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**ANTIPROTON-PROTON ELASTIC CROSS-SECTIONS
IN THE MOMENTUM RANGE BETWEEN 180 AND 600 MeV/c**

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ABSTRACT

Differential cross-sections for $\bar{p}p$ elastic scattering have been measured in the full angular range for the $\bar{p}$ momenta between 180 and 600 MeV/c. It is found that s- and p-wave scattering is dominant below 300 MeV/c. The s-wave component in the total cross-section is 40–60% below 300 MeV/c, in contrast to the NN scattering where it is about 90%. The s-, p- and d-wave scattering amplitudes are derived.

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1. INTRODUCTION

The $\bar{p}p$ reaction at low energy is characterized by a very large inelastic cross-section, which amounts to as much as 70% of the total cross-section. This large inelastic cross-section is due to the strong annihilation channel and will influence greatly the differential elastic scattering. The measurement of the differential elastic cross-section at low energies in the full angular range will allow a decomposition of the scattering amplitude into partial-wave contributions. With this information a sensitive test of the existing models of the $\bar{N}N$ potential will become possible.

So far the potentials for the $\bar{p}p$ interaction were theoretically derived from those of the NN interaction using the boson-exchange model with the G-parity transformation. In order to incorporate the effect of annihilation these models introduce an empirical imaginary potential or boundary conditions. A determination of the parameters of the complex $\bar{p}p$ potential will, therefore, test the boson-exchange description of the long-range real part (nuclear force). On the other hand, one of the intriguing aspects of the annihilation channel is that it proceeds via quark rearrangement and fusion. Therefore, the range and strength of the annihilation potential might indicate the spatial inset of the quark degree of freedom in the $\bar{N}N$ interaction.

In this present experiment we measure the spin-averaged scattering amplitudes since the spin-dependent amplitude can be studied only with a polarized $\bar{p}$ beam. Also, it should be noted that the elastic-scattering amplitude is the sum of the isospin $I = 0$ and $I = 1$ amplitudes with equal weights.

In this paper we report a measurement of the $\bar{p}p$ differential elastic cross-sections in the $\bar{p}$ momentum region between 180 and 600 MeV/c. The measurement of the differential elastic cross-sections at very forward angles and the extraction of the real-to-imaginary ratio of the forward elastic-scattering amplitude have been reported in a previous paper [1]. Differential elastic cross-sections in the full angular range below 700 MeV/c have so far been measured with bubble chambers [2-4]. Data below 400 MeV/c are very sparse and incomplete. The experiment was performed at the Low Energy Antiproton Ring (LEAR) facility of CERN, which provided for the first time a $\bar{p}$ beam of high quality below 300 MeV/c.

2. EXPERIMENTAL METHODS

A detailed description of the detector is given elsewhere [1,5]. The forward scintillator hodoscope is placed around the target at a distance of 66 cm and serves to detect antiprotons and protons. A ring of antineutron calorimeters surrounds it. The upper-, lower- and back-sides of the target are covered by the hodoscopes of plastic scintillator in order to detect pions coming from the $\bar{p}$ annihilation in the target. These hodoscopes cover 73% of the full solid angle. The multiple pion production in the $\bar{p}$ annihilation is simulated by a Monte Carlo calculation and the detection efficiency of the $\bar{p}$ annihilation in the target is $94 \pm 0.5\%$.

The elastic-scattering events are identified as follows. Firstly, the time-of-flight and energy loss in the forward hodoscope are used to distinguish antiprotons and protons from pions. The particle is then identified as an antiproton if it is not accompanied with a signal of annihilation in the target or if the annihilation signal comes at a time appropriate for annihilation in or after the forward hodoscope.

In the case where the antiproton is scattered backwards in the c.m. system, the proton is knocked out in the forward direction. The backward-scattered antiproton is of such low energy that it stops and annihilates in the target. Hence, the particle in the forward hodoscope is identified as a proton if it is accompanied by a signal of annihilation in the target.

At intermediate angles ($50^\circ < \theta_{cm} < 120^\circ$) both an antiproton and a proton are detected in the forward hodoscope. In this case the slabs of the forward hodoscope or the antineutron calorimeter next to the $\bar{p}$ signal are fired by the annihilation products.

Two liquid-hydrogen targets are used: one of 7 and one of 20 mm thickness. The beam spot on the target has a diameter of 5 mm. The beam divergence is 0.7° (r.m.s.) even at the lowest momentum, 181 MeV/c. The scattering angle is derived from the coordinate of the beam spot and the coordinate measured by a cylindrical multiwire proportional chamber (MWPC) placed before the forward hodoscope. The resolution of the scattering angle in the forward direction is determined by the beam-spot size and the MWPC resolution, and is 1.0° (FWHM). It becomes 2.0° (full width) at large angles in the measurement above 230 MeV/c because of the target length (20 mm). The 7 mm thick target is used for the lower momenta.

The resolution of the antiproton momentum is determined by the beam momentum width above 400 MeV/c and by the momentum loss in the target below 300 MeV/c. The momentum full widths of the antiproton are 10, 10, 14, 18, 23, 8, and 16 MeV/c at the central momenta of 590, 505, 287, 261, 239, 219, and 181 MeV/c, respectively.

3. DISCUSSIONS OF THE EXPERIMENTAL RESULTS

Examples of the differential elastic cross-sections at 505, 287, and 181 MeV/c are shown in Figs. 1 and 2. In Fig. 1 we compare the differential elastic cross-section for $\bar{p}p$ at 287 MeV/c with that for pp [6] at 275 MeV/c, in order to illustrate the significance of our data. At this momentum the s-wave scattering is dominant in the pp cross-section, while higher partial waves must contribute to the $\bar{p}p$ scattering.

Potential model predictions [7,8,9] for the differential elastic cross-sections are compared with the data in Fig. 2.

In order to derive the partial-wave composition in a model-independent way we have fitted the differential elastic cross-sections at $30^\circ < \theta_{cm} < 180^\circ$ with a linear combination of the Legendre functions:

$$d\sigma/d\Omega_{cm} = \sum_i a_i P_i(\cos \theta). \quad (1)$$

The χ^2/DF value is around 1.2. In Fig. 3 the coefficients a_i normalized to a_0 are plotted together with those of Sakamoto et al. [4]. At 300 MeV/c and lower momenta, a_1/a_0 and a_2/a_0 are dominant, suggesting that the s- and the p-wave play the main role. We have calculated differential elastic cross-sections using the Dover-Richard code [10] and fitted with eq. (1). The resulting coefficients are shown in Fig. 3 by the curves. Sakamoto et al. [4] have done a similar calculation and a fit using the Bryan-Phillips model [11]. The results show nearly the same tendency. The model calculations reproduce the trend of the experimental results. However, some distinct deviations are seen.

Next, we have fitted the differential elastic cross-sections in the full angular region with the Coulomb- and nuclear-scattering amplitudes of the following form:

$$d\sigma/d\Omega_{cm} = (p_{cm}^2/\pi) \cdot d\sigma/dt = |f_C + f_N|^2 \quad (2)$$

$$f_C = (2\alpha\hbar c p_{cm}/\beta t) \cdot F(t) e^{-i\delta(t)} \quad (3)$$

$$F(t) = (1 + t/0.71)^{-2} \quad (4)$$

$$\delta(t) = -[\ln(9.5t) + 0.5772]\alpha/\beta \quad (5)$$

$$f_N = (\hbar c/p_{cm}) \sum_{\ell} (2\ell + 1) T_{\ell} P_{\ell}(\cos \theta), \quad (6)$$

where α is the fine-structure constant, β the velocity of the antiproton in the laboratory frame, $F(t)$ the Coulomb form factor of the proton, $-t$ the four-momentum transfer in $(\text{GeV}/c)^2$, and T_{ℓ} 's free parameters. As mentioned in the Introduction, we have taken only the spin-independent terms in eq. (6). The amplitude T_{ℓ} is the isospin averaged one: $T_{\ell} = [T_{\ell}(I=0) + T_{\ell}(I=1)]/2$.

If we consider $\ell = 0, 1$, and 2 , for example, in eqs. (2)–(6) for the beam momenta below $300 \text{ MeV}/c$, there are six free parameters since the T_{ℓ} 's are complex numbers. From the differential cross-section of the nuclear part alone ($\theta_{cm} > 30^\circ$), we obtain five experimental quantities. This corresponds to the fact that we obtain five quantities $a_{0,1,2,3,4}$ from eq. (1), which is a linear expansion in a system of orthogonal functions. So we need one more piece of experimental information in order to fix T_0 , T_1 , and T_2 . This sixth quantity is the real-to-imaginary ratio of the forward elastic-scattering amplitude [1], $\rho = \text{Re } f_N(t=0)/\text{Im } f_N(t=0)$, which can be determined from the Coulomb–nuclear interference region.

Two solutions for T_{ℓ} correspond to one solution of a_i , as is evident from the arithmetic relation between the coefficients a_i in eq. (1) and T_{ℓ} in eqs. (2)–(6). Figures 4a and b show these two alternative solutions of T_{ℓ} 's, which give a negative real part for the s-wave amplitude and a positive real part for the p-wave amplitude (solution A), and vice versa (solution B). The d-wave amplitude T_2 is found to be small below $300 \text{ MeV}/c$.

If we derive from T_{ℓ} the elasticity η_{ℓ} and phase shift δ_{ℓ} by the relation

$$T_{\ell} = (\eta_{\ell} e^{2i\delta_{\ell}} - 1)/2i, \quad (7)$$

we find that the phase shift is small in both cases A and B: $\mp(15^\circ\text{--}30^\circ)$ for the s-wave and $\pm(0^\circ\text{--}5^\circ)$ for the p-wave. There is an ambiguity of $n\pi$ in the phase shifts, and it must be determined separately for the phase shift of each spin and isospin. The elasticity η for the s- and the p-wave is between 0.3 and 0.8 . This combination of the elasticity η_{ℓ} and the phase shift δ_{ℓ} gives the observed large ratio of the inelastic-to-elastic cross-section.

We compare the results of model calculations with these two solutions. Myhrer and Gersten [12] show the Argand diagrams of the partial-wave amplitudes using the Bryan–Phillips potential. The real parts of all the spin–isospin amplitudes of the s-wave are negative, and the real parts of the p-wave are close to zero after being averaged over the isospin. These features are in agreement with the present case A.

We have fitted the differential elastic cross-sections by an optical potential with a real and an imaginary part of the Woods–Saxon type [13]:

$$V(r) + iW(r), \quad (8)$$

where

$$V(r) = -V_0/\{1 + \exp[(r - R_R)/a_R]\}, \quad (9)$$

and

$$W(r) = -W_0/\{1 + \exp[(r - R_I)/a_I]\}. \quad (10)$$

A typical solution is $V_0 = 46.0 \pm 8.0$ MeV, $R_R = 1.89 \pm 0.10$ fm, $W_0 = 10.1 \pm 4.5$ GeV, and $R_I = 0.411 \pm 0.063$ fm, with a fixed diffuseness of 0.2 fm for a_R and a_I at the beam momentum of 287 MeV/c. The value of χ^2/DF is 1.3 for 41 data points. This solution gives $\eta_0 = 0.39$ and $\delta_0 = -34^\circ$ for the s-wave and $\eta_1 = 0.70$ and $\delta_1 = -0.4^\circ$ for the p-wave. The real part of the s-wave amplitude T_0 is negative, in agreement with the present case A.

Next, we consider the partial-wave contributions to the cross-sections. The total, elastic, and inelastic cross-sections are expressed as

$$\sigma_{\text{tot}} = 4\pi(1/k) \text{Im } f_N(t=0) = 4\pi(1/k)^2 \sum_{\ell} (2\ell+1) \text{Im } T_{\ell} \quad (11)$$

$$\sigma_{\text{el}} = 4\pi a_0 = 4\pi(1/k)^2 \sum_{\ell} (2\ell+1) |T_{\ell}|^2 \quad (12)$$

$$\sigma_{\text{inel}} = \pi(1/k)^2 \sum_{\ell} (2\ell+1) (1 - \eta_{\ell}^2), \quad (13)$$

where k is the c.m. momentum divided by $\hbar c$. The elastic and inelastic cross-sections and their s-wave components [the first term of eqs. (12) and (13)] are shown in Fig. 5. The s-wave contributions account for about 70% of the elastic cross-section and about 40% of the inelastic cross-section. In Fig. 5 the partial-wave cross-sections for the black disk, $\eta_{\ell} = 0$ or $T_{\ell} = i/2$, are shown by dotted curves for comparison. They are $\sigma_{\text{el}} = \sigma_{\text{inel}} = \pi(1/k)^2$ for the s-wave and $3\pi(1/k)^2$ for the p-wave. The black-disk value gives the unitarity limit for the inelastic cross-section. In the inelastic cross-section the s-wave component is close to the unitarity limit, while the p-wave component is less than 60% of the unitarity limit. In the elastic cross-section the s-wave component is about 60% of the black-disk value and the p-wave component is even less. The d-wave contribution to the cross-sections is less than 10%.

In conclusion, we have presented the $\bar{p}p$ elastic scattering data at low energy with high precision. It is found that s- and p-waves are dominant below 300 MeV/c. The s-wave inelastic cross-sections are close to the unitarity limit. However, the s-wave component in the total cross-sections amounts to only 40–60%, in contrast to the NN scattering where it is about 90%. The small phase shift, in combination with the elasticity $\eta = 0.3$ –0.8 gives the large ratio of the inelastic-to-elastic cross-sections of about 2.5.

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REFERENCES

- [1] W. Brückner et al., Phys. Lett. **158B** (1985) 180.
- [2] B. Conforto et al., Nuovo Cimento **54A** (1968) 441.
- [3] D. Spencer and D.N. Edwards, Nucl. Phys. **B19** (1970) 501.
- [4] S. Sakamoto, T. Hashimoto, F. Sai and S.S. Yamamoto, Nucl. Phys. **B195** (1982) 1.
- [5] W. Brückner et al., Proc. 7th European Symposium on Antiproton Interactions, Durham, 1984 (Inst. Phys. Conf. Ser. No. 73, Adam Hilger Ltd., Bristol and Boston, 1985), p. 157; and technical report in preparation.
- [6] L.H. Johnston and D.A. Swenson, Phys. Rev. **111** (1958) 212.
- [7] F. Myhrer, private communication;
O.D. Dalkarov and F. Myhrer, Nuovo Cimento **40A** (1977) 152.
- [8] M. Lacombe, private communication;
J. Côté et al., Phys. Rev. Lett. **48** (1982) 1319.
- [9] P.H. Timmers, private communication;
P.H. Timmers, W.A. van der Sanden and J.J. de Swart, Phys. Rev. **D29** (1984) 1928.
- [10] J.M. Richard, private communication;
C.B. Dover and J.M. Richard, Phys. Rev. **C21** (1980) 1466.
- [11] R.A. Bryan and R.J.N. Phillips, Nucl. Phys. **B5** (1968) 201.
- [12] F. Myhrer and A. Gersten, Nuovo Cimento **37A** (1977) 21.
- [13] E.H. Auerbach, Comput. Phys. Commun. **15** (1978) 165.

Figure captions

- Fig. 1 The differential elastic cross-sections for $\bar{p}p$ at 287 MeV/c and pp [6] at 275 MeV/c.
- Fig. 2 Differential elastic $\bar{p}p$ cross-sections at 505, 287, and 181 MeV/c. The solid, dashed and dash-dotted curves represent model calculations of Myhrer [7], Lacombe [8] and Timmers [9], respectively.
- Fig. 3 The coefficient of the linear Legendre expansion of the elastic scattering. The black diamonds, circles, squares, and triangles are the present data. The open ones are from Sakamoto et al. [4]. The curves indicate the fit to the differential cross-sections calculated with the code of Dover-Richard [10].
- Fig. 4 The partial-wave amplitudes T_ℓ in the complex plane (Argand diagram). The forward elastic-scattering amplitudes $f_N(t=0) \cdot k = T_0 + 3T_1 + \dots$ are also plotted. (a) and (b) correspond to the solutions A and B, respectively.
- Fig. 5 (a) Inelastic and (b) elastic cross-sections are shown by black squares. The black circles indicate s-wave components in the solution A, and the open ones indicate those in the solution B. In the elastic scattering these two solutions give the same s-wave component. The cross-sections corresponding to a black disk ($\eta=0$) are shown by dashed curves for comparison.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5