Near-threshold pion production in diproton reactions at ANKE

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Abstract. With the advent of chiral perturbation theory (χPT), the low-energy effective field theory of QCD, accurate calculations have become possible for hadronic reactions. The extension of the approach to pion production in nucleon-nucleon collisions requires new high precision experimental information in the near-threshold region.

Of especial interest are the processes $pp \to \{pp\}_s\pi^0$ and $pn \to \{pp\}_s\pi^-$, with the formation of a ${}^1S_0$ proton pair (diproton) in the final state. The measurements of $d\sigma/d\Omega$, A_y and the spin-correlation coefficients $A_{x,x}$ and $A_{x,z}$ will permit an amplitude analysis that should provide a non-trivial test of the χPT predictions. A combined study of these processes will lead to the isolation of the strength parameter d of the $4N\pi$ contact operator in χPT.

The ANKE spectrometer is particularly well suited for the study of reactions with a final diproton. The use of the polarised COSY beams and the ANKE polarised internal target allows one to conduct single and double polarisation experiments. Preliminary results on the near-threshold measurements at ANKE of A_y in these processes are presented. The future experimental programme, including the double-polarised experiments, is discussed.

1. Introduction

1.1. The diproton programme at ANKE

The two–nucleon systems, being the simplest cases of (un-)bound hadrons, play important roles in the studies of hadronic interactions and the structure of the lightest nuclei. The production of the deuteron, a bound state of the proton and neutron, has been studied extensively, both theoretically and experimentally, in a large number of processes. Of particular interest, though, is the investigation of the diproton, an unbound system of two protons. The selection of a very low excitation energy proton pair, $E_{pp} < 3$ MeV, ensures the dominance of the ${}^1S_0$ state of the diproton, which simplifies significantly the theoretical interpretation. The diproton, denoted below as $\{pp\}_s$, can be considered as a spin-isospin partner of the deuteron, but with different quantum numbers. As a consequence, reactions that lead to the formation of a diproton involve transitions in the NN system that are different from those in the deuteron case. In particular, the role of the Δ isobar is expected to be much suppressed because the S-wave ΔN intermediate state is generally forbidden.

The detection of a proton pair with $E_{pp} < 3$ MeV in an experiment requires excellent excitation energy resolution coupled with the ability to resolve the two spatially close proton trajectories. This explains why there have been so few attempts to study reactions with a diproton in the final state. It should be noted that the ANKE spectrometer [1] provides a resolution of $\sigma(E_{pp}) = 0.2 - 0.6$ MeV for $E_{pp} = 0 - 3$ MeV even for protons with energies in the GeV range.

The diproton programme at ANKE involves several experiments:

– Study of meson–less deuteron break-up $pd \to \{pp\}_s n$ in collinear kinematics:
  - at high momentum transfer [2, 3],
  - at low momentum transfer (charge-exchange reaction) [4, 5].

– Study of meson production in $pN \to \{pp\}_s X$, where X is:
  - a single pion [6],
  - the $(\pi\pi)$ system, used in the investigation of the ABC effect [7],
  - a heavier meson, such as the η and ω.

– Inverse diproton photodisintegration $pp \to \{pp\}_s \gamma$ [8, 9].

Near-threshold single pion production is a key double polarisation experiment in the physics programme at ANKE since the measurement of the cross-section and polarisation observables in the $pp \to \{pp\}_s \pi^0$ and $np \to \{pp\}_s \pi^-$ reactions will provide important tests of chiral perturbation theory [10].

1.2. The ANKE spectrometer at COSY

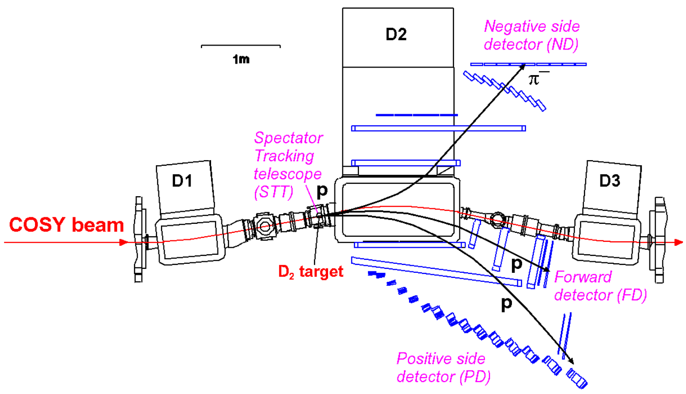

Figure 1. Top view of the ANKE setup at COSY. The positions of the dipole magnets D1, D2, D3, the cluster target spot, the Forward (FD), Positive (PD), Negative (ND) detector systems and the Silicon Tracking Telescope (STT), are shown.

The Cooler Synchrotron COSY at Jülich, Germany provides polarised proton and deuteron beams with momenta in the range 600 – 3700 MeV/c. The ANKE magnetic spectrometer [1], which is located at an internal target position of COSY (Fig. 1), includes several detection systems. Forward and Positive Detectors (FD and PD) register forward–going positively charged ejectiles, while negatively charged particles are measured in the Negative Detector (ND). A Silicon Tracking Telescope (STT), located near the interaction point, is used for the detection of slow charged particles. The FD, PD and ND allow the reconstruction of particle trajectories and momenta, and particle identification via the measurement of the time-of-flight and energy loss in scintillation counters. The STT provides measurements of the trajectory and energy of a particle and particle identification through its energy loss.

Several types of targets are used in experiments at ANKE, including H_2 and D_2 cluster–jets and a polarised internal target (PIT) that is equipped with a storage cell. The ANKE spectrometer is particularly well suited for the detection of the fast forward–going proton pairs with low excitation energy. These are recorded in the FD and PD.

2. Physics case for near–threshold single pion production

The ANKE experimental programme aims to measure the cross sections and spin observables in the $pp \to \{pp\}_s \pi^0$ and $np \to \{pp\}_s\pi^-$ reactions [11, 12]. 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 determination of the value of the parameter d, which represents the important contact term that affects the pion p–wave amplitudes.

The short range physics in chiral effective field theories, which provide a model–independent understanding of 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 $c1$–$c4$ extracted from πN analysis on the basis of chiral perturbation theory are now widely used to parameterise the short range physics in the NN-interaction, few-nucleon systems, single (and multi) pion production in NN collisions *etc.* Analogously, by studying the 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.* in $pd \to pd$), pion photoproduction $\gamma d \to nn\pi^+$ and its inverse $\pi d \to \gamma NN$. Thus, it plays a very important role connecting different low-energy reactions. It therefore needs to be determined with high accuracy.

On the practical side, the $pp \to \{pp\}_s \pi^0$ and $np \to \{pp\}_s\pi^-$ 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, which means that rescattering experiments are not required.

Four types of experiments are possible for both π^0 and π^- production. These are the measurement of the unpolarised differential cross section $d\sigma/d\Omega$, 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 either the pp or pn experiment.

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 $np \to \{pp\}_s\pi^-$ at a beam energy $T_N \approx 353$ MeV. In the future the $A_{x,x}$ for $np \to \{pp\}_s\pi^-$ will also be determined 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 $\ell = 2$. It is shown in [13] that the magnitude of one of the p-wave amplitudes is then 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 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.

2.1. Predictions

The IKP theory group has recently published a study of pion production in nucleon-nucleon collisions with the ${}^1S_0$ selection criterion [14]. Chiral effective field theory was employed to estimate the p-wave amplitudes but only at a later stage will the group 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 $np \to \{pp\}_s\pi^-$ [14], without the inclusion of the d-waves one cannot yet draw 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 [14].

We show in Fig. 2 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. [14]. As shown in [13], to order k^2 the angular dependence of this quantity is of the form $|\delta|^2 \sin^2\theta$, where $|\delta|$ is the magnitude of one of the two p-waves, k is the pion momentum, and θ its emission angle. The maximum height $|\delta|^2$ is a sensitive function of the crucial contact parameter d and estimates have been made over a wide range. The predicted behaviour of the maximum as a function of d shown in Fig. 3 follows a parabola over the interesting range of d. Theoretical prejudice seems to prefer a value in the range from 0 to +3 [14]. 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.

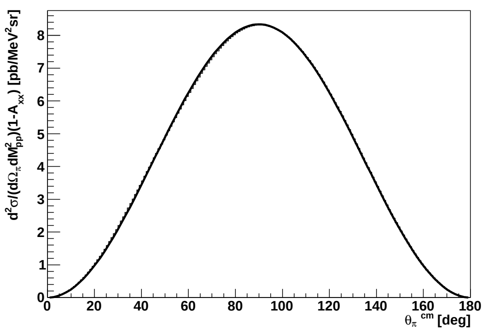

Figure 2. $(1-A_{x,x})d\sigma/d\Omega$ calculated for $d = 3$.

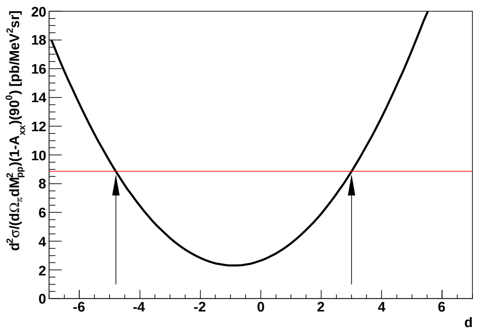

Figure 3. Dependence of $(1-A_{x,x})d\sigma/d\Omega$ at 90° on the d LEC. The value $d = 3$ favoured by the theory is shown by an arrow. The horizontal line corresponds to the measured value at $d = 3$, while another arrow at $d \sim -5$ points to the second solution for this measured value.

3. Measurement of cross section and analysing power

As a first step of the programme, measurements with a polarised proton beam incident on unpolarised hydrogen and deuterium cluster targets were performed in 2009 at a beam energy of $T_p = 353$ MeV [11, 12]. The preliminary results on the vector analysing power are presented in this section.

3.1. 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. For events with two particles hitting different counters of the scintillator hodoscope, the time-of-flight differences from the target Δt_{meas} can be determined. Using the measured particle momenta p_1 and p_2 and assuming that the involved particles are protons, Δt_{meas} can be compared to a calculated $\Delta t(\vec{p_1}, \vec{p_2})$. In Fig. 4, where Δt_{meas} is plotted against $\Delta t(\vec{p_1}, \vec{p_2})$, the proton pairs populate the line at $\Delta t_{meas} = \Delta t(\vec{p_1}, \vec{p_2})$. After the selection of the proton pairs, the $pp \to \{pp\}_s\pi^0$ events were identified by the missing–mass criterion. Events from this process form a peak at $M_x^2 = M_{\pi^0}^2$ in the missing–mass spectrum in Fig. 5.

The beam polarisation and luminosity were determined by detecting simultaneously the $\vec{p}p \to d\pi^+$ process, for which the cross section and analysing power are known with high precision

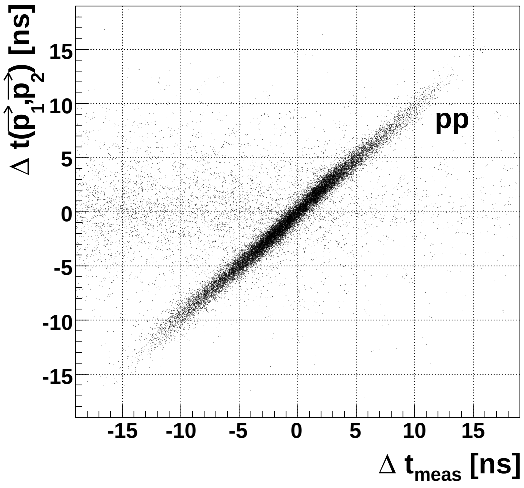

Figure 4. Distribution of events with two particles in FD, showing the measured Δt_{meas} vs the calculated $\Delta t(\vec{p_1},\vec{p_2})$ time differences.

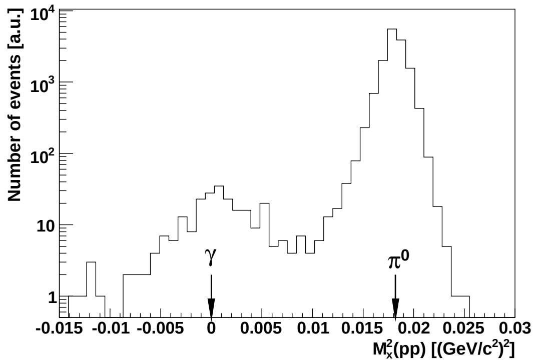

Figure 5. Missing-mass squared distribution in the process $pp \to ppX$ for the identified proton pairs.

at this energy. Excellent conditions of the polarised proton beam (polarisation $P \sim 65\%$) and the hydrogen cluster target allowed us to achieve the desired statistical precision.

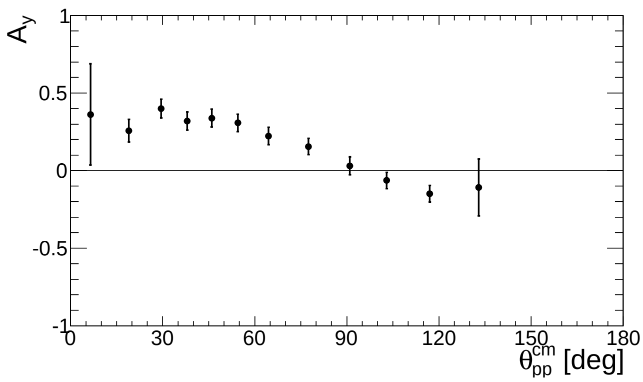

Figure 6. Analysing power A_y of the $pp \to \{pp\}_s\pi^0$ reaction at $T_p = 353$ MeV.

Figure 6 shows the results obtained for the $\vec{p}p \to \{pp\}_s\pi^0$ reaction. If one considers only pion waves with $l \leq 2$, a non-zero value of the analysing power in this process must arise from the interference between the s and d waves. The strong signal observed here shows immediately importance of this interference.

3.2. The $\vec{p}n \to \{pp\}_s\pi^-$ process

The ANKE deuterium cluster target was used in the experiment and small energies of the spectator proton, $T_{\rm spec} < 6$ MeV, were selected. This measurement was technically more involved due to the additional detector systems used to record the extra final state particles and the consequent reduction in the setup acceptance. The diproton was recorded in either the Forward or Positive side ANKE detectors. In addition, either the π^- was recorded at large cm angles

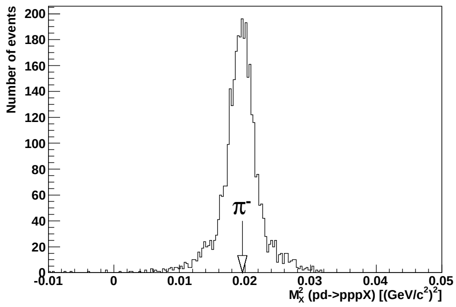

Figure 7. Missing-mass squared distribution in the process $pd \to \{pp\}_s X + p_{spec}$.

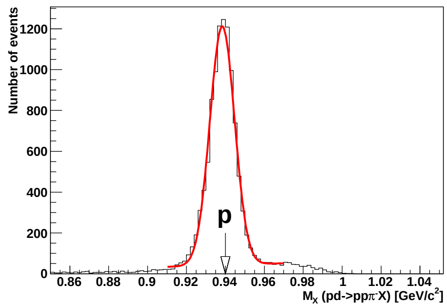

Figure 8. Missing-mass distribution in the process $pd \to \{pp\}_s X + \pi^-$.

in the Negative side Detector, or the spectator proton was measured in the Silicon Tracking Telescope. The particle identification was done on the basis of the time-of-flight information as described for the $\vec{p}p \to \{pp\}_s \pi^0$ experiment. The spectator proton detected in STT was identified through its energy loss. The kinematical identification of the $pd \to \{pp\}_s + p_{spec} + \pi^-$ is demonstrated in Fig. 7 for the case of the spectator proton detection, and in Fig. 8 for detection of π^-.

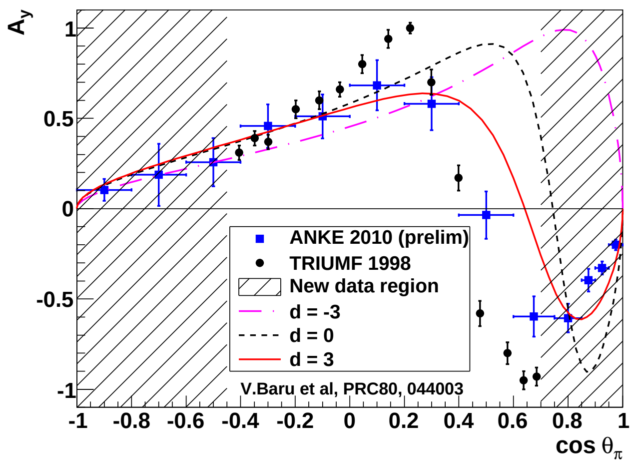

Figure 9. A_y in the $\vec{p}n \to \{pp\}_s \pi^-$ reaction at T_n=353 MeV (blue squares). Also shown are the results of calculation [14] for $d = 3$ (red solid line), $d = 0$ (black dashed line), and $d = -3$ (magenta dot-dashed line). The data from TRIUMF [15] are shown with black diamonds.

The results for the $\vec{p}n \to \{pp\}_s \pi^-$ process are presented in Fig. 9. The ANKE data are shown together with the results from TRIUMF [15] and PSI [16] and compared to the prediction of the IKP theory group [14]. The value of LEC $d = 3$ is favored, though it must be stressed that the pion d–waves have not yet been included here. The main advantage of the ANKE measurement is the extended angular range compared to the previously existing data. The data analysis for the cross section is currently in progress.

4. Future measurement of $A_{x,x}$ and $A_{y,y}$ in $\vec{n}\vec{p} \to \{pp\}_s \pi^-$

We plan to measure the spin correlation coefficients $A_{x,x}$ and $A_{y,y}$ of the quasi–free $\vec{n}\,\vec{p} \to \{pp\}_s \pi^-$ by using the vector polarised deuteron COSY beam and the polarised hydrogen target. It is suggested that the ANKE Polarised Internal Target (PIT) equipped with a long openable storage cell will be used in this experiment.

The 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 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 in 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.

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). It has been commissioned with polarised hydrogen and the following results obtained [17]:

- 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 $\vec{d}\vec{p}$–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 was imitated through the use of N_2 gas in the cell.
- Using the missing–mass technique for the measured single– and double–track events in ANKE, it has been shown that a very clean identification of the $\vec{d}\vec{p} \rightarrow d p_{\mathrm{sp}} \pi^0$ reaction is possible. This 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 using Lamb–shift Polarimeter (LSP) measurements. The goal of the measurement was to determine the target polarisation (Q_y) from the quasi–free $n\vec{p} \rightarrow d\pi^0$ reaction. The value of average target polarisation achieved 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.

To increase the luminosity, we propose to use an openable storage cell in this experiment. To maximise the areal density, 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. The lateral dimensions have therefore to be minimised during the measurements. This requirement can be reached with a cell that is widened during the injection of the beam into the storage ring and closed after beam manipulation (injection and phase space cooling). The use of an openable cell will increase the target areal density by a factor of two.

As shown in Ref. [13], the proposed experiment is essentially self-analysing. The values of $A_{x,x}$ and $A_{y,y}$ depend on the the product of the beam and target polarisations. However, this product can be controlled 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 through the 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 quasi-free $pp \rightarrow d\pi^+$ and $pn \rightarrow d\pi^0$.

The accuracies expected for $A_{x,x}$ and $(1-A_{x,x})\cdot d\sigma/d\Omega$ in the experiment can be judged from the simulated data shown in Figs. 10 and 11. In spite of the significantly higher statistics at large angles, the accuracy of $(1-A_{x,x})\cdot d\sigma/d\Omega$ is best in the small angle region where $(1-A_{x,x})$ is largest. According to these results, the factor a in the $(1-A_{x,x})\cdot d\sigma/d\Omega = a\cdot\sin^2\theta_\pi$ expression can be measured with a $\sim$ 10% accuracy after seven weeks of data taking at a luminosity $L = 2.6\times10^{29}\,\mathrm{s}^{-1}\mathrm{cm}^{-2}$. The precision to be obtained for the LEC d depends of the value of that constant. In the case of $d=3$, as favoured by theory, the expected accuracy is $\sigma_d = 0.26$, while in the worst case of $d=0$, $\sigma_d = 0.5$. In either situation, the measurement will greatly improve the current knowledge the d value.

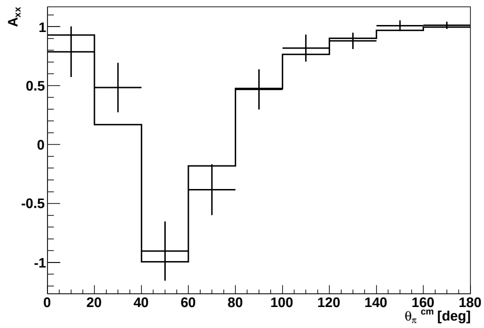

Figure 10. Predicted values of $A_{x,x}$ [14] (line) and simulated data (error bars) for the $pn\to\{pp\}_s\pi^-$ reaction.

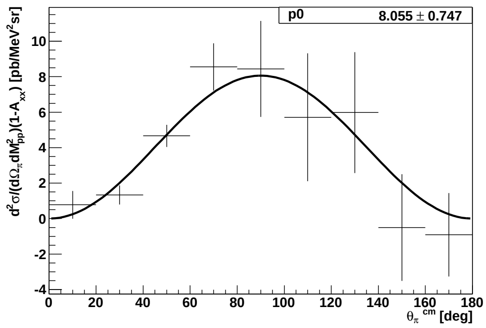

Figure 11. Simulated data for $(1-A_{x,x})\cdot d\sigma/d\Omega$ in the $pn\to\{pp\}_s\pi^-$ reaction. The curve is a fit with a $a\cdot\sin^2\theta_\pi$ dependence.

Acknowledgments
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