**MEASUREMENT OF THE ANALYSING POWER OF THE
CHARGE-EXCHANGE $\bar{p}p \rightarrow \bar{n}n$ REACTION IN THE MOMENTUM
RANGE 546–1287 MeV/c AT LEAR**

R. Birsa, F. Bradamante, A. Bressan, S. Dalla Torre-Colautti, M. Giorgi, M. Lamanna,

A. Martin, A. Penzo, P. Schiavon, F. Tassarotto

INFN Trieste and University of Trieste, Italy

M.P. Macciotta, A. Masoni, G. Puddu, S. Serici

INFN Cagliari and University of Cagliari, Italy

T. Niinikoski, A. Rijllart

CERN, Geneva, Switzerland

A. Ahmidouch, E. Heer, R. Hess, C. Lechanoine-Le Luc, C. Mascarini, D. Rapin

DPNC, University of Geneva, Switzerland

H. Catz, J.C. Faivre, F. Perrot-Kunne

CEN DAPNIA/SPhN Saclay, Gif-sur-Yvette, France

J. Arvieux, R. Bertini, R.A. Kunne

LNS, IN2P3-CNRS and DSM-CEA, CE Saclay, Gif-sur-Yvette, France

M. Agnello, F. Iazzi, B. Minetti

INFN Turin and Polytechnic of Turin, Italy

T. Bressani, E. Chiavassa, N. De Marco, A. Musso, A. Piccotti

INFN Turin and University of Turin, Italy

Abstract

Final results of the measurement of the analysing power A_{0n} of the $\bar{p}p \rightarrow \bar{n}n$ reaction are presented. Eight measurements in the range 546–1287 MeV/c incoming $\bar{p}$ momentum have been performed over the full angular range using a solid polarized proton target and the Low Energy Antiproton Ring (LEAR) at CERN antiproton extracted beams.

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1 Introduction

Antinucleon–nucleon scattering is an essential ingredient to study the $\bar{N}N$ interaction. At low energy it is common practice to consider separately the long-range and the short-range parts of the interaction. At large distances, the interaction is believed to proceed via the exchange of mesons, and the traditional nuclear physics description of the antinuclear force [1] is generally considered to be adequate. At short distances, the dominant process is the annihilation, which can be correctly described only by involving microscopic degrees of freedom. Since the nucleons are not point-like particles, annihilation occurs at distances comparable with the nucleon r.m.s. charge radius, ~ 0.8 fm. A full description of the $\bar{N}N$ interaction has the ambitious aim of providing a bridge between two well-established and successful theories, the meson-exchange potential (MEP) models and quantum chromodynamics (QCD).

Since the advent of LEAR, the Low Energy Antiproton Ring at CERN, new and accurate data have been obtained in both the $\bar{p}p \rightarrow \bar{p}p$ elastic channel and in the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange channel [2, 3]. In this paper we report the final results of experiment PS199 which measured the analysing power A_{0n} of the charge-exchange reaction at LEAR at 8 incident $\bar{p}$ momenta, ranging from 608 MeV/c to 1307 MeV/c, in approximately 100 MeV/c momentum steps, using a solid polarized target (PT). Results at 546, 656, 767, and 875 MeV/c (momenta at the centre of the target) are already published [4, 5]. Preliminary results at all momenta have already been shown at conferences [3, 6].

Basically three motivations led us to perform the measurement.

Firstly, the knowledge of the charge-exchange channel is essential to resolve the isospin structure of the $\bar{N}N$ interaction. In contrast to the pp case, the $\bar{p}p$ system is not a pure isospin state. The amplitude for the $\bar{p}p$ elastic channel is given by the sum of the $I = 0$ and the $I = 1$ amplitudes, whilst the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange amplitude is given by the difference of the two. Several experiments at LEAR have provided accurate measurements of the $\bar{p}p$ elastic channel, but a complete analysis of the system requires the measurement of the charge-exchange channel as well.

Secondly, the charge-exchange reaction is expected to be a particularly sensitive channel to probe the nucleon–antinucleon force. The long range part of the interaction should be dominated by pion exchange, a well-known ‘classical’ term in any boson exchange potential model, and the fact that $I = 1$ only is exchanged in the t -channel reduces the number of relevant exchanges.

Thirdly, no data at all existed on the spin structure of the charge-exchange channel in this energy region (only a single measurement of A_{0n} exists [7], but at a much larger energy).

Since the reaction involves four fermions, five complex amplitudes are needed to build up the scattering matrix, and the cross-section alone is inadequate to test the different theoretical models.

Experiment PS199 has been the first to measure the analysing power of the $\bar{p}p \rightarrow \bar{n}n$ reaction in this energy range. Also, the differential cross-section will be obtained from the data collected for A_{0n} (the analysis is in progress). Another important goal of PS199 has been the measurement of the depolarization parameter D_{0n0n} at two $\bar{p}$ momenta (546 and 875 MeV/c): the analysis of the data at the higher momentum is finished [8], whilst the analysis of the lower momentum data is in progress.

The experiment has been performed by detecting both the n and the $\bar{n}$ produced in the reaction, and the events on the polarized free hydrogen of the target have been identified using the time of flight (TOF) and the measured space coordinates of the two

particles. For an unambiguous determination of the scattering angle of each event, the apparatus has been designed to give a very good $\bar{n}$ identification.

The $\bar{p}p \rightarrow \bar{n}n$ channel represents less than one tenth of the total $\bar{p}p$ cross-section, and the detection of the two neutral particles in the final state could be done with an efficiency of only a few per cent. Still, the signal in the final state has a very little background, and the accuracy of the results is limited only by statistical errors. A precise estimate of the residual background has been made by measuring the charge-exchange events produced on a dummy target.

2 Apparatus

2.1 Experimental set-up

The layout of the experiment is shown in fig. 1; ANC₁ and ANC₂ are the two antineutron detectors, NC₁, NC₂ and NC₃ are the three neutron counters. In the target region, one can see the yoke and the poles of the polarized target magnet (PTM), the cryostat, and the target. The dashed line indicates the beam direction, deflected by the magnetic field. Veto and beam counters are not displayed in fig. 1, but can be seen in the close-up view of the target region (fig. 2). HB is a beam hodoscope, downstream of the experiment, to monitor the beam direction in the horizontal plane.

The layout used at 608, 1005, 1106, 1207 and 1307 MeV/c incident $\bar{p}$ momentum in May 1990 is shown in fig. 1; the data at 704, 804 and 905 MeV/c (September 1989) have been collected with a very similar set-up, described in ref. [4, 5], differing from that of fig. 1 only in a small tilt of the ANC₂–NC₁ arm. The forward reaction is measured by the detectors ANC₁–NC₁, the backward reaction with the ANC₂–NC₂ and ANC₂–NC₃. Concrete blocks (dashed in fig. 1) shield the left side of the apparatus from the right side, thus preventing the annihilation products on the $\bar{n}$ in one arm of the apparatus from hitting the detectors in the other arm.

Since the target protons are polarized along the vertical direction, the reaction is measured close to the horizontal plane (the azimuthal acceptance is anyway limited by $\pm 15^\circ$ by the poles of the PT magnet). The A_{0n} parameter is then estimated from the left–right difference in cross-section, i.e. from the difference in the $\bar{n}$ counting rate in a given detector for ‘up’ and ‘down’ target proton polarization.

In the set-up of fig. 1 an important fraction of the $\bar{n}$ coming from the target are absorbed or scattered in the NC in front of the ANC. Most of these events can be identified and rejected by using the signal in the neutron counter in front of the ANC in which the $\bar{n}$ was detected thus the net effect on the data is a loss of ‘good’ events. Still, this configuration has several advantages; namely it allows

- to veto with very high efficiency any charged particle coming from the target;
- to measure the antineutron detector efficiency at 90° in the centre of mass [9];
- to shield the two arms of the apparatus with a concrete wall, reducing to a minimum the cross-talk of each ANC with the corresponding NC in coincidence;
- to select events in which the $\bar{n}$ scatters in the NC, thus providing data to measure the polarization of the antineutrons, and hence of the polarization transfer parameter K_{n00n} [10].

2.2 Beam

The experiment has been installed and operated on the C1 line from LEAR. The extracted $\bar{p}$ beam has small emittances (5π mm·mrad in the horizontal plane and 20π mm·mrad in the vertical plane, at 600 MeV/c, decreasing with increasing momentum) and small

momentum spread ($\Delta p/p \simeq 10^{-3}$). We have used spills of one hour, with a typical intensity of $1\text{--}2 \times 10^6$ $\bar{p}$'s per second. During the spill, the intensity was fairly constant, with a microscopic duty factor of ~ 0.5 , estimated from the measured rate of delayed coincidences.

As shown in fig. 1, the target is located 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 about 1 m along the cryostat axis, passing only through two thin windows (0.1 mm Al, ending the beam pipe, and 0.125 mm Mylar, closing the PT cryostat), the beam counters, and 16 cm of air.

Two scintillator counters define the beam. The first counter B_0 is 3 cm high, 7 cm long, and 0.5 mm thick, viewed by an XP2020 photomultiplier (PM) and it is placed upstream just in front of the cryostat. The second one is a disk (1 cm in diameter and 0.5 cm thick) located inside the cryostat, 19 cm from the target centre and thus operating at a temperature of $\sim 1^\circ\text{K}$. It is viewed by two long light guides, extending out of the back window of the cryostat, and going to two different XP2020 PMs (B_1 and B_2 ; the name of the counter is B_{12}).

To keep the target polarized, the PT magnet provides a vertical magnetic field of 0.3785 T. Two correction magnets are used to steer the beam in the horizontal plane and make it enter the back window of the cryostat with the proper displacement and angle so as to reach the target centre. To monitor the beam position and to assist in the beam tuning, a retractable MWPC with horizontal and vertical read-out could be inserted just before the B_0 counter.

The coincidence $B_0 \cdot B_1 \cdot B_2$ of the three PMs defines, at the acquisition level, the antiproton entering the target and we define focalization as the ratio $(B_0 \cdot B_1 \cdot B_2)/B_0$. The mean focalization is limited by multiple scattering, and it is a function of the $\bar{p}$ momentum (about 65% at 608 MeV/c, higher than 95% at 1307 MeV/c). The focalization also monitors the stability of the extraction of the $\bar{p}$ beam from LEAR; therefore its stability during data acquisition has been used as a selection criteria in the off-line analysis.

2.3 Target

The polarized target consists of a 12 cm long, 1.8 cm diameter cartridge, filled with pentanol beads ($\text{C}_5\text{H}_{11}\text{OH}$) and cooled down to 80 m°K by a $^3\text{He}\text{--}^4\text{He}$ dilution refrigerator. The target is sited between the poles of a C-shaped dipole magnet; the field is vertical and highly homogeneous in the target region (better than 10^{-4}) and goes up to 2.5 T. Since the field lines are vertical, the spin of the protons could only be oriented 'up' or 'down'.

The target is operated in the frozen-spin mode [11]. The polarization is dynamically induced in the protons of the hydrogen nuclei of the target by RF pumping. Polarization values larger than 90% can be achieved in about three hours, although for efficiency reasons in the experiment we chose to start taking data as soon as a target polarization of $\sim 80\%$ was achieved, which required about one hour. Once the frozen-spin mode of operation was started, the PTM field was lowered from 2.5 T to 0.3785 T. In these conditions, the polarization decreases almost 2% per hour, which could be (partially) recovered during the interspill (15–20 minutes) by setting back the PTM at 2.5 T and switching on the RF system. The target polarization is calibrated with an NMR system, and the absolute uncertainty is $\pm 4\%$.

Operating the target in the frozen-spin mode is a crucial feature of the experiment. The reduction of the PTM field to 0.3785 T (corresponding to a bending power of only

0.117 T·m) allows a $\bar{p}$ beam of momentum as low as 500 MeV/c to travel safely inside the cryostat before reaching the target, thus enabling the use of a long target, parallel to the cryostat axis.

For background evaluation, we have 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, a liquid-hydrogen target (LHT) has also been used. It could be placed in the cryostat, replacing either the PT or the DT; its dimensions are 12 cm in length and 3.2 cm in diameter.

2.4 The veto box

The charge-exchange events are characterized by the fact that no charged particle leaves the target, and that n and $\bar{n}$ signals are present in one ANC-NC pair.

To keep the trigger level to a reasonable value, it is necessary to veto elastic and annihilation events in the target, and the beam transmitted through the target itself. This has been done by building a veto box, shown in fig. 2, made up of scintillator counters, surrounding the target region (outside the cryostat) on all sides, except that of the incoming beam. All these counters are equipped with Hamamatsu R249001 tubes, suitable for operation in a magnetic field, since they are situated in the fringing field of the PT magnet. The transmitted beam is vetoed by a 3 mm counter FV; on the left and the right of the target two similar counters LV and RV veto any charged particle.

In order to avoid triggering on annihilation events sending γ 's into NC-ANC, two more counters are used, one above and one underneath the target, close to the PTM poles. These so-called pole-face counters are positioned outside the geometrical acceptance of the apparatus ($\pm 15^\circ$ in the azimuthal coordinate), and are made up of four layers of scintillator (3 mm thick) and three layers of lead, with a total of 1.3 radiation lengths. These two sandwiches convert gammas from the π^0 decay with a good efficiency, vetoing also part of the annihilations with no charged mesons. Each sandwich is viewed by two phototubes whose signals are ANDed together in the trigger: the pole-face veto signal (PF) is the OR of these two parts.

2.5 Antineutron detectors

The $\bar{n}$ counters identify the antineutrons by detecting the annihilation 'stars', i.e. the trajectories of the charged products of the annihilation.

Each $\bar{n}$ detector (ANC) is built up using 5 identical basic units, the 'modules', separated by 4 iron slabs, 3 cm thick, which contain most of the mass of the detector, and where the $\bar{n}$ annihilations are expected to occur in the majority of cases. The choice of the absorber material and thickness is based on a Monte Carlo simulation and is a compromise between absorption of charged pions and conversion of γ 's from neutral pions from the annihilation point. A schematic drawing of one detector is given in fig. 3, which also shows a typical $\bar{n}$ event.

Each module is made of four vertical planes of Limited Streamer Tubes (LSTs) and one plane of scintillator counters in between, with a sensitive surface of 166×200 cm². The scintillator counter hodoscope is a set of six vertical scintillator slabs 1 cm thick, 33 cm wide, and 166 cm long. Each slab is viewed by two XP2020 PMs. The PM signals are sent to Constant Fraction Discriminators (CFDs) to avoid the time-walk problem. A slab hit is given by the mean-time coincidence of the two PMs. The hodoscopes give the trigger signal for the ANC, the time-of-flight information, and they can also be used to

counter-check the output of the LST tracking system. All PMs are monitored by a laser calibration system, described in the following section.

The LST planes are used to reconstruct the trajectories of the charged products of the $\bar{n}$ annihilation. Two planes are located on each side of the hodoscope; the LST planes have the same sensitive surface as the hodoscope. Each plane is equipped with 192 strips reading the horizontal (X) coordinate (10 mm pitch) and 160 strips for the vertical (Y) coordinate (10.5 mm pitch). The module is closed by two aluminium walls 6.3 mm thick; each module is only 155 mm thick.

The digital read-out electronics is serial (plane by plane) and based on the commercial board ‘Streamer Tube Interface’ provided by SGS. A CAMAC interface is used, the Streamer Tubes Read-out Controller (STROC). The total number of read-out channels is 14,000. A full description of the system can be found in ref. [12].

The LST system is monitored before and during the runs with cosmic rays, and efficiency maps are obtained for each plane. A typical map for one plane is given in fig. 4: the mean efficiency is 84%, and the bin-to-bin variations are compatible with the statistical fluctuations.

2.6 Neutron detectors

The three neutron counter hodoscopes, NC₁, NC₂, and NC₃ are made up of 19, 24, and 10 vertical bars respectively. Each bar is 8 cm wide and 20 cm thick and it is made of NE110 plastic scintillator. The lengths of the bars range from 40 cm to 130 cm; shorter bars are placed near the beam, since this does not reduce the geometrical acceptance for the reaction. Each bar is viewed at its ends by two XP2040 PMs. As for the $\bar{n}$ detectors, CFDs are used for all signals. The mean-time coincidence of the two PMs defines a bar hit. When a bar is hit, the complete information from the two PMs is stored for off-line analysis, i.e. both the timing (in TDCs) and the amplitudes (in ADCs) of the two signals. The vertical coordinate of the neutron is obtained from the difference in TOFs of the two PMs, whilst their arithmetic mean gives the neutron time of flight.

Due to the large volume of the three neutron counters, the natural radioactivity background is not negligible. The hardware threshold was consequently fixed at ~ 1 MeV electron equivalent. Since the neutron detection efficiency is strongly influenced by the threshold (particularly when the neutron energy is low, as in this experiment, where neutrons are detected down to 5 MeV kinetic energy), it is of particular importance to calibrate the energy response close to the threshold and to continuously monitor the gain of each PM during data taking.

The calibration at threshold has been done using the 4.4 MeV γ -rays produced by a $^{241}\text{Am}/\text{Be}(\alpha, n)$ source. Cosmic rays and annihilation pions are also used to measure the detector response for larger energy depositions and to determine the position resolution on the vertical coordinate.

A laser-monitoring system controls the stability of all the 229 PMs in the experiment, and in particular the gain and the timing of the 106 PMs used in the NC hodoscopes. The N₂ laser produces visible light via a liquid scintillator; the amount of light can be chosen with a set of filters. All the PMs are flashed in parallel with an optical fibre system. At each interspill a laser calibration is performed. These data are used on-line to pin down bad channels or drifts in the behaviour of some PM, and off-line to correct the problem (wherever possible). The laser light yield is monitored with a dedicated counter, using as reference a ^{207}Bi source. A full description of the system is given in a separate paper [13].

3 Data taking

3.1 Trigger

The charge-exchange trigger is given by the coincidence:

$$(B_0 \cdot B_1 \cdot B_2) \cdot (\overline{LV + RV + FV}) \cdot \overline{PF} \cdot (ANC_1 \cdot NC_1 + ANC_2 \cdot (NC_2 + NC_3))$$

where NC means at least one bar hit, and ANC means at least two scintillators hit in the corresponding detector.

The rate of trigger was about $300/10^6 \bar{p}$, almost independent of the beam momentum.

In the second period of data taking (May 1990), we could benefit from a beam intensity larger than in the first period (September 1989). In order not to saturate the trigger and suffer dead-time losses, we scaled down the part of the trigger coming from $ANC_1 \cdot NC_1$, which contributes to 80% of the total rate at the higher momenta. This allowed us to make a more accurate measurement in the backward hemisphere, where the cross-section is smaller, without affecting too much the accuracy of the results in the forward direction.

The scaling was done by gating the $ANC_1 \cdot NC_1$ trigger about 60–70% of the time (opening a gate each second). Beam scalers have been counted separately for the two parts of the trigger to properly compute the normalizations. ANC_1 – NC_1 events parasitically recorded during the suppressed trigger time were discarded in the off-line analysis using the trigger pattern units.

Other triggers have been used for different purposes. To calibrate the scintillation counters and to compute the offsets of the TDC channels (both TOF and vertical coordinate measurement offsets), suitable triggers defined $\bar{p}p$ annihilations into neutrals or into charged products, and have been used sometimes during the run. Also, a special trigger was dedicated to the elastic reaction $\bar{p}p \rightarrow \bar{p}p$ about 5% of the time.

A charge-exchange calibration trigger has also been setup, requiring the same beam and target signals as for the charge-exchange trigger but asking only for a signal in either ANC_1 or ANC_2 . These events have been used to determine the efficiency of the neutron counters [13].

3.2 Data acquisition

The data-acquisition system is based on a MicroVax II and three J11 Starburst processors used for parallel data reduction and event building from the CAMAC modules. A complete description of the acquisition system has already been published [14]. Here we give only a brief summary.

When a trigger occurs, the time information from the CFDs is sent to Time-to-Charge converters (TQCs) used in front of a LRS FERA ADC system. Also the pulse heights of the NC photomultipliers are digitized by the FERA ADCs. The information from the LST channels is transferred from the SGS cards to the STROC system, where the hit pattern is encoded and stored.

Two dedicated CES J11 Starburst microprocessors located in the CAMAC crates and operating in parallel read the neutron counters system and the LST information, and perform a data reduction of the experimental buffer. A third J11 takes care of the other CAMAC modules and then receives the data from the other two J11s to build the complete event, filling a multi-events buffer in its memory. Only when the memory of this third J11 is full an interrupt is sent to the MicroVax, which reads the J11 buffer in DMA mode and records the data on 6250 bpi tapes.

The mean buffer event (after the on-line data reduction) is 250 bytes and the acquisition time is of the order of 1.2 ms. The timing diagram for an average event is given in fig. 5.

The J11 reading in parallel the LST information was not present in the first run (September 1989). Its implementation allowed to decrease the read-out time by $\sim 30\%$, and consequently to improve the statistics collected in the successive runs.

3.3 On-line monitor

The on-line check tasks are carried out by the MicroVax itself and two VaxStations. The first workstation controls the scintillator counter information and the histogram display. The second workstation was mainly devoted to displaying on-line samples of events. The MicroVax is the computer performing most of the checks on the data and it also takes care of the slow control part, mainly the check of the high-voltage power supplies of both the neutron and antineutron counters. The ANC detectors were monitored directly by the MicroVax, both checking the consistency of the experimental buffer and by filling and displaying the histograms.

In the interspill, the laser calibration of the scintillator counters was performed using a PC, steering the laser system via CAMAC; the results were also sent to the MicroVax and written on the data tapes.

A Siemens Multireg C1732 recorder, with 32 channels, has been used to monitor the long-term drift of some relevant parameters in the experiment, such as the beam intensity and focalization, trigger rate, target polarization, and single rates of some particular counters. The MicroVax acquisition computer and a PC were connected with the help of an Autodata switch box MS-401 to the RS 232 serial connector of the recorder. A software environment running on the PC was developed to ease the setting up of the recorder. A NIM unit with four ratemeter integrators was also developed to monitor the counter rates [15].

Figure 6 shows a short sample of the chart recorded with the Multireg during the run of May 1990. The chart exhibits some features which illustrate the importance of this on-line graphic support. The figure covers one $\bar{p}$ spill from LEAR, over which the beam intensity varies significantly. The single rates of the counters shown (B_0 and HB) and the trigger rate (T) are proportional to the beam intensity and display a similar behaviour. The ratios of these quantities are compared directly by the recorder, and remain almost constant, as expected. The target polarization is also plotted, and the very slow decrease in time can be noticed. Also the target repolarization during a somewhat longer interspill is shown. Some spikes appear during the interspills in the ratio curves: they are associated with the laser pulses which are used to calibrate the neutron detectors. For bookkeeping, the start of each run is marked on the chart by a 'start of run' message sent to the Multireg by the MicroVax, and printed by the recorder.

3.4 Data taking

The charge-exchange reaction has been measured at eight values of the incoming $\bar{p}$ momentum. The extraction momenta were 608, 704, 804, 905, 1005, 1106, 1207, and 1307 MeV/c, corresponding to 546, 656, 767, 875, 979, 1083, 1186, and 1287 MeV/c at the centre of the target. The momentum spread in the target is 91, 66, 50, 41, 35, 31, 29, and 26 MeV/c respectively.

At these eight momenta data were collected with the PT target; DT measurements have been performed at 704, 905, 1106, and 1307 MeV/c. At 704 and 1307 MeV/c LHT

data (full and empty target) have been collected for calibration purposes.

The relevant statistics (number of $\bar{p}$'s in the target and number of events on tape) is given in table 1.

A typical measurement at one momentum lasts a couple of days (PT run only), to a total of about 30 useful spills. The interspill time is used to run the laser monitor and to increase the polarization of the target to compensate for the decay occurring during the spill. To keep systematic effects under control, the polarization is reversed every 4 spills. This operation lasts one to one and a half hours: typically the data sample at one energy is made up of 3–4 blocks of data for each target orientation.

4 Data analysis

4.1 Data reduction

In the off-line analysis, events with a ‘star’ topology are 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 any one 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. The accuracy of location of the annihilation point on the iron slab is about 1 cm. This definition of $\bar{n}$'s has been checked both on the data and with the aid of a Monte Carlo simulation: it guarantees a reasonably high antineutron efficiency ($\sim 20\%$ at 500 MeV/c), and it rejects most of the spurious events due to the interactions of charged and neutral particles in the detectors. In particular, it allows the rejection of most of the showers induced by γ 's from $\bar{p}p$ annihilation into neutrals, the most important background at the trigger level. 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 .

The time of flight of the antineutron ($\text{TOF}_{\bar{n}}$) is computed from the mean of the TOFs of the scintillator counters of the two modules sandwiching the absorber where the vertex of the annihilation ‘star’ has been reconstructed.

The TOF distributions for samples of reconstructed ‘stars’ in ANC_1 and ANC_2 are shown in fig. 7 for data collected at 1005 (fig. 7 a,b), and 1307 MeV/c (fig. 7 c,d). The $\bar{n}$ signals are clearly visible and constitute the majority of the events; the other peak in the figures is due to the γ 's which sometimes shower in the detector and satisfy the ‘star’ topology. At low momentum the separation between the two peaks is very good and a TOF cut suffices to identify the $\bar{n}$'s; at high momentum other constraints are necessary. It can be also noticed that the $\bar{n}/\gamma$ ratio is smaller in ANC_2 than in ANC_1 . This is due to the fact that the charge-exchange cross-section is strongly peaked in the forward direction, whilst the γ 's are almost isotropically distributed.

‘Star’ topologies either in ANC_1 or ANC_2 are found in about 10% of the total data sample: for these events n 's are looked for, by requiring that at most two adjacent bars be hit in the corresponding NC hodoscope. Only neutron bars showing a stable behaviour (on the basis of the laser calibrations) all over the measurement have been considered, so no ADC cuts have been applied. The neutron coordinates are given by the bar number (horizontal) and by the difference between the time given by the top and the bottom PM of each bar (vertical); the vertical coordinate is determined with a precision of 3.7 cm. The neutron TOF (TOF_n) is given by the mean of the TOFs of all PMs hit. The efficiency of the neutron counters has been measured in a dedicated calibration run with the LHT [13]. It varies between 0.30 and 0.18 in our energy range, and it agrees with a Monte Carlo calculation that uses an improved version of an existing neutron code [16].

It is important to stress that, unlike the ANC detectors, which filter out the $\bar{n}$, the NC counters also detect the $\bar{n}$'s and the γ 's with efficiencies comparable to the neutron detection efficiency.

Events with at least one $\bar{n}$ candidate are recorded on Data Summary Tapes (DSTs), containing the full event buffer plus the coordinates and the TOFs of n and $\bar{n}$ candidates.

4.2 Time-of-flight cuts

In the rest of the analysis only events with one $\bar{n}$ candidate and one n candidate in the corresponding ANC-NC detectors are considered.

To reject γ rays in the $\bar{n}$ and in the n samples, separate cuts can be applied on $\text{TOF}_{\bar{n}}$ and TOF_n . This is easy at low energy, where the time separation is very good, but could be dangerous at high energy, especially in the forward direction. Since fast (anti)neutrons from a charge-exchange event on hydrogen should be in coincidence with a slow partner, a cut on the quantity $\text{TOF}_{\bar{n}} + \text{TOF}_n$ is more appropriate and can be used at all energies. As a rule, these cuts are not chosen to be too tight, because they are needed only to simplify the latter stages of the analysis. The dashed histograms in fig. 7 show the TOF distribution for the $\bar{n}$'s in ANC_1 and ANC_2 at 1005 and 1307 MeV/c after applying the cut $\text{TOF}_{\bar{n}} + \text{TOF}_n > 21$ ns.

One more TOF cut is applied to the charge-exchange candidates to reject events in which the $\bar{n}$ either annihilated or scattered in the NC counter in front of the ANC where the $\bar{n}$ 'star' was identified. In the first case some annihilation debris (most likely a γ) produced a false 'star' in the ANC, in the second case the 'star' is a true $\bar{n}$ 'star', but displaced laterally by the scattering. Both types of events have to be rejected. This cannot be done simply on the basis of the NC bars giving a signal, because in many cases a π from the true $\bar{n}$ annihilation 'star' in the ANC does give signals in the NC. Consequently the selection is applied on the difference of TOF of the NC and the ANC: the events where the minimum TOF on the NC is greater than the TOF of the star are considered 'good' events, whilst the events to be rejected are characterized by the presence of a signal in a NC bars occurring before the signal in the ANC.

Figure 8 shows the TOF difference between NC_2 and ANC_1 for the subsample of events in which there is at least one bar hit in NC_2 (about 10% of the sample of events with one $\bar{n}$ 'star' reconstructed in ANC_1). In the scatter plot, the 'good' events and the events to be rejected are clearly separated. The position of the cut that we applied is also shown.

After these cuts the data sample is expected to contain mostly neutrons in the NC and antineutrons in the corresponding ANC. It is of interest to look at the distribution of the z-coordinate of the $\bar{n}$ -annihilation vertexes, i.e. the distribution of the distance travelled by the $\bar{n}$ in the ANC before annihilating. This quantity is plotted in fig. 9 for ANC_1 and ANC_2 at 1307 MeV/c, and clearly indicates the location of the iron absorbers inside the detector. The decrease of the number of the 'stars' in the four slabs is compatible with the (poorly) known $\bar{n}$ annihilation cross-section in Fe [17], and provides an independent measurement of this quantity [18]. One can also note that the absorption is stronger in ANC_2 , which detects the lower momentum antineutrons.

4.3 Identification of $\bar{p}p \rightarrow \bar{n}n$ events

About 50% of the events on DSTs survive the TOF cuts. For these events, the direction (θ, ϕ) of the two neutral particles in the final state are computed from the n

coordinates, from the coordinates of the $\bar{n}$ annihilation vertex, from the centre of the target, and from the average beam direction.

The charge-exchange events on hydrogen can be identified and distinguished from those occurring on the nuclear matter of the PT on the basis of coplanarity and angular correlation. To improve the signal-to-noise ratio, further cuts can also be applied on the TOF of both n 's and $\bar{n}$'s. Once the signal has been identified and all the measured quantities are checked to be unbiased, the measured n and $\bar{n}$ coordinates and TOFs are fed into a kinematical fit and the 'good' events are selected accordingly to a single χ^2 value.

The $\bar{p}p \rightarrow \bar{n}n$ kinematics at any particular momentum depends on only one quantity in the final state, and it is convenient to use as a parameter the n scattering angle. Starting from the measured θ_n , one computes the expected scattering angle in the laboratory for the antineutron $\theta_{\bar{n}}^c$ and the expected TOF's of both the n and the $\bar{n}$. Four quantities are computed: the differences between the measured and the computed TOFs for n and $\bar{n}$ (ΔTOF_n and $\Delta\text{TOF}_{\bar{n}}$), the angular correlation ($\theta_{\bar{n}} - \theta_{\bar{n}}^c$), and the coplanarity, defined simply as $\phi_{\bar{n}} - \phi_n$ (equivalent to $\phi_{\bar{n}} - \phi_n^c$). These quantities are shown in fig. 10 for the forward data at 1307 MeV/c. The histograms refer to the whole sample, whilst the dashed lines give the same quantities after cutting on the values of the other three.

The cuts are energy independent; the four cuts were set at $|\Delta\text{TOF}_n| < 5$ ns; $|\Delta\text{TOF}_{\bar{n}}| < 5$ ns; $|\text{coplanarity}| < 8^\circ$ and $|\text{angular correlation}| < 5^\circ$. In all plots the charge-exchange events on hydrogen show up as a clear peak at zero over a small background.

A direct evaluation of the amount of background events in the 'good' events sample is given by processing the data obtained with the DT in the cryostat. Figure 11 shows the angular correlation distribution ($\theta_{\bar{n}} - \theta_{\bar{n}}^c$) – after cutting in the three other quantities – for PT and DT events at 1307 MeV/c, for both forward (ANC₁) and backward (ANC₂) events, normalized on the incoming beam. The DT data reproduce well the behaviour of the tails of the PT distributions, and clearly allow to estimate the background under the signal peak.

4.4 The kinematical fit

The charge-exchange 'good' events are selected on the basis of the χ^2 of a global 3C kinematical fit of all the measured quantities: the coordinates and TOFs of the n and of the $\bar{n}$, the incoming particle momentum and direction in the target (the mean beam parameters). The only unknown coordinate, the vertex coordinate in the target along the beam direction, z_{vtx} , is determined by the fit with a precision of about 4 cm, and its fitted value can be used to select the events which occurred in the target. The fit procedure has been checked with a Monte Carlo simulation.

The χ^2 distribution for the events in the target region ($|z_{vtx}| < 15$ cm) is shown in fig. 12a for PT and DT data (normalized on the incoming beam) for ANC₁ events at 1307 MeV/c incident $\bar{p}$ momentum. The charge-exchange events on hydrogen show up very clearly as the large peak at low χ^2 . The tail of the χ^2 -distribution for the PT lies somewhat higher than that of DT events, but the difference of the two is statistically indistinguishable from the difference of the χ^2 -distributions obtained for the events collected with the LHT at the same $\bar{p}$ momentum. The χ^2 -distributions for the LHT run are shown in fig. 12b, both for the full target (FT) and the empty target (ET) conditions, normalized to the same incoming beam as the PT data (it is worth noting that the number of events in the ET run is extremely small, which means that the measurement with the

LHT is remarkably background-free).

We interpret the large χ^2 tail of the events on hydrogen as due mainly to two reasons:

- a certain fraction ($\sim 10\%$) of the $\bar{n}$'s suffer small angle scattering when going through the NC counter in front of the ANC detector, thus giving no signal in the NC, which otherwise would acts as a veto to reject the event (as explained in section 4.2);
- some of the measured quantities are affected by errors with long non-Gaussian tails (notably the TOFs).

Consequently, we do not consider this problem of any importance, a cut in χ^2 causing only the loss of a number of 'good' events somewhat larger than expected. The position of the cut ($\chi^2 = 20$) to select the charge-exchange events on the free protons has been chosen to accept as many of these events as possible, whilst keeping the background and the number of badly reconstructed events down to a reasonable level.

In fig. 13, the z_{vtx} distributions for the 'good' events ($\chi^2 < 20$) are shown for the four target conditions PT, DT, FT, and ET at 1307 MeV/c. In the case of PT and FT, the position of the target is seen very clearly, and the choice of the cut ($|z_{vtx}| < 15$ cm) to define the target is adequate. In the case of DT and ET two peaks can be noticed at the locations of the two scintillator counters B₁₂ and FV, before and after the target: some 'good' events are produced on the hydrogen content of these counters, which contribute to almost 50% of the background at low χ^2 .

4.5 Background estimate

By definition, background events are all the events surviving the kinematical cuts which are not produced on the polarized protons of the PT: this includes the events on the C and O nuclei of the pentanol beads, on the ^3He - ^4He bath cooling the target, on B₁₂, FV, and so on.

We have measured the number of background events running the experiment with the DT at 4 different momenta and interpolating the data to estimate the background at the other momenta. Running the same kinematical analysis on the PT and DT data, and applying the same z_{vtx} and χ^2 cuts (± 15 cm and 20, respectively), at each of the four momenta, we could obtain the background to total ratio $f = B/(B + S)$, 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.

Figure 14 gives the results for f as a function of $\cos(\theta_{CM})$ as given by the fit. The dominant trend of the data suggests, at each momentum, a $\sin^2(\theta_{CM})$ dependence, which can be understood by simple kinematic arguments on the Fermi motion of the bound proton on which the charge-exchange event occurred.

As expected, the ratio f increases with increasing incident $\bar{p}$ momentum. Also shown in fig. 14 are one-parameter fits of the kind $f = f_0 \sin^2(\theta_{CM})$ and fig. 15 shows the fitted f_0 values, which agree with a p^2 momentum dependence. To compute the background to total ratio at all eight momenta, we used this parametrization and for f_0 the fitted values of fig. 15.

In order to evaluate the differential cross-section, we need to know as functions of energy the efficiencies of the NC counters for neutrons and of the ANC detectors for antineutrons. Also, the geometrical acceptance must be evaluated. As a first approximation to the cross-section, let us look at the quantity:

$$N = (1 - f) \left(N^+ + N^- R \right) \frac{1}{2\text{Beam}^+},$$

where $N^\pm$ is the number of ‘good’ charge-exchange events for the two spin orientations of the target (the target polarization is almost the same), R is the ratio of the relative beams, while $Beam^+$ is the total beam for the spin-up sample. Since the energy dependence of the n and the $\bar{n}$ detection efficiencies is not very large, the quantity N is almost proportional to the cross section. As a function of $\cos\theta_{CM}$, it is shown in fig. 16, for the momenta measured in the May 1990 run.

4.6 Normalization and stability checks

The stability of the data has been checked in the off-line analysis at two levels. The first level is performed on the experimental tapes, and it is intended to check the operating conditions: pattern units and scalers, properly normalized, are plotted against time. Also the focalization, the beam intensity, the beam direction – measured by the beam hodoscope – are monitored at the various stages of the DST production.

All in all, the quality of the events on tape was high and just a few runs were discarded because of serious problems. The data with bad beam focalization (not stable within $\pm 5\%$) have been discarded (about 4% of the total statistics).

The second level of stability checks is performed on the ratio of the number of ‘good’ events (as defined by the kinematical fit) and the beam integrated intensity, which should be constant for any single block of data for a given target polarization. To perform this test the normalizer (i.e. the integrated beam in each block) has to be corrected for rate effects, mainly random coincidences in the beam definition ($B_0 \cdot B_1 \cdot B_2$) and random vetoing of the trigger, mainly caused by the FV and PF counters. The corrections are small, of the order of 1%.

After these corrections, the data have been subdivided into about 80 consecutive blocks, and the number of ‘good’ events (normalized on the beam) has been plotted as a function of time and beam intensity to spot any residual bad block of data. This check has been performed not only on the total number of ‘good’ events but also separately for each $\cos(\theta_{CM})$ bin. Examples of these stability plots are shown in fig. 17 for the data at 1307 MeV/c: no systematic effects are visible, and in particular none associated with the beam intensity.

4.7 Extraction of A_{0n}

To evaluate the asymmetry A_{0n} we have used the usual estimator:

$$A = \frac{1}{(1-f)} \frac{N^+ - N^- R}{\langle P_T \cos \phi \rangle^- N^+ + \langle P_T \cos \phi \rangle^+ N^- R},$$

where $\langle P_T \cos \phi \rangle^\pm$ are the mean values of the target polarization, weighted (event by event) by the cosine of the angle ϕ between the polarization of the target and the normal to the scattering plane.

The results for A_{0n} as a function of $\cos\theta_{CM}$ are given in tables 2– 5 for the new measurements at 979, 1083, 1186 and 1287 MeV/c. The quoted errors are the statistical errors, which dominate all the known systematics effects. The target polarization acts as a scale factor for A_{0n} and consequently the error due to the absolute uncertainty in the target polarization ($\pm 4\%$) has not been included in the quoted errors. The new results are shown in fig. 18, together with our already published data [5].

The pattern of the errors follows essentially the trend of the differential cross-section: as apparent from fig. 16, the cross-section rapidly decreases from 546 to 979 MeV/c $\bar{p}$ momentum, which causes a corresponding increase in the statistical error. This is strictly

true all over the angular range only for the measurements performed in September 1989. For the new measurements the suppression of the trigger in the forward direction also has a visible effect. Thirdly, around 90° in the centre of mass, the errors are somewhat enlarged by the higher background level at the higher energies.

The values of A_{0n} are always remarkably high and positive, often of the order of 0.20. The low energy pattern (two positive bumps, one in the forward and one in the backward direction, with a minimum value at $\sim 90^\circ$ in the centre-of-mass scattering angle) changes very rapidly. At higher energies the A_{0n} values range around almost the same values, but the two-bump structure almost disappears (around 1000 MeV/c) and then appears again, while the mean value slightly decreases.

5 Comparison with theoretical models

5.1 Interpretation of the data

Whilst the basic phenomena in $\bar{N}N$ scattering are probably understood, detailed model calculations to reproduce all the measured observables in $\bar{p}p$ elastic scattering and $\bar{p}p \rightarrow \bar{n}n$ charge exchange and to make reliable predictions of the quantities still unmeasured do not yet exist. In particular, since microscopic theories (for instance, non-perturbative QCD) still cannot calculate the annihilation process, it is necessary to use either a coupled-channel approach [19], in which only a few ‘representative’ annihilation channels (usually into two mesons) are considered, or an optical potential approach [20], where annihilation is parametrized by an imaginary potential. Most recently, model-inspired phase-shift analyses [21] have also been attempted.

It is fair to say that the bulk of the cross-section data can be reproduced rather well by simple optical models in which the MEP is taken from NN scattering according to the G-parity rule (each meson-exchange contribution changes sign if its G-parity is negative) and a local, state-independent imaginary potential with a ~ 0.8 fm range to simulate annihilation. On the contrary, neither the coupled-channel calculations, nor the simple optical models succeed in reproducing both the cross-section and the new analysing power data from the LEAR experiments: only the semi-phenomenological phase-shift analysis now provides fits with good χ^2 over the entire data basis. In particular, our A_{0n} data disagreed strongly with the predictions of the most popular MEP models, as illustrated in ref. [4], and the effort to understand the new data has led to a considerable activity and to an improvement of the theoretical tools. A critical overview of the potential model approach has been made recently in a dedicated three-day workshop, and we refer to the relevant material for more information [22]

5.2 Optical models calculations

In fig. 19(a-d) we compare our measured analysing power data at four energies with the most recent calculations from the Paris group [23]. In this model the MEP is taken as the G-parity transformed Paris potential, for $r \geq 0.8$ fm, and a phenomenological real potential at shorter distances, defined by 6 parameters in each isospin state. The (imaginary) potential describing the annihilation is inspired by the assumption that it proceeds principally via two mesons channels, and is parametrized as:

$$W_{NN}^{ann} = [g_c(1 + f_c T_L) + g_{ss}(1 + f_{ss} T_L) \vec{\sigma}_1 \cdot \vec{\sigma}_2 + g_T S_{12} + \frac{g_{LS}}{4m^2} \vec{L} \cdot \vec{S} \frac{1}{r} \frac{d}{dr}] \frac{K_o(2mr)}{r},$$

where T_L is the $\bar{p}$ kinetic energy in the laboratory frame, K_o the modified Bessel function, g ’s and f ’s are some core parameters, and the spin terms have the usual meaning. All in

all, the model contains 24 parameters, twelve for the absorption core and twelve for the short-distance behaviour of the real part of the potential. These parameters cannot be given by any theory up to now, and must be obtained from the data: actually their values are given by a fitting procedure over the entire $\bar{N}N$ scattering data base, which by now consists of over 3000 points, including our A_{0n} data at low energy [5]. For completeness we have also drawn in the same figure the predictions of the previous version of the model (dashed curves), before the parameters were optimized on the basis of the new data. It is apparent that the situation has improved considerably and that the new fit is much closer to the data.

Although the trend of the data is reproduced by the new calculation, the agreement is not very good yet; still some comments are necessary.

- The data base is very large, and contains some clear inconsistencies amongst some experimental points. All in all, the χ^2 divided by number of degrees of freedom which M. Pignone et al. quote ($\chi^2/ndf = 6.6$), based on 2506 data points is very encouraging and should be taken as a figure of merit of the model.
- The same model reproduces surprisingly well the A_{0n} data of the elastic $\bar{p}p \rightarrow \bar{p}p$ channel in the 1000-1500 MeV/c momentum range [24]. In the charge-exchange channel, the agreement is not very good, probably because in this channel there is not a single amplitude which dominates the scattering matrix. On the other hand, there now exist the ingredients to access smaller amplitudes.
- We believe that the approach of the model, i.e. to lock the long-range part of the potential with the well-known MEP and parametrize all the short-range part, not calculable by present theories, is basically correct, and the fact that some quantities such as A_{0n} for $\bar{p}p \rightarrow \bar{n}n$ are not yet fitted well, could be due to the inherent difficulties of the fitting procedure. It is possible that ‘properly’ filtering the data base (to avoid inconsistencies) and ‘properly’ treating the experimental errors, will help to obtain better results.
- Above 900 MeV/c, the model runs into difficulties, because the one-pion production threshold opens up, and anyhow one uses the MEP outside the range over which the potential has been determined.

The above considerations apply also to other MEP calculations [25], which use sophisticated parametrizations for the absorption potential. This is the reason why we preferred to compare our data only with the Paris model.

5.3 First partial-wave analysis

In fig. 19 our data are compared also with the results of the semi-phenomenological partial-wave analysis of the Nijmegen group [21]. Their approach has as the starting point a coupled-channel model, but its main feature is that the experimental data are reproduced by a complex fitting procedure.

For distances larger than 1.25 fm (the ‘boundary’ radius of the model) the G-transformed ‘soft core’ Nijmegen potential is used. Annihilation is taken care of by modifying the boundary conditions, using the P-matrix formalism [26], a procedure which the Nijmegen group has already applied successfully to the nucleon–nucleon system [27]. The conditions on the boundary are purely phenomenological, and are determined by a fitting procedure, partial wave by partial wave, over the entire data set.

A total of 3718 data points, up to 925 MeV/c incident $\bar{p}$ momentum, have been fitted. The data set includes our A_{0n} measurements at low energy [5]. 190 data points have been rejected because they were found to be more than three standard deviations

away from the fitted values. The fitted data sample thus contained 3528 data points. The fitted parameters are 29, plus 122 normalization parameters. The quoted χ^2/ndf is 1.09, and indeed the procedure provides excellent fits to all the measured quantities, including our published A_{0n} data (fig. 19e-f). Also shown in fig. 19e-f, are the uncertainties of the calculations, as quoted by the authors [28].

The agreement at the four new momenta is reasonable, taking into account that the model is not supposed to be used as such above ~ 900 MeV/c. As an example, in fig. 19(g,h) the comparison is done at two momenta. At 1083 MeV/c, the low-energy data still constrain the parameters of the model and the agreement with the measured values of A_{0n} is good. At the highest momentum (1287 MeV/c), the model seems to have lost its predictive power.

Although in this model the physical meaning of the fitted parameters is somewhat more obscure than in the more traditional potential models, its capability of reproducing the measured observables is impressive.

6 Conclusions

We have carried out the first measurements of the A_{0n} parameter in the charge-exchange $\bar{p}p \rightarrow \bar{n}n$ reaction at LEAR. Our data indicate a large A_{0n} signal, with an interesting momentum-dependent structure in scattering angle. The data cannot be reproduced by any of the existing simple $\bar{N}N$ models, in which the annihilation was parametrized as a complex absorptive potential, energy and state independent. On the contrary, our data can be reproduced only by models in which the annihilation is explicitly described as dependent on the energy, spin, and isospin. With these assumptions, both the Paris group and the Nijmegen group succeed in obtaining fair agreement between our data and model calculations in which the long-range meson exchange potential is essentially constructed from the nucleon–nucleon interaction.

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Table 1: Number of $\bar{p}$'s in the target and the corresponding number of events on tape at the various incident $\bar{p}$ momenta. For the data of May 1990, the beam relative to the suppressed trigger (ANC₁-NC₁ arm) is in parenthesis.

incident $\bar{p}$ momentum (MeV/c)	Useful beam			
	PT	DT	LHT (Full)	LHT (Empty)
608	3.7×10^{10} (0.9×10^{10})	— —	— —	— —
704	1.5×10^{10}	0.7×10^{10}	1.0×10^{10}	0.5×10^{10}
804	1.2×10^{10}	—	—	—
905	2.4×10^{10}	0.9×10^{10}	—	—
1005	3.9×10^{10} (0.9×10^{10})	— —	— —	— —
1106	3.7×10^{10} (0.8×10^{10})	1.7×10^{10} (0.4×10^{10})	— —	— —
1207	2.8×10^{10} (0.6×10^{10})	— —	— —	— —
1307	3.3×10^{10} (0.7×10^{10})	1.5×10^{10} (0.3×10^{10})	1.1×10^{10} (0.3×10^{10})	1.0×10^{10} (0.3×10^{10})
	Events on tape			
	PT	DT	LHT (Full)	LHT (Empty)
608	8.8×10^6			
704	9.8×10^6	1.3×10^6	8.3×10^6	1.3×10^6
804	4.5×10^6			
905	10.0×10^6	1.2×10^6		
1005	7.8×10^6			
1106	9.2×10^6	3.6×10^6		
1207	9.2×10^6			
1307	12.3×10^6	5.2×10^6	8.3×10^6	5.7×10^6

Table 2: Results for A_{0n} as a function of $\cos \theta_{CM}$. The bin width is always larger than $\pm 2\sigma$. The error on A_{0n} is statistical ($\pm\sigma$).

$A_{0n} (\bar{p}p \rightarrow \bar{n}n)$ at 979 MeV/c	
$\cos \theta_{CM}$	A_{0n}
0.850 ± 0.050	0.147 ± 0.028
0.750 ± 0.050	0.151 ± 0.012
0.650 ± 0.050	0.177 ± 0.014
0.550 ± 0.050	0.160 ± 0.019
0.450 ± 0.050	0.159 ± 0.025
0.350 ± 0.050	0.108 ± 0.034
0.250 ± 0.050	0.155 ± 0.045
0.150 ± 0.050	0.111 ± 0.061
0.050 ± 0.050	0.120 ± 0.073
-0.050 ± 0.050	0.164 ± 0.073
-0.150 ± 0.050	0.156 ± 0.078
-0.250 ± 0.050	0.224 ± 0.071
-0.350 ± 0.050	0.180 ± 0.069
-0.450 ± 0.050	0.237 ± 0.067
-0.550 ± 0.050	0.206 ± 0.070
-0.650 ± 0.050	0.013 ± 0.074
-0.750 ± 0.050	0.079 ± 0.077
-0.850 ± 0.050	0.144 ± 0.078
-0.925 ± 0.025	0.006 ± 0.085

Table 3: Results for A_{0n} as a function of $\cos \theta_{CM}$. The bin width is always larger than $\pm 2\sigma$. The error on A_{0n} is statistical ($\pm\sigma$).

A_{0n} ($\bar{p}p \rightarrow \bar{n}n$) at 1083 MeV/ c	
$\cos \theta_{CM}$	A_{0n}
0.850 ± 0.050	0.146 ± 0.033
0.750 ± 0.050	0.124 ± 0.013
0.650 ± 0.050	0.103 ± 0.016
0.550 ± 0.050	0.089 ± 0.021
0.450 ± 0.050	0.142 ± 0.030
0.350 ± 0.050	0.082 ± 0.041
0.250 ± 0.050	0.102 ± 0.055
0.150 ± 0.050	0.152 ± 0.080
0.050 ± 0.050	0.036 ± 0.086
-0.050 ± 0.050	0.163 ± 0.066
-0.150 ± 0.050	0.195 ± 0.055
-0.250 ± 0.050	0.206 ± 0.050
-0.350 ± 0.050	0.209 ± 0.048
-0.450 ± 0.050	0.095 ± 0.049
-0.550 ± 0.050	0.020 ± 0.047
-0.650 ± 0.050	0.085 ± 0.051
-0.750 ± 0.050	0.148 ± 0.055
-0.850 ± 0.050	0.143 ± 0.054

Table 4: Results for A_{0n} as a function of $\cos\theta_{CM}$. The bin width is always larger than $\pm 2\sigma$. The error on A_{0n} is statistical ($\pm\sigma$).

$A_{0n} (\bar{p}p \rightarrow \bar{n}n)$ at 1186 MeV/ c	
$\cos\theta_{CM}$	A_{0n}
0.850 ± 0.050	0.152 ± 0.045
0.750 ± 0.050	0.160 ± 0.016
0.650 ± 0.050	0.125 ± 0.021
0.550 ± 0.050	0.101 ± 0.028
0.450 ± 0.050	0.141 ± 0.040
0.350 ± 0.050	0.042 ± 0.057
0.250 ± 0.050	0.216 ± 0.094
0.150 ± 0.050	0.058 ± 0.108
0.050 ± 0.050	0.099 ± 0.096
-0.050 ± 0.050	-0.062 ± 0.073
-0.150 ± 0.050	0.124 ± 0.059
-0.250 ± 0.050	0.112 ± 0.053
-0.350 ± 0.050	0.064 ± 0.053
-0.450 ± 0.050	-0.071 ± 0.050
-0.550 ± 0.050	-0.011 ± 0.050
-0.650 ± 0.050	0.036 ± 0.053
-0.750 ± 0.050	0.115 ± 0.061
-0.850 ± 0.050	0.172 ± 0.060
-0.925 ± 0.025	0.074 ± 0.064

Table 5: Results for A_{0n} as a function of $\cos \theta_{CM}$. The bin width is always larger than $\pm 2\sigma$. The error on A_{0n} is statistical ($\pm\sigma$).

$A_{0n} (\bar{p}p \rightarrow \bar{n}n) \text{ at } 1287 \text{ MeV}/c$	
$\cos \theta_{CM}$	A_{0n}
0.850 ± 0.050	0.172 ± 0.053
0.750 ± 0.050	0.071 ± 0.018
0.650 ± 0.050	0.152 ± 0.022
0.550 ± 0.050	0.118 ± 0.031
0.450 ± 0.050	0.159 ± 0.044
0.350 ± 0.050	0.141 ± 0.066
0.250 ± 0.050	0.168 ± 0.114
0.150 ± 0.050	0.051 ± 0.104
0.050 ± 0.050	0.106 ± 0.101
-0.050 ± 0.050	0.092 ± 0.063
-0.150 ± 0.050	0.070 ± 0.052
-0.250 ± 0.050	0.048 ± 0.046
-0.350 ± 0.050	-0.008 ± 0.046
-0.450 ± 0.050	-0.100 ± 0.050
-0.550 ± 0.050	-0.033 ± 0.045
-0.650 ± 0.050	0.097 ± 0.049
-0.750 ± 0.050	0.036 ± 0.051
-0.850 ± 0.050	0.171 ± 0.056
-0.925 ± 0.025	0.062 ± 0.059

Figure 1: Schematic layout of the experiment (top view). ANC₁ and ANC₂ are the $\bar{n}$ detectors, NC₁, NC₂ and NC₃ the n counter hodoscopes. PTM is the polarized target magnet. HB is the beam hodoscope. The $\bar{p}$ beam line and the shielding wall are also displayed.

Figure 2: Side and front view of set-up of the target and veto counters. The veto counters are labelled as FV, LV, RV, PFU, and PFD. In the side view, the position of the beam counter B12 and the $\bar{p}$ line are also shown.

(a)

(b)

Figure 3: Side (a) and top (b) view of one ANC detector as drawn by the on-line display, showing a typical $\bar{n}$ annihilation.

Figure 4: Efficiency map of one LST plane of the ANC detectors. The cosmic-ray tracks have been selected in order to have a uniform illumination.

Figure 5: Time diagram for a typical event. The three microprocessors read the experimental buffer from the CAMAC. The third one (J11 System Crate) also acts as an *event builder*.

Figure 6: A sample of the chart recorded by the Multireg during the run of May 1990.

Figure 7: Time-of-flight spectra for ANC_1 and ANC_2 at 1005 (a,b) and 1307 MeV/c (c,d). The dashed histograms show the effect of the cut on the quantity $\text{TOF}_n + \text{TOF}_{\bar{n}}$.

Figure 8: TOF differences between ANC_1 and NC_2 (ΔT) as a function of TOF_{barn} (measured with ANC_1) for a sample of events at 1307 MeV/c. The ‘good’ events give the bump at $\Delta T < 0$; the $\bar{n}$ ’s which scatter or annihilate in NC_2 fall in the upper band at $\Delta T > 0$, and are rejected by the indicated cut.

Figure 9: Distribution of the reconstructed annihilation point in ANC_1 and ANC_2 for samples of events at 1307 MeV/c, after the cuts on TOF. The peaks correspond to the positions of the absorbers in the detectors.

Figure 10: Distributions of ΔTOF_n (a), $\Delta\text{TOF}_{\bar{n}}$ (b), coplanarity (c) and angular correlation (d), for samples of ANC_1 events at 1307 MeV/c. Before (solid line histograms) and after (hatched histograms) the cuts described in the text.

Figure 11: Angular correlation of forward (ANC_1) and backward (ANC_2) events from the PT and the DT (hatched histograms) at 1307 MeV/c.

Figure 12: (a): χ^2 distributions for the PT and the DT (hatched histogram) ANC_1 events at 1307 MeV/c after the cut in z_{vtx} . (b): same quantity for the FT and ET (hatched histogram) events.

Figure 13: Distributions of the z_{vtx} coordinate as given by the kinematical fit for the PT (a) and FT (b) events in ANC_1 at 1307 MeV/c with $\chi^2 < 20$. The shaded histograms give the same distributions for DT (a) and ET (b) data.

Figure 14: Background-to-total ratios f at 656, 875, 1083, and 1287 MeV/ c ; the expression for the curves is $f_0 \sin^2 \theta_{CM}$.

Figure 15: Fitted values of f_0 as a function of the incident $\bar{p}$ momentum, in the forward (a) and backward (b) region. The curves are best fits assuming a p^2 dependence.

Figure 16: Number of charge-exchange events in a $\pm 0.05 \cos \theta_{CM}$ bin for 10^9 incident $\bar{p}$ at 546, 979, 1083, 1186 and 1287 MeV/c.

Figure 17: Ratio of the number of 'good' charge-exchange events in a block of data and the corresponding integrated beam as a function of time and beam intensity.

Figure 18: Results for A_{0n} for the $\bar{p}p \rightarrow \bar{n}n$ reaction at all measured momenta as a function of $\cos \theta_{CM}$.

Figure 19: The results of A_{0n} at 545, 875, 1083, and 1287 MeV/c compared with theoretical calculations. In (a-d), the results of the Paris model are shown. The solid curves are the results of the most recent version of the potential, whilst the original Paris-model predictions (dashed curves) are also shown. In (e-h), the same data are compared with the Nijmegen partial-wave analysis, including our A_{0n} data at low energy in the fitting procedure; the uncertainties of the calculation are also displayed.