Studies of Di-proton production at ANKE

Sergey Dymov for the ANKE collaboration

Physikalisches Institut II, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany
Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, 141980 Dubna, Russia

Abstract. The study of NN-interactions with production of $^1S_0$ proton pairs (diprotons) provides a new approach to hadron interactions at intermediate energies. The use of the polarised COSY beams and the ANKE polarised internal target allows one to conduct single and double polarization experiments. A number of processes including $pd \to \{pp\}_s n$, production of one and two pions in pN collisions, and the $pp \to \{pp\}_s \gamma$ process, have been investigated.

Information on the near-threshold single pion production with formation of a diproton in the processes $pp \to \{pp\}_s \pi^0$ and $pn \to \{pp\}_s \pi^-$ is urgently needed for further development of chiral perturbation theory. 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 four-nucleon-pion contact interaction in χPT. Preliminary ANKE results on $d\sigma/d\Omega$ and A_y in these processes are presented, and the future experimental programme is discussed.

Keywords: Pion production; nucleon-nucleon collisions; chiral perturbation theory; di-proton reactions
PACS: 25.40.Qa, 13.60.Le

REACTIONS WITH DIPROTON FINAL STATE AT ANKE

A two-nucleon system consisting of protons with small excitation energy in the pair (a diproton) is one of the simplest hadronic systems. Selection of low excitation energy greatly enhances the $^1S_0$ state of diproton which simplifies significantly the theoretical analysis. Study of diproton production is especially instructive due to the comparison with processes where a deuteron is produced in the same kinematics.

The ANKE spectrometer [1] is particularly well suited for the study of reactions with a final diproton. The excellent resolution in the excitation energy of the proton pair, $\sigma_{E_{pp}} < 0.5$ MeV, allows one to select the range of low $E_{pp} < 3$ MeV. This ensures the dominance of the $^1S_0$ state of the final proton pair.

The diproton programme at ANKE involves several experiments: study of mesonless deuteron break-up $pd \to \{pp\}_s n$ [2-5], study of one and two pion production in pN collisions [6, 7], and of inverse diproton photodisintegration $pp \to \{pp\}_s \gamma$ [8]. Investigation of single pion production and the charge-exchange reaction are the key double polarization experiments in the future physics programme at ANKE.

NEAR-THRESHOLD SINGLE PION PRODUCTION

With the advent of chiral perturbation theory (χPT), the low-energy effective field theory of QCD, accurate predictions have become possible for hadronic reactions. The approach has been also extended to describe pion production in nucleon-nucleon collisions [9, 10]. This process is of special importance because of several reasons:

- being the first inelastic channel of NN interaction it contains information about NN inelasticity that is needed to extend NN models above pion production threshold;
- it provides nontrivial tests of χPT in the regime with large momentum transfer [11];
- it allows one to quantify the pattern of charge symmetry breaking by studying the forward-backward asymmetry of the differential cross section in $pn \to d\pi^0$ [12];
- the pion production mechanism in $NN \to NN\pi$ near threshold is closely connected to the physics behind the other low-energy hadronic reactions as demanded by chiral symmetry.

Let us focus on the last issue in more detail. The general idea of chiral effective field theory is based on clean separation of hadronic scales around the chiral limit. According to the scheme, all long-ranged operators related to the small (dynamical) scale, such as one-pion exchange, pion loops etc., are explicitly included in the evaluation of the transition amplitude whereas all short-ranged mechanisms are parametrised by local contact operators. Specifically, the short range physics of p-wave pion production in $NN \to NN\pi$ (when the pion is produced in p-wave with respect to the beam) is absorbed in the local 4Nπ contact term the strength of which – the low energy constant (LEC) d – is unknown and may be extracted from the experimental data as will be discussed below. This LEC is very important in the few body sector since it also contributes to the three-nucleon force, to electroweak processes such as $pp \to de^+\nu$, to triton β decay and muon absorption on deuterium $\mu^- d \to nn\nu_\mu$ as well as to the reactions involving photons $\pi d \to \gamma NN$ and $\gamma d \to nn\pi^+$. Thus, it is of high importance to identify what is needed to allow for a reliable extraction of this LEC from $NN \to NN\pi$. Since the LEC is connected to the p-wave pion while the nucleons are still in S-waves the efforts should be focused on measuring the observables that would allow one to extract the corresponding p-wave amplitudes from data.

Of especial interest are thus 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 $A_{x,z}$ for both reactions will permit an amplitude analysis that is necessary to single out the relevant p-wave amplitudes from the rest.

As a first step in the programme, measurements with a polarised proton beam incident on unpolarised hydrogen and deuterium cluster targets were performed at ANKE in 2009 at a beam energy of $T_p = 353$ MeV. Figure 1 shows the results obtained for the $\vec{p}p \to \{pp\}_s\pi^0$ reaction. Since A_y must be antisymmetric about 90°, the acceptance is effectively complete. 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 the importance of this interference.

The results for the $\vec{p}n \to \{pp\}_s\pi^-$ reaction are presented in Figs. 2 and 3. The ANKE data are shown together with the results from TRIUMF [13] and are compared to the prediction of the IKP theory group [14]. The value of LEC $d = 3$ is favoured, though it must be stressed that the pion d-waves have not yet been included in the calculations.

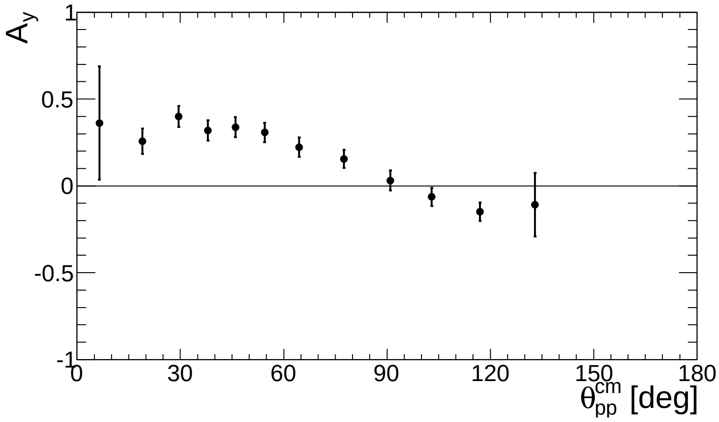

FIGURE 1. Analysing power A_y of the $pp \to \{pp\}_s\pi^0$ reaction at $T_p = 353$ MeV.

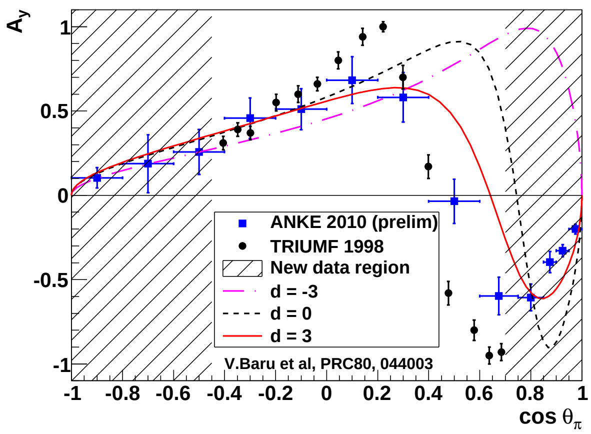

FIGURE 2. A_y in the $\vec{p}n \to \{pp\}_s\pi^-$ reaction at T_n=353 MeV (blue squares). Also shown are the results of χPT calculations for $d = 3$ (red solid line), $d = 0$ (black dashed line), and $d = -3$ (magenta dot-dashed line). The data from TRIUMF are shown as black circles.

The results were obtained with a 40 MeV wide range of effective beam energy in the free pn-scattering, *i.e.*, $T_{\text{free}} = 353 \pm 20$ MeV. The $E_{pp} < 3$ MeV cut was imposed on the data but, to facilitate the comparison with previous results, the cross section has been recalculated for the $E_{pp} < 1.5$ MeV cut used at TRIUMF. This was done using the Migdal-Watson approximation for the final state interaction in the $^1S_0$ proton pair. The main advantage of the ANKE measurement is the extended angular range compared to the pre-existing data.

The transitions involving the $4N\pi$ contact interaction correspond to p-wave pion production in the $np \to \{pp\}_s\pi^-$ reaction. The initial nucleons in this case appear in the partial waves that are coupled: $^3S_1 \to {}^1S_0p$ and $^3D_1 \to {}^1S_0p$. Due to the coupled channel effect the contact term contributes to both partial waves which may provide a richer dependence of the observables on the LEC d. Note, that a linear combination of these p-wave amplitudes may be fixed by only one measurement of $(1 - A_{x,x})d\sigma/d\Omega$ for $np \to \{pp\}_s\pi^-$ under the assumption that the interference of pion p- and d-waves is

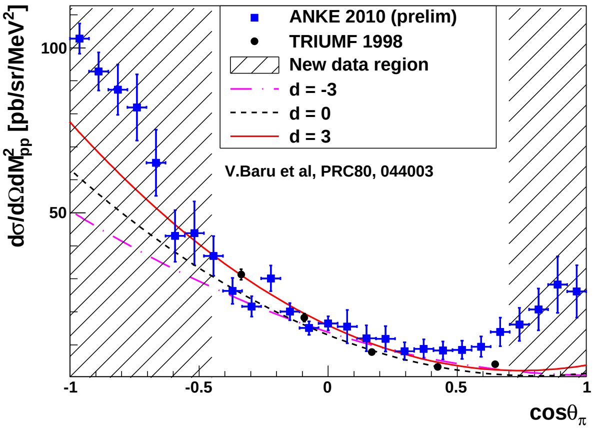

FIGURE 3. ANKE Preliminary results for the cross section of the $\vec{p}n \to \{pp\}_s\pi^-$ reaction at T_n=353 MeV in the $E_{pp} < 1.5$ MeV range. The conventions are the same as those used in the caption to Fig. 2.

small. This linear combination could be compared directly to the χPT calculation. Thus, the double polarisation experiment for the measurement of $A_{x,x}$ and $A_{y,y}$, scheduled for 2011, will greatly improve our knowledge of the LEC d. This experiment will provide the most systematics-free way to fix the value of d.

At the same time, the magnitudes of the p-wave amplitudes individually and their relative phase should be deduced from a combined analysis of these results with our cross section and analysing power data for $pp \to \{pp\}_s\pi^0$ and $np \to \{pp\}_s\pi^-$, which have already been taken. Two determinations of the LEC d will therefore be possible.

ACKNOWLEDGMENTS

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

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