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MEASUREMENT OF THE $\bar{p}p \rightarrow \bar{n}n$ CROSS-SECTION AT LOW $\bar{p}$ MOMENTA

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ABSTRACT

First measurements of the differential cross-section are presented for $\bar{p}p \rightarrow \bar{n}n$ at LEAR in the momentum range between 180 and 600 MeV/c. The differential cross-sections show a forward peaking followed by a smooth drop-off. No indication of the 'bump-dip' structure reported at higher momenta has been observed. The angle-integrated charge-exchange cross-sections are determined down to $E_{\text{cm}}^{\text{cm}} = 6.6$ MeV.

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1. INTRODUCTION

The $\bar{p}p \rightarrow \bar{n}n$ charge-exchange reaction is thought to be predominantly mediated by one-pion exchange. It is, therefore, an essential ingredient for the understanding of the long-range part of the antinucleon–nucleon interaction in the one-boson exchange models.

More generally one observes that the charge-exchange amplitude is given by the difference of the isospin 1 and 0 amplitudes, while the elastic amplitude is proportional to the sum. Therefore, a comparison of the two respective cross-sections provides a test of the isospin dependence of the antinucleon–nucleon interaction. This is especially sensitive at low momenta, where only s- and p-waves contribute significantly to the interaction.

A ‘bump-dip’ structure has been reported in the angular distributions at higher momenta by previous measurements [1, 2]. This was interpreted as an interference of the one-pion-exchange amplitude with a constant background amplitude [3]. The forward angles therefore contain some interesting information on the relative importance of these amplitudes and will put a constraint on models of the $\bar{N}N$ interaction. The data presented here were taken at 590, 505, 287 and 183 MeV/c, providing the first charge-exchange data below 300 MeV/c.

2. EXPERIMENTAL SET-UP

The experiment was performed at the low-energy antiproton ring (LEAR) at CERN. The experimental set-up is shown in fig. 1. The $\bar{p}$ beam was extracted from LEAR at 606, 306, or 202 MeV/c. A carbon or CH_2 degrader, placed about 20 m upstream from the target, was used to reach momenta below the primary momenta. Two detectors, SD and TD, and the target were inside a 50 cm radius vacuum tank in order to reduce multiple Coulomb scattering and background. The beam was defined by a coincidence of SD and TD, each of which consisted of a 50 μm thick scintillator. Two liquid-hydrogen targets, 20 mm and 7 mm thick, were used. The 20 mm target was used for momenta above 220 MeV/c and the 7 mm one for lower momenta. At several higher momenta data were also taken with the thin target in order to make a cross check of its thickness.

Detectors in the forward region were a multiwire proportional chamber (MWPC), a hodoscope array (FHD), and a ring of antineutron detectors (ANC). Above, below, and behind the vacuum tank additional scintillation detectors were mounted, which covered 70% of the solid angle for a measurement of the annihilation into charged pions. The MWPC, FHD, and ANC covered an angular region from $\pm 2.5^\circ$ to 75° in the horizontal plane and from -10° to $+10^\circ$ in the vertical direction. Both the FHD and ANC consisted of 32 modules each with an angular width of 5° in the horizontal plane, the centre of the first module being 5° from the beam line.

Each ANC module consisted of alternating sheets of 4 mm thick iron and 6 mm thick scintillator (Altustipe UV15105), with a total thickness of 50 cm. Each module had an active area of 6 cm $\times$ 20 cm at the front face, and expanded in both height and width in order to cover a constant solid angle to the $\bar{n}$'s coming from the target. The scintillator was read out via two fast wavelength shifter bars (Altustipe 390B), each 10 mm thick, placed at the top and the bottom. With this combination of scintillator/wavelength-shifter a time resolution of 1.7 ns (FWHM) was achieved. This allowed a sufficient separation of $\bar{n}$ and γ 's (resulting from π^0 decay) by time of flight (TOF) as shown in fig. 2. Details of the antineutron detectors can be found elsewhere [4].

3. PARTICLE IDENTIFICATION

Antineutrons are defined by a set of consecutive selection criteria. First, a hit in one of the ANC modules with correct TOF and no early $\pi^\pm/K^\pm$ or $\bar{p}$ signal in the FHD is required. If any other hodoscope fired, only those events showing a pion signal properly correlated with the $\bar{n}$ -annihilation in the ANC are accepted. This eliminates the events in which a $\bar{p}$ scatters at a large angle and annihilates in the vacuum-tank wall. In this case a π could enter the ANC without passing through the FHD or the sector of the MWPC belonging to the ANC module.

The $\bar{n}$ scattering angle is determined from the horizontal and vertical coordinates which are determined as follows. The position of the hit ANC module gives the cylindrical angle in the horizontal scattering plane. The vertical coordinate of the $\bar{n}$ -annihilation star is obtained from the difference of the ADC and TDC signals of the two tubes of an ANC module. The angular resolution achieved depends on the scattering angle and varies from $\pm 4.4^\circ$ in the forward direction (the first ANC module), $\pm 3.4^\circ$ for the second data point, down to $\pm 2.7^\circ$ for larger angles. For events where two or more ANC modules fired (less than 35% of all events) the cylindrical angle is randomized over the angular range covered by these modules (which does not affect the angular resolution appreciably). We have restricted the vertical acceptance to about 75% of the full geometrical height of the calorimeters to avoid systematic errors due to edge effects. In order to reject $\bar{p}$'s passing through the gap between two FHD slabs and annihilating in one of the ANC modules, events are rejected if the MWPC shows a hit within ± 8 cm of the calculated $\bar{n}$ -track.

In the kinematical region where both $\bar{n}$ and n could principally be observed, less than 5% of the events showed $\bar{n}$ - n coincidences with the correct opening angle. From this we conclude that the n -detection efficiency is sufficiently low to assume pure $\bar{n}$ -detection as expected.

The efficiency of the detectors depends on two factors: the probability of the $\bar{n}$ -annihilation in the module and the probability of detecting it once it does annihilate. The annihilation probability was determined by two different measurements. In the first, the charge-exchange cross-section was measured with one of the ANC modules in an $\bar{n}$ -beam of about 800 MeV/c. This $\bar{n}$ -beam was produced by the charge-exchange reaction using a $\bar{p}$ -beam at 800 MeV/c on a CH_2 target. By changing the thickness of iron the $\bar{n}$ -annihilation probability is determined to be $92 \pm 8\%$ for the standard module (20 cm iron). The same probability was obtained from a Monte Carlo calculation. The second measurement to determine the $\bar{n}$ -annihilation probability was done using the actual set-up for the experiment. The 3rd, 5th, 7th, and 9th modules of one side of the beam have only 0, 1/4, 1/2, and 3/4, respectively, of the normal amount of iron. The count rates measured with each of these modules were compared with those of its full partner at the equivalent angle on the opposite side of the beam. This leads to an annihilation probability of $99 \pm 1\%$. In this way we also measured the $\bar{n}$ -Fe and $\bar{n}$ -scintillator annihilation cross-section for $\bar{n}$ -momenta between 200 and 300 MeV/c, where no data existed before. We obtained $\sigma_{\bar{n}\text{Fe}} = 1030 \pm 700$ mb and $\sigma_{\bar{n}\text{Sc}} = 253 \pm 49$ mb (statistical errors only).

The detection efficiency for an $\bar{n}$ -annihilation was estimated to be over 95% by the following methods. Since part of the energy released in the $\bar{n}$ -annihilation on a nucleus goes to nuclear fragments and pions not seen, the pulse height measured in one of the ANC modules can be low. In order to estimate the fraction lost due to the finite threshold of our discriminators, we summed up the pulse-height spectra of neighbouring calorimeter modules. From the shape of these summed pulse-height spectra we determined the hardware cut-off and estimated the

detection efficiency of an $\bar{n}$ -annihilation. The results agree well with those obtained from the Monte Carlo program. The detection efficiency for minimum ionizing particles was measured to be 99% using 250 GeV/c muons. Combining these results, the detection efficiency for antineutrons in the ANC was determined to be $98 \pm 2\%$.

The module-to-module variation was measured by means of charged pions defined by their signals in the FHD and MWPC. These variations were found to be about 10% and have been corrected for in the final results.

4. DISCUSSION OF THE EXPERIMENTAL RESULTS

The differential cross-sections at 590, 505, 287, and 183 MeV/c are shown in fig. 3 (the error bars indicate only statistical uncertainties). The precision of the overall normalization is estimated to be $\pm 5\%$. This error is due partially to the uncertainty in the detection efficiency of the $\bar{n}$ -annihilation in the calorimeters and partially to uncertainties in the cuts for the background reduction. An additional systematic uncertainty of about $\pm 5\%$ is assumed for the smallest angle data point because of beam annihilations downstream of the MWPC in the anticounters BA1 and BA2. At 183 MeV/c, this effect dominates the error on the two smallest angle points.

Earlier data on the differential cross-section at higher momenta [2] showed a sharp peak followed by a little dip or shoulder (fig. 3). The data presented here (590 and 505 MeV/c) show the same peaking at small angles followed by a gentle shoulder, with no indication of a 'bump-dip' structure. At lower momenta (287 and 183 MeV/c) the data show only a smooth drop-off from small to larger angles.

A comparison of the calculations with four models are shown with the 590 and 287 MeV/c data: Nijmegen [5], Paris [6], Dover-Richard [7] and Myhrer [8]. The pronounced 'bump-dip' structure predicted by the Paris and the Dover-Richard model is not observed. The boundary-condition model of Myhrer and the Nijmegen coupled-channel calculations give a better description of the data.

Figure 4 depicts the cross-section integrated over all angles, compared with the measurements of Hamilton et al. [9]. Overall agreement above 260 MeV/c is good. At lower momenta our cross-sections fall off faster than those of Hamilton et al., which suffer from a poor momentum resolution due to the 8 cm long liquid-hydrogen target they used.

In summary, we have presented the first charge-exchange differential cross-sections below 300 MeV/c. The data provide a clear preference of the boundary-condition model and the coupled-channel calculation to the Paris and Dover-Richard models. It will be very informative to trace the origin of this deviation theoretically, which might provide a deeper insight into these otherwise very successful models.

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Figure captions

Fig. 1 : Experimental set-up: top view

Fig. 2: The TOF spectrum of $\bar{n}$ and γ in the first forward calorimeter module at 600 MeV/c, the highest momentum of this experiment. The separation is even better at lower momenta, owing to the longer TOF of the $\bar{n}$.

Fig. 3: The differential charge-exchange cross-sections at 590, 505, 287, and 183 MeV/c. The full circles are the data from this experiment, the open triangles represent the data of Nakamura et al. [2]. The curves give the predictions of different models. The solid, dashed, dotted, and dash-dotted lines represent the models of Nijmegen [5], Paris [6], Dover-Richard [7], and Myhrer [8], respectively.

Fig. 4: The angle-integrated charge-exchange cross-section as a function of the beam momentum and the c.m. energy of the $\bar{n}n$ system. The full circles show the data from this experiment, the open triangles represent the data from Hamilton et al. [9]. The horizontal error bars give the FWHM of the momentum resolution. No errors for the lowest two data points were given by the authors of ref. [9].

Fig. 1

Fig. 2

Fig. 3

Fig. 4