COSY Proposal and Beam Request

Measurement of the spin correlation parameters of the quasi–free $\vec{n}\,\vec{p} \to \{pp\}_s\pi^-$ reaction with polarised beam and target at ANKE

S. Dymov[1], E. Steffens
Physikalisches Institut II, Universität Erlangen–Nürnberg, 91058 Erlangen, Germany

T. Azarian, V. Komarov, A. Kulikov, V. Kurbatov, G. Macharashvili[2], S. Merzlyakov[3], V. Serdyuk[3], S. Trusov[3], D. Tsirkov, Yu. Uzikov
Joint Institute for Nuclear Research, 141980 Dubna, Russia

V. Baru, D. Chiladze[2], R. Engels, R. Gebel, K. Grigoryev, J. Haidenbauer, Ch. Hanhart, M. Hartmann, A. Kacharava, A. Lehrach, B. Lorentz, D. Mchedlishvili[2], M. Mikirtytchiants, M. Nekipelov, H. Ohm, D. Prasuhn, F. Rathmann, R. Schleichert, Yu. Valdau, Ch. Weidemann, H. Ströher
Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany

S. Bertelli, G. Ciullo, M. Contalbrigo, P.F. Dalpiaz, P. Lenisa, M. Stancari, M. Statera
University of Ferrara and INFN, 44100 Ferrara, Italy

P. Goslawski, A. Khoukaz, M. Mielke, M. Papenbrock
Institut für Kernphysik, Universität Münster, 48149 Münster, Germany

N. Lomidze, M. Nioradze, M. Tabidze
High Energy Physics Institute, Tbilisi State University, 0186 Tbilisi, Georgia

S. Barsov, S. Mikirtytchiants[3]
St. Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia

C. Wilkin
Physics and Astronomy Department, UCL, London, WC1E 6BT, UK

for the ANKE Collaboration

Spokesperson: Sergey Dymov

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[1] also in JINR, Dubna
[2] also in HEPI, Tbilisi
[3] also in IKP, Forschungszentrum Jülich

Abstract

We propose to measure the spin correlation coefficients ($A_{x,x}$, and $A_{y,y}$) of the quasi–free $\vec{n}\,\vec{p} \to \{pp\}_s\pi^-$ reaction for excitation energies of the final diproton less than 3 MeV. The experiment would be carried out with polarised deuteron beam and polarised hydrogen target at the ANKE spectrometer at a mean neutron energy of $T_n \approx 353$ MeV. The results will be of relevance for Chiral Perturbation Theory. These measurements are in line with the proposals outlined in the ANKE spin document.

The proposal requires in total **7 weeks** of beam time (data taking) to determine the spin correlation coefficients ($A_{y,y}$ and $A_{x,x}$) via $\vec{d}\,\vec{p} \to p_{sp}\{pp\}_s\pi^-$ at a single deuteron beam energy, $T_d = 706$ MeV. The measurement should be conducted after the Polarized Internal Target is installed at ANKE in 2011.

Contents

1 Introduction

1.1 Physics Overview

We have argued at length in previous proposals why one needs to measure cross sections and spin observables in the $pp \to \{pp\}_s \pi^0$ or $np \to \{pp\}_s \pi^-$ reactions at low excitation energies $E_{pp} < 3$ MeV of the final pp system, here denoted by $\{pp\}_s$ [1–3]. We shall therefore endeavour to be briefer regarding the motivation. To a good approximation, at such low E_{pp} the recoiling diproton system is in the $^1S_0$ state. A full data set of all observables at low beam energies would allow us to determine the partial wave amplitudes which, in turn, would provide a non-trivial test of chiral perturbation theory and also lead to the fixing of the value of the parameter d, which represents the important contact term that affects the p-wave amplitudes.

The short range physics in chiral effective field theories, which provide a model independent understanding of the nature, is encoded in the so called low energy constants (LEC). These LECs, once determined from one process, can be applied to predict many others. For example, the LECs c1-c4 extracted from πN analysis using chiral perturbation theory are now widely used to parameterise the short range physics in NN-interaction, few-nucleon systems, single (and multi) pion production in NN collisions *etc.* Analogously, by studying p-wave pion production amplitudes we get access to the $4N\pi$ contact operator, the strength of which is controlled by the low energy constant d. This LEC enters also in electroweak processes, such as $pp \to de^+\nu$ and triton β decay, in few-body operators (e.g. $pd \to pd$), pion photoproduction $\gamma d \to nn\pi^+$ and its counter partner $\pi d \to \gamma NN$. Thus, it plays a very important role connecting different low-energy reactions and therefore needs to be determined with high accuracy.

On the practical side, the $pp \to \{pp\}_s \pi^0$ or $np \to \{pp\}_s \pi^-$ reactions have the big advantage for COSY that both the pion and diproton have spin-zero, which means that the only spin degrees of freedom are connected with the initial state. There are therefore no non-trivial spin-transfer observables, so that rescattering experiments are not required.

For both π^0 and π^- production there are four types of experiments that are possible. These are the unpolarised differential cross section $(\mathrm{d}\sigma/\mathrm{d}\Omega)_0$, the beam or target analysing power A_y, the in-plane spin-correlation $A_{x,x}$, and the mixed correlation parameter $A_{x,z}$. Knowing these one can determine the magnitudes and relative phase of the two invariant amplitudes as functions of the pion production angle for the pp and pn experiments.

As part of our full pion production programme, the ANKE collaboration has taken data on the differential cross section and analysing power for both $pp \to \{pp\}_s \pi^0$ and $np \to \{pp\}_s \pi^-$ for the region of a beam energy $T_N \approx 353$ MeV and the aim of the present proposal is the determination of $A_{x,x}$ for $np \to \{pp\}_s \pi^-$ in this region.

At low energies it is reasonable to assume that data such as these can be analysed by truncating the partial wave expansion at $\ell = 2$. The relation between the observables and the partial wave amplitudes for $\ell \leq 2$ is discussed in full in the next subsection. It is shown there that the magnitude of one of the p-wave amplitudes is fixed completely by the measurement of $(1 - A_{x,x})d\sigma/d\Omega$ for $np \to \{pp\}_s\pi^-$ and that the magnitude of the other p-wave amplitude and its relative phase can then be deduced from a combined analysis of this with our already taken cross section and analysing power data for $pp \to \{pp\}_s\pi^0$ and $np \to \{pp\}_s\pi^-$. These data will provide two determinations of the LEC d. Measurements of the mixed spin-correlation parameters $A_{x,z}$ are not required for the extraction of the p-wave amplitudes, though such information is vital in order to identify the d-wave terms.

It is also important to realise that, as shown below, uncertainties in the beam/target polarisations and the relative normalisations of the $pp \to \{pp\}_s\pi^0$ and $np \to \{pp\}_s\pi^-$ cross sections can be resolved using the features of the data themselves.

1.2 Amplitudes, Observables, and Partial Waves

The spin structure of the $pp \to \{pp\}_s\pi^0$ or $np \to \{pp\}_s\pi^-$ reaction is that of $\frac{1}{2}^+\frac{1}{2}^+ \to 0^+0^-$ and parity and angular momentum conservation then require that the initial nucleon-nucleon pair has spin $S = 1$. There are only two independent spin amplitudes and these may be written as

$$\mathcal{F} = \frac{i}{\sqrt{2}}\, u_2^T\, \sigma_y\, \{A\,\sigma_x + B\,\sigma_z\}\, u_1\,, \tag{1.1}$$

where the u_i are Pauli spinors describing the initial protons, the beam direction is along $\hat{z}$, and the production lies in the $(\hat{x}, \hat{z})$ plane. Alternatively the amplitude may be written as

$$\mathcal{F} = \vec{\varepsilon}\cdot\{A\,\hat{x} + B\,\hat{z}\}\;, \tag{1.2}$$

where $\vec{\varepsilon}$ is the polarisation vector of the initial spin-triplet NN state.

The double–polarised differential cross section becomes

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 \times \tag{1.3}$$
$$\left[1 + P_yA_y^P + Q_yA_y^Q + P_yQ_yA_{yy} + P_xQ_xA_{xx} + P_zQ_zA_{zz} + P_xQ_zA_{xz} + P_zQ_xA_{zx}\right]\,,$$

where $\vec{P}$ and $\vec{Q}$ are the beam and target polarisations. The observables are then expressed in terms of the two amplitudes through

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 = \frac{k}{4p}\left(|A|^2 + |B|^2\right), \quad A_y^P = A_y^Q = -\frac{2\,Im(A^*B)}{|A|^2 + |B|^2}$$

$$A_{xx} = -A_{zz} = \frac{|B|^2 - |A|^2}{|A|^2 + |B|^2}\,, \quad A_{yy} = 1, \quad A_{xz} = A_{zx} = -\frac{2\,Re(A^*B)}{|A|^2 + |B|^2}\,. \tag{1.4}$$

Here p is the incident beam momentum in cm and k is the cm momentum of the pion. ¿From this it is seen that, up to a two–fold ambiguity, the measurement of the differential cross section, A_y and $A_{x,x}$ is sufficient to extract the magnitudes of the two amplitudes and their relative phase. The discrete ambiguity can be lifted if we have information on $A_{x,z}$. The overall phase (which can depend upon the production angle) is, of course, unmeasurable and this gives rise to continuum ambiguities, which are most easily seen in a partial wave representation.

Due to spin–parity constraints applied to the $pp \to \{pp\}_s\pi^0$ reaction, the orbital angular momentum of the pion must be even and that of the initial protons odd. Therefore the lowest partial waves that can contribute to the amplitudes of Eq. (1.2) come from the transitions ${}^3P_0 \to {}^1S_0s$, ${}^3P_2 \to {}^1S_0d$, and ${}^3F_2 \to {}^1S_0d$. These three amplitudes correspond to isospin $I = 1$ in the incident NN channel. For production in the np case, we have also to consider $I = 0$ and here the selection rules require the pion angular momentum to be odd and the initial np state to have even parity and hence even angular momentum. The lowest partial waves then involve the transitions ${}^3S_1 \to {}^1S_0p$ and ${}^3D_1 \to {}^1S_0p$. As stressed in earlier proposals, the interesting Physics that we would like to extract resides in these pion p-wave amplitudes.

Rather than working in terms of these five partial wave amplitudes, the expressions for the observables are simpler to derive and present if one uses amplitudes α, β, γ, δ, and ϵ in a non-orthogonal basis, where the $I = 1$ and $I = 0$ matrix elements are written as

$$\mathcal{F}_1 = \vec{\varepsilon}\cdot[\alpha\hat{p} + \beta\vec{k}\,(\hat{p}\cdot\vec{k}) + \gamma\hat{p}\,(\hat{p}\cdot\vec{k})^2], \tag{1.5}$$

$$\mathcal{F}_0 = \vec{\varepsilon}\cdot[\delta\vec{k} + (\epsilon-\delta)\hat{p}\,(\vec{k}\cdot\hat{p})]. \tag{1.6}$$

Clearly, $\mathcal{F}_1$ is the amplitude for $pp \to \{pp\}_s\pi^0$ but the amplitude for $np \to \{pp\}_s\pi^-$ is $(\mathcal{F}_1 + \mathcal{F}_0)/\sqrt{2}$.

It is important to note that, although γ is proportional to the ${}^3F_2 \to {}^1S_0d$ amplitude, α is a linear combination of the ${}^3P_0 \to {}^1S_0s$, ${}^3P_2 \to {}^1S_0d$ and ${}^3F_2 \to {}^1S_0d$ amplitudes. This means that if, for example, one makes the assumption that α were independent of energy, it would not lead to an s-wave amplitude that was constant.

By comparing the amplitudes of Eq. (1.2) with those of Eqs. (1.5)and (1.6), we can read off that

$$A = \beta k^2\sin\theta\cos\theta + \delta k\sin\theta\,, \tag{1.7}$$

$$B = \alpha + \beta k^2\cos^2\theta + \gamma k^2\cos^2\theta + \epsilon k\cos\theta\,, \tag{1.8}$$

where θ is the pion production angle with respect to the proton beam direction.

Since the partial wave decomposition was truncated at order k^2, we only have the right to keep contributions to the observables to this order. Looking first at the $pp \to \{pp\}_s\pi^0$ reaction, this gives

$$\begin{aligned}
\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 &= \frac{k}{4p}\left[|\alpha|^2 + 2Re\{\alpha^*\beta + \alpha^*\gamma\}k^2\cos^2\theta\right],\\
A_y\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 &= \frac{k}{4p}\left[-2Im\{\alpha^*\beta\}k^2\sin\theta\cos\theta\right],\\
A_{xz}\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 &= \frac{k}{4p}\left[-2Re\{\alpha\beta^*\}k^2\sin\theta\cos\theta\right],\\
A_{xx} &= A_{yy} = 1\,.
\end{aligned} \tag{1.9}$$

A complete measurement of these three observables over the angular range then gives us access to the values of $|\alpha|^2$, $Re\{\alpha^*\beta\}$, $Im\{\alpha\beta^*\}$, and $Re\{\alpha^*\gamma\}$. This means that, in addition to the overall phase ambiguity, there is no information on the imaginary part of γ with respect to α. However, without the $A_{x,z}$ data there is also complete uncertainty in $Re\{\alpha^*\beta\}$.

These ambiguities persist when data are included from the $np \to \{pp\}_s\pi^-$ reaction but, thankfully, they do not get any worse. Note that a k^2 dependence of $|\alpha|^2$ could be studied from such data and that this could be translated into one for the s-wave production amplitude because that would not be influenced by any uncertainty in the imaginary part of $\alpha^*\gamma$.

The formulae are similar but more complex in the $np \to \{pp\}_s\pi^-$ case:

$$\begin{aligned}
\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 &= \frac{k}{8p}\Big[(|\alpha|^2+|\delta|^2k^2)+2Re\{\alpha^*\epsilon\}k\cos\theta \\
&\quad + \left[2Re\{\alpha^*\beta+\alpha^*\gamma\}+|\epsilon|^2-|\delta|^2\right]k^2\cos^2\theta\Big], \\
A_y\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 &= \frac{k}{8p}\left[-2Im\{\alpha^*\delta\}k\sin\theta-2Im\{\alpha^*\beta+\delta\epsilon^*\}k^2\sin\theta\cos\theta\right], \\
(1-A_{xx})\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 &= \frac{k}{8p}\left[2|\delta|^2k^2\sin^2\theta\right], \\
(1+A_{xx})\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 &= \frac{k}{4p}\Big[|\alpha|^2+2Re\{\alpha^*\epsilon\}k\cos\theta+\left[2Re\{\alpha^*\beta+\alpha^*\gamma\}+|\epsilon|^2\right]k^2\cos^2\theta\Big], \\
A_{xz}\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 &= \frac{k}{8p}\left[-2Re\{\alpha^*\delta\}k\sin\theta-2Re\{\alpha\beta^*+\delta\epsilon^*\}k^2\sin\theta\cos\theta\right], \\
A_{yy} &= 1\,.
\end{aligned} \tag{1.10}$$

If we assume now that the relative normalisations of the $pp \to \{pp\}_s\pi^0$ and $np \to \{pp\}_s\pi^-$ observables can be well established, the extra information provided by the latter are the values of $|\delta|^2$, $|e|^2$, $Re\{\alpha^*\delta\}$, $Im\{\alpha^*\delta\}$, $Re\{\delta\epsilon^*\}$, and $Im\{\delta\epsilon^*\}$. This therefore adds no new ambiguities to the ones already present for the π^0 production and the interesting p-wave amplitudes can be completely determined up to the overall unknown phase of α.

Since, in principle from Eqs. (1.9) and (1.10) one could fix the values of $|\delta|^2$ and $|\epsilon|^2$ purely from the two unpolarised differential cross sections, one has to ask why it is necessary to carry out the difficult and very lengthy measurement of $A_{x,x}$. The subtraction of $|\alpha|^2$ from $|\alpha|^2+|\delta|^2k^2$ requires very accurate relative normalisations because, due to the k^2 factor, the $|\delta|^2$ contribution is not expected to be very large at low energies. The same objection may not be levelled at the $|\delta|^2-|\epsilon|^2$ extraction because there is then a k^2 factor in front of the whole $\cos^2\theta$ term.

Apart from the question of the relative luminosity, acceptance, and efficiency questions between the $pp \to \{pp\}_s\pi^0$ and $np \to \{pp\}_s\pi^-$ cross section measurements, the $(1-A_{x,x})\mathrm{d}\sigma/\mathrm{d}\Omega$ extraction requires good knowledge of the product of the beam and target polarisations. This can be achieved to the same precision as the determination of the signal by demanding that $A_{y,y}=1$ for all angles and $A_{x,x}=1$ in the forward and backward directions. These relations are valid quite independently of the partial wave decomposition presented here.

Although the extraction of $|\delta|^2$ from the $np \to \{pp\}_s\pi^-$ measurement is direct, the determination of the other p-wave amplitude will be carried out through the comparison of the $pp \to \{pp\}_s\pi^0$ and $np \to \{pp\}_s\pi^-$ observables and this will lead to a separate determination of the d parameter, which can be used as a check on the consistency of the theoretical approach. The most difficult problem to be faced in this analysis is ensuring the relative normalisation of the pp and pn experiments that are studied under different experimental conditions. This can be guaranteed by using the following analysis procedure.

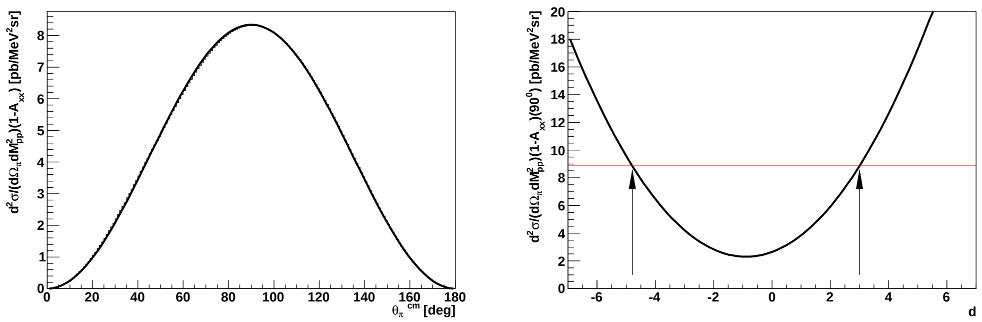
The $(1-A_{x,x})d\sigma/d\Omega$ measurement gives the value of $|\delta|^2$ with the $np \to \{pp\}_s\pi^-$ normalisation. This can then be subtracted from the $(|\alpha|^2 + |\delta|^2k^2)$ in the term independent of $\cos\theta$ in the expression for the unpolarised differential cross section to leave just the $|\alpha|^2$ contribution in Eq. (1.10), again with the $np \to \{pp\}_s\pi^-$ normalisation. When this is compared with the analogous term for π^0 production in Eq. (1.9), the relative normalisations of the $pp \to \{pp\}_s\pi^0$ and $np \to \{pp\}_s\pi^-$ data can be established. Completely equivalently, one can fit the expansion of $(1 + A_{x,x})d\sigma/d\Omega$ in Eq. (1.10) and compare the coefficients of the terms independent of $\cos\theta$. Either procedure avoids the difficulties raised by uncertainties in the effective luminosity when using a deuteron beam/target, shadowing effects *etc.*

Thus, even without measurements of $A_{x,z}$ it would be possible to extract $|\delta|^2$, $|\epsilon|^2$, and $Im\{\delta\epsilon^*\}$, so that their magnitudes and relative phase would be fixed up to one discrete ambiguity. The discrete ambiguity could only be lifted through measurements of $A_{x,z}$ which would then also constrain much more fully the d-waves. These considerations apply directly in the vicinity of 353 MeV where we have data for π^0 production. However, by using a deuteron beam and applying cuts on the c.m. energy it should nevertheless be possible to study the energy dependence of the $|\delta|^2$ contribution and therefore the consistency of the approach.

1.3 Predictions

The IKP theory group has recently published a study of pion production in nucleon-nucleon collisions with the ${}^1S_0$ selection criterion [4]. Chiral effective field theory was employed to estimate the p-wave amplitudes but it will only be at a later stage that the group will attempt to calculate the two d-wave amplitudes. Although they show that the value of the d parameter influences strongly various observables, such as the cross section for $np \to \{pp\}_s\pi^-$ [4], without the inclusion of the d-waves one cannot yet draw any firm conclusions on this from our data or those from other groups. However, the quantity $(1-A_{x,x})d\sigma/d\Omega$ for $np \to \{pp\}_s\pi^-$ gets no contribution from even pion partial waves and is directly and uniquely a measurement of the magnitude of a p-wave contribution. As a consequence the theoretical estimates of this quantity will not be affected by any deficiencies in the d-wave calculation [4].

We show in Fig. 1a the theoretical prediction for $(1-A_{x,x})d\sigma/d\Omega$ in the $np \to \{pp\}_s\pi^-$ reaction within the model of Ref. [4]. As shown in the previous section, to order k^2 the angular dependence of this quantity is of the form $|\delta|^2\sin^2\theta$. The maximum height $|\delta|^2$ is a sensitive function of the crucial contact parameter d and estimates have been made over a wide range. Figure 1b shows the predicted behaviour of the maximum as a function of d, which seems to follow a parabola over the interesting range of d. Theoretical prejudice seems to prefer a value in the range from 0 to +3 [4]. We will show later that we can measure $|\delta|^2$ with a precision of about 10%, which should allow d to be well fixed within the framework of the theoretical model.



(a) $(1 - A_{x,x})d\sigma/d\Omega$ calculated for d=3.

(b) Dependence of $(1 - A_{x,x})d\sigma/d\Omega$ at 90^o on the d LEC.

Figure 1: Theoretical predictions for the $np \to \{pp\}_s\pi^-$ reaction [4].

2 ANKE results for A_y and $d\sigma/d\Omega$ in $\vec{p}p \to pp\pi^0$ and $\vec{p}n \to pp\pi^-$

As a first step in our pion production programme, the measurements with a polarised proton beam incident on unpolarised proton and deuteron cluster targets were performed in April-March 2009 at the beam energy of T_p=353 MeV [2,3]. The preliminary results of these measurements are presented in this section.

Figure 2 shows the results obtained for the $\vec{p}p \to \{pp\}_s\pi^0$ process. The final proton pair was recorded in the ANKE forward detector and identified with the use of the time-of-flight difference between the two protons. Excellent conditions of the polarised proton beam, with polarisation of $\sim$ 65%, and of the hydrogen cluster target allowed us to achieve the desired high statistical precision.

In Fig. 3 the results for the $\vec{p}n \to \{pp\}_s\pi^-$ process are presented. The ANKE deuterium cluster target was used in the experiment and small energies of the spectator proton $T_{\text{spec}} < 6$ MeV were selected. This measurement was more technically involved due to the additional detector systems used to record the extra final state particles, and the consequent reduction of the setup acceptance. The diproton was recorded in either the Forward or the Positive ANKE detectors. In addition to that, either π^- at large cm angles was recorded in the Negative detector, or the spectator proton was measured in the Silicon Tracking Telescope. First results for A_y

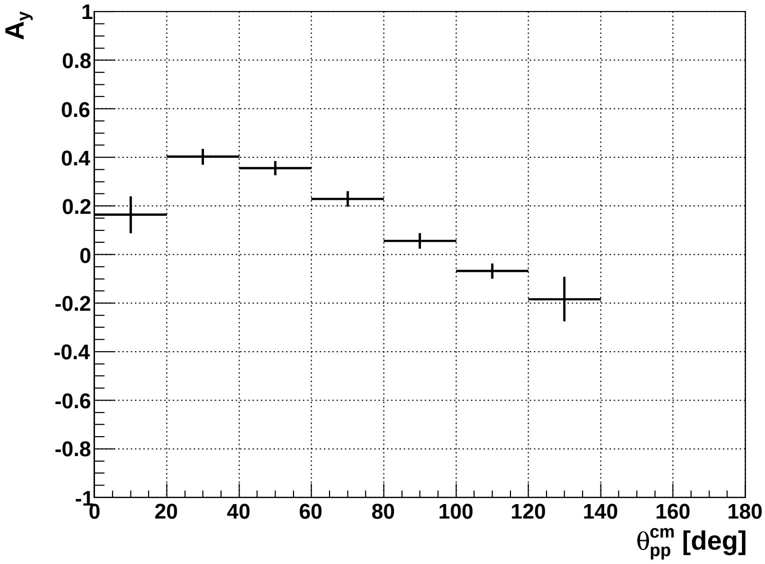


Figure 2: Preliminary ANKE results for A_y of the $pp \to \{pp\}_s\pi^0$ reaction at T_p=353 MeV [3].

are presented in Fig. 3, together with the data from TRIUMF [5] and PSI [6] and compared to the prediction of the IKP theory group [4]. The preliminary ANKE results for the differential cross section will be shown during the oral presentation.

3 Measurement of $A_{x,x}$ and $A_{y,y}$ in $\vec{n}\vec{p} \to \{pp\}_s\pi^-$

We have shown that we can study successfully reactions with polarised beams of protons [7] and deuterons [8] and, in particular, proved that we can calibrate the vector and tensor polarisations of the deuteron beam [9]. Since the necessary equipment is now commissioned, and the first double–polarised experiment has been successfully conducted last year [10], it is the right time to propose another key experiment on the double-polarised pion production at ANKE. This is the purpose of the present document.

3.1 Scheme of the experiment

We propose to measure the spin correlation coefficients ($A_{x,x}$, and $A_{y,y}$) of the quasi–free $\vec{n}\,\vec{p} \to \{pp\}_s\pi^-$ through the use of the vector polarised **deuteron COSY beam** and the polarised **hydrogen target**. The ANKE Polarised Internal Target (PIT) equipped with a long openable storage cell is suggested for use in this experiment. Possible options for the openable storage cell at ANKE are described below.

Measurement in the dp kinematics mode is favoured over the pd case due to the higher setup efficiency for the detection of the spectator proton, which is very

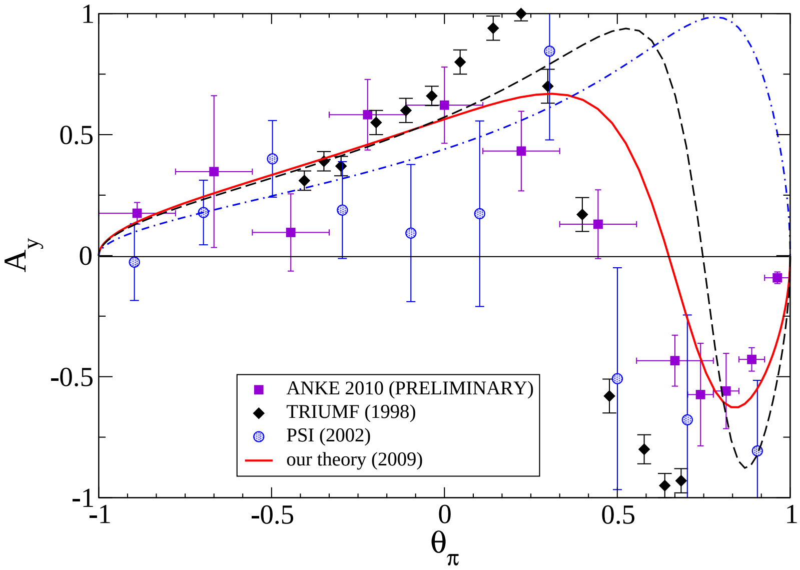


Figure 3: Preliminary ANKE results for A_y in the $\vec{p}n \to \{pp\}_s\pi^-$ reaction at T_n=353 MeV [2] (magenta squares). Also shown are the results of calculation [4] with LEC values of $d = 3$ (red solid line), $d = 0$ (black dashed line), and $d = -3$ (blue dot-dashed line). The remaining data are from TRIUMF [5] (black diamonds) and PSI [6] (blue circles).

important in a low rate double polarisation experiment. In the proposed scheme, the proton pair from the final diproton will be recorded in the ANKE Positive detector while the spectator proton from the incident deuteron beam will be seen at small laboratory angles by the Forward detector. The protons will be identified by the difference of their time-of-flight measured for each of the detected particles. Pions emitted at small angles relative to the incident neutron can be recorded in the Negative detector. This will give an additional possibility to study the systematics and the background conditions. Measuring the time-of-flight difference will let us reconstruct the vertex coordinates and correctly calculate the particle momenta.

3.2 Polarised internal target

The polarised internal target (PIT) system at ANKE consists of an atomic beam source (ABS) feeding a storage cell (SC) and a Lamb–shift polarimeter (LSP). The status of the different components is given here.

During one week of commissioning experiment in January 2007 and the four weeks beam time in October 2009, allocated to measure the Charge–Exchange break-up of polarised deuterons on a polarised hydrogen target $\overrightarrow{d}\,\overrightarrow{p} \to (pp)n$, the following results were achieved [11]:

- The expected density for the polarised hydrogen ($\vec{H}$ gas) storage cell target of $d_t = 1.34 \times 10^{13}\,\mathrm{cm}^{-2}$ was achieved.

- The clean identification of events for the $\vec{d}\vec{p}$–induced reactions when using a long cell target has been demonstrated. This was done on the basis of experimental information obtained from the $\vec{H}$ gas target and on the known shape of the background from the cell walls, which is imitated through the use of N_2 gas in the cell. The exact shape of the background under the missing–mass peak from the cell–wall events has been determined under real experimental conditions and was under control during on-line measurements.

- Using the missing–mass technique for the measured single– and double–track events in ANKE, it has been shown that very clean identification of the following reactions is possible: $\boldsymbol{\vec{d}\vec{p} \to dp_{sp}\pi^0}$, $\boldsymbol{\vec{d}\vec{p} \to (pp)n}$, $\boldsymbol{\vec{d}\vec{p} \to}$ $^3\mathrm{He}\,\boldsymbol{\pi^0}$. The $\vec{d}\vec{p} \to dp_{sp}\pi^0$ process is particularly important for measuring the vector polarisation of the beam and the target.

- In parallel to the data–taking, the ABS source was tuned with Lamb–shift Polarimeter (LSP) measurements. The goal of the measurement was to determine the target polarisation (Q_y) from the quasi–free $\boldsymbol{n\vec{p} \to d\pi^0}$ reaction. The achieved value of average target polarisation was $\langle Q_y \rangle = 0.75 \pm 0.06$. The target polarisation was maximised and the equality of positive and negative polarisations was verified on the level of a couple of percent by using on–line measurements from the LSP, repeated every 24 hours.

Given the above successes in the first handling of double–polarised data, we conclude that ANKE–COSY is ready to embark on the experimental programme that includes double–polarisation measurements.

3.3 Options for openable cell at ANKE

In the low rate conditions of the double polarisation experiment it is extremely important to exploit all the possibilities to increase the luminosity. To minimise the time spent on the measurement, we propose to use an openable storage cell in this experiment.

To achieve an areal density as high as possible, the length of the cell has to be as large as possible and the diameter as small as possible. The dimensions of the feeding tube are limited by the divergence of the incoming beam from the ABS and the length is limited by the available space. Thus, the lateral dimensions have to be made as small as possible during the measurements. This requirement can be reached with a cell which is widened during injection of the beam into the storage ring and closed after beam manipulation (injection and phase space cooling). During injection and ramping, the beam from the ABS is blocked and the two halves of the cell are separated. When the required energy is reached the cell is closed and the ABS beam is switched on.

The advantage of the storage cell that opens during the injection and acceleration phases has been discussed in Ref. [12]. It was found that the optimal dimensions of a regular cell at ANKE are 15 mm (vertical) $\times$ 20 mm (horizontal) $\times$ 390 mm.

In the case of an openable cell the cross section can be reduced to 15×12 mm^2, resulting in up to a five times higher areal density.

Recently [13], an openable cell of $12 \times 10 \times 400$ mm size was built and successfully tested in IKP for use in the PAX experiment, see Fig. 4. This development can also be adapted to the requirements of the ANKE experiments.

Although the final decision on the type of the cell still has to be made, it is clear that in either case the cell construction can be completed already in the beginning of 2011.

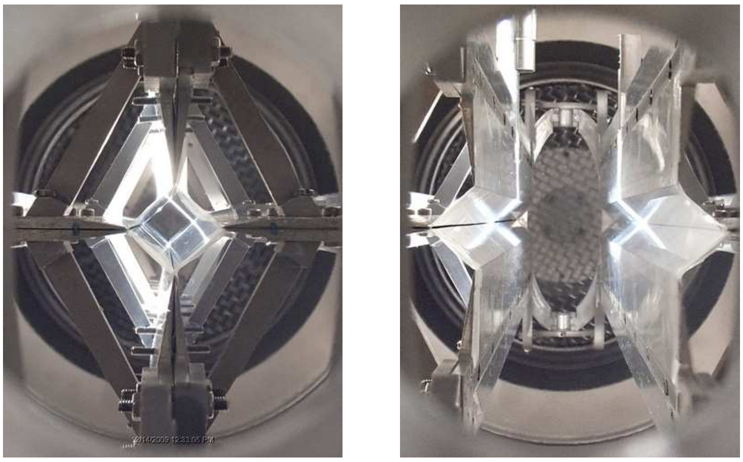


Figure 4: Photograph of the storage cell installed in the target chamber in the positions "closed" (left-hand side) and "open" (right-hand side).

3.4 $np \to pp\pi^-$ identification under PIT conditions

The commissioning studies have demonstrated the feasibility of separating the contributions from interactions occurring on the target gas from the background originating on the storage cell walls. This was shown for the $pp \to \{pp\}_s\pi^0$ reaction using data from the beam time taken in March 2006 when the 831 MeV COSY proton was used with the polarised hydrogen target. The detection scheme of this measurement differs from that proposed for the $np \to \{pp\}_s\pi^-$ process only through the absence of the spectator proton in the final state. This difference is not significant since in the π^- case the momentum of the spectator proton is measured with sufficient precision. Thus, the pp data can be used to get a qualitative understanding of the background contribution from the cell wall. As one can see in Fig. 5, the signal obtained with nitrogen has a shape that is very different from that with the hydrogen gas. Studying the background shape with the help of N_2 gas in the cell is also foreseen in the proposed experiment.

Another possibility to study the cell-wall background in the $np \to \{pp\}_s\pi^-$ process is provided by data collected with a 1.2 GeV deuteron beam incident on the polarised hydrogen target. The cell commissioning experiment of January 2007 can be used for this purpose. The $dp \to \{pp\}_s\pi^- p_{\rm sp}$ reaction can be selected in exactly the same way as in the measurement proposed here: the diproton is recorded in the Positive ANKE detector and, either the spectator proton $p_{\rm sp}$ is registered in the Forward detector, or the pion hits the Negative detector. In Fig. 6(a) the distribution in the mass of the missing particle is shown for the $p_{\rm sp}$ detection and in Fig. 6(b) an

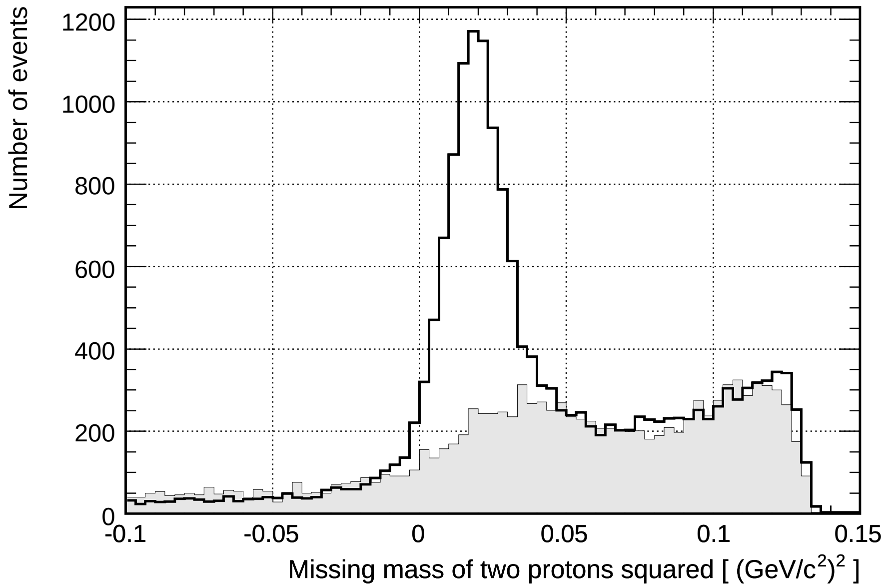


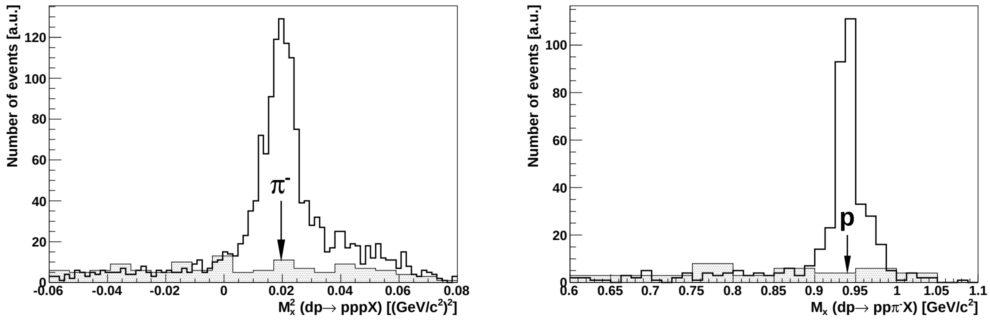
Figure 5: Missing–mass distribution for the reaction $pp \to ppX$ measured with the $(20 \times 20 \times 380\ \mathrm{mm}^3)$ storage cell and the 831 MeV proton beam. The open histogram represents the results obtained with the hydrogen gas while the shaded area shows the 'background' contributions measured with nitrogen in the cell. The latter distributions have been normalised to the hydrogen data to the right of the peaks.

analogous distribution is shown for the case of pion detection. The spectra obtained with hydrogen in the storage cell are compared to those for nitrogen. One can see that in the both cases the hydrogen spectrum demonstrates a clear signal associated with the $dp \to \{pp\}_s\pi^- p_{\rm sp}$ reaction. Although the statistics available here are much lower than for $pp \to \{pp\}_s\pi^0$, and the N_2 distributions do not fit the backgrounds in the hydrogen spectra as nicely, it is obvious that the nitrogen distributions do not mimic the $dp \to \{pp\}_s\pi^- p_{\rm sp}$ signals in the hydrogen target.

3.5 Acceptance and resolution

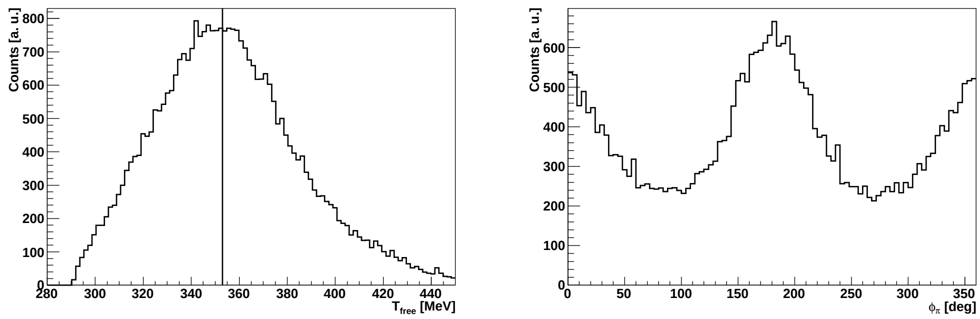
The acceptance of the Forward detector for the spectator proton starts from zero Fermi momentum and includes the whole momentum range of interest $p_{\rm spec} = 0 - 100$ MeV/c in the deuteron rest frame. The available range of effective beam energy in the free np scattering is $T_{\rm free} = 300 - 420$ MeV, as shown in Fig. 7(a). For the count rate estimation below, we limit it to the $T_{\rm free} = 353 \pm 20$ MeV range.

The acceptance of the diproton in the Positive detector as a function of the pion emission angle θ_π is rather flat. The distribution of ϕ_π obtained from a simulation for an unpolarised case is presented in Fig. 7(b). One can see that both $\phi_\pi = 0\ (180)^\circ$ and $\phi_\pi = 90\ (270)^\circ$ regions are accessible and this provides the possibility to extract



(a) $dp \to p_{\rm sp}ppX$ (b) $dp \to pp\pi^- X$

Figure 6: Missing–mass distributions used to identify the $dp \to ppp\pi^-$ reaction at 1.2 GeV. The open histograms represent the results obtained with the hydrogen gas while the shaded areas show the 'background' contributions measured with nitrogen in the cell. The latter distributions have been normalised arbitrarily. The expected positions for the missing particles are indicated.



(a) Effective beam energy of pn interaction (b) Pion polar angle

Figure 7: Simulated distributions of $T_{\rm free}$ and ϕ_π for the $np \to \{pp\}_s\pi^-$ reaction.

$A_{x,x}$ as well as $A_{y,y}$.

To reconstruct the momenta of the three final-state protons in the case of a long target, one has to correct for the spread in the vertex coordinates. This can be achieved if one fits the trajectories of the protons and their arrival times in a single procedure. The parameters of the fit are the three-momenta of the particles and the common longitudinal coordinate of the vertex. As a result, the unbiased values of the momenta can be reconstructed. The resulting accuracy of the vertex coordinate is 5.6 cm. The effective energy is reconstructed with the accuracy of $\sigma(T_{\rm free}) = 1.6$ MeV. The uncertainty in the missing mass M_x of the $pd \to pppX$ process, $\sigma(M_x) = 4$ MeV/c^2, is small enough for selection of the $dp \to \{pp\}_s\pi^-p_{\rm sp}$ reaction. The pion production angle is reconstructed with $\sigma(\theta_\pi) = 5.6^\circ$ and the diproton excitation energy with $\sigma(E_{pp}) < 0.4$ MeV in the $E_{pp} = (0-3)$ MeV range. These uncertainties were estimated from a simulation that included all the experimental smearing factors and the detector resolution. The storage cell in the simulation was considered to be made of 20 μ aluminum and 5 μ carbon.

3.6 Polarimetry

As it was pointed out in section 1.2, the proposed experiment is essentially self-analysing. From Eq. (1.3), it follows that, after subtraction of the terms proportional to A_y in an appropriate asymmetry expression, the only quantity needed to determine the values of $A_{x,x}$ and $A_{y,y}$ is the product of the beam and target polarisations. This product can be obtained by demanding that $A_{y,y} = 1$ for all angles and $A_{x,x} = 1$ in the forward and backward directions. This property of the experiment gives us also a powerful tool to study the systematic uncertainties of the measurement.

Nevertheless, the beam and target polarisation values can be determined independently by the procedure developed and successfully applied earlier at ANKE in experiments with deuteron [9] and proton beams [7]. The polarisation values can be found by simultaneous detection of processes for which the analysing powers are known. For the beam energy of interest, T_n =353 MeV per nucleon, the most suitable reactions for the ANKE conditions are the quasi-free $pp \to d\pi^+$ and $pn \to d\pi^0$ reaction. Both the deuteron and pion can be detected in ANKE in the first case, while in the second case the deuteron is detected in coincidence with the spectator proton. Values of the analysing power are available with high precision from the SAID data base [14].

Due to the absence of left–right symmetry in the ANKE spectrometer, a beam/target asymmetry cannot be measured through the left–right count–rate difference. In order to measure such an asymmetry, data have to be taken with both directions of the beam and target polarisations. To find the target polarisation, one can use the unpolarised COSY beam from the unpolarised source injected every third cycle (using the vector polarised beam with opposite polarisation signs in the first two cycles). Such an approach has been tested and used during the double-polarised measurement of the $\vec{d}\vec{p} \to \{pp\}_s n$ reaction conducted in October 2009 [10]. The direction of the target polarisation is flipped every five seconds and, to obtain the beam polarisation, one has to average over the two states of the target.

4 Count rate and precision estimation

4.1 Expected luminosity

In order to estimate the required beam time for the proposed measurements, we assume a luminosity of $L = 2.6 \times 10^{29}\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$. This includes a beam intensity of $\approx 5 \times 10^9$ stored polarised deuterons, beam revolution frequency $f_{\mathrm{rev}} = 1.3\,\mathrm{MHz}$, and a target density of $d_t = 4 \times 10^{13}\,\mathrm{cm}^{-2}$. Due to the planned use of the openable cell, the target density is increased by factor three compared to the one achieved with the cell of $15 \times 20 \times 390$ mm size used in the previous measurements at ANKE.

4.2 Count rates and precision of $A_{x,x}$ and $|\delta|^2$

A complete simulation of the $dp \to p_{sp}\{pp\}_s\pi^-$ process at ANKE has been performed with the use of the GEANT program package. The spectator proton momentum was sampled according to the Fermi-motion distribution and the off-shell kinematics effect taken into account with the help of the Pluto reaction generator. The fast proton pair was required to hit the ANKE Positive detector and the spectator proton with a kinetic energy below 6 MeV must have been detected in the Forward detector.

The predictions of $d\sigma/d\Omega$, A_y and $A_{x,x}$ obtained in Ref. [4] were used for count–rate estimation. A luminosity of $L = 2.6 \times 10^{29}\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$, a COSY beam polarisation of $P = 60\%$ and the ABS polarisation of 80% were assumed. Use of the unpolarised beam in every third cycle, the 15 minutes of stacking + 45 minutes of measurement cycle structure, and a 65% dead time correction were taken into account.

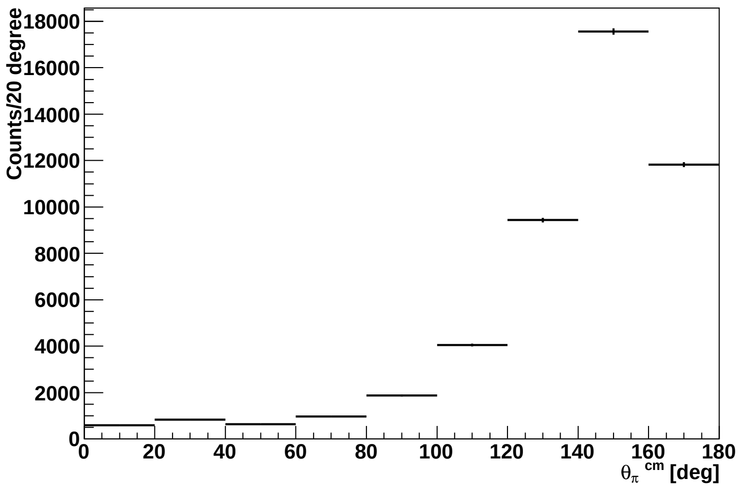


Figure 8: Estimated number of counts for the $pn \to \{pp\}_s\pi^-$ reaction collected after seven weeks at a luminosity $L = 2.6 \times 10^{29}\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$.

The expected number of events recorded after seven weeks of measurement is presented in Fig.8. Since the setup acceptance as function of θ_π is fairly flat, the distribution follows the dependence of the cross section on θ_π. The accuracies of the $A_{x,x}$ and $d\sigma/d\Omega \cdot (1 - A_{x,x})$ "reconstructed" in the simulation are shown in Figs. 9 and 10. One can see that, in spite of the significantly higher statistics at large angles, the accuracy of the $d\sigma/d\Omega \cdot (1 - A_{x,x})$ is the best in the small angle region where $1 - A_{x,x}$ is the largest. According to these results, the factor a in the $d\sigma/d\Omega \cdot (1 - A_{x,x}) = a \cdot \sin^2\theta_\pi$ parameterisation can be measured with a $\sim 10\%$ accuracy.

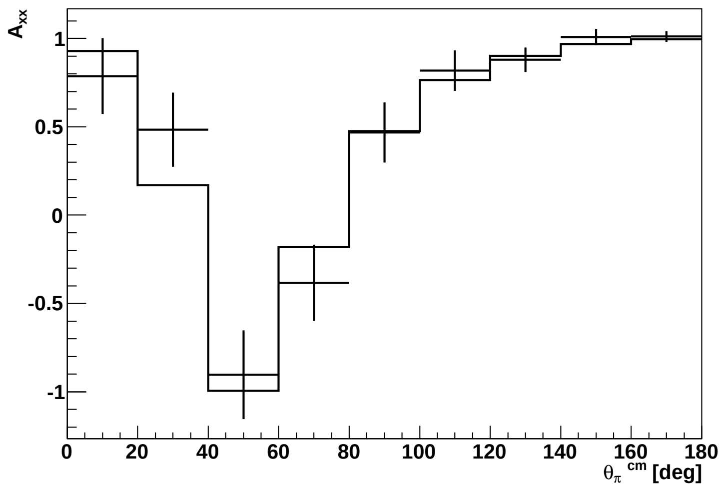


Figure 9: Predicted [4] (line) and "reconstructed" in simulation (error bars) values of $A_{x,x}$ for the $pn \to \{pp\}_s\pi^-$ reaction.

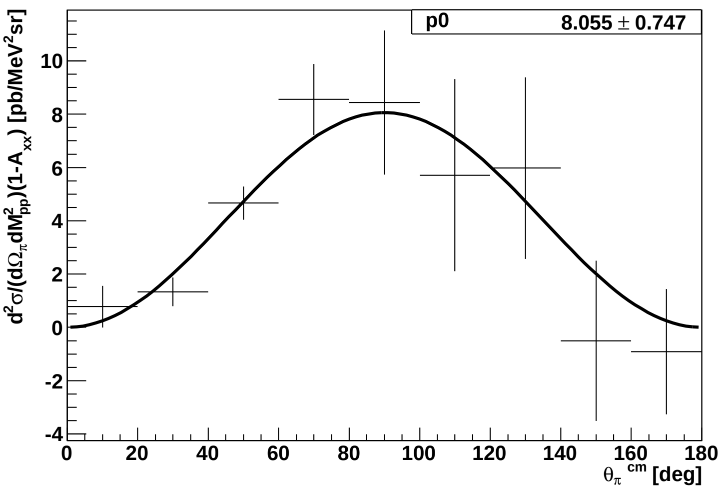


Figure 10: $d\sigma/d\Omega \cdot (1 - A_{x,x})$ for the $pn \to \{pp\}_s\pi^-$ reaction "reconstructed" in simulation. The curve is the fit with the $a \cdot \sin^2\theta_\pi$ dependence.

5 Request

The **proposal requires SEVEN weeks of beam time** for data taking (not including MD) in order to determine the $A_{x,x}$ and $A_{y,y}$ spin correlation coefficients of $\vec{n}\,\vec{p} \to \{pp\}_s\pi^-$ reaction at a deuteron beam energy of $T_d = 2 \times 353 = 706\,\mathrm{MeV}$.

Exchange of the currently installed ANKE cluster target with the Polarised Internal Target (ABS and LSP) is foreseen in 2011.

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