**MEASUREMENT OF THE ANALYSING POWER AND THE DIFFERENTIAL CROSS-SECTION
OF THE $\bar{p}p$ CHARGE-EXCHANGE REACTION AT LEAR**

R. Birsa, F. Bradamante, S. Dalla Torre-Colautti, M. Giorgi, M. Lamanna,
A. Martin^{*)}, A. Penzo, P. Schiavon and F. Tassarotto,
INFN Trieste and University of Trieste, Italy

M.P. Macciotta, A. Masoni, G. Puddu and S. Serici,
INFN Cagliari and University of Cagliari, Italy

T. Niinikoski and A. Rijllart,
CERN, Geneva, Switzerland

A. Ahmidouch, E. Heer, R. Hess, R.A. Kunne^{**)}, C. Lechanoine-Le Luc,
C. Mascarini and D. Rapin,
DPNC, University of Geneva, Switzerland

J. Arvieux, R. Bertini, H. Catz, J.C. Faivre and F. Perrot-Kunne,
CEN DPhN and LNS, Saclay, Gif-sur-Yvette, France

M. Agnello, F. Iazzi and B. Minetti,
INFN Turin and Polytechnic of Turin, Italy

T. Bressani^{*)}, E. Chiavassa, N. De Marco, A. Musso and A. Piccotti,
INFN Turin and University of Turin, Italy

ABSTRACT

As part of a programme to study the spin structure of the $\bar{p}p \rightarrow \bar{n}n$ channel, we have measured the analysing power A_{0n} and the differential cross-section at an incident antiproton beam momentum of 704 MeV/c. The analysing power exhibits a remarkable angular dependence, which is poorly reproduced by the existing potential models.

(Submitted to Physics Letters B)

^{*)} At present Research Associate at CERN, Geneva, Switzerland.

^{**) Present address: Lab. National Saturne (LNS), CEN-Saclay, Gif-sur-Yvette, France.}

The charge-exchange reaction $\bar{p}p \rightarrow \bar{n}n$ presents a special feature, i.e. the absence of $I = 0$ exchanges in the t-channel, which makes it ideal for testing the s-channel effects in the $N\bar{N}$ scattering. In particular, in the forward hemisphere the π -exchange should dominate the reaction. Spin observables should be very sensitive to this behaviour. The main goal of Experiment PS199 is to measure the angular distribution of the spin observables A_{0n} and D_{0n0n} at several momenta ranging between 0.5 and 1.5 GeV/c, at the CERN Low-Energy Antiproton Ring (LEAR). In a first run we have measured the analysing power A_{0n} at three different incident beam momenta, 704, 804, 905 MeV/c, and in this letter we present results for both A_{0n} and the differential cross-section $d\sigma/d\Omega$, at the lowest momentum. Even though several experiments [1, 2] have already measured the differential cross-section of this reaction at momenta smaller than 1 GeV, this is the first time that the polarization parameter is measured in this energy region (only one measurement [3] exists at 8 GeV/c).

The layout of the experiment is shown in fig. 1a. The neutrons (n) and the antineutrons ($\bar{n}$) produced in the charge-exchange reaction are detected with the neutron counters NC₁, NC₂, and NC₃, and the antineutron counters ANC₁ and ANC₂. A close-up of the target region is shown in fig. 1b.

The beam line used is the C1 line from LEAR, with a typical intensity of 10^6 antiprotons per second. The target sits in the nose of a cryostat. The beam pipe is terminated just before the back end of the cryostat. Thus, to reach the target, the beam travels along the cryostat axis, passing only through two thin windows (0.1 mm Al and 0.125 mm Mylar) and the beam counters. Two scintillation counters define the beam: counter B₀ (3 cm high, 7 cm long, 0.5 mm thick) is located just before the cryostat; the other counter, B₁₂ (0.5 cm radius and 0.5 cm thick), is placed inside the cryostat, as close as possible to the target (19 cm from its centre), viewed by two light-guides going to two different photomultipliers (PMs), B₁ and B₂.

The polarized target (PT), made of pentanol (C₅H₁₁OH), operates in the frozen-spin mode [4]. The pentanol beads are contained in a 12 cm long, 1.8 cm diameter cartridge, and are cooled to 80 mK in a ³He + ⁴He dilution refrigerator. The target is located in a highly homogeneous (better than 10^{-4}) vertical magnetic field of 2.5 T provided by a C-shaped dipole magnet. A target polarization as high as 96% can be achieved in two to three hours, although for efficiency reasons we preferred to start taking data with a target polarization of $\sim 80\%$, which could be reached in about one hour. As soon as the frozen-spin mode of operation is started, the magnetic field is lowered to 0.3785 T. In these conditions the bending power of the PT magnet is only 0.117 T·m, and a beam with momenta as low as 500 MeV/c can be transmitted to the target. For background evaluation we also used a fluorinated ethylene-propylene (FEP) dummy target (DT) having the same mass and density as the PT, but with all the hydrogen replaced by fluorine. For calibration purposes, the PT could be replaced by a liquid-hydrogen target (LHT), 12 cm long and 3.2 cm diameter.

To reject annihilation and elastic events at the trigger level, the target region is surrounded by a scintillation veto counter box on all sides except that of the incoming beam. The upper and lower vetoes, the so-called pole-face counters (PF), are made up of four layers of scintillator, interleaved with a total of 1.3 radiation lengths of lead to reject events involving annihilation into neutrals. The forward veto (FV) and the two lateral vetoes (RV and LV) ensure that the particles detected in the NCs and ANCs are neutral.

The three NC detectors [5] are made up of a total of 53 vertical scintillation counters (NE 110). Each scintillator bar is 8 cm wide and 20 cm thick, and its length varies from 40 to 130 cm. The bar is viewed from each end by a 5-inch PM. A coincidence between the top and bottom PM is the requirement for a bar hit. Each of the two ANC detectors [6] comprises five identical modules made of four planes of limited streamer tubes (LST) with X and Y strip readout, and one plane of scintillation counters with a sensitive surface of 166×200 cm². Again the scintillators are vertical (33 cm wide, 1 cm thick, 166 cm long) and are viewed from the top and the bottom by PMs. Each detector consists of 60 PMs and 7040 LST readout channels. The modules are interleaved with four 3 cm thick iron slabs, in which most of the antineutrons annihilate giving a characteristic star pattern in the LST modules before and after the slab.

In the geometrical arrangement shown in fig. 1 the $\bar{n}$'s undergo considerable absorption and scattering when passing through the NC detectors. Still, the configuration has several advantages; namely, it allows

- a selection of events in which an $\bar{n}$ scatters in an NC, thus providing data for the measurement of the polarization of the $\bar{n}$'s, and hence of the spin observable K_{n00n} ;
- a measurement of the efficiency of the ANC's at $\theta_{cm} = 90^\circ$;
- an excellent vetoing of ANC's against charged particles;
- easy shielding of the left side of the apparatus from the right side with concrete blocks, thus preventing the products of $\bar{n}$ annihilation in one arm of the apparatus from hitting the detectors in the other arm.

Before the run the apparatus was fully tested with cosmic rays. The threshold of the neutron counters was measured by calibration with the 4.4 MeV γ -rays from an Am/Be neutron source. During the run, all the scintillation counters were monitored continuously with a N_2 laser, which is connected to all the light-guides by optical fibres. Timing and amplitude calibrations were done between spills.

A charge-exchange trigger was given by the coincidence $(B_0 \cdot B_1 \cdot B_2) \cdot (FV + RV + LV) \cdot PF \cdot (NC_1 \cdot ANC_1 + (NC_2 + NC_3) \cdot ANC_2)$, where NC means at least one bar hit, and ANC means at least two scintillators hit, in the corresponding detector. For each event the full TDC and ADC information coming from the counter system was recorded, as well as the coordinates of the LSTs, for a total of about 400 words. The data acquisition was performed with the CERN DAQP system using a MicroVAX II computer and two CES 'Starburst' processors, with an acquisition time of ~ 2 ms per event.

In order to minimize possible systematic errors, the data were taken in different blocks. One spin orientation for the target was kept over four (one-hour) spills. Then the target polarization was reversed and data were again taken over four spills. The whole cycle was then repeated once, thus providing two sets of data for each spin orientation. Over 1.5 days we could thus collect about 10^7 events. One more day was devoted to collecting data with the DT and with the LHT.

In the off-line analysis, events with a 'star' topology were first identified by requiring that in ANC_1 (or ANC_2) there be at least three tracks in a given (horizontal or vertical) projection of the two LST modules sandwiching anyone of the four iron slabs—the tracks meeting at a common point on the slab itself—and at least two tracks in the other projection. This selection allowed the $\bar{n}$'s to be identified with an efficiency of $\sim 20\%$. The probability of misidentifying a neutron as an antineutron was measured to be less than 10^{-4} by counting the 'star' coincidences between ANC_1 and ANC_2 . Some γ 's satisfied the 'star' topology, but were completely rejected by time-of-flight (TOF) cuts. For the events with an $\bar{n}$ candidate (about 10% of the total sample), neutrons were recognized when at most two adjacent bars were hit in the NC hodoscopes. The neutron horizontal coordinate was given by the bar number, whilst the vertical coordinate was obtained through the difference between the time given at the top and the bottom PM of each bar. The directions of the two particles were computed from the neutron coordinates, from the $\bar{n}$ annihilation vertex, from the centre of the target, and from the average beam direction. The charge-exchange events on hydrogen were selected from those on the nuclear matter of the PT on the basis of coplanarity and angular correlation. Further cuts were made on the TOF of both n and $\bar{n}$. Figure 2 shows the angular correlation signal after applying all cuts: in the PT data, the events on hydrogen are seen as a peak over a small background. By comparing the events from PT and DT with $|\Delta\theta| < 5^\circ$, we derived an average ratio $f = B/(B + S)$ of 6% for the PT, where B and S indicate the background and the signal, i.e. the accepted charge-exchange events on the unpolarized and polarized protons of the PT, respectively.

To evaluate the asymmetry A_{0n} , the usual expression

$$A_{0n} = \frac{1}{(1-f)} \frac{N^+ - RN^-}{N^+ \langle P_T \cos \phi \rangle^+ + RN^- \langle P_T \cos \phi \rangle^-}$$

was used, where $N^\pm$ is the number of charge-exchange events and $\langle P_T \cos \phi \rangle^\pm$ is the average target polarization for the two spin orientations of the target; R is the ratio of the relative beam. The asymmetry was computed using only data for which the beam transmission into the target, defined by the ratio $(B_0 \cdot B_1 \cdot B_2)/B_0$, was stable within $\pm 5\%$. This represents about 70% of the total sample. Systematic effects due to variations of the $\bar{p}$ beam intensity were investigated. They contribute

$\sim 0.4\%$ of the quoted errors. The results are shown in fig. 3, together with the theoretical predictions given in the framework of some potential models [7–10]. The quoted value for the beam momentum (656 MeV/c) is the average value in the target: owing to the considerable energy loss in the target, the reaction momentum ranged from 688 to 622 MeV/c.

Even though the experiment was specifically designed to measure A_{0n} , we used part of the calibration data taken with the LHT to evaluate the differential cross-section. These data were taken with the trigger $(B_0 \cdot B_1 \cdot B_2) \cdot (FV + RV + LV) \cdot PF \cdot (ANC_1 + ANC_2)$, i.e. without requiring coincidence with the neutron counters. The $d\sigma/d\Omega$ data were obtained from the difference between the angular distributions of the $\bar{n}$'s measured with ANC_1 and ANC_2 under Full Target and Empty Target conditions. The $\bar{p}$ momentum at the centre of the target was 693 MeV/c, and the full spread along the target was 12 MeV/c. The absorption corrections have been evaluated using the parametrization of ref. [11], $\sigma_a(\bar{n}, A) = A^{2/3} (61 + 16/p)$, for nuclei, and that of ref. [12], $\sigma_a(\bar{n}, p) = (41.4 + 29/p)$, for hydrogen, with p in GeV/c and σ in mb. Since the correction is particularly important for the NC hodoscopes, we considered only $\bar{n}$'s annihilating in the first iron absorber: with this choice, the product of the probability of annihilation in ANC times that of the absorption in NC turned out to be almost independent of the $\bar{n}$ energy, and insensitive to small variations in the absorption parameters of refs. [11] and [12]. Moreover, using this choice and with an over-conservative cut in the $\bar{n}$ azimuthal angle ($|\phi_{\bar{n}}| < 11^\circ$), the evaluation of the geometrical acceptance with a Monte Carlo turned out to be very simple. In the angular range in which we give results, the corrections for the geometrical acceptance are smaller than 30%. The corrections to the angular distribution, which were due to the smearing caused by the $\bar{n}$ elastic scattering on the hydrogen and carbon contents of the NCs, were parametrized as in the Appendix of ref. [12]. They turned out to be very small (at most 3%).

The differential cross-section is shown in fig. 4, together with the same model calculations as in fig. 3. The quoted errors are statistical, and are larger than the non-uniformities of the ANC modules as measured in the calibration runs with cosmic rays. They are also larger than the estimated error in the corrections for the geometrical acceptance. The overall normalization was determined from the data at $\theta_{cm} = 90^\circ$. In the present analysis, the overall normalization error is estimated to be about 10%.

The $d\sigma/d\Omega$ data reproduce the trend of the existing data at nearby energies and of the calculations of the various potential models. The A_{0n} data of fig. 3 constitute a new piece of information and exhibit an interesting pattern, with backward and forward peaks of similar strengths and possibly a flat minimum in the central region. This simple pattern is reproduced only poorly by the theoretical predictions, apart from the prediction of ref. [8]. In particular, there are very big differences in the predictions of the various models also in the forward angles, where π -exchange is expected to dominate the reaction. In this respect the agreement between our data and the calculations of ref. [8] is extremely interesting, and understanding this agreement could help in assessing the interplay between the annihilation and the boson-exchange parts of the NN potential.

Acknowledgements

The construction of the apparatus required much technical effort, and we would like to acknowledge the invaluable contributions of J. Briatte, P. Ciliberti, J.C. Lugol, G. Menon, E. Perrin, J.P. Richeux and L. Simonetti. The assistance of L. Mazzone and G. Novellini (CERN SPS Division) in the construction of the LHT is also acknowledged. Some of the authors would like to thank the Swiss National Science Foundation for support. The excellent performance of LEAR made this experiment possible, and we are grateful to J.D. Simon, D. Dumollard, and the LEAR operating staff for their collaboration. Finally, we would like to express our appreciation to F. Dydak, former CERN EP Division Leader, for hospitality and support.

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Figure captions

- Fig. 1a: Schematic layout of Experiment PS199 at LEAR. The dashed line indicates the mean position of the $\bar{p}$ beam. Also shown are the positions of the yoke and of the coils of the PT magnet and the PT cryostat.
- Fig. 1b: Close-up of the target region (side view), showing the veto counters and the beam-defining counter B_{12} inside the cryostat.
- Fig. 2: Angular correlation $\Delta\theta = \theta_{\bar{n}}^m - \theta_{\bar{n}}^c$ for samples of PT (blank histogram) and DT (hatched histogram) events; $\theta_{\bar{n}}^m$ is the measured $\bar{n}$ scattering angle, and $\theta_{\bar{n}}^c$ is the same quantity computed from the measured n-scattering angle in the $\bar{p}p \rightarrow \bar{n}n$ hypothesis.
- Fig. 3: The analysing power A_{0n} as a function of $\cos \theta_{\bar{n}}$ in the centre of mass, measured at 656 MeV/c. The curves are potential-model calculations [7–10].
- Fig. 4: The differential cross-section $d\sigma/d\Omega$ as a function of $\cos \theta_{\bar{n}}$ in the centre of mass, measured at 693 MeV/c. The curves are potential-model calculations [7–10].

Fig. 2

Fig. 1

Fig. 3

Fig. 4