$ cm^{-2}).

As the cross sections for pp elastic and pn quasi-elastic scattering are high, the collection of enough statistics to extract differential cross sections and analysing powers will not pose a problem. However, it should be borne in mind that two additional tasks have to be fulfilled: (i) a precise normalisation entails using the Schottky technique to determine the luminosity and, (ii) the polarisation export technique has to be implemented for each of the seven energies of the investigation. The final precision ($\sim 5 - 6\%$) will therefore depend mostly on the accuracy obtained for the luminosity and beam polarisation rather than on statistics.

For the measurements outlined in the proposal, a TOTAL of **5 weeks** of beam time are requested with a polarised proton beam and unpolarised cluster target (Hydrogen and Deuterium) at **8** kinetic energies of T_p= 0.796, 1.6, 1.8, 2.0, 2,2, 2,4, 2.6, and 2.8 GeV with the aim:

1. To measure the differential cross-sections and analysing powers (A_y) for quasi-free pn elastic scattering (with the deuterium target) at about 24 (for each primary energy we will use at least 3×20 MeV intervals) energies in the angular range $5^\circ < \theta_{cm} < 40^\circ$.

2. To measure the analysing powers (A_y) for pp elastic scattering (with the hydrogen target) at 8 energies in the angular range of $5^\circ < \theta_{cm} < 30^\circ$.

3. To study a variety of other reactions in parallel, as outlined in the Introduction.

6 Time-line for the experiments at ANKE

The time-line foreseen for the relevant activities at ANKE is as follows:

- The ABS ($\vec{D}$) and Lamb–shift polarimeter will be installed in the COSY maintenance weeks #16 and #17 for ANKE experiment #201.1.

- The ANKE experiment #201.1 will start data taking with an unpolarised proton beam and polarised deuterium target in calendar week #23 and last for 2 weeks (June 2012).

- The Polarised Internal Target (PIT) will be taken out during the summer shutdown period and the cluster target installed.

- It is preferable to separate the current request from the proposed measurement of the quasi-free $pn \to d\eta$ reaction with an unpolarised proton beam by Khoukaz *et al.*. The reason is that the beam energies ($T_p = 1.35$ GeV and 1.5 GeV) required in this experiment are unsuitable for the application of the Schottky method, due to the small value of the η parameter.

- After the Khoukaz *et al.* measurements have been conducted, the COSY crew could start with the MD weeks (at least two) to prepare all eight energies for the current experiment at two different position of D2 magnet. This will also involve development of dedicated cycles for the Schottky method and the implementation of polarisation export.

- After finishing the beam development, two STT modules will be installed inside the target chamber (left and right of the beam) and normal data-taking can be started.

More details of the scheduling of ANKE beam time will be presented by the spokesperson during the PAC meeting.

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