Eur. Phys. J. C 10, 409–413 (1999)
Digital Object Identifier (DOI) 10.1007/s100529900109

THE EUROPEAN PHYSICAL JOURNAL C

Measurement of the *pp* analyzing power in the vicinity of 2.20 GeV

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Received: 24 March 1999 / Published online: 12 August 1999

Abstract. The *pp* elastic scattering analyzing power was measured in small energy steps in the vicinity of the accelerator depolarizing resonance $\gamma G = 6$ at 2.202 GeV. A vertically polarized proton beam was extracted from SATURNE II at energies above the resonance and passed through different copper degraders. The beam was focused on the beam line polarimeter CH_2 target. Its halo was removed by four powerful magnets. Measurements at degraded energies were complemented by data obtained with the directly extracted polarized beam outside the resonance region. Analyzing power results at fixed laboratory angles are compared with existing data in the region under discussion, with polynomial fits from 1.6 to 3.5 GeV, and with phase shift analysis predictions.

1 Introduction

The experiment was carried out in the framework of the Nucleon–Nucleon (NN) program at SATURNE II. Its aim was to obtain the *pp* elastic scattering analyzing power A_{oono} in the kinetic energy region close to the the accelerator depolarizing resonance $\gamma G = 6$ at 2.202 GeV. This resonance is usually crossed by a spin flip at strong focusing accelerators. The beam polarization varies strongly within the resonance region, and the interval from 2.185 to 2.215 GeV cannot be reached. For this reason the extracted energy was fixed above the resonance and was decreased by Cu degraders. We assumed that passage of the beam through the degraders does not affect the beam polarization $\vec{P}_B$. This was checked outside the depolarizing resonance region, where several points were measured under different conditions. The NN beam line polarimeter PL1 [1,2] was used to determine the *pp* elastic scattering analyzing power A_{oono} at fixed laboratory angles $\theta_{\ell ab} = 11.6°, 13.9°, 16.1°$, and $18.4°$.

The present results are compared with the interpolated values from existing measurements [3–11], with the former fits to data from 1.6 to 3.5 GeV at the two smallest angles [12], and with the predictions of the Virginia Polytechnic Institute energy dependent phase shift analysis [13] (VPI-PSA).

We use the nucleon–nucleon notation from [14], where the subscripts of any observable X_{pqij} refer to the polarization states of the scattered, recoil, beam, and target particles, respectively. Since the target was unpolarized and polarizations of outgoing particles were not analyzed, only the beam spin index i remained. The polarizations of the incident particles in the laboratory system are oriented along the basic unit vectors $\vec{k}$, $\vec{n} = [\vec{k} \times \vec{k}']$, $\vec{s} = [\vec{n} \times \vec{k}]$, where $\vec{k}$ and $\vec{k}'$ are the beam and scattered particle directions, respectively, and $\vec{n}$ is the normal to the scattering plane.

$\vec{P}_B$ was oriented along the vertical direction and its sign changed every accelerator spill, whereas $|P_B|$ remained the same [15]. The particles were scattered on a CH_2 target and the asymmetry of the counts N^+ and N^-, recorded with $\pm|P_B|$, respectively, yielded

$$\epsilon(CH_2) = (N^+ - N^-)/(N^+ + N^-) = A(CH_2) \cdot P_B. \quad (1)$$

Here $A(CH_2)$ is the analyzing power of the target. For individual events, the azimuthal angle of the detectors

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$\phi \neq 0$, but its mean value is zero. On the other hand, ϕ is small enough to assume $\langle \cos\phi \rangle \sim 1$. This may decrease the A_{CH_2} value only negligibly. Under this condition one may assume that $\vec{n}$ is oriented vertically, and the remaining spin index $i = n$. An observable with spin index $i = s$ behaves as $\sin\phi$ and cancels out, since its mean value $\langle \sin\phi \rangle = 0$. Due to parity conservation, the $\vec{k}$ component of $\vec{P}_{\mathrm{B}}$ provides no asymmetry at all.

From the measured $\epsilon(CH_2)$ one can deduce the asymmetry $\epsilon(pp) = A_{oono}(pp) \cdot P_{\mathrm{B}}$ for elastic pp scattering (Sect. 2). Dedicated measurements of P_{B} allow the determination of $A_{oono}(pp)$.

2 Beam extraction and polarimeter set-up

The polarized proton beam with a spread smaller than 200 keV was extracted at 2.305, 2.258, and 2.250 GeV. Copper degraders were inserted close to the extraction point and a magnetic analysis by four powerful dipoles considerably reduced the beam halo. Inserting a particular degrader, the calculated magnet currents were first set and then the beam spot was checked by profilers. A disagreement between the calculated and measured spot positions indicated a possible correction to the degraded energy. It was always found to be smaller than ~ 2.0 MeV. Protons were focused by a quadrupole pair and tuned by another dipole at the polarimeter target. In addition, at some energies outside the resonance region the extracted beam was used directly in order to compare the results obtained with and without degraders.

The NN beam line polarimeter PL1 [1,2] had two pairs of kinematically conjugated arms in the horizontal plane: a left pair ("L") and a right pair ("R"). Each arm was equipped with two scintillation counters, and quadruple coincidences of signals from each pair were recorded. The forward scattering angles $\theta_{\ell ab}$ were fixed at each measurement. The angles of the backward arms were set by remote control. They were tuned to obtain a maximum of correlated counts for each pair of arms. The beam intensity was monitored by two pairs of scintillation counter monitors, positioned up ("U") and down ("D") in the vertical scattering plane.

The polarimeter target, either CH_2 or carbon, was a rectangular bar 5 mm thick (in the beam direction), 2 mm wide, and 15 mm high. The full scattering angle interval, $\Delta\theta_{\ell ab}$, accepted by the polarimeter definition counters was $\pm 1.9°$ in the laboratory frame. This provided $\Delta\theta_{\ell ab} = \pm 1°$ (half width at half maximum) for the polarimeter conjugate angle distribution. The vertical acceptance was $\pm 4.3°$.

The mean effective asymmetry is provided by the ion source opposite polarization states and by the counting rates in the "L" and "R" polarimeter arms. This allows for removal of an instrumental asymmetry using the so called "crossing formula". It is given by the arithmetical average ratio where the individual terms are geometrical averages of the L and R counts for two polarization states "+" and "−":

$$\epsilon(\mathrm{mean}) = \frac{\sqrt{N(\mathrm{L}+)N(\mathrm{R}-)} - \sqrt{N(\mathrm{L}-)N(\mathrm{R}+)}}{\sqrt{N(\mathrm{L}+)N(\mathrm{R}-)} + \sqrt{N(\mathrm{L}-)N(\mathrm{R}+)}}. \quad (2)$$

For the measurement in one angular position and with one target all the monitor normalization factors drop out in (2). In [1,2] a method is described which allows the determination of the pp elastic scattering asymmetry from the polarimeter measurements. The pp asymmetry obtained with the CH_2 target and with the polarimeter arms positioned at the pp elastic scattering conjugate angles is altered by contributions from pp quasielastic scattering on protons in the carbon, and from inelastic reactions on free and bound nucleons. A second measurement with a carbon target at the same position determines the asymmetry contribution from bound protons. To subtract background from inelastic reactions, the asymmetry with both CH_2 and C targets outside the pp elastic kinematics must be determined. The four measurements at each energy, normalized by U and D counts, determine $\epsilon(pp) = A_{oono} \cdot P_{\mathrm{B}}$, as well as the ratio

$$R = \epsilon(CH_2)/\epsilon(pp) = A(CH_2)/A_{oono}(pp), \quad (3)$$

in which P_{B} drops out. The ratio R depends on the polarimeter design only, and $R \leq 1.0$. The equality is valid for a very small acceptance only, but such a polarimeter needs a high beam intensity. The polarimeter PL1 was constructed for a continuous monitoring of P_{B} in simultaneous measurements with a polarized target, positioned downstream on the same beam line, which required the particle flux reduced to $\sim 2 \cdot 10^8$ protons/spill. For the present measurements the proton flux was about 50 times higher. The beam intensity was changed for each degrader in order to obtain roughly the same number of counts/spill in the detectors.

In the present experiment only the asymmetry $\epsilon(\mathrm{CH}_2)$ was measured and the asymmetry $\epsilon(pp)$ was deduced using (3) and the previously calibrated ratio R. It was accurately determined at the forward angles where A_{oono} is close to its maximum. Below $T_{\mathrm{kin}} = 1.0$ GeV this corresponds to $\theta_{\ell ab} = 18.4°$. In the energy interval from 0.92 to 1.45 GeV the angle of 16.1° was used [2], and 11.6° or 13.9° were optimal angles above this energy. The energy dependence of R at the two smaller angles is the same. Other data suggest that it behaves similarly also at 16.1° and 18.4°.

In many NN experiments P_{B} was determined independently. The beam and target analyzing powers A_{oono} and A_{ooon}, respectively, were measured simultaneously using the polarized beam and the polarized target. From the Pauli principle $A_{oono} = A_{ooon}$. The equality of these observables relates the energy dependent P_{B} to the energy independent target polarization P_{T}. The latter was accurately calibrated in a dedicated experiment at lower energy, where P_{B} was well known. In all measurements the polarimeter data were also recorded and $A_{oono}(pp)$ were deduced. The energy dependences at 11.6° and 13.9° were fitted. The data from other experiments between 1.6 and 3.5 GeV [5,12] were also included in the fits.

The linear fit to all previously existing $A_{oono}(11.6°)$ data as a function of the kinetic energy T yielded

$$A_{oono}(11.6°) = (0.507 \pm 0.019) - (0.108 \pm 0.009) \cdot T, \quad (4)$$

Table 1. The analyzing power A_{oono} in *pp* elastic scattering. The Cu degrader thickness is given for the extracted beam energy in each group. Errors of experimental values contain very small statistical uncertainties ($\leq \pm 0.003$), random-like errors from partial result dispersions, and systematic errors ($\sim \pm 5\%$) due to the angular bin width of $\pm 1^\circ(\ell ab)$. The different errors were added in quadrature. The relative normalization error on $\Delta P_{\rm B}$ (not included) is ±3%. In addition, at 16.1° and 18.4° a common multiplicative factor ranging from 1.00 to 1.10 may move all data of a given set together

		$\theta_{\ell ab} = 11.6^\circ$		$\theta_{\ell ab} = 13.9^\circ$		$\theta_{\ell ab} = 16.1^\circ$	
$T_{\rm kin}$ (GeV)	Cu (cm)	$\theta_{\rm CM}$ (deg)	$A_{oono}(pp)$	$\theta_{\rm CM}$ (deg)	$A_{oono}(pp)$	$\theta_{\rm CM}$ (deg)	$A_{oono}(pp)$
2.258	out	33.9	0.254 ± 0.013	40.3	0.190 ± 0.010	46.4	0.138 ± 0.007
2.219	3.0	33.7	0.303 ± 0.014			46.2	0.152 ± 0.007
2.206	4.0			40.1	0.190 ± 0.010	46.1	0.139 ± 0.008
2.180	6.0	33.6	0.264 ± 0.014	40.0	0.203 ± 0.011	46.0	0.153 ± 0.009
2.250	out	33.9	0.266 ± 0.013	40.3	0.202 ± 0.011	46.3	0.136 ± 0.007
2.224	2.0	33.8	0.229 ± 0.017	40.2	0.182 ± 0.013	46.2	0.142 ± 0.007
2.217	2.5	33.7	0.256 ± 0.014	40.2	0.217 ± 0.011	46.2	0.141 ± 0.007
2.211	3.0	33.7	0.257 ± 0.013	40.1	0.206 ± 0.010	46.1	0.140 ± 0.007
2.205	3.5	33.7	0.265 ± 0.014	40.1	0.205 ± 0.010	46.1	0.142 ± 0.007
2.198	4.0	33.7	0.271 ± 0.014	40.1	0.209 ± 0.011	46.1	0.142 ± 0.007
2.305	out	34.1	0.263 ± 0.013	40.6	0.217 ± 0.012	46.6	0.137 ± 0.007
2.279	2.0	34.0	0.260 ± 0.013	40.4	0.204 ± 0.011	46.5	0.138 ± 0.007
2.253	4.0	33.9	0.267 ± 0.013	40.3	0.211 ± 0.011	46.4	0.135 ± 0.007
		$\theta_{\ell ab} = 11.6^\circ$		$\theta_{\ell ab} = 16.1^\circ$		$\theta_{\ell ab} = 18.4^\circ$	
2.100	out	33.3	0.275 ± 0.014	45.6	0.162 ± 0.009	51.7	0.109 ± 0.006
2.175	out	33.6	0.287 ± 0.014	46.0	0.158 ± 0.008	52.1	0.120 ± 0.006
2.225	out	33.8	0.308 ± 0.016	46.2	0.186 ± 0.010	52.4	0.087 ± 0.005
2.272	out	33.9	0.279 ± 0.014				
2.297	out	34.0	0.276 ± 0.014				

where T is in GeV. The fit describes 28 contributing points with $\chi^2 = 14.97$ and is shown in Fig. 1.

The linear fit to $A_{oono}(13.9^\circ)$ data yielded

$$A_{oono}(13.9^\circ) = (0.623 \pm 0.012) - (0.180 \pm 0.005) \cdot T. \quad (5a)$$

It describes 75 contributing points with $\chi^2 = 90.28$.

The quadratic fit to the same data yielded

$$A_{oono}(13.9^\circ) = (0.798 \pm 0.074) - (0.331 \pm 0.063) \cdot T + (0.032 \pm 0.013) \cdot T^2, \quad (5b)$$

with $\chi^2 = 87.39$ and it is shown in the same figure. Note that the contribution of the quadratic term in (5b) is weak and its error is ±41%. The difference between the two fits (5a) and (5b) is negligible.

Using $\epsilon(pp)$ and the A_{oono} value at one given angle we obtain $P_{\rm B}$. Since it is independent of the polarimeter scattering angle $\theta_{\ell ab}$, the same $P_{\rm B}$ value may be used to obtain A_{oono} values at other angles, if the ratio R is known.

3 Results and discussion

The $A_{oono}(pp)$ data are given in Table 1 where they are divided into four groups. The data of each of the first three groups were taken with a fixed extracted beam energy. The energy was reduced by inserting different Cu degraders with thicknesses shown in the table. The degraded energies were corrected by the beam spot position, if necessary. The last group was measured with an extracted beam only. Statistics of counts at each angle and energy varied from $2 \cdot 10^5$ to 10^8 in both polarimeter arms. The beam polarization was deduced from dedicated measurements at $13.9^\circ(\ell ab)$ at energies where no degraders were used.

At 16.1° and 18.4° the factor R of (3) has been assumed to be the same as at 13.9°. This assumption introduces an additional common uncertainty of less than 10%.

Errors on the experimental values contain statistical uncertainties and systematic errors due to the angular bin width of $\pm 1^\circ(\ell ab)$. The normalization error $\Delta P_{\rm B}$ is ±3%.

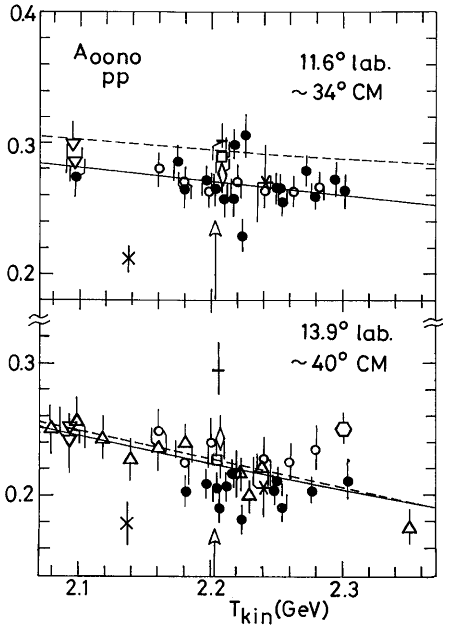

Fig. 1. A_{oono} energy dependence at $11.6°(\ell ab) \sim 34°$(CM) and $13.9°(\ell ab) \sim 40°$(CM). The meaning of the symbols is as follows. $\bullet$ is for this experiment, $\bigtriangledown$ for [3], $\circ$ for [4], $\bigtriangleup$ for [5], $\star$ for [6], $+$ for [7], $\times$ for [8], hexagon for [9], $\diamondsuit$ for [10], an open square for [11]; arrows are for the depolarizing resonance energy, solid curves for fits referring to [12] and dashed curves for VPI-PSA [13]

The results for the two smaller angles are plotted in Fig. 1 and for the larger angles in Fig. 2. Existing data in the energy region from 2.08 to 2.36 GeV are shown. The ANL-ZGS data [7–11] are plotted without normalization factors as recommended in [16]. The arrows in the figures denote the energy of the accelerator depolarizing resonance. The nominal ZGS energies cannot be taken literally, since the uncertainty in beam momentum was relatively large ($\sim \pm 3.5\%$). The solid lines in Fig. 1 represent the fits (4) and (5b) to all previously existing data over the region from 1.6 to 3.5 GeV [12] (Sect. 2). The dashed curves in both figures are the predictions of VPI-PSA [13], where the present data were included. Both curves are in excellent agreement at 13.9°. The PSA predictions at other angles give systematically larger A_{oono} values than the majority of the data points.

In general, no PSA represents an ideal tool for the absolute beam polarimetry. This is simply due to the goal of a PSA, which is to describe the angular dependence of all independent observables together. Such a description depends, among other things, on the number of free phase shifts. For an energy dependent PSA, in addition, the prediction at one energy depends on data in a large energy region and local structures may be averaged away.

Note that the laboratory angles 16.1° and 18.4° were used to monitor the beam polarization at low energies. They are not a good choice for a *pp* polarimeter setting between $T_{\rm kin}$ from 1.5 to 3 GeV. The $A_{oono}(pp)$ value around 16.1° strongly depends on the angle. Around 18.4° and above 2 GeV, the analyzing power is close to its first min-

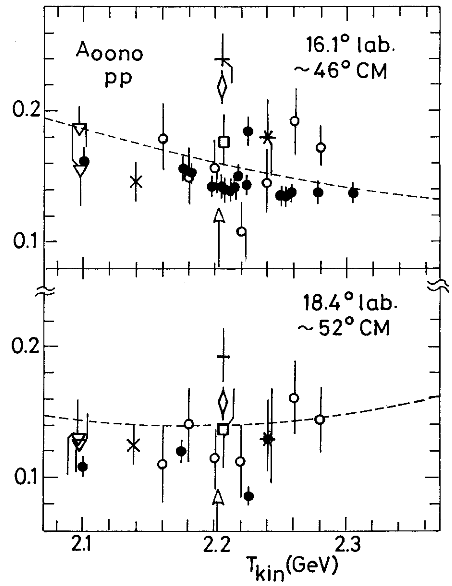

Fig. 2. A_{oono} energy dependence at $16.1°(\ell ab) \sim 46°$(CM) and $18.4°(\ell ab) \sim 52°$(CM). The meaning of the symbols is the same as in Fig. 1

imum [17]. This can be seen for the latter angle from the VPI-PSA prediction in Fig. 2.

4 Conclusions

The present results agree well with existing data and complete the information necessary for beam polarization measurements. They show no anomaly in the *pp* analyzing power energy dependence in the region of the strong depolarizing resonance $\gamma G = 6$. Our results suggest that energy degraders may be used in the otherwise forbidden interval over the depolarizing resonance width. In this special case the fits to the analyzing power data at small angles provide a better description than the PSA predictions.

Acknowledgements. The authors thank the SATURNE II operators and engineers for their efficient help. This work was supported in part by the U.S. Department of Energy, Division of Nuclear Physics, Contract No. W-31-109-ENG-38 and by the Swiss National Science Foundation.

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