**POLARIZATION AT SMALL ANGLES IN ANTIPROTON-CARBON
ELASTIC SCATTERING AT LEAR ENERGIES**

A. Martin¹⁾, R. Birsa¹⁾, K. Bos²⁾, F. Bradamante¹⁾, D.V. Bugg³⁾, S. Dalla Torre-Colautti¹⁾,
J.R. Hall^{3,*)}, E. Heer⁴⁾, R. Hess⁴⁾, J.C. Kluyver²⁾, R.A. Kunne^{2,**)}, C. Lechanoine-Leluc⁴⁾,
A. Penzo¹⁾, D. Rapin⁴⁾, P. Schiavon¹⁾, F. Tessarotto¹⁾, A. Villari¹⁾ and A.M. Zanetti¹⁾

(SING Collaboration)

- 1) INFN Trieste and University of Trieste, Trieste, Italy
- 2) NIKHEF-H, Amsterdam, The Netherlands
- 3) Queen Mary College, London, England
- 4) DPNC, University of Geneva, Geneva, Switzerland.

ABSTRACT

A double-scattering experiment of antiprotons on carbon has been carried out at the Low-Energy Antiproton Ring (LEAR) at CERN, to measure the polarization parameter $A_{\bar{p}C}$ in antiproton-carbon elastic scattering at small angles. The polarization parameter has been inferred from the azimuthal distribution of the antiprotons after the second scattering. Data have also been collected with a liquid-hydrogen target as the second scatterer, thus allowing the sign of $A_{\bar{p}C}$ to be determined. The experiment has been performed at two momenta of the extracted antiproton beam, 800 and 1100 MeV/c. A small positive value of the polarization has been observed, compatible with energy independence and a linear increase with the momentum transfer q . Parametrizing $A_{\bar{p}C}$ as $a_c q$, we get $a_c = +0.72 \pm_{0.10}^{0.09} (\text{GeV}/c)^{-1}$. This result is compared with potential model predictions for $\bar{N}N$ amplitudes through a Glauber theory calculation.

(Submitted to Nuclear Physics A)

*) Present address: BNL, Upton, NY, USA.

**) Present address: DPNC, University of Geneva, Geneva, Switzerland.

1. INTRODUCTION

At energies between 100 and 1000 MeV carbon exhibits a large analysing power for protons (~ 0.4 at 10° scattering angle) which has turned out to be quite useful in the investigation of the nucleon-nucleon interaction because of the possibility of producing a polarized proton beam by elastic scattering on a carbon target, or of analysing the proton polarization with a carbon polarimeter. In the same way, if carbon has a large analysing power for antiprotons, one could produce a polarized $\bar{p}$ beam by scattering and one could analyse the $\bar{p}$ polarization in a carbon polarimeter. First calculations¹⁾ indicated small values for $A_{\bar{p}C}$ (the polarization parameter in $\bar{p}C$ elastic scattering) mainly because of strong absorption due to the annihilation channel; however, lack of precise $\bar{p}p$ and $\bar{p}n$ data as input to the nuclear-model calculations, and uncertainties in the nuclear-model calculations themselves, suggested the measurement of $A_{\bar{p}C}$ at LEAR²⁾.

In this spirit, as part of the program of experiment PS172 at LEAR, we constructed a 'polarized' $\bar{p}$ beam line³⁾ and carried out a double-scattering experiment on elastic $\bar{p}C$ scattering at small angles. The beam extracted from LEAR hit a first carbon target, located some 20 m upstream of the experimental apparatus. The antiprotons elastically scattered at an angle θ (variable between -9° and $+9^\circ$) and with polarization equal to $A_{\bar{p}C}(\theta)$ were focused by the large-acceptance beam channel onto the second carbon scatterer. The good momentum resolution of the beam line ensures rejection of the inelastically scattered antiprotons. The angular distribution after the second scattering was measured with a system of multiwire proportional chambers (MWPCs). The analysing power of carbon is inferred from the azimuthal distribution of the antiprotons after the second scattering.

A liquid-hydrogen (LH_2) target was located just before the second carbon target and the angular distribution of antiprotons scattering from hydrogen was measured in parallel with the scattering on carbon. The analysis of the hydrogen data provided a second measurement of $A_{\bar{p}C}$ which has a statistical error about twice as large as the value from the carbon data, but it allows the determination of its sign. These data also provided a measurement of ρ , the real-to-imaginary ratio of the forward $\bar{p}p$ scattering⁴⁾.

We performed a first measurement of this kind in 1984 with an extracted $\bar{p}$ beam of 608 MeV/c. The results of such a measurement and a short description of the experimental technique have already been published⁵⁾. The measured asymmetries were statistically compatible with zero, too small to produce a polarized $\bar{p}$ beam, at least at this energy. However, the result was interesting when compared with nuclear-model predictions, and in August 1986 we repeated the measurement at two different momenta of the extracted $\bar{p}$ beam, 800 and 1100 MeV/c.

Section 2 describes the beam line and the experimental apparatus. Details on data taking are given in section 3, while section 4 is devoted to the analysis of the data and the procedure used to estimate the asymmetry. The results are presented in section 5 together with theoretical predictions. Section 6 gives the conclusions.

2. THE BEAM LINE AND EXPERIMENTAL APPARATUS

2.1 The 'polarized' antiproton beam line

The layout of the beam line is shown in fig. 1. There, F_1 and F_2 give the position of the first and second carbon scatterers, which are located at two focal points.

The beam optics is illustrated in fig. 2. The layout was symmetric between the focus F_1 and F_2 (where the experimental apparatus was located), so the magnification is 1. Momentum analysis is

*) The analysis of the ρ parameter is still in progress. Preliminary data were shown at the 4th LEAR Workshop⁴⁾.

performed by the horizontal collimator C_H put at the intermediate focus. The main characteristics of the beam are:

- i) the possibility of sweeping the extracted LEAR beam in the horizontal plane with the first two bending magnets D_1 and D_2 so as to hit the carbon scatterer in F_1 at an angle varying from -9° to $+9^\circ$; by changing the sign of this angle one could change the sign of the beam polarization;
- ii) large angular acceptance, ± 18 mrad horizontally and ± 36 mrad vertically, giving a reasonable intensity in the scattered beam ($\sim 10^{-3}$ per incident antiproton at $\pm 8^\circ$);
- iii) good momentum resolution, $\Delta p/p = \pm 1\%$, necessary to reject antiprotons inelastically scattered from carbon which might have a different polarization;
- iv) achromatism, to minimize the beam spot, obtained with the use of the quadrupole Q_4 in between the two momentum-analysing bending magnets D_3 and D_4 .

All the elements of the beam line were controlled with the on-line computer. The beam at F_1 was monitored continuously using a MWPC with 1 mm wire spacing and a scintillation counter B_0 .

2.2 The experimental apparatus

The experimental set-up, shown in fig. 3, is designed around the LH_2 target and the carbon target; PC_1 – PC_9 are MWPCs, with horizontal and vertical wires spaced by 1 mm (PC_1 – PC_3) or 2 mm (PC_4 – PC_9); the sensitive surfaces of the chambers are: 95×95 mm² (PC_1 – PC_3), 190×190 mm² (PC_4), 510×510 mm² (PC_5 – PC_7) and 640×640 mm² (PC_8 , PC_9). The incoming antiprotons were defined by the coincidence B of the signals of the counters B_0 , B_1 , and B_2 ; the diameters of B_1 and B_2 were 70 and 30 mm respectively. The narrow beam coincidence completely rejected the contamination of pions ($< 10^{-3}$) from the carbon scatterer (the time of flight difference was 22 ns at 1100 MeV/c).

The LH_2 target had a length of 9.5 cm and a diameter of 4 cm. To identify annihilation events in the off-line analysis, the target was surrounded by a box of 5 counters S_1 – S_5 , covering 90% of the solid angle. The two counters on the beam line (S_1 and S_5) had a hole (diameter 60 and 100 mm respectively).

The carbon scatterer (48 cm downstream of the LH_2 target) was 5.25 g/cm² in length and had a diameter of 5 cm. The counters P_1 – P_5 , again used for off-line rejection of the annihilation events, covered about 78% of the solid angle; the diameters of the holes in P_1 and P_5 (the counters on the beam line) were 30 and 110 mm respectively.

The counter V (diameter 80 mm; distance from LH_2 target 2 m) was used during data taking to reject events with a particle in the beam direction. Two rectangular counters, L_1 and L_2 , 410 mm high and 210 mm wide, were positioned in the vertical plane at 10 cm from the nominal beam line and 1.5 m downstream of the hydrogen target; they were used to check the rejection of the veto boxes in the off-line analysis.

3. DATA TAKING

The measurement was performed with antiprotons having momenta at extraction of 800 and 1100 MeV/c, corresponding respectively to momenta of 783 and 1091 MeV/c at the centre of the first carbon target, 757 and 1077 MeV/c at the centre of the LH_2 target and 738 and 1066 MeV/c at the centre of the second carbon scatterer. At 800 MeV/c we fixed the first scattering angle $\theta_1 = 8^\circ$, while at 1100 MeV/c we collected data both with $\theta_1 = 8^\circ$ and $\theta_1 = 5^\circ$; at the end of each 1 h long spill we reversed the sign of θ_1 .

For each measurement we also collected data with the LH_2 target empty, for background evaluation.

The scattered beam intensity varied with initial momentum and θ_1 settings: for instance, with 0.5×10^6 antiprotons per second on B_0 (mean beam intensity during the experiment), we typically had $B = 250$ counts per second at 800 MeV/c, $B = 100$ counts per second at 1100 MeV/c, $\theta_1 = 8^\circ$, and $B = 500$ counts per second at 1100 MeV/c, $\theta_1 = 5^\circ$. Since the acquisition system saturated at 500 events per second, we used two different requirements for event acquisition:

- i) At low intensity we required only the coincidence B .
- ii) At high intensity, to reject straight track events, the first-level trigger condition was $B\bar{V}$, while a second-level rejection was performed by the fast microprogrammable processor ESOP. The processor used the wires hit in the last MWPC, PC_9 , to compute the distance between all the possible combinations of horizontal and vertical coordinates from the centre of the beam distribution on that chamber; only if all the computed distances were larger than a minimum value (chosen on the basis of beam spot and required geometrical acceptance at small angles), or if one or both the planes were empty, was the event accepted. Typical rejections were 33% using the counter V in the trigger and 60% applying also the second-level rejection.

To be able to estimate the geometrical acceptance of trigger condition 2 in the off-line analysis, we took samples of data at all settings with trigger condition 1, writing on tape the information of counter V and the decision of the processor.

For each accepted event, the information written on tape was:

- i) all MWPC hits,
- ii) analog-to-digital converter (ADC) and time-to-digital converter (TDC) readings for counters P_1 , P_5 , L_1 , and L_2 ,
- iii) TDC readings for the counters S_1 - S_5 , P_2 , P_3 , P_4 , B_0 , and V .

All the signals from the counters went also to CAMAC scalers and their contents, as well as the temperature of the LH_2 target, were written on tape at regular intervals, to check their stability off-line.

During the four days of the run we collected the statistics given in table 1; B_0 and B indicate the numbers of antiprotons on the first carbon target and on the LH_2 target respectively; trigger B and $B\bar{V}E$ refer to the conditions 1 and 2.

4. DATA ANALYSIS

4.1 $\bar{p}C$ data

4.1.1 Event reconstruction

The incoming $\bar{p}$ trajectory was reconstructed using the information from the telescope formed by PC_1 , PC_3 , PC_4 and PC_5 ; the outgoing particles were measured by the last four MWPCs (PC_6 - PC_9 in fig. 3). The reconstruction algorithm required:

- i) in both horizontal and vertical projections of the telescopes at least three aligned hits to define a track;
- ii) at least one incoming track in both projections having a distance less than 50 mm from the nominal beam axis at the C target position;
- iii) at least one outgoing track in both projections having a distance less than 600 mm from the nominal beam axis at the C target position;
- iv) one and only one vertex (defined as the mean point of the minimum distance between one incoming and one outgoing track, if this distance was less than 20 mm) inside a 100×100 mm² region centred on the C target.

The requirements of the reconstruction program eliminated all events with more than one track in the first or second telescope (mainly annihilation events).

The percentage of reconstructed events was between 40% and 80%, depending on the trigger conditions.

The reconstructed events, written on data summary tapes (DSTs), were further analysed accepting only those events with:

- i) incoming trajectory projection at the P_1 position inside a circle of radius 12.5 mm;
- ii) minimum distance between incoming and outgoing track less than 4 mm;
- iii) vertex position along the nominal beam axis inside a range depending on the scattering angle θ_2 [distance from the target centre less than $(15 + 3/\theta_2)$ mm].

The first requirement ensured that no incoming antiproton hit the counter P_1 . No similar condition was required for the outgoing track, because no particle scattered off carbon in the interesting angular range could hit P_2 .

The number of events on raw data tapes, on DSTs, and accepted by the complete analysis is given in table 2.

4.1.2 Angular acceptance

The angular acceptance at large scattering angles was limited by the dimensions of the last chambers. Because of the track definition used by the reconstruction program, we expect that the acceptance decreased when the scattering angle of the outgoing particle was such that it did not hit PC_9 : in this case PC_6 , PC_7 , and PC_8 must be fully efficient to reconstruct the event. This effect is influenced by the spot and divergence of the beam and by the square shape of the chambers. The geometrical acceptance is calculated with a Monte Carlo program, using as input the measured beam.

At small angles, the acceptance was complete for the events collected with trigger B. However, with trigger $B\bar{V}E$, we must allow for the rejection efficiency of counter V and of the ESOP algorithm. In this case, the geometrical acceptance was evaluated using the B trigger data, by counting the events which had neither the V counter bit on nor the reject flag from ESOP.

The overall geometrical acceptance is shown in fig. 4.

4.1.3 Angular distributions

According to the presence or absence of signals in the veto counters P_1 – P_5 in coincidence with the beam signal, the events accepted by the analysis program can be divided into two classes, which will be called V_{on} and V_{off} respectively.

Most ($\sim 90\%$) of the accepted events were of the V_{off} type, and correspond to elastic- and inelastic-scattering events. The angular distribution of these events is shown in Figs. 5a and b at 800 and 1100 MeV/c and exhibit the typical diffraction-like pattern expected for elastic $\bar{p}C$ scattering. The V_{on} events are clearly annihilation events, and are characterized by a flat angular distribution, as shown in Figs. 5a and b. All the distributions are corrected for angular acceptance.

The $\bar{p}C$ elastic scattering angular distributions (dashed curves in fig.5) have been computed using Glauber theory and $\bar{N}N$ amplitudes (more details are given in the Appendix). The ratio $\alpha = N_{el}/N_{tot}$, the fraction of elastic events in each data bin, could thus be computed. Comparing the V_{off} data points with the computed angular distribution it is apparent that at small angles most of the V_{off} events are elastic. At large angles, at and beyond the diffraction minimum, the expected number of elastic events is small and the majority of the V_{off} events is due to quasi-elastic and inelastic $\bar{p}C$ scattering.

4.1.4 Background events

At all angles some background events are present in the V_{off} sample, owing to two effects:

- i) Antiproton annihilation. The veto counters surrounding the carbon target covered about 78% of the solid angle; this means that not all annihilation events will give a prompt signal in the veto box. With a Monte Carlo calculation, we evaluated the percentage of annihilations in the V_{off} events to be about 5% of the V_{on} events (dash-dotted line in fig. 5). This number was checked

using the TDC and ADC information from the L counters, which at 800 MeV/c allow us to separate pions from antiprotons. This can be seen in figs. 6a and b, for V_{off} and V_{on} samples respectively. As apparent from fig. 6b, annihilation events show either a pion or a proton in the forward telescope. The residual annihilation events in the V_{off} sample is estimated on the basis of unambiguously identified pions (i.e. events in the region R). In terms of percentage of V_{on} events it is just the ratio $V_{\text{off}}/V_{\text{on}}$ in the region R which turns out to be compatible with the 5% value given by the Monte Carlo calculation.

- ii) Double elastic $\bar{p}C$ scattering. Given the thickness of the carbon target (5.25 g/cm^2) we cannot neglect the probability of an incoming antiproton scattering twice in the target, in particular at large angles. We computed the angular distribution for double elastic scattering starting from the elastic-scattering differential cross-section. At small angles this can be parametrized as

$$f_1 = a\{e^{-\theta^2/2\theta_0^2}\}$$

so that the angular distribution for double-scattered $\bar{p}$ is given by

$$f_2 = b\{e^{-\theta^2/4\theta_0^2}\}.$$

To evaluate the ratio b/a we assumed that the total elastic cross-section is $\sigma_{\text{el}} = 0.35 \sigma_{\text{tot}}$, with σ_{tot} being the total $\bar{p}C$ cross-section, and that $P_2 = 0.5 P_1^2$, with P_1 being the probability of having a single scattering and P_2 the probability of double scattering. The computed angular distribution is the dotted line in fig. 5.

As apparent from fig. 5, both types of events constitute at all angles a small fraction of the measured sample of events, so their effect on the measured asymmetries will be neglected in the following.

Adding up the contribution of the background events to the computed angular distribution for elastic scattering in fig. 5 one gets the full curve. The difference between the full curve and the measured points V_{off} gives a measurement of the quasi-elastic- and inelastic-scattering events, which at large angle outnumber the elastic $\bar{p}C$ events.

4.1.5 Asymmetry evaluation

The technique used to measure the analysing power of C for antiprotons is the double-scattering method. The antiprotons transmitted by the beam line have been elastically scattered off carbon at an angle θ_1 and they have a polarization $A_{\bar{p}C}(\theta_1)$, where $A_{\bar{p}C}$ is the polarization parameter of the reaction. After the second scattering, the angular distribution of $\bar{p}$ is given by

$$N(\theta_2, \phi) = N_0(\theta_2)\{1 + \epsilon(\theta_1, \theta_2)\cos \phi\}, \quad (1)$$

where θ_2 is the second scattering angle and ϕ is the angle between the first and the second scattering planes. The azimuthal asymmetry ϵ is given by

$$\epsilon(\theta_1, \theta_2) = A_{\bar{p}C}(\theta_1)A_{\bar{p}C}(\theta_2) \quad (2)$$

if the second reaction is again $\bar{p}C$ elastic scattering.

Provided that the full range of ϕ is within the acceptance of the detectors, in a given θ_2 bin, the best statistical estimate of the asymmetry is

$$\epsilon = 2 \langle \cos \phi \rangle, \quad (3)$$

having variance

$$\text{var}(\epsilon) = \{1 - \epsilon^2\}/2N, \quad (4)$$

where N is the number of events in the angular bin.

Experimental asymmetries of the apparatus, mainly due to non-uniform efficiency of the MWPCs, are crucial for such a measurement. At first order in $\cos\phi$ these asymmetries have been cancelled by alternating the sign of the first scattering angle θ_1 during data taking, and evaluating the asymmetry ϵ as

$$\epsilon = \langle \cos \phi \rangle^+ - \langle \cos \phi \rangle^-, \quad (5)$$

where $^+$ and $^-$ refer to the first scattering condition. The sign of θ_1 has been changed at each spill to compensate possible slow variations of the MWPC efficiency during data taking. As a check of the stability of the apparatus, we divided all the data into small samples. The result was good: all the considered samples gave values for $\langle \cos \phi \rangle$ that are statistically compatible. As an example, fig. 7 shows the behaviour of $\langle \cos \phi \rangle$ in a typical θ_2 bin.

An example of measured azimuthal distribution at 800 MeV/c is shown in fig. 8 for positive and negative angles in the first scattering and $10.7^\circ < \theta_2 < 12.7^\circ$. The curves show the expected behaviour: $N^\pm(\phi) = N_0^\pm (1 \pm \epsilon \cos \phi)$ assuming for ϵ the estimate obtained with Eq. (5). In fig. 9 the values

$$E(\phi) = [N^+(\phi) - rN^-(\phi)]/[N^+(\phi) + rN^-(\phi)] \quad (6)$$

are plotted; r is the beam normalization factor. The expected dependence on ϕ is $\epsilon \cos \phi$ (full curve).

We also compared the values of ϵ obtained from eq. (5) with the results of the χ^2 minimization procedure on the $E(\phi)$ values defined in eq. (6), assuming $E(\phi) = \epsilon \cos \phi$; the two results were essentially the same.

As already pointed out, expression (1), with ϵ given by eq. (2), is correct only in the absence of background events, which is not the case, as seen in sub-subsections 4.1.3 and 4.1.4. Indicating by N_{el} the number of elastic events (with analysing power $A_{\bar{p}C}$), N' and N'' the number of events due to annihilation and to inelastic reactions (analysing power a' and a'' respectively), and $N_{tot} = N_{el} + N' + N''$ the total number of events, the measured asymmetry is

$$\begin{aligned} \epsilon(\theta_1, \theta_2) &= \langle \cos \phi \rangle^+ - \langle \cos \phi \rangle^- \\ &= A_{\bar{p}C}(\theta_1) \{ \alpha A_{\bar{p}C}(\theta_2) + \beta a' + \gamma a'' \} \\ &= A_{\bar{p}C}(\theta_1) A'_{\bar{p}C}(\theta_2), \end{aligned} \quad (7)$$

where $\alpha = N_{el}/N_{tot}$, $\beta = N'/N_{tot}$, $\gamma = N''/N_{tot}$. If $a' = a'' = 0$, we will measure an asymmetry decreased by a factor α . Annihilation events are expected to have zero asymmetry and hence to dilute the measured asymmetry, but the contamination is so small that such a dilution is negligible. The analysing power of the other reactions (quasi-elastic and inelastic $\bar{p}C$ scattering) is not known, so in general our measurement will provide information on $A'_{\bar{p}C}(\theta_2)$, the analysing power for all scattering events at angle θ_2 , elastic plus inelastic. Only at small angles, where $\alpha \simeq 1$, can one assume $A'_{\bar{p}C}(\theta_2) = A_{\bar{p}C}(\theta_2)$ and extract $A_{\bar{p}C}$ from the measured asymmetry.

4.2 $\bar{p}p$ data

The events scattered on the LH₂ target, have been analysed in a similar way to the carbon events.

The same reconstruction program was used, but in this case the incoming and scattered particles were detected by different sets of MWPCs: the incoming antiproton was defined by PC₁, PC₂, and PC₃; to define a track at least two hits aligned with the LH₂ target were demanded in each projection. The outgoing trajectory was measured by PC₄, PC₅, PC₆, and PC₈. The following cuts were applied to the events written on DST:

- i) incoming trajectory projection at the centre of the target inside a circle of radius 11 mm;
- ii) minimum distance between incoming and outgoing track less than 16 mm;
- iii) vertex position along the nominal beam axis inside a range depending on the scattering angle θ_2 [distance from target centre less than $(39 + 2/\theta_2)$ mm].

Table 3 gives the number of full target events on raw data tapes, on DSTs, and at the end of the analysis.

The angular acceptance was evaluated as described in sub-subsection 4.1.2 and is shown in fig. 10. At small scattering angles, the events are rejected mainly by counter V and the ESOP algorithm, while at large angles the acceptance is limited by the dimensions of the MWPCs.

The annihilation events were identified using the TDC information of the S₁-S₅ counters. The angular distributions for V_{off} and V_{on} events, defined as in sub-subsection 4.1.3., are given in fig. 11. Also in this case we measured the rejection of the veto box (covering 90% of the solid angle) by looking at the L counters ADC-TDC spectra. The scatter plots shown in fig. 12 give the pulse height to time of flight correlations. In $\bar{p}p$ scattering, the residual annihilations in the V_{off} sample is of the order of 3% of the V_{on} events.

The asymmetry was estimated as for $\bar{p}C$ scattering and the same checks were made. In the hydrogen case, assuming no background in the second scattering, the measured asymmetry is

$$\epsilon(\theta_1, \theta_2) = A_{\bar{p}C}(\theta_1)A_{\bar{p}p}(\theta_2) , \quad (8)$$

with $A_{\bar{p}p}$ being the analysing power in $\bar{p}p$ elastic scattering. The only important background is the scattering on the Mylar windows of the LH₂ target, which has been evaluated using the empty target data. These background events are mainly $\bar{p}C$ elastic scattering, which turn out to have a polarization parameter very similar to that of elastic $\bar{p}p$ scattering.

5. RESULTS

5.1 $\bar{p}C$ scattering

5.1.1 Angular range

To avoid systematic errors due to geometrical acceptance, the asymmetries have been estimated in the angular range characterized by full acceptance: we considered only the events with $5.5^\circ < \theta_2 < 16.8^\circ$ at 800 MeV/c and $3.1^\circ < \theta_2 < 17.2^\circ$ at 1100 MeV/c. At small angles, where the acceptance is not yet 100%, only events with trigger B were used.

Table 4 gives the angular bins taken into consideration and the corresponding momentum transfer $q_2 = \sqrt{-t}$. The binning in q_2 is the same as in the previous measurement at 608 MeV/c.

5.1.2 Measured asymmetries

The measured asymmetries $\epsilon(\theta_1, \theta_2) = A_{\bar{p}C}(\theta_1)A'_{\bar{p}C}(\theta_2)$ are given in table 4. The mean value of $\alpha = N_{el}/N_{tot}$ is given in the last column of the same table; α is evaluated only for the first bins, because in the diffraction minimum our model calculation is not accurate enough.

The measured asymmetries at 800 MeV/c, 8° , and 1100 MeV/c, 8° and 5° , are plotted against q_2 in fig. 13, together with the results at 608 MeV/c. The curves have been calculated from Glauber

theory (see Appendix), using as input the small angle $\bar{p}p$ and $\bar{p}n$ amplitudes from Dover–Richard (dashed curve) and Paris (dash-dotted curve) models. The data give an indication for a small positive value of the asymmetry. There seems to be no dependence on the energy of the analysing power.

For each set of data, the statistical errors are too large to distinguish clearly between zero and the prediction of the different models. To increase the statistical significance of the data we have combined our measurements, taken at different first scattering angle and at three different energies, into a single set of asymmetry values. This procedure is justified because in the nuclear models the energy dependence is expected to be very weak, and at fixed energy the polarization should increase linearly with the momentum transfer at small angles.

Assuming $A_{\bar{p}C}(q) = a_c q$ for $q < 150$ MeV/c and that a_c does not depend on the energy, the asymmetries can be written as

$$\epsilon(q_1, q_2) = a_c q_1 A'_{\bar{p}C}(q_2) , \quad (9)$$

where q_1 and q_2 are the momentum transfers in the first and second scattering respectively. The measured asymmetries were normalized to a momentum transfer in the first scattering $q_1^0 = 100$ MeV/c:

$$\epsilon^0(q_1^0, q_2) = \epsilon(q_1, q_2)(q_1^0/q_1) \quad (10)$$

and we made a weighted average of the new values.

The resulting asymmetries are shown in fig. 14. The full and dashed curves are again the computed values of the asymmetry, obtained by averaging the predictions plotted in fig. 13, using as weight the total number of events at each setting. The full straight line represents the best fit obtained from the first four points; at these values of q , α is always greater than 0.82 and one can assume $A'_{\bar{p}C}(q) = A_{\bar{p}C}(q) = a_c q$, obtaining, from eq. (9):

$$\epsilon^0(q_1^0, q_2) = a_c^2 q_1^0 q_2 . \quad (11)$$

Fitting our data we get

$$a_c^2 = 0.52 \pm 0.13 \text{ (GeV/c)}^{-2} ,$$

and

$$|a_c| = 0.72 \pm_{0.10}^{0.09} \text{ (GeV/c)}^{-1} . \quad (12)$$

The first four points are compatible with the predictions of the Dover–Richard model [$a_c^2 \approx 0.80 \text{ (GeV/c)}^{-2}$, giving $\Delta\chi^2 = 4.4$, with a confidence level (CL) of 0.04], but not with the values obtained with the Paris model [$a_c^2 \approx 1.80 \text{ (GeV/c)}^{-2}$, giving $\Delta\chi^2 = 93$] or with the hypothesis $a_c^2 = 0$ [$\Delta\chi^2 = 16$, with a CL of 10^{-4}].

5.2 $\bar{p}p$ scattering

5.2.1 Angular range

In $\bar{p}p$ scattering the main background is due to scattering on the Mylar windows of the LH₂ target and has been measured in empty-target runs. The angular distribution for these events shows a peak at small angles; the fraction of hydrogen events in the full target sample $\alpha = (N_F - N_E)/N_F$ (with N_F and N_E being the number of events in the full and empty samples respectively) is somewhat smaller than 1 only in the forward direction. The angular range in which we evaluated the asymmetry

($4.36^\circ < \theta_2 < 15.27^\circ$ at 800 MeV/c and $4.55^\circ < \theta_2 < 15.05^\circ$ at 1100 MeV/c) was fixed to have $\alpha > 0.90$ in the first bin and a geometrical acceptance greater than 90% in the last one; with this choice, the geometrical acceptance in the first angular bin is already 100% also for the trigger condition $B\bar{V}E$, thus all events were used.

5.2.2 Measured asymmetries

The measured asymmetries at each setting are given in table 5; the last column gives the values of the fraction α of elastic $\bar{p}p$ events. The background events are always less than 10% and, since they are mostly $\bar{p}C$ scattering, with analysing power very similar to that of $\bar{p}p$ scattering, we did not apply any correction to the measured asymmetries.

The asymmetries at 800 MeV/c, 8° , and 1100 MeV/c, 5° and 8° , are plotted in fig. 15 together with the results at 608 MeV/c; the curves are the computed values obtained using Paris (dash-dotted line) and Dover–Richard (dashed line) models.

To improve the statistical significance of the data, we averaged the measured asymmetries following the same procedure as used for $\bar{p}C$ data: we assumed in the first scattering $A_{\bar{p}C}(q) = a_c q$ and we took as reference value in the $\bar{p}C$ interaction $q_1^0 = 100$ MeV/c, so that the new values ϵ^0 of the asymmetries are again computed using expression (10). In this procedure we did not use the results at 608 MeV/c, but only the data at 800 and 1100 MeV/c, because $A_{\bar{p}p}$ in this momentum range is roughly energy independent and increases at lower momenta, as measured in the polarized target runs of our experiment⁶⁾.

The averaged values of the asymmetries are plotted in fig. 16. The curves are the predictions from Paris (dash-dotted) and Dover–Richard (dashed) models, obtained from the weighted average of the values plotted in fig. 15. The full line is the best fit to the data, assuming $A_{\bar{p}p}(q) = a_p q$ and

$$\epsilon^0(q_1^0, q_2) = a_c a_p q_1^0 q_2, \quad (13)$$

which gives

$$a_c a_p = 0.48 \pm 0.17 (\text{GeV/c})^{-2}. \quad (14)$$

As for the $\bar{p}C$ scattering, our data are compatible with the Dover–Richard model [$a_c a_p \approx 0.73 (\text{GeV/c})^{-2}$, giving $\Delta\chi^2 = 2.1$, with a CL of 0.15] but not with the Paris model [$a_c a_p \approx 1.53 (\text{GeV/c})^{-2}$, giving $\Delta\chi^2 = 37$]; the CL for the hypothesis $a_c a_p = 0$ is 0.006 [$\Delta\chi^2 = 7.8$].

These data allow us to determine the sign of $A_{\bar{p}C}$, since a_p is known from the measurement with the polarized target. Figure 17 shows the small q elastic $\bar{p}p$ data on $A_{\bar{p}p}$ at 783 and 1089 MeV/c from ref. 6, which are best fitted with a straight line with

$$a_p = 0.83 \pm 0.04 (\text{GeV/c})^{-1} \quad (15)$$

(full line in the figure). Taking $|a_c|$ as obtained from the $\bar{p}C$ data [eq.(12)] one gets

$$|a_c| a_p = 0.60^{+0.08}_{-0.09} (\text{GeV/c})^{-2}. \quad (16)$$

The results (14) and (16) are perfectly consistent if $a_c > 0$ [$\Delta\chi^2 = 0.45$, with a CL of 0.50] while the hypothesis $a_c < 0$ must be rejected [$\Delta\chi^2 = 36$]. We can conclude that at small angles the polarization parameter in $\bar{p}C$ elastic scattering is positive, as in $\bar{p}p$ elastic scattering.

5.3 Estimate of $A_{\bar{p}n}$

As pointed out in the Appendix, the $A_{\bar{p}C}$ data can be used to extract information on $A_{\bar{p}n}$, the polarization parameter in elastic $\bar{p}n$ scattering, which, at present, is not measured. At small angles, under the hypothesis explained in section 3 of the Appendix, the following approximate relations hold:

$$A_{\bar{p}p} \approx 2q\xi_p ,$$

$$A_{\bar{p}n} \approx 2q\xi_n ,$$

$$A_{\bar{p}C} \approx 2q\eta_c ,$$

where ξ_p and ξ_n are the ratios between the slope of the spin-orbit amplitude and the central amplitude at $q = 0$ in $\bar{p}p$ and $\bar{p}n$ elastic scattering. Assuming that the $\bar{p}p$ and $\bar{p}n$ total cross-sections are equal, as suggested by existing data⁷⁾, one has

$$\eta_c = (\xi_p + \xi_n)/2 ,$$

which means

$$a_n/2 = \xi_n = a_c - a_p/2 .$$

Using for a_c and a_p the value given in expressions (12) and (15), we get

$$a_n = 0.61^{+0.18}_{-0.20} (\text{GeV}/c)^{-1} ,$$

which gives a value of $A_{\bar{p}n}$ compatible with the measured value of $A_{\bar{p}p}$.

6. CONCLUSIONS

From the double-scattering measurements at 608, 800, and 1100 MeV/c we obtain the final result that at small values of the momentum transfer ($q < 150$ MeV/c) the polarization parameter in elastic $\bar{p}C$ scattering can be parametrized as

$$A_{\bar{p}C}(q) = a_c q ,$$

where

$$a_c = + 0.72^{+0.09}_{-0.10} (\text{GeV}/c)^{-1} .$$

This value of a_c is compatible with Glauber theory predictions when using as input the $\bar{p}$ -nucleon amplitudes from the Dover-Richard model; when the Paris amplitudes are used, the computed values are no longer compatible with our data.

From this measurement and from the measurement of a_p of ref. 6, we infer

$$a_n = + 0.61^{+0.18}_{-0.20} (\text{GeV}/c)^{-1} ,$$

namely a value of $A_{\bar{p}n}$ compatible with the measured value of $A_{\bar{p}p}$.

APPENDIX

1. The Glauber theory

To evaluate the polarization in $\bar{p}C$ elastic scattering we used the formalism developed by Osland and Glauber⁸⁾, which gives the p -nucleus amplitudes using as input the p -nucleon elastic-scattering amplitudes at small angles.

Following Osland and Glauber, we have assumed for the $\bar{p}$ -nucleon scattering matrix

$$f_j(q) = A_j(q) + \vec{\sigma} \cdot \hat{n} q C_j(q) , \quad (A1)$$

where $j = n$ or p labels the target nucleon, $q = \sqrt{-t}$ is the momentum transfer, $\vec{\sigma}$ is the incoming $\bar{p}$ spin operator and $\hat{n} = \hat{k} \times \hat{q}$, with $\hat{k}$ being the beam direction. In eq. (A1) terms depending on the spin degrees of freedom of the target nucleons are neglected, since they give contributions of the order of $1/A$ on a heavy spin-zero nucleus. The central and spin-orbit amplitudes are parametrized as

$$A_j(q) = (ikA_{oj}/4\pi) \exp \{-\beta_{aj}q^2/2\} , \quad (A2)$$

$$C_j(q) = (ikC_{oj}/4\pi) \exp \{-\beta_{cj}q^2/2\} , \quad j = n, p,$$

with $A_{oj} = \sigma_j(1 - i\alpha_{aj})$, $C_{oj} = \lambda_j(1 - i\alpha_{cj})$ and k being the beam momentum in the centre-of-mass system.

Neglecting Coulomb interactions, the $\bar{p}$ -nucleus scattering operator is

$$M(q) = F(q) + \vec{\sigma} \cdot \hat{n} G(q) ,$$

where

$$F(q) = ik \int db \, b \, J_0(qb) \{1 - \exp[-\Sigma_\ell^{1/2} A_{0\ell} T_\ell(b, \beta_{A\ell})] \times \cos[\Sigma_\ell^{1/2} C_{0\ell} T'_\ell(b, \beta_{c\ell})]\} ,$$

$$G(q) = -ik \int db \, b \, J_1(qb) \exp[-\Sigma_\ell^{1/2} A_{0\ell} T_\ell(b, \beta_{A\ell})] \times \sin[\Sigma_\ell^{1/2} C_{0\ell} T'_\ell(b, \beta_{c\ell})] ,$$

$$T_\ell(b, \beta_\ell) = [1/(2\pi)^2] \int dz \int d^2s \, \varrho_\ell(s, z) \int d^2q \exp[-i\vec{q} \cdot (\vec{b} - \vec{s})] \times \exp[-1/2 \beta_\ell q^2] ,$$

$$T'_\ell(b, \beta_\ell) = (\partial/\partial b) T_\ell(b, \beta_\ell) .$$

Here $\varrho_\ell(r)$ is the nucleon density function; for C we used the harmonic oscillator model with a radius $a_0 = 1.51$ fm.

The differential cross-section and the polarization in $A_{\bar{p}C}$ in $\bar{p}C$ elastic scattering are:

$$(d\sigma/d\Omega)_{\bar{p}C} = |F(q)|^2 + |G(q)|^2 \quad (A3)$$

$$A_{\bar{p}C}(d\sigma/d\Omega)_{\bar{p}C} = 2 \operatorname{Re} \{F(q)G^*(q)\} . \quad (A4)$$

The polarization has a strong dependence on $\xi_j = \lambda_j/\sigma_j$ and, as stressed by Osland and Glauber⁸⁾, the measurement of the polarization parameter in small-angle $\bar{p}C$ elastic scattering can be used to determine the imaginary part of the $\bar{p}n$ spin-orbit amplitude.

2. Small-angle $\bar{p}$ -nucleon amplitudes

To evaluate the $\bar{p}$ -nucleon amplitudes at small q we used the Dover-Richard⁹⁾ and Paris¹⁰⁾ models. In the range $0 < q < 1$ fm, the parametrization (A2) reproduces very well the q^2 dependence of the imaginary parts of $A_j(q)$ and $C_j(q)$. The corresponding real parts are predicted to vary more quickly than the imaginary parts and it is not obvious how to fix the values of α_{aj} and α_{cj} . For our calculations we put $\alpha_{aj} = \alpha_{cj} = 0$ because

- i) at small q values, the models predict for the real parts of the amplitudes values much smaller than for the imaginary parts;
- ii) $A_{\bar{p}C}$ at small angles depends weakly on α_{aj} and α_{cj} ;
- iii) at our momenta, the measured values of α_{ap} are less than 0.25.

The values of the parameters used as input to the Glauber theory are given in table 6.

3. Small-angle approximation

Assuming $\alpha_{aj} = \alpha_{cj} = 0$ and $\beta_{aj} = \beta_{cj} = \beta_j$, $j = n, p$, the $\bar{p}$ -nucleon small-angle scattering amplitudes, given by eq. (A2), become

$$A_j(q) = (ik/4\pi)\sigma_j \exp \{ -\beta_j q^2/2 \} ,$$

$$C_j(q) = (ik/4\pi)\lambda_j \exp \{ -\beta_j q^2/2 \} = \xi_j A_j(q),$$

where $\xi_j = \lambda_j/\sigma_j$. The polarization is given by:

$$A_{\bar{p}j}(q) = [2\xi_j q / (1 + \xi_j^2 q^2)] \approx 2\xi_j q .$$

In $\bar{p}C$ elastic scattering, $\alpha_{aj} = \alpha_{cj} = 0$ implies that the real parts of the amplitudes vanish. Assuming $\beta_n = \beta_p = \beta^*$ and considering only the first-order terms in $\Sigma_\ell \frac{1}{2} \lambda_\ell T_\ell(b, \beta_{c\ell})^{**}$, one gets

$$\text{Im } G(q) \approx \eta \text{Im } F(q) ,$$

where $\eta = (\lambda_p + \lambda_n)/(\sigma_p + \sigma_n)$, and

$$A_{\bar{p}C}(q) \approx 2\eta q .$$

*) Recent computations¹¹⁾ at momenta up to 600 MeV/c do not disagree with this assumption.

**) As pointed out in ref. 8 this approximation is not valid in the diffraction minima region.

Acknowledgements

We are indebted to P. Ciliberti, G. Menon and F. Pucci for their help in constructing the detectors and for their skilful technical assistance all throughout the experiment.

We should like to thank C.B. Dover, B. Loiseau and J.M. Richard for providing us with the results of their potential models and for fruitful discussions. The invaluable collaboration of the late G. Alberi is acknowledged here.

We are grateful for the assistance of CERN and particularly of D. Dumollard and D.J. Simon and all the LEAR operating group.

REFERENCES

- 1) G. Alberi et al., Antiproton-carbon elastic scattering, Proc. 5th European Symposium on Nucleon-Antinucleon Interactions, Bressanone, Italy, 1980 (CLUEP, Padua, 1980) p. 51.
- 2) R. Birsa et al., Study of spin effects in $\bar{p}p$ total cross-section and elastic scattering at LEAR, Letter of Intent CERN/PSCC/79-55, PSCC/I6 (1979).
- 3) J. Bailey et al., Proc. Workshop on Physics at LEAR with Low-Energy Cooled Antiprotons, Erice, 1982, eds. U. Gastaldi and R. Klapisch (Plenum, New York, 1984), p. 455.
- 4) R. Birsa et al., Antiproton-proton small-angle elastic scattering at 550, 800 and 1100 MeV/c, to be published in Proc. 4th LEAR Workshop, Villars-sur-Ollon, 1987.
- 5) R. Birsa et al., Phys. Lett. **155B** (1985) 437.
- 6) R.A. Kunne et al., preprint CERN/EP 88-22 (1988), and submitted to Phys. Lett. B.
- 7) T. Armstrong et al., Phys. Rev. **D36** (1987) 659.
- 8) P. Osland and R.J. Glauber, Nucl. Phys. **A326** (1979) 255.
- 9) C.B. Dover and J.M. Richard, Phys. Rev. **C21** (1982) 1466.
- 10) J. Côté et al., Phys. Rev. Lett. **48** (1982) 1319.
- 11) G. Bendiscioli et al., Nucl. Phys. **A469** (1987) 669.

Table 1

Statistics of the three measurements. The total number of antiprotons is B_0 on the first and B on the second scatterer. The number of collected events is given for the two trigger conditions explained in the text.

p (MeV/c)	θ_1 (°)	B_0	B	Events on tape	
				Trigger B	Trigger $B\bar{V}E$
800	± 8	2.0×10^{10}	11×10^6	0.8×10^6	4.0×10^6
1100	± 5	1.9×10^{10}	18×10^6	1.6×10^6	6.2×10^6
1100	± 8	2.6×10^{10}	6×10^6	5.8×10^6	–

Table 2

Statistics for $\bar{p}C$ scattering: number of events on raw data tapes (RDT), on data summary tapes (DST), and at the end of the analysis.

p (MeV/c)	θ_1 (°)	Events on RDT	Events on DST	Accepted events
800	± 8	4.8×10^6	2.7×10^6	1.7×10^6
1100	± 5	7.8×10^6	3.8×10^6	2.6×10^6
1100	± 8	5.8×10^6	3.0×10^6	2.4×10^6

Table 3

Statistics for $\bar{p}p$ scattering: number of events on raw data tapes (RDT), on data summary tapes (DST), and at the end of the analysis.

p (MeV/c)	θ_1 (°)	Events on RDT	Events on DST	Accepted events
800	± 8	4.0×10^6	2.4×10^6	1.1×10^6
1100	± 5	6.2×10^6	3.8×10^6	2.4×10^6
1100	± 8	4.0×10^6	2.5×10^6	1.7×10^6

Table 4

Results for $\bar{p}C$ asymmetries ϵ at 800 and 1100 MeV/c: θ_1 and θ_2 are the first and second scattering angles; q_2 is the momentum transfer in the second scattering and α the ratio between the number of elastic events and the total number of events in each bin.

p (MeV/c)	θ_1 (°)	θ_2 (°)	q_2 (MeV/c)	ϵ	α
800	± 8	6.0 ± 0.5	71.2 ± 13.2	$+0.0060 \pm 0.0057$	0.98
		7.6 ± 1.0	97.5 ± 13.2	$+0.0024 \pm 0.0043$	0.97
		9.6 ± 1.0	123.8 ± 13.2	$+0.0032 \pm 0.0050$	0.91
		11.7 ± 1.0	150.2 ± 13.2	$+0.0207 \pm 0.0064$	0.82
		13.7 ± 1.0	176.5 ± 13.2	-0.0096 ± 0.0086	
		15.8 ± 1.0	202.8 ± 13.2	-0.0053 ± 0.0118	
1100	± 5	3.8 ± 0.7	71.2 ± 13.2	$+0.0023 \pm 0.0122$	0.98
		5.2 ± 0.7	97.5 ± 13.2	-0.0005 ± 0.0054	0.97
		6.6 ± 0.7	123.8 ± 13.2	$+0.0095 \pm 0.0045$	0.95
		8.1 ± 0.7	150.2 ± 13.2	-0.0035 ± 0.0056	0.87
		9.5 ± 0.7	176.5 ± 13.2	$+0.0043 \pm 0.0074$	
		10.9 ± 0.7	202.8 ± 13.2	-0.0030 ± 0.0098	
		13.0 ± 1.4	242.3 ± 26.4	-0.0067 ± 0.0085	
		15.8 ± 1.4	295.0 ± 26.4	$+0.0114 \pm 0.0092$	
1100	± 8	3.8 ± 0.7	71.2 ± 13.2	$+0.0090 \pm 0.0076$	0.98
		5.2 ± 0.7	97.5 ± 13.2	$+0.0125 \pm 0.0081$	0.97
		6.6 ± 0.7	123.8 ± 13.2	$+0.0131 \pm 0.0092$	0.95
		8.1 ± 0.7	150.2 ± 13.2	$+0.0248 \pm 0.0114$	0.87
		9.5 ± 0.7	176.5 ± 13.2	$+0.0129 \pm 0.0153$	
		10.9 ± 0.7	202.8 ± 13.2	-0.0181 ± 0.0201	
		13.0 ± 1.4	242.3 ± 26.4	$+0.0038 \pm 0.0175$	
		15.8 ± 1.4	295.0 ± 26.4	$+0.0133 \pm 0.0189$	

Table 5

Results for $\bar{p}p$ asymmetries ϵ at 800 and 1100 MeV/c: θ_1 and θ_2 are the first and second scattering angles; q_2 is the momentum transfer in the second scattering, and α the ratio between the number of $\bar{p}p$ scattering events and the total number of events in each bin.

p (MeV/c)	θ_1 ($^\circ$)	θ_2 ($^\circ$)	q_2 (MeV/c)	ϵ	α
800	± 8	5.45 ± 1.09	71.5 ± 14.5	$+0.0067 \pm 0.0135$	0.89
		7.63 ± 1.09	100.0 ± 14.0	$+0.0114 \pm 0.0125$	0.93
		9.82 ± 1.09	128.0 ± 14.0	$+0.0111 \pm 0.0120$	0.96
		12.00 ± 1.09	155.5 ± 13.5	-0.0032 ± 0.0120	0.98
		14.18 ± 1.09	182.5 ± 13.5	$+0.0069 \pm 0.0123$	0.98
1100	± 5	5.30 ± 0.75	100.0 ± 14.0	$+0.0031 \pm 0.0113$	0.92
		6.80 ± 0.75	128.0 ± 14.0	-0.0001 ± 0.0109	0.94
		8.30 ± 0.75	155.5 ± 13.5	$+0.0259 \pm 0.0106$	0.97
		9.80 ± 0.75	182.5 ± 13.5	$+0.0030 \pm 0.0107$	0.98
		11.30 ± 0.75	209.5 ± 13.5	-0.0188 ± 0.0110	0.99
		12.80 ± 0.75	236.5 ± 13.5	$+0.0106 \pm 0.0116$	0.99
1100	± 8	14.30 ± 0.75	263.5 ± 13.5	$+0.0240 \pm 0.0126$	0.99
		5.30 ± 0.75	100.0 ± 14.0	-0.0148 ± 0.0261	0.92
		6.80 ± 0.75	128.0 ± 14.0	-0.0180 ± 0.0252	0.94
		8.30 ± 0.75	155.5 ± 13.5	-0.0071 ± 0.0242	0.97
		9.80 ± 0.75	182.5 ± 13.5	$+0.0561 \pm 0.0245$	0.98
		11.30 ± 0.75	209.5 ± 13.5	$+0.0125 \pm 0.0251$	0.99
		12.80 ± 0.75	236.5 ± 13.5	$+0.0393 \pm 0.0264$	0.99
		14.30 ± 0.75	263.5 ± 13.5	$+0.0572 \pm 0.0289$	0.99

Table 6

Values of the $\bar{p}$ -nucleon parameters obtained from Dover-Richard (DR) and Paris models and used as input to the Glauber theory calculations

p (MeV/c)	608		800		1100	
Model	DR	Paris	DR	Paris	DR	Paris
$\sigma_p(\text{fm}^2)$	16.7	16.0	14.1	12.7	12.0	10.6
α_{AP}	0	0	0	0	0	0
$\beta_{AP}(\text{fm}^2)$	0.91	0.84	0.75	0.68	0.63	0.57
$\lambda_p(\text{fm}^3)$	2.2	2.9	1.6	2.0	1.1	1.2
α_{cp}	0	0	0	0	0	0
$\beta_{cp}(\text{fm}^2)$	1.18	0.98	1.10	0.73	1.12	0.54
$\sigma_n(\text{fm}^2)$	15.6	14.0	13.5	11.8	11.6	10.0
α_{An}	0	0	0	0	0	0
$\beta_{An}(\text{fm}^2)$	0.80	0.69	0.67	0.59	0.56	0.49
$\lambda_n(\text{fm}^3)$	0.85	1.75	0.80	1.44	0.70	1.22
α_{cn}	0	0	0	0	0	0
$\beta_{cn}(\text{fm}^2)$	1.03	0.78	1.00	0.58	1.26	0.50

Figure captions

Fig. 1: Layout of the beam line: Q denotes quadrupoles, D bending magnets and C_H and C_V collimators in the horizontal and vertical planes. The first and second carbon scatterers are located at the two focal points F_1 and F_2 .

Fig. 2: Beam envelope in the horizontal and vertical planes, calculated for the maximal acceptance (± 18 and ± 36 mrad in the horizontal and vertical planes respectively).

Fig. 3: Top view of the experimental apparatus: PC denotes multiwire proportional chambers, B,S,P,L, and V scintillation counters.

Fig. 4: Angular acceptance for $\bar{p}C$ events at 800 MeV/c. At small angles the acceptance has been measured, while at large angles it has been evaluated with a Monte Carlo, as explained in the text.

Fig. 5: Angular distribution, corrected for acceptance, for $\bar{p}C$ scattering events without ($\blacksquare$) and with ($\blacktriangle$) signal in the veto box at 800 MeV/c (a) and 1100 MeV/c (b). The curves are the computed distributions for elastic scattering (dashed), double elastic scattering (dotted), and residual annihilation (dash-dotted) events; the full curve is the sum of these distributions.

Fig. 6: Scatter plots of amplitude as a function of time of flight (TOF) of counter L_2 for $\bar{p}C$ scattering events at 800 MeV/c without (a) and with (b) signal in the veto box; R indicates the region used to evaluate the residual annihilation in the V_{off} sample.

Fig. 7: Check of the stability of the apparatus during data taking at 800 MeV/c (see text).

Fig. 8: Example of azimuthal distribution in $\bar{p}C$ scattering at 800 MeV/c with $\theta_1 = +8^\circ$ (a) and -8° (b); the curves are the expected behaviour $N^\pm(\phi) = N_0^\pm (1 \pm \epsilon \cos \phi)$.

Fig. 9: Normalized difference between the distributions of fig. 8; the expected dependence on ϕ is $\epsilon \cos \phi$ (full curve).

Fig. 10: Angular acceptance for $\bar{p}p$ events at 800 MeV/c. At small angles the acceptance has been measured, while at large angles it has been evaluated with a Monte Carlo calculation, as explained in the text.

Fig. 11: Angular distribution for $\bar{p}p$ scattering events without ($\blacksquare$) and with ($\blacktriangle$) signal in the veto box at 800 MeV/c (a) and 1100 MeV/c (b).

Fig. 12: Scatter plot of amplitude as a function of TOF of the L_2 counter for $\bar{p}p$ scattering events at 800 MeV/c without (a) and with (b) signal in the veto box.

Fig. 13: Measured $\bar{p}C$ asymmetries at 608, 800, and 1100 MeV/c; the curves have been computed using Dover–Richard (dashed curve) and Paris (dash-dotted curve) models.

Fig. 14: Weighted averages of the measured asymmetries on carbon (see text). The curves are the asymmetries computed with Dover–Richard (dashed) and Paris (dash-dotted) models; the full line is the best fit to the first four points assuming $A'_{\bar{p}C} = A_{\bar{p}C} = a_c q$.

Fig. 15: Measured $\bar{p}p$ asymmetries at 608, 800, and 1100 MeV/c; the curves have been computed using Dover–Richard (dashed curve) and Paris (dash-dotted curve) models.

Fig. 16: Weighted averages of the measured asymmetries on hydrogen (see text). The curves are the asymmetries computed with Dover–Richard (dashed) and Paris (dash-dotted) models; the full line is the best fit assuming $A_{\bar{p}p} = a_p q$.

Fig. 17: Measured values of the polarization parameter in $\bar{p}p$ elastic scattering at 783 and 1089 MeV/c from ref. 6.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17