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Measurement of the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange differential cross-section

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Abstract

The aim of this proposal is a measurement of the differential cross-section of the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange reaction with a point-to-point precision of 1% in the forward direction, and an absolute normalization error of 3%. The high precision of the data should allow, inter alia, a determination of the πNN coupling constant to better than 2%.

The measurement will be done using the existing neutron and antineutron detectors built for experiment PS199 and a liquid hydrogen target. In one week of running time, with a $\bar{p}$ beam intensity of 3×10^5 $\bar{p}$'s/sec, the reaction will be measured at three $\bar{p}$ momenta, 546, 675 and 880 MeV/c.

Introduction

The charge-exchange channel $\bar{p}p \rightarrow \bar{n}n$ is known to be a very good laboratory to test our understanding of $\overline{N}N$ interaction. At low energies, hadron-hadron interactions are described successfully by meson-exchange potentials (MEP) models. In the case of $\overline{N}N$ interactions, to take care of the annihilation channels, the MEP is supplemented by phenomenological descriptions of this process, e.g. the introduction of complex parts in the potential or a treatment in a coupled-channel framework. In the case of the $\bar{p}p \rightarrow \bar{n}n$ reaction, only isovector mesons can be exchanged in the t-channel, thus enabling us to use the well-known π exchange term to learn about the heavier meson exchanges and the parameters of the annihilation potential.

Experiment PS199 has measured for the first time and with a good precision the analyzing power (at 8 momenta) and the depolarization parameter (at 2 momenta) of this reaction [1,2]. The existing differential cross-section data do not have similar accuracy and in some cases show inconsistencies. PS199 will provide differential cross-sections as a by-product of the polarization measurement, but not over the entire angular range (and notably not in the very forward direction), and with limited precision, since the experiment was performed with a penthanol polarized target. Consequently we propose to use the neutron [3] and antineutron [4] detectors we have developed for the experiment PS199 and a liquid hydrogen target to perform at a few energies a precision measurement of the charge-exchange differential cross-section. The energy range indicated (from ≈ 100 MeV to the one pion production threshold) is the best choice for the MEP approach.

Experimental situation

Fig.1(a) and 1(b) show typical differential cross-section data at low energies and at low momentum transfer t for $\bar{p}p \rightarrow \bar{n}n$[5,6] and for the similar reaction np → pn [7]. The np charge-exchange cross-section is essentially constant with the energy in the forward direction, and its t-dependence is also universal. In the case of $\bar{p}p \rightarrow \bar{n}n$ charge exchange, the data are not as accurate, but it is also possible to identify a universal behaviour.

The solid curves in Fig.1 are MEP model calculations [8,9] using the Paris potential [10]. For both reactions the forward peak is usually interpreted in terms of the leading $[1 - t/m_\pi^2]^{-2}$ Yukawa part of the one-pion exchange (OPE) potential. The agreement between data and calculations for the np → pn reaction is impressive, and in this sense this reaction at about 0° is usually quoted as a "text-book" example of one-pion exchange potential [11]. In principle the $\bar{p}p \to \bar{n}n$ reaction can be calculated with the same accuracy, by parametrizing the absorption parameters on existing $\overline{N}N$ scattering data [12]. This challenge to meson physics can lead to meaningful conclusions only if precise $\bar{p}p \to \bar{n}n$ differential cross-section data become available. The aim of this proposal is a measurement of the $\bar{p}p \to \bar{n}n$ differential cross-section with a precision equal to that shown in Fig.1(b), and over most the angular range.

Relevance of the measurement

As explained already in 1967 by Phillips [13], and reviewed recently by Shibata [14], the differential cross-section of the $\bar{p}p \to \bar{n}n$ reaction is dominated by the OPE potential. This can be seen in Fig.2(a) where the calculated cross-section in a popular MEP model (Dover-Richard I) is compared with the same quantity evaluated by switching off all exchanges but the one-pion contribution. The cross-section differences in the two cases are smaller than 10%, indicating that the other exchanges contribute considerably less than the one-pion exchange (switching off also the OPE, no cross-section is left, since in this model the annihilation potential has no isospin dependence, and OPE is the driving term of the reaction). In this simple OPE model, the dip-bump structure is generated by the different t-dependence of the spin-spin and tensor part of the OPE potential, namely:

$$V_{SS}(\vec{r}) = \frac{1}{3}\frac{f^2}{4\pi}\left[\frac{e^{-m_\pi r}}{r} - \frac{4\pi}{m_\pi^2}\delta^3(\vec{r})\right] \vec{\sigma}_1\cdot\vec{\sigma}_2 \; \vec{\tau}_1\cdot\vec{\tau}_2$$

$$V_t(\vec{r}) = \frac{1}{3}\frac{f^2}{4\pi}\left[1 + \frac{3}{m_\pi r} - \frac{3}{m_\pi^2 r^2}\right]\frac{e^{-m_\pi r}}{r} \; S_{12}(\vec{r}) \; \vec{\tau}_1\cdot\vec{\tau}_2$$

The contributions to the cross-section from these two terms are shown separately in Fig.2(b). The dip-bump structure has been observed experimentally [5,6,15], and it seems to exhibit an energy dependence, tending to become a shoulder at very low energies (≤ 50 MeV). Also alternative explanations of the structure have been put forward, particularly at higher energy [16].

Although OPE is the leading term in the $\bar{p}p \to \bar{n}n$ exchange structure, the detailed t-dependence of the differential cross-section depends on all the exchanges. The different contributions are shown separately in Fig.2(c), again for the Dover-Richard I model. In the forward direction, from t=0 to t of the order of a few m_{π}^{2}, the differential cross-section depends critically on the strength of the vector mesons exchanges compared to the strength of the pion exchange (which is known). As pointed out by F.Myhrer [17], the strength of the vector mesons can be screened by adjusting the short-range cut-offs, or playing with the annihilation potential, so it is very important to know precisely the t-dependence of the differential cross-section to separate the various contributions.

The power of the theoretical calculations used to crunch the $\overline{N}N$ data can be appreciated by looking at Fig.3(a) and 3(b), which show recent fits of the Nijmegen group [18] to some PS199 data. Also, a phase-shift analysis [19] to the whole $\overline{N}N$ database has allowed a determination of the charged pion coupling constant. The quoted precision ($f_c^2 = 0.0751 \pm 0.0017$) is comparable with the one provided by the most recent standard analysis on πN scattering data ($f_c^2 = 0.0735 \pm 0.0015$) [20]. Both these estimates of f_c^2 are smaller than the "classical" value ($f_c^2 = 0.079 \pm 0.001$) which has been used over many years, and a big debate is presently going on about the numerical value of f_c^2 [21]. In the Nijmegen approach, preliminary attempts to study masses and couplings of different mesons (as the ρ meson) also look promising.

The πNN coupling constant is a crucial constant, fundamental in various applications, and it is a scale factor in some of the most accurately measured and investigated quantities in nuclear physics. The $\bar{p}p$ charge-exchange cross-section depends on f_c^4, so a measurement with an absolute precision of 3-4% can contribute to the present debate at the same level of accuracy as (or better than) measurements in other physical systems. Clearly, the absolute normalization is a key point, and in this sense a precision measurement of the $\bar{p}p$ charge exchange cross-section is badly needed.

In the standard MEP approach of the Paris group, the new LEAR data for $\bar{p}p$ elastic and $\bar{p}p$ charge exchange have been inserted in the data base, and satisfactory fits could be obtained by readjusting the absorption core parameters [12]. While in this new fits good agreement could be obtained with the analysing power data of the elastic channel, in the charge-exchange channel analyzing power and differential cross-section data could not be fitted simultaneously [22]: assuming that the analyzing power data are correct, the model would suggest that the cross-section data are off by as much as 50%. Clearly a new measurement would be beneficial.

In summary, beside a clarification of existing contradictions in the data, a precise measurement of the differential cross-section of the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange reaction should provide:

- a hint to a universal t-dependence (if any) of the cross-sections
- an important step forward in the knowledge of the $N\bar{N}$ potential
- estimates for the meson-nucleon coupling constants, independent from NN interactions, and in particulary the πNN coupling constant f_c^2

Experimental apparatus

The measurement will be performed by detecting the $\bar{n}$'s produced by the extracted LEAR $\bar{p}$ beam passing through a 10 cm long liquid hydrogen target (LHT). In part of the angular range the $\bar{n}$'s will be detected in coincidence with the associated neutron. The target will be surrounded by a scintillator counter box, to veto at the trigger level events in which charged particles are produced (annihilation and $\bar{p}p$ elastic events). Above and below the target the veto counters consist of sandwiches of lead and scintillators, to reject also annihilation events into neutrals. For background evaluation, data will be taken alternating full target (FT) and empty target (ET) runs.

The layout of the experiment is shown in Fig.4. The apparatus is basically the one used for experiment PS199, presently installed in the C1 beam area. ANC labels the antineutron detectors, while NC indicates the neutron counters. A small magnet (e.g., MNPA30, 0.2 Tm) will sweep the $\bar{p}$ leaving the target away from the 0° direction, thus allowing to measure the differential cross-section down to 0°.

The antineutron detectors are made up of iron slabs (3 cm thick) and modular structures of four planes of limited streamer tubes (LST) and one plane of scintillator counter hodoscopes. The LST modules detect the charged products of the $\bar{n}$ annihilation, which is thus identified from its characteristic "star" pattern. The efficiency of the detector is essentially 0 for neutrons and 20% for the $\bar{n}$. The energy dependence of the $\bar{n}$ efficiency is very well known from the measured attenuation of the $\bar{n}$'s inside the counter itself in the PS199 data. Typical attenuation data are shown in Fig.5 [23].

The neutron counters are made up of NE110 scintillator bars $130 \times 20 \times 8$ cm^3 , viewed by XP2040 PM's from top and bottom. Fig.6 shows one of the hodoscopes used in PS199.

Typical energy calibration data for one counter are shown in Fig.7(a). The low energy scale (dashed line) is fixed from a fit to the 4.4 MeV γ-line from an Am-Be neutron source (Fig.7b). The high-energy response is obtained using cosmic muons, and Fig.7(c) shows a typical Landau spectrum for muons crossing the counter from the narrow side. The counter efficiency for neutrons is computed using a modified version of the Cecil neutron code [24], and counter-checked with an absolute calibration procedure which uses the $\bar{n}$'s produced in the charge-exchange reaction itself. A full description of the counters and of the calibration and monitoring procedures has been sent out for publication [3].

The neutron counter NC2 will be used also to measure the $\bar{n}$'s angular distribution in the backward hemisphere. To this end it is surrounded by two LST modular structures to detect the charged $\bar{n}$ annihilation products. The counter NC1 will be used for part of the run for calibration purposes.

The differential cross-section will be derived from the measured $\bar{n}$ angular distribution in the three antineutron detectors. The angular range covered by the three detectors is shown in Fig.8. There is sufficient overlap of the three angular ranges to allow for relative normalization. In the backward region, the measurement will extend down to $\bar{n}$'s of ~ 3 MeV energy.

To reduce the systematic errors it is very important to measure at least in part of the angular range coincidence rates between n's and $\bar{n}$'s. In the $100° < \theta_{cm} <40°$ angular range, coincidence data between ANC2 and NC2 will be collected all the time, thus allowing

— an independent measurement of the angular distribution in that range

— a measurement of the $\bar{n}$ smearing in the ANC detector

— an absolute calibration of the detectors efficiencies for n's and $\bar{n}$'s

The key difficulty in an experiment with neutral particles (like np charge exchange) is clearly the absolute normalization. In this experiment the absolute normalization will be derived from the data sample itself: the basic idea is that by correlating the scattering angle and the TOF of the detected particle (n or $\bar{n}$) in ANC (or NC), one can define the efficiency of the corresponding detector (NC or ANC) as the ratio of the ANC·NC coincidences on the number of the detected particles in the first detector. The problem with this method is that, at any given angle, the NC counters respond both to neutrons and antineutrons, and the ratio of these two types of particles depends on the cross-section, which is the quantity we just want to measure. The basic trick we have already used in PS199 [1] uses the fact that at $\theta_{cm} = 90°$ the number of neutrons and of antineutrons is the same, so that by placing a symmetric configuration of n- and $\bar{n}$-detectors at this angle an unambiguous solution exists for all the efficiencies of all the detectors. Already in PS199 in a liquid hydrogen target calibration run, we could determine the absolute normalization with a 10% precision. In this experiment, with a dedicated LHT, we aim at lowering this number by a factor from 2 to 3, mainly by the improved statistics, and somewhat by the better geometry, which would allow a determination of f_c^2 from this single measurement with a precision of better than 2%.

Running time

As stated in section 2, we aim at a point-to-point precision similar to that obtained in $np \to pn$ charge exchange, i.e. 1% error in a 1° angular bin in the laboratory frame in the forward hemisphere.

The quality of the LEAR beam and the resolution of the coordinates of the $\bar{n}$ annihilation vertex as reconstructed by the ANC detectors, insure the angular resolution. Assuming:

- 10 cm length for the LHT
- 1 mb/sr for the differential cross-section
- 2×10^{10} "useful" antiprotons
- ±15° azimuthal acceptance, ±0.5° scattering angle binning
- 20% efficiency of the ANC counters

the required precision should be obtainable.

Our experience in PS199 has been that two days of beam time are necessary to have 2×10^{10} "useful" $\bar{p}$'s in the target. Since no coincidence is required in the trigger between neutron and antineutron, a low $\bar{p}$ rate is adequate (2-3×10^5 $\bar{p}$'s/sec).

We would like to perform the experiment at three momenta, i.e. 546 MeV/c, 675 MeV/c and 880 MeV/c. Allowing for one day of setting up, our request to SPSLC is for seven days of running time. Some days in parasitic mode will be needed for tuning the equipment.

Request to CERN

The apparatus exists and has been used in PS199. It is presently installed in the C1 area. The C1 beam has the requirements we need for the measurement, therefore we ask the use of this area to perform the experiment. Most of the material for the LHT is standard existing material belonging to the cryogenic group (AT division), and we ask CERN the use of this material and some help for its installation and operation. Therefore our request to CERN are:

- 7 days of beam time (C1 line), with an intensity of $2\text{–}3\times10^5$ $\bar{p}$'s/sec.
- installation, assembly and assistance in the operation of the LHT
- some computing time (1000 CPU hours under CERNVM)

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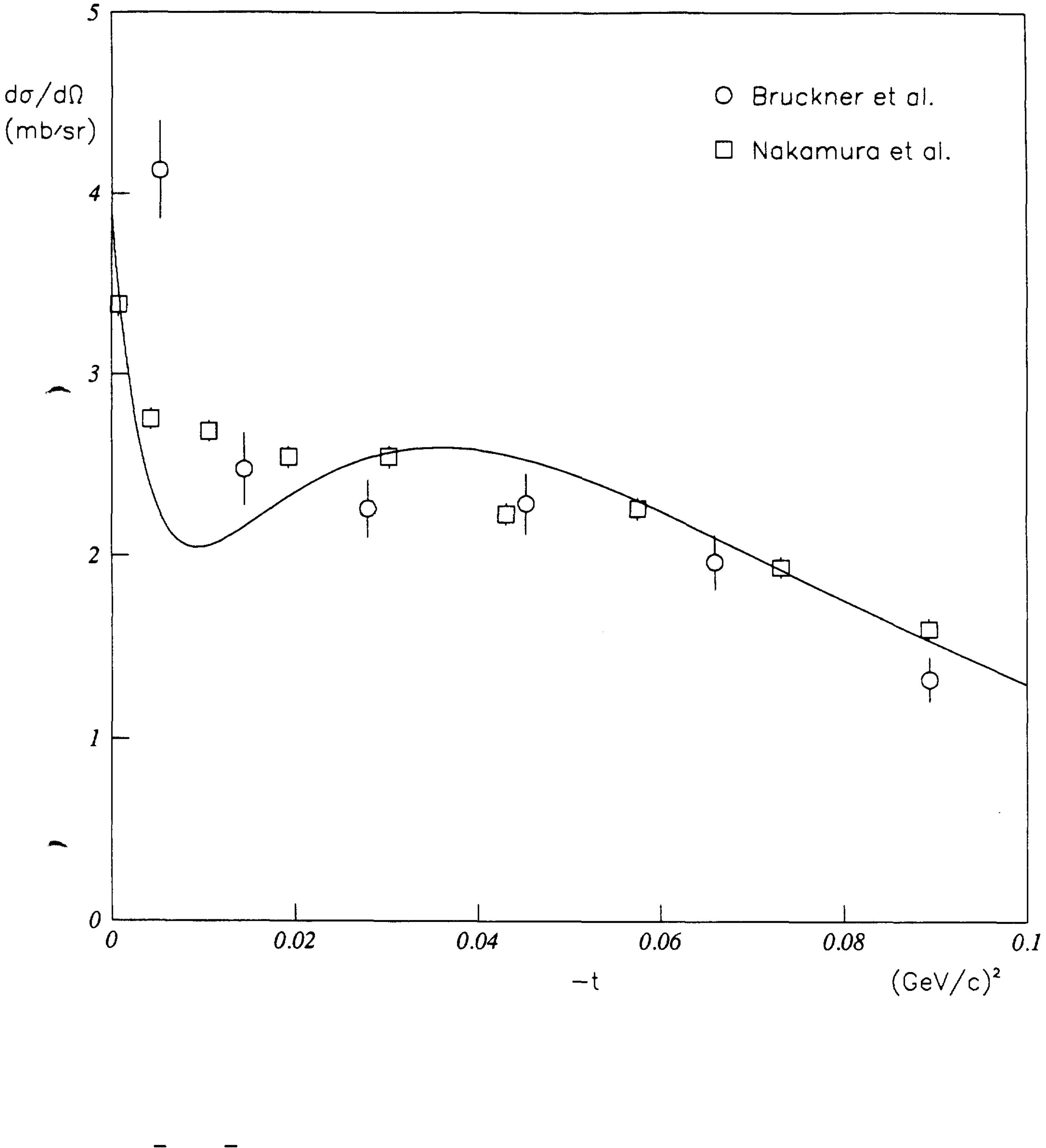

Fig.1(a) $\bar{p}p \rightarrow \bar{n}n$ charge-exchange differential cross-section data from Brückner et al. [5] and Nakamura et al. [6] at 590 MeV/c incoming $\bar{p}$ momentum. The solid curve is a prediction of the Dover-Richard I model [8].

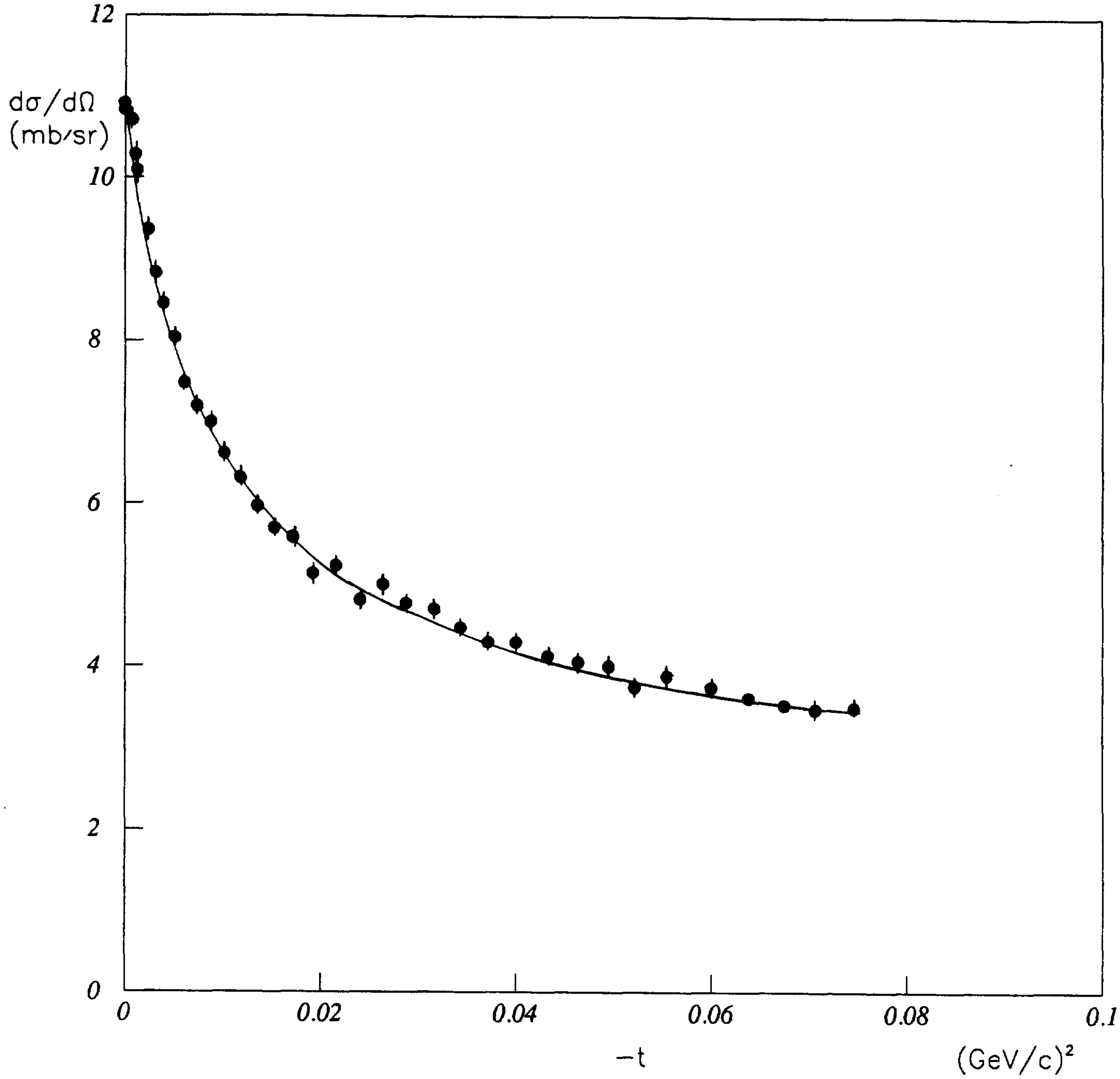

Fig.1(b) np → pn charge-exchange differential cross-section data from Hürster et al. [7] at 900 MeV/c incoming momentum. The solid curve is a MEP calculation [9] which uses the Paris NN potential.

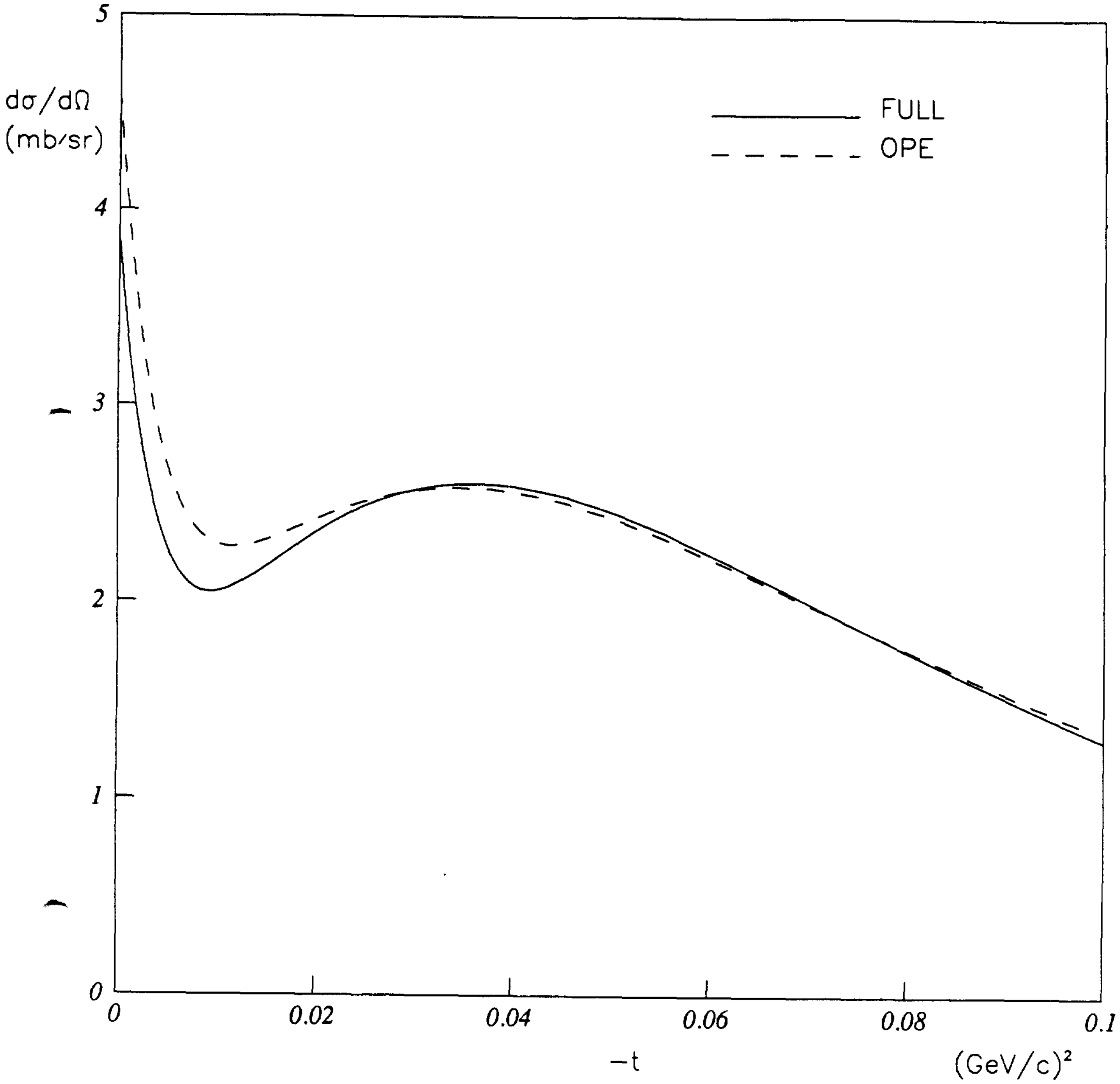

Fig.2 Calculations of the $\bar{p}p \rightarrow \bar{n}n$ differential cross-section at 590 MeV/c incident $\bar{p}$ momentum, using the Dover-Richard I model [8].

(a) Comparison between full calculation (solid curve) and calculation with only OPE as meson exchange term.

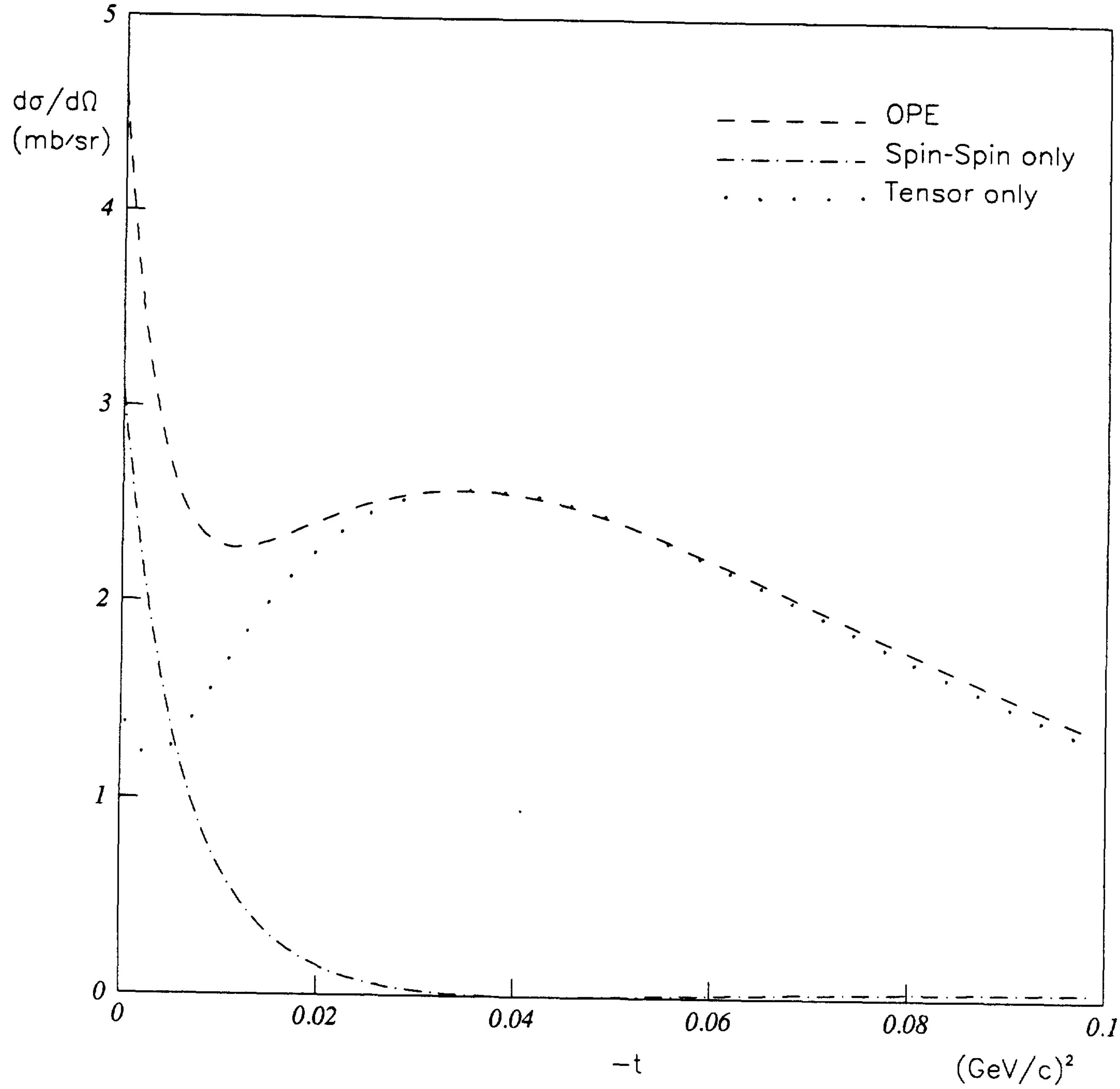

Fig.2 Calculations of the $\bar{p}p \rightarrow \bar{n}n$ differential cross-section at 590 MeV/c incident $\bar{p}$ momentum, using the Dover-Richard I model [8].

(b) The calculation in which only OPE is used as exchange term (dashed curve) is split up into its two contributed terms, i.e. the spin-spin term (dash-dotted curve) and the tensor term (dotted curve).

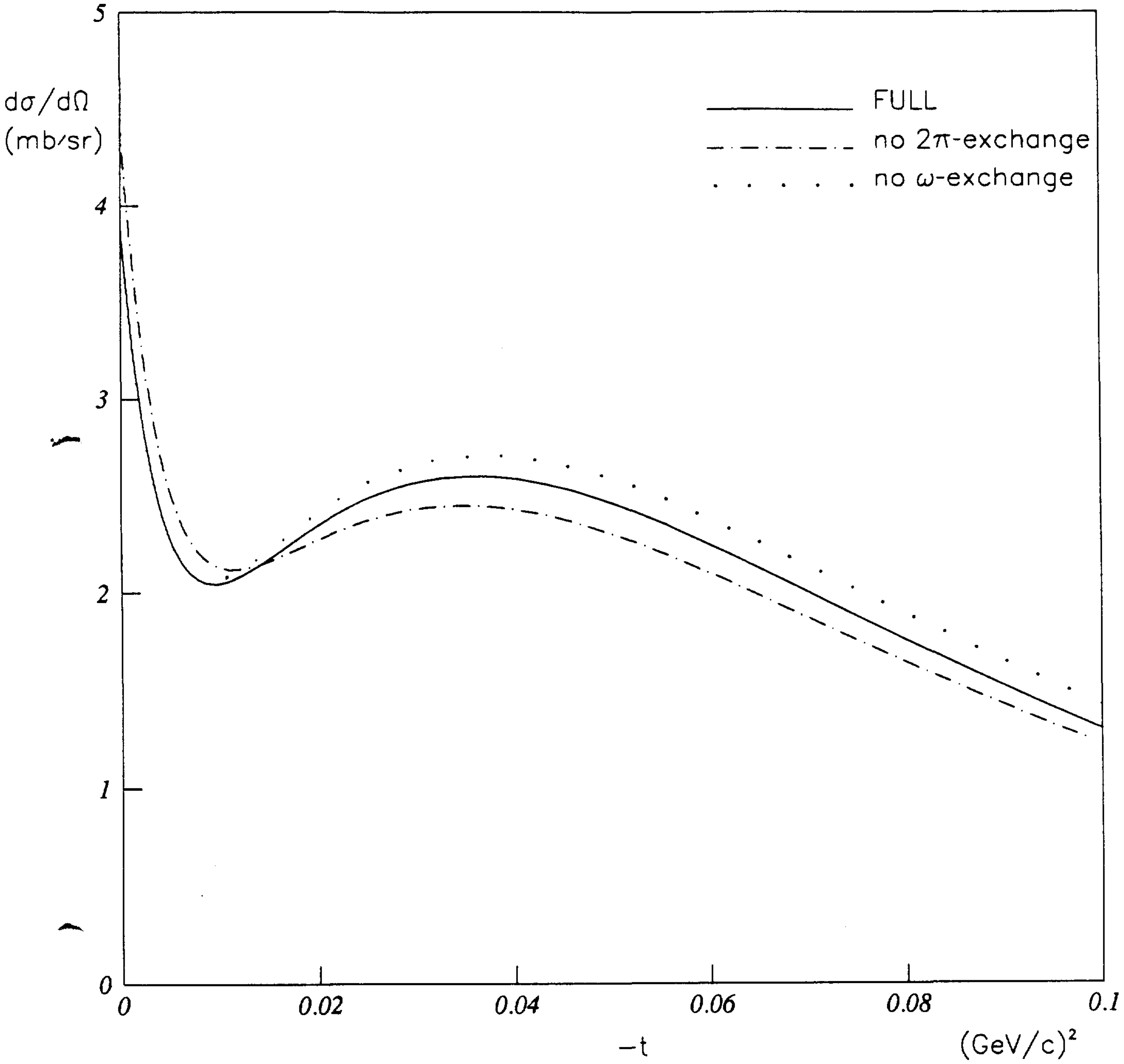

Fig.2 Calculations of the $\bar{p}p \rightarrow \bar{n}n$ differential cross-section at 590 MeV/c incident $\bar{p}$ momentum, using the Dover-Richard I model [8].

(c) Comparison between full calculation (solid curve) and calculations in which the 2π-exchange term is set to zero (dash-dotted curve) or the ω-exchange is set to zero (dotted curve).

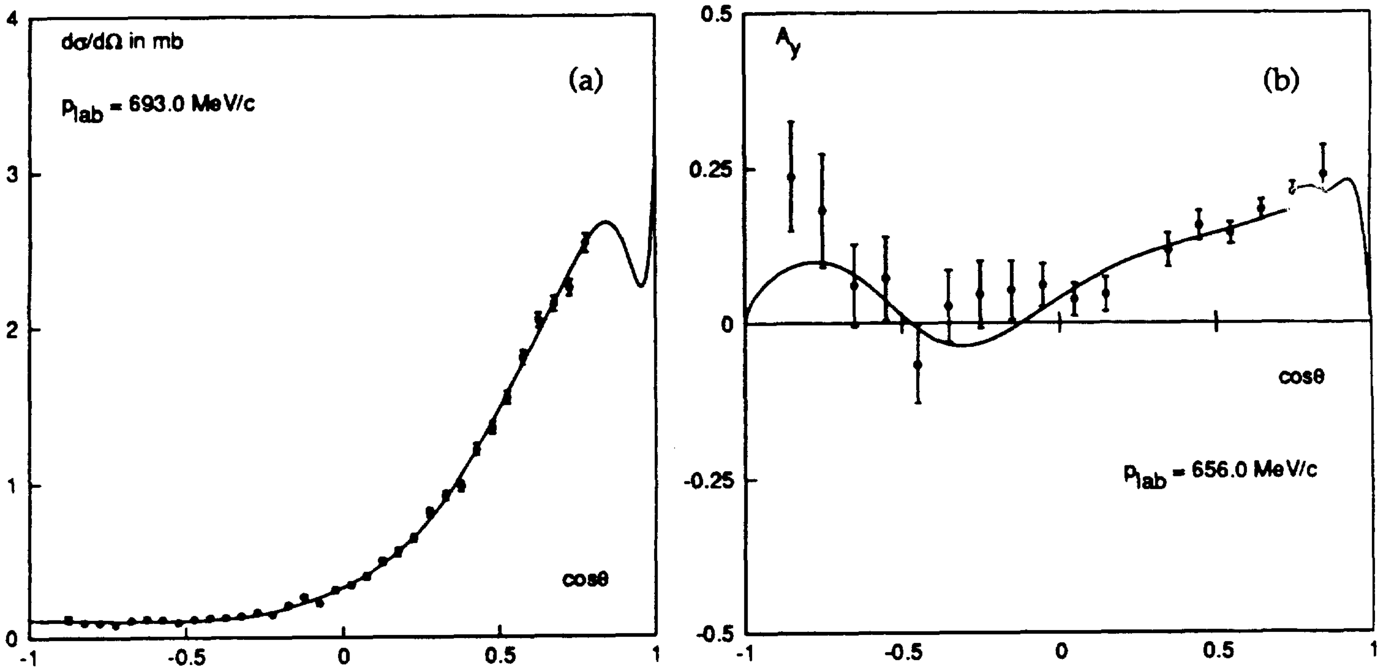

Fig.3 Comparison between the $\bar{p}p \rightarrow \bar{n}n$ charge-exchange differential cross-section (a) and analyzing power (b) measured by experiment PS199 and recent Nijmegen model calculations [18].

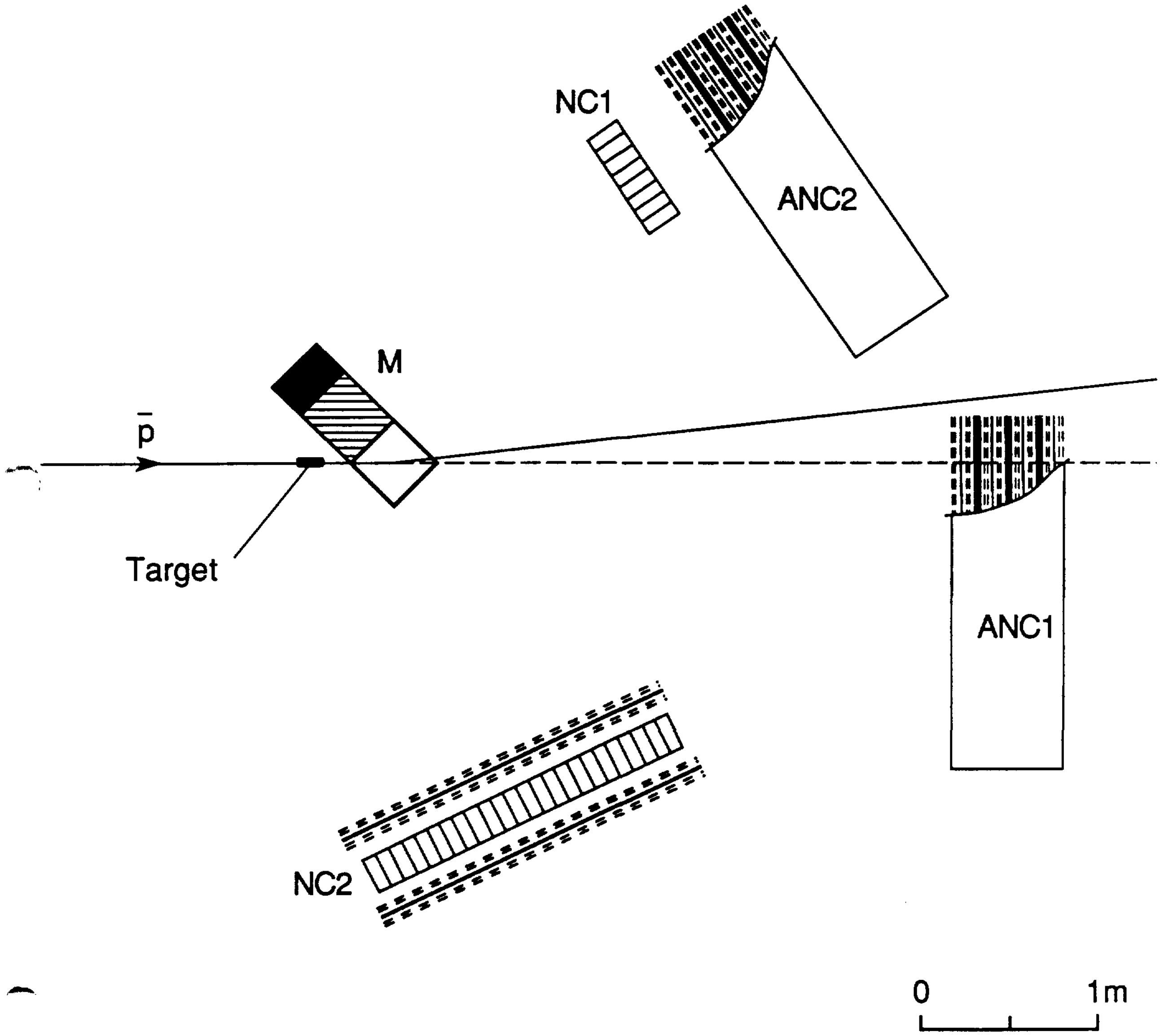

Fig.4 Schematic lay-out of the experiment. The ANC's and the NC counters are the n̄'s and the n's detectors already used in PS199. The target is surrounded by a veto counters box (not shown) to reject annihilation and p̄p elastic events at the trigger level. The special arrangement of LST planes around NC2 will allow this detector to identify also n̄'s.

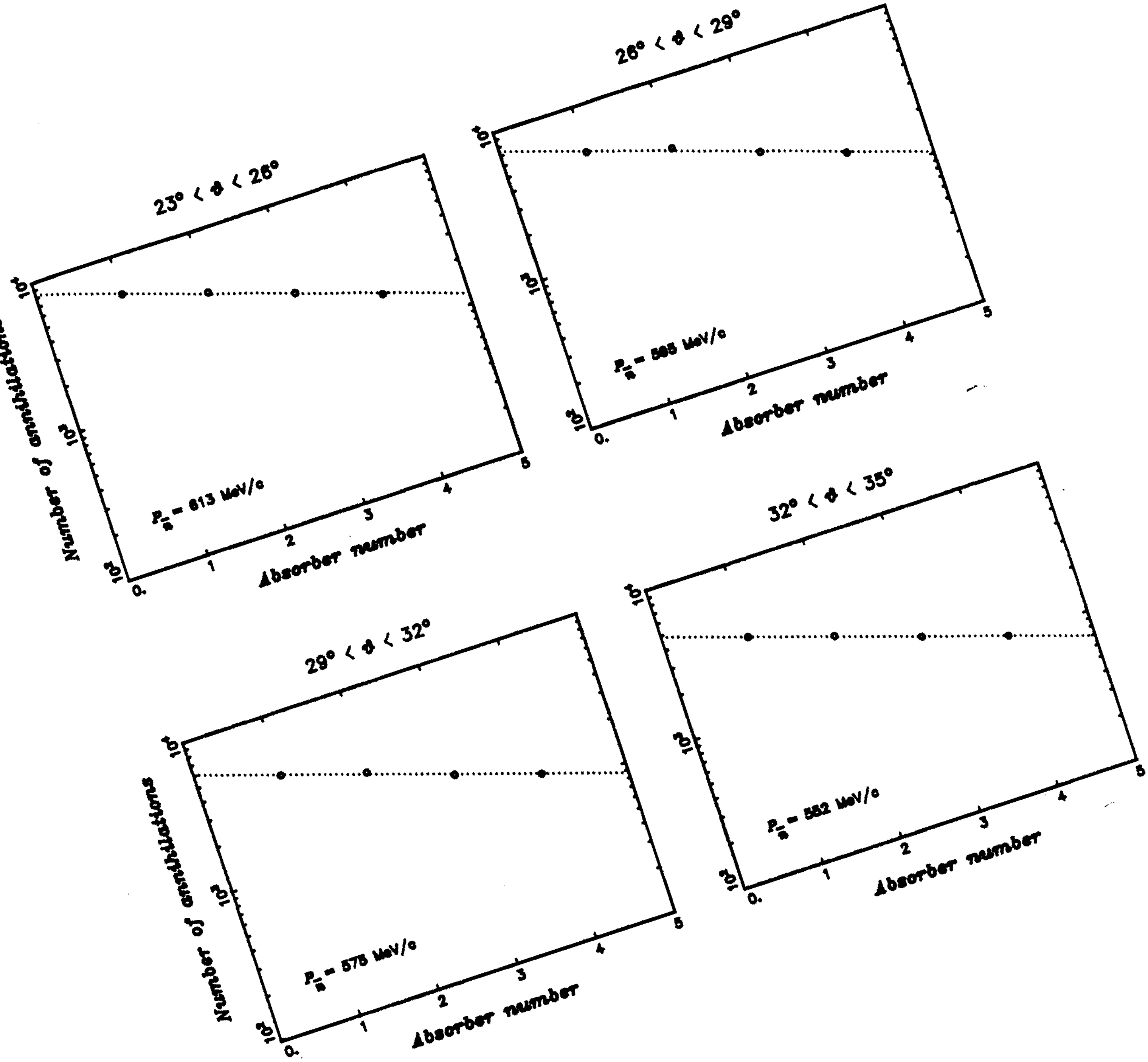

Fig.5 Attenuation data of $\bar{n}$ in the ANC detectors at various momenta. The data refer to a LHT calibration run of PS199 at 700 MeV/c incident $\bar{p}$ momentum. Good charge-exchange events are used as entries to the six plots, each of which refers to a different angular (i.e. momentum) range of the $\bar{n}$'s.

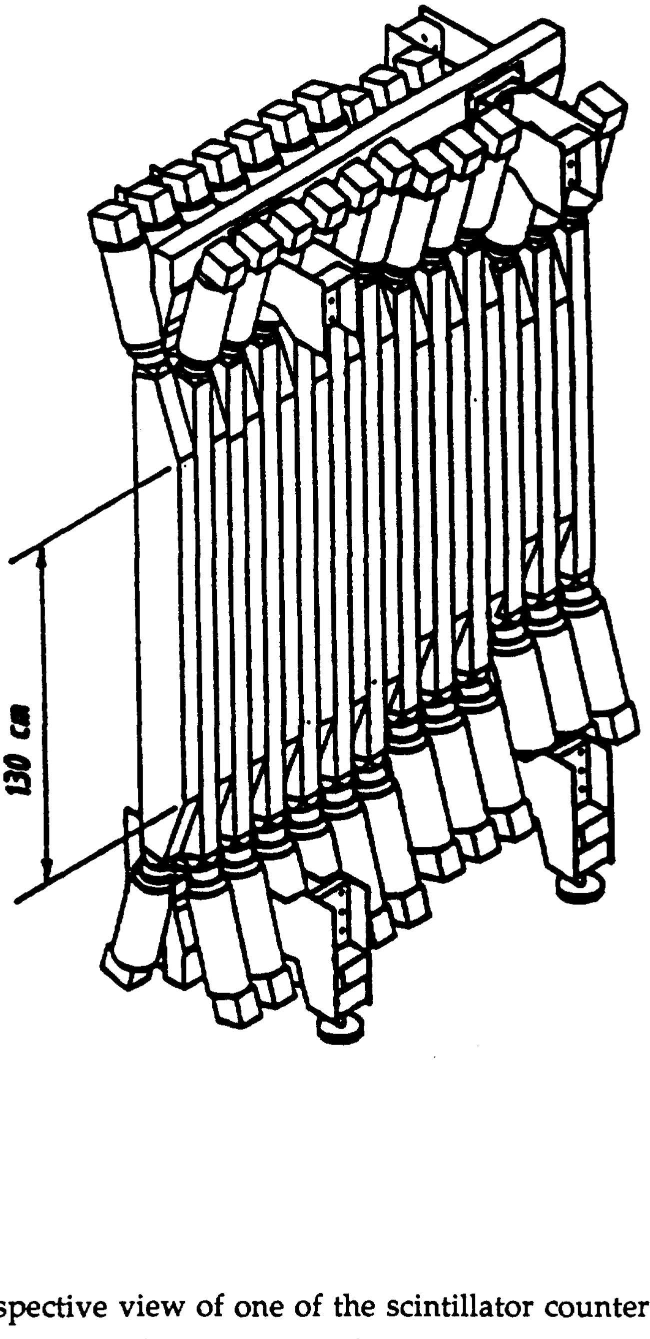

Fig.6 Perspective view of one of the scintillator counters hodoscopes used in experiment PS199 to detect the neutrons.

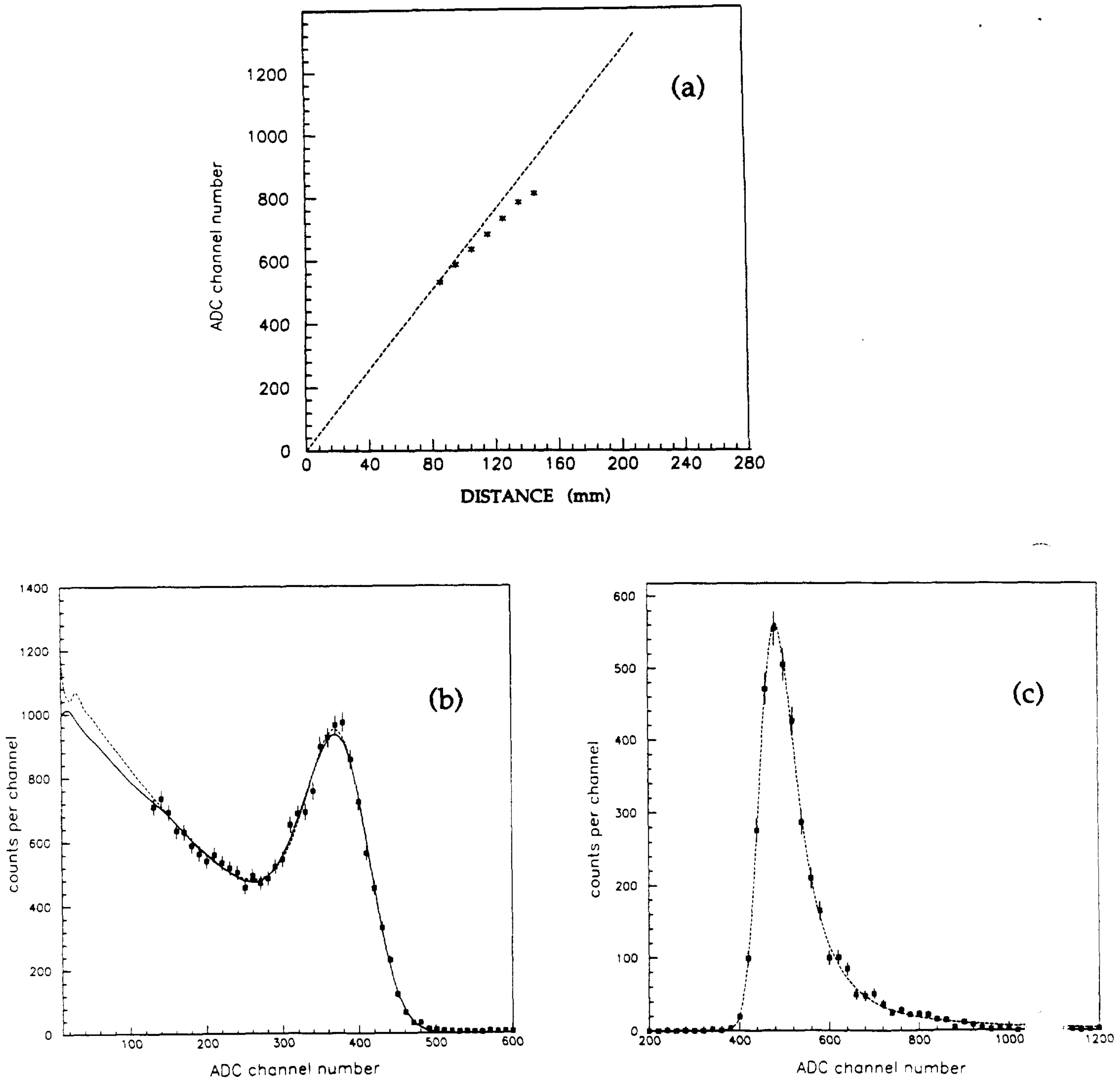

Fig.7 Energy response of one of the neutron counters bars.

(a) Energy calibration. The dashed line comes from the low energy calibration with the γ's of 4.4 MeV, while the points are obtained from cosmic muons crossing the counter.

(b) Calibration with the 4.4 MeV γ signal from an Am/Be source. The signal is fitted with a gaussian plus a polynomial to describe the background.

(c) Distribution of energy loss of cosmic muons crossing the NC bar. The fit is a Landau distribution folded with a gaussian.

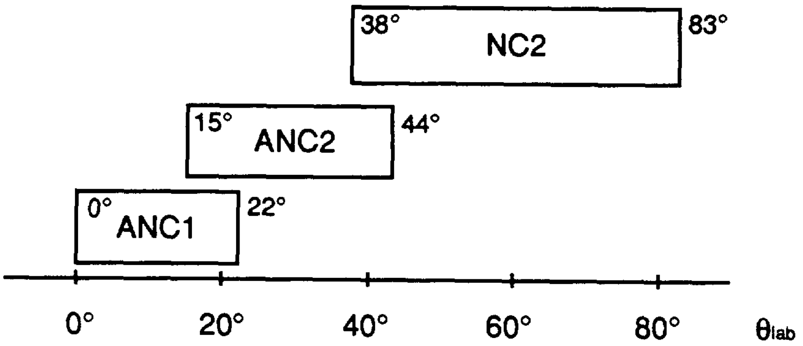

Fig.8 Angular ranges covered (in the laboratory) by the three $\bar{n}$'s detectors (full efficiency).