TOTAL π-p CROSS SECTIONS AT HIGH ENERGIES

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The total π^-p cross sections were measured at 3.4, 3.9, 4.9, 7.0, and 9.2 BeV/c. The results of the measurements indicate that the cross section decreases slowly with increasing energy.

1. INTRODUCTION

A number of theoretical predictions have been made on the behavior of the total cross sections for interactions between elementary particles at high energies. On the basis of charge independence and arguments indicating that the charge-exchange cross section asymptotically tends to zero, Pomeranchuk and Okun'[1,2] have shown that the total cross sections for interactions of pions and nucleons with nucleons should not depend on the isospin of the system. With the aid of the dispersion relations and under the assumption that the total cross sections tend to a constant limiting value, Pomeranchuk[3] has also shown that at high energies the total cross sections for interactions of particles and antiparticles with the same target should be equal. Recently, however, there have been indications[4,5] that there are difficulties connected with the suggestion on the tendency of the cross sections to approach constant value and that the cross sections may decrease with increasing energy. The limits of applicability for this behavior cannot be determined theoretically. It is therefore of interest to determine experimentally how the total interaction cross sections vary at energies available in accelerators.

The total π^-p cross sections $\sigma_t(\pi^-, p)$ in the region above 1 BeV have been measured by a number of workers,* but detailed data are available only for energies up to ~2 BeV. The values of $\sigma_t(\pi^-, p)$ measured at CERN[7] for 4.75—10 BeV/c have large errors due to the inaccurate determination of the muon contamination in the beam. In the 2–4.75-BeV interval, no systematic measurements of $\sigma_t(\pi^-, p)$ have been made, and the individual results available have large errors.

In this experiment, we measured $\sigma_t(\pi^-, p)$ at 3.4, 3.9, 4.9, and 7.0 BeV/c and obtained an estimate of the cross section at 9.2 BeV/c.

*For a summary of the data and a bibliography see [6].

2. EXPERIMENTAL ARRANGEMENT

The measurements for the first three momenta were performed with the arrangement shown in Fig. 1. The π^- mesons produced in an internal target T inside the proton synchrotron were focused by two quadrupole lenses ML-7, deflected by the magnet SP-57, and struck a liquid-hydrogen target H_2. The number of particles striking the target was recorded by three scintillation counters S_1 (9 cm dia), S_2 (9 cm dia), and S_3 (6 cm dia) located along a base of 11 m. The particles passing through the target without interaction were recorded by scintillation counters S_A, S_B, S_C.

The conditions for the best extrapolation of the cross section to zero solid angle required that these counters (of diameter 14.6, 18.5, and 35 cm, respectively) subtended angles greater than the beam divergence but the solid angle seen from the center of the target had to be as small as possible, while, at the same time, the corrections for Coulomb scattering in hydrogen had to be kept small. Solid angles of 0.62, 0.86, and 2.23 msr, respectively, were chosen.

The counting rate of counters S_A, S_B, S_C, in the absence of the target, was 90-95% of the monitor counting rate. The photomultiplier in these counters looked directly at a plastic scintillator without the use of light pipes.

The block diagram of the electronic equipment is shown in Fig. 2. The photomultipliers were connected to a cable with a 92-Ω wave resistance

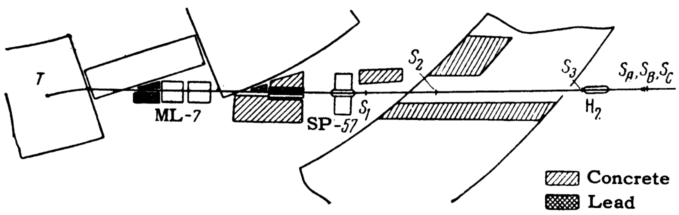

FIG. 1. Experimental arrangement for the measurement of $\sigma_t(\pi^-,p)$ at 3.4, 3.9, and 4.9 BeV/c.

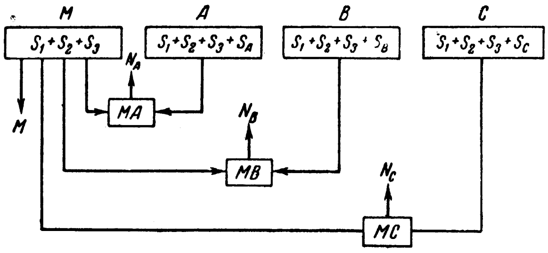

FIG. 2. Block diagram of electronic equipment.

through a limiter-multiplier* which limited pulses to the 0.8-V level. The pulses were applied to a diode coincidence circuit with a resolving time of 2×10^{-8} sec at circuit M and 0.8×10^{-8} sec at circuits A, B, and C. The coincidence circuits MA, MB, and MC also consisted of diodes with a resolving time of ~ 1 μsec. The dead times of the coincidence circuits satisfied the condition $\tau_M > \tau_{A,B,C} > \tau_{MA, MB, MC}$. The number of chance coincidences was negligible.

The particles were momentum analyzed primarily with the aid of the magnetic field of the accelerator. We varied the energy of the pions bombarding the target by changing the energy of the accelerated protons and the current in the magnet and the quadrupole lenses. The momentum of the beam particles was determined with a gas Cerenkov counter by a method described previously.[8] The momentum spread of the beam particles was about ± 10%.

The vacuum liquid-hydrogen target used in the experiment was 166 cm long. The wall thickness traversed by the beam was 0.6 g/cm^2 (stainless steel).†

The attenuation of the beam by the target was measured in successive runs with hydrogen and without hydrogen. Each run consisted of several tens of individual measurements, the consistency of which was then checked by statistical methods. In the determination of the quantity of hydrogen in the target, corrections were made for the sphericity of the vessel walls and for the dependence of the hydrogen density on the evaporation rate (the presence of gas bubbles in the liquid). The measurements for the target without hydrogen were corrected for residual gas.

The value of $\sigma_t(\pi^-, p)$ at 7.0 and 9.2 BeV/c was measured with another beam[9] by the CH_2-C difference method. The CH_2 absorber contained 3.4 g/cm^2 of hydrogen. A brief account of these measurements was given in[10].

*The limiter-multiplier was a multiplier with a common input.

†A description of the target will be published in the journal Pribory i tekhnika éksperimenta (Instruments and Measurement Techniques).

3. ANALYSIS OF THE RESULTS

The total cross section for the interaction of π^- mesons with hydrogen was determined from the formula

$$\sigma = (1/n) \ln \alpha/\beta,$$

where n is the number of hydrogen nuclei in the target per cm^2 (7.04×10^{24}), α is the "transparency" of the target without hydrogen, and β is the "transparency" of the target with hydrogen.

The ratio α/β was obtained from the extrapolation to zero solid angle of the experimentally observed ratio α_i/β_i corrected for Coulomb scattering, where $\alpha_i, \beta_i = N_i/M$ (i = A, B, and C is a subscript denoting the coincidence circuits in which counters S_A, S_B, and S_C were connected) with allowance for the muon contamination in the beam.

In order to obtain better statistical accuracy with a limited operating time at the accelerator, the measurements with counters S_A, S_B, and S_C were made simultaneously. This complicated somewhat the reduction of the data, owing to the existence of a correlation between the measurements. The correlation coefficients could be determined from the error matrices for the experimental ratios (uncorrected for Coulomb scattering) of α_{ie} and β_{ie} constructed from the results of all the runs. On the basis of these matrices, we obtained a combined matrix for the ratio α_{ie}/β_{ie}. The Coulomb correction γ_i was introduced in accordance with the formula $\alpha_i/\beta_i = \alpha_{ie}/\beta_{ie}\gamma_i$ (see below for the determination of γ_i) and the error matrix was changed correspondingly.

The obtained values of α_i/β_i were extrapolated to zero solid angle by the method of regression analysis[11] with a slight change in the analysis program due to the presence of the correlation. The best agreement between the error estimate s_1 characterizing the statistical accuracy and the error estimate s_2 characterizing the deviation of the ratio α_i/β_i from the regression curve, was obtained with a linear extrapolation.

The extrapolated value α_0/β_0 was corrected for the muon contamination of the beam by the formula

π^- momentum BeV/c	$\sigma_t(\pi^-, p)$ mb	μ mesons in beam %
3,4	31,4±0,7	12,4±0,2
3,9	30,0±0,5	12,8±0,2
4,9	29,6±0,6	13,3±0,2
7,0	27,8±0,8	6,5±0,4
9,2	25±4	—

$$\alpha/\beta = (1 - n_\mu)/(\alpha_0/\beta_0 - n_\mu),$$

where n_μ is the relative number of muons in the beam measured with a target without hydrogen (see below for the determination of n_μ).

The total $\pi^- p$ cross sections calculated in this way are shown in the table.

4. DETERMINATION OF COULOMB CORRECTION

The experimental determination of the corrections for Coulomb scattering were based on the following considerations. The change in the ratio α_{ie}/β_{ie} from one solid angle to another depended on both the nuclear and Coulomb scattering of π^- mesons on hydrogen. If a substance could be found for which, with a given Coulomb scattering, the nuclear scattering is small or at least changes very little within the limits of those solid angles for which the measurements were made, then the determination of the Coulomb correction would not be difficult. Heavy elements, for example lead, satisfy this requirement. As a matter of fact, it can be shown on the basis of Belen'kiĭ's paper[12] that the elastic diffraction scattering of pions on lead lies inside these solid angles, while it is seen from the results of Barashenkov et al.[13] that the inelastic scattering of the particles on lead has a broader angular distribution than for light nuclei. In the experiment with hydrogen, the change in the cross section from a solid angle of 2.23 msr to 0.62 msr was (5-10) % of the total cross section for the various energies. The corresponding changes for lead will apparently be considerably smaller.

The correction γ_i was determined experimentally in the following way. Calculation showed that for the counter S_C the Coulomb correction was negligible. For counters S_A and S_B we measured π^- mesons knocked out during the traversal of a lead plate ~ 1 mm thick having the same radiation length as the hydrogen target and, consequently, of equivalent Coulomb scattering. The nuclear scattering on lead was taken the same for all three solid angles. Then $\gamma_i = a_i b_c / b_i a_c$ ($i = A, B$), where a_i is the counter efficiency, b_i is the "transparency" of the lead plate, and a_c and b_c are the corresponding quantities for the counter S_C.

5. DETERMINATION OF THE NUMBER OF MUONS IN THE BEAM

We determined the muon contamination in the beam by measuring the attenuation of the beam in two blocks of material. Four measurements were carried out: 1) without absorbers; 2) with absorber No. 1; 3) with absorber No. 2; 4) with both absorbers Nos. 1 and 2. For these measurements, we can write the equations

$$\xi (n_\pi + n_\mu) = d, \quad (1)$$

$$\xi (n_\pi \alpha_\pi A_\pi + n_\mu A_\mu) = a, \quad (2)$$

$$\xi (n_\pi \beta_\pi B_\pi + n_\mu B_\mu) = b, \quad (3)$$

$$\xi (n_\pi \gamma_\pi C_\pi + n_\mu C_\mu) = c, \quad (4)$$

where a, b, c, and d are measured values, α_π, β_π, and γ_π are the fractions of π^- mesons which do not experience nuclear scattering in the block of material, A_π, B_π, C_π, and A_μ, B_μ, C_μ are the corresponding fractions of π^- and μ^- mesons which do not experience Coulomb scattering in the block of material (determined by calculation), n_π and n_μ are the relative amounts of pions and muons in the beam ($n_\pi + n_\mu = 1$), and ξ is the counter efficiency.

The absorber thickness and the counter dimensions were so chosen that the attenuation of the π^--meson beam as a result of nuclear scattering was large, while the attenuation as a result of Coulomb scattering was small. As absorbers we used lead 60-100 cm thick (No. 1) and graphite 180 cm thick (No. 2).

Since the energy of the incident pions was large and the slowing down in absorber No. 2 (which was first in the path of the beam) was slight, it can be assumed that the total effect of the two absorbers is expressed by the product $\gamma_\pi = \alpha_\pi \beta_\pi$. Under this condition, the muon contamination in the beam can be determined from Eqs. (1)-(4). The measurements were made for momenta of 3.4, 4.9, and 7.0 BeV/c (see table). For the remaining momenta, the muon contamination was calculated with the aid of these data.

6. DISCUSSION OF RESULTS

1. The value found for $\sigma(\pi^-, p)$ at 3.4 BeV/c is in agreement with the value obtained by the extrapolation of the results of measurements at lower energies.[14]

2. The obtained data indicate that the total $\pi^- p$ cross section decreases in the interval 3.5-7 BeV/c. Further measurements of $\sigma_t(\pi^-, p)$ in the high-energy region show that either the observed drop is characteristic only for the given region or that the cross section displays the asymptotic behavior of the cross section corresponding to the theoretical predictions.[4,5]

3. Comparison of the data obtained for $\sigma_t(\pi^-, p)$ with the results for $\sigma_t(\pi^+, p)$ measured by other groups[15,16] indicates that the $\pi^- p$ and the $\pi^+ p$

cross sections become equal within the limits of experimental accuracy at an energy of 4-5 BeV. It should, however, be noted that here we are comparing data obtained under different experimental conditions, and caution must be exercised in the estimate of the accuracy of the agreement.

4. On the basis of the relation

$$4\pi\lambda \, \mathrm{Im}\, A^0_{ex} = (1/\sqrt{2})\,[\sigma_t(\pi^-, p) - \sigma_t(\pi^+, p)]$$

and assuming that $\sigma_{ex}/\sigma_e = (\mathrm{Im}\, A^0_{ex}/\mathrm{Im}\, A^0_e)^2$, where A^0_{ex} and A^0_e are the amplitudes for charge exchange ($\pi^0 p \to \pi^+ n$, $\pi^- p \to \pi^0 n$) and elastic scattering at the angle 0°, while σ_{ex} and σ_e are the total charge-exchange and elastic scattering cross sections, we can obtain an estimate of the charge-exchange cross section if we know the difference $\sigma_t(\pi^-, p) - \sigma_t(\pi^+, p)$ and σ_e. At 5 BeV we have $\sigma_e \approx 5.5$ mb.[6] If at this energy we set $\sigma_t(\pi^-, p) - \sigma_t(\pi^+, p) = 1$ mb, we obtain $\sigma_{ex} = 0.003$ mb; for $\sigma_t(\pi^-, p) - \sigma_t(\pi^+, p) = 2$ mb, we obtain $\sigma_{ex} = 0.012$, i.e., the elastic charge-exchange cross section should be very small.

5. In a recent experiment at CERN,[17] $\sigma_t(\pi^-, p)$ and $\sigma_t(\pi^+, p)$ were measured over the momentum interval 4.5-10 BeV/c and it was shown that the total pion-proton cross section in this momentum region decreases. The data of this group are in good agreement with the results of the present study.

In conclusion, the authors express their gratitude to the proton synchrotron crew for the faultless operation of the accelerator and to the cryogenic group for aid with the liquid-hydrogen target.

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