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Measurements of the Antiproton-Proton Elastic Cross Section in the Beam Momentum Range between 180 and 600 MeV/c

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Abstract

The differential cross section for antiproton-proton elastic scattering has been measured for the beam momenta between 180 and 600 MeV/c. The real-to-imaginary ratio of the forward elastic scattering amplitude is derived from the Coulomb-nuclear interference. The ratio is found to be close to zero between 180 and 500 MeV/c with a minimum of $\rho = -0.14$ at 260 MeV/c. This result is contrary to model predictions. The phase shifts for the s-, p- and d-waves are extracted. The partial wave compositions of the elastic and inelastic cross sections have been determined. A large contribution of the p-wave is identified in the antiproton-proton interactions at small momenta.

1 Introduction

In this paper we report the results of measurements of the antiproton-proton elastic cross section for beam momenta between 180 and 600 MeV/c. Short reports of the experiment have already been published[1,2]. The apparatus[3] of the experiment was designed for a simultaneous measurement of the elastic, annihilation, and charge-exchange ($\bar{p}p \rightarrow \bar{n}n$) cross sections. The analyses and the results of the annihilation and charge-exchange cross sections have been reported elsewhere[4,5,6].

The antiproton-proton elastic cross section with a reasonable precision had been limited to the beam momenta above 400 MeV/c[7-13] before the present experiment. The data below 400 MeV/c[14,15,16] were poor both in statistics and in the beam momentum resolution. With the high quality antiproton beam from LEAR (Low Energy Antiproton Ring) we were able to extend the measurements down to 180 MeV/c.

The main motivation for measuring the antiproton-proton differential elastic cross section for small momenta is as follows. First, the real-to-imaginary ratio of the forward elastic scattering amplitude, which can be extracted by the Coulomb-nuclear interference method, is a sensitive parameter to possible structures such as resonances in the antiproton-proton system. Second, at small momenta where only a few partial waves are involved, one can decompose the partial wave components from the differential cross section in the full angular range. Note that the antiproton-proton scattering amplitude has four times as many free parameters as the nucleon-nucleon scattering because of the annihilation channel and the absence of the Pauli exclusion principle. Third, as de Broglie wave length becomes large at small momenta the gross features of potentials can be tested independently of the detail of its shape, as discussed in refs. 17 and 18.

The paper is organized as follows. The experimental method is described in chapter 2, and the analysis procedure in chapter 3. The first part of chapter 4 is devoted to the extraction of the real-to-imaginary ratio of the forward elastic scattering amplitude. The phase shifts and the partial wave compositions of elastic and inelastic cross sections are determined in the second part of chapter 4. Conclusions are given in chapter 5.

2 Experimental Method

In this section we describe those elements which are related to the measurement of the differential elastic cross section. The detailed description of the experiment can be found elsewhere[3,5].

The beam is extracted from LEAR for the present experiment at three different momenta: I: 605, II: 305, and III: 190 MeV/c. The emittance of the beam from LEAR is 5π mm mrad in the horizontal direction and 20π mm mrad in the vertical direction. The beam is first focused at 20 m upstream of the apparatus of the experiment, where a plastic scintillator F1 and carbon degraders[19] are placed. The above mentioned momenta are those before the degraders. The degrader is selected so that the following beam momentum are obtained at the center of the target: 590, 550, 505, 475, 442, 287, 261, 239, 219 and 181 MeV/c. The detail of the beam is described in section 4.1 for the real-to-imaginary ratio measurements and in section 4.2 for the large angle differential cross section measurements.

Horizontal and vertical cross sections of the apparatus are shown in Fig.1. In the antiproton experiment at low momenta, materials placed before the target affect the beam profile due to the multiple Coulomb scattering. We therefore made an effort to minimize the material around the target. The vacuum tank of 1 m diameter, which contains the target, is directly connected to the beam line without a window. Owing to the small emittance of the antiproton beam from LEAR, the incident beam can be defined solely by thin plastic scintillators placed in the vacuum, and a good resolution of the scattering angle is obtained without vertex reconstruction.

The start detector, SD, of 17 mm diameter is located 60 cm before the target while the target detector, TD, of 7 mm diameter is located 15 cm before the target. Both detectors are made of 50 μ m thick plastic scintillator(NE111). The incident beam is defined and counted by a triple coincidence: F1-SD-TD. The tail of the beam phase space is cut out by this coincidence. A calculation by the TRANSPORT program[20], taking into account the acceptance of the beam line, shows that the beam divergence on the target can be limited to 8 mrad with this coincidence. The beam momentum width as measured by the time-of-flight over 20 m between F1 and SD is 0.9%(FWHM). At the beam momentum below 300

MeV/c, the beam momentum resolution is determined by the energy loss of the beam in the target as described in the next chapter. The diameter of the beam spot on the target is about 4 mm. The beam anti-counter, BAC, is 70 cm from the target and 3 cm in diameter. It is used to veto the events in which the antiproton which did not interact in the target.

In the apparatus shown in Fig.1, the forward hodoscopes (FHD) and the semi-cylindrical multi-wire proportional chamber (Cy-MWPC) are the main elements for the measurement of scattered antiprotons and protons. The FHD is 66 cm from the target and made of 32 slabs. Each slab is 3 mm thick and 30 cm high, and covers 5 degrees in the horizontal scattering plane. Each slab of the forward hodoscope is read out by two photomultipliers placed on the top and at the bottom.

The Cy-MWPC is 30 cm high and is made of two anode wire planes and three cathode planes, separated by 10 mm. The distances from the target to the inner and outer anode wire planes are 56.5 and 58.5 cm, respectively. The anode wires are tilted to the vertical direction by $\pm 12^\circ$ in order to allow the determination of the two-dimensional coordinates. The wires are 20 μm in diameter, composed of tungsten(97%) and rhenium(3%), and coated by gold. The wires are spaced by 2 mm and soldered to the printed circuit board with a tension of 70 gram. The cathode consists of a 50 μm -thick carbon coated Mylar foil, having a surface resistance of 200-400 $\text{k}\Omega/\text{cm}^2$. The resistance suppresses possible sparks between the anode wires and the cathode plane, thus increasing the stable region of the high voltage plateau. A gas mixture of Argon 65.5%, Isobutane 30%, Methylal 4% and Freon13 0.5% is used with a flow rate of 13 L/hour . A high voltage of -5.3 kV is applied to the cathode plane. The signals from the preamplifiers are encoded by means of RMH system[21] with a threshold of 15 mV.

Liquid hydrogen targets of two different thicknesses were used, depending on the beam momentum. The thicker target is a vertical cylinder with 19.8 ± 0.2 mm diameter, and the thinner one is a planar disk of 7.2 ± 0.3 mm thickness. The density of the liquid hydrogen target is measured to be 0.0703 ± 0.0005 g/cm^3 . Empty targets of the same designs were used for background measurements.

The upper-, lower-, and backward-hodoscopes (U,L,BHD) in Fig.1 are plastic scintillators which surround the target. Together with the FHD, their total acceptance is 73% of

4 π . The antineutron calorimeter (ANC) consists of 32 modules and surrounds the forward hodoscope. In the present measurement these hodoscopes and ANC are used to measure the events in which the proton is knocked out of the target and the antiproton annihilates in the target.

During each beam spill, which lasts about one hour, five different measurements are done in sequence: (F·B), (F·R), (E·B), (E·R) and (E·B), where F is the full target, E the empty target, R the ‘reaction’ trigger, and B the ‘beam’ trigger. With the ‘beam’ trigger all events which satisfy the beam condition of the triple coincidence are recorded. In order to select the events in which the antiproton interacted in the target, the ‘reaction’ trigger imposes an additional condition: no hit in the BAC and at least one hit in one of the hodoscopes.

3 Analysis Procedure

3.1 Identification of scattered Antiprotons and knocked out Protons

Antiprotons are identified using the time-of-flight and the energy loss information from the forward hodoscope[3]. Using the TDC and ADC values of the two relevant photomultiplier channels, the mean time and the mean energy loss of the hit in each slab are determined off-line.

When the antiproton is scattered at a large angle it stops and annihilates in the target while the proton is knocked out in the forward direction. In these events several pions are generated and detected in the hodoscopes surrounding the target in early timing. Therefore, the proton is identified in the forward hodoscope in coincidence with pion signals in FHD, U/LHD or BHD.

When the antiproton is scattered to the medium angle, $60^\circ < \theta_{cm} < 120^\circ$ at 300 MeV/c for example, both the antiproton and the recoil proton come out of the target and can be detected with the Cy-MWPC and the forward hodoscope. In this case the slabs of FHD or ANC next to the FHD-slab with the $\bar{p}$ signal are fired by annihilation products. The two tracks on the Cy-MWPC in Fig.2 show a clear angular correlation which corresponds to a back-to-back geometry in the center-of-mass frame.

3.2 Background Subtraction with Empty-Target Runs

The background from the scattering in the SD, TD and the target vessel is measured with the empty target runs. It is then subtracted from the angular distributions obtained in the full target runs. In the process of the subtraction the beam momentum loss in the liquid hydrogen is taken into account. At 239 MeV/c, which is the lowest momentum measured with the 20 mm target, the background is less than 5% for the entire angular region ($\theta_{Lab} > 5^\circ$) which is used for the analysis. At 181 MeV/c, where the measurement is done with the 7 mm target, the background is less than 10% for $\theta_{Lab} > 7^\circ$.

3.3 Determination of the Beam Axis

In the analysis of the differential elastic cross section it is important to know the beam axis as the scattering angle is defined with respect to it. At the beginning of the measurement of new beam momenta the electric currents of the magnets in the beam line are tuned in order to optimize the beam transmission from F1 through SD to TD. The actual beam axis, however, does not always coincide with the geometrical axis of the beam line and the apparatus. Indeed, the beam position measured on the Cy-MWPC with the 'beam' trigger shows a shift of a few mm in some of the runs. The beam axis is determined from this measurement. Fig.3 shows the horizontal and vertical projections of the beam profile at 181 MeV/c with the empty target.

As a further check, the beam axis during the 'reaction' trigger runs is monitored in the following way. The differential cross section is first evaluated separately in four different sectors of the Cy-MWPC: (upper-left, upper-right, bottom-left, bottom-right). As the small angle scattering, dominated by the Coulomb scattering, falls steeply with the increasing angle, one can identify a shift of the beam axis, if any, by a disagreement among the cross sections determined from the different sectors. The accuracy of the beam axis thus determined and monitored is $\pm 0.3^\circ$.

3.4 Angular Resolution

The scattering angle is determined from the coordinates of the hit in the Cy-MWPC and the geometrical center of the target. The error in the scattering angle calculation therefore

arises from (i) the angular divergence of the incident beam, (ii) the distribution of the reaction vertex in the target volume, and (iii) the spacial resolution of the Cy-MWPC. The effect (i) is evaluated from the 'beam' trigger as shown in Fig.3. The beam divergence was found to be 1.3° at the lowest momentum. As for the effect (ii), the vertex distribution in the plane perpendicular to the beam axis contributes most at forward angles. It is therefore determined by the beam spot size on the target. On the other hand, the vertex distribution along the beam in the target contributes most at large angles.

The effect (iii) is investigated in the following way. The horizontal angle distribution of the Cy-MWPC is plotted in Fig.4 for the event in which the antiproton is identified in the forward hodoscope slab extending from 12.5° to 17.5° . Open circles and open squares in Fig.4 are the events for the two adjacent slabs. As the forward hodoscope is located near the Cy-MWPC, this plot can be regarded as the projection of the three slabs of the forward hodoscope onto the Cy-MWPC. The diffuseness is therefore due to the spacial resolution of the Cy-MWPC and was found to be 0.5° . The spacial resolution of the Cy-MWPC at very small angles was studied in a similar way, using BAC in coincidence or anticoincidence. Again nearly the same resolution is observed.

The angular resolution, which is determined from the several effects mentioned above, is dependent on the angle but does not exceed 1 degree. The angular resolution was tested around $\theta_{Lab} = 45^\circ$ with an independent method: co-linearity of the antiproton-proton coincidence events, which gave a consistent result with the above estimates.

3.5 Multiple Coulomb Scattering at small Angles

The angular distribution of elastic scattering at 181 MeV/c is shown in Fig.5. The scattering at small angles is affected not only by single Coulomb scattering but also by multiple Coulomb scattering in the target and its vicinity. The angular distribution is well reproduced by a formula of Molière scattering[22]. In the following analysis the differential cross section above 7° at 181 MeV/c and above 5° at higher momenta are used.

3.6 Corrections for the Efficiency of the Cy-MWPC

The efficiency is measured using the following three methods: (i) with the beam, (ii) with the antiproton scattered from the target, and (iii) with pions from antiproton annihilation in the target. In each case the particles are identified with plastic scintillators, BAC or FHD, by time-of-flight and energy loss. An efficiency of 98-99% is obtained in both anode planes. It is however observed that the efficiency drops at the edge of the height. The central part in height of the cylindrical MWPC, ± 10 cm from the beam axis, is therefore used in the analysis of the data.

3.7 Corrections for the Solid Angle Acceptance

The scattering angle and the acceptance are calculated with respect to the beam axis determined experimentally as described in section 3.3. The acceptance of the Cy-MWPC in azimuthal angle (ϕ) is shown in Fig.6 as a function of the scattering angle θ_{Lab} . If we take 2π acceptance the acceptance is constant up to 10 degrees where it starts to decrease and reaches 11% at 90° . The acceptance is zero from 24 to 27 degrees because of the pole in the vacuum tank. If we take instead π acceptance at small angles, i.e. two $\pi/4$ sectors at the right and left sides, the acceptance stays flat till 14 degrees as shown with the solid line and then decreases. These two acceptances of the Cy-MWPC are used in the analysis and the consistency between the resultant cross sections are confirmed.

3.8 Beam Momentum Resolution

Although the momentum straggling depends on the thickness of the degraders in F1, the momentum width is limited by the acceptance of the beam line and the coincidence requirement between F1 and SD. The beam momentum bite is measured to be 0.9% (FWHM) by a time-of-flight over 20 m between F1 and SD. Below 300 MeV/c the momentum resolution is limited by the momentum loss in the liquid hydrogen target. In this case the momentum distribution is nearly rectangular and the r.m.s is 0.29 times the full width.

4 Results and Discussions

4.1 Real-to-Imaginary Ratio of the Forward Elastic Scattering Amplitude

The real-to-imaginary ratio of the forward elastic scattering amplitude is determined from the Coulomb-nuclear interference in the differential elastic cross section. The analysis was done for the beam momenta of 590, 505, 287, 261, 239, 219 and 181 MeV/c. These are the beam momenta at the center of the target. The momentum width is listed in Table 1. The first five momenta were with the 19.8 mm thick target and the last two momenta were with the 7.2 mm target. Following the parametrization by Bourrely et al.[23], the elastic scattering cross section is expressed as the square of a coherent sum of the amplitudes due to the Coulomb force and the strong force:

$$\frac{d\sigma}{dt} = \frac{\pi}{p_{cm}^2} \frac{d\sigma}{d\Omega_{cm}} \quad (1)$$

$$= |f_C(t) + f_N(t)|^2, \quad (2)$$

$$f_C(t) = \frac{\sqrt{4\pi}\alpha\hbar c}{\beta t} F(t)^2 e^{-i\delta_C}, \quad (3)$$

$$f_N(t) = \frac{\sigma_{tot}}{4\hbar c\sqrt{\pi}}(\rho + i)e^{-bt/2}, \quad (4)$$

$$\delta_C(t) = -[\ln(9.5t) + 0.5772]\frac{\alpha}{\beta} \quad (5)$$

$$F(t) = (1 + \frac{t}{0.71})^{-2} \quad (6)$$

where $-t$ is the four momentum transfer in units of $(\text{GeV}/c)^2$, f_C the Coulomb scattering amplitude, f_N the nuclear scattering amplitude, α the fine-structure coupling constant, β the velocity of the incident antiproton in the laboratory frame, $F(t)$ the proton form factor, δ_C the phase of Coulomb amplitude. The cross section is thus composed of a Coulomb part, an interference part, and a nuclear part:

$$\frac{d\sigma}{dt} = \frac{d\sigma_C}{dt} + \frac{d\sigma_I}{dt} + \frac{d\sigma_N}{dt}, \quad (7)$$

where

$$\frac{d\sigma_C}{dt} = 4\pi(\frac{\alpha\hbar c}{\beta t})^2 F(t)^4 \quad (8)$$

$$\frac{d\sigma_I}{dt} = \left(\frac{\alpha\sigma_{tot}}{\beta t}\right) F(t)^2 e^{-bt/2} (\rho \cos\delta_C - \sin\delta_C) \quad (9)$$

$$\frac{d\sigma_N}{dt} = \left(\frac{\sigma_{tot}}{4\hbar c\sqrt{\pi}}\right)^2 (1 + \rho^2) e^{-bt} \quad (10)$$

The parameters to be determined are σ_{tot} , ρ and b . The δ_C is a monotonic function[24] and takes, for example, a value of 5.2° at $\theta_{cm} = 5^\circ$ for the beam momentum 300 MeV/c. It should be noted that the interference term, eq.9, can be negative even when ρ is slightly positive because of the $\sin\delta_C$ term. In the process of the χ^2 fit the angular resolution is folded in the fit function. The fits are shown in Fig.7. The results of the fits are summarized in Table 1 and are shown in Fig.8.

According to ref.23, a factor $(1 + \eta^2)$ has to be included in eq.10 because of spin effects:

$$\frac{d\sigma_N}{dt} = \left(\frac{\sigma_{tot}}{4\hbar c\sqrt{\pi}}\right)^2 (1 + \rho^2)(1 + \eta^2) e^{-bt} \quad (11)$$

where η is the spin-dependent amplitude which is determined from three helicity amplitudes. In a potential model calculation by Lacombe et al.[25] η^2 ranges between 0.106 and 0.089 in the momentum region between 310 and 528 MeV/c. In the fit the effect of η^2 on ρ is small as shown in Fig.9. The result in Table 1 is obtained with $\eta = 0$.

In eq.2 it is assumed that the contributions from the Coulomb force and the nuclear force are additive at the level of the scattering amplitude. At low momenta, however, the Coulomb force could distort the incident and outgoing waves, thus affecting the nuclear part of the amplitude indirectly. We have investigated this effect using a simple Woods-Saxon potential[26] with a real and an imaginary part.

$$V(r) + iW(r), \quad (12)$$

where

$$V(r) = -\frac{V_0}{\{1 + \exp(\frac{r-R_R}{a_R})\}} \quad (13)$$

and

$$W(r) = -\frac{W_0}{\{1 + \exp(\frac{r-R_I}{a_I})\}} \quad (14)$$

The parameters adjusted to reproduce the differential elastic cross section at 287 MeV/c are $V_0 = 46$ MeV, $R_R = 1.9$ fm, $W_0 = 10$ GeV, and $R_I = 0.41$ fm, with a_R and a_I fixed at

0.2 fm. The fit is performed in the presence of the Coulomb potential. We then switch off the Coulomb potential and observe that the ρ parameter changes only by 0.01. The effect of the Coulomb force on ρ is therefore small even at low momenta.

In Fig.8 the present results together with the results from the other experiments are plotted: Kaseno et al.[8], Iwasaki et al.[10], Cresti et al.[11], Linssen et al.[27] and Schiavon et al.[28].

The ρ parameter has been analysed by various theoretical approaches: following the earlier analysis by Kaseno[29] and Grein[30], Iwasaki et al.[10] used the dispersion relation analysis with a fitted pole at 1864 MeV, which is 12.6 MeV below the $\bar{p}p$ threshold. This analysis predicts a very large negative value at small momenta and deviates from the present results. Kroll and Schweiger[31] have done the dispersion relation analysis taking into account the data from LEAR. Another analyses were made with potentials with real and imaginary parts[32], and with the coupled channel method[33]. A parametrization with the scattering length and effective range was used in refs.34-36. Systematic studies combined with analyses of the differential elastic cross section in the full angular range and of annihilation cross section are important in order to have a coherent picture of the interactions.

4.2 Differential Elastic Cross Section for the Full Angular Range

4.2.1 Comparison with pp and pn Scattering

The differential cross section for elastic scattering was analysed at 590, 550, 505, 475, 442, 287, 261, 239, 219 and 181 MeV/c. These are the beam momenta at the center of the target. The target is 19.8 mm thick except for the last two beam momenta which are with the 7.2 mm thick target. The differential cross section at 590, 505, 287 and 181 MeV/c is shown in Figs.10-11. The cross sections in Fig.11 are listed in Table 2.

The most outstanding feature of the differential cross section for antiproton-proton elastic scattering is that it is strongly forward peaked even at small momenta: the forward cross section, apart from the Coulomb scattering, is larger than the backward cross section by a factor of 30 at 287 MeV/c and by a factor of 20 at 181 MeV/c. This indicates a large contribution of $\ell \geq 1$ partial wave as a pure s-wave should yield an isotropic distribution. In

Fig.10 the proton-proton cross section at 39.4 MeV[37] and neutron-proton cross section at 47.5 MeV[38] are shown for comparison. The proton-proton cross section is shown only up to 90 degrees as it is symmetric. In the comparison, however, attention should be paid to the following point. These three interactions are subject to the Pauli exclusion principle in different ways: In pp scattering the total isospin is one and therefore the p-wave interaction requires a total spin of one and s-wave interaction requires a total spin of zero. As the result there is no interference between s- and p-wave due to the orthogonality in spin space. In pn scattering the restriction is less severe: for spin one, the $I=0$ s-wave interferes with the $I=1$ p-wave. Likewise, for spin zero, the $I=1$ s-wave interferes with the $I=0$ p-wave. In $\bar{p}p$ scattering all states with total spin one can interfere with each other, and the same is true for all states with total spin zero. Therefore, a conclusion on the partial wave composition cannot be drawn only from the slope of the differential cross sections. However, as we will show later, we extract the s- and p-wave amplitudes from the present data and a comparison is possible at the level of the phase shifts.

The curves in Fig.11 show the potential model calculations[39-41] which were done prior to the present experiment. The parameters of each potential had been adjusted to the cross section at high momenta which were available when these models were built. The model calculations agree rather well with the data.

Various analyses of differential elastic cross section have been done so far with potential models[32,33]. The differential cross section has been used also for the fit with the effective range expansion[34-36].

4.2.2 Expansion with a linear Legendre polynomial

The differential cross section has been fitted with a Legendre polynomial:

$$\frac{d\sigma}{d\Omega_{cm}} = \sum_i a_i P_i(\cos\theta). \quad (15)$$

The forward region where the Coulomb-scattering dominates, $0^\circ < \theta_{cm} < 30^\circ$ at 181 MeV/c for example, is excluded in the fit. The ratios a_i/a_0 are plotted in Fig.12. The present data of a_i/a_0 are in good agreement with those from earlier experiments[9] at 400-600 MeV/c, and show a monotonic decrease down to 181 MeV/c. The solid curves show the fit with eq.15

to the differential cross section calculated with the Dover-Richard model[42]. Sakamoto et al.[9] have done a similar fit to the calculation with the Bryan-Phillips model[43]. These two results show the same tendency. The model calculations reproduce the general trend of the data.

4.2.3 The partial Wave Amplitudes and Phase Shifts

Next, a formula of the partial wave expansion was fitted to the data below 300 Mev/c where only a few partial waves are involved.

$$\frac{d\sigma}{d\Omega_{cm}} = |f_N|^2, \quad (16)$$

$$f_N = \left(\frac{\hbar c}{p_{cm}}\right) \sum_{\ell} (2\ell + 1) T_{\ell} P_{\ell}(\cos\theta) \quad (17)$$

where T_{ℓ} 's are taken as free complex numbers. This amplitude T_{ℓ} is isospin averaged: $T_{\ell} = (T_{\ell}^{I=0} + T_{\ell}^{I=1})/2$. It should be noted that T_{ℓ} 's cannot be determined from the nuclear scattering alone. The reason is the following. If we consider $\ell = 0, 1$, and 2, for example, there are six free parameters as the T_{ℓ} 's are complex. On the other hand only five parameters, $a_i (i = 0, \dots, 4)$, can be determined by the linear Legendre expansion, eq.17, up to the corresponding order ($i=4$). Since the linear Legendre expansion is a projection to an orthogonal system we have used up the information from the experiment. The T_{ℓ} 's can be, however, determined with the addition of the sixth experimental information, the real-to-imaginary ratio of the forward elastic scattering amplitude, $\rho = \text{Re } f_N(t=0)/\text{Im } f_N(t=0)$, which is obtained from the Coulomb-nuclear interference. This information represents a phase of the amplitude.

Two alternative solutions for T_{ℓ} 's are obtained from one set of a_i 's. This duality of the solution can easily be checked arithmetically when only s- and p-waves are considered. Now the T_{ℓ} 's are plotted in the complex plane (Argand diagram) in Fig.13(a) and (b). The forward amplitude multiplied by the wave number, $f_N(0) \cdot k$, is also plotted in the figure,

$$f_N(0) \cdot k = T_0 + 3T_1 + \dots \quad (18)$$

The T_{ℓ} 's can be related to the phase shift δ_{ℓ} and the elasticity η_{ℓ} :

$$T_{\ell} = \frac{(\eta_{\ell} e^{2i\delta_{\ell}} - 1)}{2i} \quad (19)$$

It is useful to compare the present result to the calculation with a simple isospin-independent Woods-Saxon potential which is mentioned in section 4.1. This potential gives $\eta_0 = 0.39$ and $\delta_0 = -34^\circ$ for s-wave, and $\eta_1 = 0.70$ and $\delta_1 = -0.4^\circ$ for p-wave at 287 MeV/c. This calculation is consistent with the present solution A.

Myhrer and Gersten[44] calculate the phase shifts with Bryan-Phillips potential[43] and show the Argand diagram of each spin-isospin state. The real part of the s-wave amplitude is negative in each state, and the real part of the p-wave is close to zero if isospin is averaged. This result is again consistent with the present solution A.

4.2.4 The partial Wave Components in Elastic and Inelastic Cross Sections

Using T_ℓ and η_ℓ defined in eqs.18-19, the total, elastic and inelastic cross sections are expressed as follows:

$$\sigma_{tot} = \frac{4\pi}{k} \text{Im} f_N(t=0) \quad (20)$$

$$= \frac{4\pi}{k^2} \sum_{\ell} (2\ell + 1) \text{Im} T_{\ell} \quad (21)$$

$$\sigma_{el} = 4\pi a_0 \quad (22)$$

$$= \frac{4\pi}{k^2} \sum_{\ell} (2\ell + 1) |T_{\ell}|^2 \quad (23)$$

$$\sigma_{inel} = \frac{\pi}{k^2} \sum_{\ell} (2\ell + 1) (1 - \eta_{\ell}^2). \quad (24)$$

Note that, in the notation which we use in this paper, the inelastic cross section consists of the annihilation and charge-exchange cross sections. In the case of the black disk, $\eta_{\ell} = 0$ or $T_{\ell} = i/2$, the inelastic cross section has its maximum value of:

$$\sigma_{inela} = \sigma_{el} = \frac{\pi}{k^2} \sum_{\ell} (2\ell + 1) \quad (25)$$

The elastic and inelastic cross sections and their s-wave components are plotted in Fig.14. The s-wave inelastic cross section is close to the geometrical limit. The p-wave inelastic cross section becomes smaller than the geometrical limit as the beam momentum decreases. However, it is remarkable that a significant fraction of the inelastic cross section is due to the p-wave even at very small momenta.

4.2.5 Comparison with Charge-Exchange Cross Section

The differential cross sections for elastic scattering and charge-exchange reaction[6] at 287 MeV/c are compared in Fig.15. T_t in eq.18 denotes an isospin averaged amplitude $T_t = (T_t^{I=0} + T_t^{I=1})/2$; if we change it to $(T_t^{I=0} - T_t^{I=1})/2$, the charge-exchange cross section is expressed. The elastic cross section obtained from the experiment is larger than the charge-exchange cross section by a factor of 3-5. This indicates that $|(T_t^{I=0} + T_t^{I=1})/2|$ is larger than $|(T_t^{I=0} - T_t^{I=1})/2|$, meaning that the vector of the $I = 0$ amplitude $T_t^{I=0}$ and the $I = 1$ amplitude $T_t^{I=1}$ tend to have a small opening angle.

5 Conclusion

The differential cross section for antiproton-proton elastic scattering has been measured for beam momenta between 180 and 600 MeV/c. The present experiment is the first precision measurement in this momentum range, owing to the high quality antiproton beam from LEAR and the detector optimized for low momenta.

The real-to-imaginary ratio of the forward elastic scattering amplitude is derived from the Coulomb-nuclear interference. The ratio is found to be close to zero down to 181 MeV/c with a minimum of -0.14 at 260 MeV/c, contrary to the model predictions.

The phase shifts for the s-, p- and d-waves are extracted and the partial wave composition of the elastic and inelastic cross sections have been determined. A large contribution of the p-wave is found in the antiproton-proton interactions at small momenta.

6 Acknowledgement

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Table 1. The results of the fits with ρ , σ_{tot} and b .

Momentum (MeV/c)	Momentum full width (MeV/c)	ρ	σ_{tot} (mb)	b (GeV/c) ⁻²	χ^2/DF
590	10	0.203 ± 0.110	140.0 ± 2.6	22.8 ± 0.94	57.8/49
505	10	-0.046 ± 0.119	162.7 ± 2.6	26.4 ± 1.14	69.6/48
287	14	-0.103 ± 0.018	229.3 ± 2.0	32.3 ± 1.70	40.6/39
261	18	-0.142 ± 0.026	252.4 ± 2.0	39.2 ± 2.00	41.3/39
239	23	-0.028 ± 0.032	261.2 ± 5.7	52.4 ± 3.80	60.3/46
219	8	0.093 ± 0.098	292.1 ± 23.6	61.2 ± 16.5	32.0/41
181	16	0.100 ± 0.084	339.4 ± 30.6	83.7 ± 24.0	39.1/43

Table 2. The differential cross section for antiproton-proton elastic scattering. The errors shown are only statistical.

590 MeV/c			
θ_{cm} (deg)	$(\frac{d\sigma}{d\Omega})_{cm}$ (barn/sr)	θ_{cm} (deg)	$(\frac{d\sigma}{d\Omega})_{cm}$ (barn/sr)
4.7	0.397E+00 $\pm$ 0.35E-01	94.0	0.598E-03 $\pm$ 0.92E-04
7.6	0.504E-01 $\pm$ 0.57E-02	99.7	0.290E-03 $\pm$ 0.50E-04
10.4	0.295E-01 $\pm$ 0.25E-02	105.5	0.187E-03 $\pm$ 0.33E-04
13.3	0.262E-01 $\pm$ 0.20E-02	111.2	0.193E-03 $\pm$ 0.33E-04
16.2	0.230E-01 $\pm$ 0.11E-02	117.0	0.155E-03 $\pm$ 0.33E-04
19.1	0.218E-01 $\pm$ 0.92E-03	122.8	0.224E-03 $\pm$ 0.42E-04
22.0	0.223E-01 $\pm$ 0.81E-03	128.5	0.175E-03 $\pm$ 0.35E-04
24.8	0.182E-01 $\pm$ 0.73E-03	145.8	0.302E-03 $\pm$ 0.65E-04
27.7	0.166E-01 $\pm$ 0.92E-03	151.6	0.468E-03 $\pm$ 0.65E-04
30.6	0.170E-01 $\pm$ 0.69E-03	157.3	0.540E-03 $\pm$ 0.60E-04
33.5	0.161E-01 $\pm$ 0.64E-03	163.1	0.660E-03 $\pm$ 0.85E-04
36.4	0.128E-01 $\pm$ 0.62E-03	168.8	0.790E-03 $\pm$ 0.11E-03
39.2	0.118E-01 $\pm$ 0.71E-03		
42.1	0.110E-01 $\pm$ 0.53E-03		
45.0	0.853E-02 $\pm$ 0.49E-03		
47.9	0.804E-02 $\pm$ 0.53E-03		
59.4	0.381E-02 $\pm$ 0.45E-03		
62.3	0.402E-02 $\pm$ 0.38E-03		
65.2	0.314E-02 $\pm$ 0.47E-03		
68.0	0.298E-02 $\pm$ 0.36E-03		
70.9	0.173E-02 $\pm$ 0.30E-03		
73.8	0.152E-02 $\pm$ 0.24E-03		
76.7	0.167E-02 $\pm$ 0.24E-03		
79.6	0.158E-02 $\pm$ 0.23E-03		
82.4	0.124E-02 $\pm$ 0.21E-03		
85.3	0.116E-02 $\pm$ 0.22E-03		
88.2	0.500E-03 $\pm$ 0.16E-03		

505 MeV/c			
θ_{cm} (deg)	$(\frac{d\sigma}{d\Omega})_{cm}$ (barn/sr)	θ_{cm} (deg)	$(\frac{d\sigma}{d\Omega})_{cm}$ (barn/sr)
4.7	0.287E+00 $\pm$ 0.33E-01	91.1	0.995E-03 $\pm$ 0.18E-03
7.6	0.424E-01 $\pm$ 0.74E-02	94.0	0.118E-02 $\pm$ 0.25E-03
10.4	0.440E-01 $\pm$ 0.48E-02	96.8	0.130E-02 $\pm$ 0.25E-03
13.3	0.254E-01 $\pm$ 0.25E-02	99.7	0.933E-03 $\pm$ 0.17E-03
16.2	0.179E-01 $\pm$ 0.14E-02	102.6	0.860E-03 $\pm$ 0.16E-03
19.1	0.211E-01 $\pm$ 0.10E-02	105.5	0.691E-03 $\pm$ 0.16E-03
22.0	0.207E-01 $\pm$ 0.84E-03	108.4	0.329E-03 $\pm$ 0.15E-03
24.8	0.186E-01 $\pm$ 0.88E-03	111.2	0.592E-03 $\pm$ 0.18E-03
27.7	0.180E-01 $\pm$ 0.69E-03	114.1	0.622E-03 $\pm$ 0.14E-03
30.6	0.172E-01 $\pm$ 0.64E-03	117.0	0.595E-03 $\pm$ 0.18E-03
33.5	0.155E-01 $\pm$ 0.61E-03	119.9	0.457E-03 $\pm$ 0.15E-03
36.4	0.135E-01 $\pm$ 0.57E-03	122.8	0.858E-03 $\pm$ 0.20E-03
39.2	0.122E-01 $\pm$ 0.64E-03	125.6	0.320E-03 $\pm$ 0.18E-03
42.1	0.116E-01 $\pm$ 0.49E-03	134.3	0.371E-03 $\pm$ 0.22E-03
45.0	0.945E-02 $\pm$ 0.44E-03	137.2	0.345E-03 $\pm$ 0.16E-03
47.9	0.683E-02 $\pm$ 0.54E-03	140.0	0.685E-03 $\pm$ 0.14E-03
50.8	0.660E-02 $\pm$ 0.83E-03	142.9	0.230E-03 $\pm$ 0.16E-03
59.4	0.486E-02 $\pm$ 0.43E-03	145.8	0.574E-03 $\pm$ 0.12E-03
62.3	0.451E-02 $\pm$ 0.36E-03	148.7	0.749E-03 $\pm$ 0.15E-03
65.2	0.439E-02 $\pm$ 0.37E-03	151.6	0.845E-03 $\pm$ 0.16E-03
68.0	0.350E-02 $\pm$ 0.30E-03	154.4	0.621E-03 $\pm$ 0.17E-03
70.9	0.285E-02 $\pm$ 0.25E-03	157.3	0.857E-03 $\pm$ 0.22E-03
73.8	0.242E-02 $\pm$ 0.32E-03	160.2	0.757E-03 $\pm$ 0.26E-03
76.7	0.253E-02 $\pm$ 0.33E-03	163.1	0.142E-02 $\pm$ 0.30E-03
79.6	0.173E-02 $\pm$ 0.22E-03	166.0	0.115E-02 $\pm$ 0.44E-03
82.4	0.165E-02 $\pm$ 0.19E-03	168.8	0.143E-02 $\pm$ 0.71E-03
85.3	0.130E-02 $\pm$ 0.20E-03		
88.2	0.123E-02 $\pm$ 0.19E-03		

287 MeV/c			
θ_{cm} (deg)	$(\frac{d\sigma}{d\Omega})$ (barn/sr)	θ_{cm} (deg)	$(\frac{d\sigma}{d\Omega})_{cm}$ (barn/sr)
5.4	0.108E+01 $\pm$ 0.27E-01	90.0	0.271E-02 $\pm$ 0.17E-03
6.5	0.373E+00 $\pm$ 0.84E-02	92.9	0.275E-02 $\pm$ 0.17E-03
7.6	0.160E+00 $\pm$ 0.47E-02	95.8	0.204E-02 $\pm$ 0.16E-03
8.3	0.998E-01 $\pm$ 0.34E-02	98.6	0.229E-02 $\pm$ 0.20E-03
9.4	0.633E-01 $\pm$ 0.24E-02	101.5	0.183E-02 $\pm$ 0.15E-03
10.4	0.479E-01 $\pm$ 0.19E-02	104.4	0.167E-02 $\pm$ 0.14E-03
12.2	0.291E-01 $\pm$ 0.72E-03	107.3	0.113E-02 $\pm$ 0.14E-03
15.1	0.221E-01 $\pm$ 0.62E-03	110.2	0.774E-03 $\pm$ 0.20E-03
18.0	0.193E-01 $\pm$ 0.42E-03	115.9	0.102E-02 $\pm$ 0.14E-03
20.9	0.170E-01 $\pm$ 0.38E-03	118.8	0.972E-03 $\pm$ 0.14E-03
23.8	0.158E-01 $\pm$ 0.37E-03	121.7	0.884E-03 $\pm$ 0.13E-03
26.6	0.158E-01 $\pm$ 0.35E-03	124.6	0.736E-03 $\pm$ 0.12E-03
29.5	0.143E-01 $\pm$ 0.33E-03	136.1	0.577E-03 $\pm$ 0.68E-04
32.4	0.139E-01 $\pm$ 0.39E-03	139.0	0.536E-03 $\pm$ 0.77E-04
35.3	0.133E-01 $\pm$ 0.31E-03	141.8	0.619E-03 $\pm$ 0.80E-04
38.2	0.127E-01 $\pm$ 0.30E-03	144.7	0.570E-03 $\pm$ 0.74E-04
41.0	0.131E-01 $\pm$ 0.30E-03	147.6	0.424E-03 $\pm$ 0.87E-04
43.9	0.113E-01 $\pm$ 0.28E-03	150.5	0.457E-03 $\pm$ 0.72E-04
58.3	0.863E-02 $\pm$ 0.34E-03	153.4	0.399E-03 $\pm$ 0.95E-04
61.2	0.906E-02 $\pm$ 0.34E-03	156.2	0.500E-03 $\pm$ 0.12E-03
64.1	0.818E-02 $\pm$ 0.34E-03	159.1	0.336E-03 $\pm$ 0.95E-04
67.0	0.732E-02 $\pm$ 0.36E-03	162.0	0.433E-03 $\pm$ 0.13E-03
69.8	0.772E-02 $\pm$ 0.30E-03	164.9	0.228E-03 $\pm$ 0.13E-03
72.7	0.632E-02 $\pm$ 0.23E-03	167.8	0.416E-03 $\pm$ 0.12E-03
75.6	0.568E-02 $\pm$ 0.28E-03	170.6	0.628E-03 $\pm$ 0.19E-03
78.5	0.564E-02 $\pm$ 0.23E-03		
81.4	0.440E-02 $\pm$ 0.22E-03		
84.2	0.326E-02 $\pm$ 0.17E-03		
87.1	0.264E-02 $\pm$ 0.16E-03		

181 MeV/c			
θ_{cm} (deg)	$(\frac{d\sigma}{d\Omega})_{cm}$ (barn/sr)	θ_{cm} (deg)	$(\frac{d\sigma}{d\Omega})_{cm}$ (barn/sr)
7.9	0.172E+01 $\pm$ 0.42E-01	91.4	0.602E-02 $\pm$ 0.25E-02
10.8	0.298E+00 $\pm$ 0.12E-01	94.3	0.508E-02 $\pm$ 0.23E-02
13.7	0.130E+00 $\pm$ 0.61E-02	100.1	0.546E-02 $\pm$ 0.21E-02
16.6	0.858E-01 $\pm$ 0.45E-02	103.0	0.507E-02 $\pm$ 0.14E-02
19.4	0.485E-01 $\pm$ 0.34E-02	107.3	0.500E-02 $\pm$ 0.20E-02
22.3	0.260E-01 $\pm$ 0.22E-02	111.6	0.676E-02 $\pm$ 0.11E-02
25.2	0.195E-01 $\pm$ 0.20E-02	114.5	0.421E-02 $\pm$ 0.99E-03
28.1	0.181E-01 $\pm$ 0.21E-02	117.4	0.408E-02 $\pm$ 0.12E-02
31.0	0.169E-01 $\pm$ 0.17E-02	120.2	0.399E-02 $\pm$ 0.11E-02
33.8	0.157E-01 $\pm$ 0.17E-02	123.1	0.445E-02 $\pm$ 0.10E-02
36.7	0.132E-01 $\pm$ 0.15E-02	134.6	0.367E-02 $\pm$ 0.21E-02
39.6	0.118E-01 $\pm$ 0.15E-02	137.5	0.396E-02 $\pm$ 0.83E-03
42.5	0.132E-01 $\pm$ 0.16E-02	140.4	0.311E-02 $\pm$ 0.76E-03
45.4	0.105E-01 $\pm$ 0.15E-02	143.3	0.284E-02 $\pm$ 0.72E-03
59.8	0.947E-02 $\pm$ 0.18E-02	146.2	0.216E-02 $\pm$ 0.97E-03
62.6	0.860E-02 $\pm$ 0.20E-02	149.0	0.304E-02 $\pm$ 0.81E-03
65.5	0.541E-02 $\pm$ 0.15E-02	151.9	0.288E-02 $\pm$ 0.83E-03
68.4	0.534E-02 $\pm$ 0.15E-02	154.8	0.322E-02 $\pm$ 0.90E-03
71.3	0.735E-02 $\pm$ 0.18E-02	157.7	0.472E-02 $\pm$ 0.11E-02
74.2	0.615E-02 $\pm$ 0.21E-02	160.6	0.340E-02 $\pm$ 0.75E-03
77.0	0.612E-02 $\pm$ 0.16E-02	163.4	0.331E-02 $\pm$ 0.73E-03
79.9	0.547E-02 $\pm$ 0.13E-02	166.3	0.405E-02 $\pm$ 0.93E-03
85.7	0.574E-02 $\pm$ 0.23E-02	169.2	0.504E-02 $\pm$ 0.16E-02

Figure Captions

Fig.1 (1)Vertical and (2)horizontal plane cuts of the apparatus.

Fig.2 Antiproton-proton coincidence events in the cylindrical MWPC. The horizontal and vertical axes are angles on the right- and left-side of the beam in the lab. frame.

Fig.3 A beam profile on the cylindrical MWPC at 181 MeV/c from 'beam' trigger run with the empty 7.2 mm target. The closed circles show the horizontal distribution and the open circles the vertical distribution.

Fig.4 A projection of the three adjacent slabs of the forward hodoscope on the cylindrical MWPC. Pions are identified and selected in the hodoscope. The horizontal axis is the angle in the horizontal scattering plane.

Fig.5 The angular distribution of $\bar{p}$ at 181 MeV/c with the 2 cm liquid hydrogen target. The data are well reproduced if Molière scattering is taken into account. The deviation above 7° is due to the strong interaction.

Fig.6 The azimuthal angle acceptance for elastic scattering. The solid curve is for the π acceptance and the dashed curve is for the 2π acceptance. See the text for the detail.

Fig.7 The fits to the cross section (a) at 287 MeV/c and (b) at 181 MeV/c. The interference term with a reversed sign and the nuclear term are also plotted.

Fig.8 The real-to-imaginary ratio, ρ , of the forward elastic scattering amplitude as a function of the beam momentum. The present result along with the data of Kaseno et al.[29], Iwasaki et al.[10], Cresti et al.[11], Linssen et al.[27], Schiavon et al.[28] are shown.

Fig.9 The effect of the spin-dependent parameter η on ρ , σ_{tot} , and b at 287 MeV/c; σ_{tot} , ρ and b are fitted to the data at fixed η -value between 0 and 0.6.

Fig.10 A comparison of the differential cross sections for $\bar{p}p$, proton-proton and proton-neutron scattering around 287 MeV/c.

Fig.11 Differential cross sections for elastic $\bar{p}$ scattering in the full angular range. The solid, dashed and dash-dotted curves represent model calculations of Myhrer et al.[39], Lacombe et al.[40], and Timmers et al.[41], respectively. At 590 MeV/c the calculation by Timmers et al. is not plotted as it almost overlaps the one by Lacombe et al.

Fig.12 The coefficients of the linear Legendre expansion of the elastic scattering, a_i/a_0 . The black circles are present data. The open circles are from ref.9. The curves indicate the fit to the cross sections calculated with the Dover-Richard potential[42].

Fig.13 The partial wave amplitudes T_l in the complex plane (the Argand diagram). The forward elastic scattering amplitudes $f(t=0) * p_{cm}$ are also plotted. (a) The solution with a negative $\text{Re}T_0$ and a positive $\text{Re}T_1$, (b) the solution with a positive $\text{Re}T_0$ and a negative $\text{Re}T_1$.

Fig.14 (a)The inelastic cross section and its s-wave component. The squares show total inelastic cross section. The full circles are the s-wave inelastic cross section calculated from the solution A and the open circles from B. (b)The elastic cross section and its s-wave component. The squares show total elastic cross section. The solutions A and B give the same s-wave elastic cross section which is shown with the full circles. The dashed curves show cross sections corresponding to a black disk with s-wave only and with s- and p-waves.

Fig.15 A comparison of the differential cross sections for $\bar{p}p$ elastic scattering and for charge-exchange reaction ($\bar{p}p \rightarrow \bar{n}n$)[6] at 287 MeV/c.

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