MEASUREMENT OF THE POLARIZATION PARAMETER IN pp ELASTIC SCATTERING AT 150 GeV/c

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ABSTRACT

The polarization parameter in pp elastic scattering at 150 GeV/c, and in the momentum transfer interval $0.4 \leq -t \leq 3.0 \text{ GeV}^2$, has been measured in a MWPC and scintillation counter experiment at the CERN SPS using a polarized proton target. The polarization is decreasing steadily from zero to $\sim -10\%$ in the range $0.4 < -t < 1.3 \text{ GeV}^2$; for higher $|t|$ the data suggest a change of sign. Results are also given for the differential cross-section, which exhibits a small dip at $-t = (1.46 \pm 0.01) \text{ GeV}^2$.

1. INTRODUCTION

In the early 1970's considerable attention was devoted to the pp system, which had shown novel features in the first ISR experiments [1,2] and in a polarization experiment at Serpukhov [3]. We refer to an unexpected increase with energy of the total cross-section [1], the development of a diffraction minimum in the elastic differential cross-section [2], and possibly a large polarization parameter [3] in elastic scattering at an energy at which the total cross-section was a minimum. Spin effects had for a long time been expected to be negligible at energies larger than the PS energies. The possibility that they might indeed again turn out to be important was very tempting, and we decided to investigate this point up to the highest SPS energies. The underlying aim when starting out on this program of measurements was of course that at sufficiently high energies, and at sufficiently high momentum transfer, the spin dependence of the hard pp scattering would provide information about the spin of the proton constituents.

We report here on pp elastic scattering polarization data taken at an incident momentum of 150 GeV/c in the four-momentum transfer range $0.4 \leq -t \leq 3.0 \text{ GeV}^2$. The experiment has been run at the CERN Super Proton Synchrotron (SPS) during July 1978. The results of a previous preliminary run with less statistics have already been published [4].

In the following we give a detailed description of the apparatus used, the trigger logic, and the method of analysis. We have used an intense beam and a long polarized proton target to get a reasonable number of events even at the highest $|t|$ values, where the differential cross-section goes down to $\sim 10 \text{ nb/GeV}^2$. We have measured the momentum and direction of both outgoing particles in order to have the maximum number of constraints and to reach a good background rejection. Multiwire proportional chambers (MWPCs) and scintillation counter hodoscopes have been employed as detectors to take the highest possible trigger rate and still obtain good resolution in the scattering angles.

2. EXPERIMENTAL SET-UP

The layout of the apparatus is given in figs. 1 and 2. The polarized target (PT) is installed in the centre of a C-type magnet with circular coils and pole faces. The centre of the magnet is taken as the origin of the right-handed coordinate system, with the z-axis in the direction of the beam momentum and the y-axis vertical, pointing upwards. The scattered proton is detected by the scintillation counters S1 and S2 before the two forward spectrometer magnets, and by the hodoscopes FV and FH after the magnets. Its trajectory and momentum are measured by two telescopes of MWPCs (F1-F4 and F5-F8), before and after the magnets.

The recoil proton is detected by the counters T1 and T2, located close to and parallel with the target cryostat, and by the hodoscopes BH and BV after a flight path of about 3.8 m. Its trajectory and momentum are measured by two MWPCs (B1 and B2) located inside the PT magnet gap, and by a telescope of MWPCs (B3-B6) outside the field region.

2.1 The beam

The experiment makes use of the H3 beam [5] in the SPS West Area, produced at 0.5 mrad by the 210 GeV/c external proton beam impinging on a $0.4 \times 0.4 \times 50 \text{ cm}^3$ beryllium target. The central value of the momentum p is 151 GeV/c with $\sigma_p = 1.5 \text{ GeV/c}$. Two wobbling magnets compensate for the PT magnet deflection up to the PT centre. The values of the horizontal and vertical divergence at the PT are (see also Section 4.3) $\sigma_{x'} = 0.14 \text{ mrad}$ and $\sigma_{y'} = 0.18 \text{ mrad}$, with a beam spot of $\sigma_x = 3.4 \text{ mm}$, $\sigma_y = 2.4 \text{ mm}$.

The beam profile is monitored by two sets of charge-integrating MWPCs [6] located 3.4 m upstream and 49 m downstream of the PT. The average intensity is 5×10^7 protons per burst (7×10^{11} incoming primary protons in an $\sim 0.8 \text{ s}$ effective spill time, every 8.4 s). It is monitored at the last quadrupoles ($\sim 30 \text{ m}$ upstream of the PT) by two threshold Čerenkov counters 10 and 8 m long, respectively, filled with helium and tuned on pions ($\sim 4\%$ of the beam).

2.2 The target

A 1,2 propanediol ($C_3H_8O_2$) target, doped with Cr^V complexes, is used for the polarization measurement. The beads are contained in a cavity, 15 cm long and 20 mm in diameter, with silver-plated copper walls 0.1 mm thick. The target is cooled to 0.55 K in a 3He evaporation refrigerator, inside a 2.5 T magnetic field uniform within $\pm 2.5 \times 10^{-4}$ T. Dynamic nuclear polarization is achieved with 50 mW of microwave power.

On the average a polarization of $\sim 90\%$ is obtained for the free protons (effective density 0.07 g cm^{-3}). It is measured by three NMR coils, coaxial with the target, one at the centre and the others at the two ends. Their signals are calibrated by measuring the thermal equilibrium polarization at 0.7 K, before and after the data-taking period. A typical time for reversing the polarization to 60% of the opposite sign is ~ 15 minutes.

The beam reaches the target by passing through a 0.1 mm stainless-steel window inside the cryostat. The latter protrudes in the high-field region through a cylindrical hole in the magnet yoke. The cryostat and the target are centred along the z-axis, as shown in fig. 2.

A carbon target (CT) is used during $\sim 20\%$ of the running time to measure the background distributions from scattering on bound protons (these have a density, in the PT, 4.3 times that of free protons). The carbon target consists of 10 graphite disks, 5 mm thick, equally spaced (10 mm) in a copper container, of the same size as the PT, which had been sealed after heating to 725°C in vacuum in order to remove any water.

2.3 The magnets

In the target region (~ 20 cm diameter and 10 cm gap) the PT magnet provides a vertical field of 2.5 T, directed upwards. The field, which has cylindrical symmetry around the y-axis, is also used for the measurement of the recoil proton momentum. The total bending power from the centre of the magnet is $0.95 \text{ T}\cdot\text{m}$ and the vertical acceptance $\pm 15^\circ$ with respect to the median plane. The field has

been mapped over the solid angle of interest, and its cylindrical symmetry has been verified to better than 1% also in the fringing field region. A two-dimensional field representation is therefore adequate; it is evaluated, describing the field by a superposition of Helmholtz coils [7].

In the forward spectrometer two H-magnets are used, with a total bending power of 6.8 T·m (corresponding to ~ 13 mrad deflection for a 150 GeV/c particle) and a 20 cm gap. The field, whose main component is also vertical and directed upwards, has been measured with a 0.4% accuracy. The field map is divided into 648 boxes, in each of which the three field components are approximated by third-order polynomials fulfilling Maxwell equations [8] (6000 coefficients in total). This is a reasonable compromise between the storage space and the computer time necessary to evaluate the field at a given point.

2.4 The scintillation counters

The forward and the recoil hodoscopes are both made of two arrays of counters: vertical ones to define the polar angle θ of the particles with respect to the beam direction, and horizontal ones to define the azimuthal angle ϕ . All these counters are 10 mm thick and are made of NE110 scintillator.

The forward vertical hodoscope (FV) consists of 16 strips, 320 mm long and 30 mm wide. The horizontal one (FH) is made of 10 strips, 485 mm long with a tapered shape, 40 mm wide on the side far from the beam (where the light-guides and photomultipliers are located) and 15 mm wide on the side close to the beam. Each strip has an acceptance of $\sim 3^\circ$ in the azimuthal angle ϕ .

In the recoil hodoscope there are 11 vertical strips (BV), each 1600 mm long and 100 mm wide, and 16 horizontal strips (BH), 1100 mm long and 100 mm wide.

All these counters, except those of FH, are viewed by photomultipliers at both ends in order to eliminate noise and to improve the time definition in the trigger by the use of mean-timers.

Counters S1 and S2, placed downstream of the target and perpendicular to the scattered particle direction, are wedge-shaped and 4 mm thick. To define different t-regions in the trigger, S2 is divided into three separate vertical parts: counters A, B, and C, for small (A+B) and large (B+C) scattering angles, respectively.

Counter T1, 5 mm thick, parallel to the beam at 3 cm distance, covers the useful target dimensions and is seen by photomultipliers at both ends. Counter T2, 3 mm thick, parallel to T1 at 9 cm from the beam, limits the solid angle to the region of interest for the elastic recoil protons.

All counters are equipped with 12-stage Philips-RTC photomultipliers XP2020 and fed by a specially developed power supply*) capable of standing high rate operation (up to 10 MHz) and allowing remote high-voltage setting and monitoring under computer control.

The plateaux of all the hodoscope counters were determined in a test beam. By slightly adjusting the individual high-voltage setting, an amplitude equalization within $\pm 8\%$ was obtained and the time resolution after mean-timing was $\sigma = 0.2$ ns over the entire surface. This value is also obtained during the experiment when comparing adjacent horizontal and vertical hodoscopes. The relative delays between counters of the same hodoscope are equalized to better than ± 0.2 ns.

2.5 The proportional chamber telescopes

2.5.1 Forward arm

As shown in fig. 1b, each of the two chamber telescopes, before and after the spectrometer magnets, consists of two blocks with four sense-wire planes orthogonal to the z-axis. The chambers are made of a sandwich of self-supporting foam plates coated with aluminium to provide the cathodes for the sense gaps, requiring reduced frame dimensions for supporting the anode wire planes only. This construction allows the sense wires to come close to the beam with almost no material in the high rate region. Each module has two gaps (6 mm half width) with

*) Now CERN standards EP4239 and EP4240.

mutually orthogonal sense-wire planes (2 mm spacing). The modules F1, F2, F3, F5, and F7 measure the horizontal and vertical coordinates x and y , while the modules F4, F6, and F8 are rotated by 30° and measure the u and v coordinates. Chambers F1 and F2 have an area of $500 \times 250 \text{ mm}^2$, while all the others are $500 \times 500 \text{ mm}^2$.

2.5.2 Backward arm

The chamber B1 ($320 \times 50 \text{ mm}^2$) consists of three gaps with sense wires 1 mm apart, placed parallel to the target and as close as possible to the beam axis (5 cm) in the 2.5 T field region between the poles of the PT magnet. It measures the z coordinate twice, and the y once. The chamber B2 ($640 \times 150 \text{ mm}^2$) consists of two gaps placed in a field region of $\sim 1 \text{ T}$; it is shaped as a sector of a cylinder (310 mm radius) whose axis is the symmetry axis of the PT magnet. Each gap contains an array of 2 mm step vertical sense wires, measuring α , the polar angle in the horizontal plane. The radius has been chosen to optimize the momentum resolution.

The chambers B3-B6 ($1020 \times 1020 \text{ mm}^2$) outside the magnetic field region consist of modules containing two gaps with horizontal and vertical sense wires (2 mm spacing). Only the solid angle of interest is read out, as sketched in figs. 1a and 2. A detailed description of the backward arm can be found elsewhere [9].

2.5.3 Chamber operation

The chambers are filled with a "magic gas" mixture ($\sim 70\%$ argon, 25% isobutane, 5% methylal, 0.3% freon). The modules F1, F2, F3, F4, F6, F8, B4, and B5 are connected to a read-out system with monostable delay, while B1, B2, B3, B6, F5, and F7 are equipped with cable delay and fast, non-destructive, multiple access read-out [10], which allows high input rates and fast event selection as described in Section 3.2.

3. DATA TAKING

The electronics for data selection and acquisition is organized in three levels: the counter trigger, a fast decision logic (FDL) system, and the data acquisition system. These three parts can be identified in the electronics block diagram (fig. 3).

3.1 The counter trigger

The counter trigger requires:

- a) an INTERACTION signal corresponding to one and only one particle in the forward arm (FORWARD = 1) and at least one particle in the backward direction (TARGET); the two signals from S2, high-t (A+B) and low-t (B+C) are put separately in coincidence with FV1-8 and FV9-16;
- b) one and only one particle in BH and BV;
- c) a recoil time-of-flight window (WINDOW) set according to the FV strip hit (correlation between scattering angle and recoil energy); in this coincidence, the FV signals are suitably delayed to match the elastic recoil proton time of flight;
- d) a signal from a Coincidence Matrix (CMV), which imposes a rough angular correlation between strips in FV and BV.

To avoid trigger saturation by low-t events, the signals from the FV counters corresponding to low-t are scaled down by convenient factors. The reason for this is that the differential cross-section spans about five orders of magnitude, when -t ranges from 0.4 to 3.0 GeV².

The trigger scheme is shown in fig. 4. The rates at various stages are given in table 1 for a typical beam intensity (5×10^7 /burst).

For events satisfying the trigger, the counter pattern and timing information are strobed into CAMAC modules, and the chamber signals are strobed into the read-out system.

3.2 The fast decision logics (FDL)

The trigger also enables the FDL modules, a specially built system to refine the selection by using coordinates from the chambers. It checks the horizontal coordinates of B3 and B6, F5 and F7, using also the information from the hodoscope FV. All pairs of hits in B3 and B6 are correlated to see if any belong to a positive particle coming from the target; in the same way, all pairs of hits in F5

and F7 are used to search for pairs belonging to a positive particle of approximately 150 GeV/c coming from the same target. Taking advantage of the better time resolution of the counters, this condition is reinforced by the similar requirement that the hits of F5 should also match the hits in FV. Finally, a limit on the number of hits in the vertical wires of B1 is set, to eliminate events overcrowded with particles traversing the chambers nearest to the beam.

A negative decision (Reject) resets all the electronics; a positive one (Accept) sends an interrupt to the computer, initiating the acquisition of the event.

The main component of the FDL system [11] is the Programmable Track Selector (PTS) which performs decisions on the data coming from two chambers. It contains a 1024 20-bit-word random access memory (RAM) which acts as a look-up table; this memory is loaded and checked via a special CAMAC module, with a bidimensional plot giving the selected range of wire addresses. The binary numbers representing the wire addresses are read out in parallel and reach the PTS with a minimum delay of ~ 100 ns. As this read-out [10] is non-destructive, the coordinates can still be read into the computer in the case of accepted events.

The time required to take a decision depends on the number of wires hit: typically, for one hit in each chamber a time of 100 ns is required for Reject and of 40 ns for Accept.

3.3 Data acquisition

The data acquisition is performed by a Hewlett-Packard 2112 computer (128 kbytes memory) connected, via a special short-length, high-speed, parallel data link, to a second computer, HP 2108 (64 kbytes memory) acting as a buffer for records to be written on tape.

The main computer is also connected to the Experimental Area (EA) computer (NORD-10) dedicated to the monitoring of the beam lines, and to the PT computer (HP 2100 A), which supervises the target apparatus and transmits the polarization readings every minute.

The tasks of the main computer are:

- a) to read the relevant data of the incoming events, namely wire coordinates from the read-out of MWPCs, the contents of scalers, pattern units, and time-to-digital converters, and store them for recording;
- b) to read information regarding the status of the beam from the EA computer and store it for recording;
- c) to read the values of the polarization from the PT computer, and store them for recording, and to give an alarm if the polarization is not uniform over the three coils or drops below 60%;
- d) to monitor the target apparatus by checking the PT magnet field value, the temperature in the cryostat, and the condensation pressure;
- e) to provide a constant monitoring of the MWPCs by displaying histograms of the measured quantities, by reconstructing tracks for a significant sample ($\sim 20\%$) of the collected events, by evaluating efficiencies, and by showing on a storage display a layout of the chambers with hits and reconstructed tracks;
- f) to check the counters periodically by monitoring single rates and coincidence rates at various levels of the trigger;
- g) to load the memories of the FDLs and the Coincidence Matrix and to check, with simulated events, the correctness of their performances.

All this information is available at any time during data acquisition.

The blocks to be recorded are sent through the fast link, to the second computer. Most of its memory is used for buffering (~ 62 kbytes) in such a way that the dead-time of the magnetic tape unit (~ 60 ms/record) has no effect on the over-all data acquisition dead-time. The maximum effective rate is ~ 140 kbytes/burst, corresponding to ~ 900 events per burst.

Data are collected at an average incoming proton intensity of $\sim 5 \times 10^7$ /burst, and the complete trigger (counters plus scaling factors, Coincidence Matrix, and FDL) has a rate of ~ 150 events/burst. Approximately 100 magnetic tapes have been recorded, each one containing typically five files of 30,000 events each, for a

total of 13×10^6 triggers. For the PT data the polarization sign is reversed every second tape (~ 40 changes in total).

4. DATA ANALYSIS

The events have been processed by a chain of three programs:

- a) POLREC, for the track-finding procedure (Section 4.1);
- b) GEOFIT, performing a geometrical fit of the tracks and of the interaction vertex (Section 4.2);
- c) KINFIT, applying a kinematical fit in the hypothesis of elastic scattering on free (Section 4.4.1) and bound protons (Section 4.4.2). Part of the events passing GEOFIT are analysed with a BEAM program (Section 4.3) to determine the beam parameters.

The analysis has been performed on the CDC 7600 at CERN, on a CYBER 74 in Vienna, and on a CDC 7600 in Bologna. The time required to process one input event is, on the average, 10 ms of CDC 7600 CPU time in the pattern recognition, 25 ms in the geometrical fit, and 12 ms for the two kinematical fits.

The average rejection factor is 70% for POLREC, 25% for GEOFIT, and 3% for KINFIT, giving a global figure of $\sim 80\%$ for the whole chain.

4.1 The pattern recognition (POLREC)

The pattern recognition program reads the experimental tapes and performs the track-finding separately on the 16 MWPC planes of the forward arm and on the 13 MWPC planes of the backward arm, using also the information from the FV, FH, BV, and BH hodoscopes and the constraint that particles have to come from the PT fiducial volume. Up to four candidate tracks are retained in each arm and written on data summary tapes (DSTs).

4.1.1 Forward arm

The search for tracks is done independently in telescope F1-F4 and in telescope F5-F8 before and after the spectrometer magnets, respectively (see fig. 1b). The latter is processed first because of the larger particle trajectory dispersion

and of the lower background. The recognition is carried out in the following steps:

- i) The program looks for points in space in each block; for the point definition, at most one of the four coordinates is allowed to be missing.
- ii) In each telescope the coordinates of the selected points in the two blocks are checked to see whether they lie on a straight line in space. A χ^2 test is used to choose the best one among candidates sharing the same point in a block.
- iii) In telescope F5-F8 the tracks are extrapolated to FV to check whether they could have produced the trigger, and back to the plane $z = 0$ (centre of the PT), requiring an associate momentum of about 150 GeV/c. Similarly for telescope F1-F4 it is checked that the tracks come from the target volume.
- iv) The straight tracks found separately in the two telescopes must match on the medium plane of the spectrometer magnets (fig. 5).

Typical efficiencies for chamber planes F1-F8 on reconstructed tracks are 98%.

The hit location accuracy is ~ 0.3 times the wire spacing.

4.1.2 Backward arm

In the backward arm the track-finding is performed in two steps:

- i) In the chambers outside the magnetic field (B3-B6), straight tracks are reconstructed in the x and y projections separately, requiring at least three hits. The trigger condition is checked by intersecting the tracks with BH and BV. Geometrical cuts are then applied to select positive particles coming from the target volume.
- ii) Using a fast algorithm, an estimate of the recoil particle momentum and of the intercept of the trajectory with chamber B2 are obtained from the parameters of the horizontal projection of the track in telescope B3-B6 and from the horizontal coordinate in chamber B1. For all hits in the first plane of B1 (or in the second, if the first has no hit) one chooses, on a χ^2 basis,

the hits on the two planes of B2 lying on the computed trajectory. To guarantee a good momentum resolution and track identification, one requires for the reconstructed track at least one hit in B1 and one hit in B2.

Typical efficiencies for reconstructed tracks are 97% for B3-B6, 95% for B1, and 85% for B2. The hit location accuracy is the same as in the forward telescope, except for chamber B1, where it is 0.5 mm. Figure 6 shows the distributions of the residuals in the two planes of B1, a chamber that is very important for momentum resolution and operating in severe conditions.

4.1.3 Forward-backward correlation

The angular and momentum resolution of the reconstructed trajectories are already adequate for selecting elastic events, as shown in fig. 7, where angular correlation and coplanarity distributions are given for all events passing POLREC. The elastic reaction shows up as the large peak at zero. Due mainly to the tight requirements of the trigger, the contribution from non-elastic events is small, as suggested by the tails of the distributions. These correlations are not used for data selection, and all events accepted by POLREC are processed by GEOFIT.

4.2 The geometrical fit (GEOFIT)

The geometrical fit program consists of three separated parts: two single fits for forward and backward tracks, and a vertex fit combining these single fits and requiring the particles to come from a common vertex*). Each track is represented by an array of five parameters $\vec{a}(x, y, dx/dz, dy/dz, 1/p)$, defined on a reference plane.

For the single fits the coordinates c_i ($i = 1, \dots, 13$ for backward chambers and $i = 1, \dots, 16$ for forward chambers) given by pattern recognition are taken as measurements and are represented as functions f_i of these five parameters $\vec{a}$. For the backward particle, the functions f_i are computed by means of a parametrization [7] obtained by finding an approximate solution to the equation of motion

*) A detailed description of the program is given in CERN Physical Data Handling Notes DD/US/35/6.10 and 7.25.

which takes advantage of the cylindrical symmetry of the magnetic field. For the forward particle, the functions f_i are found by means of a parametrization which connects the track parameters before the magnet with the coordinates after the magnet [12]; for the few events that are not suitable for this method, tracking is used. The two parametrizations speed up the fitting procedure by a factor of 2 as compared to the conventional Runge-Kutta tracking.

The expression $\sum_{i,j} w_{i,j} [f_i(\vec{a}) - c_i] [f_j(\vec{a}) - c_j]$ is minimized with a least squares fit. The weight matrix $w_{i,j}$ takes into account all errors due to multiple scattering in the air and the detectors [13], as well as the chamber resolution. Tracks which obviously could not fulfil the geometrical requirements ($\chi^2 > 100$) are discarded.

As a result of the two single fits, one gets the fitted parameters on two reference planes with their associated error matrices. These are used as virtual measurements for the vertex fit. When tracking the backward particle through the target, energy losses and multiple scattering are taken into account. The final results are the vertex coordinates and the directions and momenta of the particles at this point together with their error matrix.

The vertex coordinates are obtained with an accuracy of better than 1 mm: in fig. 8 the z-vertex distribution for the carbon target (CT) data is displayed. The momentum resolution of the forward arm is $\sim 1\%$ for 150 GeV/c particles, while for the backward arm it is $\sim (2p)\%$, where the momentum p is given in GeV/c.

4.3 The beam program (BEAM)

The beam program is used to determine the beam parameters that are needed for the kinematical fit, i.e. mean directions and divergences, momentum, and momentum spread. This is necessary since the incident particle direction and momentum are not measured in individual events. For a fraction of events on each experimental tape the momenta of the forward and backward particles, as given by GEOFIT, are added for each individual event. If the event is elastic, the resultant $\vec{p}_F + \vec{p}_B$ is just the beam momentum $\vec{p}$. After a rotation of $\vec{p}$ at the plane $z = 0$, a distribution of p_x/p_z and p_y/p_z gives the mean beam direction and divergence at the PT centre.

In order to be left with only a negligible number of non-elastic events, an uncorrelated tight cut is applied, i.e. the momentum conservation is imposed in p_y when looking at p_x/p_z , and vice versa. The cut is chosen at one standard deviation σ in each projection of the elastic signal because the evaluation of the beam divergences proved to be stable against a further narrowing down of the cut. The non-elastic background is estimated from CT data to be less than 10%. A Gaussian fit is applied to the resulting distributions within $\pm 3\sigma$, and by unfolding the experimental resolution the final values of the divergences are obtained.

The beam parameters agree well with the beam data given by the EA computer and recorded on tape, and turn out to be stable in time.

The same procedure is applied to the data collected with the CT in order to extract the Fermi momentum of the bound protons from the broadening of the p_x/p_z and p_y/p_z distributions. Using the beam parameters as obtained from the runs with the PT by simply unfolding the r.m.s. of the Fermi momentum distribution, $\sqrt{\langle p_x \rangle^2} = \sqrt{\langle p_y \rangle^2} \approx 110 \text{ MeV/c}$ is determined (and hence is equal to $\sqrt{\langle p_z \rangle^2}$ by isotropy requirement).

4.4 The kinematical elastic fit (KINFIT)

The results of the geometrical fit are the input to the kinematical fit, together with the beam parameters. The beam direction at the vertex in each event is computed taking into account the beam bending in the PT magnet.

4.4.1 The elastic fit

This fit is a conventional 4C-fit, testing the elastic hypothesis by applying energy and momentum conservation by Lagrange multipliers.

The resulting probability distribution is flat up to the 6% level, which is thus taken as a convenient cut to define reliable elastic events (Elastic Fit hypothesis: EF). The distribution shows the expected increase below that level due to quasi-elastic (i.e. elastic on bound protons) and inelastic events (fig. 9).

The t -resolution $\delta(\text{GeV}^2)$ is computed from the kinematical fit. The relative t -resolution $\delta/|t|$ is shown in fig. 10 and can be well reproduced by $\delta/|t| = 0.0175|t|$, where t is in GeV^2 .

4.4.2 The quasi-elastic fit

For normalization purposes and to evaluate the background contamination in the previously defined elastic events, we find it useful to select in the data the quasi-elastic scattering events. This is performed with a fit identical to the elastic fit, except for the target proton being given a Fermi momentum with zero average value and 110 MeV/c standard deviation in the x, y, and z directions according to Gaussian distributions (see Section 4.3).

The probability distribution of the fit is shown in fig. 11a for the carbon target data. The peak at low probability is due to inelastic events. The enhancement at high probabilities is attributed to the trigger selection (especially to the Coincidence Matrix) which preferably accepts events close to the elastic pattern. This has been verified with a Monte Carlo calculation (fig. 11b). A 6% probability cut seems adequate for selecting the quasi-elastic events.

Figure 11c shows the corresponding distribution for the PT data. The picture is quite similar, except for the presence of the elastic events showing up as the sharp peak at large probability. A convenient selection of quasi-elastic events (QF) can therefore be obtained for both targets by applying a 6% probability cut in the QF fit but accepting only the events which do not satisfy the EF criterion. The resulting probability distributions are as shown in fig. 12 for the two targets.

5. RESULTS

Fiducial cuts over the target volume are applied to all events passing the kinematical fit. Only events with a single FV hodoscope strip present in the trigger and no signal in the two threshold Čerenkov counters are retained.

The previously defined EF events, obtained by the 6% probability cut in the elastic kinematical fit, consist mostly of elastic events, as is apparent from fig. 13a, which shows the χ^2 distribution for all the PT data. In the figure the arrow points at the probability cut. The level of the distribution at large χ^2 suggests that the background contamination at low χ^2 must be very small. Making use of the QF events in the PT and CT data this contamination is determined as a function of t, Section 5.1.

The same QF events in the PT data are used as a monitor M^+ to normalize the rates of elastic events for positive and negative values of the target polarization P_T^+ , and evaluate, from these, the asymmetry of the elastic events and the polarization parameter (Section 5.4).

The geometrical acceptance of the apparatus is computed with a simulation program (Section 5.2) so that we are also able to present results for the differential cross-section (Section 5.3).

5.1 Background subtraction

The presence of some non-elastic events in the EF sample of the PT data can be realized by looking at fig. 13b, which shows the χ^2 distribution for the elastic kinematical fit for the CT data. As expected there is no elastic peak, and most of the events have very large χ^2 . However, some events associated with very small Fermi momentum of the target proton, still satisfy the EF selection criterion. A corresponding contribution is therefore also expected from the bound protons of the PT.

To investigate the nature of these background events, those events in the CT which do not fulfil the quasi-elastic fit (6% cut) are selected. Their χ^2 distribution in the elastic fit (fig. 13c) has almost no events at small χ^2 . Therefore the contribution of the inelastic events to the $(EF)_{CT}$ sample is negligible, and the background events in the $(EF)_{PT}$ sample consist essentially of protons quasi-elastically scattered on bound protons.

To evaluate the number BG of these background events, we use for each t-bin the expression

$$BG = \frac{(EF)_{CT}}{(QF)_{CT}} (QF)_{PT}$$

where, in the case of a QF event, t is taken from the elastic fit to the same event. The ratio $(QF)_{PT}/(QF)_{CT}$ is shown in fig. 14a for different values of -t: as expected it is constant, depending only on the number of bound protons in the two targets and the ratio of the incident fluxes. The complete t-range can then

be used to define $(QF)_{PT}/(QF)_{CT}$ when evaluating, as function of $-t$, $\rho = BG/(EF)_{PT}$ (i.e. the relative background contamination of the EF sample) which is shown in fig. 14b, averaged over negative and positive P_T runs. It turns out to be 3.5% on most of the t -range, and grows to a maximum of $\sim 20\%$ in the region around $-t \sim 1.5 \text{ GeV}^2$.

5.2 The geometrical acceptance

The geometrical acceptance is essentially defined in ϕ by the backward hodoscope, parallel to the beam, and in t by the forward hodoscope, perpendicular to the beam, and it is roughly constant when $-t$ ranges from ~ 0.5 to $\sim 3.0 \text{ GeV}^2$.

A detailed calculation of the acceptance of the apparatus for elastic events is made with a Monte Carlo program, the final version of which uses the framework of the general-purpose Monte Carlo program GEANT [14]. The program is constructed in a modular way. The first stage is the generation of the kinematical quantities. Using the available information about the beam, i.e. spot size, momentum dispersion, divergences, and direction at the centre of the PT magnet as obtained from the beam program (4.3), a vertex is generated as well as a value for the momentum transfer and the azimuthal angle ϕ .

In the second stage, tracks are generated in space. The standard way to do this is by Runge-Kutta tracking through the apparatus, but all the parametrizations for the tracks are also available (see Section 4.2). The tracking includes the calculation of energy loss in the target, the cryostat, and the scintillators; multiple scattering is also taken into account.

In the third stage the program computes the track intersections with all the different detectors, and the last stage includes all the correlations used in the trigger, i.e. the Coincidence Matrix, the S2-FV correlation, and all the FDLs.

The geometrical acceptance is computed with high statistical accuracy in the $-t$ regions from 0.25 to 1.0 GeV^2 and 2.5 to 3.5 GeV^2 , where it goes from zero to its full value given by the azimuthal acceptance (7.9%). This is shown in fig. 15.

5.3 The differential cross-section

By subtracting in each t -bin the background events BG from the $(EF)_{PT}$ events, we obtain the elastic events $N^{\pm} = (EF)_{PT}^{\pm}(1-\rho^{\pm})$ for positive and negative values of P_T , respectively. When $N^{\pm}$ is divided by the geometrical acceptance, we get the corresponding angular distributions. We consider the range $0.5 < -t < 3.0 \text{ GeV}^2$, where the acceptance is always larger than 90% of its maximum value, so that the corrections to the data are only few percent. The internal consistency among various runs is defined with the analysis of Section 5.5.

The sum of the two angular distributions, properly normalized by $M^{\pm}$ (Section 5.4), is proportional to the differential cross-section (spin averaged). To obtain an absolute normalization, we use the measurement of $d\sigma/dt$ at $-t = 0.65 \text{ GeV}^2$ from Rusak et al. [15]. We stress that the experiment is designed to measure the polarization and no accurate monitoring of the absolute cross-section is done.

The resulting differential cross-section values are given in table 2 and shown in fig. 16; they are discussed in Section 6.1. The quoted errors include the statistical errors in the data, enlarged by a scaling factor (Section 5.5), and the statistical errors in the geometrical acceptance ($\leq 1.3\%$ in the low t -range). They do not include the normalization error.

5.4 The polarization parameter

The polarization parameter P is calculated in each t -bin using the expression

$$P(t) = \frac{[N^-(t)/M^-] - [N^+(t)/M^+]}{\langle P_T^+ \rangle [N^-(t)/M^-] + \langle P_T^- \rangle [N^+(t)/M^+]}$$

where the asymmetry sign follows the Basel Convention [16], $M^{\pm}$ is the number of monitor events used to normalize positive and negative target polarization data, and $\langle P_T^{\pm} \rangle$ is the average absolute value of the target polarization for the two signs respectively (same and opposite sense as the PT magnet field). The target polarization is taken as the mean of the readings of the three NMR coils.

The monitor events M are the previously defined events $(QF)_{PT}$ on the bound (unpolarized) protons for which the rates are expected to show no asymmetry, over the whole t -range, with respect the P_T sign. We choose this monitor because the topology of a quasi-elastic event is quite similar to that of an elastic event, so that the assumption that the efficiency of the apparatus (counters, plus MWPCs, plus analysis) is the same for the two cases seems well justified. Within statistics (the M- and the N-samples have about the same size) it is verified that the monitor events show no asymmetry as function of t , and they can therefore be summed up, in the interval $0.5 < -t < 3 \text{ GeV}^2$, to give for each sign of P_T a single normalization factor $M^\pm$ common to all t -bins ($M^-/M^+ = 1.094 \pm 0.008$). As a matter of fact, it turns out that even all the events not satisfying the EF hypothesis up to the 1% level show no t -dependent asymmetry within an error which, for $-t > 1 \text{ GeV}^2$, is 2-3 times smaller than the asymmetry error for the elastic events. The ratio between the number of these non-elastic events for the two signs of the P_T is 1.108 ± 0.008 , consistent with M^-/M^+ .

Table 3 and fig. 17 give the results for the polarization parameter in the t -range from -0.4 to -3.0 GeV^2 . The fact that there is no full acceptance in the t -range from -0.4 to -0.5 GeV^2 has no importance for the evaluation of the asymmetry. The quoted errors include statistical errors in the data, enlarged by a scaling factor (Section 5.5). They do not include the uncertainty ($\sim 4\%$) in the absolute calibration of the target polarization, which is just an over-all scale factor.

5.5 Errors evaluation

To evaluate the errors we consider the time fluctuations of the data, checking it against the statistical errors. In each t -bin k the ratio $r_{ik} = (EF)_{PT}/(QF)_{PT}$, for a particular run i , is compared with the ratio R_k between the corresponding total number of events, summed separately over all the runs, for the positive (R_k^+) and the negative (R_k^-) values of P_T . We use the quantity $X_{ik} = (r_{ik} - R_k^\pm)/\Delta_{ik}$, and its variance $\text{var } X_{ik}^\pm$, where Δ_{ik} is the statistical error on r_{ik} .

Very large X-values (≥ 10) in a t-bin turn out to be associated with some malfunctioning of the apparatus, and the corresponding runs are discarded (three runs out of a total of 383). Also rejected are runs with large X values in several t-bins, so that $\sum_k X_{ik}^2 > 100$, where the summation extends over all the t-bins and the value of the cut is adjusted on the real distributions (fifteen runs).

Figure 18a shows for a typical t-bin the distribution of X over the negative target polarization runs: the distribution is roughly Gaussian, but the standard deviation is somewhat larger than one. This indicates that the error on each r_{ik} is larger than the statistical error by the scaling factor $[\text{var } X_k^+]^{\frac{1}{2}}$. Consequently we enlarge the statistical error on R_k^+ by the same factor, when computing the errors, as given in tables 2 and 3.

The quantity $\epsilon_k^* = [\text{var } X_k - 1]^{\frac{1}{2}} \epsilon_k$, where ϵ_k is the relative statistical error on R_k , gives a measure of the non-statistical fluctuations in R_k , and is shown in figs. 18b and 18c for the negative and positive P_T runs, respectively. In both cases, ϵ_k^* turns out to be constant in most of the t-range, at the 0.5-0.6% level, independent of the statistical error, and should not be neglected at low t (up to $-t > 1 \text{ GeV}^2$) where the statistical error is $\sim 0.5\%$.

6. DISCUSSION OF RESULTS

6.1 The differential cross-section

As mentioned in Section 5.3, we are able to give the differential cross-section over the first minimum and second maximum with high statistics and good t-resolution (fig. 16).

In the low t-region $0.6 < -t < 1.15 \text{ GeV}^2$, our data are well described by a single exponential Ae^{Bt} , with $B = 10 \pm 0.1 \text{ GeV}^2$.

A clearly visible minimum is observed around $t = -1.46 \text{ GeV}^2$, which means that the dip already found at the ISR [17] and FNAL [15,18,19] is persistent down to 150 GeV/c, the smallest momentum where it has been seen up to now. The second maximum is around $t = -1.8 \text{ GeV}^2$ and is followed by an exponential decrease with a slope of $d = 1.7 \text{ GeV}^{-2}$, much smaller than the slope of the forward peak.

It is tempting to attribute this shape of $d\sigma/dt$ to the destructive interference of two amplitudes, as already proposed by Barger and Phillips [20]. In order to obtain the position of the first minimum and the second maximum we parametrize the differential cross-section by an expression with two amplitudes described by five parameters

$$\frac{d\sigma}{dt} = A \left| e^{b(t-t_0)/2} + e^{d(t-t_0)/2 + i\phi} \right|^2. \quad (1)$$

This function is then folded with a Gaussian error distribution to fit the observed cross-section in each t -bin k :

$$\frac{\Delta\sigma_k}{\Delta t_k} = \frac{1}{\Delta t_k} \int_{t_k}^{t_{k+1}} dt' \int_{-\infty}^{+\infty} \frac{d\sigma}{dt}(t) \frac{\exp [-(t-t')^2/2\delta_k^2]}{\sqrt{2\pi}\delta_k^2} dt, \quad (2)$$

where the average t -resolution δ_k is taken (Section 4.4) as

$$\delta_k = \delta \left[\frac{|t_k| + |t_{k+1}|}{2} \right].$$

The result of this fit is shown in table 4 with two different but overlapping t -regions, and it is easily verified that the fit is stable against changes of cuts in t . The t -range of the second column in table 4 covers the same region of the fit to the ISR data. It turns out that the same function describes well the two sets of data, and that the $|t|$ value of the first minimum is larger in our case, which is to be expected when extrapolating these ISR data.

The most striking difference comes from a change of $\cos \phi$ from -1.0 at $p_{\text{lab}} = 290 \text{ GeV}/c$ to -0.86 in our case at $150 \text{ GeV}/c$, which is a hint that the interference responsible for the dip is gradually becoming weaker with decreasing beam momentum.

6.2 The polarization parameter

The results for the polarization in the range $0.4 < -t < 3.0 \text{ GeV}^2$ are shown in fig. 17 and table 3. At $-t \approx 0.4 \text{ GeV}^2$ the data are consistent with the trend observed previously [4], namely a change of sign at $t = -0.4 \text{ GeV}^2$, attributed to a zero in the real part of the spin-flip amplitude. The polarization shows then slowly increasing negative values up to $-t = 1.3 \text{ GeV}^2$, where it is already around

-10%. At higher $|t|$ values the polarization changes sign at the position of the dip, a feature connected to a zero in the imaginary part of the spin-non-flip amplitude, reaching $\sim 20\%$ at the position of the second maximum. Even if in this region the errors are large, our data show a definite positive polarization. This over-all trend is also suggested by the data at 300 GeV/c from a similar experiment at Fermilab [19]. Within errors, it also agrees with the t -dependence of the 150 GeV/c data from a hydrogen jet-target experiment at Fermilab [21], in which the recoil proton polarization was measured with a polarimeter. When compared with our preliminary results [4], the present measurement shows a somewhat smaller polarization. Detailed checks of both the detector and of the analysis procedures were undertaken to investigate this point. As a result we found a malfunctioning of the S1 counter used in [4], which caused a slight t -dependence bias in the measured asymmetry, and we regard the present data as the final ones.

Using the same procedure as in Section 6.1, we fit the data for positive and negative values of P_T separately. The results of these fits, dN^+/dt and dN^-/dt , are then used to calculate a "fitted" polarization parameter:

$$P(t) = \frac{(1/M^-)[dN^-(t)/dt] - (1/M^+)[dN^+(t)/dt]}{\langle P_T^+ \rangle (1/M^-)[dN^-(t)/dt] + \langle P_T^- \rangle (1/M^+)[dN^+(t)/dt]} .$$

The meaning of the quantities $M^\pm$ and $\langle P_T^\pm \rangle$ is given in Section 5.4.

The resulting $P(t)$ is shown in fig. 19 and the parameters of the fits are displayed in table 5 for $0.8 < -t < 3.0 \text{ GeV}^2$. Agreement with the data is very good: this corresponds to the fact that both angular distributions are well described by the fits. The curve in fig. 19 is only meant as a useful parametrization of the data.

7. CONCLUSIONS

We have described an experiment which measures the differential cross-section and the polarization parameter of pp elastic scattering at 150 GeV/c, in the momentum transfer interval $0.4 < -t < 3 \text{ GeV}^2$.

The differential cross-section exhibits the high-energy trend observed at the ISR; in particular it shows a small dip at $-t = 1.46 \text{ GeV}^2$.

The polarization is clearly negative before the dip, and the data suggest a change of sign while going across the dip, to the highest measured $|t|$ values.

The experiment has therefore shown that spin effects in pp scattering are not negligible at this energy, and theories on the structure of hadrons must take this into account. Of course, the question about the energy dependence of our result is important; the measurement we are performing at 200 GeV/c should contribute somewhat to this point.

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Table 1

Trigger rates at a typical beam intensity (50 M/burst)

Counter	Rate (burst ⁻¹)	Counter	Rate (burst ⁻¹)
T1	7.8 M	FV hod. strips	220-680 K
T2	4.6 M	FH " "	390-560 K
S1	2.1 M	BV " "	420-530 K
S2 = A+B+C	1.6 M	BH " "	200-460 K
Coincidence		Rate (burst ⁻¹)	
FV FH	= (FV $\geq$ 1) • (FH $\geq$ 1)		2.33 M
$\overline{F \geq 2}$	= ($\overline{FV \geq 2}$) • ($\overline{FH \geq 2}$)		490 K
FORWARD	= S1 • S2 • FV FH		250 K
(FORW. = 1)	= FORWARD • ($\overline{F \geq 2}$)		220 K
TARGET	= T1 • T2		4.5 M
$\overline{B \geq 2}$	= ($\overline{BV \geq 2}$) • ($\overline{BH \geq 2}$)		530 K
INTERACTION	= TARGET • (FORW = 1)		97 K
WINDOW	= (FV delayed $\geq$ 1) • (BV $\geq$ 1) • (BH $\geq$ 1)		26 K
CMV	= (FV _i • BV _j)		31 K
SEMI-MASTER	= INTERACTION • WINDOW ($\overline{B \geq 2}$)		7100
MASTER	= (SEMI-MASTER) • CMV		3600
	(-20% Computer + FDL dead-time		3000)
FDL ACCEPT			160

Table 2

Differential cross-sections of elastic pp scattering at 150 GeV/c

$ t $ interval (GeV ²)	$d\sigma/dt$ ($\mu\text{b}\cdot\text{GeV}^{-2}$)	$ t $ interval (GeV ²)	$d\sigma/dt$ ($\mu\text{b}\cdot\text{GeV}^{-2}$)
0.500 - 0.525	$(4.801 \pm 0.086) \times 10^2$	1.00 - 1.05	3.072 ± 0.067
0.525 - 0.550	$(3.750 \pm 0.067) \times 10^2$	1.05 - 1.10	1.772 ± 0.050
0.550 - 0.575	$(2.888 \pm 0.052) \times 10^2$	1.10 - 1.15	1.082 ± 0.038
0.575 - 0.600	$(2.325 \pm 0.042) \times 10^2$	1.15 - 1.20	$(5.89 \pm 0.28) \times 10^{-1}$
0.600 - 0.625	$(1.853 \pm 0.033) \times 10^2$	1.20 - 1.30	$(2.51 \pm 0.14) \times 10^{-1}$
0.625 - 0.650	$(1.447 \pm 0.026) \times 10^2$	1.30 - 1.40	$(8.42 \pm 0.91) \times 10^{-2}$
0.650 - 0.675	$(1.158 \pm 0.021) \times 10^2$	1.40 - 1.50	$(4.89 \pm 0.60) \times 10^{-2}$
0.675 - 0.700	$(9.084 \pm 0.162) \times 10^1$	1.50 - 1.60	$(5.51 \pm 0.56) \times 10^{-2}$
0.700 - 0.725	$(6.978 \pm 0.125) \times 10^1$	1.60 - 1.70	$(7.57 \pm 0.62) \times 10^{-2}$
0.725 - 0.750	$(5.479 \pm 0.099) \times 10^1$	1.70 - 1.80	$(6.94 \pm 0.67) \times 10^{-2}$
0.750 - 0.775	$(4.301 \pm 0.079) \times 10^1$	1.80 - 2.00	$(6.69 \pm 0.42) \times 10^{-2}$
0.775 - 0.800	$(3.365 \pm 0.063) \times 10^1$	2.00 - 2.20	$(5.77 \pm 0.39) \times 10^{-2}$
0.800 - 0.850	$(2.302 \pm 0.032) \times 10^1$	2.20 - 2.40	$(4.63 \pm 0.35) \times 10^{-2}$
0.850 - 0.900	$(1.402 \pm 0.021) \times 10^1$	2.40 - 2.60	$(3.69 \pm 0.32) \times 10^{-2}$
0.900 - 0.950	(8.446 ± 0.141)	2.60 - 2.80	$(2.11 \pm 0.27) \times 10^{-2}$
0.950 - 1.00	(5.213 ± 0.099)	2.80 - 3.00	$(1.49 \pm 0.23) \times 10^{-2}$

Table 3

Polarization parameter P in pp elastic scattering at 150 GeV/c

$ t $ interval (GeV ²)	P	$ t $ interval (GeV ²)	P
0.400 - 0.425	0.0001 ± 0.0061	0.80 - 0.90	-0.0191 ± 0.0073
0.425 - 0.450	-0.0038 ± 0.0063	0.90 - 1.00	-0.033 ± 0.011
0.450 - 0.475	-0.0048 ± 0.0065	1.00 - 1.15	-0.034 ± 0.015
0.475 - 0.500	-0.0094 ± 0.0066	1.15 - 1.30	-0.107 ± 0.039
0.500 - 0.525	-0.0065 ± 0.0067	1.30 - 1.45	-0.074 ± 0.081
0.525 - 0.550	-0.0040 ± 0.0070	1.45 - 1.60	$+0.006 \pm 0.098$
0.550 - 0.575	-0.0093 ± 0.0072	1.60 - 1.80	$+0.051 \pm 0.069$
0.575 - 0.600	-0.0154 ± 0.0073	1.80 - 2.00	$+0.228 \pm 0.071$
0.600 - 0.650	-0.0124 ± 0.0058	2.00 - 2.50	$+0.043 \pm 0.053$
0.650 - 0.700	-0.0168 ± 0.0057	2.50 - 3.00	$+0.047 \pm 0.080$
0.700 - 0.800	-0.0144 ± 0.0055		

Table 4

Parameters of Eq. (1) describing $d\sigma/dt$ with two amplitudes in two different t -ranges

	t-range	
	$0.8 < -t < 3.0 \text{ GeV}^2$	$1.05 < -t < 2.5 \text{ GeV}^2$
b	$8.72 \pm 0.11 \text{ GeV}^{-2}$	$8.6 \pm 0.5 \text{ GeV}^{-2}$
d	$1.69 \pm 0.10 \text{ GeV}^{-2}$	$1.6 \pm 0.3 \text{ GeV}^{-2}$
$-t_0$	$1.387 \pm 0.004 \text{ GeV}^2$	$1.395 \pm 0.008 \text{ GeV}^2$
$\cos \phi$	-0.86 ± 0.02	-0.86 ± 0.04
χ^2/DF	72/83	49/53
$-t_{\min}$	$1.46 \pm 0.01 \text{ GeV}^2$	$1.46 \pm 0.02 \text{ GeV}^2$
$-t_{\max}$	$1.78 \pm 0.02 \text{ GeV}^2$	$1.81 \pm 0.06 \text{ GeV}^2$
$\frac{d\sigma}{dt} _{t_{\max}} / \frac{d\sigma}{dt} _{t_{\min}}$	1.38 ± 0.13	1.43 ± 0.57

Table 5

Parameters of Eq. (1) describing dN/dt with two amplitudes in the t -range $0.8 < -t < 3.0 \text{ GeV}^2$ for the two signs of the target polarization

	Negative polarization	Positive polarization
b	$8.58 \pm 0.16 \text{ GeV}^{-2}$	$8.79 \pm 0.16 \text{ GeV}^{-2}$
d	$1.84 \pm 0.13 \text{ GeV}^{-2}$	$1.70 \pm 0.15 \text{ GeV}^{-2}$
$-t_0$	$1.378 \pm 0.005 \text{ GeV}^2$	$1.400 \pm 0.006 \text{ GeV}^2$
$\cos \phi$	-0.89 ± 0.02	-0.84 ± 0.03
χ^2/DF	77/83	84/83
$-t_{\min}$	$1.44 \pm 0.02 \text{ GeV}^2$	$1.49 \pm 0.02 \text{ GeV}^2$
$-t_{\max}$	$1.78 \pm 0.02 \text{ GeV}^2$	$1.78 \pm 0.03 \text{ GeV}^2$
$\frac{d\sigma}{dt} _{t_{\max}} / \frac{d\sigma}{dt} _{t_{\min}}$	1.54 ± 0.24	1.25 ± 0.13

Figure captions

- Fig. 1 : Layout of the apparatus: a) B3-6 and F1-8 are MWPCs; FV, FH, BV, and BH are scintillator hodoscopes; S1 and S2 are scintillation counters. The envelope of the forward and backward proton trajectories is also shown. b) Sketch of the forward arm showing the relative distances of the detectors.
- Fig. 2 : Detail of the target region: T₁ and T₂ are scintillation counters; B1 and B2 are MWPCs. The envelope of the recoil proton trajectories in the accepted $|t|$ region is also shown.
- Fig. 3 : Electronics block diagram for data selection and acquisition. The counter trigger strobes the data from the detector into the read-out system and into CAMAC modules. It also triggers the FDL, which either resets all the electronics (REJECT) or sends an interrupt to the computer (ACCEPT).
- Fig. 4 : Counter trigger flow diagram (the time scale is drawn on the left).
- Fig. 5 : Distributions of the differences, a) Δx between the horizontal and b) Δy between the vertical coordinates of the straight tracks in the telescopes F1-F4 and F5-F8 respectively, at the medium plane between the two spectrometer magnets.
- Fig. 6 : Distributions of the residuals Δz of the coordinates of a) the first and b) the second gap of MWPC B1 after track finding.
- Fig. 7 : a) Angular correlation ($\theta_m - \theta_c$); $\theta \equiv$ forward polar angle ($m \equiv$ measured, $c \equiv$ calculated from the recoil particle direction under the elastic hypothesis).
b) Coplanarity ϵ , where $\sin \epsilon = (\vec{k}_r \times \vec{k}_f) \cdot \vec{k}_i / |\vec{k}_r \times \vec{k}_f|$; the $\vec{k}$'s are the unit vectors of the recoil, forward, and beam particles, computed by POLREC at the interaction vertex.

- Fig. 8 : Distribution of the z-coordinate of the vertex of the reaction as found by the geometrical fit for a carbon target run. The 10 carbon disks, 5 mm thick, are well separated.
- Fig. 9 : Probability distribution of the elastic fit for the PT data. The high peak at low probability (a) is due to non-elastic events. The same distribution is shown in (b) with a 6% probability cut, and exhibits the expected flat behaviour.
- Fig. 10 : The relative t-resolution $\delta/|t|$ of the elastic fit as a function of $-t$.
- Fig. 11 : Probability distributions of the quasi-elastic fit for a) the carbon target data, b) the Monte Carlo generated data, and c) the polarized target data. Except at low probability (inelastic events) or high probability (elastic events), the three distributions exhibit the same shape.
- Fig. 12 : Probability distributions of the quasi-elastic fit for (QF) events in a) the polarized target and b) the carbon target.
- Fig. 13 : χ^2 -distributions of the elastic fit for a) all polarized target data, b) all carbon target data, and c) carbon target data not fulfilling the quasi-elastic fit within a 6% probability cut. The arrow points to the χ^2 -value corresponding to the 6% probability cut.
- Fig. 14 : a) The ratio $(QF)_{PT}/(QF)_{CT}$ and b) the relative background $BG/(EF)_{PT}$ of the elastic events, as functions of $-t$.
- Fig. 15 : Geometrical acceptance of the apparatus as a function of $-t$ normalized to its maximum value. The dashed line marks the region where it is flat.
- Fig. 16 : Results for the differential cross-section versus $-t$.
- Fig. 17 : Results for the polarization parameter versus $-t$.

- Fig. 18 : a) Distribution of the reduced variable X in the t -bin $0.575 \leq -t \leq 0.600 \text{ GeV}^2$, over the 182 runs with negative target polarization.
- b) The quantity $\epsilon^* = \sqrt{\text{var } X - 1} \epsilon$ as function of $-t$ for negative target polarization runs.
- c) The same as (b) for positive target polarization runs.
- Fig. 19 : The polarization $P(t)$, calculated (see text) from the separately fitted functions dN^+/dt and dN^-/dt , is shown (solid line) together with the experimental points.

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

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