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# ANGULAR DEPENDENCE OF pp SPIN CORRELATION AND RESCATTERING OBSERVABLES BETWEEN 1.80 AND 2.10 GeV

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## ABSTRACT

A polarized proton beam extracted from SATURNE II and the Saclay polarized proton target were used to determine the spin correlation parameter $A_{oosk}$ and the rescattering observables $K_{os''so}$, $D_{os''ok}$, $N_{os''sn}$, and $N_{onsk}$ at 1.80 and 2.10 GeV. The beam polarization was oriented perpendicular to the beam direction in the horizontal scattering plane and the target polarization was directed either along the vertical axis or longitudinally. Left-right and up-down asymmetries in the second scattering were measured. A check for the beam optimization with the beam and target polarizations oriented vertically provided other observables, of which results for $D_{onon}$ and $K_{onno}$ at 1.80, 1.85, 2.04, and 2.10 GeV are listed here. The new data at 2.10 GeV suggest a smooth energy dependence of spin triplet scattering amplitudes at fixed angles in the vicinity of this energy.

## 1. INTRODUCTION

We present the data resulting from an experiment at SATURNE II performed to resolve an observed ambiguity in the *pp* elastic scattering direct amplitude reconstruction at 2.1 GeV [1]. Most of the *pp* amplitude determinations, based on previously measured data at 11 energies between 0.8 and 2.7 GeV, have resulted in a unique type of solution [1]. However two solutions were obtained at 2.1 GeV. The most probable of the two solutions differs from the type of solution that was found at the other energies, indicating the existence of a possible resonance in a spin-triplet amplitude in the vicinity of this energy. In contrast, the solution with the lower probability did not suggest a resonance. In order to choose between the two solutions at 2.1 GeV, all measurable quantities were calculated using both sets of amplitudes. The predictions differ most for the observables $K_{os''so}$ and $N_{onsk}$. In the original data $K_{os''so}$ was determined with insufficient accuracy, while $N_{onsk}$ was measured as an linear combination with other observables [2]. A comparison of the predictions with the new experimental results presented here may rule out one of the solutions. Measurements of these two observables were performed both at 1.80 and 2.10 GeV. In addition, the quantities $A_{oosk}$, $D_{onon}$, $K_{onno}$, $D_{os''ok}$, and $N_{os''sn}$ were obtained as by-products. The tuning of the accelerator at 1.85 and 2.04 GeV for other purposes resulted in measurements of $D_{onon}$ and $K_{onno}$ at two additional energies.

Our results are compared with previous Saclay data [2 to 7], with BNL Cosmotron data for $D_{onon}$ and $D_{os''os}$ at 1.9 GeV [8], with ANL-ZGS data for $D_{onon}$ at 2.205 GeV [9] and with predictions from a phase shift analysis [10]. Throughout the paper we use the NN formalism and the four-index notation for observables given in Ref. [11]. The observables in the notation of Halsen-Thomas are listed in [12,13].

## 2. NUCLEON-NUCLEON OBSERVABLES

The subscripts of any observable $X_{oqij}$ refer to the polarization states of the scattered, recoil, beam, and target particles, respectively. For the so-called "pure experiments," the polarizations of the incident and target particles in the laboratory system are oriented along the basic unit vectors $\vec{k}$, $\vec{n}$, $\vec{s} = [\vec{n} \times \vec{k}]$. The recoil protons are analyzed in the directions $\vec{k}''$, $\vec{n}$, $\vec{s}'' = [\vec{n} \times \vec{k}'']$.

where the unit vector $\vec{k}''$ is oriented along the direction of the recoil particle momentum.

The most general formula for the correlated nucleon-nucleon scattering cross section $\Sigma$ is given in [11]. It assumes that both initial particles are polarized and the polarization of scattered and recoil particles are analyzed. The formula does not includethe simplifications resulting from the application of conservation laws and is valid in any reference frame. It can be simplified, when one or more of the four polarization states involved is not measured in an experiment. Here we give the formula valid for the polarized beam and target and for the analyzed recoil particle labeled "2".

$$\Sigma(P_B,P_T,P_2) = I_2(\frac{d\sigma}{d\Omega})_0\Big((1 + A_{ooio}P_{Bi} + A_{oooj}P_{Tj} + A_{ooij}P_{Bi}P_{Tj})$$

$$+ P_2(P_{oqoo} + K_{oqio}P_{Bi} + D_{oqoj}P_{Tj} + +N_{oqij}P_{Bi}P_{Tj})n_{2q}\Big). \quad (2.1)$$

The summation is implicit over the indices $o,q,i,j$. Indices $i,j$ correspond to the basis vectors for incident and target protons, respectively, index $q$ refers to the unit vectors for recoil protons, index "o" denotes zero. $(d\sigma/d\Omega)_0$ is the differential cross section for single scattering of unpolarized incident and target particles. $P_{Bi}$ and $P_{Tj}$ are the beam and target polarization components, respectively. $I_2$ and $P_2$ denote the cross section and the analysing power for the recoil particle analyzer "2", respectively. If there is no rescattering ($q = o$), $I_2 = 1$ and $P_2 = 0$. The unit vector $\vec{n}_2 = [\vec{k}'' \times \vec{k}_r]$ is along the direction of the normal to the recoil particle analysing plane. Here $\vec{k}_r$ is a unit vector in the direction of the rescattered particle. The scalar product $(\vec{n},\vec{n}_2)$ determines the components $n_{2q}$ for different directions of $\vec{n}_2$.

In absence of a magnetic field between the first target and the analyzer the scalar product $n_{2k''}$ is zero, since the vectors $\vec{k}''$ and $\vec{n}$ are perpendicular. The scalar products $n_{2n}$ and $n_{2k''}$ are then to be understood as cosines of the angles between the normal $\vec{n}_2$ and the direction to which the $\vec{n}$ and $\vec{k}''$ of the recoil particle polarization have been rotated by the magnetic field. Note that in any experiment, residual components of the beam and target polarizations in non-dominant directions might exist, providing combinations of "pure observables".

We suppose that $\vec{P}_B$ and $\vec{P}_T$ are oriented strictly along the basis vectors and that we analyze the recoil particle polarization components along $\vec{n}$ and $\vec{s}''$.

a) For $P_{Bs}$ and $P_{Tk}$ from the single scattering we obtain $A_{oosk}$. From the Down-Up (D-U) asymmetry in the second scattering and if the central direction of $\vec{n}_2$ in the scalar product $n_{2q}$ is oriented along $\pm\vec{s}''$, we obtain $K_{os''so}$ and $D_{os''ok}$. The Left-Right (L-R) second scattering asymmetry gives $P_{onoo}$ and $N_{onsk}$. The PPT holding coil fringe field may rotate recoil proton spins from $\vec{k}''$ in the $\vec{s}''$ direction and contribute by a very small fraction $\epsilon(K_{ok''so}P_{Bs} + D_{ok''ok}P_{Tk})$. These second order contributions were treated in detail in Refs.[7,14] and were mostly suppressed in the present experiment (see below).

b) For $P_{Bs}$ and $P_{Tn}$ the single scattering gives the target analyzing power $A_{ooon}$. In the present paper it was imposed by interpolated results of Ref. [15]. $P_{onoo}$, $D_{onon}$ are determined from the L-R asymmetry in the second scattering, the D-U one provides $K_{os''so}$ and $N_{os''sn}$. A small residual contribution $\epsilon(K_{ok''so} + N_{ok''sn})$ is almost suppressed.

c) For $P_{Bn}$ and $P_{Tn}$ Eq.(2.3) reduces to the single scattering gives $A_{oono}$, $A_{ooon}$ and the spin correlation $A_{oonn}$. The analyzing scattering gives $P_{onoo}$, $D_{onon}$, $K_{onno}$ and $N_{onnn}$ from the L-R asymmetry. In this spin configuration residual observables are negligible.

$A_{oono}$ and $A_{ooon}$ are equal due to Pauli principle [11]. In order to determine $D_{onon}$ and $K_{onno}$ the knowledge of $A_{oonn}$ and $N_{onnn}$ is not needed. $K_{onno}$ is independent of $P_T$ and $D_{onon}$ is independent of $P_B$. The number of events averaged over $P_B$ represents an unpolarized beam and the terms containing $A_{oonn}$, $K_{onon}$ and $N_{onnn}$ cancel out. Similar considerations are valid for $P_{Tn}$, where only $P_{onoo}$, $K_{onno}$ and $A_{oono}$ survive. The observable $K_{onno}$ at the angle $\theta_{CM}$ is equal to $D_{onon}$ at the angle $180° - \theta_{CM}$. The rescattering observables $P_{onoo} = N_{onnn}$ are equal to the single scattering quantities $A_{oono}$ and $A_{ooon}$, which are known with better accuracy. We therefore fixed in the calculations $P_{onoo}$ by the single scattering $A_{oono} = A_{ooon}$ data from [15]. All other observables are equal to zero due to conservation laws.

The observables $K_{os''so}$ and $D_{onon}$ were each measured in the two different beam and target spin configurations. The configuration "a)" would have been sufficient to determine both the desired observables $K_{os''so}$ and $N_{onsk}$, but the additional measurement in the configuration "b)" removes many undesirable residual quantities and checked internal compatibility of the experiment. This procedure has been discussed in Refs.[2,5,6,7].

## 3. POLARIZED BEAM AND EXPERIMENTAL SET-UP

The polarization of the extracted proton beam at SATURNE II was oriented vertically and its direction was flipped at each accelerator spill. We have measured the beam particle scattering asymmetry with three polarimeters (Fig. 1). $P_B$ was monitored by a first beam polarimeter (PL1) [16], having two pairs of kinematically conjugate arms in the horizontal plane and beam intensity monitors in the vertical plane. It measured the L-R scattering asymmetry $\epsilon = P_B * A$, where $A$ is the analyzing power. In the present experiment the $p - CH_2$ asymmetry was measured at 13.9°;*lab* and the *pp* elastic scattering asymmetry was deduded using the known ratio of the $CH_2$ and the *pp* asymmetries for this polarimeter [17]. $P_B$ was calculated using the energy dependence of $A_{oono}$ at fixed angles [18].

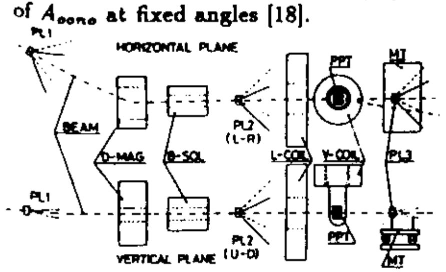

Fig. 1. Beam line (not to scale). PL1, PL2 and PL3 are polarimeters, D-MAG is a bending dipole, B-SOL is the beam solenoid, COIL $\vec{k}$ is the longitudinal holding coil, COIL $\vec{n}$ is the vertical one. MT is the movable table.

The vertical beam polarization could be rotated around the beam axis by a superconducting solenoid. The resulting $\vec{P}_B$ was checked by a second beam polarimeter (PL2) upstream of the PPT. PL2 measured L-R and D-U scattering asymmetries [16,19], depending on the solenoid current IS (Fig 2).

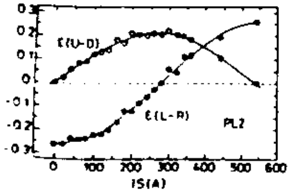

Fig. 2. L-R (o) and U-D (•) asymmetries, measured with PL2 as functions of IS. For the $(P_{Bs}, P_{Tn})$ measurement IS setting corresponds to the zero cross of the dashed curve and IS is zero for (the $P_{Bn}, P_{Tn}$) one.

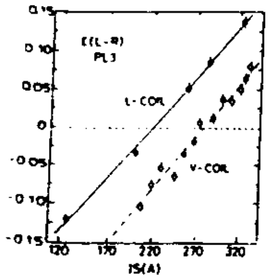

Fig. 3. L-R asymmetries measured with PL3 as functions of IS. The dashed line zero cross is the IS setting for the $(P_{Bs}, P_{Tn})$ measurement, the solid curve zero cross is the IS setting for the $(P_{Bs}, P_{Tk})$ measurement.

60 cm upstream of the PPT, was situated the longitudinal superconducting holding coil, which provided the nominal holding field of 0.33 T at the target center. Particles passed through this coil and sideways-oriented spins were rotated around the beam axis. In order to obtain the sideways beam polarization in the PPT center, the beam solenoid current was adjusted to correct for the spin rotation due to the holding coil.

For the present experiment a new polarimeter (PL3) was constructed and positioned 7 m downstream of the PPT on a remotely-controlled movable table. The procedure to obtain the correct compensation was as follows. The beam position at the PL3 target was first found without the longitudinal target holding field. Then the D-U asymmetry was measured with PL2, and L-R asymmetries were simultaneously obtained with PL2 and PL3. The solenoid current corresponding to the value where both of the L-R asymmetries crossed zero could be rapidly determined. At the nominal longitudinal holding coil current, the beam position was again checked. Then a new L-R zero crossing

point for the PL3 asymmetry was found as a function of IS. This function is shown in Fig. 3 in the vicinity of the zero crossing point with and without the longitudinal holding field. The solenoid current for sideways beam polarization was found with an accuracy better than ±1%.

When the PPT was polarized along the vertical axis, the vertical magnetic holding coil provided only a weak bending field. The bending of the beam particles could be easily determined by the difference of the beam spot positions, with and without the vertical holding field, measured by varying the PL3 location. A similar measurement without the vertical holding field determines a possible difference between the incident beam direction and the geometrical beam axis.

The sideways beam polarization in the vertical holding field rotated negligibly around the vertical axis. The polarization direction of the recoil particles may slightly rotate for any direction of the target field, as described in [19].

The Saclay frozen spin PPT, 35 mm thick, 40 mm long, and 49 mm high, contained pentanol-1 doped by paramagnetic centers [20]. The typical target polarization was ~ +80%. The target worked in the frozen spin mode at a small magnetic holding field. The relaxation time of the target averaged around 25 days. The longitudinal target polarization may be inverted either by a PPT repolarization using a different hyperfrequency, or by magnetic field inversion. Applying both methods, one considerably decreases the contributions of undesired observables [19].

The present measurements were carried out using the Nucleon-Nucleon experimental set-up. This apparatus and additional information on the data analysis is described in detail in Ref. [19]. It consisted of a two-arm spectrometer with an analyzing magnet in the forward arm. Each arm was equipped with single scintillation counters and counter hodoscopes selecting events with pairs of charged particles. These signals triggered eight multi-wire proportional chambers (MWPC's) with three wire planes each. Recoil particles were rescattered on a 6 cm-thick carbon analyzer and L-R and D-U rescattering events were recorded. The *pp*-elastic events from the PPT were selected in the OFF-LINE analysis by kinematic conditions, bending of scattered protons in the analyzing magnet, and by TOF information. Rescattering events with one outgoing particle from the carbon analyzer, with a lab. scattering angle from 4° to 20°, were accepted in the OFF-LINE data analysis. They represented about 2% of the single scattering events. The $p - C$ analyzing power was interpolated from the results given in [8,21-30].

Finally note that in the present experiment, only the two states of the ion source with large polarizations were used. The magnitudes of the polarizations were shown to be equal in Ref. [31].

## 4. RESULTS AND DISCUSSION

The results for the spin correlation parameter $A_{oosk}(pp)$ are plotted in Fig. 4. The random-like systematic error, estimated to be ±5%, was provided by MWPC efficiency fluctuations between PPT polarization reversals. The normalization systematic error in $P_B$ was ±3% [18,19], and the same error was attributed to the PPT polarization [20].

The results are compared with the previously-measured Saclay data from Refs. [3,4], and with the predictions of an energy-dependent PSA [10]. The data [3,4] were measured with the beam having nonzero polarization components in both the $\vec{s}$" and $\vec{k}$" directions, and had large statistical errors. At small angles, the angular distribution changes rapidly with energy [3,4]. Above 60°$CM$, the new $A_{oosk}$ data are consistent with zero at both 1.80 and 2.10 GeV.

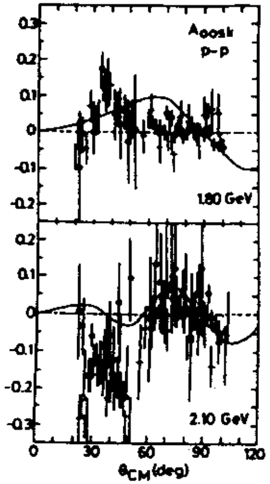

Fig. 4. $A_{oosk}(pp)$ at 1.80 GeV and 2.10 GeV Solid curves are predictions of the energy dependent PSA [8]. • ... present results, ○ ... Ref.[3], + ... Ref.[4].

In Fig. 5 are shown the rescattering observables with two and three spin indices measured with $\vec{P}_B$ in the $\pm\vec{s}$ direction and with $\vec{P}_T$ either in the $\pm\vec{k}$ or $\pm\vec{n}$ directions. They are compared with previously-measured $K_{os''so}$ [2] and $D_{os''ok}$ [2,7] Saclay data. The point $D_{os''os}(90°) = K_{os''so}(90°)$ measured at 1.9 GeV in a triple scattering experiment at the BNL Cosmotron [8] is plotted together with the data at 1.80 GeV. The PSA predictions [10] are also shown. The new data for $K_{os''so}$ were averaged over measurements with two target spin configurations. Also shown in Fig. 5 are the amplitude analysis predictions at 2.10 GeV and 66°$CM$ for both the non-resonant (Sol. 1) and the resonant solutions (Sol. 2) from Ref. [1]. The new results for the $K_{os''so}$ and $N_{onsk}$ agree well with Sol. 1.

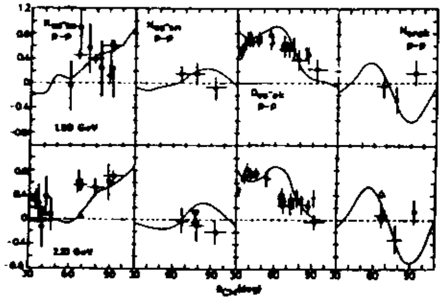

Fig. 5. $K_{os''so}$, $D_{os''ok}$, $N_{os''sn}$ and $N_{onsk}$ at 1.80 GeV and 2.10 GeV. Solid curves ... PSA [10], • ... present results, ○ ... [2], + ... [7], ◃ ... [8], ▹ ... [9], ▽ ... Sol. 1 (non-resonant), △ ... Sol. 2 [1].

$D_{onon}$ and $K_{onno} = D_{onon}(180° - \theta_{CM})$ results are plotted in Fig. 6, together with the previously-existing data [5,6], one point at 1.9 GeV from [8], three points at 2.2 GeV measured at the ANL-ZGS [9] and the PSA predictions [10].

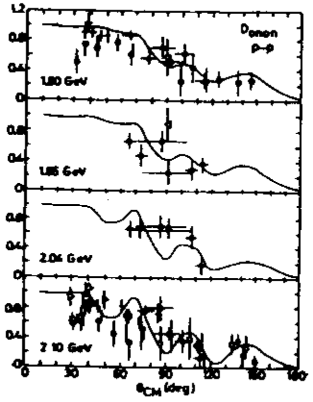

Fig. 6. $D_{onon}$ and $D_{onon}(180° - \theta_{CM}) = K_{onno}(\theta_{CM})$ at four energies. Solid lines ... PSA [10], •....present results, ○....[5], +....[6], ◃ ....[8], ▹ .... [9], ▽.... Sol. 1 [1], △.... Sol. 2 [1].

The random-like and the target polarization systematic errors were negligibly small for the $K_{os''so}$ and $K_{onno}$ observables. For other quantities they were of the same magnitude as for $A_{oosk}$ data. The systematic errors are also provided by a normalisation uncertainty in the $p-C$ analyzing power. This normalising error is around ±6% for the recoil proton energy up to ~ 1 GeV. Angular bins for rescattering observables are large, due to small statistics of the events.

The $p-C$ analyzing power was applied to each accepted event at its true energy and angle and then the results were averaged over the bins.

## 5. CONCLUSIONS

Previous measurements of $A_{oosk}$ were published in [3,4], of $K_{os''so}$ in [2,8], of $D_{os''ok}$ in [2,7], of $D_{onon}$ in [5,6,8,9], and of $K_{onno}$ in [5,6]. $N_{os''sn}$ and $N_{onsk}$ were not measured as the "pure observables" previously in 2 GeV region. All quantities treated here were determined at 6 GeV/c at the ANL-ZGS and used in the direct reconststruction of the scattering matrix at this beam momentum [13]. $K_{os''so}$ and $N_{onsk}$ behave similarly at 1.80 and 2.10 GeV and support the validity of the amplitude solution with the non-resonant spin-triplet partial waves. All the present results improve the existing database for $pp$ elastic scattering. They are not yet included in the PSA. A sideways-oriented polarized proton beam, with immeasurably-small residual polarization components at the target center, was achieved for the purposes of the present experiment.

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