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A_y Measurement in $\vec{p}p$ -Elastic Scattering at Small Angles

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The proton analysing power in $\vec{p}p$ 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 polarized proton beam. 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. The sources of the systematic uncertainties and the time stability issue were considered. The ANKE data at the higher energies lie well above the predictions of the most recent partial wave solution at small angles. An updated phase shift analysis that uses the ANKE results together with the World data leads to a better description of these new measurements.

Keywords: proton-proton elastic scattering; analyzing power; systematic uncertainties; polarization phenomena.

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1. Introduction

The present experiment was carried out using the ANKE magnetic spectrometer [1] positioned inside the storage ring of the COoler SYnchrotron (COSY) [2] of the Forschungszentrum Jülich. Although the ANKE facility is equipped with other elements, the only detectors used in this experiment were the forward detector (FD) [3] and the silicon tracking telescopes (STT) [4].

The fast protons from elastic pp scattering were measured in the forward detector which, for pp elastic scattering, covered $10^\circ - 30^\circ$ in c.m. polar angles and $\pm 30^\circ$ in azimuth. The FD comprises a set of multiwire proportional and drift chambers (MWCs) and a two-plane scintillation hodoscope. The counters were used to measure the energy losses required for particle identification,[3]. The two STT were placed symmetrically inside the vacuum chamber, to the left and right of the beam near the unpolarized hydrogen cluster-jet target [5]. Each telescope consists of three sensitive silicon layers of 70 μm, 300 μm, and 5 mm thickness and covers the laboratory polar angles $75^\circ < \theta_{\rm lab} < 140^\circ$ and $|\phi| < 25^\circ$. The ANKE experiment used a vertically polarized proton beam incident on an unpolarized proton target. Two modes, with spin up (↑) and down (↓), were supplied by the source and the polarizations of the injected beam were optimised using a low energy polarimeter (LEP) [6,7]. The polarizations were measured using the EDDA detector as a polarimeter [9].

The experiment at ANKE was carried out at six energies, $T_p = 796$, 1600, 1800, 1965, 2157, and 2368 MeV. The EDDA target effectively consumes all the beam so that it could not be used before an ANKE measurement in a cycle. So the last 20 s of each cycle was reserved for the measurement of the beam polarization. The 7 μm diameter carbon fibre target is moved into the beam from below. Consistent results were achieved with EDDA after the short ($180\,s$) and long ($300\,s$) cycles which implies that beam polarization is not lost over a COSY cycle [8]. The systematic uncertainty of the beam polarization measurements was estimated to be 3 % at each energy [9]. The variation of the beam polarization cycle by cycle was checked with the asymmetry of the counts in STT and found to be around 0.04 (RMS).

2. Data Analysis (STT)

The upper limit of the kinetic energy of stopped in the third layer protons equals to $30\,MeV$. For the protons passed the third layer the kinetic energy unambiguously can be defined by the deposited energy. The kinetic energy of protons passed the third layer is reconstructed by the *feed forward neural network* [10]. The *relative* uncertainty of kinetic energy reconstruction is defined during the network training procedure. It equals to 2% at $30\,MeV$ (lower limit of kinetic energy of punch-through protons) and to 4% at $90\,MeV$ (upper limit). Reconstruction of kinetic energies of punch-through protons expanded the measured kinetic energy range from 30 to $90\,MeV$ which results to significant expansion of the acceptable scattering angles.

The greater precision in the angle of the recoiling proton is achieved by deducing it from the kinetic energy measured in the STT rather than from a direct angular measurement. In STT the elastic *pp* scattering events identified through the evaluation of the missing mass for the detected protons. There is very little ambiguity in the isolation of the proton peak. Varying the selection criteria in a reasonable ranges does not change the measured asymmetry beyond the 68 % confidence interval ($\pm\sigma$).

In case of double-sided detector with stable detector efficiences the measured *cross-ratio* asymmetry [11] does not contain sources of the systematics in first order [12]

$$\begin{aligned} \varepsilon &= \frac{\sqrt{R_\uparrow L_\downarrow} - \sqrt{L_\uparrow R_\downarrow}}{\sqrt{R_\uparrow L_\downarrow} + \sqrt{L_\uparrow R_\downarrow}} = \\ &= PA\left[1 - \frac{2\,PA}{1-P^2A^2}\,\varepsilon_P\varepsilon_A + \frac{P^2A^2}{1-P^2A^2}\,(\varepsilon_P^2+\varepsilon_A^2)\right] + \mathcal{O}(\varepsilon^4)\,. \end{aligned} \quad (1)$$

The asymmetry sign is defined according to the *Madison Convention* [13]. Here ε_P accounts the beam polarization up and down modules inequality $P_{\uparrow\downarrow} = P(1 \pm \varepsilon_P)$ with the average polarization P and the asymmetry ε_A comes from misalignment of the left and right telescopes in the same way. The number of events L and R

correspond to the telescopes placement with respect to y axis, directed upwards in the lab system and the arrows show the beam polarization direction.

$$L(R)\uparrow = B_\uparrow \cdot \Omega_{L(R)}\ (1 \pm P_\uparrow \langle cos\phi\rangle_{L(R)} A(\vartheta))\,, \tag{2}$$

$$L(R)\downarrow = B_\downarrow \cdot \Omega_{L(R)}\ (1 \mp P_\downarrow \langle cos\phi\rangle_{L(R)} A(\vartheta))\,, \tag{3}$$

whwrw $B_{\uparrow\downarrow}$ are the luminosities of up and down polarized beams respectively, $\Omega_{L(R)}$ are the efficiencies of L and R telescopes integrated on the solid angle. ϑ always denotes the scattering angle in the c.m. system. From now on we use P to denote the *effective* beam polarization omitting the $\langle cos\phi\rangle = 0.966$ factor. We estimated that the ϕ acceptances of the telescopes are almost the same. Even at a larger difference between the acceptances it does not affect the measured asymmetry. A_y is the analysing power. It has to be stressed that the luminosity (B) and the dead-time differences for up and down polarized beams do not cause the systematics.

The only factor that could affect the asymmetry measured with such a two-arm detector is any instability in the ratio of the efficiencies of the left and right telescopes. Introducing the counts ratios for the beam up and down polarizations

$$\omega_\uparrow = \frac{L_\uparrow}{R_\uparrow} = r_\uparrow \frac{1+P_\uparrow A}{1-P_\uparrow A} \quad \text{with} \quad r_\uparrow = \left(\frac{\Omega_L}{\Omega_R}\right)_\uparrow\,, \tag{4}$$

$$\omega_\downarrow = \frac{L_\downarrow}{R_\downarrow} = r_\downarrow \frac{1-P_\downarrow A}{1+P_\downarrow A} \quad \text{with} \quad r_\downarrow = \left(\frac{\Omega_L}{\Omega_R}\right)_\downarrow\,, \tag{5}$$

we can measure $w_\uparrow$ and $w_\downarrow$ and using the measured values of P and $A(\vartheta)$ estimate whether the ratio $r_\uparrow/r_\downarrow$ is close to 1.

$$\frac{\omega_\uparrow}{\omega_\downarrow} = \frac{r_\uparrow}{r_\downarrow}\frac{1+2PA+P^2A^2(1-\varepsilon_P^2)}{1-2PA+P^2A^2(1-\varepsilon_P^2)} \simeq \frac{r_\uparrow}{r_\downarrow}\frac{(1+PA)^2}{(1-PA)^2}\,. \tag{6}$$

Keeping the average efficiency ratios constant during the simultaneously analyzed runs guarantees that the instability does not induce the fake asymmetry (in other words the systematic error) even when the individual efficiencies change. In case the ratio $r_\uparrow/r_\downarrow$ is not close to 1 we introduced the corresponding correction term (c_Ω) to the analysing power. The dependence of the correction term c_Ω on the telescope efficiencies ratio instability can be deduced from Eq.(1):

$$c_\Omega = \frac{1\,+\,P^2A^2}{2PA}\left(1\,-\,\sqrt{\frac{r_\uparrow}{r_\downarrow}}\right)\,. \tag{7}$$

So we could correct the measured $A_y(\vartheta)$ in the following way

$$A(\vartheta)\,\rightarrow\,A(\vartheta)\,(1\,+\,c_\Omega(\vartheta))\,. \tag{8}$$

The instability correction term, which was studied at all energies, does not exceed in absolute value 1.3% that was found at 1.8 GeV. Where it is needed the relevant corrections of the analysing power $c_\Omega(\theta)A_y(\vartheta)$ were added for each angular bin [10].

We estimated the upper limit of the second order correction terms in Eq.(1) for all beam energies assuming $\varepsilon_P = 0.10$ (most unfavorable case) and $\varepsilon_A = 0.03$ (also the overestimated value). The latter is estimated using the angular resolution of the telescopes and the derivative of A_y. The upper limit of the second correction term does not exceed 0.0015 for all measurements. The third correction term is less than $0.0005\,A_y$. The overall relative systematic uncertainty in the asymmetry measurement with STT does not exceed 0.3% [10].

3. Data Analysis (FD)

We measured the analysing power also with the FD independently. The Forward detector is a single-sided detector, so the measured asymmetry is more sensitive to the distorsion factors like the beam polarization modules inequality and geometry misalignment. It is necessary to normalize precisely the number of events collected at the beam polarization up and down. The number of the elastic protons was determined from the missing mass spectra after subtracting a linear background from the peak in each angular bin. The momentum reconstruction and other details of analysis and selection cryteria are described in Ref. [14].

The integral luminosties of the up and down polarized beams were used for the normalization of the events. The luminosity could be obtained by counting events in the regions where the analysing power vanishes, at extremly small ϑ or around $|\phi| \simeq 90^o$. The statistical uncertainty (σ_f) of the luminosity ratio has to be interpreted as a source of the systematic uncertainty in the asymmetry measurement changing it to $\varepsilon = PA\,[1 - \frac{\sigma_f}{2}\,\frac{1-P^2A^2}{PA}] < PA\,(1 - \sigma_f/2)$. The systematic uncertainty of asymmetry due to the luminosity normalization does not exceed 0.3 %. Since the normalizing events are selected with the same trigger as the ones of elastic scattering, the dead-time difference for the spin up and down data is taken into account in the relative luminosity factor. For the FD data there is a possible contribution associated with the assumption of equal up and down polarizations of the beam. The contribution has a form $\varepsilon = PA\,(1 + \varepsilon_P\,PA)^{-1}$, so for the extreme case $\varepsilon_P = 0.1$ the relative systematic uncertainty is less than 2.5 %. For the pp -elastic scattering a momentum reconstruction provides the uncertainty of the scattering angle $\sigma_\vartheta < 0.15^o$. One can compare the scattering angles in the $pp \to pp$ process when one proton is detected in FD and the another in STT. The difference is about 0.3^o. It is not possible to judge which detector is responsible for the difference. The FD efficiency for the beam up and down polarizations differs by less than 10^{-3}, and this difference is within the statistical uncertainty.

We estimated the overall systematic uncertainty in the asymmetry measurement with the FD as 5 % including the beam polarization systematic uncertainty.

4. Results

The analysing power in $pp \to pp$ elastic scattering is measured at first time at the beam energies of $1.6 - 2.4\,GeV$ in the angular range of $4 - 28$ degree; Study of the sources of the systematic errors revealed that all of them are negligible with reliable confidence. The results of A_y measurement for all six beam energies are shown in Fig. 1. Only statistical uncertainties are shown [15]. We have measured the analysing power in *pp* elastic scattering at 796 MeV and at five energies from 1.6 GeV up to 2.4 GeV using both the silicon tracking telescopes and the ANKE forward detector. The consistency between these two independent measurements showed that the only major systematic uncertainty is associated with the calibration of the EDDA polarimeter. Though the overall uncertainties are slightly larger for the FD data, these results are important because they extend the coverage to slightly larger scattering angles.

In the small angle range the new data are consistent with older measurements around 796 MeV [16,17] and also with the SAID SP07 predictions at this energy [18]. At higher energies the ANKE results lie significantly above the SP07 solution and also display a different angular dependence. By adjusting some of the phases and inelasticities in the low partial waves of this solution it has been possible to obtain a much better description of the ANKE A_y data with reasonable values of χ^2/ndf [18]. The new fits correspond to relatively modest changes to the parameters for several of the lower waves, with the bigest change being in $^3F_2$.

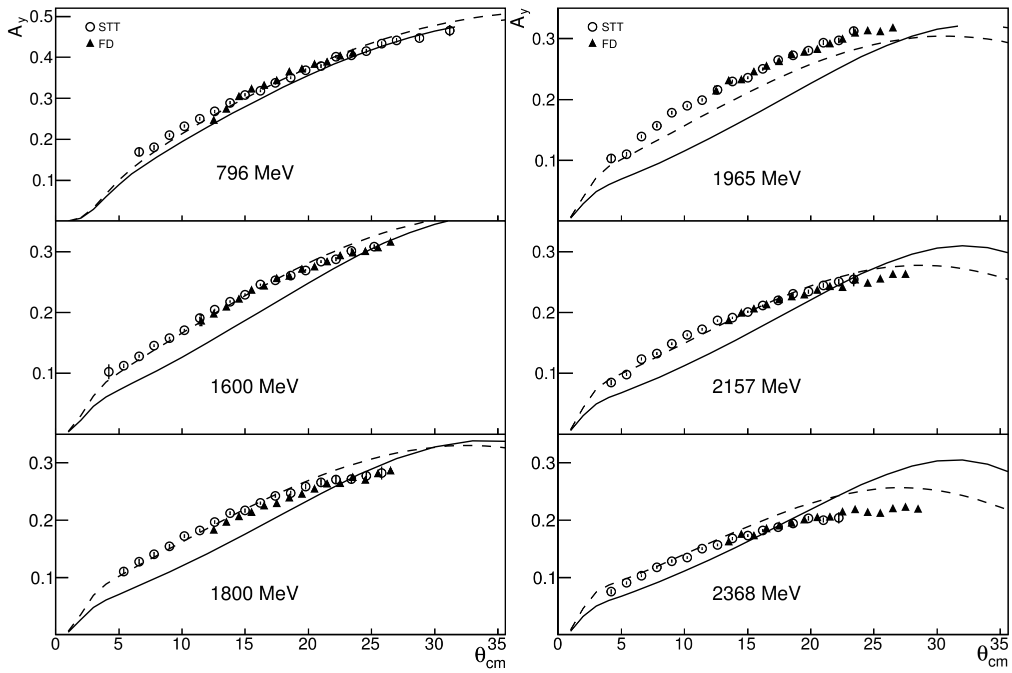

Fig. 1. Comparison of the ANKE measurements of the proton analysing power in *pp* elastic scattering using the STT (clear circles) and FD (black triangles) systems with the curves corresponding to the SAID SP07 (solid line) and the revised fit (dashed line) solutions.

The beam polarization measurement systematic uncertainty dominates in our results. The close coincidence of our measurements with the results of other experiments at 796 MeV [16,17] indicates that actually the systematic uncertainty due to the beam polarization measurement is negligible.

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