**HIGH-PRECISION MEASUREMENT OF THE $\bar{p}p \rightarrow \bar{n}n$
CHARGE-EXCHANGE DIFFERENTIAL CROSS-SECTION**

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Abstract

The differential $\bar{p}p \rightarrow \bar{n}n$ charge-exchange cross section has been measured at the CERN Low Energy Antiproton Ring (LEAR), at two incident $\bar{p}$ momenta, 601 and 1202 MeV/c. The main features of the differential cross-section near the forward direction, i.e. a sharp peak at 0° scattering angle followed by an energy dependent dip-bump structure, are confirmed and measured with good precision and high statistical accuracy. The data show very clearly that the shape of the cross-section is a manifestation of the pion-exchange amplitude, and a simple extrapolation to the pion pole already indicates that the pion-nucleon coupling constant f_c^2 can be determined with good precision.

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Experiment PS206 has measured at LEAR, the Low Energy Antiproton Ring at CERN, the charge-exchange $\bar{p}p \rightarrow \bar{n}n$ differential cross-section using a liquid hydrogen target. The motivation of the experiment was to measure with good precision and high statistical accuracy the shape of the differential cross-section at small values of the momentum transfer ($-t \sim m_\pi^2$), where a sharp forward peak has been observed followed by a dip-bump structure [1]. Also, by measuring the differential cross-section over the entire angular range and with a small normalization error, it aimed at providing data for a new and independent evaluation of the πNN coupling constant f_c^2 .

The forward peak has been observed over a wide range of incident momenta [2]. A similar peak has been known since long time in the line-reversed reaction $np \rightarrow pn$, again both at low and high momenta, and in the past it has been the object of considerable theoretical activity. For both reactions the peak can be explained in terms of the pion-exchange amplitude, interfering destructively with some ‘background’ amplitude [3,4].

The experiment was run in a parasitic way and could be performed only at two incoming $\bar{p}$ momenta, 612 and 1206 MeV/c. The layout of the experiment is shown in fig. 1 for the measurements at 612 MeV/c (a) and 1206 MeV/c (b). Fig. 1b shows also a close-up of the target region.

ANC₁ and ANC₂ are the antineutron detectors used to measure the angular distribution in the forward region; ANC₃ detects both n and $\bar{n}$ in the backward hemisphere. The different geometry of the low-momentum and high-momentum run was motivated by the requirement of using time of flight (TOF) to separate $\bar{n}$ ’s from the γ ’s produced by the $\bar{p}$ -annihilations in the target. The differential cross-section is obtained from the $\bar{n}$ ’s angular distribution alone, without requiring the presence of the associated neutron: the neutrons are detected over a small angular range, and only to determine the efficiency of the $\bar{n}$ detectors.

The dashed line indicates the $\bar{p}$ beam direction. The incoming $\bar{p}$ ’s are defined by two scintillator counters B₁ and B₂, measuring the total beam flux and the beam entering the target respectively. Three proportional chambers (PBC₁, PBC₂, and PBC₃) monitor the beam direction and position. A C-shaped magnet (MN) is used to sweep the $\bar{p}$ leaving the target away from the 0° direction, thus allowing to measure the differential cross-section in the very forward region. The scintillator counter hodoscope HB monitors the beam direction in the horizontal plane. During the run, the typical beam intensity was about 5×10^5 $\bar{p}$ ’s. At the target centre, at 612 MeV/c extraction momentum, the beam momentum was 601.5 MeV/c and the total spread was 14 MeV/c. The 1 σ beam divergence, 6.8 mrad in both planes, was dominated by multiple scattering. At 1206 MeV/c extraction momentum, the beam momentum in the target centre was 1202.3 MeV/c with a total spread of 5 MeV/c and the 1 σ beam divergence was about 3.3 mrad.

The liquid hydrogen target (LHT), 10.61 cm long and 3 cm diameter, could be filled and emptied in a few minutes; inside the target, a diode measured its temperature in order to monitor the filling operations and to evaluate the residual hydrogen density when the target was empty.

To reject annihilation and elastic events at the trigger level, the target is surrounded by a scintillator counter box on all sides, except that of the incoming beam. The forward and the two lateral counters (FV, RV, and LV) ensure that no trigger caused by charged particles in the ANCs is accepted. The upper and lower vetoes (UV and DV) are made up of four layers of scintillator, interleaved with a total of 1 radiation lengths of lead to reject annihilation events into neutrals.

The $\bar{n}$ detectors ANC₁ and ANC₂ are the same we already used in Experiment

PS199 [5,6]. Each detector is made up by three identical units, a unit consisting of an iron slab 3 cm thick, sandwiched between two modules of four planes of limited streamer tubes (LST) with x and y strip readout and one hodoscope of six vertical scintillation counters. Most of the $\bar{n}$ annihilations take place in the iron absorbers, giving a characteristic ‘star’ pattern in the LST modules and the $\bar{n}$ ’s are identified by reconstructing the tracks of the charged particles produced in the annihilation. The sensitive surface of the modules is $166 \times 200 \text{ cm}^2$ and the distance between the iron slabs is 19.5 cm. The stability of LST system was monitored by measuring the signal amplitude of a test limited streamer tube identical to those making up the ANC’s, and flushed with the same gas mixture and operated at the same high voltage as all the others LST’s. Each two hours, the signal spectrum was checked and, if necessary, the high voltage changed correspondingly in order to have a constant gain. In between spills, data were taken with a cosmic-ray trigger, for off-line measurement of the LST efficiency during the whole run.

ANC₃ consists of a neutron counter (NG) sandwiched by two LST and scintillation counters modules, identical to those making up ANC₁ and ANC₂. The neutron counter [7] is a hodoscope of 27 vertical scintillator bars, 8 cm wide and 20 cm thick; the bar heights range from 110 to 130 cm. The bars are viewed from each end by a photomultiplier and both TDC and ADC information are recorded. A system based on a N₂ laser has been used during all the run to monitor the NG bars as well as the ANC scintillation counters.

The trigger used to select charge-exchange events for the measurement of the differential cross-section described in this paper is given by the coincidence:

$$(B_1 \cdot B_2) \cdot (\overline{LV + RV + FV}) \cdot (\overline{UV + DV}) \cdot (ANC_1 + ANC_2 + NG)$$

where $ANC_{1,2}$ means at least two scintillation counter hits in the corresponding antineutron detector. NG means at least one bar hit in the neutron counter and the events characterized by this signal in the trigger have been used only for the measurement of the efficiency of the ANC detectors.

For background evaluation, data have been taken alternating full target (FT) and empty target (ET) runs. With the full target, we collected about 75×10^6 events at 601 MeV/c and 17×10^6 events at 1202 MeV/c corresponding to a useful beam of 38×10^9 and 21.5×10^9 $\bar{p}$ respectively; the statistics with empty target are 5×10^6 and 3×10^6 events on tape and 8.7×10^9 and 15.6×10^9 incoming $\bar{p}$ at 601 MeV/c and 1202 MeV/c respectively. In this paper we give results in the forward hemisphere, based on the full statistics at 1202 MeV/c, and on a useful beam of 4.5×10^9 $\bar{p}$ ’s at 601 MeV/c. Most of the data at 601 MeV/c have been collected using also a second level trigger based on the number of hits in the ANC which gave the trigger signal; these data, together with the measurement in the backward region, need a separate analysis, which has still to be finalized.

In the off-line analysis, events with an $\bar{n}$ candidate are first selected looking for ‘star’ topologies in the LST modules, i.e. we ask that in both x and y projections there be at least three reconstructed tracks in any two adjacent modules crossing in a common point on the iron slab in between. This definition is more restrictive than the one of ref. [6] and allows a better rejection of ‘star’ events generated by γ ’s. When an $\bar{n}$ annihilates in ANC, it can happen that the true annihilation vertex is lost, and that a shower developed at some distance from the annihilation point satisfies the star topology. The net result is a ‘smearing’ of the resolution of the location of the $\bar{n}$ annihilation point (about 1.5 cm for true $\bar{n}$ ‘stars’), for some fraction of events. To further reduce the percentage of these events, a cut is applied to the ‘sphericity’ $S^2 = S_x^2 + S_y^2$, with $S_k^2 = \Sigma_i (\alpha_{k,i} - \alpha_{k,i}^m)^2$, where $k = x, y$ and i runs from 1 to the total number of tracks of the ‘star’ in the given

projection; $\alpha_{k,i}$ is the angle of the i -th track of the ‘star’ and $\alpha_{k,i}^m$ is the arithmetic mean of $\alpha_{k,i}$. The ‘sphericity’ distributions for samples of $\bar{n}$ and γ ’s events are shown in fig. 2a and 2b respectively. The distributions are quite different and after the cut ($Q^2 \geq 1.5$) the $\bar{n}$ and the γ samples are reduced to about 64% and 15% respectively. With this algorithm the probability of reconstructing $\bar{n}$ ’s is more than 100 times larger than the probability of reconstructing γ ’s, and the ‘smearing’ effects due to badly reconstructed events are considerably reduced.

For the events with the good topology, the measured time of flight of the antineutron ($t_{\bar{n}}$) is computed from the mean of the TOF’s of the scintillation counters of the two hodoscopes sandwiching the absorber where the $\bar{n}$ annihilation point has been reconstructed; only the scintillation counters crossed by at least one reconstructed track in the x projection are used. The scattering angle in the laboratory system $\theta_{\bar{n}}$ is measured from the mean beam direction, the target centre, and the coordinates of the reconstructed annihilation point. The final selection of the charge-exchange events is done on the basis of the $\bar{p}p \rightarrow \bar{n}n$ kinematics: from the measured value of $\theta_{\bar{n}}$ we compute the expected time of flight of the antineutron ($t_{\bar{n}}^c$) and the time difference $\Delta t_{\bar{n}} = t_{\bar{n}} - t_{\bar{n}}^c$; the final sample of good charge-exchange events contains only the events with $-5 \leq \Delta t_{\bar{n}} \leq 8$ ns.

Conservative cuts have been applied to the data to avoid any problem related to the geometrical acceptance and not constant detection efficiency; in particular, the efficiency of the ANC’s is flat in the central region, but falls rapidly in the vicinity of the edges: from Monte Carlo simulation it turns out that the efficiency at about 20 cm from the edge is reduced to 90% of its maximum value. To be sure that no effect is present in the vertical projection, only events with a distance from the upper and lower edge larger than 40 cm have been used.

The whole chain of analysis selecting the good charge-exchange events has been repeated for the ET data; to take away the small background due to charge-exchange events on the counters close to the target and on the target walls, the final angular distribution has been obtained by subtracting the FT and the ET distribution, and correcting for the residual hydrogen gas present in the target; this correction is smaller than 1%.

To extract the differential cross-section from the angular distribution an essential ingredient is the detection efficiency. Using the n detector NG, we could measure it for ANC₂ at $\theta_{\bar{n}} = 55^\circ \pm 5^\circ$ both at 601 and 1202 MeV/c. The procedure we followed is quite similar to that described in ref. [8]. Using only part of the statistics we could measure it with a relative error of 3%. The measured values are 9.1% at 601 MeV/c and 9.9% at 1202 MeV/c if the annihilations on all the irons are considered; the measured efficiency includes both the probability that an $\bar{n}$ annihilates in the detector (P_a) and the ‘star’ reconstruction efficiency (ϵ_r). To evaluate the $\bar{n}$ detection efficiency at all the angles, we have evaluated the angular dependence of both P_a and ϵ_r .

The probability P_a has been estimated for each angular bin with the same techniques and the same cross-section parametrization as in ref. [8], using the mean momentum of the antineutron and the effective path of the $\bar{n}$ in all the materials up the absorber. The error in the absolute value of P_a is quite large due to the large absolute normalization error of the existing $\bar{n}$ -nucleus annihilation cross-section data (20%). However, we are interested only in the angular dependence of P_a and the error on its variation is much smaller, and has been added to the systematic uncertainties.

The reconstruction efficiency has a smooth dependence on the $\bar{n}$ momentum: using the Monte Carlo program [9] we estimated that it varies by only a few percent in our momentum range. ϵ_r depends also from the LST efficiency; following the procedure

described in ref. [10], we have corrected it of about 2% going from ANC_2 to ANC_1 to take into account the difference in the overall LST efficiency of the two detectors. The LST efficiency include the effect of the plastic ‘wire holders’ (0.5 cm large), located in the middle and near the edges of the tubes, which cause a well-localized region of high inefficiency.

The data at 601 MeV/c turn out to be very stable and all the good charge-exchange events have been used to extract the differential cross-section. At 1202 MeV/c some scintillation counters of ANC_1 and ANC_2 and one box of 8 LST’s in the last module on ANC_1 had not a stable behaviour, thus the differential cross-section has been measured using only the $\bar{n}$ annihilations on the first two iron slabs.

The differential cross-section has been evaluated only in the angular bins where the total correction for the loss of detection efficiency due to the ANCs edge effects and ‘wire holders’ has been evaluated to be less than 30%. The angular bins in $\theta_{\bar{n}}$ have a width of 1° and 0.5° at 601 and 1202 MeV/c respectively. The estimated overall normalization error is just the error on the measured ANCs efficiency, namely 3% at 601 MeV/c and 4% at 1202 MeV/c; we believe that no relevant error is due to the useful beam measurement (since the mean $\bar{p}$ intensity was quite low during all the run) nor to the length of the target.

The results are shown in fig. 3a. Numerical values are available upon request [11]. Statistical and systematic errors have been added in quadrature. A blow-up of the small scattering angle region is given in fig. 3b. The forward peak is very sharp (the slope at $t=0$ is about $100 (\text{GeV}/c)^{-2}$), and the energy-dependence of the dip-bump structure shows up very clearly. Also shown in fig. 3b are measurements at nearby momenta from the KEK [12] and the LEAR [13] most recent experiments. These two recent experiments have also provided data at 590 MeV/c which agree, within errors, with our result, and which have not been plotted for clarity. On the other hand, the only existing data around 1200 MeV/c, the bubble chamber data at 1130 MeV/c from ref. [14], disagree with our result, and are a factor of two too small. It is clear from fig. 3b that the t -dependance of the $\bar{p}p \rightarrow \bar{n}n$ differential cross-section varies considerably with energy, and does not show the almost universal shape exhibited by the $np \rightarrow pn$ cross-section.

It has been shown in ref. [15] that a semi-phenomenological phase-shift analysis of the existing $\bar{p}p \rightarrow \bar{n}n$ data base could provide a value of the pion-nucleon coupling constant f_c^2 which agrees with other more standard determinations [16,17] and has comparable errors. We consider it particularly interesting to see how precisely this coupling constant can be determined from the differential cross-section alone, and we have done a first step in this direction by performing the simple extrapolation to the pion pole that Chew suggested already in 1958 [18]. Following his notation, we have multiplied $d\sigma/d\Omega$ by the pole-term denominator x^2 , where $x=1-\cos\theta_{cm}+m_\pi^2/2k^2$, and divided it by the constant $A=M^4 f_c^4/k^4 E^2$ (M is the proton mass, k and E are the $\bar{n}$ momentum and energy in the c.m.s.). For f_c^2 we have assumed 0.075, as suggested by the most recent analyses [16,17]. The quantities $x^2 \cdot A^{-1} \cdot d\sigma/d\Omega$ are shown in fig. 4a for the $\bar{p}p \rightarrow \bar{n}n$ data at 601 and in fig. 4b for the $\bar{p}p \rightarrow \bar{n}n$ data at 1202 MeV/c, together with some $np \rightarrow pn$ data at nearby momenta [19,20], on which this analysis has already been performed [20,21]. Also shown are some polynomial fits to the four sets of data which nicely extrapolate to about one, i.e. to values of the coupling constant very close to the input reference value, and suggest that the data are rich of information on this quantity. The error in the extrapolation is very small, still at this stage we prefer not to quote any result, and regard this analysis just as an indication that more powerful theoretical methods should be able to extract from

these data values of f_c^2 at least as accurate as from the other reactions used at present.

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References

- [1] J.C. Lee et al., *Nucl. Phys.* **B52** (1973) 292.
- [2] M. Bodgansky et al., *Phys. Lett.* **62B** (1976) 117, and references therein.
- [3] R. J. N. Phillips, *Phys. Lett.* **4** (1963) 19.
- [4] E. Leader, *Phys. Lett.* **60B** (1976) 290.
- [5] R. Birsa et al., *Nucl. Instrum. Methods* **A300** (1991) 43.
- [6] R. Birsa et al., *Nucl. Physics* **B403** (1993) 25.
- [7] A. Ahmidouch et al., *Nucl. Instrum. Methods* **A326** (1993) 538.
- [8] A. Martin et al., *Nucl. Instrum. Methods* **A346** (1994) 237.
- [9] A. Bressan et al., “A Monte Carlo code for antineutrons”, *INFN int. rep. TC-93/14*.
- [10] M. Lamanna et al., ‘A high-statistics measurement of the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange reaction at 875 MeV/c’, CERN-PPE/94-137 and submitted to *Nuclear Physics*.
- [11] Numerical values have been sent to HEPDATA. They can also be requested to BRES-SAN@TRIESTE.INFN.IT.
- [12] K. Nakamura et al., *Phys. Rev. Lett.* **53** (1984) 885.
- [13] W. Brückner et al., *Phys. Lett.* **169B** (1986) 302.
- [14] A. Colebourne et al., *Nucl. Phys.* **B70** (1974) 205.
- [15] R. G. Timmermans et al., *Phys. Rev. Lett.* **67** (1991) 1074.
- [16] R. A. M. Klomp, *Phys. Rev.* **C44** (1991) 1258.
- [17] R. A. Arndt et al., *Phys. Rev. Lett.* **65** (1990) 157.
- [18] G.F. Chew, *Phys. Rev.* **112** (1958) 1380.
- [19] T. Rönqvist et al., *Phys. Rev.* **C45** (1992) 496.
- [20] A. Ashmore et al., *Nucl. Phys.* **36** (1962) 258.
- [21] P. Ciffra and M. J. Moravcsik, *Phys. Rev.* **116** (1959) 226.

Figure 1: Schematic layout of the experiment PS206 during the 601 (a) and 1202 MeV/ c (b) runs (top view). Also shown in (b) is a close-up view of the target and veto-counter system.

Figure 2: ‘Sphericity’ (S^2) distributions of ‘star’ events in case of $\bar{n}$ ’s (a) and γ ’s (b). Also indicated is the position of the cut applied to the data.

Figure 3: Differential cross-section $d\sigma/d\Omega$ results at 601 MeV/c (ANC₁ closed points, ANC₂ closed squares) and at 1202 MeV/c (ANC₁ open points, ANC₂ open squares) as a function of θ_{cms} (a). In (b), the forward data are shown in terms of $d\sigma/dt$ as a function of $-t$. Also shown are the measurements from the KEK experiment at 780 MeV/c [12] (open triangles) and from the CERN experiment at 470 MeV/c [13] (closed triangles).

Figure 4: Plots of the $\frac{x^2}{A} \frac{d\sigma}{d\Omega}$ versus $(m_\pi^2 - t)$ for $np \rightarrow pn$ data (solid points) and our $\bar{p}p \rightarrow \bar{n}n$ data (open points), at the indicated momenta. Also shown are some polynomial fits to the data. A value of one for the extrapolation at zero corresponds to $f_c^2 = 0.075$.