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Antineutron–proton total cross section from 50 to 400 MeV/c

OBELIX Collaboration

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Abstract

The antineutron–proton total cross section has been measured in the low momentum range 50–400 MeV/c (below 100 MeV/c for the first time). The measurement was performed at LEAR (CERN) by the OBELIX experiment, thanks to its unique antineutron beam facility. A thick target transmission technique has been used. The measured total cross section shows an anomalous behaviour below 100 MeV/c. A dominance of the isospin $I=0$ channel over the $I=1$ one at low energy is clearly deduced.

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1. Introduction

In this Letter we report the measurement of the antineutron ($\bar{n}$) – proton (p) total cross section $\sigma_T(\bar{n}p)$ in the $\bar{n}$ momentum range from 50 MeV/c (corresponding to a kinetic energy $T_{\bar{n}}$ of 1.33 MeV) to 400 MeV/c ($T_{\bar{n}} = 81.6$ MeV), performed by the OBELIX experiment at the LEAR machine at CERN.

There were at least two motivations pushing to measure $\sigma_T(\bar{n}p)$ in the low energy range: (i) to study the dependence of the antinucleon ($\bar{N}$) – nucleon (N) interaction upon the isospin (strictly related to the meson exchange in the medium and long range part of the strong interaction); (ii) to explore whether near the ($\bar{N}$–N) threshold the cross sections would exhibit a different behaviour with respect to a smooth rise, as predicted by the well established potential models [1].

Concerning the last item, it must be recalled that the existence of the so called ‘‘quasi-nuclear’’ bound states or resonances was predicted years ago by Shapiro [2] and had a quite controversial story from the experimental point of view. For a recent review see Ref. [3].

The ($\bar{N}$–N) experimental data actually available in literature show a large amount of $\bar{p}p$ total and annihilation cross sections over 200 MeV/c [4], $\bar{p}p$ annihilation cross sections at low energy by the OBELIX Collaboration [5], $\bar{n}p$ annihilation cross sections from 20 to 400 MeV/c [6–8] and one set of $\bar{n}p$ total cross sections from 100 to 500 MeV/c [6]. Indirect information on the $\bar{p}n$ system at low momenta has been obtained from measurements in deuterium [9] and light nuclei [10].

A lack of measurements at low energy is evident, in particular of total cross sections. With the present work the OBELIX Collaboration supplies more data in this range having used $\bar{n}$'s as projectiles, because of their characteristics at low energy; in fact:

1. $\bar{n}$ can penetrate consistent amounts of LH_2 without suffering from energy loss, as it happens with $\bar{p}$: therefore the counting rates inside thick targets are quite large and overcompensate the low flux of incident $\bar{n}$'s;
2. the $\bar{n}$ beam of OBELIX had a wide momentum band (50–400 MeV/c) but the momentum of each antineutron annihilating inside an LH_2 target can be directly measured: thus the cross sections as a function of energy can be measured in one single data-taking;
3. last but not least, the $\bar{n}p$ system is a pure $I=1$ state, whereas the $\bar{p}p$ one is a mixture of $I=0$ and $I=1$ states: hence the measurement of $\bar{n}p$ cross sections compared to the $\bar{p}p$ ones should lead to an unambiguous determination of the isospin dependence in the ($\bar{N}$–N) interaction, better than the indirect measurements on the $\bar{p}n$ system.

2. Experimental apparatus and technique

The experiment was performed at the M2-branch of the LEAR Machine at CERN with the $\bar{n}$ beam facility coupled to the OBELIX spectrometer. Both devices are described in details in Refs. [11] and [12] respectively: in the following their main features are shortly recalled.

The $\bar{n}$ beam was obtained by means of the charge-exchange (CEX) reaction $\bar{p} + p \to \bar{n} + n$. The incident $\bar{p}$ momentum was 406 MeV/c, and the

CEX LH_2 target (called Production Target, PT) was 400 mm long. In such a length the $\bar{p}$ were brought to rest and produced, during their slowing down, an $\bar{n}$ beam with a continuous momentum distribution, at a rate of $(36 \pm 1) \times 10^{-6}\ \bar{n}/\bar{p}$. A suitably shaped Lead collimator selected the $\bar{n}$ emitted in the forward direction and the $\bar{n}$ momentum distribution, ranging from ~ 50 to $\sim$ 400 MeV/c, is shown in Fig. 1. A second cylindrical LH_2 target (called Reaction Target, RT), 250 mm long and with a diameter of 150 mm, was located ~ 2 m downstream the production target, in the center of the detector.

OBELIX was a magnetic spectrometer consisting of several detectors optimized for different tasks, all located in between the two poles of the Open Axial Field Magnet. In the present experiment only the Jet Drift Chamber (JDC) and the two Time-Of-Flight barrels (TOF) were used: the first detector to measure the momenta of the particles produced in the $\bar{n}$ annihilation and the position of the annihilation vertex in RT with a precision of 0.5 cm; the second detector to provide the first level trigger. The vertex was determined by requiring the intersection of at least two long, well recognized, tracks. The inner element of the TOF system allowed the measurement of the momentum of each $\bar{n}$ annihilating in RT by means of the time-of-flight technique described in Ref. [11]. The error on the determination of $p_{\bar{n}}$ ranged from 3% at 50 MeV/c to 5% at 400 MeV/c.

With this experimental set up it was possible to measure $\sigma_T(\bar{n}p)$ by a simple thick target and narrow beam transmission technique. The principle is straightforward: in RT a fraction of the $\bar{n}$ beam (from $\sim 15\%$ to $\sim 25\%$, depending on the momentum $p_{\bar{n}}$) annihilates. By reconstructing the annihilation vertices it is possible to determine the number $\Delta N_{ann}(p_{\bar{n}}, z)$ of $\bar{n}$ of a given momentum $p_{\bar{n}}$, annihilating in the interval $(z, z+\Delta z)$, at a depth z in the target:

$$\Delta N_{ann}(p_{\bar{n}}, z) = \sigma_{ann}(p_{\bar{n}})\, I_{\bar{n}}(p_{\bar{n}}, z)\, \rho \mathcal{N}_A \Delta z \qquad (1)$$

where $\sigma_{ann}(p_{\bar{n}})$ is the $(\bar{n}, p)$ annihilation cross section at $p_{\bar{n}}$, $I_{\bar{n}}(p_{\bar{n}}, z)$ the flux of the $\bar{n}$'s of momentum $p_{\bar{n}}$ at the depth z, ρ the density of LH_2 and $\mathcal{N}_A$ the Avogadro's number. $I_{\bar{n}}(p_{\bar{n}}, z)$ is given by:

$$I_{\bar{n}}(p_{\bar{n}}, z) = I_{\bar{n}}(p_{\bar{n}}, 0)\, e^{-\sigma_T \rho \mathcal{N}_A z} \qquad (2)$$

where $I_{\bar{n}}(p_{\bar{n}}, 0)$ is the flux of $\bar{n}$ of momentum $p_{\bar{n}}$ at the entrance of the LH_2 target. Then:

$$\frac{\Delta N_{ann}(p_{\bar{n}}, z)}{\Delta z} = I_{\bar{n}}(p_{\bar{n}}, 0)\, \sigma_{ann}(p_{\bar{n}})\, \rho \mathcal{N}_A e^{-\sigma_T \rho \mathcal{N}_A z} \qquad (3)$$

From (3) it is clear that σ_T is simply deduced by the exponential slope of $\Delta N_{ann}(p_{\bar{n}}, z)/\Delta z$

This technique does not introduce systematic errors due to the measurement of $\bar{n}$ flux, of no importance in the extraction of $\sigma_T(\bar{n}, p)$, but needs a very careful study of the ''fiducial volume'' inside RT, in which the annihilations are considered.

A first trial of applying this technique was reported in Ref. [13]. The sample of annihilation events at disposal was small $(\sim 4 \times 10^4)$, and the $\bar{n}$ beam was an early version of that described here, with incident $\bar{p}$ of 300 MeV/c and a lower cut on the $\bar{n}$ momentum at 70 MeV/c. The fiducial volume inside RT was taken simply as a cylinder, 230 mm long and with a diameter of 130 mm, instead of a frustum of cone, which is the proper shape. The selection criteria for accepting the two tracks defining the vertex were quite loose and then some background survived in the final sample of events retained for the analysis of $\sigma_T(\bar{n}, p)$. These oversimplifications had two effects on the evaluation of the cross section. The use of a cylinder instead than a frustum of cone for the fiducial volume introduced a $\sim 20\%$ overestimation of the cross section and the presence of the background, tolerable for events with $p_{\bar{n}} >$ 140 MeV/c, introduced a larger effect for the lower momenta (up to a factor 3 for the point at 80 MeV/c).

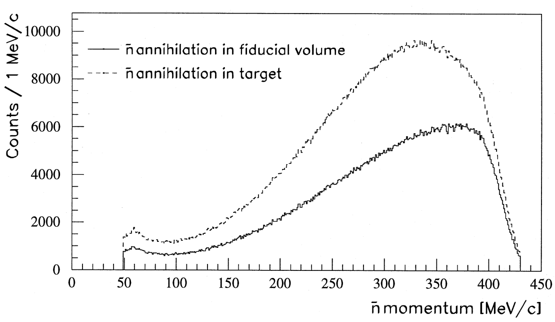

Fig. 1. $\bar{n}$ momentum distribution for annihilations reconstructed inside the fiducial volume (solid line, 1207920 events) and inside the overall reaction target (dotted line, 1874954 events).

Starting from these considerations, a new version of the $\bar{n}$ beam was designed and built, and a statistics ~ 50 times larger was collected.

In the present work the data taken in 1994 and 1995 have been analysed: the total sample of reconstructed annihilations in the geometrical volume was of $\sim 2 \times 10^6$ events, nearly half from 1994 data (SET94) and half from 1995 data (SET95). Thanks to this large number of events it was possible to map accurately the spatial distribution of the annihilation vertices inside RT and a deformation with respect to the expected frustum of cone, coaxial to RT, was found in both SET94 and SET95: this asymmetry was due to a drift of the $\bar{p}$ spot on PT. During the data taking the position of the spot was monitored and periodically corrected but not to the necessary precision and this effect produced an average misalignment of the cone of the outgoing $\bar{n}$'s.

In order to determine the correct axis and aperture of such a cone (and consequently of the fiducial volume) a first procedure (referred in the following as A) was applied to the vertex distributions of SET94 and SET95. We determined the spatial distributions of the $\bar{n}$ annihilation vertices recorded during the whole period of data taking in subsequent slices of RT, 1 cm thick. Afterwards we calculated the center of annihilations (weighted by the vertex density) for each slice. The centers were aligned within the errors on a straight line, passing through PT and parallel to the z-axis, but slightly displaced in x and y. From these values we determined the true geometry of the frustum of cone that took into account the $\bar{p}$ beam misalignment. The number of the survived events in the corresponding fiducial volume reduced to 1.2×10^6 (see Fig. 1). The quite small aperture of the frustum ($\sim 1.31°$) makes the evaluation of the transmitted $\bar{n}$'s quite free from the distortion due to the annihilations occurred after scattering, that were estimated by a dedicated Montecarlo program to decrease from $\sim 5\%$ at 50 MeV/c to 2% at 400 MeV/c.

Afterwards a second procedure (referred in the following as B) for the correction of the misalignment has been applied to both SET94 and SET95. More severe cuts on the quality of the $\bar{n}$ vertex and momentum reconstruction were applied and furthermore the effect of the misalignment was evaluated for each single run. The aperture of the frustum was reduced to 0.8°. As a consequence of these more severe constraints the number of the survived events in the fiducial volume reduced to $\sim 0.45 \times 10^6$. The results obtained with procedure B were in fair agreement with those obtained with procedure A, also if affected by larger statistical errors.

3. Experimental results

The total range of the $\bar{n}$ momentum has been divided in different intervals and the central value $p_{\bar{n}}$, has been attributed to each interval, as reported in the first and second columns of Table 1. For each sample of data and for each procedure (SET94A, SET94B, SET95A, SET95B) the annihilation vertex distribution along the beam axis (z-axis) has been fitted, as described in the previous section and from each slope the value of the total cross section $\sigma_T(p_{\bar{n}})$ has been evaluated. The fits were performed by means of the standard MINUIT code. It must be remarked that this procedure is quite free from systematic errors (possible bubbling of the LH_2 target, fluctuations of the electronics, ...) that may happen in long runs since, in addition to the continuous control, all the data corresponding to different momenta were taken at the same time.

Table 1
Total $\bar{n} - p$ cross section $\sigma_T(\bar{n}p)$

Momentum interval (MeV/c)	Central value $p_{\bar{n}}$ (MeV/c)	$\sigma_T(p_{\bar{n}})$ (barn)	stat. (barn)	syst. (barn)
49–59	54	0.657	±0.059	±0.020
59–70	64.5	0.417	±0.057	±0.026
70–90	80	0.363	±0.045	±0.019
90–110	100	0.443	±0.049	±0.019
110–130	120	0.379	±0.038	±0.017
130–150	140	0.306	±0.033	±0.014
150–170	160	0.285	±0.031	±0.015
170–190	180	0.305	±0.026	±0.018
190–210	200	0.303	±0.023	±0.014
210–230	220	0.284	±0.020	±0.018
230–250	240	0.269	±0.024	±0.010
250–270	260	0.262	±0.020	±0.013
270–290	280	0.244	±0.016	±0.012
290–310	300	0.239	±0.015	±0.018
310–330	320	0.227	±0.014	±0.019
330–350	340	0.247	±0.016	±0.021
350–370	360	0.222	±0.014	±0.013
370–390	380	0.206	±0.013	±0.017

In the region (50–110) MeV/c, where a significant fluctuation against a smooth trend was observed, many trials with different bin widths and bin central values were performed. All the different representations were consistent within the errors, showing the same fluctuation. A particular care was devoted to the check of all the instrumental effects that could introduce some bias in the data. A non-linearity of the TDC response, that could affect the $\bar{n}$ momentum reconstruction, done by a TOF measurement is excluded. A straightforward demonstration can be found by Fig. 1; the $\bar{n}$ spectrum exhibits a regular, non oscillating behaviour in the 60–110 MeV/c range. Fig. 2 shows the distribution

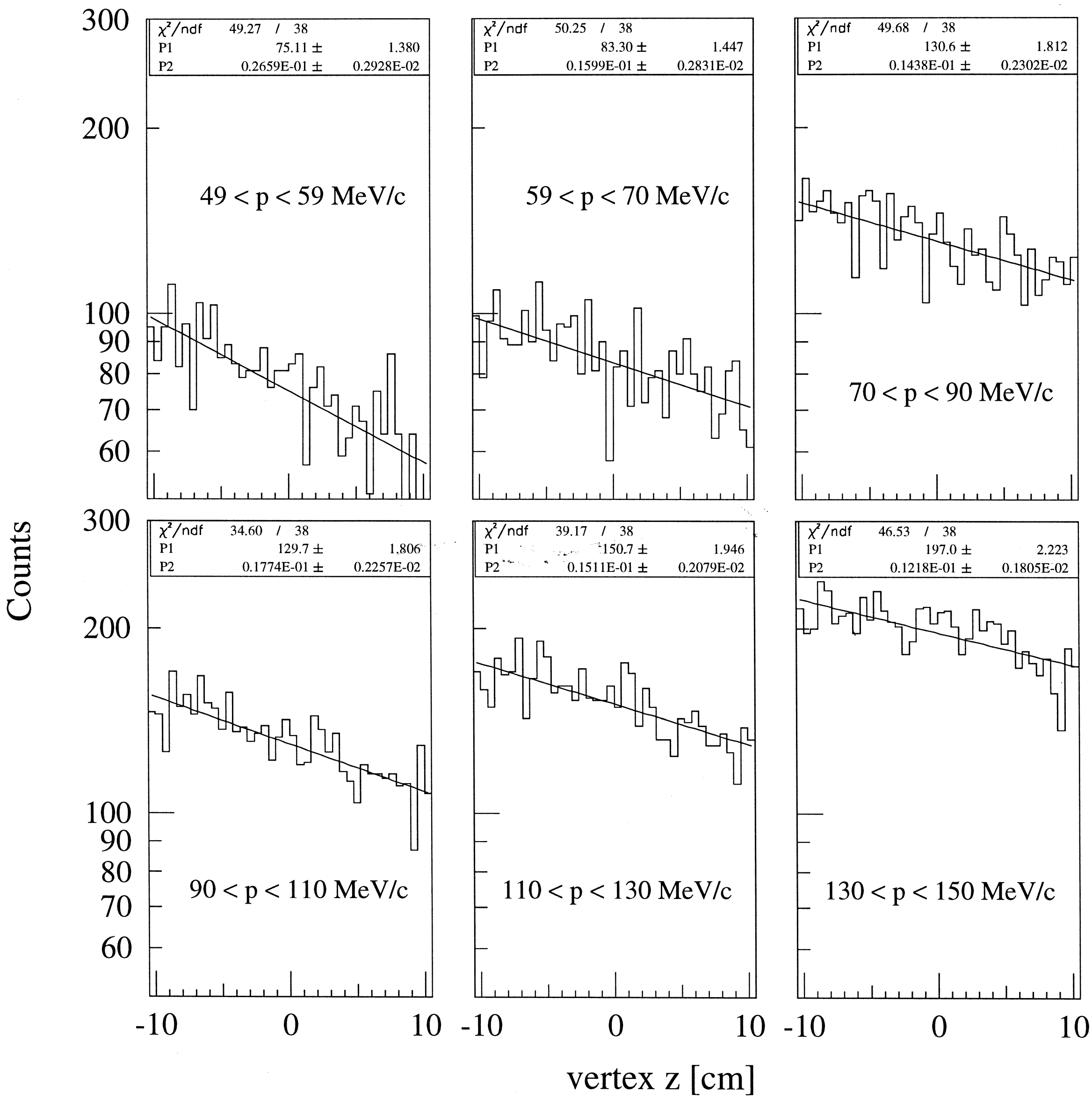

Fig. 2. Annihilation vertex distribution as function of $p_{\bar{n}}$ (semilog scale) in 6 momentum intervals: $54 \pm 5, 64.5 \pm 5.5, 80 \pm 10, 100 \pm 10, 120 \pm 10, 140 \pm 10$ MeV/c (data from SET94A, see text).

$dN_{\rm ann}(p_{\bar{n}},z)/dz$ for the first six values of $p_{\bar{n}}$, obtained with SET94A, that allows to appreciate the changes in the slope. Preliminary results based on this analysis were already published [14]. The values of the cross sections are reported in the third column of Table 1 together with their errors. We have chosen a constant bin width of 20 MeV$/c$ apart for the first two channels for which a width of 10 MeV$/c$ was chosen.

4. Discussion of the results

The $\sigma_T(\bar{n}p)$ of Table 1 are plotted in Fig. 3, as function of $p_{\bar{n}}$, together with the only existing published data of Ref. [6] and $\sigma_T(\bar{p}p)$ of Ref. [4]. The data of Armstrong et al. [6] start from 105 MeV$/c$. For a coherent comparison we have added in quadrature the statistical and systematic errors of both experiments. With equal binning our $\sigma_T(\bar{n}p)$ are affected by errors lower by $\sim 40\%$. The agreement with the OBELIX measurements in the range where they overlap is very good within the error bars, although the present data show a smoother behavior. Concerning $\sigma_T(\bar{p}p)$, there exist a large amount of data over 200 MeV$/c$ and they agree very well together (for an exhaustive discussion see Bendiscioli and Karzeev [15]). The curve of Fig. 3 is the best fit of the measurements of Bugg et al. [4], reported as representative of the hadronic contribution to $\sigma_T(\bar{p}p)$. It seems to become slightly higher than $\sigma_T(\bar{n}p)$ at the lower momenta ($\lesssim 200$ MeV$/c$). In the lower momentum region the OBELIX data show a trend quite anomalous, suggesting a dip around 80 MeV$/c$. We analyzed our data taking into account that we were already able to reproduce [8] very well our data on $(\bar{n}p)$ annihilation cross section ($\sigma_{\rm ann}(\bar{n}p)$) by an Effective Range (ER) Expansion technique with the values of the parameters given by Mahalanabis et al. [16]. We based our analysis on this parametrization, since the other parametrizations and models ([17], [18], [19], [20]), that we tried in order to reproduce $\sigma_{\rm ann}(\bar{n}p)$, gave results of worse quality. On the other hand the use of these parameters [8] for the description of $\sigma_T(\bar{n}p)$ gave a result not at all satisfactory ($\chi^2/ndf = 6.1$), as shown by Fig. 4. The agreement is even worse if we take out from the analysis the two data points at 64.5 and 80 MeV$/c$, in the hypothesis that they are wrong for some unknown reason. The χ^2/ndf increases to 10.6.

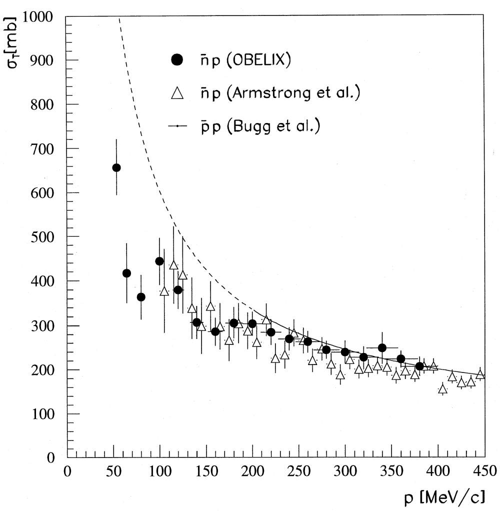

Fig. 3. Comparison of $\overline{N}N$ total cross section at low momenta: ●: $(\bar{n}p)$ present work, △: $(\bar{n}p)$ Armstrong et al. (Ref. [6]). The solid curve represents the fit of Bugg et al. to the $(\bar{p}p)$ data (Ref. [4]), the dashed part represents the extrapolation to the lower momenta.

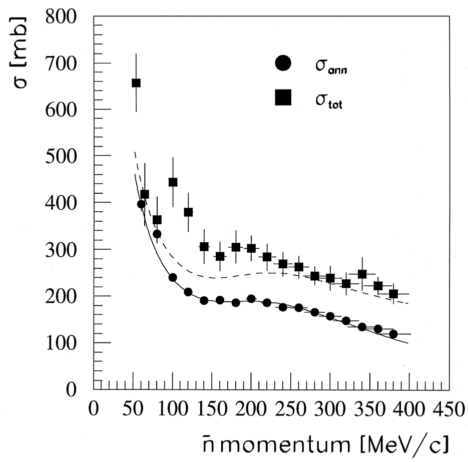

Fig. 4. Experimental values of the total (■: present work) and annihilation (●: Ref. [8]) $\bar{n}p$ cross sections. The solid curve represents the calculation of $\sigma_{\rm ann}(\bar{n}p)$ performed in Ref. [8], the dotted one the calculation of $\sigma_T(\bar{n}p)$ by using the same parameters.

We performed several trials to fit our $\sigma_T(\bar{n}p)$ data by adopting different truncations of the ER expansion and we found in all cases parameters providing satisfactory fits ($\chi^2/ndf \simeq 1.0$–1.4). On the other hand such parameters did not succeed to represent at all $\sigma_{ann}(\bar{n}p)$. In previous analyses it was tried to fit the data with a classical Breit-Wigner resonance in addition to the ER expansion parameters [14] but a more thorough inspection of the results showed that the conclusions were not unambiguous.

Therefore it seems impossible to find a set of parameters able to describe correctly at the same time both $\sigma_{ann}(\bar{n}p)$ and $\sigma_T(\bar{n}p)$. The reason is that the elastic cross section $\sigma_{el}(\bar{n}p) = \sigma_T(\bar{n}p) - \sigma_{ann}(\bar{n}p)$, shown by Fig. 5, exhibits an unexpected trend. A dip at low momenta is observed. The two points at 64.5 and 80 MeV/c are close to the lower bound imposed by the unitarity constraints for s-wave [21]:

$$\sigma_{el} \geq \frac{k^2}{4\pi} \cdot \sigma_T^2 \tag{4}$$

where k is the *c.m.* $\bar{n}$ momentum.

The vanishing of the elastic cross section is a quite rare, although possible, situation, whose more known manifestation is the Ramsauer–Townsend effect for the low energy electron scattering from atoms.

On the other hand these data allow to draw a firm conclusion concerning the relative contributions of the $I=0$ and $I=1$ components to the $(\bar{N}-N)$ interaction. To this purpose we compare the experimental value of $\sigma_{ann}(\bar{p}p)$ at 69.5 MeV/c with the experimental values of $\sigma_{ann}(\bar{n}p)$ and $\sigma_T(\bar{n}p)$ at the nearest momenta. We choose the momentum value 69.5 MeV/c since a measurement of $\sigma_{ann}(\bar{p}p)$ exists [5] and this momentum is lower than the threshold of the charge-exchange channel ($p_{\bar{p}} = 98$ MeV/c) but quite high in order to minimize the effects due to the Coulomb interaction [22]. A straightforward observation is that the value of $\sigma_{ann}(\bar{p}p)$ (615 mbarn) is more than 50% higher than $\sigma_T(\bar{n}p)$ ($\sim$ 400 mbarn) and 70% higher than $\sigma_{ann}(\bar{n}p)$ ($\sim$ 350 mbarn). More quantitatively, we may compare the value of $\sigma_T(\bar{p}p)$ obtained by the fit of Ref. [4] and of $\sigma_T(\bar{n}p)$ obtained by the fit with ER approximation. To that purpose we remind that, even though not good for the physical interpretation, this fit may be considered just as a good numerical parametrization. At 70 MeV/c we find for the ratio $R \equiv \sigma_T(\bar{p}p)/\sigma_T(\bar{n}p)$ a value of 1.78 $\pm$0.25. By using the simple expression:

$$R \equiv \frac{\sigma_T(\bar{p}p)}{\sigma_T(\bar{n}p)} = \frac{\sigma_T(I=0) + \sigma_T(I=1)}{2\,\sigma_T(I=1)} \tag{5}$$

in which $\sigma_T(I=0)$ and $\sigma_T(I=1)$ are the total cross sections related to the $I=0$ and $I=1$ components of the $(\bar{N}-N)$ interaction we observe a strong dominance of the $I=0$ component at low momenta. In fact the ratio $\sigma_T(I=0)/\sigma_T(I=1)$ is 2.5 ± 0.4 at 70 MeV/c, to be compared to 1.1 ± 0.1 at 300 MeV/c. If we neglect the data points at 64.5 and 80 MeV/c and we use the corresponding ER parametrization to $\sigma_T(\bar{n}p)$, we find $R = 1.55 \pm 0.22$ and $\sigma_T(I=0)/\sigma_T(I=1) = 2.1 \pm 0.3$. We consider the value $R = 1.78$ the more appropriate; a circumstance strengthening this conclusion is that the experimental ratio between $\sigma_{ann}(\bar{p}p)$ and $\sigma_{ann}(\bar{n}p)$ at 70 MeV/c is 1.76 ± 0.11 and it is simply the ratio between two experimental numbers, not resulting from extrapolations and parametrizations of data showing perhaps an unexpected behaviour.

Following Dover et al. [1], this effect could be a manifestation of the coherence of the ρ, ω, δ and σ meson exchange in the central and tensor terms of the $(\bar{N}-N)$ medium range force. An indirect indication of such an effect following measurements in light nuclei was previously reported in Ref. [10]. A more appealing and fundamental explanation of the

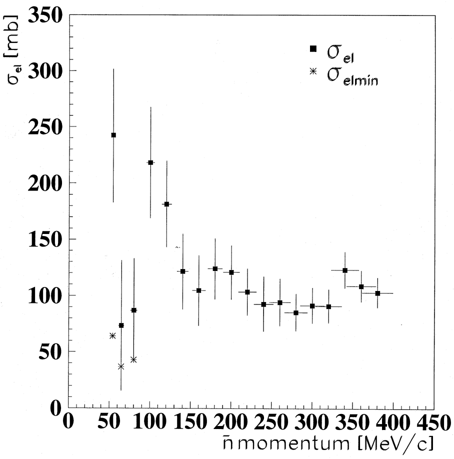

Fig. 5. Elastic $\bar{n}p$ cross section (■) as a function of $p_{\bar{n}}$, obtained from the difference between total (present results) and annihilation (Ref. [8]) values; the asterisks represent the lower limits of the elastic cross section due to the unitarity constraints.

dominance of the $I=0$ channel was suggested [23]. It is based on the observation that the $I=0$ channel has the same isospin quantum number of the QCD vacuum. Then both quarks and gluons contribute to the interaction, whereas in the $I=1$ channel only quarks may interact. The phenomenon is manifesting itself at low momenta in the $(\bar{N}-N)$ interaction since only *s*- and *p*-partial waves contribute. The idea that explanations well accepted in the high energy domain (deep inelastic scattering) may hold also at low energy seems to be supported by some recent observations for the $(\bar{N}-N)$ system [24].

5. Conclusions

The total $\bar{n}p$ cross section has been measured in the range from 50 to 400 MeV$/c$. Below 100 MeV$/c$ these are the first measurements, while over 100 MeV$/c$ the agreement with the existing data is good.

We observe an anomalous behaviour of $\sigma_T(\bar{n}p)$ with respect to $\sigma_{\rm ann}(\bar{n}p)$. The parameters of the ER expansion that reproduce well $\sigma_{\rm ann}(\bar{n}p)$ are unable to reproduce in a satisfactory way $\sigma_T(\bar{n}p)$. This unexpected behaviour seems related to the elastic channel. We recall that an anomalous behaviour of the elastic channel in the $(\bar{p}p)$ system appeared in the real-to-imaginary ratio of the forward scattering amplitude ρ [25]. Even if based on calculations whose validity may be questioned at low momenta, the ρ-parameter showed an irregular behaviour below 300 MeV$/c$.

It would be appealing to relate the observed anomaly below 100 MeV$/c$ to the presence of a near-threshold resonance as suggested in the past [26]; this resonance should be an interesting above threshold metastable state, close to the below threshold state seen by the FENICE Collaboration in (e^+e^-) collisions [27].

From the comparison between $\sigma_T(\bar{n}p)$ and $\sigma_T(\bar{p}p)$ a dominance of the $I=0$ channel of the $(\bar{N}-N)$ interaction over the $I=1$ one at low momenta is clearly observed.

Unfortunately these interesting data cannot be remeasured with better statistics in the short term, since the CERN LEAR complex has been dismantled. In the future the only machines in sight for this kind of measurements [28] are the japanese hadronic machine JHF and the slow antiproton ring AD at CERN.

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