Total Cross Sections of Protons, Antiprotons, and π and K Mesons on Hydrogen and Deuterium in the Momentum Range 6–22 GeV/c†

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The total cross sections σ_T of p, $\bar{p}$, $\pi^{\pm}$, and $K^{\pm}$ on hydrogen and deuterium have been measured between 6 and 22 GeV/c at intervals of 2 GeV/c to an accuracy greater than previously reported. The method utilized was a conventional good-geometry transmission experiment with scintillation counters subtending various solid angles at targets of liquid H_2 and D_2. With the increase in statistical accuracy of the data, it was found that a previously adopted procedure of linearly extrapolating to zero solid angle the partial cross sections measured at finite solid angles was not a sufficiently accurate procedure from which to deduce σ_T. The particle-neutron cross sections are derived by applying the Glauber screening correction to the difference between the particle-deuteron and particle-proton cross sections. The cross sections $\sigma_T(\pi^+d)$ and $\sigma_T(\pi^-d)$ are equal at all measured momenta, which confirms the validity of charge symmetry up to 20 GeV/c. Results are presented showing the variation of cross sections with momentum; evidence is presented for a small but significant decrease in $\sigma_T(pp)$ [and $\sigma_T(pn)$] in the momentum region above 12 GeV/c.

I. INTRODUCTION

MEASUREMENTS of the total cross sections for the interactions of particles and antiparticles with protons affords a relatively direct method for studying the behavior of strong interactions. Experiments of this type have yielded a wealth of information about the nucleon-nucleon, pion-nucleon, and kaon-nucleon forces at lower momenta ($\lesssim$4 GeV/c) where the formation of isobars and resonances reveal themselves as peaks in the total cross section at the appropriate energies.[1–3] The behavior of cross sections at higher momenta (above about 5 GeV/c) suggests that the formation of recognizable states corresponding to excited nucleons, if they exist, has a small effect on the total cross section. Earlier experiments[4–8] have indicated that the cross sections of particles on protons fall esentially continuously with energy, with the exception of $\sigma_T(pp)$ and $\sigma_T(K^+p)$. For the exceptions, the cross section remained constant for K^+p[9] over a wide range of momentum (3–19 GeV/c) and for pp appeared to be constant[4,5,7] within errors above about 10 GeV/c.

At the outset of the present experiment comparatively little had been done to study the particle-neutron cross sections. The direct measurement of $\sigma_T(n,p)$ has been undertaken at momenta up to 9 GeV/c[10–12] using secondary neutron beams from proton synchrotrons. The p"n" cross section, where "n" denotes that the neutron is bound in a deuteron, has been derived in "difference" experiments (CD_2-CH_2 or D_2O-H_2O)[7] as have the ($\bar{p}$"n") cross sections (D_2-H_2).[13] The now well-known screening effect of one nucleon by the other in deuterium, first investigated theoretically by Glauber,[14] enables one to apply a correction to the difference between $\sigma_T(x,d)$ and $\sigma_T(x,p)$, where x is any particle, from which $\sigma_T(x,n)$ can then be calculated. This correction, see Eq. (4), and the accuracy to which it can be made are discussed further in Sec. IV; it should be noted that this procedure is the only one available for determining the total cross sections of π and K mesons and

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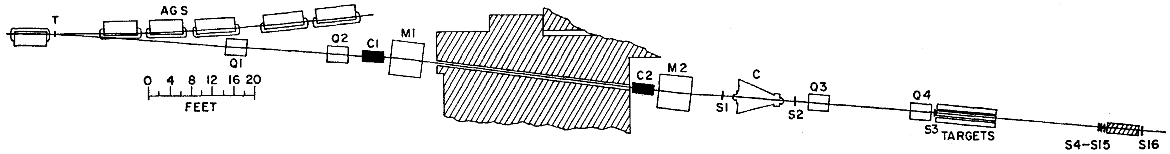

FIG. 1. Experimental arrangement at Brookhaven Alternating Gradient Synchrotron (AGS). T—aluminum wire (0.03-in.-diam) target inside AGS vacuum tank. Q—quadrupoles, 8-in.-diam aperture 48 in. long. M—bending magnets, 6-in. gap, 72 in. long. $C1$, $C2$—collimators. C—gas Čerenkov counter. $S1$, $S2$—plastic scintillation counters, 1 in. width, $5\frac{1}{2}$ in. height. $S3$—plastic scintillation counter 3 in.×3 in. $S4\cdots S16$—circular plastic scintillation counters of diameter $1\frac{1}{2}$, 2, $2\frac{1}{2}$, 3, 4, 5, 6, 7, 8, 10, 12, 14, and 18 in., respectively.

antiprotons on neutrons. In order to apply the Glauber correction, a value for the parameter $\langle r^{-2}\rangle$, where r is the mean separation of the nucleons in deuterium, can be found by measuring $\sigma_T(\pi^+p)$, $\sigma_T(\pi^-p)$, and either $\sigma_T(\pi^+d)$ or $\sigma_T(\pi^-d)$ at the various momenta. By charge symmetry, the latter two cross sections are expected to be equal. Measurements of these cross sections have been made at momenta between 2.5 and 5 GeV/c,[15] and show, in fact, that charge symmetry of the pion-nucleon force does hold in this range of momenta. Measurements have also been made of $\sigma_T(K^+n)$ and $\sigma_T(K^-n)$ in the momentum region 1–5 GeV/c.[15,16]

There have been two main theoretical developments in this field. One, the Pomeranchuk theorem,[17] predicted that particle and antiparticle cross sections should become equal at sufficiently high energies. The other, the Regge-pole theory[18] of strong interaction phenomena, was able to account for the apparent constancy of $\sigma_T(pp)$ and the behavior of the diffraction pattern for pp elastic scattering as functions of momentum.[19,20] Independently, however, of any theoretical models which may be invoked for interpreting such data, accurate measurements of all particle and antiparticle total cross sections on a given nucleon at high momenta, and their relative behavior as a function of momentum, are of value to the theoretical understanding of strong interactions.

The purpose of the present work was to measure with greater accuracy than hitherto attained the particle-proton total cross sections at high energy and to deduce particle-neutron cross sections from particle-deuteron cross-section measurements in the previously unexplored region above 6 GeV/c.

It is necessary in this type of experiment to correct the data because detectors and particle beams have to be of finite rather than point size. This had been done by extrapolating linearly to zero solid angle the partial cross sections which are measured by detectors subtending various solid angles at the target. The extrapolated value of σ at zero solid angle then is a measure of the total cross section σ_T. It soon became apparent in the present work that such a procedure was an approximation only; the increased statistical accuracy of the measurements showed that the partial cross sections lay on a curve rather than on a straight line. A similar behavior was observed by Amaldi *et al.*[8] who fitted their data to two exponentials. The fitting procedure in the present work is discussed in Sec. III(ii).

In order to minimize systematic errors, three identical targets were used in this experiment, one continuously full of liquid hydrogen, one of liquid deuterium, and the third maintained under vacuum; each in turn was placed in the beam. The magnitude of density fluctuations in these targets is discussed in Sec. III.

The results of the experiment are presented in both tabular and graphical form, the latter enabling easier comparison with other work. The main conclusions and a discussion of their significance will be found in Secs. IV and V.

II. EXPERIMENTAL ARRANGEMENT

(i) Particle Beam

The beam layout is shown schematically in Fig. 1. To obtain the high intensity of secondary particles of both polarities, the beam was designed to accept particles emitted at an angle of approximately 4.5° with respect to the forward direction from a target T located in a field-free straight section of the Brookhaven AGS. Because the beam line crosses the fringe field of a succeeding AGS magnet unit, the position of the target in the machine determines uniquely the momentum which will pass along the axis of the beam-handling system defined by the quadrupoles $Q1$ and $Q2$, the bending magnets $M1$ and $M2$ and the quadrupoles $Q3$ and $Q4$.

The focusing action of the quadrupole system is as follows. $Q1$ focuses particles in the horizontal plane, $Q2$ in the vertical, producing, at the first collimator, a nearly parallel beam of small horizontal width. The selection of the momentum band ($\Delta p/p=\pm 1.75\%$) transmitted by this system is achieved by means of the dispersive action of $M1$ (3° bend) and the slit of 1-in.

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TABLE I. Secondary particle-beam intensities per pulse at hydrogen target. Internal AGS beam, 3×10^{11} protons per pulse; $\Delta\Omega=16.5\times10^{-6}$ sr; $\Delta p/p=\pm1.75\%$.

Momentum (BeV/c)	π^+	π^-	K^+	K^-	p	$\bar{p}$
6	2×10^5	5×10^4	2×10^3	7×10^2	8×10^4	1×10^3
10	6×10^4	6×10^4	5×10^3	1.4×10^3	1×10^5	6.3×10^2
14	1×10^4	1×10^4	1×10^3	1.6×10^2	6×10^4	5.2×10^1
18	1.3×10^3	1.3×10^3	1.2×10^2	1.5×10^1	1.3×10^4	2
20	3.3×10^2	3.3×10^2	3×10^1	5	4×10^3	3.5×10^{-1}

horizontal width at collimator $C2$. Momenta are recombined by the action of $M2$ (3° bend) and the beam then passes through the differential gas Čerenkov counter C. The "parallel" beam is refocused to an image at the region of the transmission counters S4-15 by the quadrupoles $Q3$ and $Q4$, which form a symmetrical system with $Q1$ and $Q2$, the last element $Q4$ focusing in the horizontal plane.

$S1$, $S2$, and $S3$ constitute the particle telescope counters [see Sec. II (iii)]. A steel absorber (6 ft long) separates the transmission counters ($S4$-$S15$) from the final counter $S16$, which detects muons from the decay in flight of π and K mesons. The focusing of the beam at each momentum was checked by using a beam profile indicator consisting of small solid-state detectors.[21] The final beam-spot size (full width at half-maximum) at the focus was approximately 1 in. vertically by $\frac{1}{3}$ in. horizontally at 18 GeV/c; at 6 GeV/c the corresponding spot size was 2 in.$\times\frac{2}{3}$ in. The particle intensities in the beam are given in Table I.

(ii) Hydrogen Targets

Three targets of identical design were mounted on rails, which enabled each, in turn, to be moved into the beam line. Each target had a double-jacketed container. The outer jacket was filled with liquid hydrogen boiling at atmospheric pressure to provide a constant temperature bath for the inner central container which was filled with H_2, D_2 or was evacuated (empty target). The inner container was sealed off after filling. Once filled, a target was kept essentially in this steady state throughout the run; the reservoirs required filling at intervals of about 10 h.

The temperatures of the liquid hydrogen and deuterium were measured at hourly intervals throughout the experiment, using hydrogen vapor-pressure thermometers. The hydrogen temperature[22] remained within the range 20.60–20.85°K and the deuterium within the range 20.60–20.78°K corresponding to mean densities of 0.0703 ± 0.0001 g cm^{-3} and 0.1697 ± 0.0002 g cm^{-3}, respectively.[23] The length of the hydrogen target was determined by direct measurement, while it was full, to an accuracy of ±0.1 in., i.e., $\pm0.1\%$ approximately. The deuterium target was essentially identical so that it was possible to calculate its length when full, to the same accuracy. These lengths correspond to 21.51 ±0.06 g cm^{-2} and 51.86 ± 0.10 g cm^{-2} for H_2 and D_2, respectively. The over-all errors ascribed to these absorption lengths take into account systematic errors in length measurements together with errors due to fluctuations in the densities of liquid hydrogen and deuterium.

(iii) Counters

The counters were made of plastic scintillator with Lucite light guides cemented to RCA type-7746 photomultiplier tubes. The sizes of the counters are noted in the caption of Fig. 1. The gas Čerenkov counter has been described elsewhere[24]; in the present work the counter was filled with CO_2 gas.

(iv) Electronics

A block diagram of the electronics used in the experiment is shown in Fig. 2. The basic logic was as follows:

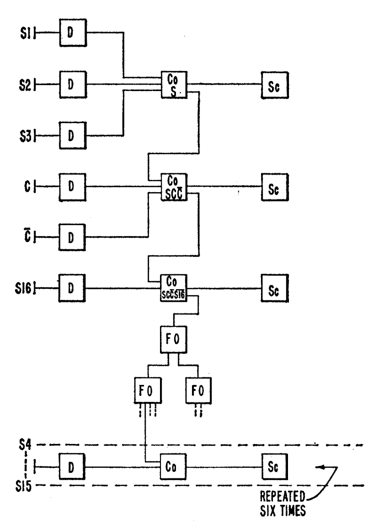

FIG. 2. Block diagram of electronics. S—signals from plastic scintillation counters S_n, ($n=1\cdots16$). C—signal from Čerenkov counter (wanted particle). $\bar{C}$—antisignal from Čerenkov counter (unwanted particle). D—discriminators. Co—coincidence units. Sc—scalers. FO—fan-out units.

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Telescope counters $S1$, $S2$, $S3$ were put into 3-fold coincidence ($S=S_1S_2S_3$) to define the charged-particle beam entering the hydrogen targets. Output signal S was then put into coincidence with the gas Čerenkov-counter signal, denoted by $C\bar{C}$, where C is the wanted particle signal and $\bar{C}$ is the antisignal, to sharpen the resolution of the Čerenkov counter.[24] The signal $SC\bar{C}$ represents an incoming pion, kaon, or proton, depending upon the value of refractive index of the gas in the Čerenkov counter. The signal from counter $S16$ was put into anticoincidence with $SC\bar{C}$, the output signal $SC\bar{C}\bar{S}_{16}(=B)$ then being associated with a particle which has not decayed in flight. The signal B was then "fanned out" to individual coincidence units for the transmission counters S_n, $n=4\cdots15$, any six counters being put into coincidence with B at any one time giving transmission rates BS_n. Accidentals were recorded during data taking in two other channels not shown in Fig. 2. The resolving times of all coincidence units were $2\tau=5\times10^{-9}$ sec. They had a maximum pulse repetition rate of 10 Mc/sec with one exception; the coincidence unit $SC\bar{C}$ had a maximum repetition rate of 1 Mc/sec and controlled the over-all dead time of the succeeding circuits.

(v) Experimental Procedure

A set of data at a given momentum usually comprised a series of alternating runs with the H_2, D_2 and empty targets. When empty, all three targets were observed to attenuate the beam identically. Counter efficiencies were checked at the beginning and end of each set of data. In this way the internal consistency of the data with a given target could be readily checked and the systematic errors, due to the time-dependent fluctuations in the experimental conditions, kept to a minimum. The raw data comprised scaler readings, at a given momentum, of $SC\bar{C}$, B, $BS_n\cdots BS_{n+5}$ and two random rates (corresponding to the largest and smallest transmission counters used at the given momentum). These data were transferred subsequently to punched cards for processing on an IBM-7094 computer.

III. DATA REDUCTION

(i) General

The raw data were examined for consistency and small corrections were then applied for effects of accidentals and circuit dead-time.

TABLE II. Total cross sections of π mesons.

Momentum (BeV/c)	$\sigma_T(\pi^+p)$ (mb)	$\sigma_T(\pi^-p)$ (mb)	$\sigma_T(\pi^+d)$ (mb)	$\sigma_T(\pi^-d)$ (mb)
6	26.2±0.2	28.5±0.3	52.8±0.5	52.7±0.5
8	25.1±0.2	27.5±0.3	50.5±0.5	51.0±0.5
10	24.8±0.2	26.5±0.3	49.3±0.5	49.3±0.5
12	24.2±0.2	25.9±0.3	48.2±0.5	47.9±0.5
14	23.9±0.2	25.4±0.3	46.9±0.5	47.1±0.5
16	23.4±0.2	25.1±0.3	46.6±0.5	46.4±0.5
18	23.5±0.2	25.0±0.3	46.3±0.5	46.4±0.5
20	23.4±0.2	24.8±0.3	45.9±0.5	45.8±0.5

The corrected data comprised a series of measurements of the transmission factors ($T_n=BS_n/SC\bar{C}$) for counters of different solid angles or, to compare conveniently one momentum with another, at different $-t$ values where t is the square of the four-momentum transfer in the collision. At a given t the partial cross section recorded by a counter is then expressed by the relation

$$\sigma(t)=(1/N)\ln(T_E/T_F), \qquad (1)$$

where $N=$ the number of nuclei per cm^2 in the target and T_F, T_E are the transmission factors for a full (F) and empty target (E), respectively. The statistical error on $\sigma(t)$ is given by

$$\Delta\sigma=(1/N)\Delta(T_E/T_F)/(T_E/T_F). \qquad (2)$$

The over-all errors to be ascribed to each of these measurements will be discussed in Sec. III (iii).

(ii) Extrapolation Procedure

The partial cross sections measured at various $-t$ values were fitted by a polynomial of the form

$$\sigma(t)=\alpha_0+\alpha_1t+\alpha_2t^2. \qquad (3)$$

This is basically a similar procedure to that adopted by Amaldi *et al.*[8] who used two exponential functions to fit their data.

This polynomial fit, with a term higher than one linear in t, was made when it became apparent from the data that at higher momenta (larger t range) the partial cross sections lay on a curve rather than a straight line when plotted as a function of $-t$.

By using various combinations of counter sizes at different momenta, different values of the α coefficients

TABLE III. Total cross sections of K mesons.

Momentum (BeV/c)	$\sigma_T(K^+d)$ (mb)	$\sigma_T(K^+p)$ (mb)	$\sigma_T(K^+n)$ (mb)	$\sigma_T(K^-d)$ (mb)	$\sigma_T(K^-p)$ (mb)	$\sigma_T(K^-n)$ (mb)
6	33.4±0.3	17.0±0.1	17.5±0.4	44.1±0.3	24.0±0.3	21.9±0.4
8	33.9±0.3	17.3±0.1	17.6±0.4	41.7±0.3	23.6±0.2	19.7±0.4
10	33.8±0.3	17.3±0.1	17.5±0.4	41.5±0.3	22.5±0.2	20.6±0.4
12	33.9±0.3	17.3±0.1	17.6±0.4	40.3±0.3	21.6±0.2	20.2±0.4
14	33.8±0.3	17.4±0.1	17.5±0.4	40.1±0.3	21.5±0.2	20.1±0.4
16	33.4±0.3	17.0±0.1	17.4±0.4	40.1±0.4	21.3±0.4	20.3±0.6
18	33.7±0.3	17.1±0.1	17.6±0.4	39.9±0.7	21.0±0.8	20.3±1.1
20	34.2±0.3	17.5±0.1	17.7±0.4	···	22.4±4.6	···

TABLE IV. Total cross sections of protons and antiprotons.

Momentum (BeV/c)	$\sigma_T(pd)$ (mb)	$\sigma_T(pp)$ (mb)	$\sigma_T(pn)$ (mb)	$\sigma_T(\bar{p}d)$ (mb)	$\sigma_T(\bar{p}p)$ (mb)	$\sigma_T(\bar{p}n)$ (mb)
6	77.4±1.3	40.6±0.6	42.6±1.7	106.9±1.3	59.3±1.1	59.5±4.0
8	76.2±1.3	40.0±0.6	41.8±1.7	102.7±1.3	56.4±0.8	57.3±3.9
10	75.8±1.3	39.9±0.6	41.5±1.7	...	...	...
12	74.4±1.3	39.4±0.6	40.4±1.7	96.1±1.3	51.7±0.8	53.8±3.7
14	74.0±1.3	39.1±0.6	40.2±1.7	95.0±1.4	50.7±0.9	53.4±3.7
16	73.7±1.3	38.7±0.6	40.2±1.7	93.2±1.6	49.2±0.8	52.7±3.7
18	72.8±1.3	38.7±0.6	39.2±1.7	87.2±6.1	50.3±3.6	44.4±9.0
20	72.1±1.3	38.4±0.6	38.7±1.7	...	...	...
22	71.6±1.3	38.3±0.6	38.2±1.7	...	...	...

were found for the various particles. Two sets (large diameter and small diameter) of counter sizes were used depending upon the beam momentum. There was a systematic discontinuity of about 1% magnitude in the extrapolated value α_0 at those momentum regions where the two sets of counters were used to determine σ_T, giving an over-all saw-tooth effect to the behavior of σ_T with momenta. It was found that for $-t=0.02$ (GeV/c)^2, which always lay within the range of counter sizes used, the partial cross sections were essentially independent of the counters used to determine them. To find a true value of $\alpha_0(=\sigma_T)$ at each momentum, the values of the coefficients α_1, α_2, and $\sigma(0.02)$, averaged over the results for the different sets of counters used, were then substituted back into Eq. (3), solving for α_0. The results are given in Tables II, III, and IV.

(iii) Corrections and Errors

In addition to basic data corrections mentioned in Sec. III (i), the following corrections were also considered:

(*a*) *Decay of unstable particles*. Because of energy loss in the hydrogen target, there is a target full-empty difference in the fraction of K mesons decaying into muons. This effect is noticeable for kaons at low momenta; at 6 GeV/c the effect produces a 1% change in σ_T. Above 8 GeV/c, it is negligible.

(*b*) *Beam contamination*. At the highest momenta there is some difficulty in discriminating between pions and kaons in the incident beam; consequently the kaon beam will have a slight admixture of unresolved pions. The structure of the pressure curve shows that pion contamination produces a negligible effect compared with the final error quoted for the cross section.

(*c*) *Effect of multiple Coulomb scattering in the targets*. Because of the wide momentum range covered, it is important to recognize the effect of multiple Coulomb scattering in the smaller counters at some momenta. The Coulomb correction is somewhat uncertain to make because of uncertainty in the beam shape; consequently it is better practice to exclude the counter(s) affected. The appearance of Coulomb effects in the smallest counters was easily recognized, in clear contrast to the negligible Coulomb contribution to the partial cross section at $-t=0.02$ (GeV/c)^2.[25]

(iv) Glauber Screening Correction

In order to calculate particle cross sections on neutrons, use is made of the Glauber screening correction originally written in the following form:

$$\sigma_d=\sigma_n+\sigma_p+\frac{\langle r^{-2}\rangle}{4\pi}\left\{\left(\frac{4\pi}{K}\right)^2 \mathrm{Re}f_n(0)\,\mathrm{Re}f_p(0)-\sigma_n\sigma_p\right\}, \quad (4)$$

where $\mathrm{Re}f_n(0)$ is the real part of the forward scattering amplitude of the particle off a neutron, $\mathrm{Re}f_p(0)$ is the real part for scattering off a proton, σ_d, σ_n, σ_p are the total cross sections for the particle on the deuteron, neutron and proton, respectively, and $\langle r^{-2}\rangle$ is a parameter representing the mean inverse square of the separation of nucleons in the deuteron.

Experimental evidence suggests that the real parts of the forward scattering amplitude, if present, are small. In order to calculate neutron cross sections, it is assumed that the product of the real parts for all particles is sufficiently small to be put equal to zero, giving an expression for the particle-neutron cross section of the form

$$\sigma_n=\{\sigma_d-\sigma_p\}/\{1-(4\pi)^{-1}\langle r^{-2}\rangle\sigma_p\}. \quad (5)$$

A value of the parameter $\langle r^{-2}\rangle$ may be found from the cross-section measurements of pions on hydrogen and deuterium. Because of charge symmetry we can write

$$\langle r^{-2}\rangle=4\pi\{\sigma_T(\pi^+p)+\sigma_T(\pi^-p)-\sigma_T(\pi^\pm d)\}/\sigma_T(\pi^+p)\sigma_T(\pi^-p). \quad (6)$$

It should be noted that the above form of the Glauber theory assumes that the particle-nucleon force range is small in comparison with the neutron-proton separation in the deuteron. Recently, extensions of the Glauber theory, involving integration over the ground-state

[25] In the present work the only data which include corrections for Coulomb scattering were those for protons and antiprotons at 6 GeV/c. The corrections were calculated following the procedure outlined by R. M. Sternheimer, Rev. Sci. Instr. 25, 1070 (1954).

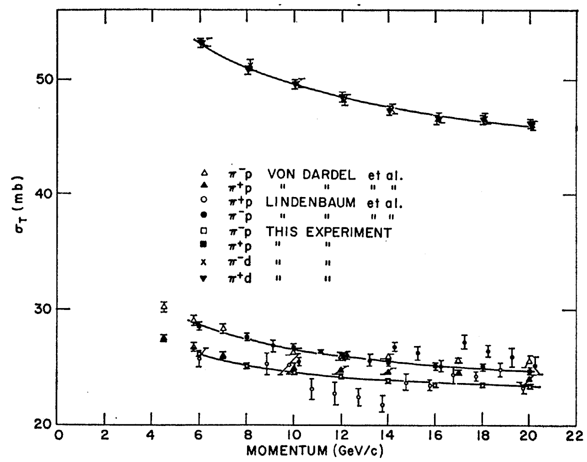

FIG. 3. Total cross sections of π mesons on protons and deuterons.

deuteron wave function, for which various forms can be assumed, have been made by Franco[26] and Harrington.[27] For purposes of the present experiment, the Glauber equations [e.g., Eqs. (5), (6) above] will be retained in deriving the results presented in Sec. IV.

IV. RESULTS

For all measurements except those for incident K^- and $\bar{p}$ at the highest momenta, the main source of error in the cross sections was in the extrapolation procedure [$\pm 1\%$, see Sec. III (ii)]. The statistical errors were in general much smaller (typically $\pm\frac{1}{4}\%$).

(i) π-Meson Cross Sections

The total cross sections for pions are given in Table II and shown in Fig. 3.

The results for $\sigma_T(\pi^\pm p)$ are in agreement with the trend of the earlier experiments.[4–6] The good agreement of the total cross sections for π^+ and π^- on deuterium (to better than 1%)[28] shows that the charge symmetry of the pion-nucleon force is a valid hypothesis up to the highest momentum attained in the present work (20 GeV/c). Baker *et al.*[15] concluded that in the momentum range 2.5–6 GeV/c the same hypothesis is also valid.

The Glauber screening correction derived from the difference between the total cross sections on H_2 and D_2 yields a value of the parameter $\langle r^{-2}\rangle$. Within our accuracy, $\langle r^{-2}\rangle$ is essentially constant over the momentum range (6–20 GeV/c). The mean value of $\langle r^{-2}\rangle$ is 0.042 ± 0.003 mb^{-1}, corresponding to a value of r of 1.54 ± 0.06 F.

Baker *et al.*[15] note that the numerical values for $\langle r^{-2}\rangle$ are very sensitive to the values used for the densities of liquid hydrogen and deuterium. In the present work, the systematic errors arising from these values can give rise to an additional error of ±0.005 mb in the above value of $\langle r^{-2}\rangle$. Baker *et al.*[15] found $\langle r^{-2}\rangle$ to be 0.0239 ± 0.0014 mb^{-1} with a larger systematic error ±0.009 mb. Thus, within the limits of the combined errors, in the two experiments, the difference in the values of $\langle r^{-2}\rangle$ is not significant.

For calculations of the particle-neutron cross sections the above value of $\langle r^{-2}\rangle=0.0423$ mb^{-1} will be used in the Glauber correction term and, in general, the uncertainties in the neutron cross sections are determined by the accuracy of this term coupled with uncertainties in the absolute values of the total H_2 and D_2 cross sections. There is still an unknown correction which depends upon the over-all validity of applying Eq. (4) to the data.

(ii) K-Meson Cross Sections

These are given in Table III and shown in Fig. 4. The following points may be noted:

(a) The K^+p and K^+d cross sections are constant over the momentum range 6–20 GeV/c. Previous measurements of $\sigma_T(K^+p)$ by Baker *et al.*[9] also showed this cross section to be momentum independent.

(b) Applying the Glauber correction and defining $\sigma_T(K^+n)$ by Eq. (5), we find $\sigma_T(K^+n)$ is also constant and to within our accuracy, equal to $\sigma_T(K^+p)$. The difference $\sigma_T(K^+n)-\sigma_T(K^+p)=0.31\pm0.36$ mb, averaged over the momentum range 6–20 GeV/c.

(c) The K^-p and K^-d cross sections are falling smoothly with momentum up to 12 GeV/c. Above that momentum the results are consistent with either a con-

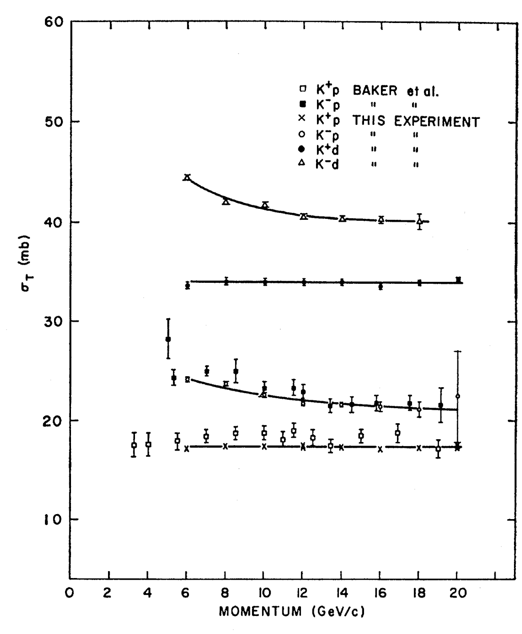

FIG. 4. Total cross sections of K mesons on protons and deuterons.

[26] V. Franco, thesis, Harvard University, Cambridge, Massachusetts, 1963 (unpublished).

[27] D. R. Harrington, Phys. Rev. **135**, B358 (1964).

[28] We note in passing that the partial cross sections at $-t=0.02$ (GeV/c)^2 were equal to within $\pm0.2\%$.

stant cross section or one that is decreasing very slowly with increasing momentum.

(d) The same general behavior is found for the K^-n cross section, and it is smaller in value than the K^-p cross section. At 6 GeV/c the value of $\sigma_T(K^-p) - \sigma_T(K^-n) = 2.1 \pm 0.5$ mb and this difference falls with increasing momentum to a value of 0.7 ± 1.4 mb at 18 GeV/c.

(iii) Proton- and Antiproton-Nucleon Cross Sections

Proton- and antiproton-nucleon cross sections are given in Table IV and are shown in Fig. 5(a), (b).

The proton-proton and proton-deuteron cross sections appear to be falling steadily with momentum up to the highest momentum studied (22 GeV/c). The values obtained are generally in statistical agreement with those of earlier experiments[4,5] but the systematic behavior with momentum was not apparent in the earlier work.[28a] A subtraction of the pd and pp cross sections, coupled with the Glauber correction, reveals that the proton-neutron cross section also has a similar behavior.

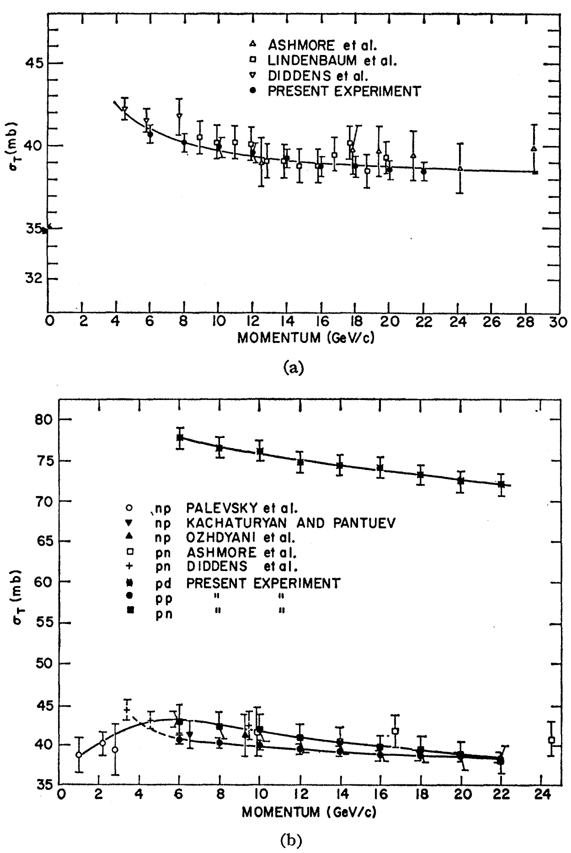

FIG. 5. (a) Total cross sections of protons on protons. (b) Total cross sections of protons on deuterons, protons and neutrons.

The falling pp cross section is clearly indicated in the present results and it appears that the high energy limit of the Pomeranchuk theorem has not yet been reached in the case of protons. This evidence is contrary to one of the initial assumptions in the application of the Regge pole theory which was based upon a constant total pp cross section in this energy interval.

The $\sigma_T(pn)$ cross sections deduced here are in good agreement with the direct measurements of $\sigma_T(np)$ using neutron beams.[29]

The difference between $\sigma_T(pp)$ and $\sigma_T(pn)$ is of some theoretical interest since measurements of charge exchange scattering can be related to the cross-section difference $[\sigma_T(pp) - \sigma_T(pn)]$. Ahmadzadeh[30] points out that the data of Palevsky *et al.*[11] and Diddens *et al.*[19] can be explained in terms of a Regge-pole theory.[31] In particular, the theory predicts a fall in the cross-section difference $[\sigma_T(pp) - \sigma_T(pn)]$ to a value of zero at about 6 GeV/c, becoming negative above this value. The Pomeranchuk theorem calls for equality and constancy of $\sigma_T(pp)$ and $\sigma_T(pn)$ at the high-energy limit, consequently the cross-section difference might be expected to exhibit a negative minimum at some momentum above 6 GeV/c and a gradual rise to zero once again as the Pomeranchuk limit is approached. The observed behavior of the cross-section difference $[\sigma_T(pp) - \sigma_T(pn)]$ in the present experiment is entirely consistent with such behavior; the error in the cross-section difference is, however, too large to make more than a qualitative agreement at present.

The $\bar{p}p$ cross sections at high momenta fit smoothly with the data of Amaldi *et al.*[8] at lower momenta (see Fig. 6). For the $\bar{p}n$ cross sections, the Glauber correction is larger here and the $\bar{p}p$ and $\bar{p}n$ cross sections appear to be equal within the statistical accuracy of the measurements. The equality within errors of $\bar{p}p$ and $\bar{p}n$ total cross sections at lower momenta has been noted by Elioff *et al.*[13]

V. CONCLUSIONS

It would appear that the ultimate limit of accuracy in determining particle-neutron cross sections in deuterium-hydrogen difference experiments is set by the two factors: (a) the over-all validity of the Glauber theory, and (b) the accuracy to which one can determine $\langle r^{-2} \rangle$ for the Glauber correction from the pion data. The latter factor is more dependent on the system-

[28a] *Note added in proof.* Recently published data of G. Bellettini, G. Cocconi, A. N. Diddens, E. Lillethun, J. Pahl, J. P. Scanlon, J. Walters, A. N. Wetherell, and P. Zanella appearing in Phys. Letters **14**, 164 (1965) confirm the fact that $\sigma_T(pp)$ is falling with increase in momentum in the region between 10 and 22 GeV/c. The results of measurements of $\sigma_T(pp)$ are: 40.0 ± 0.3 mb at 10.11 GeV/c, 38.9 ± 0.3 mb at 19.33 GeV/c, and 38.8 ± 0.3 mb at 26.42 GeV/c. These data are in very good agreement with the results presented here.

[29] Palevsky *et al.* (Ref. 11) at lower momenta found $\sigma_T(np) = 40.3 \pm 1.4$ mb at 3.0 GeV/c and $\sigma_T = 39.4 \pm 3.3$ mb at 3.6 GeV/c. Kachaturyan and Pantuyev (Ref. 12) found $\sigma_T(np) = 41.2 \pm 1.7$ mb at 6.5 GeV/c and Ozhdyani *et al.* (Ref. 12) found $\sigma_T(np) = 41.2 \pm 2.6$ mb at 9.2 GeV/c.

[30] A. Ahmadzadeh, Phys. Rev. **134**, B633 (1964).

[31] A. Pignotti, Phys. Rev. **134**, B630 (1964).

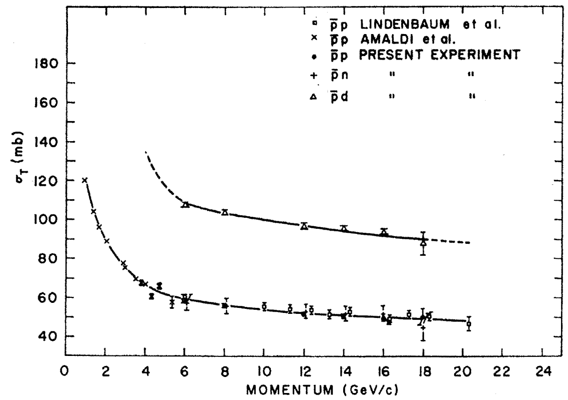

FIG. 6. Total cross sections of antiprotons on deuterons, protons and neutrons.

atic errors present in an experiment than in the statistical accuracy to which one determines the relative total cross sections.

As seen from Eq. (4), the Glauber correction also has the additional term in its exact form which brings in a dependence upon the real part of the forward scattering amplitudes for pion-nucleon scattering. Even with extreme precision in determining cross sections, the presence (say) of a momentum dependence in the value of $\langle r^{-2}\rangle$ so found does not allow us to draw unambiguous conclusions about the behavior of the real parts of the scattering potentials. However, this does not exclude the possibility of drawing significant conclusions about real parts in pion-nucleon scattering from the difference in π^+- and π^--hydrogen total cross sections which can be determined to a high degree of relative accuracy.[3]

The results of the present experiment show that there still remain unanswered questions about the "asymptotic" limits of particle-nucleon total cross sections at high energies. The hypothesis that particle and antiparticle cross sections become equal in the asymptotic limit of high energy, while plausible from the trends observed in the data for $p^\pm$ and $\pi^\pm$, is less apparent for $K^\pm$ mesons. The fact (see Table III) that $\sigma_T(K^-n)$ may be constant above 8 GeV/c and that $\sigma_T(K^-p)$ is approaching $\sigma_T(K^-n)$ as momentum increases, coupled with the observation that $\sigma_T(K^+p)$ and $\sigma_T(K^+n)$ are equal, independent of momentum and less than $\sigma_T(K^-n)$ by 2–3 mb, indicates that if the cross sections are converging with increasing energy they are doing so at a lower rate. Cross section measurements at higher energies than are available with present day accelerators are required to clarify the situation.

The slope $(d\sigma_T/dt)_0$ of the extrapolations in the present work at $t=0$ are significantly greater than $(d\sigma_{el}/dt)_0$ derived from the optical model or as measured in the experiments on differential elastic scatterings.[20] It is therefore of interest to examine the contributions made to this slope by inelastic processes $(d\sigma_{inel}/dt)_0$. The behavior of the differential distribution for this process has not been widely studied so far, but the results of the present work indicate that the combined contribution to the slope of the total cross section extrapolation of this process is comparable to that of the elastic process and consistent with a peaking in the forward direction. This indication of the behavior of inelastic processes is of sufficient interest to warrant further investigation in experiments to study the effect *per se.*

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