Deuteron analysing powers in deuteron-proton elastic scattering at 1.2 and 2.27 GeV

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Abstract

The vector (A_y^d) and tensor (A_{xx} and A_{yy}) analysing powers in deuteron-proton elastic scattering have been measured in the forward hemisphere at deuteron kinetic energies of $T_d = 1.2$ GeV and 2.27 GeV using the ANKE spectrometer at the COSY storage ring. The results are compared with other experimental data and with predictions made within the framework of Glauber multiple scattering theory.

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Key words: Deuteron-proton elastic scattering; analysing powers

1 Introduction

There has been an extensive programme using the ANKE spectrometer at the COSY Cooler Synchrotron of the Forschungszentrum Jülich to measure the analysing powers in small-angle deuteron charge exchange on hydrogen, $dp \to ppn$ [1]. At low excitation energies of the final diproton system, these measurements have yielded valuable information on the spin-spin amplitudes in large-angle neutron-proton elastic scattering [2]. However, in order to measure such analysing powers, it is first necessary to determine the polarisation of the incident deuteron beam.

The polarisation of deuteron beams has been studied in several different ways at COSY [3]. The circulating deuteron beam is polarised perpendicularly to the horizontal plane of the machine. The beam vector (P_z) and tensor (P_{zz}) polarisations are labeled conventionally in the reference frame of the source. In contrast, all the spin observables discussed later refer to the right-handed coordinate system of the reaction frame, where the beam defines the Z-direction while the stable spin axis of the beam points along the Y-direction, which is perpendicular to the COSY orbit.

The deuteron beam is injected into the COSY ring at 75.6 MeV and the vector polarisation P_z of the beam is measured at this stage with the low energy polarimeter (LEP) [4]. After acceleration in COSY, the deuteron vector and tensor (P_{zz}) polarisations could be measured in the EDDA polarimeter [5]. Tight limits were placed on any loss of polarisation during acceleration by measuring in parallel in ANKE the analysing powers for elastic deuteron-proton scattering, quasi-free $\vec{n}p \to d\pi^0$, and the $\vec{d}p \to {}^3\text{He}\,\pi^0$ reaction [3] but subsequent research has shown that the most efficient tensor polarimeter is based upon the charge exchange $\vec{d}p \to \{pp\}_s n$ reaction, where only diproton events $\{pp\}_s$ with low excitation energy are retained [1,3]. The use of this reaction as a tensor polarimeter was first advocated in Ref. [2].

The methodology for carrying out these measurements has been described at length in previous publications [1] and so the experimental description given in Section 2 will be relatively brief. Emphasis is there laid on the polarised source modes used in the experiment and how the results of the different modes can be combined effectively. Numerical values of the analysing powers are to be

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found here. The model used to interpret the experimental results, which is presented in Section 3, is based upon the Glauber eikonal approach [6], which has already been used at a variety of energies [7].

The results of our measurements of A_y^d, A_{yy}, and A_{xx} at small angles at 1.2 GeV and 2.27 GeV are shown graphically in Section 4, where they are compared with the more extensive data sets in the 1.2 GeV region from ANL [8] and SATURNE [9]. The results are in general agreement with the predictions of the modified Glauber model, though the description seems to get better as the energy increases. The data at 2.27 GeV are especially important because they were used to determine the deuteron beam polarisations that were needed in the study of the analysing power in neutron-proton elastic scattering in the search for a dibaryon [10]. Our conclusions are drawn in Section 5.

2 The experiment

The experiments were carried out at the COoler SYnchrotron (COSY) of the Forschungszentrum Jülich using the ANKE magnetic spectrometer, which is located at an internal target position within a chicane in the storage ring. Although ANKE contains several detection possibilities, only those of the Forward Detector were used to measure elastically scattered deuterons or the two fast protons from the $dp \to \{pp\}n$ charge-exchange reaction. Further details on the set-up are to be found in the earlier publications [1].

For this experiment, the COSY polarised source was tuned to produce seven different combinations of deuteron vector and tensor polarisations plus an unpolarised beam (#8), as summarised in Table 1. The results shown in the table were obtained using the LEP polarimeter at injection and ANKE measurements at 1.2 GeV of the deuteron charge-exchange reaction on hydrogen for P_{zz} and the quasi-free $np \to d\pi^0$ reaction for P_z. It is important to note that, due to its low anomalous magnetic moment, there are no depolarising resonances for deuteron kinetic energies below 11 GeV and, as a consequence, it is not expected that deuterons should depolarise during acceleration at COSY, where the maximum energy is less than 2.3 GeV. This belief was confirmed by all the ANKE data taken at a variety of energies [1].

Since the vertical acceptance of the ANKE spectrometer is very small, away from the forward cone it is not possible to measure the full azimuthal distribution of any reaction and this makes it difficult to separate effects arising from the deuteron vector and tensor polarisations. It is therefore desirable to have beam polarisations that are purely vector or tensor. This is possible for P_z and mode #1 is produced with $P_{zz} = 0$, which makes it ideal for the measurement of the vector analysing power in a reaction. On the other hand, combinations of modes are employed to deliver effectively "pure" tensor polarisations and for this more care has to be taken in the handling of the data shown in Table 1. This table shows the ideal values of the polarisations, as requested of the source, as well as values measured with the LEP and at ANKE.

#	P_z^I	P_{zz}^I	P_z by LEP	P_z by ANKE	P_z calibrated	P_{zz} by ANKE	P_{zz} calibrated
1	$-\frac{2}{3}$	0	-0.541 ± 0.008	-0.522 ± 0.053	-0.500 ± 0.033	0.004 ± 0.021	
2	$+\frac{1}{3}$	-1	0.197 ± 0.008	0.307 ± 0.056	0.223 ± 0.024	-0.548 ± 0.022	-0.443 ± 0.020
7	-1	-2	-0.491 ± 0.012	-0.255 ± 0.057	-0.451 ± 0.033	-0.228 ± 0.022	
3	$-\frac{1}{3}$	$+1$	-0.331 ± 0.011	-0.382 ± 0.053	-0.294 ± 0.028	0.498 ± 0.022	0.548 ± 0.017
4	0	$+1$	0.031 ± 0.009	-0.024 ± 0.056	0.060 ± 0.023	0.558 ± 0.019	
5	-1	$+1$	-0.758 ± 0.007	-0.746 ± 0.052	-0.712 ± 0.041	0.524 ± 0.019	0.465 ± 0.017
6	$+1$	$+1$	0.659 ± 0.008	0.676 ± 0.058	0.675 ± 0.038	0.411 ± 0.020	
8	0	0	-0.007 ± 0.010	—	0.023 ± 0.023	—	

Table 1
Vector and tensor polarisations for eight different configurations of the polarised deuteron ion source. The ideal values, P_z^I and P_{zz}^I, are compared to those obtained using the LEP and ANKE facilities. The methods used to derive the calibrated values of P_z and P_{zz} are described in the text.

The "calibrated" values of P_z shown in Table 1 were obtained by taking the linear fit

$$P_z(\text{ANKE}) = 0.030 + 0.979 P_z(\text{LEP}) \tag{2.1}$$

and reading off the values of P_z obtained at the P_z(LEP) points. This corrects some imprecision in the ANKE vector analysing power measurements for different reactions. The "calibrated" tensor values were then obtained by taking the results of pairs of source modes where the signs of P_z are opposite but those of P_{zz} are the same. It was then possible to take linear combinations of the results in order to cancel (within error bars) the effects of the vector polarisation and the average tensor polarisation for the pair is given as P_{zz}(calibrated). The differences between the values of P_{zz}(calibrated) obtained with the above-mentioned procedure using the directly measured P_z(ANKE) or the "calibrated" values of P_z are well within the quoted error.

The differential cross section for deuteron-proton elastic scattering induced by a polarised deuteron depends upon the azimuthal angle φ of the recoil deuteron as well as its polar angle ϑ through the vector (A_y^d) and tensor (A_{xx}, A_{yy}) analysing powers of the reaction,

$$\frac{\mathrm{d}\sigma(\vartheta,\varphi)}{\mathrm{d}\Omega} = \left(\frac{\mathrm{d}\sigma(\vartheta)}{\mathrm{d}\Omega}\right)_0 \Big[1 + \tfrac{3}{2} P_z A_y^d(\vartheta)\cos\varphi$$
$$+ \tfrac{1}{4} P_{zz}\{A_{xx}(\vartheta)(1-\cos 2\varphi) + A_{yy}(\vartheta)(1+\cos 2\varphi)\}\Big], \tag{2.2}$$

where $(\mathrm{d}\sigma(\vartheta)/\mathrm{d}\Omega)_0$ is the unpolarised cross section and P_z and P_{zz} are vector and tensor polarisations of the beam, respectively.

Deuteron-proton elastic scattering has a very large cross section at small momentum transfers and the reaction can be identified from the single-particle momentum spectrum of the fast deuteron measured in the ANKE Forward Detector (see Fig. 12 in Ref. [3]). Triton production through the $dp \to {}^3\mathrm{H}\,\pi^+$ reaction is negligible in comparison. The corresponding missing-mass spectra (shown in Fig. 1) are very clean, with essentially no background, which confirms the reaction identification. Events lying within a band of $\pm 3\sigma$ of the central proton peak were retained and classified as corresponding to deuteron-proton elastic scattering.

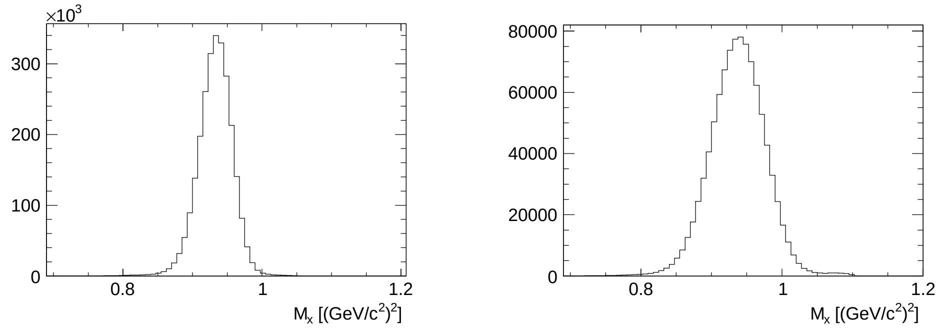

Fig. 1. Missing-mass spectra for the $p(d,d)X$ reaction at 1.2 (left) and 2.27 GeV (right).

Values of the vector analysing power A_y^d were obtained by fitting the normalised $\cos\varphi$ distribution using only polarised mode #1, where the tensor polarisation is zero. Numerical results are presented in Table 2 in terms of the deuteron c.m. scattering angle. They are also illustrated graphically in Section 4 after the theoretical model has been described. The vector analysing power signal at 2.27 GeV is significantly smaller than at 1.2 GeV, and is also smaller than that measured at Argonne at 2 GeV [8]. This is consistent with Argonne data taken at 1.2, 1.6 and 2 GeV, that clearly show a decrease in the vector analysing power signal as the beam energy is raised.

The tensor analysing powers A_{xx} and A_{yy} were determined from fits to the normalised $\cos 2\varphi$ distributions separately for the three different pairs of polarisation modes listed in Table 1. The results, averaged over these modes, are also given in terms of the deuteron c.m. scattering angle in Table 2. Due to the limitations imposed by the ANKE vertical acceptance, the values of φ are always close to zero so that the precision on the measurements of A_{xx} is much poorer than for A_{yy}. Just as for A_y^d, the new results for A_{yy} agree well with existing data in the 1.2 GeV region. It is seen from the Argonne data at 1.2, 1.6 and 2 GeV that the zero-crossing point tends to move towards smaller angles as the energy increases and this is not inconsistent with new ANKE

T_d	ϑ_{cm}	A_y^d	A_{yy}	A_{xx}
1.20 GeV	16.3°	0.354 ± 0.009	0.204 ± 0.017	-0.25 ± 0.15
	18.5°	0.384 ± 0.011	0.279 ± 0.021	-0.39 ± 0.12
	20.4°	0.400 ± 0.011	0.297 ± 0.021	-0.36 ± 0.15
	22.8°	0.403 ± 0.010	0.365 ± 0.022	-0.49 ± 0.18
	25.5°	0.405 ± 0.013	0.434 ± 0.027	-0.63 ± 0.30
	28.5°	0.399 ± 0.015	0.514 ± 0.033	
	31.7°	0.350 ± 0.019	0.567 ± 0.029	
2.27 GeV	17.7°	0.256 ± 0.012	0.333 ± 0.023	-0.62 ± 0.20
	19.7°	0.263 ± 0.016	0.411 ± 0.033	-0.68 ± 0.19
	21.6°	0.274 ± 0.015	0.482 ± 0.032	-0.55 ± 0.22
	24.0°	0.288 ± 0.017	0.640 ± 0.039	-1.02 ± 0.30
	26.6°	0.281 ± 0.025	0.801 ± 0.055	
	29.4°	0.210 ± 0.036	0.692 ± 0.064	
	32.5°	0.045 ± 0.045	0.380 ± 0.072	

Table 2
Vector and tensor analysing powers of the $\vec{d}p \to dp$ reaction measured at 1.20 and 2.27 GeV in bins centred at the centre-of-mass angles shown. Note that, due to the much smaller vertical acceptance than horizontal, the error bars on A_{xx} are significantly bigger than those on A_{yy}. At the larger angles the errors on A_{xx} increase so much that it is not useful to quote values.

results at 2.27 GeV. However, some of this effect is kinematic in the sense that the data are far more stable if presented in terms of the momentum transfer t. Further discussion of the results is deferred until the theoretical model has been presented in the next section.

3 Theoretical model

The Glauber single and double-scattering model [6] has been used to estimate the values of the spin observables in proton-deuteron elastic scattering, following the formalism developed in Ref. [11]. This approach, which includes the full spin dependence of the elementary proton-nucleon scattering amplitudes and the S- and D-state components of the deuteron wave function, allows the calculation of the unpolarised differential cross section as well as vector and tensor analysing powers. This formalism was further developed in the Madison reference frame and extended to allow the calculation of spin-correlation parameters [7]. Numerical results obtained at the rather low proton beam energies of 135 - 250 MeV were found to be in reasonable agreement with existing experimental data in the forward hemisphere [7].

The $dp \to dp$ transition matrix element can be written as

$$\langle\, p'\mu', d'\lambda'|T|p\mu, d\lambda\,\rangle = \bar{u}_{\mu'}\varepsilon_{\beta}^{\lambda'\dagger} T_{\beta\alpha}(\vec{p}, \vec{p'}, \vec{\sigma})\, \varepsilon_{\alpha}^{\lambda} u_{\mu}, \tag{3.1}$$

where u_μ ($u_{\mu'}$) is the Pauli spinor of the initial p (final p') proton in the state with the spin projection μ (μ'), $\varepsilon_\alpha^\lambda$ ($\varepsilon_\beta^{\lambda'}$) is the polarisation vector of the initial d (final d') deuteron in the state with spin projection λ (λ'), and $T_{\beta\alpha}$ is a tensor of second rank ($\beta, \alpha{=}x, y, z$), constructed from the momenta $\vec{p}$ and $\vec{p'}$ and the Pauli matrices $\vec{\sigma}$. After imposing parity conservation and invariance under rotations, it can be shown that the transition matrix element of Eq. (3.1) contains 18 invariant amplitudes, which reduces to 12 once time-reversal invariance is invoked. The model can therefore also be used to investigate the violation of time-reversal invariance in nucleon-nucleon interactions [12].

In the Madison coordinate system, where the z-axis lies along $\vec{p}$, the y-axis along $\vec{p}\times\vec{p'}$ and the x-direction is chosen to form a conventional right-handed coordinate system, one can express the nine elements of $T_{\beta\alpha}$ as

$$\begin{array}{lll}
T_{xx} = M_1 + M_2\sigma_y, & T_{xy} = M_7\sigma_z + M_8\sigma_x, & T_{xz} = M_9 + M_{10}\sigma_y, \\
T_{yx} = M_{13}\sigma_z + M_{14}\sigma_x\ , & T_{yy} = M_3 + M_4\sigma_y, & T_{yz} = M_{11}\sigma_x + M_{12}\sigma_z, \\
T_{zx} = M_{15} + M_{16}\sigma_y, & T_{zy} = M_{17}\sigma_x + M_{18}\sigma_z, & T_{zz} = M_5 + M_6\sigma_y,
\end{array} \tag{3.2}$$

where σ_x, σ_y, and σ_z are the Pauli matrices, and M_i ($i = 1, \ldots, 18$) are the 18 complex amplitudes.

In the work of Platonova and Kukulin [11] the $pd \to pd$ transition amplitude was written in an alternative reference frame, where the x axis lay along $\vec{q} = \vec{p} - \vec{p'}$ and the z-axis along $\vec{k} = \vec{p} + \vec{p'}$, with the y-axis ($\hat{n}$) forming the right-handed coordinate frame. This choice is dictated by the desire to keep the symmetry between the initial and final states that has often proved useful in Glauber theory [6]. It also has the added benefit of allowing time-reversal invariance to be imposed in a much simpler way than is possible directly in the Madison frame. In order to recast the formulae of Ref. [11] in the Madison frame, one has to perform a rotation of their reference frame around the OY axis through an angle $\theta/2$, where θ is the scattering angle, and to make the replacements $OY \to -OY$ and $OX \to -OX$. The 18 amplitudes M_i can be expressed as linear combinations of the 12 time-reversal-invariant amplitudes

A_i, which were derived in Ref. [11]. The corresponding formulae for M_i are given in Eq. (5) of Ref. [7].

The vector and tensor analysing powers are expressed in terms of the M_i amplitudes through:

$$A^d_y = -2Im\Big[M_1M_9^*+M_2M_{10}^*+M_{13}M_{12}^*+M_{14}M_{11}^*+M_{15}M_5^*+M_{16}M_6^*\Big]/\sum_{i=1}^{18}|M_i|^2,$$

$$A_{yy} = 1-3\Big[|M_3|^2+|M_4|^2+|M_7|^2+|M_8|^2+|M_{17}|^2+|M_{18}|^2\Big]/\sum_{i=1}^{18}|M_i|^2,$$

$$A_{xx} = 1-3\Big[|M_1|^2+|M_2|^2+|M_{13}|^2+|M_{14}|^2+|M_{15}|^2+|M_{16}|^2\Big]/\sum_{i=1}^{18}|M_i|^2. \quad (3.3)$$

The $pd \to pd$ invariant amplitudes M_i are calculated using the spin-dependent single and double scattering Glauber model, as described in Ref. [7]. The elementary proton-nucleon elastic scattering amplitudes are taken in the following form [11]:

$$\begin{aligned} M_N(\vec{p},\vec{q};\vec{\sigma},\vec{\sigma}_N) = {} & A_N + C_N\vec{\sigma}\cdot\hat{n} + C'_N\vec{\sigma}_N\cdot\hat{n} + B_N(\vec{\sigma}\cdot\hat{k})(\vec{\sigma}_N\cdot\hat{k}) + \\ & +(G_N+H_N)(\vec{\sigma}\cdot\hat{q})(\vec{\sigma}_N\cdot\hat{q}) + (G_N-H_N)(\vec{\sigma}\cdot\hat{n})(\vec{\sigma}_N\cdot\hat{n}), \quad (3.4) \end{aligned}$$

where the complex amplitudes $A_N, C_N, C'_N, B_N, G_N, H_N$ $(N = p, n)$ have been calculated from the SAID program [13] and parametrised as sums of Gaussians.

4 Results

The numerical values of our measurements of the deuteron vector and tensor analysing powers of $\vec{d}p \to dp$ elastic scattering are to be found in Table 2. Here we wish to compare the results with other data and with the Glauber model predictions in the form of figures.

As seen in Fig. 2, there is good agreement on the deuteron vector analysing power between the current data and the published experimental results in the vicinity of 1.2 GeV [8,9] and at 2.27 GeV [10]. Also shown in the figure are curves corresponding to the predictions of the extended Glauber model of Section 3.

The analogous results and calculations for the tensor analysing power A_{yy} are to be seen in Fig. 3. Of particular note here is the behaviour of the WASA

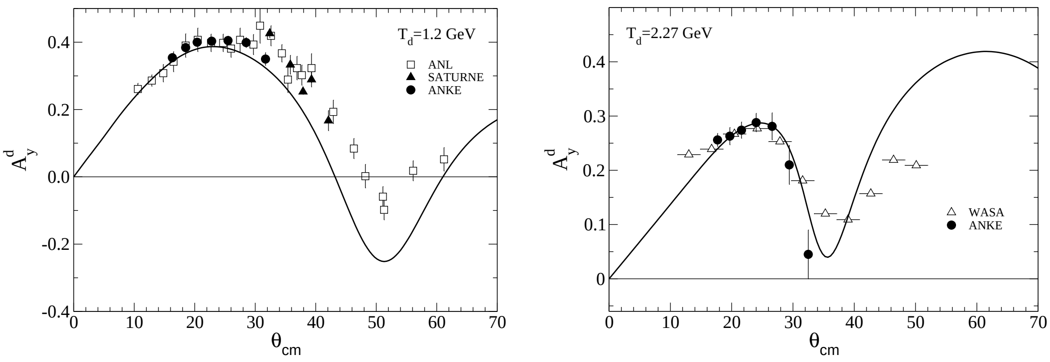

Fig. 2. Deuteron vector analysing power A_y^d of elastic deuteron-proton scattering at 1.2 GeV (left) and 2.27 GeV (right). The ANKE data (closed circles) at both energies are compared to the predictions of the extended Glauber model discussed in Section 3. The SATURNE data at 1.2 GeV [9] are shown as triangles and the ANL data at 1.194 GeV [8] as open squares. The WASA data at 2.27 GeV [10] are shown by open triangles. It should be noted here that the ANKE results at small angles were used to determine the beam polarisation in the WASA analysis.

data which, though they show a dip at $\theta_{cm} \approx 40^\circ - 45^\circ$, this is not as deep as in the model which, as shown in Ref. [11], reproduces the dip seen in the ANL data at the neighbouring energy of 2.0 GeV [8].

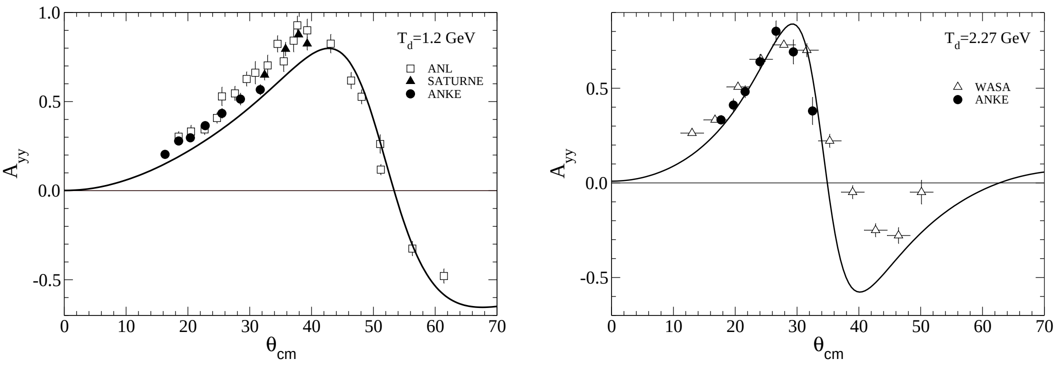

Fig. 3. The results and predictions for the tensor analysing power A_{yy} using the same notation as that employed for the vector analysing power in Fig. 2.

Finally in Fig. 4 we compare the current measurements of A_{xx} at 1.2 GeV and 2.27 GeV with the model predictions. As previously stressed, the limited acceptance of the ANKE exit window in the y direction means that the errors on A_{xx} are significantly larger than those shown for A_{yy}. Nevertheless, the data do follow the trends of the theoretical curves.

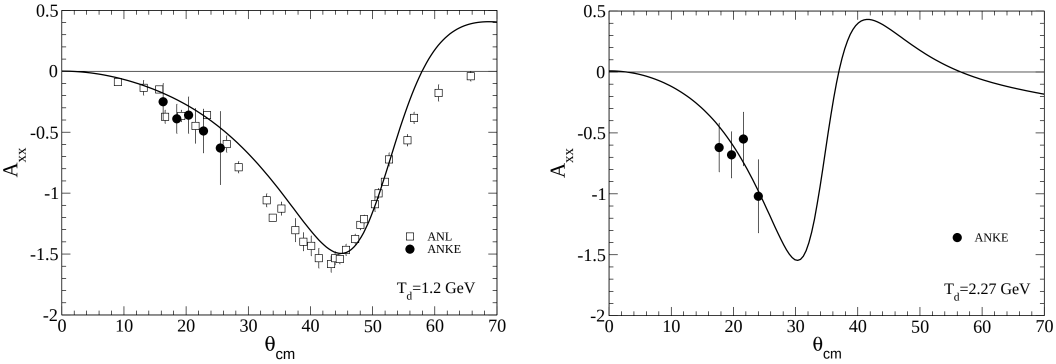

Fig. 4. ANKE measurements (black circles) of the tensor analysing power A_{xx} at 1.2 GeV (left) and 2.27 GeV (right) are compared with the ANL data at 1.2 GeV [8] (open squares) and to the predictions made within the framework of the extended Glauber model of Section 3.

5 Conclusions

We have presented new measurements of the deuteron analysing powers A_y^d, A_{yy}, and A_{xx} in small-angle deuteron-proton elastic scattering at $T_d = 1.2$ GeV and 2.27 GeV. The values of A_y^d and A_{yy} obtained at the lower energy are completely consistent with those derived earlier at ANL [8] and SATURNE [9]. It should be noted that at the higher energy there is agreement by construction with the WASA results [10] at the smallest angles because the WASA data were normalised to those of ANKE in this region. However, the A_y^d data may start diverging at the largest angles.

We have also shown the results of an extended single- plus double-scattering Glauber model [12] that has proved very useful at small angles. By comparing its predictions with the ANL data at 1.2, 1.6, and 2.0 GeV [8], it seems that the approach becomes more reliable as the energy increases. The model reproduces the main features of the ANKE data and this brings into question the WASA data at 2.27 GeV, which seem to have a quantitatively different behaviour to the model in the dip regions of both A_y^d and A_{yy}.

Though the error bars on the ANKE values of A_{xx} are understandably quite large, the data are not in conflict with the model though the 1.2 GeV data on both this and A_{yy} would even fall on the theoretical curves with a slight increase in beam tensor polarisation. However, this possibility seems unlikely in view of the ANL and SATURNE data. On the other hand, ANKE measurements of various spin observables in deuteron charge exchange on hydrogen, and subsequent theoretical analysis, suggest that there might be improvements to the SAID neutron-proton charge exchange amplitudes at 1.135 GeV [1]. This energy is, of course, close to the limit of the SAID neutron-proton predictions [13].

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