COSY Proposal and Beam Request

Measurement of spin observables in $\vec{p}\vec{d}$ elastic and inelastic scattering with polarised beam and target at ANKE–COSY

Z. Bagdasarian[1,2], S. Barsov[3], U. Bechstedt[1], J. Carbonell[4], D. Chiladze[1,2], S. Dymov[5,6], R. Engels[1], R. Gebel[1], P. Goslawski[7], B. Gou[8], K. Grigoryev[1,3], A. Kacharava[1], V. Kamerdzhiev[1], A. Khoukaz[7], A. Kulikov[5], A. Lehrach[1], N. Lomidze[2], B. Lorentz[1], G. Macharashvili[2,5], R. Maier[1], D. Mchedlishvili[1,2], M. Mielke[7], M. Mikirtytchiants[1,3], S. Mikirtytchiants[1,3], S. Merzliakov[1], A. Nass[1], M. Nioradze[1,2], D. Oellers[1], M. Papenbrock[7], D. Prasuhn[1], F. Rathmann[1], R. Schleichert[1], D. Schröer[7], V. Shmakova[1,5], R. Stassen[1], H.J. Stein[1], H. Stockhorst[1], H. Ströher[1], M. Tabidze[2], S. Trusov[1], Yu. Uzikov[5], Yu. Valdau[1], A. Vasilyev[3], Ch. Weidemann[1], and C. Wilkin[9]

[1]Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany
[2]High Energy Physics Institute, Tbilisi State University, 0186 Tbilisi, Georgia
[3]High Energy Physics Department, PNPI, 188350 Gatchina, Russia
[4]Institut de Physique Nucléaire, Université Paris-Sud, IN2P3-CNRS, F-91406 Orsay, France
[5]Joint Institute for Nuclear Research, LNP, 141980 Dubna, Russia
[6]Physikalisches Institut II, Universität Erlangen–Nürnberg, 91058 Erlangen, Germany
[7]Institut für Kernphysik, Universität Münster, 48149 Münster, Germany
[8]Institute of Modern Physics, Chinese Academy of Sciences, 730000 Lanzhou, P.R. China
[9]Physics and Astronomy Department, UCL, London WC1E 6BT, UK

for the **ANKE Collaboration**

Spokespersons: Sergey Barsov, David Mchedlishvili, Colin Wilkin

Jülich, February 27, 2013

Abstract

A key feature of the experiments, both ongoing and planned at ANKE–COSY, is the use of polarised beams and targets, which will allow the performance of double-polarised measurements. It has been stressed many times that the ANKE collaboration has embarked on an extensive programme to add valuable information to the nucleon-nucleon (NN) scattering database. The importance of such a data was discussed extensively in the ANKE SPIN document (proposal #152) and in recent COSY proposals (#200, #201, #212). The abundance plots (angle *versus* energy up to 3 GeV) of published NN elastic data, shown in our last beam request to the COSY PAC, proves that there are remarkably large gaps in the measurement of spin observables. These need urgently to be explored to arrive at a consistent systematic database of pp and pn channels to be used in various subsequent analyses. Any facility that can make significant and new contributions in this field should do so. In the recommendation regarding the last ANKE proposal (#212), PAC underlined that ANKE at COSY has the capability to do this in the small-angle range where, in particular, the pn channel requires special treatment to cope with the departure from the quasi-free region.

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 the continuation of the programme would be in inverse kinematics, with a proton beam incident on a polarised deuterium gas cell.

It is here suggested to extend the energy range up to about 2.9 GeV by using a polarised proton beam incident on a polarised deuterium target and detecting TWO slow protons in an array of solid state telescopes. The interaction vertex is then very well located within the long target, making it unnecessary to measure the fast neutron in the ANKE facility to identify the $\vec{d}(\vec{p}, pp)n$ reaction. Eventually this approach might be extended to the production of the $\Delta^0(1232)$ isobar with some of its decay products being detected in ANKE. Given the successes in the *first* handling of the double-polarised data from the polarised deuterium target, we can confidently conclude that ANKE–COSY is now ready to start on the experimental programme of double–polarisation measurements using the deuterium gas target. In a first phase of this programme the experiment with a polarised proton beam and unpolarised cluster target (hydrogen and deuterium) has been approved and is scheduled to be conducted in March/April 2013 (around the time of next PAC meeting, April 8/9). It is hoped that some of the on-line results from these measurements will be presented during the PAC meeting.

In the framework of the PRESENT proposal and beam request, based on past experience and the first results from the single-polarised $p\vec{d}$ ($\vec{p}d$) measurements, the ANKE collaboration asks for the approval of **six weeks** of beam time with a polarised proton beam at the energies $T_p = 1.135, 1.4, 1.6, 1.8$ GeV (including the target polarimetry energy $T_p = 0.6$ GeV) that were prepared for the $d\sigma/d\Omega$ and A_y measurements. In parallel to the $\vec{p}\vec{d}$-breakup measurements of deuteron spin observables ($T_{20}, T_{22}, C_{y,y}, C_{x,x}$), we will advance the np elastic programme through the determination of the spin-correlation parameters ($A_{x,x}$, $A_{y,y}$). Although our principal aims in this proposal are the investigations of the deuteron charge-exchange breakup reaction and np quasi-elastic scattering, valuable data will also be accumulated on the quasi-two-body $\vec{p}\vec{p} \to d\pi^+$ and $\vec{p}\vec{n} \to d\pi^o$ and other reactions.

Contents

1 Introduction **4**

2 Short summary of the $\vec{p}(\vec{d}, pp)X$ breakup studies at ANKE **5**

2.1 The neutron-proton charge-exchange amplitudes 5

2.2 $\boldsymbol{\Delta}$ excitation in the $\vec{n}p \to \vec{p}\Delta^0$ reaction 6

3 Predictions for breakup spin observables at higher momentum transfers **8**

4 Database on pn elastic spin-correlation parameters **8**

5 Examples of by-product measurements **8**

6 Preliminary results from the deuterium commissioning run **9**

6.1 The target polarisation 9

6.2 The quasi-elastic NN scattering identification at ANKE 11

6.3 The breakup process in inverse kinematics $\vec{d}(\vec{p}, pp)X$ at ANKE 12

7 The new measurements proposed at ANKE **13**

8 Beam-time request **13**

1 Introduction

A key feature of the ongoing and planned experiments at ANKE–COSY is the use of polarised beams and targets, which will allow us to perform double-polarised measurements [1]. By measuring the cross section, deuteron analysing powers, and spin-correlation parameters in the $\vec{d}\vec{p} \to \{pp\}_s n$ reaction, where $\{pp\}_s$ represents the ${}^1S_0$ state, information has been obtained on small-angle neutron-proton spin-flip charge-exchange amplitudes [2, 3, 4]. 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. Furthermore, the range in the three-momentum transfers that were accessible, $q < 180$ MeV/c, was constrained by the spectrometer design. 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, which allows us to extend the range in three-momentum transfers up to $q \approx 400$ MeV/c.

The energy range can be increased up to about 2.9 GeV by using a polarised proton beam incident on a polarised deuterium target ($\vec{D}$). The TWO slow 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. The interaction vertex is then very well located within the long target, making it unnecessary to measure the fast neutron in the ANKE facility to identify the $\vec{d}(\vec{p}, pp)n$ reaction. This will allow us to study np observables up to the maximum COSY beam energy of ≈ 2.9 GeV. Eventually this approach might be continued with the production of the $\Delta^0(1232)$ isobar, where some of the Δ decay products are detected in ANKE.

It has been emphasised many times that the ANKE collaboration has embarked on an extensive programme to add valuable information to the nucleon-nucleon (NN) scattering database. The abundance plots (angle *versus* energy up to 3 GeV) of published NN-elastic data, shown in our last beam request to COSY PAC, proves that there are remarkably large regions where there are no measurements of some spin observables. Any facility that can make significant and new contributions in this field should do so. In particular, the pn channel deserves a special treatment to cope with the departure from quasi-free kinematics. Within the proposed $\vec{p}\vec{d}$ breakup experiment, we advance in parallel also the np-elastic programme through measurements of the spin-correlation parameter ($A_{x,x}$, $A_{y,y}$) above 1.1 GeV. In a first phase of this programme, the experiment with a polarised proton beam and unpolarised cluster target (hydrogen and deuterium) has been approved and is scheduled to be conducted in March/April 2013 (around the time of the next PAC meeting, April 8/9).

In order to link up quantitatively with previous deuteron beam data at T_d=2.27 GeV, we would like to start the measurements with proton beam energy of T_p=1.135 GeV and provide new data at (at least) three higher energies up to 1.8 GeV.

After these measurements are completed, we intend to come to the next PAC with a proposal for the second part of this program at beam energies above $T_p \geq 2.0$ GeV. Furthermore, after the commissioning of the Siberian snake at COSY, the collaboration plans to advance the np studies further through the use of longitudinally polarised proton beams.

2 Short summary of the $\vec{p}(\vec{d}, pp)X$ breakup studies at ANKE

In this section we summarise the main results of the charge-exchange breakup studies obtained using the polarised deuteron beams at COSY.

2.1 The neutron-proton charge-exchange amplitudes

A great effort has been made in the investigation of the spin-dependent terms in large angle neutron-proton scattering. It was pointed out many years ago that the $dp \to \{pp\}_s n$ charge exchange at small angles is very sensitive to the spin-spin terms in the $np \to pn$ amplitude provided the excitation energy E_{pp} in the final pp system was kept low [5]. Under such conditions the $\{pp\}_s$ is in a ${}^1S_0$ state and the charge exchange necessarily involves a spin flip from the initial np spin-triplet of the deuteron. Furthermore, measurements of the deuteron tensor analysing powers A_{xx} and A_{yy} allow one to distinguish between the contributions from the three np spin-spin amplitudes.

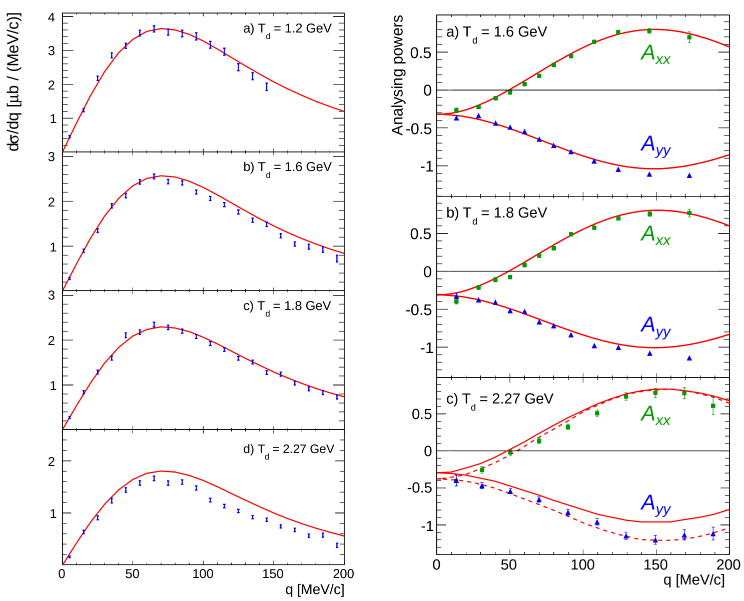

Figure 1: Differential cross sections (left panel) and cartesian deuteron analysing powers (right panel) for the $\vec{d}p \to \{pp\}_s n$ reaction for $E_{pp} < 3$ MeV at $T_d = 1.2$, 1.6, 1.8, and 2.27 GeV. The impulse approximation predictions [8] have been evaluated with the SAID amplitudes [13] (solid curves) and also, at the highest energy, when the longitudinal spin-spin amplitude is scaled by a factor of 0.75 (dashed curves).

Measurements were carried out at Saclay [6, 7] but only in regions where the NN amplitudes were reasonably well known. These have been extended to higher energy at ANKE in fine steps in momentum transfer q. A cut of $E_{pp} < 3$ MeV was typically imposed but any contamination from triplet P-waves was taken into account in the theoretical modelling [8]. The ANKE differential cross section (including the 1.2 GeV data) and analysing power results at $T_d = 1.6$, 1.8, and 2.27 GeV are compared in Fig. 1 to these impulse approximation predictions using as input up-to-date np amplitudes [13]. The satisfactory agreement at lower energies, and also in the values of the differential cross sections, shows that the theoretical description is adequate here. Above about 1 GeV, neutron-proton data become rather sparse. It comes therefore as no surprise that, when the same approach is employed on the higher energy data shown in Fig. 1, the current SAID amplitudes [13] give a poor overall description of the results. However, if the longitudinal spin-spin amplitude is reduced by a global factor of 0.75, the agreement is much more satisfactory. The charge exchange data can have a useful impact on the NN database.

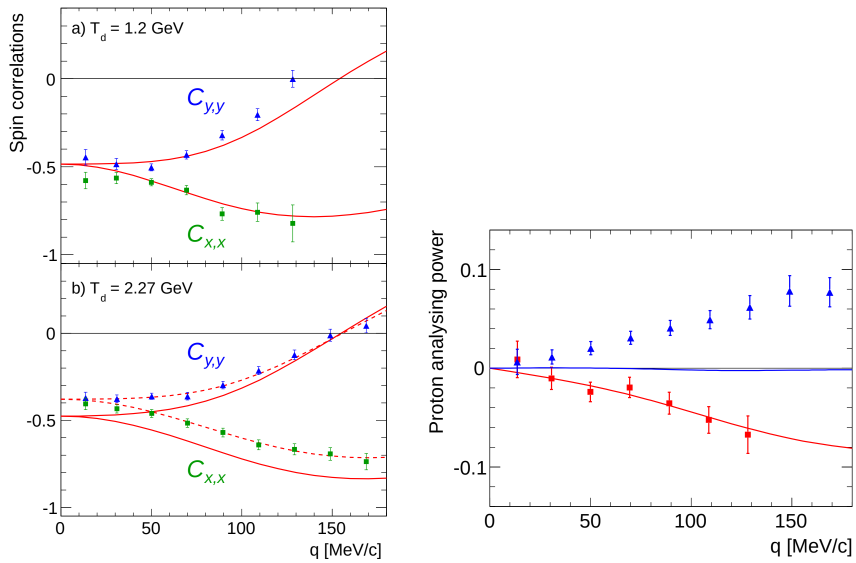

Figure 2: Left panel: Transverse spin correlation parameters in the $\vec{d}\vec{p} \to \{pp\}_s n$ reaction at (a) 1.2 and (b) 2.27 GeV compared to the predictions of an impulse approximation model (solid curves). Better agreement is found at the higher energy if the longitudinal input is scaled by a factor of 0.75 (dashed curves). Right panel: Proton analysing power in the $d\vec{p} \to \{pp\}_s n$ reaction at 1.2 GeV (red squares) and 2.27 GeV (blue triangles) compared to impulse approximation predictions. Note that, with the current SAID input [13], the latter almost vanish at the higher energy.

Confirmation of these conclusions is to be found in the measurements of the deuteron-proton spin correlation parameters studied with the polarised hydrogen gas cell. Results on this are shown in Fig. 2 (left panel). In impulse approximation, these are sensitive to the interference between the longitudinal spin-spin amplitude and the two transverse ones. Whereas there is satisfactory agreement with the theoretical predictions at 1.2 GeV, the model is much more satisfactory at 2.27 GeV if the longitudinal input is scaled by the 0.75 factor.

In addition to measuring the spin correlations with the polarised cell, data were also obtained in parallel on the proton analysing power in the $d\vec{p} \to \{pp\}_s n$ reaction and the results are shown in right panel of Fig. 2. The message here is very similar to that for the other observables. At 600 MeV per nucleon the SAID input reproduces the experimental points very well but it seems that at 1135 MeV the SAID description of the spin-orbit amplitude has serious deficiencies.

2.2 Δ excitation in the $\vec{n}p \to \vec{p}\Delta^0$ reaction

Theory suggests that much information on the np amplitudes could be extracted by studying the $dp \to \{pp\}_s X$ deuteron charge-exchange break-up reaction [5]. Two channels are of interest here: $X = n$ and $X = \Delta^0$. In impulse approximation these reactions can be considered as $np \to pn$ or $np \to p\Delta^0$ scattering with a spectator proton. This approach was implemented in detail for the neutron channel (Fig. 3a) and predicts the analysing powers, spin-correlation coefficients, and cross sections already mentioned. In the ${}^1S_0$ limit, the $\vec{d}\vec{p} \to \{pp\}_s n$ reaction observables are directly related to the np spin-dependent amplitudes.

Recent measurements with the ANKE spectrometer at 1.6, 1.8, and 2.3 GeV have extended the deuteron charge-exchange measurements into the pion-production region to investigate the

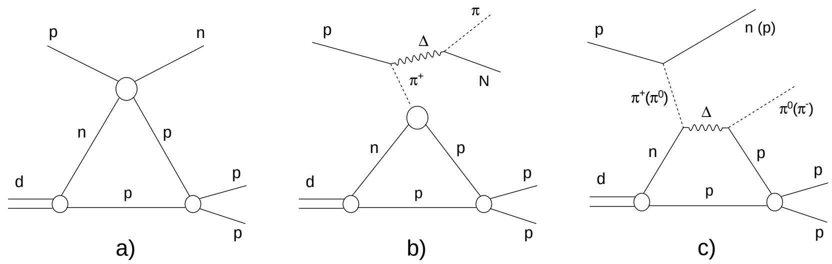

Figure 3: Deuteron charge-exchange break-up diagram for the neutron channel (a), the direct Δ^0 production channel (b), and Δ excitation in the incident deuteron (c).

excitation of the $\Delta(1232)$ isobar in the $dp \to \{pp\}\Delta^0$ reaction. It had already been demonstrated many years ago at Saclay that at $T_d = 2.0$ GeV the Δ can indeed be excited in this reaction [14]. Within the framework of direct Δ^0 production shown in Fig. 3b, such a measurement would correspond to one of a spin transfer from the initial neutron to the final proton in the $np \to \Delta^0 p$ reaction, and this would provide valuable information about the spin structure in the excitation of the Δ isobar. However, the simple one-pion-exchange model for the $pn \to p\Delta^0$ amplitude gives to little cross section at low M_x, as is seen in Fig. 4. One possible explanation for this is the contribution from Δ excitation in the deuteron, corresponding to the graph of Fig. 3c.

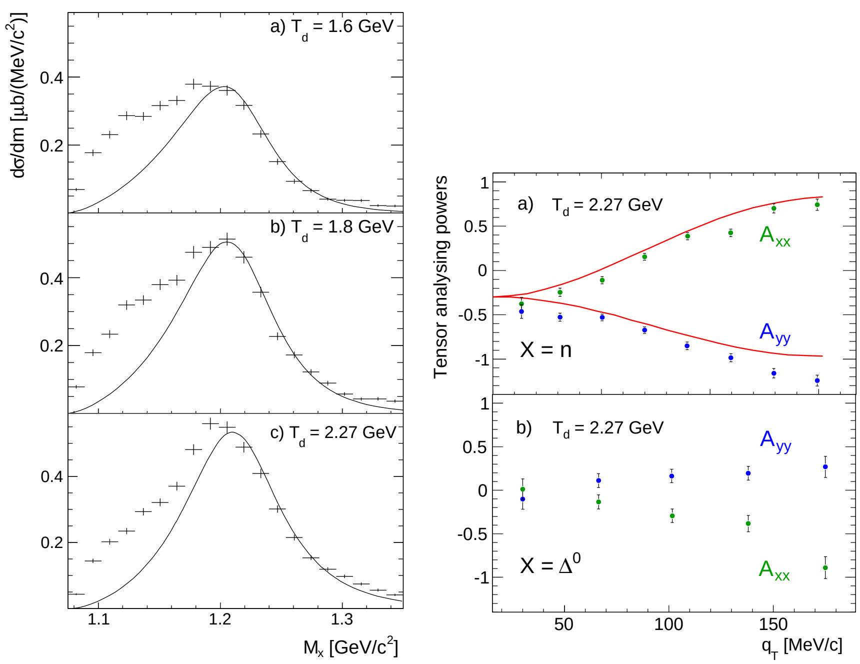

Figure 4: Left panel: differential cross section for the $dp \to \{pp\}X$ reaction for $M_x > M_N + M_\pi$ at three beam energies. Curves correspond to one-pion-exchange predictions. Right panel: Cartesian tensor analysing powers for the $dp \to \{pp\}_s X$ reaction at $T_d = 2.27$ GeV: with a neutron (a) or Δ^0 isobar (b) in the final state. In the Δ case the variable used is the transverse momentum transfer q_T. The red solid lines in the neutron panel are the results of an impulse approximation calculation.

The first indications shown in Fig. 4 are that the Cartesian analysing powers are largely opposite in sign to those for $\vec{d}p \to \{pp\}_s n$ [15]. These data will therefore yield information on the amplitude structure of the $NN \to N\Delta$ reaction. More theoretical work is required and calculations are in progress [16]. This leaves us with the tantalising possibility of studying isobar excitation in the $pd \to \{pp\}_s\Delta(N^*)$ reaction, where the two slow protons are detected in the STT and the proton or the negative pion from the $\Delta(N^*)$ decay in ANKE. This would then provide a measurement of the tensor polarisation of the isobar.

3 Predictions for breakup spin observables at higher momentum transfers

In order to allow estimates of counting rates for the $p\vec{d} \to \{pp\}_s n$ reaction, the impulse approximation program was run out to larger values of the momentum transfer using the standard SAID np charge-exchange amplitudes as input. The results at 1.135 GeV are shown in Fig. 5, where the usual $E_{pp} < 3$ MeV cut was imposed.

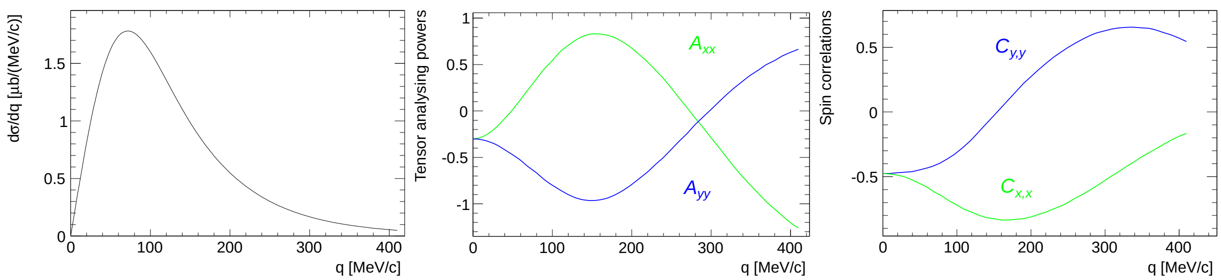

Figure 5: Impulse approximation predictions for the differential cross section (left panel), Cartesian tensor analysing powers (middle panel), and transverse spin correlation parameters (right panel) for the $pd \to \{pp\}n$ reaction at $T_p = 1.135$ GeV for three-momentum transfers up to $q = 400$ MeV/c.

Although the values of A_{xx}, A_{yy}, $C_{x,x}$, and $C_{y,y}$ are expected to be quite significant, this must be balanced against the much smaller cross section predicted at large q. The changes in the analysing power signals from double scattering in the deuteron are small for the kinematics of our earlier experiments but certainly cannot be neglected at the larger momentum transfers shown in Fig. 5. Such effects can be taken into account in the modelling [5].

4 Database on *pn* elastic spin-correlation parameters

The existing database of elastic pp and pn observables was shown in our last proposal to the COSY PAC [18], as abundance plots (angle *versus* energy up to 3 GeV). As was stressed there, for the spin observables there are remarkably large regions of virgin territory. This will be changed when the existing ANKE data are finalised [17, 18]. We want now to advance further the np programme by obtaining data on the spin-correlation parameters. The neutron-proton measurements have similar gaps for the $A_{y,y}$ and $A_{x,x}$ abundance plots as were shown for other spin observables. (New plots will be shown during the PAC session). There are essentially no measurements above 1.1 GeV and the experiments proposed here can also fill in the gaping holes at the small scattering angles that lie within the acceptance of the ANKE spectrometer.

5 Examples of by-product measurements

Although the main thrust of this proposal is the investigation of proton-deuteron charge-exchange breakup and proton-neutron elastic scattering, valuable data will also be collected on a variety of other reactions when using the polarised deuterium target. These include:

- High-momentum-transfer (backward) deuteron charge-exchange breakup, $pd \to \{pp\}_s n$, with the di-proton being detected in the FD system. We have already investigated this using an unpolarised beam and target and determined the differential cross sections [9, 10]. Using a polarised proton beam, we have also obtained the angular distributions of the analysing power at $T_p = 500$ and 800 MeV [11]. Considerable clarification of the dominant reaction mechanism will be obtained through the measurement of a combination of the deuteron tensor analysing power and the transverse $\vec{p}\vec{d}$ spin-correlation parameter [12];

- 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 quasi-free $pd \to n_{\text{spec}} d\pi^+$ and $pd \to p_{\text{spec}} d\pi^0$ reactions. 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 [13]. This gives a valuable check on the relative beam & target polarisations;

- Quasi-free $pd \to p_{\text{spec}} dX$, with the fast deuteron being detected in ANKE, allows one to study the small angle $\vec{p}\vec{n} \to dX$ reaction, which includes the isoscalar $\pi\pi$ system in the final state. By putting a cut on the missing mass at say $m_X \lesssim 320$ MeV/c^2, this channel will be analysed to study further the recent WASA observation of a resonance-like behaviour in this reaction;

- Diproton production in $pd \to p_{\text{spec}} \{pp\}_s \pi^-$, with two fast protons being detected in ANKE.

6 Preliminary results from the deuterium commissioning run

In June 2012, we conducted an experiment (COSY proposal #201) for the commissioning of the polarised internal deuterium gas target at ANKE and the starting of an initial research programme. The ANKE detection system used in these measurements, including the TWO Silicon Tracking Telescope (STT) system positioned around to the left and right of the storage cell target, are described in the earlier proposal [19].

6.1 The target polarisation

One of the main aims of the commissioning run was the determination of the vector and tensor polarisations of the deuterium storage cell gas target by studying various nuclear reactions. The experiment was done using about $6-8\times10^9$ stored unpolarised protons with a beam energy of $T_p = 600$ MeV and a (vector and tensor) polarised deuterium gas target of density $n_d \leq 10^{13}$ cm^{-2}. This resulted in an average luminosity value of $L \approx 5-7\times10^{28}$ s^{-1}cm^{-2}. The data-taking lasted for around 10 days.

A cell made from 25 μm thick aluminium foil (99.95% Al) was used in the run [20]. In order to minimise the depolarisation on the cell surface, the inner walls were coated with Teflon. The cell had dimensions $X \times Y \times Z = 20 \times 15 \times 370$ mm^3, where Z is measured along the beam direction with X and Y referring to the horizontal and vertical directions, respectively. A dedicated beam development was prepared to ensure that the COSY beam passed successfully through the cell. Electron cooling and stacking injection were employed, with fifty injections per cycle to increase the number of stored protons in the beam. In order to avoid excessive background coming from the interactions of the beam halo particles with the cell wall, scrapers were installed upstream of the target region.

The ABS source [21] was prepared to produce two mixed (vector and tensor) and two pure (only tensor) polarisation modes. The unpolarised gas was provided by the UGSS system [20]. The polarisation modes of the target was changed every ten seconds. The configurations used for the polarised deuterium target are presented in Table 1. Later in the text we refer to the modes '1' and '2' as "vector" modes and the '3' and '4' as "tensor" modes.

	Modes	Q_y	Q_{yy}
unpolarised target	0	0	0
polarised target	1	+1	+1
	2	-1	+1
	3	0	+1
	4	0	-2

Table 1: The different configurations of the polarised deuterium gas target used in experiment #201 carried out with the unpolarised proton beam. This shows the nominal (ideal) values of the vector (Q_y) and tensor (Q_{yy}) polarisations.

The $p\vec{d} \to n_{\rm sp} d\pi^+$ reaction was used in the determination of the vector polarisation (Q_y) of the target. This was identified by detecting both charged particles, either in the forward detector (Fd & Fd), or deuterons in the forward and pions in the positive detection system (Fd & Pd). For a two-track event the particle identification can be done using the arrival-time difference for two particles, measured in the scintillation hodoscope. After recognising the $d\pi^+$-pairs, the reaction is finally isolated on the basis of missing-mass distribution [4]. See the corresponding plots in Figure 6.

The quasi-free $p\vec{p} \to d\pi^+$ data were binned in deuteron c.m. angles. The background subtraction was performed separately for each bin and distributions in $\cos\phi$ built for both "vector" modes (1 and 2). Assuming that both vector polarisations have same magnitude, the ratios of the difference to the sum of the data for the two polarised modes were than fitted with a linear function in $\cos\phi$ and the value of the product $Q \cdot A_y$ deduced. Taking the mean analysing power $\langle A_y \rangle$ in each θ_d^{cm} bin from the SAID database [13], this resulted in the value $< Q_y >= 0.70 \pm 0.05$ (PRELIMINARY).

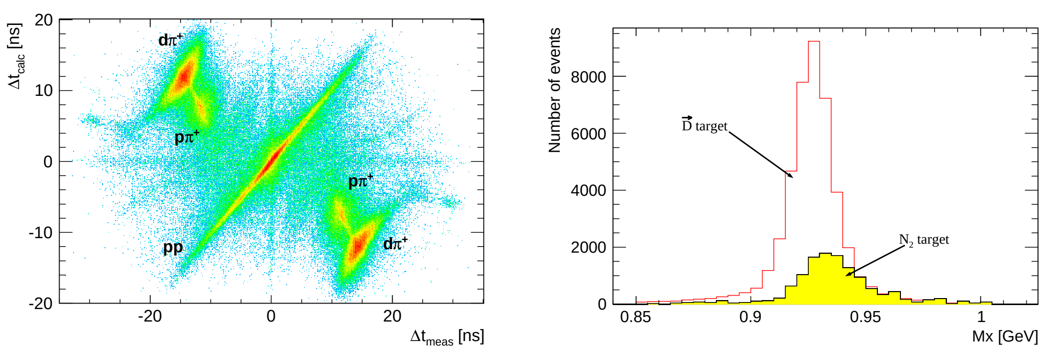

Figure 6: Left panel: Scatter plot of measured (ΔT_m) and calculated (ΔT_c) time differences between pairs of charged particle registered in the ANKE forward detector at T_p =600 MeV. ΔT_c was calculated assuming that both particles were protons. Right panel: Comparison of the $(p, d\pi^+)$ missing-mass distributions when using a polarised deuterium target or filling the cell with nitrogen gas. The missing neutron peak is clearly seen.

In contrast to the $p\vec{p} \to d\pi^+$ reaction, $p\vec{d}$ elastic scattering depends strongly on both the vector and tensor polarisations of the deuterium target, which is demonstrated in Figure 7.

Fortunately the analysing powers A_y and A_{yy} of this reaction have been measured with polarised deuteron beams at Argonne [23] for $T_d = 1194\,\mathrm{MeV}$ and SATURNE [24, 25] for $T_d = 1198\,\mathrm{MeV}$. The ANKE acceptance is sufficient to allow us to extract the analysing powers for the deuterium target from this reaction at $T_p = T_d/2$.

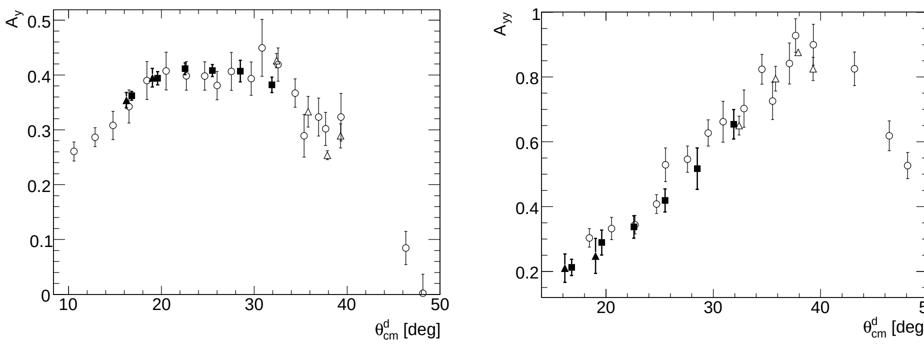

Figure 7: Vector (left panel) and tensor analysing powers (right) for elastic deuteron–proton scattering at small forward angles. The ANKE data at T_d=1170 MeV [22] (solid squares) were obtained using information solely from the forward detector system whereas two points (solid triangles) resulted from coincidence measurements with the silicon telescope. These data are compared to the results from Argonne at 1194 MeV [23] (open circles) and SATURNE at 1198 MeV [24, 25] (open triangles). It should be noted that the tensor beam polarisation at SATURNE was the subject of a series of very careful calibrations.

To identify events from pd elastic scattering in the long cell target, the use of STT system is mandatory. After stopping deuterons in different layers of the silicon detectors and requiring a track in coincidence in the FD detector, one can obtain a very clean signal corresponding to pd elastic scattering. Typical spectra from one run demonstrating such possibilities are given in Fig. 8. On the right panel of figure the left/right asymmetry (between STT1 and STT2) in the angular distribution of deuterons are shown for the "vector" modes. In order to use the measured analysing powers from dp elastic scattering (see Fig. 7), the deuteron angle (from pd elastic) is represented in dp c.m. system. Using this asymmetry, together with the target polarisation of Q_y=70% determined from quasi-free $p\vec{p} \to d\pi^+$, results for the vector analysing power A_y were obtained that were consistent with those measured at other laboratories [24, 25]. Analysis of the "tensor" runs is in progress and values of Q_{yy} will be presented during PAC session.

6.2 The quasi-elastic *NN* scattering identification at ANKE

The data collected during the commissioning run were used to test the selection of quasi-free NN elastic scattering at small momentum transfer. Such a process was identified by detecting a fast proton in the FD system in coincidence with a low energy ($3 < T_p < 30$ MeV) proton in one of two STT placed to the left (STT1) or right (STT2) of the storage cell target. Knowing the momenta of both protons, the missing-mass distributions were reconstructed, and an example of this is shown in the upper row of Fig. 9. For both STT there are clear peaks near the neutron mass coming from the $pd \to ppn$ reaction. These can be seen at any proton angle covered by the corresponding STT. The distributions in Θ_p^{Lab} presented in the lower row of Fig. 9 were obtained for missing masses in the range $0.85 < M_X(pp) < 0.97$ GeV/c^2.

Analogous angular distributions obtained by MC simulation of the $pd \to (pp)n_{sp}$ and $pd \to (pn)p_{sp}$ reactions are presented in Fig. 10. The reactions were simulated with the PLUTO event

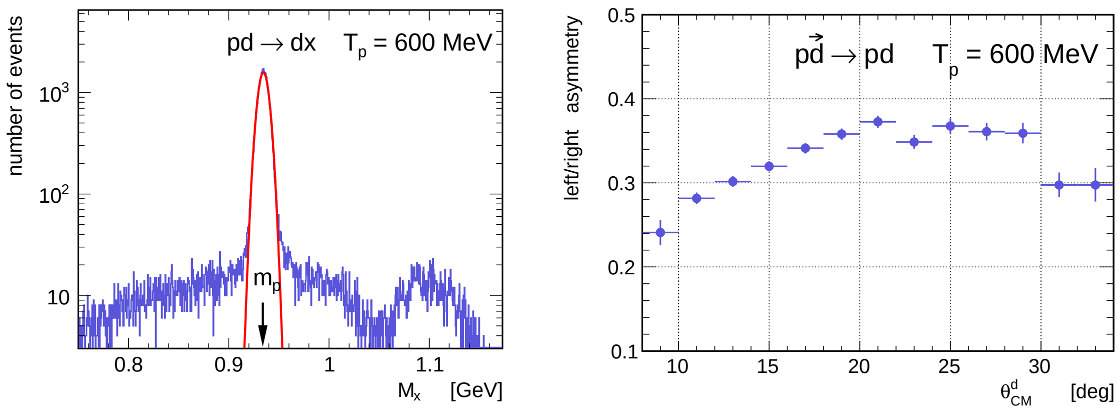

Figure 8: $pd \to pd$ elastic scattering at $T_p = 600$ MeV measured by detecting deuterons in the silicon telescopes. Left panel: the missing-mass distribution of the events when deuterons are isolated in STT1 or STT2. Right panel: The left/right asymmetry in the deuteron angular distributions in the dp c.m. system arising from elastic scattering for two different "vector" spin modes (see Table 1).

generator, which has the Fermi-motion of nucleon inside the deuteron implemented. The total number of generated events are equal for both reactions because of their total cross sections are practically the same. The differential cross sections introduced are those given by SAID [13]. The distributions of events take into account the experimental cuts in the proton angles and energies.

The results of the simulation reproduce well the main features of corresponding experimental angular distributions (Fig. 9, lower panels). As seen from Fig. 10, the count rate in STT1 is dominated by quasi-free pp elastic scattering. However, due to an asymmetric ϕ-acceptance of the ANKE forward detector, the contribution from this process is strongly suppressed in STT2, which is placed on the opposite side of cell. This allows us to approach the quasi-free pn elastic scattering study under quite clean background conditions.

However, it must be stressed that at small momentum transfers there will be significant modifications to the quasi-free picture due to np final state interactions and quantum-mechanical interference effects, which will require modelling [26].

6.3 The breakup process in inverse kinematics $\vec{d}(\vec{p}, pp)X$ at ANKE

As mentioned in the introduction, the main motivation in this proposal is the study of the $pd \to \{pp\}_s n$ break up, where both slow protons are detected in the STT. The results of the MC simulation are shown in Fig. 11 (left panel). The simulation also showed that the acceptance for this reaction changes little with beam energy. However, the design of the current silicon tracking telescopes unfortunately does not allow one to access the region where E_{pp} and q are simultaneously small. The STT have three layers and, in order to get a good kinematic determination, the proton has to pass through the first, which 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. If the protons are detected in separate STT, q can be small but the excitation energy E_{pp} must be at least twice 2.5 MeV. These conclusions are backed up by experimental data shown in the same figure.

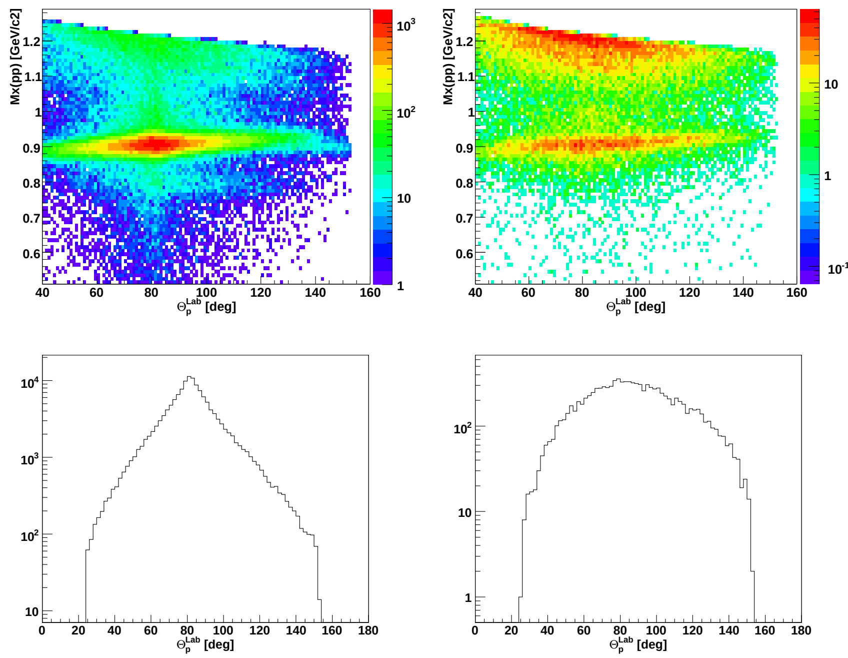

Figure 9: The upper panels represent the missing mass of the $pd \to (pp)X$ reaction. One proton is detected in the ANKE forward detector and the second one - either in STT1 (left) or in STT2 (right). The data are plotted *versus* the laboratory $\Theta_p^{\rm Lab}$ angle of the proton detected in the corresponding STT. The horizontal band near 0.92 GeV/c^2 corresponds to the $pd \to ppn$ reaction. Lower panels represent $\Theta_p^{\rm Lab}$ distributions of events whose missing masses were found to lie within the 0.85–0.97 GeV/c^2 range.

7 The new measurements proposed at ANKE

The measurement of the deuteron breakup reaction and quasi-free pn elastic scattering requires mainly the use of the forward detector system and the silicon tracking telescopes. However, to facilitate the data-taking of the by-product reactions, all detection systems, including the positive and negative side detectors, will be used. The ANKE collaboration has considerable experience in extracting the required reactions from the background using these detection systems. To get a better understanding of the acceptance, Monte Carlo simulations were performed at all the requested energies using the GEANT4 software package. Such results were partly shown in our previous proposal [18] and the pictures using the long cell target will be updated and shown during the PAC session.

8 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" polarisations of $P^{\uparrow,\downarrow} \sim 60\%$) and polarised deuterium target (with polarisations $Q_y^{\uparrow,\downarrow} \sim 70\%$ and $Q_{yy} \sim 70\%$). We assume a luminosity on the order of $L = 1 \times 10^{29}$ s^{-1}cm^{-2} ($\approx 5 \times 10^9$ stored polarised protons, $f_{\rm rev} \sim 1.2 - 1.6$ MHz, and $n_T = 2 \times 10^{13}$ cm^{-2}).

For the measurements outlined in the proposal, a TOTAL of **six weeks** of beam time are requested at **five** proton beam energies 0.6, 1.135, 1.4, 1.6, and 1.8 GeV.

The aims are:

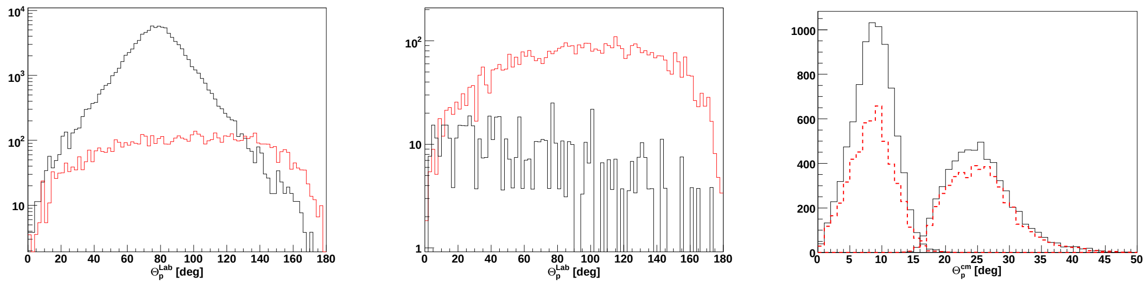

Figure 10: Simulated proton angular distributions in STT1 (left panel) and STT2 (middle panel) in coincidence with a fast proton found within the forward detector acceptance for quasi-free pp (black histogram) and pn (red histogram) elastic scattering. See text for more details. Right panel: Experimental angular distributions of protons detected in the forward detector in coincidence with STT1 ($\Theta_p^{cm} < 15^\circ$) and STT2 ($\Theta_p^{cm} > 15^\circ$) obtained for two different vector polarisation ("vector" runs) of the deuterium target. Since the target polarisation direction was flipped every 10 seconds, the difference between black and red histograms directly demonstrates an asymmetry. According to the SAID database, the analysing powers for pp and pn elastic scattering have the same sign in the ANKE angular domain.

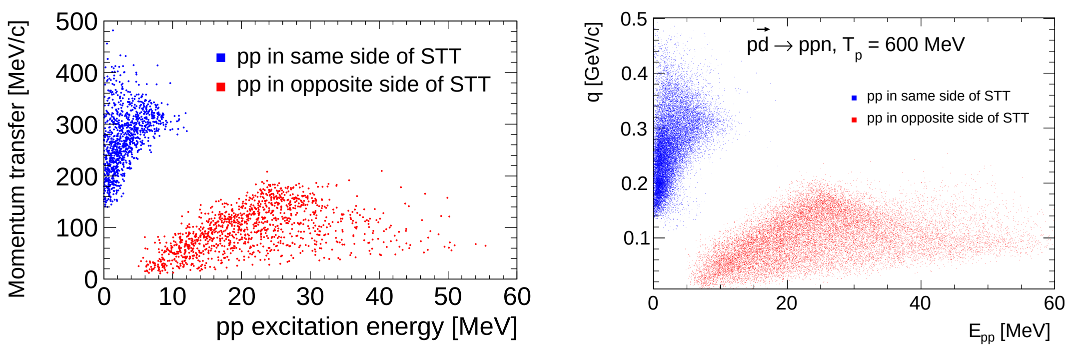

Figure 11: Three-momentum transfer q versus the pp excitation energy for $pd \to ppn$ at $T_p = 600$ MeV, when both slow protons are detected in the STT. Left panel: MC simulation; Right panel: Experimental data from the commissioning run at ANKE.

1. To measure the tensor analysing powers (T_{20}, T_{22}) and the transverse spin correlation parameters $(C_{y,y}, C_{x,x})$ for $\vec{d}(\vec{p}, pp)X$ breakup with $X = n$ or $X = \Delta^0$ in the final state.

2. To measure the spin correlation parameters $(A_{y,y}, A_{x,x})$ for quasi-free pn elastic scattering at about twelve energies in the angular range $5^\circ < \theta_{cm} < 40^\circ$. For each primary energy we will use at least 3×20 MeV intervals.

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

References

[1] A. Kacharava, F. Rathmann, and C. Wilkin for the ANKE Collaboration, COSY Proposal #152, *Spin Physics from COSY to FAIR*, arXiv:nucl-ex:0511028.

[2] D. Chiladze et al., *Vector and tensor analysing powers in deuteron-proton breakup reactions at intermediate energies* Phys. Lett. B **637** (2006) 170.

[3] D. Chiladze et al., *The $dp \to ppn$ reaction as a method to study neutron–proton charge–exchange amplitudes*, Eur. Phys. J. A **40** (2009) 23.

[4] D. Mchedlishvili et al., *The neutron-proton charge-exchange amplitudes measured in the $dp \to ppn$ reaction*; Accepted by Eur. Phys. J. A (2013), arXiv:1212.2365 [nucl-ex].

[5] D. V. Bugg and C. Wilkin, Nucl. Phys. A **467** (1987) 575.

[6] C. Ellegaard et al., Phys. Rev. Lett. **59** (1987) 974.

[7] S. Kox et al., Nucl. Phys. A **556** (1993) 621.

[8] J. Carbonell, M. B. Barbaro, and C. Wilkin, Nucl. Phys. A **529**, (1991) 653.

[9] S. Dymov *et al.*, Phys. Rev.. **C 81**, (2010) 044001.

[10] J. Haidenbauer and Yu.N. Uzikov, Phys. Lett. **B 562**, (2003) 227.

[11] S. Yaschenko *et al.*, Phys. Rev. Lett. **94**, (2005) 072304.

[12] Yu.N. Uzikov, J. Phys. G: Nucl. Part. Phys. **28**, (2002) B13.

[13] SAID data base, *available from* http://gwdac.phys.gwu.edu.

[14] C. Ellegaard et al., Phys. Lett. B **231** (1989) 365.

[15] D. Mchedlishvili et al., *The Δ isobar excitation in the $dp \to ppX$ reaction*; in preparation (2013).

[16] Yu. Uzikov, J. Haidenbauer, and C. Wilkin, *The charge-exchange reaction $dp \to pp_sN\pi$ in the Δ-isobar region.* ANKE internal report #97 (2012),
available from `www.collaborations.fz-juelich.de/ikp/anke`.

[17] D. Chiladze *et al.*, *Absolute measurement of pp elastic scattering at ANKE-COSY using the Schottky technique*, COSY proposal/Beam Request #200.0, Spokesperson: D. Chiladze. Available from `www.collaborations.fz-juelich.de/ikp/anke`.

[18] D. Chiladze *et al.*, *Measurement of nucleon-nucleon elastic scattering at small angles up to the maximum COSY energy*, COSY proposal/Beam Request #212.0, Spokespersons: D. Chiladze, A. Kacharava, C. Wilkin (2012). Available from `www.collaborations.fz-juelich.de/ikp/anke`.

[19] S. Barsov *et al.*, *Commissioning and Initial Research with the Polarised Internal Deuterium Gas Target at ANKE*, COSY proposal/Beam Request #201.0, Spokespersons: D. Chiladze, K. Grigoryev (2011). Available from `www.collaborations.fz-juelich.de/ikp/anke`.

[20] K. Grigoryev *et al.*, AIP Conf. Proc. **915** (2007) 979.

[21] M. Mikirtychyants *et al.*, submitted to Nucl. Instr. Meth. A; arXiv:1212.1840 [physics.ins-det].

[22] D. Chiladze *et al.*, Phys. Rev. ST Accel. Beams. **9** (2006) 050101.

[23] M. Haji-Said *et al.*, Phys. Rev. C **36** (1987) 2010.

[24] J. Arvieux *et al.*, Nucl. Phys. **A 431** (1984) 613.

[25] J. Arvieux *et al.*, Nucl. Instr. Meth. **A 273** (1988) 48.

[26] B. S. Aladashvili *et al.*, J. Phys. G **3** (1977) 7.