EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PPE/93-175

23 September, 1993

**AN ANTINEUTRON DETECTORS CALIBRATION METHOD FOR
 $\bar{p}p \rightarrow \bar{n}n$ CHARGE-EXCHANGE DIFFERENTIAL CROSS-SECTION
MEASUREMENT**

A. Martin, R. Birsa, F. Bradamante, A. Bressan, S. Dalla Torre-Colautti, M. Giorgi,
M. Lamanna, A. Penzo, P. Schiavon, F. Tessarotto
INFN Trieste and University of Trieste, Trieste, Italy

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

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 DPNIA/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

Two modular antineutron detectors have been built and used to detect the low energy antineutrons produced in the charge-exchange reaction $\bar{p}p \rightarrow \bar{n}n$ in an experiment at LEAR. A novel calibration method has been used to measure the absolute efficiencies of the detectors, and allows for a precise measurement of the reaction differential cross-section.

Submitted to Nuclear Instruments and Methods in Physics Research A

1 Introduction

We have designed, built, and operated in an experiment at the Low Energy Antiproton Ring (LEAR) at CERN, two identical modular antineutron detectors, to detect the $\bar{n}$'s produced in the charge-exchange $\bar{p}p \rightarrow \bar{n}n$ reaction.

Each of the two $\bar{n}$ detectors (ANC) consists of five identical modules made up of four planes of limited streamer tubes (LSTs), and one scintillator counter hodoscope for trigger purposes and time-of-flight measurement. Adjacent modules are interleaved with 3 cm thick iron plates, which make up most of the mass of the detector, and where the $\bar{n}$ annihilations are expected to occur in the majority of cases. The LST planes are used to reconstruct the trajectories of the charged products of the $\bar{n}$ annihilation, and the $\bar{n}$'s are identified by a characteristic 'star' topology. The modular design of the detector is meant to optimize the annihilation vertex location and maximize the detection efficiency of the $\bar{n}$'s once they annihilate in the detector material, while keeping the overall efficiency as good as possible. A distinctive feature of the detector is that it is blind to neutrons.

The detectors have been used in experiment PS199 to measure the analysing power A_{0n} and the spin depolarization parameter D_{0n0n} in the charge-exchange reaction $\bar{p}p \rightarrow \bar{n}n$, using a 12 cm long pentanol 'frozen-spin' polarized-proton target (PT). In order to reduce the overall background, and specifically to single out the reactions occurring on the polarized protons from those occurring on the nuclear matter of the target, the neutrons are also detected in coincidence with the $\bar{n}$'s. Thick vertical scintillator bar hodoscopes are used to detect and to locate the neutrons, and the charge-exchange events are then identified via angular correlation and coplanarity.

The whole sample of data was collected during 1989 and 1990. The analysing power was measured at eight $\bar{p}$ momenta, between 608 and 1307 MeV/c, whilst the depolarization parameter was measured at only two beam momenta (608 and 905 MeV/c). Results of A_{0n} at all momenta are published [1, 2, 3] as well as the measurement of D_{0n0n} at the higher momentum [4].

A further goal of the experiment PS199 is to obtain, from the angular distributions measured with the polarized target, the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange reaction differential cross-sections (the analysis is in progress). To this end the efficiencies of both the neutron and antineutron detectors are needed. In principle, accurate neutron codes exist and can be used to estimate the efficiency of the neutron counters. In the case of the antineutron detectors, a Monte Carlo simulation surely helps to understand the detector, but the uncertainties in the many inputs limit the accuracy of the result, and particularly the estimate of the absolute efficiency. In both cases direct measurements of the efficiency are clearly necessary and most welcome. To measure the efficiency of the antineutron detectors we have devised a novel calibration procedure. To be most effective, it requires the use of a liquid-hydrogen target (LHT). Thus in designing the experiment we had taken provisions that a LHT could be inserted in the polarized target cryostat, at the place where the PT would normally be located, and, during the experiment, we took some sample data with the LHT and with special triggers. Thanks to the geometrical arrangement of the detectors, we could use these hydrogen data to measure the absolute efficiency of the antineutron detectors at a few $\bar{n}$ momenta (most of the data were taken at 704 MeV/c incident $\bar{p}$ momentum, but some data also at 804 and 1307 MeV/c). The data at 704 MeV/c covered the full angular range, and we have been able to obtain and publish the differential cross-section [1]. Furthermore, to work out the efficiency of the $\bar{n}$ -detectors, it is necessary to know the efficiency of the neutron counters (NCs), therefore we have used the same calibration method to measure the efficiency of the NCs. These

results are also published [5], and agree with Monte Carlo calculations.

This paper is devoted to the description of the calibration technique we have developed to measure the efficiency of the antineutron detectors. The analysis of the LHT data provides the absolute efficiency of the antineutron detectors at some specific $\bar{n}$ energies and the efficiency of the neutron counters for a wide neutron energy range. The interpolation and the extrapolation of these results at all the energies is done by means of Monte Carlo simulations. The presence of two neutral particles in the final state makes it particularly difficult to measure the differential cross-section of the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange reaction with an error in the absolute value of the order of 10%. We believe that our method has achieved this goal.

2 Apparatus

2.1 Experimental layout

The experimental layout used in the calibration run at 804 MeV/c is shown in fig. 1; details of the target region are shown in fig. 2. The experiment was installed in the C1 beam line at LEAR; the dashed line is the $\bar{p}$ beam direction. The neutron and the antineutron produced in the charge-exchange reaction are detected by means of one of the two neutron counters, NC₁ or NC₂, and one of the two antineutron counters, ANC₁ or ANC₂, respectively. The symmetrical arrangement of the detectors shown in the figure differs only slightly (an overall rotation of $\sim 15^\circ$) from the standard geometry, used for all the measurements of A_{0n} [3]. Even if in this arrangement the antineutrons undergo considerable absorption and scattering passing through the NC detectors, this geometry has remarkable advantages, such as an easy shielding of the two arms from crossing particles, an excellent vetoing of the ANC detectors from any charged particle coming from the target, and finally a way to measure the ANC efficiency at $\theta_{cm} = 90^\circ$ scattering angle in the center-of-mass system, which is the referred to in this paper.

The liquid hydrogen target, 12 cm long and 32 mm diameter, is sited inside the nose of a 1 m long cryostat (shown together with the polarizing magnet PTM in fig. 1), and to reach the target the beam travels along the cryostat axis. The beam intensity was typically between 1 and 1.5×10^6 antiprotons per second. Two scintillator counters define the beam. The first counter (B₀) is placed upstream, just in front of the cryostat. The second one is located inside the cryostat, 19 cm from the target centre, and is viewed by two long light guides, extending out of the back window of the cryostat, and going to two different photomultipliers (B₁ and B₂; in fig. 2 the name of the counter is B₁₂). The target is surrounded by a scintillator veto counter box (fig. 2) on all sides, except that of the incoming beam, to reject annihilation and elastic scattering events at the trigger level. The top and bottom vetoes (PFU and PFD) lie on the polar expansions of PTM and are made up of four layers of scintillator, interleaved with a total of 1.3 radiation lengths of lead, to detect photons produced in π^0 decay, and reject annihilation into neutrals. The forward scintillator (FV) and the lateral ones (LV and RV) ensure that only neutral particles are detected in the ANC and NC counters.

Whilst the normal trigger involved a coincidence requirement between each ANC and the corresponding NC hodoscope, the data suitable for this measurement have been collected with a special calibration trigger given by

$$Tr1 = TIN \cdot (ANC_1 \cup ANC_2 \cup NC_1 \cup NC_2).$$

The quantity

$$TIN = (B_0 \cdot B_1 \cdot B_2) \cdot (FV \cup LV \cup RV \cup PFU \cup PFD)$$

Incoming $\bar{p}$ momentum (MeV/c)	Date	Full target		Empty target	
		Useful beam	Events on tape	Useful beam	Events on tape
804	May 1989	2.4×10^9	5.2×10^6	1.2×10^9	1.3×10^6
704	Sep. 1989	2.7×10^9	6.0×10^6	1.0×10^9	1.1×10^6
1307	May 1990	2.1×10^9	1.3×10^6	1.4×10^9	0.5×10^6

Table 1: Number of $\bar{p}$'s in the target and corresponding number of events on tape at the various $\bar{p}$ -momenta, for both full and empty target conditions. The time when the data were collected is also given.

defines a charge-exchange event in the target, requiring a beam trigger and no signals from the veto box. *NC* means that at least one bar of the neutron counter was hit, while *ANC* that at least two scintillators of the ANC have given a signal. Both for the NC and the ANC, a bar hit means a mean time coincidence of the up and down PMs of the corresponding scintillator bar.

The relevant statistics are given in table 1. A complete description of the set-up, of the data taking, of the data reduction, and of the data analysis is given in ref. [3], whilst, the NC counters and the LST system of the ANC detectors are the subjects of the two dedicated articles (refs. [5] and [6] respectively). Here we give a brief summary just to understand the problematic and the procedure of the calibration.

2.2 The neutron detectors (NC)

The NC detectors are made up of a total of 53 scintillator bars (BC 412, equivalent to the standard NE 110) arranged along the vertical direction and grouped together in different combinations to build up three NC hodoscopes. Only two are drawn in the layout of fig. 1 (NC_1 and NC_2), since the third one, which detects particles at small angles, is not relevant to this measurement. The bars are 8 cm wide and 20 cm thick, to provide a good neutron location and interaction probability respectively. The length of the bars ranges from 40 cm to 130 cm, with the smaller ones near the beam axis. Each end of each bar is viewed by a 5 in. PM. When a bar is hit, the complete information from the two PMs is stored on tape, i.e. both the timings (in TDCs) and the amplitudes (in ADCs) of the two signals. This allows the measurement of the interaction point along the bar using the difference between the top and the bottom measured time-of-flights (TOF). The hardware threshold was fixed at about 1 MeV_{ee}, since the natural radioactivity background for such large volume detectors is not negligible. Since the neutron detection efficiency depends strongly on the threshold, during the runs the NCs were monitored continuously in amplitude with a N₂ laser, connected by means of optical fibres to each light guide. Before and after the data-taking periods the apparatus was fully tested with cosmic rays and the hardware thresholds of the NCs were measured with a 4.4 MeV γ -rays from an Am/Be neutron source.

In the off-line analysis a neutron is defined as a cluster of at most two adjacent bar hits. Its TOF is obtained from the average of the top and bottom PM's TOFs. The pulse amplitude from each bar is taken as the geometrical mean of the top and bottom PM's pulse heights, and a software threshold cut can be applied (usually at 1.5 MeV_{ee}).

2.3 The antineutron detectors (ANC)

The principle and a general description of the antineutron detectors are given in the Introduction. Fig. 3 shows the cross-section of one of the ANCs. The detector consists of five modules, each module being made up of four LST layers with x and y external read-out. The external pick-ups of the LST consist of aluminium strips; the x strips are parallel to the anode wires and have a 10 mm pitch, whilst the y horizontal strips have a 10.5 mm pitch. The active area of these planes is $202 \times 166 \text{ cm}^2$ (horizontal $\times$ vertical). Each module contains in its middle plane one scintillator counter hodoscope, made up of six vertical slabs 1 cm thick, 33 cm wide, and 166 cm long, each viewed by two PMs. Two aluminium walls, 6.3 mm thick, close up each module, which is only 155 mm thick. Adjacent modules are separated by 3 cm thick iron slabs: together with the two aluminium walls they constitute 90% of the interaction length of the detector, and in the following they will be referred to as the absorbers.

The efficiency of the LSTs was measured with cosmic-ray tracks every two to three days, and continuously monitored on the data themselves in the off-line analysis. The scintillators were continuously monitored with the same laser system used for the NC counters.

The concept of this detector is an upgraded elaboration of that of an existing $\bar{n}$ -detector [7] already used in a LEAR experiment, and its design benefits from that previous experience. Some simpler and less performing $\bar{n}$ -detectors, which use successive layers of converters and scintillators, have also been used recently [8, 9, 10].

The geometry is optimized for an unambiguous detection of antineutrons annihilating in any of the four absorbers. For these annihilations the tracks of the charged particles (mainly $\pi^\pm$ directly produced in the annihilation and $e^\pm$ coming from the conversion of the photons created in the π^0 decay) are expected to give a characteristic star pattern in the LST planes of the two modules sandwiching the relevant absorber. More specifically, in the off-line reconstruction program, the star pattern is defined requiring in these two modules a total of three or more tracks, meeting at a common point in either the vertical or the horizontal projection of the detector, and at least two tracks in the other projection.

This definition of $\bar{n}$'s has been checked both on the data and with a Monte Carlo simulation: it guarantees a reasonably high antineutron efficiency, as will be seen in the following, and it rejects most of the spurious events due to the interactions of charged and neutral particles in the detector. Most important, it ensures that the ANC detector can be considered insensitive to neutrons: the probability of misidentifying a neutron as an antineutron is measured to be less than 10^{-4} by counting the reconstructed 'star' coincidences between ANC_1 and ANC_2 .

Figure 4 shows the distribution of the z -coordinate of the annihilation vertex as reconstructed by the off-line program, i.e. the coordinate along the detector axis. The peaks correspond to the absorber locations, where, as anticipated, most of the annihilations take place. Conversely, a cut on this quantity allows to select $\bar{n}$'s that annihilated on some specific absorber.

2.4 Estimate of the efficiency of the antineutron detector

To compute the efficiency of the ANCs two ingredients are necessary, the probability of annihilation (P_a) and the efficiency of reconstructing a 'star' topology (P_r) for a given $\bar{n}$ annihilation. The evaluation of P_a is straightforward from the existing annihilation cross-section, although not many $\bar{n}$ -nucleus annihilation cross-section data exist, and the precision of the measurements is not very good. We have used the measurement of $\bar{n}$ -Fe

of ref. [11], scaling the measured values with an $A^{2/3}$ dependence for the other materials. For $\bar{n}$ -H annihilation we referred to the data of ref. [12]. The result as a function of the $\bar{n}$ -momentum is given in fig. 5. The band indicates the uncertainty ($\pm 1\sigma$) in the input data as quoted by the authors.

The evaluation of P_r is much more complicated work, and it required the writing of a full Monte Carlo program to generate $\bar{n}$ -annihilation events in ANC, to simulate the interactions of the annihilation products in the detector, to simulate the detector response, and to write output files. Finally these Monte Carlo events are analysed with the reconstruction program looking for standard ‘star’ topologies. The ratio between the reconstructed and the generated events gives the efficiency P_r , which is also shown in fig. 5. As expected, P_r depends very little on the $\bar{n}$ momentum. P_r is affected by a scale error of about $\sim 10\%$, which is shown in fig. 5 as shaded area: given the complexity of the physical processes this number can just be regarded as an educated guess.

The product of P_a and P_r gives the ANC efficiency E_{ANC} . It is a smooth function of the energy, and the uncertainty band can clearly be reduced considerably even if only a few efficiency points are measured. This paper is devoted to the technique we have used to measure the ANC efficiency.

The $\bar{n}$ -simulation code has been used to understand many features of the $\bar{n}$ -detector, and not only its efficiency. In particular, we have investigated the accuracy of location of the annihilation vertex, the geometrical acceptance, and the smearing corrections which are relevant to this work (see section 6.5).

A full description of the Monte Carlo code is given elsewhere [13]. Some relevant points are:

- The simulation of the $\bar{n}$ annihilation process inside the nucleus is made using the Intra-Nuclear Cascade (INC) code of refs. [14, 15], in which the nucleus is described as a mixture of degenerate Fermi gases of protons and neutrons confined in a spherical potential well. The advantages of using the cascade model, rather than $\bar{n}$ annihilation on free nucleons, are in the description of all the steps following the annihilation on the nucleon, such as the interaction of the produced pions with the nuclear matter. This can lead to pion absorption and to a thermalized nuclei production with a subsequent de-excitation of the nucleus. Concerning our needs, this simulation gives a more realistic pion multiplicity and energy distribution of the particles produced.
- The interactions of γ ’s from π^0 decay in the various materials are treated by means of the standard EGS package.
- Charged pions can undergo elastic and inelastic scattering, nuclear absorption, and charge-exchange reactions. Energy loss and multiple scattering are included.
- All detector inefficiencies and location errors are properly taken into account.

2.5 Measurement of the differential cross-section

Although E_{ANC} is the absolute efficiency of the $\bar{n}$ detector described in this paper, it is very important to stress that it is not the relevant number when we want to measure a cross-section. In the layout of fig. 1 the $\bar{n}$ ’s, before entering ANC_1 or ANC_2 , have to go through NC_2 or NC_1 respectively; therefore to get the probability of detecting a $\bar{n}$ one has to multiply E_{ANC} by P_t , the probability of an $\bar{n}$ not being absorbed in NC. Also P_t is shown in fig. 5, and again the shaded area indicates the ($\pm 1\sigma$) band: in the momentum range of the experiment P_t varies considerably with the $\bar{n}$ momentum. The product of E_{ANC} and P_t thus is affected by an important $\bar{n}$ -momentum dependence, and the uncertainties in the nuclear absorption data of the $\bar{n}$ ’s are the limiting factors in the

point-to-point precision of the measurement of the differential cross-section.

The solution we adopted to minimize in our data this effect was to consider for this measurement only those events with a $\bar{n}$ annihilation vertex reconstructed on the first absorber. For these events, P_a and P_t compensate almost exactly, and their product is essentially constant over the full $\bar{n}$ -momentum range of our experiment, and to a large extent independent of the measuring errors of refs. [11] and [12], as will be shown in section 7. The price we have to pay is a reduction of statistics by a factor of two, but the reduction of the systematic errors is far more important.

We have to stress that experiment PS199 was optimized to measure the analysing power of the $\bar{p}p \rightarrow \bar{n}n$ reaction and not the differential cross-section. As a matter of fact, a dedicated new experiment (PS206 [16]), with a modified geometry, was proposed and run at LEAR by part of the collaboration to perform a high-precision measurement of the differential cross-section.

3 The charge-exchange reaction signal

At any given incoming antiproton momentum, in the centre-of-mass system the kinematics of the charge-exchange $\bar{p}p \rightarrow \bar{n}n$ reaction is fully fixed by the knowledge of one quantity, i.e. the scattering angle. In the laboratory, where both the particles are produced in the forward hemisphere, there are two possible choices for the momentum, starting from the scattering angle, but one of these (that with the lower value) is removed by the timing of the trigger. So we are able to determine all the kinematical quantities by the knowledge of either the scattering or the recoil angle, evaluated from the LHT centre and either the $\bar{n}$ annihilation point, or the location of the n -hit in NC. As we will see in the following, this is very useful in the calibration method.

The $\bar{n}$'s in ANC and the n 's in NC allow separately to identify the charge-exchange reaction, as shown in figs. 6 and 7. Figure 6(a) gives, event by event, the correlation between the measured TOF of the $\bar{n}$ 'star' and the measured scattering angle for some ANC₁ data at 804 MeV/c; also indicated is the expected correlation between these two quantities for the $\bar{p}p \rightarrow \bar{n}n$ reaction. The reaction signal is very clean and the background level (mostly γ 's from annihilations into neutral pions which shower in ANC and give a 'star' topology) is rather low. This can be seen even better in fig. 6(b), where the measured time-of-flight ($\text{TOF}_{\bar{n}}^m$) is compared with the time-of-flight computed for the $\bar{p}p \rightarrow \bar{n}n$ reaction from the measured scattering angle of the $\bar{n}$ ($\text{TOF}_{\bar{n}}^c$), for both full- and empty-target conditions. Subtracting the empty-target data, we obtain a very clean signal around $\Delta\text{TOF}_{\bar{n}} = \text{TOF}_{\bar{n}}^m - \text{TOF}_{\bar{n}}^c = 0$. In fig. 6(c) this signal is compared with the corresponding one obtained by asking for a n candidate in NC and applying all possible kinematical cuts (angular correlation, coplanarity and ΔTOF_n). From this comparison we conclude that the $\bar{n}$ -stars in the ANC detectors are quite adequate to identify the $\bar{p}p \rightarrow \bar{n}n$ events, as long as $\bar{n}$ -stars can be separated by TOF from the background due to γ 's from annihilations in the target.

Exactly the same analysis can be repeated for the events in which the NC₁ counter has given a trigger: using the same data we obtain the figs. 7(a-c), analogous to the previous ones, but showing the correlation between the angle and the TOF of the detected neutron. Also in this case the reaction signal is clearly visible, but

- more background events are present, in particular more γ -events are detected (the NC scintillators are as good in detecting high-energy γ 's as neutrons),
- not all the background comes from the target walls and the counters nearby,
- the detected particle in the NC counter can also be $\bar{n}$, so there is an intrinsic ambiguity

in calculating θ_{cm} , the $\bar{n}$ scattering angle in the c.m. system.

The relevance of this last point can be understood by looking at fig. 8, which shows the differential cross-section of the charge-exchange reaction we have measured at 704 MeV/c. The data exhibit a behaviour which is typical of this reaction in our energy range, i.e. a large forward-backward anisotropy. This means that, at a given laboratory angle, in the forward hemisphere many more $\bar{n}$'s than n 's are produced, whilst the opposite is true for angles close to the maximum angle ($\sim 82^\circ$). Only at $\theta_{cm} = 90^\circ$, corresponding to $\sim 43^\circ$ in the laboratory, the numbers of neutrons and antineutrons are identical. These properties are all exploited in the calibration method.

4 The calibration method

From the previous section it is apparent that the main characteristic of the LHT data is that the signature of the charge-exchange event is well defined, even if only one of the two particles is detected. This means that, apart from some background, once we have identified a neutron or an antineutron in one arm, we can look for the signal of the second particle in the other arm, thus obtaining the efficiency from the number of times the antineutron or the neutron was detected. This is the basic idea of the method.

The method has two main advantages. First of all, the efficiencies are measured 'on the floor', in operating conditions, and the absorption of n and $\bar{n}$ in the target region as well as in the other materials before the dedicated detector (i.e. the absorption of antineutrons in NC) is automatically taken into account. Secondly, the efficiencies of both the detectors for both the produced particles can be measured: the NC efficiency for neutrons, the ANC efficiency for antineutrons – together with the contamination of neutrons in ANC and of antineutrons in NC. Clearly, our main interest is the determination of the ANC efficiency for $\bar{n}$, but this quantity can be obtained only if we know the response of the NC hodoscopes to $\bar{n}$'s. The application of the method to evaluate the NC efficiency for neutrons provides an important check of the overall procedure and of the neutron code.

As such, this calibration method is essentially a revisit of the old 'associated particle method' of nuclear physics, e.g. to define a neutron beam produced in the $d[T,He]n$ reaction by tagging the associated α -particle. For the charge-exchange reaction, tagging the 'neutron beam' is easier than tagging the 'antineutron beam'. In fact, as stated in section 2.3, the response of the ANC to neutrons turns out to be negligible, since we ask for a star topology to identify the $\bar{n}$ annihilation. Therefore, the antineutron detection is unambiguous in the ANC counters (indeed, the cross-section data of fig. 8 have been obtained from the measured $\bar{n}$'s angular distribution alone, without requiring a neutron signal in coincidence) and we can look at the neutron signal in the NCs over the full acceptance range. More problems arise in the opposite situation, namely in tagging the $\bar{n}$ beam, since neutron detectors are also sensible to antineutrons, as stressed in ref. [17] also. Even if a $\bar{n}$ annihilation in a NC usually differs from a neutron signal in the number of bars hit and in the amount of the energy deposition, some $\bar{n}$ interactions such as elastic scattering will show no difference from the neutron events.

Denoting by $N(\theta)$ the number of antineutrons scattered in a small angular bin $\Delta\theta$ centered at an angle θ (identical, of course, to the number of recoil neutrons at the kinematically correspondent angle θ'), we can write the following relations:

$$N_{NC_1}(\theta') = N(\theta) \cdot (\epsilon_1 + R\nu_1) \quad (1.a)$$

$$N_{NC_2}(\theta) = N(\theta) \cdot (R\epsilon_2 + \nu_2) \quad (1.b)$$

$$N_{ANC_1}(\theta) = N(\theta) \cdot \eta_1 \quad (1.c)$$

$$N_{ANC_2}(\theta') = N(\theta) \cdot R\eta_2 \quad (1.d)$$

for the single counts, and

$$N_{NC_1 \cdot NC_2}(\theta', \theta) = N(\theta) \cdot (\varepsilon_1 \nu_2 + R\varepsilon_2 \nu_1) \quad (2.a)$$

$$N_{ANC_1 \cdot NC_1}(\theta, \theta') = N(\theta) \cdot \eta_1 \varepsilon_1 \quad (2.b)$$

$$N_{ANC_2 \cdot NC_2}(\theta, \theta') = N(\theta) \cdot R\eta_2 \varepsilon_2 \quad (2.c)$$

for the coincidences between the detectors. Here $N_{ANC}(\theta)$ and $N_{NC}(\theta')$ are the number of hits of the ANC and NC detectors at the angles θ and θ' ; R is the ratio between the charge-exchange differential cross-section at the angles θ' and θ ; ε 's and ν 's are the NC efficiencies for n and $\bar{n}$ respectively, while η 's are the ANC efficiencies for antineutrons. In the second set of equations, $N_{ANC \cdot NC}(\theta, \theta')$ is the number of coincidences between ANC and NC, and $N_{NC_1 \cdot NC_2}(\theta, \theta')$ are the coincidences between the two neutron detectors NC₁ and NC₂. The system is not directly solvable, since there are seven equations and eight variables; so we need either some assumption, or some simplification. As anticipated, the hint comes from kinematical considerations, and the procedure will be spelled out in section 6. In short, advantage is taken from the fact that in the symmetric configuration, at $\theta_{cm} = 90^\circ$, the number of neutrons and antineutrons is the same ($R = 1$), so that the probability ν that an NC counter detects an $\bar{n}$ can be estimated from the number of coincidences $N_{NC_1 \cdot NC_2}$, if ε is known.

5 Measurement of the NC efficiency for neutrons

The measurement of the NC efficiency is done in quite a straightforward way; the ANC counters are split into angular bins and ε is evaluated in every bin as the ratio between the number of coincidences $N_{ANC_i \cdot NC_i}$ ($i = 1, 2$) and the total number of detected antineutrons, as from eqs. (2.b) and (1.c), or (2.c) and (1.d). Of course, a full geometrical acceptance is required. The empty target configuration is used to subtract the background events. As discussed in section 3, after this subtraction, essentially no background is left, either in the coincidence signal or in the 'single' ANC counts.

Figure 9 shows some $\Delta TOF_{\bar{n}}$ distributions for the data at 704 MeV/c: the sequence of the histograms is the same as in fig. 6, and the quality of the $\bar{n}$ signal is also the same. Figures 9(b) and (c) show the signal after empty target subtraction, and the efficiency of the NC counter is just the ratio of the contents of the two peaks at 0 ns.

The kinematical cuts on the coincidence events have been kept rather loose ($\pm 8^\circ$ for angular correlation, $\pm 9^\circ$ for coplanarity and ± 5 ns for ΔTOF) in order to allow for the smearing of the $\bar{n}$'s momentum vector when going through the NC counter in front of the ANC. The effect on the measured efficiency has been estimated using the $\bar{n}$ Monte Carlo program, and with these cuts it turns out to be less than 2% (see section 6.5); consequently no smearing corrections has been applied to the data.

The resulting neutron efficiency data over the whole angular range are shown in fig. 10, from ref. [5]. The continuous line superimposed on the data is the result of the Monte Carlo evaluation of the NC efficiency. The code used is a modified version of the Cecil program [18], in which, the cross-section and the kinematics of the neutron-carbon inelastic channels have been refined. The code was further implemented with the C(n,2n) reaction, the quenching relation for the proton from ref. [19], and the relativistic kinematics for all the reactions. The geometrical arrangement of adjacent bars of our hodoscope was also introduced, taking into account the optical separation between the bars to reproduce the cross-talk of charged particles from the neutron interactions.

Within statistics there is a good agreement between the data and the calculation, which makes us confident that our calibration method works correctly and that the NC efficiency behaviour is well reproduced by the neutron simulating code.

6 Measurement of the ANC efficiency for antineutrons

The measurement of the ANC efficiency for antineutrons is the most important result of the method. In this analysis, the antineutron beam is defined by the detected neutron, but, as just mentioned, some $\bar{n}$ interactions inside the NC counters can simulate a neutron signal. The first step therefore is to measure the efficiency of NC for $\bar{n}$: this has been done at $\theta_{cm} = 90^\circ$.

6.1 Redefinition of the neutron signal in NC

In order to optimize the measurement of η , the efficiency of ANC, it is important to minimize the neutron content of the $\bar{n}$ beam. To this end it is convenient to adopt a more stringent neutron definition in NC, asking for:

- one and only one bar hit in NC;
- no signals present in any of the scintillators of the ANC located after the relevant NC (i.e. ANC_2 for NC_1 , and ANC_1 for NC_2).

With these constraints the n efficiency somewhat decreases, but the $\bar{n}$ contamination decreases by large factors, since the $\bar{n}$ annihilations in NC often give clusters with many bars hit, and $\bar{n}$'s which scattered in NC often annihilate in ANC and give some signal there. The net result is that the $n/\bar{n}$ ratio of the antineutron beam, which at $\theta_{cm} = 90^\circ$ is just $r = \nu/\varepsilon$, is expected to be rather small. The NC efficiency for neutrons of course has to be remeasured using the new definition. This is done in the usual way, and fig. 11 shows the relevant plots. The data refer to $\bar{n}$'s reconstructed in the ANC_2 detector from the 704 MeV/c run, and cover an angular range of $\pm 2^\circ$ in the laboratory around the symmetrical configuration.

The measured efficiencies are obtained by dividing the number of events in the peak of fig. 11(c) by the events in the corresponding peak of fig. 11(b). Numerically, they turn out to be

$$\varepsilon_1 = 0.139 \pm 0.016$$

$$\varepsilon_2 = 0.137 \pm 0.018$$

for NC_1 and NC_2 respectively (the neutron momentum is ~ 474 MeV/c). Since these two numbers are fully compatible, we assume in the following that the NC_1 and NC_2 efficiencies are the same ($\varepsilon = 0.138 \pm 0.012$).

6.2 Efficiency of NC for antineutrons

The procedure can be more easily followed if we assume that the response of ANC_1 and ANC_2 , and of NC_1 and NC_2 be the same (a reasonable assumption, since the detectors are identical and the energies of all the particles are the same). Equations (1.a), (2.a) and (2.b) can then be simplified and rewritten as

$$N_{NC_1} = N \cdot \varepsilon \cdot (1 + r) \tag{3.a}$$

$$N_{NC_1 \cdot NC_2} = N \cdot 2 \cdot \varepsilon^2 \cdot r \tag{3.b}$$

$$N_{ANC_1 \cdot NC_1} = N \cdot \eta \cdot \varepsilon \tag{3.c}$$

from which we obtain the contamination r :

$$r = \frac{N_{NC_1 \cdot NC_2}}{2 \cdot \varepsilon \cdot N_{NC_1} - N_{NC_1 \cdot NC_2}} \tag{4}$$

and the ANC efficiency for antineutrons:

$$\eta = \frac{N_{ANC_1 \cdot NC_1}}{N_{NC_1}^{corr}} \quad \text{where} \quad N_{NC_1}^{corr} = \frac{N_{NC_1}}{(1 + r)}. \quad (5)$$

The NC efficiency for neutrons ϵ comes from the results given in section 6.1.

The ΔTOF_n distribution for NC_2 at $\theta_{cm} = 90^\circ$ for the 704 MeV/c run is given in fig. 12(a). It has the typical shape we have discussed in section 3: after subtracting the empty-target data, some background is left, but, the reaction signal can be estimated rather reliably by interpolating the measured distributions under the signal. Figure 12(b) shows the same distribution, after demanding a kinematically correlated signal in NC_1 . It is immediately apparent that $N_{NC_1 \cdot NC_2} \ll N_{NC_2}$, indicating that r is very small, as expected. Numerically we get

$$r = 0.055 \pm 0.013 \quad (p_{\bar{n}} = 474 \text{ MeV}/c)$$

from the data at 704 MeV/c, and

$$r = 0.049 \pm 0.016 \quad (p_{\bar{n}} = 540 \text{ MeV}/c)$$

from the data at 804 MeV/c.

This means that at this angle, with the neutron definition of section 6.1, only $\sim 5\%$ of the particles selected on the NC detectors ‘in single’ are antineutrons.

6.3 Efficiency of ANC for antineutrons at $\theta_{cm} = 90^\circ$

The knowledge of r allows us to correct N_{NC} according to eq. (5) and define the intensity of the $\bar{n}$ beam at $\theta_{cm} = 90^\circ$. The relevant histogram to work out the ANC efficiency is given in fig. 12(c), which shows the distribution of ΔTOF_n for NC_2 after requiring the usual kinematical correlation with the $\bar{n}$ ’s reconstructed in ANC_2 . Since the goal of this analysis is the determination of the charge-exchange differential cross-section, we have used only stars detected on the first absorber of the ANC detector.

According to eq. (5), the ANC_2 efficiency is obtained from the ratio of the peak content in fig. 12(c) with the corresponding events in fig. 12(a), divided by $(1 + r)$. In an analogous way η can be evaluated for ANC_1 , and the procedure has been repeated also for the 804 MeV/c run. The resulting efficiencies for ANC_1 and ANC_2 are equal within errors, and can be combined into the following values

$$\eta = \begin{cases} 0.055 \pm 0.006 & 474 \text{ MeV}/c & \text{(from data at 704 MeV/c)} \\ 0.052 \pm 0.009 & 541 \text{ MeV}/c & \text{(from data at 804 MeV/c)} \end{cases}$$

As expected, these values are about a factor of four smaller than the ANC efficiency given in fig. 5: one factor of two comes from the absorption of the $\bar{n}$ ’s in the NC counter before the relevant ANC, the second factor of two from the fact that only $\bar{n}$ ’s annihilating in the first absorber are taken into consideration. A full discussion is postponed to section 7.

Most of the quoted errors come from the uncertainty in the background content in the ΔTOF distributions for the NC events [see for example fig. 12(a), or fig. 7(c)]. The background is evaluated by linearly interpolating the tails of the distributions under the signal, and conservative errors have been derived from the difference between the highest and lowest counting channels, within the intervals used for the estimate.

6.4 Efficiency of ANC for forward-scattered antineutrons

The low value of the contamination r that results from the previous analysis allows the measurement of the ANC efficiency also for forward-going $\bar{n}$'s. In fact, from eq. (1) we know that the percentage of neutrons in the $\bar{n}$ beam goes as $\sim R \cdot r$ and it can be neglected in the forward region, since both R and r are very small. As an example, the differential cross-section data of fig. 8 gives $R \sim 0.05$ for the forward bins, which means a totally negligible contamination of $\sim 0.25\%$. Hence the ANC efficiency in the forward region is given simply by the ratio between the antineutron-neutron coincidences and single NC counts, without any correction. Moreover, the higher statistics collected in this angular region allows a considerable reduction of the statistical error, and the large separation between the signal and the photon peak makes easier the estimate of the background.

It has to be stressed that this analysis is possible because of the smallness of r , which is a consequence of the redefinition of the neutron signal in NC, and in particular of the use of the ANC detectors behind as a veto to reject $\bar{n}$'s. Also, the angular distribution of the $\bar{n}$'s we reconstruct in the ANC's provide us with values of R independent from the published data, and we can check for each incident $\bar{p}$ momentum the assumption that $r \cdot R$ is negligible in a given angular bin. Lastly, the smallness of $r \cdot R$ is a guarantee that any reasonable variation of r with the momentum of the detected particle is totally irrelevant. The fact that r has little energy dependence has been verified by investigating the ratio $N_{NC_1 \cdot NC_2} / N_{NC_1}$, which, for forward angles (small values of R) gives directly with a good approximation the quantity ν [as can be seen from eqs. (1) and (2)].

For the analysis of the forward-going scattered $\bar{n}$'s we can use all the three samples of data collected at 704, 804, and 1307 MeV/c. The data at 1307 MeV/c were taken after we had already worked out r from the run at 704 MeV/c; therefore we concentrated on the goal of having the ANC efficiency measured at a momentum as large as possible. This was obtained by using a dedicated trigger

$$Trigger = TIN \cdot (NC_1)_3,$$

where $(NC_1)_3$ means the OR of only 3 bars of NC_1 , centred around the 63° recoil angle in the laboratory. The use of this trigger allowed a large reduction of the acquisition dead-time.

The ΔTOF_n distributions of backward neutrons are shown in figs. 13(a-d) and 14(a-d) for the data at 804 and 1307 MeV/c respectively. Figures. 13 and 14(a) give the single neutron counts, for a full- and an empty-target respectively, whilst figs. 13 and 14(c) give the same histograms, after demanding the usual kinematical cuts with the $\bar{n}$'s stars reconstructed in the first absorber of ANC_1 . The small signal which survives the kinematical cuts in the empty target events is due to charge-exchange events on the hydrogen content of B_{12} and FV counters. Figures 13 and 14(b) and (d) show the same events of figs. 13 and 14(a) and (c) after empty-target subtraction, and the ANC efficiency is obtained from the ratio of the contents of the peaks at 0.

The results can be summarized as follows:

$$\eta = \begin{cases} 0.050 \pm 0.003 & \text{at } 601 \text{ MeV/c} & (\text{from data at 704 MeV/c}) \\ 0.050 \pm 0.003 & \text{at } 692 \text{ MeV/c} & (\text{from data at 804 MeV/c}) \\ 0.048 \pm 0.007 & \text{at } 1160 \text{ MeV/c} & (\text{from data at 1307 MeV/c}) \end{cases}$$

Within the errors, the measured efficiency shows no energy dependence, as expected. As was the case for the analysis at $\theta_{cm} = 90^\circ$ the largest contribution to the errors comes

from the estimate of the background under the peak of the ΔTOF_n distribution, which is indicated by the dashed lines in fig. 13(b) and fig. 14(b).

6.5 Smearing corrections

Measuring errors in both the neutron and antineutron TOFs and interaction points in NC and ANC causes some smearing of the measured angular distribution, which affects somewhat the evaluation of the efficiencies in the calibration method. A further source of bias is given by the antineutron elastic and inelastic interactions inside the NC and ANC detectors, which spread the antineutrons away from the incoming direction. This ‘smearing’ effect, which also flattens a little the ‘single arm’ measured cross-section as described in ref. [1], can destroy the kinematical correlation between the antineutron detected by ANC and the neutron in NC, if the $\bar{n}$ is scattered out of the angular acceptance. This gives a reduction of the number of coincidences and consequently of both the ANC efficiency for antineutrons and the NC efficiency for neutrons.

The selection of $\bar{n}$ ‘stars’ detected only on the first absorber causes a reduction of the smearing, because all the smearing inside the ANC detector can be neglected. To decrease the smearing due to $\bar{n}$ elastic scattering in the NC, we have selected only events with no hit on the NC in front of the ANC in which the antineutron was detected, and events with a measured $\text{TOF}_{NC} > \text{TOF}_{ANC}$ (that is with an $\bar{n}$ annihilation on the ANC and a produced pion that hit the NC counter). The use of the NC signal considerably reduces the smearing in this detector, in particular it vetoes $\bar{n}$ elastic scattering on hydrogen when the recoil proton acquires an energy over the detection threshold (~ 4 MeV).

The overall smearing effect is evaluated by means of the Monte Carlo simulation described in section 2.4, using antineutrons generated according to the charge-exchange differential cross-section over the whole angular range covered by the detectors. For any of the three incident antiproton beam momenta, the charge-exchange events are generated uniformly along the length of the target, within $-20^\circ \leq \phi \leq 20^\circ$. The smearing effect is then evaluated by comparing the results of two simulations, one with all the measuring errors and the elastic scattering of the antineutron in the NC turned on and one with these effects turned off. The procedure used to evaluate the smearing effect is the same both for the measurement of the ANC efficiency for antineutrons η and for the NC efficiency for neutrons ϵ .

For every bin of the angular distribution, the smearing factors are given by

$$S_\eta(\theta_i) = \frac{M_{ANC-NC}^{off}}{M_{ANC-NC}^{on}} \cdot \frac{M_{NC}^{on}}{M_{NC}^{off}}, \quad (6.a)$$

$$S_\epsilon(\theta_i) = \frac{M_{ANC-NC}^{off}}{M_{ANC-NC}^{on}} \cdot \frac{M_{ANC}^{on}}{M_{ANC}^{off}}, \quad (6.b)$$

where M is the number of generated Monte Carlo events in the relevant conditions, with the smearing effects ‘on’ and ‘off’ respectively. The results of the simulation for forward scattering at 704 MeV/c are summarized in table 2. As anticipated in section 5, they are very small, and they are even smaller for ANC_2 and NC_2 , since the charge-exchange differential cross-section varies much less in the backward region. Also given in the table is the contribution to the smearing coming from the scattering of the $\bar{n}$ ’s in the NC counter alone. The smearing effect is corrected for by multiplying the measured efficiencies by the quantities $S(\theta_i)$.

Smearing factors at 704 MeV/c							
$S_\eta(\theta_i)$ for ANC ₁	θ_n (lab. system)						
	43.0°	49.0°	55.0°	61.0°	67.0°	73.0°	80.0°
total	1.007	1.006	1.009	1.011	1.014	1.020	–
NC only	1.004	1.004	1.007	1.008	1.011	1.016	–
$S_\epsilon(\theta_i)$ for NC ₁	$\theta_{\bar{n}}$ (lab. system)						
	19.0°	25.0°	31.0°	37.0°	43.0°	49.0°	55.0°
total	1.026	1.012	1.008	1.007	1.009	–	–
NC only	1.011	1.006	1.003	1.002	1.006	–	–

Table 2: Smearing corrections for antineutron and neutron efficiency for various angular bins. Also shown is the contribution coming from the $\bar{n}$ -scattering in the NC alone.

7 Results

All the measured values for η are shown in fig. 15. In order to make it possible to compare data taken at slightly different angles, and thus $\bar{n}$'s going through different absorber thicknesses, the data have been referred to a geometry in which the $\bar{n}$'s are perpendicular to the ANC detectors. Figure 15 shows also the relevant factors to the efficiency, namely:

- P_a^1 , the annihilation probability in the first absorber;
- P_r^1 , the efficiency of reconstructing $\bar{n}$ ‘stars’ in the first absorber;
- P_t , the transmission of $\bar{n}$ through NC (as in fig. 5);
- P_o , the transmission of $\bar{n}$ through all the remaining material in the layout of the experiment, i.e. the LHT, the target and cryostat walls, and the air path.

The product of P_o , P_a^1 , and P_t is shown as the F function in fig. 15: as anticipated in section 2.5, absorption on the first ANC absorber and overall transmission compensate, so that the F -function shows very little dependence on the $\bar{n}$ -momentum. The measured angular distribution of the $\bar{n}$'s annihilating on the first absorber therefore to a good approximation has the same shape of the differential cross-section itself. Also the effect of the uncertainties in the $\bar{n}$ -nucleus absorption data is strongly reduced, as evidenced by the width of the ($\pm 1\sigma$) band in the F -function, also shown in fig. 15.

The product of P_r^1 and the function F gives the overall ANC efficiency η_{ANC} for $\bar{n}$ -stars reconstructed on the first iron. The agreement with the measured points is remarkable, and the fact that the measured efficiency shows little energy dependence is according to expectation. When we published our differential cross-section at 704 MeV/c the $\bar{n}$ Monte Carlo code was still in a primitive stage and could not give reliable estimates of P_r . Still, it was reasonable to assume that, in the $\bar{n}$ momentum range covered by our measurement, the probability of reconstructing a ‘star’ topology P_r did not depend on the $\bar{n}$ -momentum, and we took as $\bar{n}$ detection efficiency the F -function normalized to the measured points (full dots in the figure). From fig. 15 it is clear that the assumption a constant P_r^1 led to an excellent approximation for η .

It is important to stress that this measured efficiency also includes the absorption of the antineutrons in the detector; therefore it is the relevant quantity for evaluating a cross-section. The data shown in fig. 15 have been collected over a time span of more than one year. The agreement among the results from the different runs can be taken as an indication that the systematic effects are well under control. Combining all the data, the relative error of the $\bar{n}$ efficiency turns out to be smaller than 5%.

8 Acknowledgements

We would like to acknowledge the support from CERN in the construction and operation of the target, and we would like to thank G. Bochaton, L. Mazzone, T. Niinikosky, Ch. Policella, and G. Novellini for their help. Some of the authors would like to thank the Swiss National Foundation for support. We are grateful to J.D. Simon, D. Dumolard and all the LEAR operating staff for their collaboration and for the excellent LEAR performances.

References

- [1] R. Birsa et al., *Phys. Lett.* **B246** (1990) 267.
- [2] R. Birsa et al., *Phys. Lett.* **B273** (1991) 533.
- [3] R. Birsa et al., *Nucl. Physics* **B403** (1993) 25.
- [4] R. Birsa et al., *Phys. Lett.* **B302** (1993) 517.
- [5] A. Ahmidouch et al., *Nucl. Instrum. Methods* **A326** (1993) 538.
- [6] R. Birsa et al., *Nucl. Instrum. Methods* **A300** (1991) 43.
- [7] T. Bressani et al., *Nucl. Instrum. Methods* **A292** (1990) 563.
- [8] T. Brando et al., *Nucl. Instrum. Methods* **180** (1981) 461.
- [9] K. Nakamura et al., *Phys. Rev.* **C31** (1985) 1853.
- [10] W. Brueckner et al., *Phys. Lett.* **B166** (1986) 1.
- [11] M. Agnello et al., *Europhys. Lett.* **7** (1) (1988) 13.
- [12] T. Armstrong et al., *Phys. Lett.* **D 36** (1987) 659.
- [13] A. Bressan et al., "A Monte Carlo code for antineutrons", *INFN int. rep. TC-93/14*.
- [14] A. S. Iljinov et al., *Nucl. Physics* **A382** (1982) 378.
- [15] Y. Golubeva et al., *Nucl. Physics* **A483** (1988) 539.
- [16] F. Bradamante et al., "Measurement of the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange differential cross-section", CERN/SPSLC/92-17, SPSLC/P269.
- [17] L. Cugusi et al., *Nucl. Instrum. Methods* **A270** (1988) 354.
- [18] R.A. Cecil et al., *Nucl. Instrum. Methods* **161** (1979) 439.
- [19] R. Madey et al., *Nucl. Instrum. Methods* **151** (1978) 445.

Figure 1: Schematic layout of the experiment PS199 for the 804 MeV/c run (top view). NCs are the neutron counter hodoscopes; ANCs are the antineutron detectors, while PTM labels the yoke of the polarizing magnet.

Figure 2: Cross-sectional view of the target region. LHT is the liquid-hydrogen target. PFU and PFD are the pole face vetoes. FV, LV, and RV are the forward, left, and right vetoes respectively.

Figure 3: Cross-section of the ANC detector (top view).

Figure 4: Distribution of the reconstructed annihilation points in ANC₁ and ANC₂ for samples of events at 1307 MeV/c. The peaks correspond to the positions of the iron absorbers in the detectors.

Figure 5: Computed efficiency $E_{ANC} = P_a \cdot P_r$ of the $\bar{n}$ -detector, as a function of the $\bar{n}$ momentum. Also shown are the quantities: P_a , the $\bar{n}$ annihilation probability in ANC, P_r , the off-line 'star' reconstruction probability, and P_t , the $\bar{n}$ transmission probability through NC. The bands indicate the estimated uncertainties.

Figure 6: (a) Distribution of the $\bar{n}$ measured time-of-flight on the ANC_1 detector as a function of the scattering angle for the 804 MeV/c data; the line indicates the time-of-flight expected from the charge-exchange kinematics. (b) Distribution of $\Delta TOF_{\bar{n}}$ for full- and empty-target data. (c) Distribution of $\Delta TOF_{\bar{n}}$ after the empty-target subtraction; also shown (dashed histogram) is the same quantity for events with a neutron signal in NC_1 .

Figure 7: (a) Distribution of the n measured time-of-flight on the NC_1 detector as a function of the scattering angle for the 804 MeV/c data; the line indicates the time-of-flight expected from the charge-exchange kinematics. (b) Distribution of ΔTOF_n for full- and empty-target data. (c) Distribution of ΔTOF_n after the empty-target subtraction; also shown (dashed histogram) is the same quantity for events with an $\bar{n}$ detected in ANC_1 (multiplied by a factor of five).

Figure 8: The $\bar{p}p \rightarrow \bar{n}n$ charge-exchange differential cross-section measured at 704 MeV/c incoming $\bar{p}$ momentum (ref. 1). The full circles are the points given by ANC₁, whilst the open boxes comes from ANC₂.

Figure 9: Distribution of $\Delta\text{TOF}_{\bar{n}}$, the difference between the measured time-of-flight and that calculated starting from $\theta_{\bar{n}}$, for the 704 MeV/c run. Histogram (a) shows both full- and empty-target data for ANC₁ ‘in single’. Figure (b) shows the ANC₁ ‘in single’ data after the empty-target subtraction. Figure (c) is the same quantity for events with also a neutron signal in NC₁.

Figure 10: Measured NC efficiency for neutrons as a function of the neutron kinetic energy at 704 MeV/ c incoming antiproton beam momentum, for a threshold of 1.5 MeV_{ee}. The solid line shows the Monte Carlo calculations.

Figure 11: Distribution of $\Delta\text{TOF}_{\bar{n}}$, the difference between the measured time-of-flight and that calculated starting from $\theta_{\bar{n}}$, for the 704 MeV/c run at $\theta_{cm} = 90^\circ$. Histogram (a) shows both full- and empty-target data for ANC_2 'in single'. Figure (b) shows the ANC_2 'in single' data after the empty-target subtraction. Figure (c) is the same quantity for events with also a neutron signal in NC_2 .

Figure 12: (a) Distribution of ΔTOF_n for NC_2 'in single' at $\theta_{cm} = 90^\circ$, and after the empty-target subtraction. (b) Distribution of ΔTOF_n for NC_2 at $\theta_{cm} = 90^\circ$ for events with also a signal in coincidence in the NC_1 detector. (c) Distribution of ΔTOF_n for NC_2 for events with also a $\bar{n}$ signal detected in the ANC_2 detector.

Figure 13: Distributions of ΔTOF_n for neutrons at 59° (804 MeV/c run). Histogram (a) shows both full- and empty-target data for NC_1 'in single'. Figure (b) shows the NC_1 'in single' data after the empty-target subtraction; the dashed line is the estimated background level. Figure (c) is the ΔTOF_n distribution for events with also an antineutron signal in ANC_1 in both full- and empty-target conditions. Figure (d) is the same distribution after the subtraction of the few empty events.

Figure 14: Distributions of ΔTOF_n for neutrons at 63° (1307 MeV/c run). Histogram (a) shows both full- and empty-target data for NC_1 'in single'. Figure (b) shows the NC_1 'in single' data after the empty-target subtraction; the dashed line is the estimated background level. Figure (c) is the ΔTOF_n distribution for events with also an antineutron signal in ANC_1 in both full- and empty-target conditions. Figure (d) is the same distribution after the subtraction of the few empty events.

Figure 15: Measured ANC efficiencies for antineutrons reconstructed on the first absorber as a function of the $\bar{n}$ momentum. The solid curve η_{ANC} is calculated using the reconstruction efficiency P_r^I given by the $\bar{n}$ Monte Carlo program. Also shown are P_o , the $\bar{n}$ transmission probability from the target to NC and from NC to the first absorber; P_t , the transmission probability through NC, and the function $F = P_o \cdot P_t \cdot P_a^I$.