EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/89-105

22 August 1989

**MEASUREMENTS OF THE ANTIPROTON-PROTON
ANNIHILATION CROSS-SECTION IN THE BEAM MOMENTUM RANGE
BETWEEN 180 AND 600 MeV/c**

W. Brückner¹, B. Cujec⁵, H. Döbbling^{2,a)}, K. Dworschak¹, F. Güttner¹,
H. Kneis^{1,a)}, S. Majewski^{2,b)}, M. Nomachi^{2,c)}, S. Paul¹, B. Povh¹,
R.D. Ransome⁴, T.-A. Shibata³, M. Treichel^{1,d)} and Th. Walcher³

- 1 Max-Planck-Institut für Kernphysik, Heidelberg, Fed. Rep. Germany.
- 2 Physikalisches Institut der Universität, Heidelberg, Fed. Rep. Germany.
- 3 Institut für Kernphysik der Universität, Mainz, Fed. Rep. Germany.
- 4 Rutgers University, Piscataway, NJ, USA.
- 5 Université Laval, Québec, Canada.

ABSTRACT

The antiproton-proton annihilation cross-section has been measured for antiproton beam momenta between 180 and 600 MeV/c. The annihilation cross-section is found to be larger than the geometrical limit of the s-wave inelastic cross-section in this momentum range, indicating a significant p-wave contribution even at low momenta.

(Submitted to Zeitschrift für Physik A)

Present addresses:

- a) PSI, Villigen, Switzerland.
- b) University of Florida, Gainesville, FL, USA.
- c) KEK, Tsukuba, Ibaraki, Japan.
- d) Neuchâtel University, Switzerland.

1. INTRODUCTION

In this paper we present the results of a measurement of the antiproton-proton annihilation cross-section for the beam momenta between 180 and 600 MeV/c. This measurement was undertaken as part of a series of antiproton-proton cross-section measurements [1–5] at the Low-Energy Antiproton Ring (LEAR) at CERN. The annihilation cross-section below 300 MeV/c is measured systematically for the first time in the present experiment. A brief report on the measurement of the annihilation cross-section between 400 and 600 MeV/c has already been given elsewhere [4] and the upper limit of a possible resonance is discussed there. In this paper we present the general trends of the momentum dependence of the annihilation cross-section between 180 and 600 MeV/c and discuss its physics implications.

The goal of the present measurement is to investigate the s- and p-wave contributions to the annihilation cross-section at small momenta. In an earlier analysis of the differential elastic cross-section between 180 and 300 MeV/c [2] we have extracted phase shifts and determined elastic and inelastic cross-sections for s- and p-waves. In this analysis a significant contribution of the p-wave was found particularly in the inelastic [annihilation + charge-exchange ($\bar{p}p \rightarrow \bar{n}n$)] cross-section even at very small momenta. This differs from nucleon-nucleon scattering where the p-wave contribution to the total cross-section is less than 10% at 300 MeV/c. However, a more direct experimental approach is to measure the annihilation cross-section and compare it with the geometrical limit of the s-wave inelastic cross-section, i.e. the so-called black disk value ($\eta_0 = 0$) of $\pi(1/k)^2$. As we shall see, the annihilation cross-section alone, without adding the charge-exchange cross-section, already exceeds the s-wave geometrical limit and therefore we can conclude that there exists a significant p-wave contribution.

From the theoretical point of view the potential models with boson exchanges and phenomenological annihilation potentials have had some success in reproducing different cross-sections. On a deeper level, quark rearrangement models have been applied to describe the annihilation. However, so far only specific meson annihilation channels have been described successfully. A crucial test of the quark rearrangement models would be to reproduce the total annihilation cross-section, which amounts to 70% of the total cross-section at small momenta. The annihilation cross-section in the momentum region below 300 MeV/c is essential for this test because here only s- and p-waves contribute, thus simplifying the calculations.

The annihilation cross-section around 500 MeV/c has been measured several times [4, 6–14] in order to search for the X(1935) (formerly S) resonance [15, 16], but the measurements below 300 MeV/c are scarce and inaccurate [17–20]. This was due to the poor quality of antiproton beams at low momenta before LEAR. The intense antiproton beam from LEAR, with a small emittance and no pion contamination, made it possible to extend the measurements to momenta as low as 180 MeV/c. The technical details of the apparatus have been reported elsewhere [5].

2. EXPERIMENTAL METHOD

2.1 The beam line and the degrader

The high-quality antiproton beam from LEAR is a prerequisite for the present measurement. The beam transport system between LEAR and the experimental set-up, however, is equally important for a precision measurement of the cross-section because the beam momentum is scanned during the measurement over a wide range. The components of the beam line are shown in Fig. 1. After extraction from LEAR the antiproton beam is focused at the intermediate focus point F1, which is 20 m upstream of the experimental set-up. The beam line between F1 and the experimental set-up is achromatic and consists of two dipole magnets, two sets of triplet quadrupole magnets, and a quadrupole magnet. An additional small dipole magnet D3 serves for vertical steering. The

emittance of the antiproton beam at F1 is 5π mm·mrad in the horizontal direction and 20π mm·mrad in the vertical direction, with a momentum spread of 0.1%. The intensity of the antiproton beam used in the present measurement is typically 2×10^5 per second at F1.

The vacuum of the antiproton extraction beam line is terminated by a 100 μ m thick aluminium foil at 5 cm upstream of F1. A degrader [21] is placed at F1 in order to reach the beam momenta between the extraction momenta which have a step width of about 50 MeV/c. The degrader used for the beam momenta above 400 MeV/c consists of two wheels on each of which there are 11 carbon blocks of different thicknesses. By rotating these wheels an appropriate combination of the two carbon blocks can be selected. For the beam momenta below 300 MeV/c a varying number of 200 μ m thick polyethylene foils are used.

The beam momentum is measured by time of flight over 20 m between F1 and the experimental set-up. For the beam momenta above 400 MeV/c a 5×5 cm² plastic scintillator with 1 mm thickness is placed at F1. The beam position at F1 is monitored by a multiwire proportional chamber (MWPC). For the beam momenta below 400 MeV/c a 17 mm diameter plastic scintillator of 50 μ m thickness is used instead. After F1 the beam passes through a 35 cm air gap and a 125 μ m thick Mylar window, and enters a vacuum tube which is connected to the apparatus.

2.2 Apparatus

Cross-sections of the apparatus in the horizontal and vertical planes are shown in Figs. 2a and 2b, respectively. The details of the apparatus are described in Ref. [5]. The essential elements used for the measurement of the annihilation cross-section are the beam-defining detectors SD and TD, and the plastic scintillator hodoscopes covering the vacuum tank.

Two plastic scintillators of 50 μ m thickness detect the antiproton before the target. The SD, a 17 mm diameter scintillator, is viewed by two photomultipliers and is located 60 cm from the target. The start signal for the time of flight measurement is taken from this detector. The time resolution is 500 ps (FWHM). The TD, a 7 mm diameter scintillator, is 15 cm upstream of the target and is viewed by a single photomultiplier. The incident antiproton beam is defined and counted by a triple coincidence of F1, SD, and TD.

The liquid-hydrogen target shown in Fig. 3 is placed in the centre of the 1 m diameter vacuum tank which has 1 cm thick aluminium walls. Two target cells of different thicknesses are used, depending on the beam momentum. The cell of the thick target is a vertical cylinder of 2 cm diameter, 45 mm in height, made of 100 μ m thick Mylar walls. The cell of the thin target is a 7 mm thick planar disk made of a 12 μ m thick Mylar wall on the upstream side and a 25 μ m thick one on the downstream side. Empty targets with identical constructions are used for the background measurements. These four target cells are mounted on a vertical bar and can be moved up and down in the vacuum by a remote control.

Charged mesons from antiproton annihilation are detected by the plastic scintillator hodoscopes surrounding the vacuum tank. The slabs of the upper and lower hodoscopes (UHD/LHD) in Fig. 2 are of trapezoidal shape and are at a distance of 69 cm from the target. The backward hodoscope (BHD) consists of 8 slabs of rectangular shape placed at 80 cm from the target. The forward hodoscope (FHD) is made of 32 slabs, each of which covers 5° in the horizontal plane, and is located at 66 cm from the target. The fraction of the solid angle covered by each hodoscope is 54% (U/LHD), 9.6% (BHD), and 9.6% (FHD), for a total 73% of 4π .

The gamma-rays from π^0 are converted to electron-positron pairs in the wall of the vacuum tank with the average probability of 6%. The all-neutral channels such as $\pi^0\pi^0\pi^0$ are detected if at least one gamma-ray is converted in the region covered by the hodoscopes. The efficiency and acceptance of π^0 detection are included in the simulation program which is described later.

A 3 cm square, 3 mm thick scintillation detector (BAC) located on the beam axis 70 cm downstream of the target is used to veto antiprotons that did not interact strongly in the target. The cylindrical MWPC is used to monitor the beam profile. It consists of two wire planes which are inclined at 24° to each other. The spatial resolution is 2 mm in the horizontal direction and 5 mm in the vertical direction.

2.3 Electronics and trigger logic

Each slab of the upper/lower hodoscope, the backward hodoscope, the forward hodoscope, is viewed by two photomultipliers, one at each end. Signals from each photomultiplier are split into two: one is sent to the pulse-height discriminator and the other to the analog-to-digital converter (ADC). The signals which have passed the discriminator are fed to the ECL coincidence unit where the coincidence of signals from two corresponding photomultipliers is required. The signals from these coincidence units are summed up to 6 groups according to the geometrical location of the hodoscopes and sent to two stages of the programmable logic units (PLU, LeCroy 4508). The trigger is accepted when the combination of these input signals matches the condition which has been downloaded from the host computer to the PLU. The data taking is performed by a CAMAC auxiliary crate controller ACC 2180 with a host computer PDP-11/34.

2.4 Momentum scan

The momenta of the beam extracted from LEAR for the scan above 400 MeV/c are the following: I: 605, II: 547, III: 527, and IV: 467. These are the momenta before the degrader. The beam is then degraded with the carbon degrader described in Section 2.1 with a step of 5 MeV/c near 500 MeV/c, and 10 MeV/c elsewhere. In each of these four sets the highest beam momentum in the beam line shown in Fig. 1 is obtained without using the degrader, and the lowest degraded momentum is I: 537, II: 475, III: 468, and IV: 411, respectively. Regions I and IV are scanned once, region II twice, and region III three times.

The momenta of the beam extracted from LEAR for the measurement below 400 MeV/c are the following: V: 397, VI: 305, VII: 243, and VIII: 190. The measurement below 400 MeV/c is performed at each extraction momentum without the degrader and at one degrader momentum to fill the gap. Thus, the beam momenta after the degrader are 397, 358, 305, 278, 243, 221, and 190 MeV/c. The beam further loses the momentum in the detectors in front of the target and also in the target. The beam momenta at the centre of the target are listed in Tables 1 and 2.

Two types of triggers are used in the present measurement: the 'beam' trigger to monitor the beam profile and the 'reaction' trigger to record the antiproton-proton reaction events. The beam is defined by a triple coincidence:

$$\text{'BEAM'} = F1 \cdot SD \cdot TD .$$

In the 'beam' trigger all the events that satisfy the 'beam' condition are recorded. The 'reaction' trigger requires no hit in the beam anticounter (BAC) and at least one hit in the hodoscopes:

$$\text{'REACTION'} = \text{'BEAM'} \cdot \overline{\text{BAC}} \cdot \text{PLU} .$$

One spill of the beam extraction from LEAR lasts ~ 1 hour. In each spill the data are taken with the following combinations of the targets and the triggers: (F·B), (F·R), (E·B), (E·R), and (E·B) in sequence, roughly for 3, 30, 3, 20, and 3 minutes, respectively, where F means the full target, E the empty target, R the 'reaction' trigger, and B the 'beam' trigger.

3. ANALYSIS AND RESULTS

3.1 The stability of the beam and the beam flux normalization

The time of flight of the antiproton beam between F1 and SD is shown in Fig. 4 for the nominal momentum of 190 MeV/c. The FWHM is 3 ns, corresponding to 0.9% in $\Delta p/p$. At 500 MeV/c $\Delta p/p$ is 0.8%. The antiproton momentum spread of the cross-section measurement is determined by the convolution between the incident beam momentum width and the beam energy loss in the target. However, the latter becomes dominant at low momenta: below 400 MeV/c with the thick target and below 250 MeV/c with the thin target.

The transmission rate between F1 and SD varies with different beam momenta because the multiple Coulomb scattering in the material around F1 and in the degrader increases at low momenta. It is well reproduced by a calculation with the multiple Coulomb scattering and the acceptance of the beam line. The transmission rate, therefore, provides a good monitor of the stability of the whole beam transport system. In the final analysis we use only those spills where the transmission rate does not deviate from the average value by more than 1%. The variation of the annihilation cross-section due to the beam instability is evaluated to be 0.6% by repeated measurements at the identical momenta [4].

A fraction of the antiproton beam annihilates in SD or TD, giving a large pulse height in the appropriate detector. In this case the charged pions generated in the annihilation could travel 50 cm and hit TD or SD, respectively, falsely fulfilling the triple coincidence condition for the beam definition. In order to eliminate these events an ADC cut is applied to SD and TD. The scaler values of the incident beam flux in the 'reaction' trigger runs are accordingly corrected by analysing the data in the 'beam' trigger runs with the same ADC cut on SD and TD. The precision of the beam flux measurement, after applying this correction, is $\pm 1\%$.

3.2 Identification of the antiproton annihilation in the target

The identification of an antiproton in the vicinity of the target is based on the time of flight and the pulse height of charged mesons detected with the plastic scintillator hodoscopes surrounding the vacuum tank. The annihilation is identified if at least one of the mesons is detected in the hodoscopes. Figure 5a shows a TDC-ADC scatter plot of one slab of the upper/lower hodoscope at the antiproton momentum of 297 MeV/c. A cluster of the charged mesons from the annihilation in the target is clearly seen at around the TDC channel 330. The late signals are charged mesons from the antiproton annihilation in the beam anticounter, the forward hodoscope, the antineutron calorimeter, or the vacuum tank wall. Since these materials are at least 60 cm away from the target these events can be eliminated on the basis of the time of flight. Figure 5b shows a TDC-ADC scatter plot for one of the slabs of the forward hodoscope at the same beam momentum. In this plot the elastically scattered antiprotons are also seen with a large height. In the forward hodoscope the antiproton annihilation in the target is identified using both TDC and ADC information. The annihilation in TD or in the Mylar walls of the target cell cannot be eliminated with these methods. This effect is corrected for by the background subtraction with the empty target runs.

3.3 Subtraction of the background with empty target runs

As mentioned in Section 2.4 the empty target runs are interleaved with the full target runs in order to subtract the background due to annihilations in the materials near the target. Figure 6 shows the fraction of the beam annihilation which is the number of the annihilation events divided by the incoming beam flux. In the figure the annihilation rates with the thick and thin full targets as well as the corresponding empty targets are shown. The annihilation rate with the empty target is only several per cent of that with the thick full target, and does not exceed 20% of that with the thin full

target. The apparatus is designed to minimize heavy materials around the target. The experimentally confirmed low background indicates that the apparatus is functioning as designed.

The rate of antiproton annihilation in the material downstream of the target is slightly different for full and empty target runs because of the beam momentum loss in the hydrogen. A correction for this effect is made in the background subtraction procedure by using the momentum dependence of the fraction of the beam annihilating in the empty target runs.

3.4 The effect of the antiprotons stopping in the vicinity of the target

The full width of the momentum distribution of the antiproton beam in LEAR is about 0.1%. It becomes larger in the extracted beam, particularly at low momenta. The tail of the momentum distribution caused by the straggling in the degrader at F1 is eliminated by the momentum acceptance of the beam line over 20 m and by the time of flight cut. The momentum tail due to the straggling in SD is also eliminated by the cut on the time of flight between SD and TD. Therefore, the straggling which could cause the stopping around the target is due to TD and the target itself.

The effect of the antiproton beam stopping in the liquid hydrogen or in the Mylar foils at the end of the target cell is calculated to be less than 0.5% of the annihilation in flight in the full target, using the Vavilov distribution [22]. The scaling parameter in this distribution is the ratio between the first term in the Bethe-Bloch formula for the energy loss and the maximum possible energy loss of the antiproton in a single collision with a free electron. Since the value of this ratio is large in the present experiment, the Vavilov distribution can be well approximated by a Gaussian distribution.

The antiproton loses most of the kinetic energy when it is elastically scattered at large angles in the liquid hydrogen, so that it stops in the target and annihilates there. This effect is corrected for in the evaluation of the annihilation cross-section. For the antiproton beam momentum of 190 MeV/c the critical scattering angle with the thin target is 45° in the lab system: the probability of the antiproton coming out of the target drops for larger angles. The correction to the annihilation cross-section for this effect is evaluated using the differential elastic scattering cross-section reported in Ref. [2]. The corrections are listed in Table 1.

3.5 Corrections for the solid-angle acceptance and the pion time of flight cut efficiency

The total solid-angle acceptance of the hodoscopes for charged mesons is 73% of 4π . An annihilation event is identified if at least one charged particle is detected in these hodoscopes. Therefore, the efficiency of detecting the annihilation events is substantially higher than 73%, and depends on the multiplicity distribution of the charged mesons. For each multiplicity channel and neutral mesons the events are generated according to the phase space with the CERN simulation program FOWL [23]. The probability of detecting at least one charged particle is evaluated with the actual geometrical configuration of the hodoscopes. The total efficiency is then determined by applying the weights according to the multiplicity distribution in Refs. [6], [13], and [24]. Below 300 MeV/c the only available multiplicity distribution is that from stopped antiproton-proton annihilations. Since the multiplicity distribution differs very little between 300 MeV/c [6] and zero energy [25] the interpolated values are used in the present analysis. This is supported by the fact that the multiplicity distribution observed with our apparatus changes little in the momentum range of the present experiment.

The width of the cut applied to the TDC spectrum of the time of flight between SD and the hodoscopes is 3 ns in UHD/LHD and BHD, and 2 ns in FHD. The cut efficiency in the individual slabs of the hodoscopes is about 80%. The correction to the measured cross-section for the acceptance and the pion time of flight cut efficiency is altogether $+10.4 \pm 1.0\%$.

3.6 Correction for the all-neutral channels

In order to derive the total annihilation cross-section the all-neutral channels such as $\pi^0\pi^0\pi^0$ are taken into account as follows. The fraction of the all-neutral channels for the stopped antiproton-proton annihilation has been measured to be 3–4% in bubble-chamber experiments [18, 25]. The fraction of the all-neutral channels for the antiproton-proton annihilation in flight is evaluated to be 4–5% by subtracting the charge-exchange cross-section [3, 26] from the zero-prong cross-section [6, 13] at the momenta above 300 MeV/c. It is known that the s-wave is dominant in the stopped antiproton annihilation [25], and the s- and p-waves are dominant in the annihilation at 300 MeV/c [2]. The fractions of s- and p-waves in the annihilation cross-section change gradually as a function of the beam momentum. The value interpolated from 300 MeV/c and from zero can therefore be used in the simulation of the present experiment. As described in Section 2.2 the hodoscopes have a limited efficiency for detecting π^0 's. The correction for the all-neutral channels applied to the measured annihilation cross-section is $+3.0 \pm 1.1\%$ at 297 MeV/c.

The multiplicity distribution of the charged particles at 394 MeV/c is shown in Fig. 7 along with the result of the simulation. The pion multiplicity distribution is taken from Ref. [13]. The simulation is performed with the knowledge of the detector acceptance, the pion time-of-flight cut efficiency, and the electron-positron conversion of gammas from π^0 decay. The precision of the simulation is limited because the branching ratios of the channels which contain more than two neutral pions are not known. Nevertheless the features of the present experimental data are well reproduced by the simulation in Fig. 7.

3.7 Target thickness

The diameter of the cylindrical thick target is measured by filling the cell with nitrogen gas at 2 atm with an outside pressure of 1 atm. Next, the effect of the finite beam spot size on the target is evaluated using the CERN program TRANSPORT [27] with an actual beam coincidence condition between F1, SD, and TD. The effective target thickness is determined to be 19.8 ± 0.2 mm. The thickness of the planar thin target is determined to be 7.2 ± 0.3 mm by comparing the annihilation cross-sections measured with the thick and thin targets above 395 MeV/c.

The vapour pressure of the hydrogen target is measured during the experiment, allowing the temperature of the hydrogen to be evaluated with an accuracy of 0.1° . The density of the liquid hydrogen is thus determined to be 0.0703 ± 0.0005 g/cm³.

4. DISCUSSION OF THE RESULTS

4.1 Fit with a simple formula

The annihilation cross-section after all the corrections is shown in Table 2 and plotted in Fig. 8. This cross-section includes the annihilation into all-neutral channels. The cross-section is fitted with a formula,

$$\sigma_{\text{anni}} = a + b/p + c \cdot p, \quad (1)$$

where p is the antiproton momentum in GeV/c. The fitted parameters are $a = -30.1 \pm 6.3$ mb, $b = 46.6 \pm 1.3$ mb·(GeV/c), and $c = 60.3 \pm 7.6$ mb/(GeV/c), with $\chi^2/\text{DF} = 77.1/53$. The systematic errors in the fifth column in Table 2 are included in the fit. The relatively large errors are due to correlations among the parameters. The second term in Eq. (1) becomes dominant if extrapolated to lower energy. However, it should be noted that the parametrization in Eq. (1) is phenomenological and the validity of an extrapolation to lower momenta is not known.

4.2 Comparison with the data from earlier experiments

The comparison of the annihilation cross-section from different experiments is shown in Table 3 and Fig. 9. Care must be taken in comparing the results of various measurements of the annihilation cross-section because of the different methods used and the assumptions made in the analyses. Loken and Derrick [18] measured the antiproton-proton total annihilation cross-section between 220 and 400 MeV/c. The fraction of zero-prong annihilations in the total annihilation is measured to be $3.5 \pm 0.3\%$ at rest where the charge-exchange reaction does not take place because of the proton-neutron mass difference. In deriving the total annihilation cross-section the fraction of zero-prong annihilation is assumed to be the same in the annihilation in flight [18]. These data are consistent with the present result.

Sai et al. [13] measured the antiproton-proton inelastic (0, 2, 4, and 6 prongs) cross-section for the beam momentum between 374 and 680 MeV/c. The charged annihilation cross-section is obtained by summing the 2-, 4-, and 6-prong cross-sections. It agrees with the present result at 440 MeV/c if the annihilation cross-section for the all-neutral channels, which is 4–5%, is taken into account, but it is smaller than the present result by about 5% at 540 MeV/c. Chaloupka et al. [6] measured the charged annihilation cross-section in the same way for the beam momentum between 306 and 551 MeV/c. It is about 5% higher than the present result for the entire momentum range if the annihilation to all neutral channels is added. The momentum dependence agrees well with the present result. Brückner et al. [7] measured the charged annihilation cross-section between 400 and 850 MeV/c. The non-resonant background part at 500 MeV/c is consistent with the present result but shows a steeper momentum dependence.

The following five data are not directly comparable with the present result: Hamilton et al. [8] measured the charged annihilation cross-section between 350 and 1070 MeV/c. This cross-section contains the elastic antiproton scattering at angles greater than 38° in the laboratory as well as recoil protons with sufficient momentum to escape from the target (> 250 MeV/c). The cross-section for the reaction antiproton-proton neutrals with $\bar{n}$ of γ interacting in the target or in the surrounding veto box is also included. These effects increase the measured cross-section by about 15% at 500 MeV/c [8].

Kalogeropoulos et al. [9] measured the antiproton-proton total annihilation cross-section for antiproton momenta between 270 and 470 MeV/c using a deuteron target. The charge-exchange contribution is estimated from associated $\bar{n}$ stars and is subtracted. The Fermi motion and the nuclear binding in the deuteron target could however modify the antiproton-proton annihilation cross-section.

Jastrzemski et al. [10] measured the charged annihilation between 420 and 600 MeV/c, but the direct normalization of the cross-section is not given. Lowenstein et al. [12] measured the charged annihilation cross-section between 430 and 590 MeV/c. This measurement does not provide independent information on the absolute cross-section as it has been normalized to the results from earlier measurements including Refs. [6] and [7]. Brando et al. [14] measured the charged annihilation cross-section between 300 and 590 MeV/c. It has been normalized to the results from the earlier measurements [6–8].

4.3 Comparison with the black disk value

As mentioned in the Introduction, it is useful to compare the measured annihilation cross-section with the black disk value, which gives the geometrical limit of the inelastic cross-section. In the interaction with the black disk the inelastic cross-section is equal to the elastic cross-section:

$$\sigma_{el} = \sigma_{inel} = (\pi/k^2) \sum_{\ell} (2\ell + 1), \quad (2)$$

where ℓ is the partial wave and k is the c.m. momentum. The inelastic cross-section here consists of annihilation and charge-exchange cross-sections. The measured annihilation cross-section, shown in Fig. 10, is larger than the black disk value of the s-wave inelastic cross-section in all the momentum range down to 180 MeV/c, indicating a p-wave contribution even at a very small momentum.

4.4 Comparison with potential model calculations

Several potential model calculations [28–31] exist for the beam momenta of the present measurement. The parameters in these potential models have been adjusted to the experimental cross-sections above 400 MeV/c which were available when these models were constructed. The calculation of the cross-sections at lower momenta can therefore be regarded as a prediction. The model predictions deviate from each other and also from the experimental cross-section at low momenta as shown in Fig. 11. It is interesting to see whether the models can reproduce the cross-section by retuning the parameters or whether completely new ingredients have to be introduced in the models. The cross-sections calculated with the strong force alone can be different from the experimental value because of the Coulomb distortion of the incident waves. This effect has been studied for the total cross-section [32]. Similar theoretical studies are necessary also in the annihilation cross-section for small momenta.

5. CONCLUSIONS

The cross-section for antiproton-proton annihilation has been measured with a good precision for beam momenta between 180 and 600 MeV/c. A substantial p-wave contribution to the annihilation cross-section has been identified at energy as low as $E_{\text{cm}} = 8.2$ MeV, in contrast with the nucleon-nucleon reaction where the p-wave contribution is less than 10% at this energy.

Acknowledgements

We wish to thank the LEAR machine group and the beam line group for their efforts to produce a low-energy antiproton beam of high quality. The design and manufacturing of the liquid-hydrogen target was performed skilfully by the CERN cryotarget group. The assistance of our technicians Z. Kenesei and J. Zimmer is gratefully acknowledged. We thank C.B. Dover, M. Lacombe, F. Myhrer and P.H. Timmers for providing us with the results of their potential model calculations. The present work was supported financially by the Bundesministerium für Forschung und Technologie of the Federal Republic of Germany.

REFERENCES

- [1] W. Brückner et al., Phys. Lett. **158B** (1985) 180.
- [2] W. Brückner et al., Phys. Lett. **166B** (1986) 113.
- [3] W. Brückner et al., Phys. Lett. **169B** (1986) 302.
- [4] W. Brückner et al., Phys. Lett. **197B** (1987) 463, **199B** (1987) 596(E).
- [5] W. Brückner et al., Nucl. Instrum. Methods **A269** (1988) 527.
- [6] V. Chaloupka et al., Phys. Lett. **61B** (1976) 487.
- [7] W. Brückner et al., Phys. Lett. **67B** (1977) 222.
- [8] R.P. Hamilton et al., Phys. Rev. Lett. **44** (1980) 1182.
- [9] T. Kalogeropoulos and G.S. Tzanakos, Phys. Rev. **22D** (1980) 2585.
- [10] E. Jastrzembski et al., Phys. Rev. **D23** (1981) 2784.
- [11] J. Franklin, Phys. Lett. **184B** (1987) 111. This paper presents a reanalysis of a part of the data in Ref. 10.
- [12] D.I. Lowenstein et al., Phys. Rev. **D23** (1981) 2788.
- [13] F. Sai, S. Sakamoto and S.S. Yamamoto, Nucl. Phys. **B213** (1983) 371.
- [14] T. Brando et al., Phys. Lett. **158B** (1985) 505.
- [15] L. Montanet, Phys. Rep. **63** (1980) 201.
- [16] L.N. Bogdanova, O.D. Dalkarov and I.S. Shapiro, Ann. Phys. **84** (1974) 261.
- [17] D. Spencer and D.N. Edwards, Nucl. Phys. **19B** (1970) 501.
- [18] J.G. Loken and M. Derrick, Phys. Lett. **3** (1963) 334.
- [19] B. Cork et al., Nuovo Cimento **25** (1962) 497.
- [20] U. Amaldi Jr. et al., Nuovo Cimento **46A** (1966) 171.
- [21] J. Bailey et al., PS172 proposal CERN-PSCC/80-76/P16.
- [22] S.M. Seltzer and M.J. Berger, Nuclear Science Series (National Research Council, Washington, 1964), vol. 39, p. 187.
- [23] F. James, CERN program library FOWL W505 (1972).
- [24] V. Flaminio, W.G. Moorhead, D.R.O. Morrison and N. Rivoire, CERN-HERA 84-01 (1984).
- [25] R. Armenteros and B. French, High energy physics, ed. E.H.S. Burhop (Academic Press, New York, 1969), vol. IV, p. 237.
- [26] R.P. Hamilton et al., Phys. Rev. Lett. **44** (1980) 1179.
- [27] K.L. Brown et al., CERN 80-04 (1980).
- [28] F. Myhrer, private communication (1985).
O.D. Dalkarov and F. Myhrer, Nuovo Cimento **40A** (1977) 152.
- [29] C.B. Dover, private communication (1985).
C.B. Dover and J.M. Richard, Phys. Rev. **C21** (1980) 1466.
- [30] M. Lacombe, private communication (1985).
J. Côté et al., Phys. Rev. Lett. **48** (1982) 1319.
- [31] P.H. Timmers, private communication (1985).
P.H. Timmers, W.A. van der Sanden and J.J. de Swart, Phys. Rev. **D29** (1984) 1928.
- [32] W. Derks, P.H. Timmers and J.J. de Swart, Proc. 7th European Symposium on Antiproton Interactions, Durham, 1984, ed. M.R. Pennington (Adam Hilger, Bristol and Boston, 1985), p. 503.

Table 1
Corrections of the annihilation cross-section and
the sources of the systematic errors

$\bar{p}$ momentum (MeV/c)	Correction for $\bar{p}$ scattering at large angles followed by $\bar{p}$ annihilation (mb)
<i>Thick target:</i>	
200.0	-25.64 ± 5.96
227.8	-13.80 ± 4.28
267.9	-5.55 ± 1.50
297.1	-2.37 ± 0.55
352.8	-0.56 ± 0.15
393.9	-0.19 ± 0.05
500.0	-0.98 ± 0.02
600.0	-0.63 ± 0.02
<i>Thin target:</i>	
176.8	-25.11 ± 5.65
213.1	-10.98 ± 1.79
237.0	-5.65 ± 0.80
355.8	-0.27 ± 0.03
396.1	-0.13 ± 0.01
<i>Other systematic errors:</i>	
Point-to-point systematic error due to the beam instability:	$\pm 0.6\%$
Correction for acceptance and the pion time-of-flight cut efficiency:	$\pm 1\%$
Correction for the all-neutral channels:	$\pm 1.1\%$
Beam flux normalization:	$\pm 1\%$
Target hydrogen density:	$\pm 0.7\%$
Thickness of the thick target:	$\pm 1\%$
of the thin target:	$\pm 4\%$

Table 2
Antiproton-proton annihilation cross-section

$\bar{p}$ momentum (MeV/c)	FWHM (MeV/c)	Cross-section (mb)	Statistical error (mb)	Systematic error (mb)
<i>Thick target:</i>				
200.0	28.0	206.12	1.22	6.11
227.8	21.2	181.43	1.18	4.43
267.9	14.6	160.71	2.03	1.78
297.1	11.4	143.35	0.83	1.00
352.8	7.5	120.08	1.18	0.71
393.9	6.0	110.13	1.69	0.64
424.1	5.2	104.44	0.50	0.63
435.7	5.1	102.65	1.50	0.62
447.4	5.0	100.93	0.51	0.61
456.9	4.9	100.25	0.55	0.60
472.4	4.8	95.91	0.93	0.58
472.5	4.8	95.95	0.82	0.58
472.5	4.8	97.48	0.64	0.58
475.0	4.8	97.52	0.60	0.59
475.1	4.8	96.22	0.64	0.58
481.0	4.8	95.35	1.04	0.57
481.0	4.8	94.77	0.47	0.57
483.6	4.7	96.06	0.77	0.58
487.8	4.7	96.32	0.72	0.58
488.0	4.7	93.83	0.53	0.56
489.8	4.7	94.86	0.50	0.57
492.2	4.6	93.78	0.74	0.56
492.2	4.6	93.96	0.66	0.56
494.0	4.6	93.04	0.56	0.56
495.8	4.6	94.21	0.53	0.57
499.6	4.6	94.08	0.40	0.56
503.6	4.6	93.79	0.52	0.56
<i>Thin target:</i>				
506.4	4.6	94.13	0.56	0.56
506.4	4.6	94.37	0.64	0.57
507.6	4.6	92.08	0.48	0.55
512.7	4.5	92.16	1.34	0.55
512.7	4.5	91.50	0.66	0.55
513.7	4.5	92.10	0.47	0.55
517.0	4.5	92.63	0.50	0.56
518.2	4.5	92.50	0.61	0.55
518.2	4.5	92.70	0.76	0.56
523.1	4.5	89.71	0.57	0.54
527.9	4.5	89.59	0.55	0.54
527.9	4.5	89.55	0.41	0.54
537.5	4.5	88.27	0.54	0.53
537.5	4.4	88.78	0.58	0.53
539.2	4.4	89.72	0.33	0.54
544.7	4.4	87.47	0.28	0.52
547.4	4.4	86.66	0.69	0.52
558.0	4.4	86.23	0.82	0.52
567.6	4.3	85.56	0.41	0.51
567.6	4.3	86.25	0.70	0.52
588.2	4.2	83.52	0.57	0.50
<i>Thin target:</i>				
176.8	15.4	266.72	1.39	5.92
213.1	9.3	205.08	2.26	2.21
237.0	7.2	179.68	1.82	1.37
355.8	4.4	125.18	3.53	0.75
396.1	4.2	109.79	2.69	0.66

The cross-section at the identical $\bar{p}$ momentum is listed twice in some cases as the scan was repeated.
The systematic errors in the fifth column consist of the point-to-point fluctuation due to the beam instability (0.6%) and the error in the correction for $\bar{p}$ backward scattering followed by $\bar{p}$ annihilation in the target in Table 1.
In addition there is the overall normalization error, 2.2% for the thick target and 4.4% for the thin target, which arises from the rest of the systematic errors listed in Table 1.

Table 3
Fitted parameters of the annihilation cross-section

a (mb)	b (mb·GeV/c)	c [mb/(GeV/c)]	Fit range (MeV/c)	Reference	Comments
-30.1 ± 6.3	46.6 ± 1.3	60.3 ± 7.6	177–590	Present experiment	Total annihilation cross-section
-0.6 ± 5.7	43.1 ± 2.7	–	374–680	Sai et al. [13]	Charged annihilation
8.5 ± 2.5	40.7 ± 1.3	–	300–590	Brando et al. [14]	Charged annihilation, no absolute normalization

Figure captions

- Fig. 1 The beam line between the intermediate focus point F1 and the experimental set-up.
- Fig. 2 The apparatus in (a) the vertical and (b) the horizontal planes.
- Fig. 3 The target assembly.
- Fig. 4 The time of flight between F1 and SD at the nominal momentum of 190 MeV/c. The FWHM of 3 ns corresponds to 0.9% in $\Delta p/p$.
- Fig. 5 TDC-ADC scatter plot of (a) the upper and lower hodoscopes (UHD/LHD) and (b) the forward hodoscope (FH) at the antiproton momentum of 297 MeV/c.
- Fig. 6 The fraction of the beam annihilating with the thick and thin full targets and with the corresponding empty targets.
- Fig. 7 Multiplicity distribution of charged particles in the annihilation events at the beam momentum of 394 MeV/c. The black histogram shows the present experimental data. The open histogram is the result of the simulation. The dashed histogram is the charged prong distribution in Ref. [13] used as the input for the simulation.
- Fig. 8 The annihilation cross-section with a fitted curve.
- Fig. 9 The annihilation cross-sections from the present measurement and from the earlier measurements by Chaloupka et al. [6], Sai et al. [13], and Loken and Derrick [18].
- Fig. 10 The black disk value of the s-wave inelastic cross-section, shown by the curve, is compared with the annihilation cross-section from the present experiment.
- Fig. 11 Potential model calculations are compared with the annihilation cross-section from the present measurement. The broken curve is obtained by the Myhrer et al. [28] model using a black sphere and a Bryan-Scott potential, the solid curve by the Dover-Richard model [29], the dotted curve by the Paris model [30], and the dash-dotted curve by the Nijmegen model [31].

Fig. 1

Fig. 2

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11