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An Apparatus for the Measurement of Antiproton – Proton Cross Sections at Low Momenta

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Abstract: An experiment which aims at a precise measurement of $\bar{p}p$ cross sections at low momenta is presented. Its design and performance are described with emphasis on the particle identification capabilities. A calorimeter – like detector array which serves for the detection of antineutrons is discussed in some detail. Its properties were measured in a test experiment and are compared to Monte – Carlo calculations.

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1. Introduction

This paper describes an apparatus which was built to measure the differential cross sections for $\bar{p}p$ elastic scattering ($\bar{p}p \rightarrow \bar{p}p$) and for charge exchange ($\bar{p}p \rightarrow \bar{n}n$) and the cross section for the $\bar{p}p$ annihilation into charged and neutral pions, in the momentum range between 150 MeV/c and 600 MeV/c with the intense antiproton beam at the Low Energy Antiproton Ring (LEAR) of CERN. A part of the results from this experiment has been published elsewhere [1–4].

At these low energies, the beam definition and the detection of elastically scattered antiprotons requires thin detectors and targets, in order to minimize multiple Coulomb scattering effects and background annihilations. On the other hand, annihilations of antiprotons in the target and annihilations of both antiprotons and antineutrons in the detectors release an energy of about 2 GeV. This energy is mostly carried by charged pions and energetic photons (from the decay of neutral pions). For the detection of these particles, large calorimeter-like detectors are needed. The setup for this experiment, therefore, combines low-energy techniques such as thin scintillators for the beam definition and a vacuum scattering chamber with typical high-energy techniques such as large hodoscopes, iron-scintillator sandwich calorimeters and wire chambers.

The general layout of the setup, a brief description of the beam defining scintillators and target is outlined in the following chapter. A more detailed description of the various detectors is contained in chapter 3. The test measurements and Monte-Carlo simulations of the antineutron detectors are treated in a separate section. In chapter 4 we discuss the performance of the setup with special emphasis on the particle identification capabilities. Conclusions are drawn in chapter 5.

2. General Layout, Beam Definition and Target

The apparatus sketched in fig. 1 was used at the C2 beam line in the LEAR experimental area at CERN. The liquid hydrogen target is placed in the center of an aluminium vacuum tank with roughly 1 m diameter and 1 cm wall thickness. A 250 μm thick mylar window on the front side of the tank allows slow scattered antiprotons and recoil protons to be detected outside the vacuum. A semicylindrical multiwire proportional chamber (MWPC) in front of this window measures the scattering angle of charged particles. The forward scintillator hodoscope (FHD) serves for the particle identification by energy loss and time-of-flight measurement. Neutral particles in forward direction are detected in a calorimeter-like detector array (ANC), placed behind the forward hodoscope. Charged mesons arising from annihilation events are identified by energy loss and time-of-flight measurement in large scintillator hodoscopes (UHD, LHD, BHD) surrounding the target and covering 73% (including the forward hodoscope) of the total solid angle. Neutral pions, which immediately decay into two gamma rays, can be detected in the 126 lead glass blocks (PbG) and in ANC.

A beam particle is defined by a coincidence between two thin scintillators (50 – 200 μm , depending on the incident momentum) which are placed in the intermediate focus of the beam line (IF, 20 m upstream) and 85 cm in front of the target. The latter one (SD) is also used as a start detector for the time-of-flight measurements and is sketched in fig. 2. It consists of a thin NE111 foil attached on a 10 μm thick polyethylene backing and placed inside a cylindrical mirror which is made of 10 μm thick aluminized mylar. The scintillation light is converted into a fast electronic signal by means of two photomultipliers (Philips XP2020). The time resolution (FWHM) of this detector as measured with an electron source is about 400 ps.

Later on, a third scintillator (TD) in Fig.2(c) was installed about 15 cm in front of the target. It consists of a 50 μm thick NE111 foil mounted on a 10 μm thick polyethylene backing inside the plastic housing of a photomultiplier (EMI 9814 B). In coincidence with the SD it rejects the beam halo, thus limiting the divergence to less than 0.7 mrad. The construction of these detectors was inspired by similar devices used in heavy ion TOF spectrometers [5,6].

The target arrangement is shown in fig. 3. Two cells of different thickness are available: a tube with a diameter of 20 mm, made of 100 μm thick mylar, having its axis perpendicular to the beam direction, and a 7 mm thick disc, made of 12 μm and 25 μm thick mylar foils. The liquid hydrogen is supplied by a cryogenic system on top of the vacuum vessel. Two identical empty cells serve for background measurements. A small carbon target (diameter 3 mm, thickness 5 mm), glued onto two mylar foils between the two 6 mm cells, is used for beam focussing by monitoring the annihilation rate. The entire arrangement is surrounded by six layers of 2.5 μm thick aluminized mylar foil for thermal insulation. It can be moved up and down by an electrical rack – and – pinion drive which is mounted on top of the vacuum vessel.

The high vacuum ($\approx 2 \cdot 10^{-6}$ mbar) inside the tank is achieved and maintained by a cryopump mounted at the lower flange. The beam pipe and the start detector housing, which also contains the connection to a roughing pump, can be disconnected by two plate valves.

3. Detectors

3.1 Elastic Scattering: Forward Hodoscope and Wire Chamber

The forward hodoscope identifies scattered antiprotons and recoil protons by time – of – flight and energy loss measurement. It consists of 32 pieces of NE102A plastic scintillators ($200 * 50 * 3 \text{ mm}^3$) at a distance of 66 cm from the target, each of which is connected to two fast photomultipliers (EMI 9814 B) via a plexiglas light guide. The covered angular range extends from 2.5° to 82.5° on both sides of the beam. A single slab is 5° wide. The solid angle amounts to 1.2 steradians.

The scattering angle is precisely measured by means of a semi – cylindrical multiwire proportional chamber which is placed 10 cm in front of the forward hodoscope. It has two planes with 704 wires each, inclined by 12° to the vertical. The wire spacing is 2 mm, 96 wires cover 20° . In this way the az-

imuthal angle Θ can be measured with a precision of 0.2° (3.6 mrad) and the height above the scattering plane z with an accuracy of 5 mm. The scattering angle ϑ_{LAB} is determined using the formula:

$$\cos \vartheta_{\text{LAB}} = \cos \Theta / \sqrt{1 + (z/R)^2},$$

R being the distance between the target and the chamber. The resolution of the scattering angle depends on Θ and z , and varies between 0.2° and 0.3° .

The geometry of the wire chamber with reference to the beam axis is sketched in fig. 4. It should be noticed that the two planes are pieces of a hyperbolic surface. Therefore, the distance to the cylindrical cathode planes depends on the height above the scattering plane. Nevertheless, the efficiency for antiprotons and protons on the plateau (about 5.2 kV) was measured to be more than 99% in the region covered by the forward hodoscope.

3.2 Charge Exchange: Antineutron Detectors

The neutral particles created in the charge exchange reaction ($\bar{p}p \rightarrow \bar{n}n$) can only be detected in an indirect manner via the energy loss of charged secondary particles arising from annihilations in the detector material. For this purpose a calorimeter-like detector array has been constructed, which consists of 32 independent modules and is geometrically adapted to the forward hodoscope. The distance of the front plates to the target is 82.5 cm. The design of a combined forward hodoscope/calorimeter module is sketched in fig. 5. It consists of an aluminium box which contains 50 slabs of 6 mm thick plastic scintillator (Altustipe UV 15105, emission wave length: 375 nm, [7]) and 50 plates of 4 mm thick iron, stacked alternatively and kept in place by two long screws. The total thickness is determined to be 2.5 absorption lengths using measurements of the antineutron absorption cross section at 1.4 GeV/c by Besch et al. [8]. This corresponds to an absorption probability of 92%. At lower momenta the cross sections and thus the absorption probability are even bigger. Annihilations will mostly take

place in the iron and release charged particles (mainly pions and protons) which produce scintillation light in the interleaved plastic sheets. This light propagates to the wave length shifter (Altustipe WLS 390 B) where it is absorbed and reemitted in the blue domain. It is finally converted by fast photomultipliers (EMI 9814 B) with rubidium cathodes, which are 20% more sensitive to the blue part of the spectrum than conventional alkali cathodes. This combination of materials provides a high light output and a fast timing needed for a good particle identification. Furthermore, the strong attenuation of ultraviolet light in the plastic allows for a rough determination of the interaction point by comparing the pulse heights in the two photomultipliers.

A prototype of these detectors was tested in an electrostatically separated antiproton beam at the CERN proton synchrotron. It had a slightly different geometry than the final version having 45 scintillators and 45 iron plates of 5 mm thickness each. Different scintillator/wave length shifter combinations were tested. The results for the UV 15105/WLS 390 B version are presented below and compared to the prediction of the Monte – Carlo simulation.

3.2.1 Monte – Carlo Simulation of the Calorimeter Response

An antinucleon absorption in the detector will take place via an annihilation on a nucleus, in about 80% of the cases on an iron nucleus. The final state mesons, mostly pions, will interact with the nuclear matter and transfer energy to the nucleons. The signature of such an event will thus be a "star" of mesons and nucleons which has an almost isotropic angular distribution because of the small center – of – mass velocity of the antinucleon – nucleon system. There will be no hadronic showering because the energies of the secondary particles are predominantly below the pion production threshold. Therefore, the bulk of the energy released in the scintillators will be due to the fast charged annihilation products. Additionally, gamma rays from the decay of neutral pions will give rise to electromagnetic showers.

These processes have been simulated in a Monte – Carlo calculation which consists of two parts:

1. a simulation of the multipion – nucleus interaction on the basis of a very simple intranuclear cascade model and
2. the calculation of the energy loss including an electromagnetic shower simulation.

The intranuclear cascade described the nucleus as a Fermi gas in which the pions propagate and scatter off free nucleons. The energy dependence of the πN cross section included all resonances up to $M = 2$ GeV. Isospin invariance was used to describe processes which are experimentally not accessible such as $\pi^0 N$ scattering, using existing $\pi^+ N$ and $\pi^- N$ data. Nucleons were assumed to be free if they had acquired a kinetic energy of more than 8 MeV above the Fermi level. This model gave similar inclusive spectra like more elaborate descriptions [9,10].

The detector response on pions, protons, neutrons, electrons and gamma rays has also been investigated using the same codes in order to compare it to the antinucleon detection and to the test measurements.

The visible energy loss is calculated using the Bethe – Bloch formula and describing the light absorption in the scintillators and the wave length shifters by the formula: $I(x) = I(0) \cdot \exp(-x/\lambda)$, λ being 30 cm for the scintillator and 250 cm for the wave length shifter. As most of the energy is deposited in a rather small volume around the annihilation position, this absorption leads to an up/down pulse height difference which can be used for a rough position determination. Fig. 6 shows the correlation between the annihilation vertex and the normalized pulse height difference $(E_{up} - E_{down})/(E_{up} + E_{down})$. Additionally, the time – of – flight difference between the two tubes can be used for the same purpose.

The figures 7 and 8 show the calculated pulse height spectra of antineutrons and antiprotons at 800 MeV/c for one and three adjacent modules, respectively. The maximum of the antineutron spectrum (for one module) is at about 30 MeV, while the antiproton spectrum peaks at about 60 MeV. This difference is due to the electronic energy loss of the antiprotons before the annihilation. Further-

more, it allows an estimate of the partition of the energy loss before and after the annihilation: The total energy of the antinucleon – nucleon system in the laboratory frame is given by the sum of the rest masses and the kinetic energy: $E = T + M \approx (0.3 + 1.9) \text{ GeV}$. The visible energy loss can be parametrized as:

$$\Delta E(\bar{p}) = \alpha T + \beta M \approx 0.06 \text{ GeV}$$

$$\Delta E(\bar{n}) = \beta M \approx 0.03 \text{ GeV}.$$

This yields $\beta = 0.014$ and $\alpha = 0.114$. Thus, α is approximately given by the ratio of scintillator and iron densities. On the average, only 1.4% of the energy released in the annihilation is actually detected in the hit module. This can be improved by adding the energy loss in the two adjacent modules since a larger part of the available kinetic energy is absorbed as can be seen by comparing the two parts of fig. 7 and 8.

The single module pulse height spectra for neutrons, protons and charged pions with an incident momentum of 800 MeV/c are shown in the figures 9–11. They are computed by including hadronic interactions with the same program as for the energy deposition of the annihilation products in the antinucleon case. The charged particle spectra exhibit a sharp peak due to penetrating particles which do not suffer a hadronic interaction, on a smooth background which is produced by scattered particles and nuclear fragments.

Gamma rays and electrons create electromagnetic showers by subsequent pair production, bremsstrahlung and Compton scattering processes. Neutral pions from antinucleon annihilations inside the detector immediately decay into two energetic gamma rays which give rise to showers. Pulse height spectra have been computed for 800 MeV electrons and 100 MeV gamma rays (the average energy of photons from the decay of annihilation pions). They are shown in fig. 12 and 13. The fact that the visible energy of electromagnetic showers is evidently smaller than the visible hadronic energies helps to distinguish photons and antineutrons.

3.2.2 Test Results

Test measurements with a prototype module were done at a separated $\bar{p}/\pi^-$ beam from the CERN proton synchrotron with a nominal momentum of 800 MeV/c. Spectra for antiprotons, antineutrons and negative pions are shown in fig. 14. Pions were identified by the time-of-flight method and a coincidence scintillator which was placed behind the detector in order to trigger on penetrating particles. The shoulder at low pulse heights of the π^- curve is most likely due to the electron and muon impurities in the beam. Antiprotons were separated by a time-of-flight/energy loss trigger using beam defining plastic scintillators. A CH_2 target was used for the production of antineutrons via the charge exchange reaction. The antineutron spectrum was measured by putting a veto scintillator in front of the detector in order to assure that only neutral particles are detected. A reduction of the γ background was done in the off-line analysis by time-of-flight and pulse height cuts. The three curves are normalized such that the maximum of the π^- spectrum falls on top of the calculated electronic energy loss of 800 MeV/c charged pions. The Monte-Carlo calculations agree well with these results. Furthermore, the time resolution (FWHM) of the detector was measured to be 1.7 ns (to be compared to 2.2 ns using blue scintillators and BBQ as wave length shifter). The detection efficiency was determined by using the measured detection probabilities for 0, 1/3, 2/3 and complete iron filling and fitting the function:

$$P(x) = 1 - \exp [-(x/\lambda)_{\text{Sc}} - (x/\lambda)_{\text{Fe}}]$$

to it. The result is shown in fig. 15. The fitted parameters $\lambda_{\text{Fe}} = (15.4 \pm 10)$ cm and $\lambda_{\text{Sc}} = (25.6 \pm 7.5)$ cm yield a total thickness of (2.3 ± 1.0) absorption lengths in good agreement with the calculated value 2.5. Hence, the absolute detection efficiency was measured to be $(90 \pm 6)\%$ at 800 MeV/c.

Also shown in fig. 15 is the result obtained during the actual experiment at 300 MeV/c with partially filled modules in the final arrangement (see fig.1). By comparing antineutron yields from the modules in the left side and in the right side, the detection efficiency was determined to be $(98 \pm 2)\%$ at 300 MeV/c[3].

3.3 Annihilation: The Upper, Lower and Backward Hodoscope, Lead Glass

The annihilation products, mainly pions, can be emitted at any angle because of the low center-of-mass velocity of the antiproton-proton system. Therefore, large plastic scintillators (Röhm GS 2003, 1 cm thick) are mounted around the target, covering 63% of the total solid angle (73% including the forward hodoscope). Sixteen trapezoidal detectors make up the upper and lower hodoscope (UHD, LHD). Measured from the vertical axis, they cover angles between 12.6° and 62.8° (UHD), and between 117.2° and 167.4° (LHD). Another eight rectangular slabs form the backward hodoscope (BHD). The shortest distance of the upper and lower hodoscope to the target amounts to 69 cm, the backward hodoscope forms a semicircle of 80 cm radius around the target.

The gamma rays from the decay of neutral pions are detected in 126 lead glass blocks via the Čerenkov radiation of the charged shower particles. These detectors cover 25% of the solid angle. An additional 10% is covered by antineutron calorimeter.

3.4 The Laser Calibration System

All scintillators and the $\bar{n}$ detectors are monitored by means of a nitrogen laser, which emits fast pulses of ultraviolet light ($\lambda = 337.1$ nm) at a repetition rate of 20 Hz. The intensity of one pulse is 0.1 mJ ($1.7 \cdot 10^{14}$ photons), its duration about 3 ns (FWHM), its risetime about 1 ns. The wavelength is then shifted to ≈ 390 nm by a dye, in order to match the peak of the quantum efficiency curve of the photomultipliers. The dye is a mixture of 50% toluene and 50% methylalcohol containing about 1.7 mg/cm³ BBQ. The secondary beam from the dye is emitted perpendicularly to the primary one, and fed into a system of optical fibres which guide the light into small lucite boxes glued onto the scintillators or the light guides. The start detector phototubes (see Fig.2(a) and (b)) are exposed via a cylindrical lucite light guide attached on the lid of the vacuum box. This laser system is used for the adjustment of the relative timing and (in combination with cosmic ray runs) of the pulse height of all scintillators in the experiment.

3.5 Electronics and Data Acquisition

The three beam defining detectors in front of the target (intermediate focus, start detector and target detector) and the first beam veto counter are used for the trigger. In addition, one of the start detector photomultipliers defines the common start for the time-of-flight measurements with the hodoscopes. A block diagram of the trigger is shown in fig. 16. On the first level an interacting antiproton is recognized by the coincidence $T = SD \cdot F1 \cdot TD \cdot \overline{BAI}$. High/low discriminators are used in order to achieve good timing and an efficient rejection of beam impurities like pions. The minimal electronic dead time is set by a gate generator to $3 \mu s$ in order to allow a fast clear of CAMAC electronics in case of a rejection on the second level. The actual dead time, however, is dominated by the time needed by the computer to read an event ("PDP busy"). The strobe and gate signals for the ADC's, TDC's and the wire chamber read-out are generated on this level. On the second level a coincidence with ECL programmable logic units (PLU's) can be performed. This allows a selection of events according to their topology as shown by the detectors. The influence of dead times and logical operations is monitored by scalers which make a correction of these effects in the off-line analysis possible.

The data acquisition is done by a PDP 11/34 computer which reads the CAMAC and wire chamber information via a fast microprocessor in the system crate. An event contains data of the pattern units, the ADC's, TDC's and wire chamber information and has an average length of 50 16-bit words.

During data taking a monitoring task runs on a VAX 11/780 computer which is connected to the PDP through a fast transmission line (50 kbaud). The acceptable rate of the data-taking is only limited by the tape speed to about 1000 events per second.

4. Performance of the Apparatus

The determination of cross sections from the data relies on the identification of the final state by time-of-flight and energy loss separation. In this chapter the method is demonstrated and its particle identification capabilities are discussed. Fig. 17 displays an ADC versus TDC scatterplot of a forward hodoscope slab, taken at two different momenta. Four regions can be distinguished and interpreted as follows:

1. pions coming from annihilations in the start detector,
2. pions coming from annihilations in the target,
3. elastically scattered antiprotons and recoil protons,
4. pions from annihilations behind the experiments and back splashing pions from annihilations in the calorimeter.

These assignments make use of the fact that protons and antiprotons are slower and cause more ionization than pions. The number of events with hits in region 1 is used to renormalize the $\bar{p}$ flux arriving at the target, the regions 2 and 3 are taken for the calculation of the annihilation cross section and the differential elastic cross section, respectively. The upper, lower and backward hodoscopes have similar spectra, but the antiproton/proton peak is missing because they are kinematically excluded or stopped in the tank wall.

The actual determination of the final state is done not only by time-of-flight and pulse height cuts but also on the basis of the event topology. For example, backward elastic scattering can be identified by the presence of a forward hodoscope hit in region 3, due to the recoil proton, and hits with annihilation characteristics in the other detectors, caused by the annihilation of the scattered antiproton, which is stopped in the target.

As demonstrated by the test measurements and the Monte-Carlo calculations, antineutrons can not be distinguished from gamma rays by a pulse height discrimination. Therefore, a good time resolution of the calorimeter is needed for the identification of charge exchange events. The figures 18 and 19 show typical ADC/TDC scatterplots of a calorimeter module for charged particles, together with time-of-flight spectra for identified neutral particles, measured at 600 MeV/c and 300 MeV/c, respectively, after a correction for pulse height slewing. At low energies it is hence possible to recognize antineutrons almost free of background by time-of-flight only, whereas at higher energies additional information from the topology is needed.

From the pulse height spectrum displayed in figures 7 and 14, it is apparent that the detection efficiency for antineutrons depends on the energy threshold imposed by the quantum efficiency of the photomultipliers and by the pulse height threshold of the discriminators. It can, however, easily be determined by measuring the detection efficiency for identified minimum ionizing particles and normalizing it to the module with the highest efficiency. Variations of the order of 10% have been observed.

5. Conclusions

We have built and put into operation a detector for the measurement of antiproton-proton cross sections at low energies. All detectors work as designed. The time-of-flight and pulse height separation of the different final states has proved to be sufficient. The use of a calorimeter-like antineutron detector array has enabled us to measure differential cross sections of the charge exchange reaction $\bar{p}p \rightarrow \bar{n}n$ down to about 200 MeV/c. It was especially important for this purpose to understand the detection process in detail. This was achieved by comparing Monte-Carlo calculations to the results of test measurements.

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Figure Captions

Fig.1 Apparatus of the experiment PS173 (a) in the vertical plane and (b) in the horizontal plane.

ANC:	antineutron calorimeter
BA1,BA2:	beam anticounters
BHD:	backward hodoscope
FHD:	forward hodoscope
LHD:	lower hodoscope
MWPC:	multiwire proportional chamber
PbG:	lead glass detectors
SD:	start detector
TD:	target detector
UHD:	upper hodoscope

Fig.2 (a) The start detector viewed from the beam direction

(b) The start detector viewed from the direction perpendicular to the beam

(c) The target detector

Fig.3 The target arrangement

Fig.4 The wire chamber geometry

Fig.5 The antineutron calorimeter

Fig.6 a) Monte Carlo correlation between up/down pulse height difference
and the height of the annihilation vertex

b) Observed correlation between pulse height and time differences
and the height of the $\bar{p}$ impact as measured in the MWPC

Fig.7 Monte – Carlo pulse height spectrum for 800 MeV/c antineutrons

a) one module b) sum spectrum of three adjacent modules

Fig.8 Monte – Carlo pulse height spectrum for 800 MeV/c antiprotons

a) one module b) sum spectrum of three adjacent modules

Fig.9 Monte – Carlo pulse height spectrum for 800 MeV/c neutrons

Fig.10 Monte – Carlo pulse height spectrum for 800 MeV/c protons

Fig.11 Monte – Carlo pulse height spectrum for 800 MeV/c pions

Fig.12 Monte – Carlo pulse height spectrum for 800 MeV electrons

Fig.13 Monte – Carlo pulse height spectrum for 100 MeV gamma rays

Fig.14 Measured pulse height spectra for negative pions,
antiprotons and antineutrons at 800 MeV/c

Fig.15 Efficiency curve for a calorimeter module

Fig.16 Block diagram of the trigger

Fig.17 ADC/TDC scatterplots of a forward hodoscope slab (a) at 600 MeV/c and (b) at 300 MeV/c

Fig.18 (a) ADC/TDC scatterplot of charged particles and (b) TDC spectrum of neutral particles of
a calorimeter module at 600 MeV/c

Fig.19 (a) ADC/TDC scatterplot of charged particles and (b) TDC spectrum of neutral particles of
a calorimeter module at 300 MeV/c

Fig.1(a)

Fig.1(b)

Fig.2(a)

Fig.2(b)

Fig.2(c)

Fig.3

Fig.4

Fig.5

Fig.6(a)

Fig.6(b)

Fig.7

Fig.8

Fig.9

Fig.10

Fig.11

Fig.12

Fig.13

Fig.14

Fig.15

Fig.16

Fig.17

Fig.18

Fig.19