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Recent results from the NN-interaction studies with polarized beams and targets at ANKE-COSY

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Abstract. Adding to the nucleon-nucleon scattering database is one of the major priorities of the ANKE collaboration. Such data are necessary ingredients, not only for the understanding of nuclear forces, but also for the description of meson production and other nuclear reactions at intermediate energies.

By measuring the cross section, deuteron analysing powers, and spin-correlation parameters in the $dp \to \{pp\}_s n$ reaction, where $\{pp\}_s$ represents the ${}^1S_0$ state, information has been obtained on small-angle neutron-proton spin-flip charge-exchange amplitudes.

The measurements of pp elastic scattering by the COSY-EDDA have had a major impact on the partial wave analysis of this reaction above 1 GeV. However, these experiments only extended over the central region of c.m. angles, $30^0 < \theta_{\rm cm} < 150^0$, that has left major ambiguities in the phase shift analysis by the SAID group. In contrast, the small angle region is accessible at ANKE-COSY, that allowed measurement of the differential cross section and the analysing power at $5^0 < \theta_{\rm cm} < 30^0$ in the $0.8 - 2.8$ GeV energy range.

The data on the pn elastic scattering are much more scarce than those of pp, especially in the region above 1.15 GeV. The study of the $dp \to \{pp\}_s n$ reaction provides the information about the pn elastic scattering at large angles. The small angle scattering was studied with the polarized proton COSY beam and an unpolarised deuterium gas target. The detection the spectator proton in the ANKE vertex silicon detector allowed to use the deuterium target as an effective neutron one. The analysing powers of the process were obtained at six beam energies from 0.8 to 2.4 GeV.

1. Introduction

The nucleon-nucleon interaction is fundamental to the whole of nuclear physics and hence to the composition of matter as we know it. Apart from its intrinsic importance, it is also a necessary ingredient in the description of meson production and other processes. The meticulous investigation of the nucleon-nucleon interaction must be a communal activity across laboratories, with no single facility providing the final breakthrough.

The complete description of the NN interaction requires data as input to phase-shift analyses (PSA), from which the scattering amplitudes can be reconstructed. The PSA generally requires experiments with both beam and target particles polarised in the initial state, as well as polarisation determination of the final particles [1].

The existing database of elastic pp and pn differential cross sections is shown in the abundance plots of Fig. 1 (taken from Ref. [2]). Note that in the pp case the cross section is symmetric about 90° and so few points are plotted in the backward hemisphere. There is a heavy concentration of pp points for $40^\circ < \theta_{\rm cm} < 90^\circ$, corresponding to the EDDA measurements [3], but there are very few at smaller angles, though this will be changed when the ANKE data are finalised [4]. On the other hand, it is seen that the pn database is even more sparse above 1.15 GeV (the maximum energy of the SATURNE "monochromatic" neutron beam).

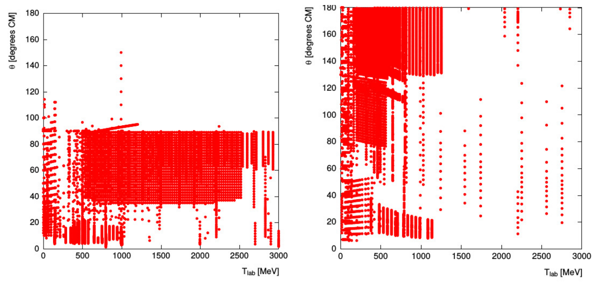

Figure 1. Abundance plots for elastic differential cross section experiments for pp (Left) and np (Right), taken from the SAID compilation [2].

The situation is broadly similar in the A_y measurements summarised in Fig. 2. For *pp* elastic scattering this parameter is antisymmetric around 90° but is seen from the figure that there have been relatively few measurements for $\theta_{\rm cm} < 30^\circ$ for beam energies above 1.0 GeV. In the case of np scattering, there is no longer this antisymmetry but there are even fewer measurements above 1.15 GeV. It is important to note that isospin invariance requires the analysing powers for polarised protons and neutrons shown in the middle and right panels, correspondingly should be the same. It is in the context of these gaping holes in the nucleon-nucleon database that the ANKE NN programme should be judged.

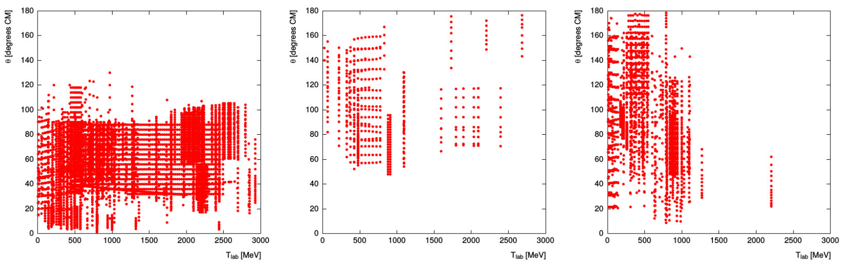

Figure 2. Abundance plots for experiments on the analysing power of (left) pp elastic scattering, (middle) the proton in pn elastic scattering, and (right) the neutron in pn elastic scattering.

2. The neutron-proton charge-exchange amplitudes

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

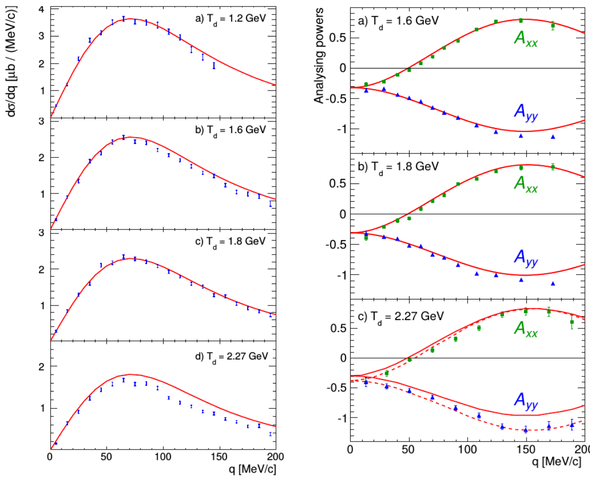

Figure 3. Differential cross sections (left panel) and cartesian deuteron analysing powers (right panel) for the $\vec{d}p \to \{pp\}_s n$ reaction for $E_{pp} < 3$ MeV at $T_d = 1.2$, 1.6, 1.8, and 2.27 GeV [9, 10, 11]. The impulse approximation predictions [8] have been evaluated with the SAID amplitudes [2] (solid curves) and also, at the highest energy, when the longitudinal spin-spin amplitude is scaled by a factor of 0.75 (dashed curves).

Measurements were carried out at Saclay [6, 7] but only in regions where the NN amplitudes were reasonably well known. These have been extended to higher energy at ANKE in fine steps in momentum transfer q. A cut of $E_{pp} < 3$ MeV was typically imposed but any contamination from triplet P-waves was taken into account in the theoretical modelling [8]. The ANKE differential cross section (including the 1.2 GeV data) and analysing power results at $T_d = 1.6$, 1.8, and 2.27 GeV [9, 10, 11] are compared in Fig. 3 to these impulse approximation predictions using as input up-to-date np amplitudes [2]. The satisfactory agreement at lower energies, and also in the values of the differential cross sections, shows that the theoretical description is adequate here. Above about 1 GeV, neutron-proton data become rather sparse. It comes therefore as no surprise that, when the same approach is employed on the higher energy data shown in Fig. 3, the current SAID amplitudes [2] give a poor overall description of the results. However, if the longitudinal spin-spin amplitude is reduced by a global factor of 0.75, the agreement is much more satisfactory. The charge exchange data can have a useful impact on the NN database.

Confirmation of these conclusions is to be found in the measurements of the deuteron-proton spin correlation parameters studied at ANKE with the polarised hydrogen gas cell [11]. Results on this are shown in Fig. 4 (left panel). In impulse approximation, these are sensitive to the interference between the longitudinal spin-spin amplitude and the two transverse ones. Whereas there is a satisfactory agreement with the theoretical predictions at 1.2 GeV, the model is much more satisfactory at 2.27 GeV if the longitudinal input is scaled by the 0.75 factor. In addition to measuring the spin correlations with the polarised cell, data were also obtained in parallel on the proton analysing power in the $d\vec{p} \to \{pp\}_s n$ reaction and the results are shown in right panel of Fig. 2. The message here is very similar to that for the other observables. At 600 MeV per nucleon the SAID input reproduces the experimental points very well but it seems that at 1135 MeV the SAID description of the spin-orbit amplitude has serious deficiencies.

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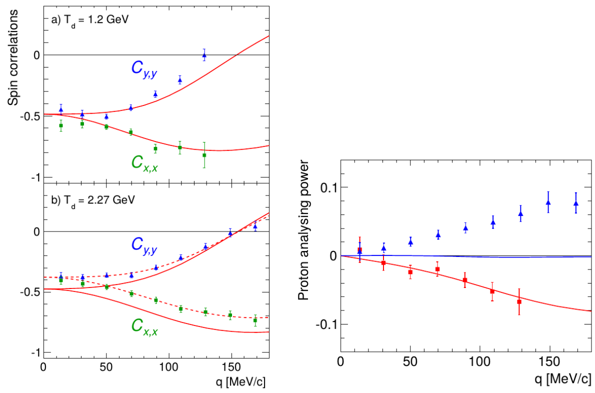

Figure 4. Left panel: Transverse spin correlation parameters in the $\vec{d}\vec{p} \to \{pp\}_s n$ reaction [11] at (a) 1.2 and (b) 2.27 GeV compared to the predictions of an impulse approximation model (solid curves). Better agreement is found at the higher energy if the longitudinal input is scaled by a factor of 0.75 (dashed curves). Right panel: Proton analysing power in the $d\vec{p} \to \{pp\}_s n$ reaction at 1.2 GeV (red squares) and 2.27 GeV (blue triangles) compared to impulse approximation predictions. Note that, with the current SAID input [2], the latter almost vanish at the higher energy.

2.1. Recent results

The vector and tensor analysing powers, A_y and A_{yy} , of the $\vec{p}\vec{d} \to \{pp\}_s n$ charge-exchange reaction have been measured at a beam energy of 600 MeV at ANKE by using an unpolarised proton beam incident on an internal storage cell target filled with polarised deuterium gas [12]. The low energy recoiling protons were measured in a pair of silicon tracking telescopes placed on either side of the target. By analysing events where both protons entered the same telescope, the charge-exchange reaction was measured for momentum transfers $q \geq 160$ MeV/c. These data provide a good continuation of the earlier results at $q \leq 140$ MeV/c obtained with a polarised deuteron beam [11]. They are also consistent with impulse approximation predictions with little sign evident for any modifications due to multiple scatterings.

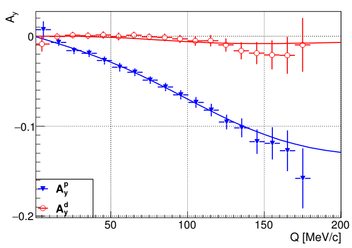

Figure 5. Values of the deuteron (vector) analysing power A_y^d (red circles) and proton analysing power A_y^p (blue triangles) for the $\vec{d}\vec{p} \to \{pp\}_s n$ reaction at 726 MeV. The curves are impulse approximation estimates [8].

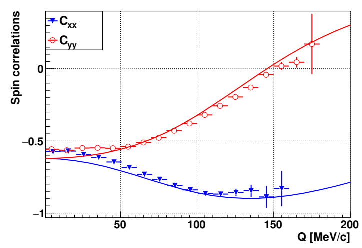

Figure 6. Values of the spin correlations $C_{y,y}$ (red circles) and $C_{x,x}$ (blue triangles) for the $dp \to \{pp\}_s n$ reaction at 726 MeV.

The charge exchange of vector polarised deuterons on a polarised hydrogen target has been studied at ANKE in a high statistics experiment at a deuteron beam energy of $T_d = 726$ MeV [13]. The measured analysing powers and spin correlations are sensitive to interference terms between specific neutron-proton charge-exchange amplitudes at a neutron kinetic energy of $T_n \approx \frac{1}{2}T_d = 363$ MeV. An impulse approximation calculation, which takes into account corrections due to the angular distribution in the diproton, describes reasonably the dependence of the data on both E_{pp} and the momentum transfer, as shown in Figs. 5, 6.

3. Analysing power in proton-proton elastic scattering at small angles

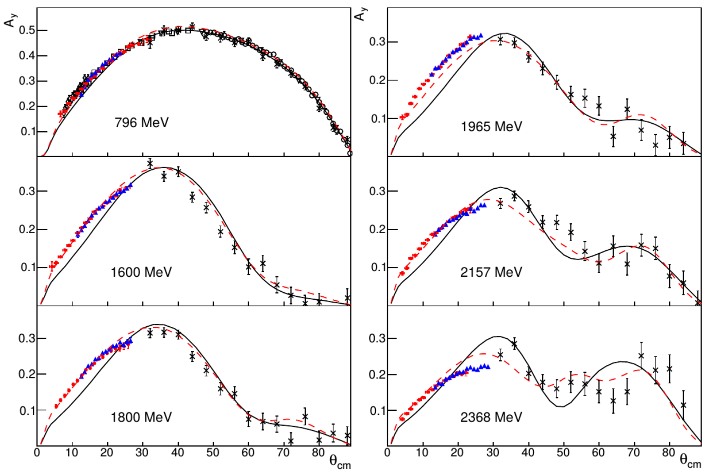

Figure 7. Comparison of the ANKE measurements of the proton analysing power in *pp* elastic scattering using the STT (red filled circles) and FD (blue filled triangles) systems with the curves corresponding to the SAID SP07 (solid black line) and the revised fit (dashed red) solutions [2]. Only statistical errors are shown. Also shown are selected results from EDDA (black crosses) [3] at the energies different by no more than 7 MeV and, at 796 MeV, LAMPF [17, 18, 19], and SATURNE [20] (black open symbols).

The proton analysing power in *pp* elastic scattering has been measured at small angles at COSY-ANKE at 796 MeV and five other beam energies between 1.6 and 2.4 GeV using a polarised proton beam [14]. In a strong-focusing synchrotron, such as COSY, resonances can lead to losses of polarisation of a proton beam during acceleration. In order to compensate for these effects, adiabatic spin-flip was used to overcome the imperfection resonances and tune-jumping to deal with the intrinsic ones [15]. The stripped-down version of the EDDA detector used as a polarimeter at COSY was calibrated during the EDDA data-taking periods against the full detector setup. The systematic uncertainty of the measurements of the polarisation was estimated to be 3% at each energy [16].

The asymmetries obtained by detecting the fast proton in the ANKE forward detector or the slow recoil proton in a silicon tracking telescope are completely consistent (see Fig. 7). Although the analysing power results agree well with the many published data at 796 MeV, and also with the most recent partial wave solution at this energy [2], the ANKE data at the higher energies lie well above the predictions of this solution at small angles. An updated phase shift analysis that uses the ANKE results together with the World data leads to a much better description of these new measurements.

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4. Absolute differential cross section of proton-proton elastic scattering at small angles

The differential cross section for proton-proton elastic scattering has been measured at a beam energy of 1.0 GeV and in 200 MeV steps from 1.6 to 2.8 GeV for centre-of-mass angles in the range from $12^\circ - 16^\circ$ to $25^\circ - 30^\circ$, depending on the energy [4, 24].

The biggest challenge that has to be faced when measuring the absolute value of a cross section in a storage ring experiment is to establish the beam-target luminosity at the few percent level. It has been shown that this can be achieved by studying the energy loss through electromagnetic processes as the coasting uncooled beam passes repeatedly through the target chamber. There is a resulting change in the frequency of the machine that can be determined with high accuracy by studying the Schottky power spectrum of the beam [25], leading to a precise determination of the effective target density. The measurement of the beam intensity is a routine procedure for any accelerator and is performed at COSY using the high precision Beam Current Transformer device. In result, absolute normalisations of typically 3% were achieved.

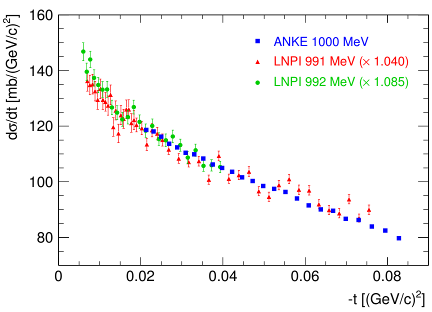

Figure 8. Differential cross section for *pp* elastic scattering. The ANKE data at 1000 MeV (blue squares) are compared to the Gatchina hydrogen data at 992 MeV (green circles) [21] scaled by a factor of 1.085 and methane results at 991 MeV (red triangles) [22] scaled by a factor of 1.04.

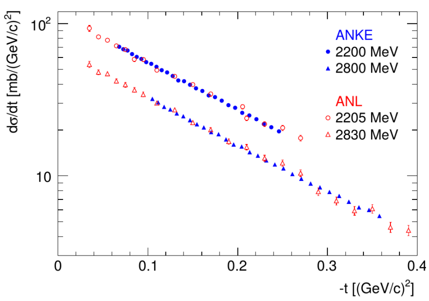

Figure 9. The ANKE *pp* differential cross section data at 2.2 GeV (closed blue circles) and 2.8 GeV (closed blue triangles) compared to the ANL results [23] at 2.2 GeV (open red circles) and 2.83 GeV (open red triangles). For presentational purposes, both higher energy data sets have been scaled downwards by 1.5.

There are very few data sets to which the ANKE results can be compared and these data are plotted together with our measurements in Figs. 8 and 9. In the vicinity of 1 GeV there are two measurements by the Gatchina group that were made with the IKAR recoil detector [21, 22]. Data are also available from the Argonne National Laboratory at 2.2 and 2.83 GeV [23].

The ANKE results shown for all energies in Fig. 10 could clearly have an impact on the current partial wave solutions. This is demonstrated in Fig. 11, where they are compared to both the SAID SP07 solution [2] and a modified one that takes the present data at all eight energies into account. Scaling factors in the partial wave analysis consistent with the overall uncertainties, have been included in the figure. The major changes introduced by the new partial wave solution are in the $^1S_0$ and $^1D_2$ waves at high energy. It should be noted that the modified solution does not weaken the description of the ANKE proton analysing powers presented in [14].

After extrapolating the values of the Coulomb-corrected differential cross section to the forward direction, the results are broadly compatible with the predictions of forward dispersion relations.

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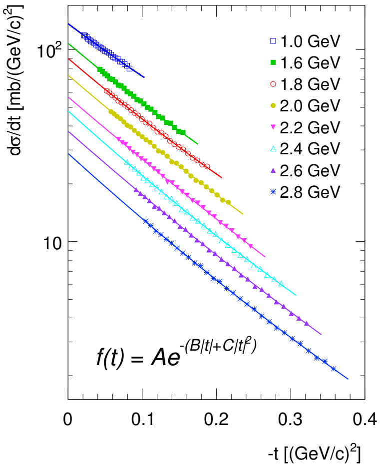

Figure 10. Combined ANKE data set of differential cross sections compared to fits of the $A\exp(-B|t|+C|t|^2)$ dependence. The data are scaled down sequentially in energy by factors of 1.2.

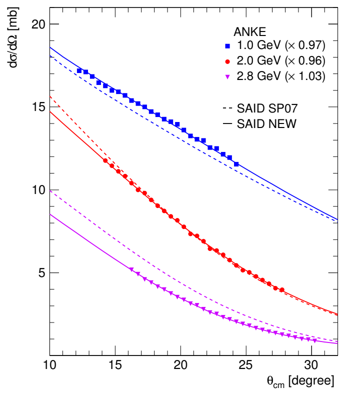

Figure 11. Scaled ANKE data at 1.0, 2.0, and 2.8 GeV compared to the SAID SP07 solution [2] and a modified (new) partial wave solution where the ANKE data have been taken into account. The 2.0 and 2.8 GeV data and curves have been reduced by factors of 0.5 and 0.25, respectively.

5. Analysing power in quasi-elastic proton-neuteron scattering at small angles

The analysing power in $\vec{p}n$ quasi elastic scattering has been measured at small angles at COSY-ANKE at 796 MeV and five other beam energies between 1.6 and 2.4 GeV using a polarised proton beam and unpolarised deuteron target. The asymmetries were obtained by detecting the fast proton in the ANKE forward detector and the slow recoil proton in a silicon tracking telescope.

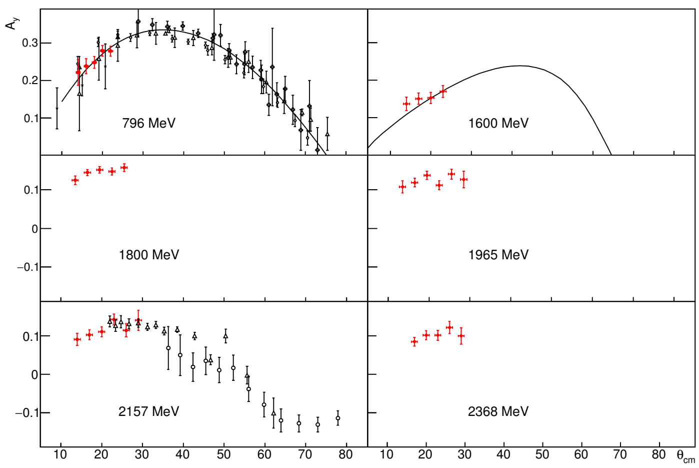

Figure 12. (Preliminary) ANKE measurements of the analysing power in pn quasi-elastic scattering (red filled circles). The results at 0.8 GeV are compared with the curves corresponding to the SAID SP07 (solid black line) [2] and other existing measurements [26, 27, 28, 29, 30, 31] (black open symbols). Only statistical errors are shown. Also shown are selected results from Argonne National Laboratory at 2.2 GeV energy [30, 31] (black open symbols).

The results of all the ANKE measurements are shown for the six energies in Fig. 12. The SAID SP07 solution [2], which is only valid up to 1.3 GeV kinetic energy, is shown by the solid black line at the lowest energy. The agreement between the new ANKE data and other existing data at 796 MeV and also with the SP07 SAID predictions at this energy is very good. Using our data, the SAID group was able to provide the preliminary modified solution for pn quasi-elastic scattering at 1.6 GeV, also shown in black in Fig. 12. The dominant systematic error is that arising from the determination of the beam polarisation in the EDDA polarimeter, which was estimated to be 3% [16].

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