PROCEEDINGS OF SCIENCE

Pion production in diproton reactions with polarized beams at ANKE-COSY

S. Dymov for the ANKE collaboration[*†]
Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, 141980 Dubna, Russia
Physikalisches Institut II, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany
E-mail: s.dymov@fz-juelich.de

An experimental program to study near threshold pion production in the reactions $pp \to \{pp\}_s\pi^0$ and $pn \to \{pp\}_s\pi^-$, is undertaken at ANKE-COSY. The selection of the final proton pair $\{pp\}_s$ in the $^1S_0$ state, realized by cutting on the pair excitation energy $E_{pp} < 3$ MeV, simplifies the theoretical analysis of the processes. The combined study of these reactions is motivated by the extension of Chiral Perturbation Theory (χPT) to pion production in NN collisions. The measurement of $d\sigma/d\Omega$, A_y^p and the spin-correlation coefficients A_{xx} and $A_{y,y}$ will provide a non-trivial test of the χPT predictions, and lead to the isolation of the strength parameter d of the four-nucleon-pion contact interaction in χPT.

Use of the polarized COSY beam and the ANKE polarized internal target allows one to conduct single and double polarization experiments. The results of the measurement of $d\sigma/d\Omega$, A_y^p in the two processes, carried out with the polarized proton beam, is reported. The first analysis of the recent double polarized measurement of A_{xx} and $A_{y,y}$ in $pn \to \{pp\}_s\pi^-$, conducted with a polarized deuteron beam and a polarized hydrogen target, is also presented.

8th International Conference on Nuclear Physics at Storage Rings-Stori11,
October 9-14, 2011
Laboratori Nazionali di Frascati dell'INFN, Italy

*Speaker.
†A footnote may follow.

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.

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. 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.

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 [2, 3]. 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 [4] 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.

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 unpolarized differential cross section $d\sigma/d\Omega$, the beam or target analyzing 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.

At low energies it is reasonable to assume that data can be analysed by truncating the partial wave expansion at $\ell = 2$. It is shown in [5] 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 cross section and analyzing 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.

3. Measurement of cross section and analyzing power

As a first step of the programme, measurements with a polarized proton beam incident on unpolarized hydrogen and deuterium cluster targets were performed in 2009 at a beam energy of $T_p = 353$ MeV [2, 3].

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. 1, where Δt_{meas} is

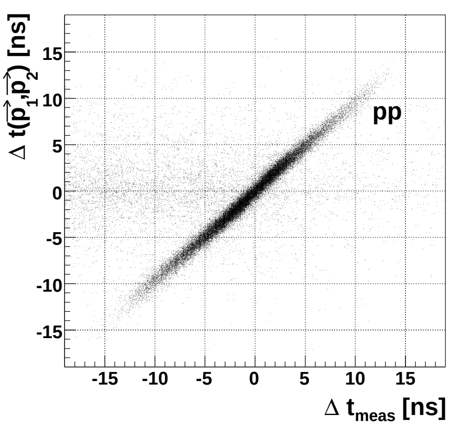

Figure 1: Distribution of events with two particles in FD, showing the measured Δt_{meas} vs the calculated $\Delta t(\vec{p}_1, \vec{p}_2)$ time differences.

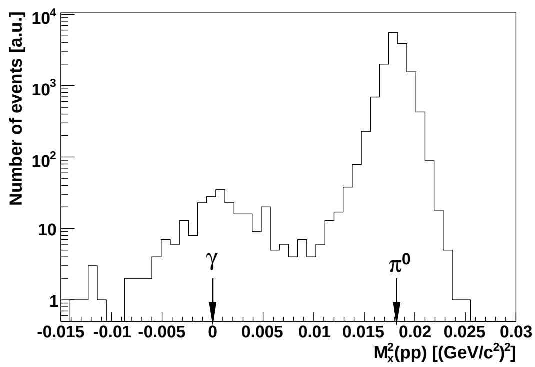

Figure 2: Missing-mass squared distribution in the process $pp \to ppX$ for the identified proton pairs.

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. 2.

The beam polarization and luminosity were determined by detecting simultaneously the $\vec{p}p \to d\pi^+$ and $\vec{p}p \to pp$ processes, for which the cross section and analyzing power are known with high precision at this energy. Excellent conditions of the polarized proton beam (polarization $P = 68 \pm 3\%$) and the hydrogen cluster target allowed us to achieve the desired statistical precision.

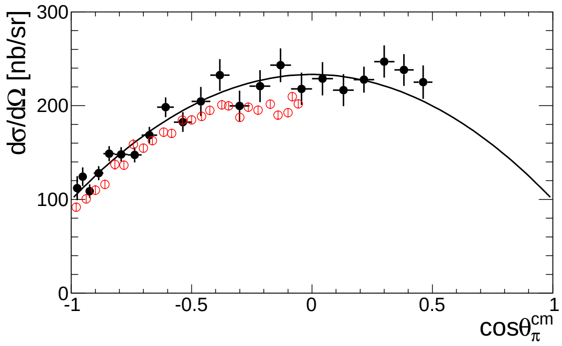

Figure 3: Differential cross section for the $pp \to \{pp\}_s\pi^0$ reaction at 353 MeV as a function of the cosine of the pion c.m. angle. The solid (black) circles represent the ANKE measurements. Open (red) circles are CELSIUS data obtained at 360 MeV [6]. The curve is a linear fit in $\cos^2\theta_\pi$ to our data.

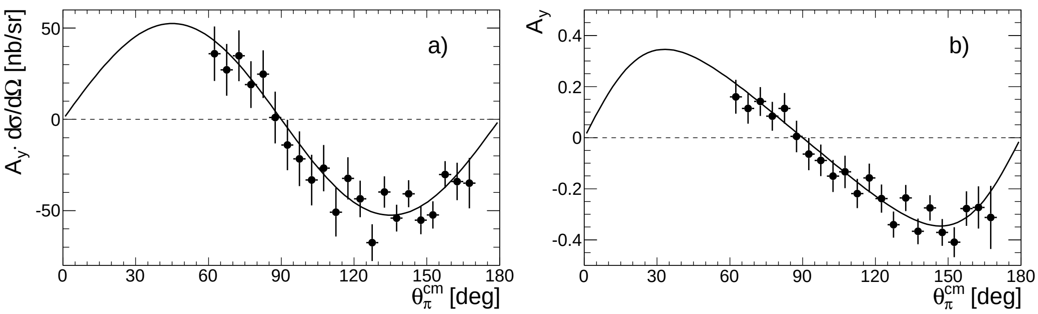

Figure 4: (a) The product of the measured analyzing power and differential cross section for the $pp \to \{pp\}_s\pi^0$ reaction. The curve represents the best fit of Eq. (3.2) with the terms up to b_2. (b) Measured values of A_y for the $pp \to \{pp\}_s\pi^0$ reaction. The line represents the quotient of the best fit in panel-a and the fit to the cross section.

For a spin-singlet diproton, the spin structure of the $pp \to \{pp\}_s\pi^0$ or $np \to \{pp\}_s\pi^-$ reaction is that of $\frac{1}{2}^+\frac{1}{2}^+ \to 0^+0^-$. Parity and angular momentum conservation require that the initial nucleon-nucleon pair to have spin $S = 1$. The pion orbital angular momentum ℓ and the initial nucleon-nucleon isospin I are then linked by $\ell + I =$ odd so that, for the $pp \to \{pp\}_s\pi^0$ reaction, only even pion partial waves are allowed. As a consequence, the unpolarized cross section for π^0 production, and this times the proton analyzing power A_y, must be of the form

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\left(a_0 + a_2\cos^2\theta_\pi + a_4\cos^4\theta_\pi + \cdots\right), \tag{3.1}$$

$$A_y\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\sin\theta_\pi\cos\theta_\pi\left(b_2 + b_4\cos^2\theta_\pi + \cdots\right), \tag{3.2}$$

where θ_π is the pion c.m. production angle with respect to the direction of the polarized proton beam. Here p is the incident c.m. momentum and k that of the produced pion which, at 353 MeV, have values $p = 407$ MeV/c and $k \approx 94$ MeV/c.

Figures 3 and 4 show 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 analyzing 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

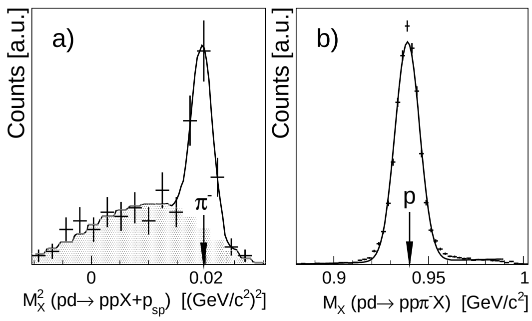

Figure 5: Kinematic identification of the $pd \to p_{\rm sp}\{pp\}_s\pi^-$ reaction. a) Missing-mass squared when the spectator proton is detected, showing the experimental spectrum (with error bars), the background (shaded area), and the sum of this plus a Gaussian for the π^- peak (solid curve). b) Missing-mass distribution when the π^- is detected. The curve shows the fit to the experimental data with the sum of a Gaussian centered on the mass of the proton and a linear background.

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 in the Negative side Detector, or the spectator proton was measured in the Silicon Tracking Telescope (STT). 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. 5. Most of the angular range was covered by the coincidence with the spectator proton, when no time information was available from STT. The main source of background in this case were accidental coincidences. The background shown by the shaded area in Fig. 5 a) was modeled with the use of experimental data. The polarization of the proton beam and the luminosity were both estimated from quasi-free $\vec{p}n \to d\pi^0$ data that were taken in parallel.

The unpolarized cross section for π^- production, and this times the proton analyzing power

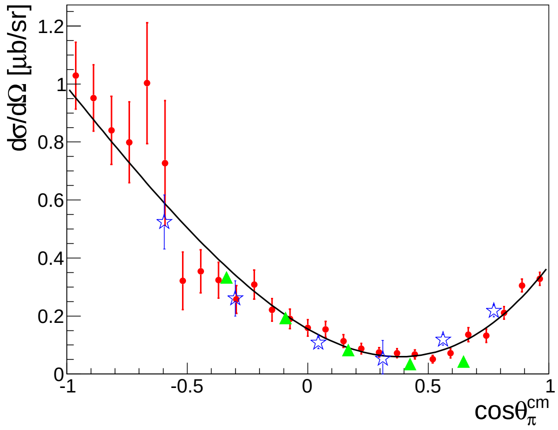

Figure 6: Unpolarized differential cross section for the $pn \to \{pp\}_s\pi^-$ reaction at ≈ 353 MeV. The ANKE data are shown by red circles and the TRIUMF results [7] by green triangles. The arbitrarily scaled TRIUMF cross sections extracted from $\pi^{-3}\mathrm{He} \to pnp_{\mathrm{sp}}$ data [8] are also included (blue stars). The curve is a cubic fit to the ANKE data.

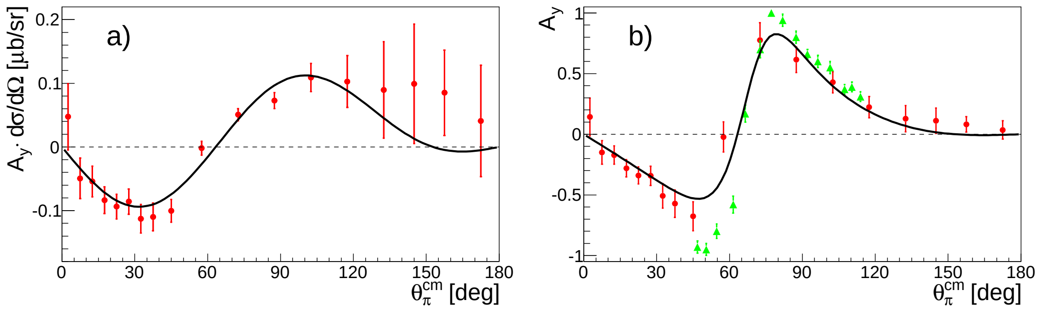

Figure 7: (a) The product of the measured analyzing power and differential cross section for the $pn \to \{pp\}_s\pi^-$ reaction at 353 MeV. The curve represents the best fit of Eq. (3.4) with b_1, b_2, and b_3 terms. (b) Measured values of A_y for the $pn \to \{pp\}_s\pi^-$ reaction showing both the ANKE (circles) and TRIUMF data [9] (triangles). The line represent the quotient of the fit in panel-a and that to the cross section.

A_y, must be of the form

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\sum_{n=0} a_n \cos^n\theta_\pi, \tag{3.3}$$

$$A_y\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\sin\theta_\pi \sum_{n=0} b_{n+1}\cos^n\theta_\pi, \tag{3.4}$$

where θ_π is the pion c.m. production angle, p is the incident c.m. momentum and k that of the produced pion.

Whereas the TRIUMF results only cover the central region of pion angles [7], the current data extend over the whole angular domain (Fig. 6). The two data sets are consistent in the backward hemisphere but the TRIUMF. measurements show no indication of the rise at forward angles that is seen at ANKE. Some confirmation of the ANKE angular shape is offered by pion absorption data, $\pi^{-3}\mathrm{He} \to pnp_{\mathrm{sp}}$, where the unobserved slow proton is assumed to be a spectator [8]. In this case the reaction can be interpreted as being $\pi^-\{pp\}_s \to pn$, though the internal structure of the diproton is very different to that in the production data. The forward/backward peaking is in complete contrast to the results found for π^0 production [6] and is an indication of the dominance of the $I = 0$ p-wave amplitudes in this reaction.

The results for the analyzing power of the $pn \to \{pp\}_s\pi^-$ reaction are displayed in Fig. 7, with $A_y(d\sigma/d\Omega)$ being shown in panel a and A_y in panel b. The agreement with the TRIUMF A_y data [9] is reasonable and both show the strong and rather asymmetric fluctuation in the central region of angles.

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

Measurement of 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 polarized deuteron COSY beam and the polarized hydrogen target was done at ANKE in 2011. The ANKE Polarized Internal Target (PIT) [10] equipped with a long storage cell was used in this experiment.

The hydrogen polarized target has been commissioned at ANKE and a polarization of $\sim 80\%$ was achieved in the experimental conditions. The measurement in the dp kinematics mode is also 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 polarization experiment.

The three final protons were detected in the Positive side and Forward detectors of ANKE, and the arrival time was measured for each of them. The main source of background were interactions of the beam particles with the aluminum storage cell walls. In order to obtain the shape of the background in the missing mass spectra, a dedicated measurement was done with the N_2 gas in the storage cell. In Fig. 8 an example of kinematical identification of the $dp \to \{pp\}_s\pi^- + p_{sp}$ is shown.

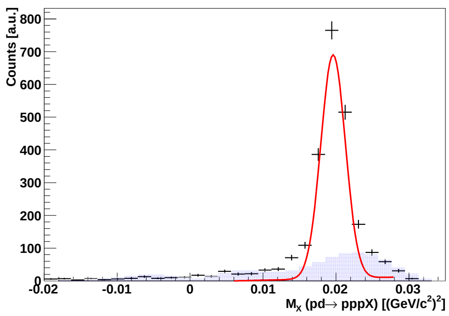

Figure 8: Missing mass spectra for the $dp \to \{pp\}_s\pi^- + p_{sp}$ process. The hydrogen histogram is shown with error bars, the shaded area is the N_2 background and the Gaussian curve is the background free signal.

As shown in Ref. [5], the proposed experiment is essentially self-analyzing. The values of $A_{x,x}$ and $A_{y,y}$ depend on the the product of the beam and target polarizations. 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 polarization values can be determined independently through the simultaneous detection of processes for which the analyzing 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 $pn \to d\pi^0$. In Fig. 9 the experimental asymmetry in this process is shown for the case of the target polarization determination.

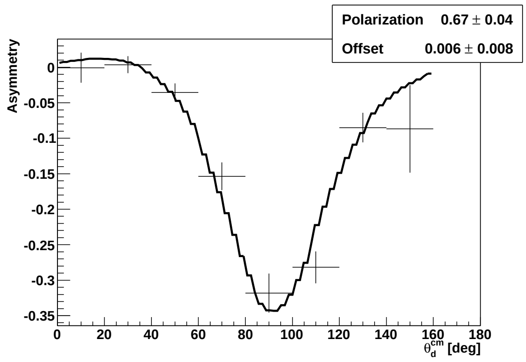

Figure 9: Experimental asymmetry in $pn \to d\pi^0$ process compared with the vector analyzing power of $pp \to d\pi^+$ reaction at 353 MeV, scaled with the value of polarization.

The results of the $A_{x,x}$ measurement are expected to become available in 2012. They will make the amplitude analysis more robust. These will then give the information necessary for chiral perturbation theory to provide quantitative links to other non-mesonic reactions.

This work has been partially supported by the COSY-FFE programme, and by the DFG (436 RUS 113/965/0-1) and GNSF (ST09-1024-4-200) grants.

References

[1] Barsov S *et al* 2001 *Nucl. Instrum. Methods Phys. Res.* A **462** 364

[2] Dymov S 2008 COSY proposal #192,
available from `www.fz-juelich.de/ikp/anke/en/proposals.shtml`.

[3] Kulikov A 2007 COSY proposal #158,
available from `www.fz-juelich.de/ikp/anke/en/proposals.shtml`.

[4] Hanhart C 2004 *Phys. Rep.* **397** 155

[5] Dymov S 2010 COSY proposal #205,
available from `www.fz-juelich.de/ikp/anke/en/proposals.shtml`.

[6] R. Bilger *et al* 2001 *Nucl. Phys.* A **693** 633

[7] F. Duncan *et al* 1998 *Phys. Rev. Lett.* **80** 4390

[8] H. Hahn *et al* 1996 *Phys. Rev.* C **53** 1074

[9] Hahn H *et al* 1999 *Phys. Rev. Lett.* **82** 2258

[10] Engels R *et al* 2009 *AIP Conf. Proc.* **1149** 890