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Total Cross-Sections of Protons, Anti-Protons, π Mesons and K Mesons on Hydrogen and Deuterium in the Momentum Range 6-22 GeV/c*

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Total cross sections of protons, anti-protons, π mesons and K mesons on hydrogen and deuterium have been measured in a transmission experiment at the Brookhaven Alternating Gradient Synchrotron. The measurements were made over a momentum interval from 6 to 22 GeV/c and with an absolute accuracy of 1 to 2%.

The experimental arrangement is shown in Fig. 1. The beam was designed to accept particles produced from target T at an angle of approximately 4.5°. Because of the fringing field of the succeeding AGS magnet unit, the radial position of the target was varied so that its virtual position lay on the beam axis for all momenta. Quadrupoles Q_1 and Q_2 produce a parallel beam for the central momentum, defined by M_1. A momentum bite of 3.5% is defined by collimator C_2. It is followed by bending magnet M_2 which recombines momenta and produces a near par-

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allel beam for the differential Cerenkov counter C. Quadrupoles Q_3 and Q_4 refocus the beam to an image at the center of the transmission counters S_4-S_{15}. Scintillation counters S_1, S_2 and S_3 in coincidence with C formed the incident beam telescope. The desired particles which were selected by varying the index of refraction of the CO_2 gas in the Cerenkov counter, were incident on one of three 10-foot-long targets (liquid hydrogen, liquid deuterium, or vacuum). Particles which passed through the selected target were detected by six transmission counters. The outputs from these counters were taken in coincidence with the telescope and scaled. The muons not resolved by C were rejected by the anticoincidence counter S_{16} situated behind 6 feet of steel.

After small corrections for effects of accidentals and dead time were made to the raw data, the partial cross-sections as measured by the transmission counters were fitted to a polynomial of the form

$$\alpha(t) = \alpha_o + \alpha_1 t + \alpha_2 t^2 \tag{1}$$

where -t is the square of the four-momentum transfer. By using various combinations of transmission counter sizes at different momenta, different values of the α coefficients were found for the various particles. An arbitrary choice of $-t = 0.02\ (\mathrm{GeV}/c)^2$ was made at which all partial cross-sections $\sigma(t)$ were compared and the result of this comparison showed that the partial cross-sections at the given t were essentially independent of the counters used to determine $\sigma(t)$. To find the true limit of $\sigma(t)$ for $t \to 0$, (i.e., α_o or σ_T) at each momentum, the values of the coefficients α_1, α_2, and $\sigma(t)$ averaged over different transmission counter combinations were then substituted back into equation (1), solving for α_o.

In calculating K-meson cross-sections, account had to be taken of the increased decay rate of K mesons behind a full target due to the energy loss by ionization. This effect was only noticeable at low momenta producing a 1% change in σ_T at 6 GeV/c. Above 8 GeV/c, it was negligible.

In order to determine cross-sections on neutrons, use is made of the Glauber screening correction which may be expressed in the following form.

$$\sigma_d = \sigma_n + \sigma_p - \sigma_n \sigma_p \frac{\langle r^{-2} \rangle}{4\pi} \quad . \qquad (2)$$

if the real parts of the forward scattering amplitudes are neglected. The expression for the particle-neutron cross-section takes the form

$$\sigma_n = (\sigma_d - \sigma_p)/(1 - \frac{\langle r^{-2} \rangle}{4\pi} \sigma_p) \qquad (3)$$

where $\langle r^{-2} \rangle$ is the average value of the inverse square of the neutron proton separation in deuterium.

Fig. 2 shows the experimental results obtained for π mesons, including previous data[1,2] for π-p total cross-sections. It is clear that $\sigma_T(\pi^- d) = \sigma_T(\pi^+ d)$ within errors, as one would expect from charge symmetry. It follows then that $\sigma_T (\pi^- p) = \sigma_T(\pi^+ n)$. By substituting the π meson total cross-section data into (3) an experimental value of $\langle r^{-2} \rangle$ has been obtained. $\langle r^{-2} \rangle$ so found is essentially independent of momentum and has a mean value of $0.0423 \pm 0.003\ \text{mb}^{-1}$ corresponding to a value of r of 1.54 ± 0.06 fermis. This value of r is very sensitive to the values used for the densities of liquid hydrogen and deuterium. The error quoted on the value of r does not include any systematic errors which may be present in these density measurements. The above value is in agreement with the value $r = 2.05 \pm 0.45$ fermi obtained at lower momenta.[3]

It appears that the ultimate limit of accuracy in determining particle-neutron cross-sections in deuterium-hydrogen difference experiments is set by the accuracy to which one can determine $\langle r^{-2} \rangle$ for the Glauber correction in the pion data, and this is more dependent on the systematic errors present in an experiment than in the statistical accuracy to which one determines the relative total cross-sections. It is also assumed throughout that, at the momenta considered here, the real part of the forward scattering amplitude can be neglected.

Results of measurement of total cross-sections of K mesons on hydrogen and deuterium are shown in Fig. 3. As has been pointed out before,[4] $\sigma_T(K^+p)$ is constant. It can be seen that $\sigma_T(K^+d)$ is constant and thus also $\sigma_T(K^+n)$. 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 a constant cross-section or one that is decreasing very slowly. The same general behavior is found for the K^-n cross section.

In Fig. 4 are shown the proton proton total cross-sections, which are falling steadily with momentum up to the highest momentum studied (22 GeV/c). The values obtained are in statistical agreement with those of earlier experiments,[5-7] but the systematic behavior with momentum did not appear in the earlier work. Figure 5 shows the p-d cross-sections which are also falling with momentum. A subtraction of the p-d and p-p cross-sections reveals that this difference also falls with momentum. When the Glauber correction is applied, the proton-neutron cross-section behaves in the manner indicated in Fig. 5.

The difference between σ_{pp} and σ_{pn} is of some theoretical interest since measurements of charge exchange scattering can be related to the cross-section difference $(\sigma_{pp} - \sigma_{np})$. Ahmadzadeh[8] points out that the data of Palevsky, et al[9] and Diddens, et al[7] can be explained in terms of two Regge trajectories.[10] In particular, the theory predicts a fall in the cross-section difference $(\sigma_{pp} - \sigma_{pn})$ to a value of zero at about 6 GeV/c, becoming negative above this value. The Pomeranchuk theorem[11] calls for equality of σ_{pp} and σ_{pn} at very high energy, 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 $(\sigma_{pp} - \sigma_{pn})$ in the present experiment is entirely consistent with such behavior within the experimental errors.

The $\sigma_T(pn)$ cross-sections deduced here may be compared with the direct measurements of $\sigma_T(np)$ using neutron beams. Palevsky, et al[9] at lower momenta find $\sigma_T(np) = 40.3 \pm 1.4$ mb at 3.0 GeV/c and $\sigma_T = 39.4 \pm 3.3$ mb at 3.6 GeV/c. Kachaturyan and Pantuyev[11] find $\sigma_T(np) = 41.2 \pm 1.7$ mb at 6.5 GeV/c and Ozhdyani, et al [13] find $\sigma_T(np) = 41.2 \pm 2.6$ mb at 9.2 GeV/c.

The anti-proton cross-sections are given in Fig. 6. Here the Glauber correction is larger. The $\bar{p}p$ and $\bar{p}n$ cross-sections are equal within the accuracy of the measurements.

The $\bar{p}p$ cross-sections at high momenta fit smoothly with the data of Amaldi, et al [14] at lower momenta.

A summary of the total cross-sections of π mesons, K mesons, protons, and anti-protons on protons and neutrons is shown in Fig. 7.

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Figure Captions

Fig. 1 Experimental arrangement at Brookhaven AGS.

Fig. 2 Total cross-sections of pi-mesons on hydrogen and deuterium.

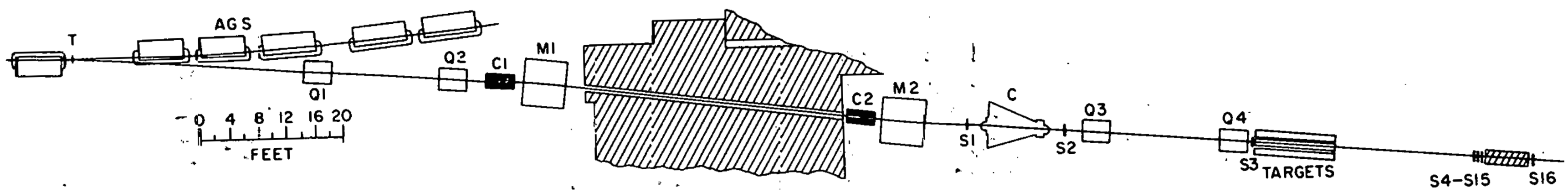
Fig. 3 Total cross-sections of K-mesons on hydrogen and deuterium.

Fig. 4 Total cross-sections of protons on hydrogen.

Fig. 5 Total cross-sections of protons on hydrogen and deuterium. The proton-neutron total cross section is derived by applying the Glauber correction to the difference $\sigma_T(pd) - \sigma_T(pp)$.

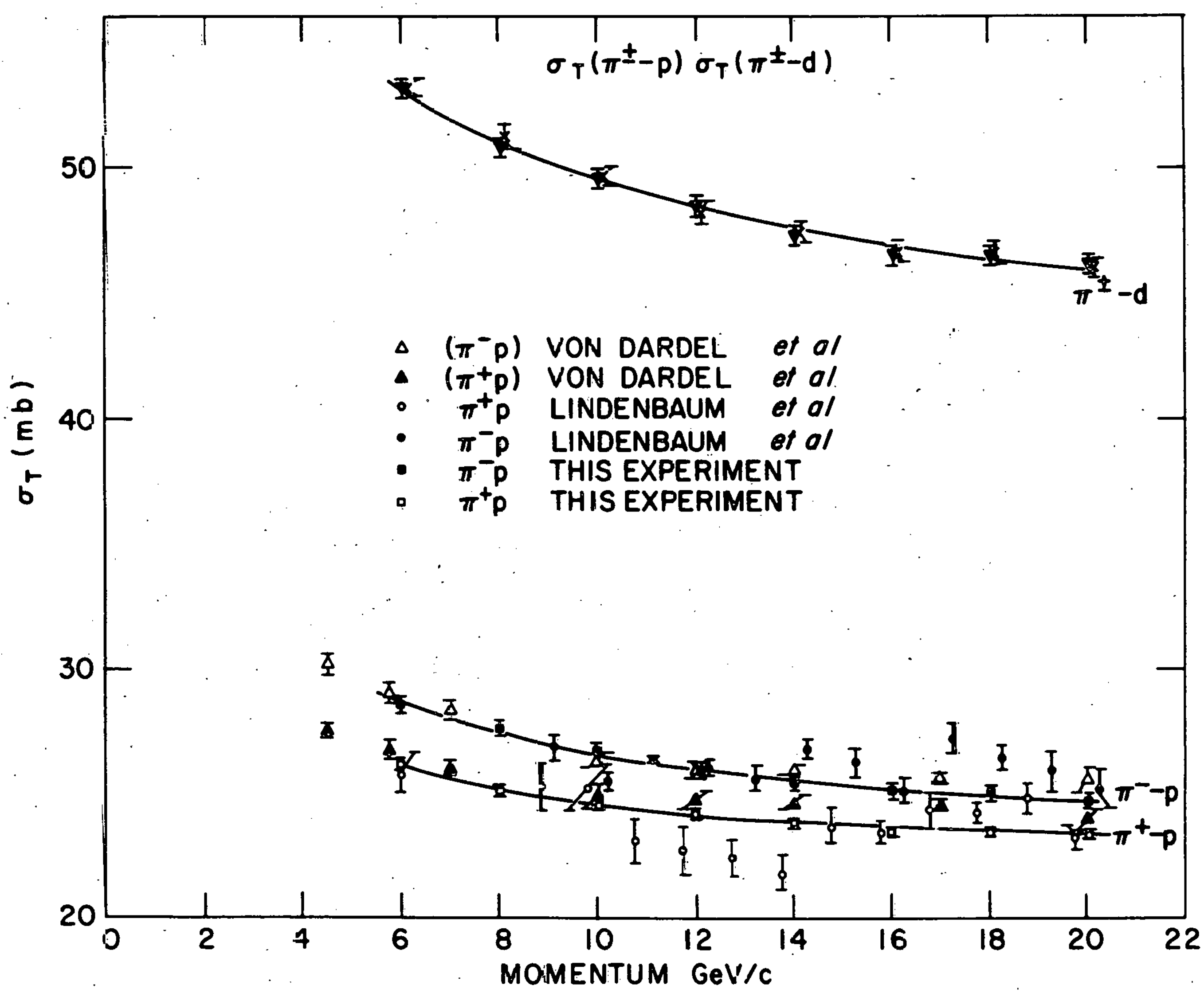
Fig. 6 Total cross-section of anti-protons on hydrogen and deuterium.

Fig. 7 Particle-nucleon cross-sections at momenta above 6 GeV/c.



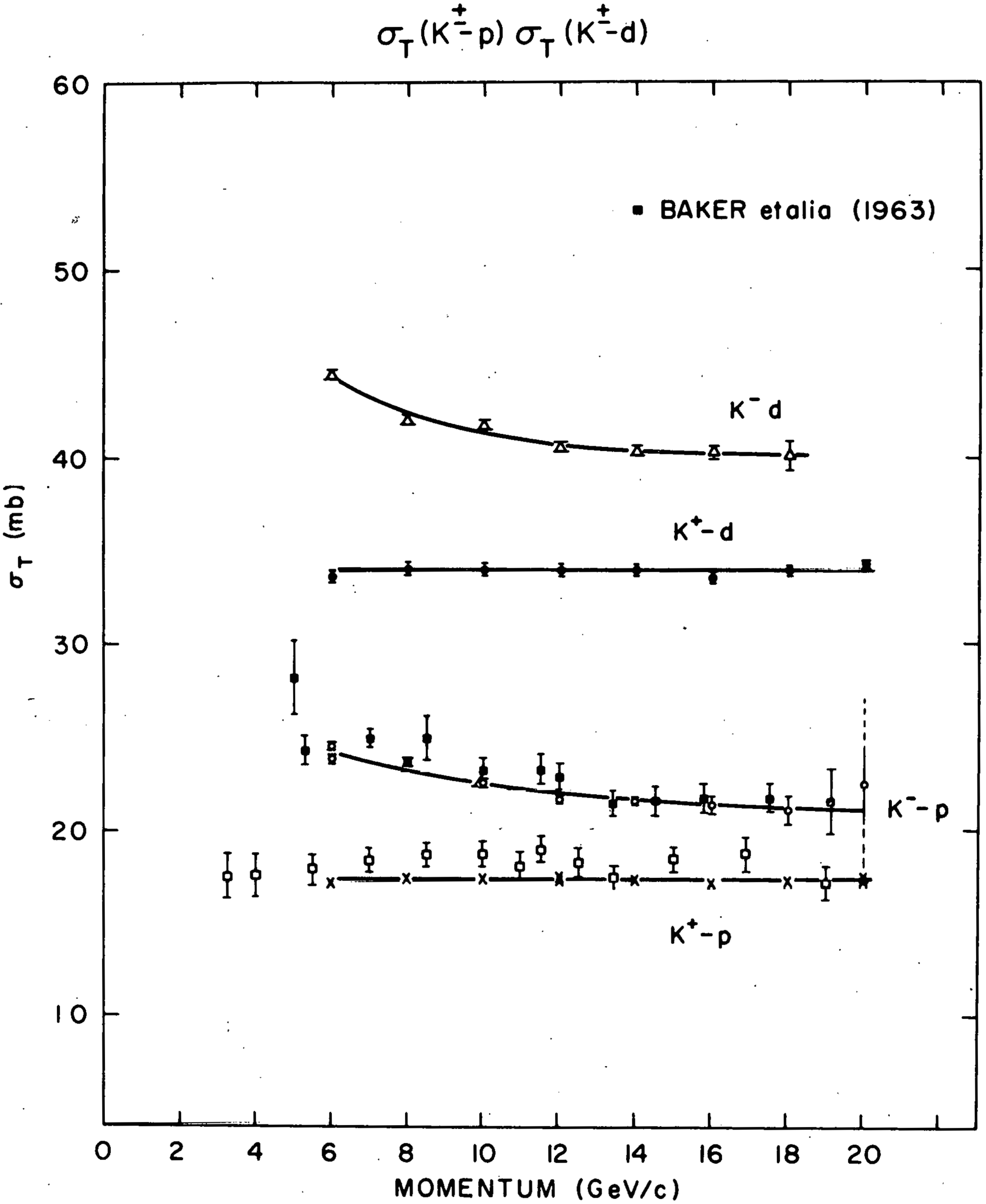
T
AGS
Q1
Q2
C1
M1
0 4 8 12 16 20
FEET
C2
M2
C
S1
S2
Q3
Q4
S3
TARGETS
S4-S15
S16

FIGURE 1



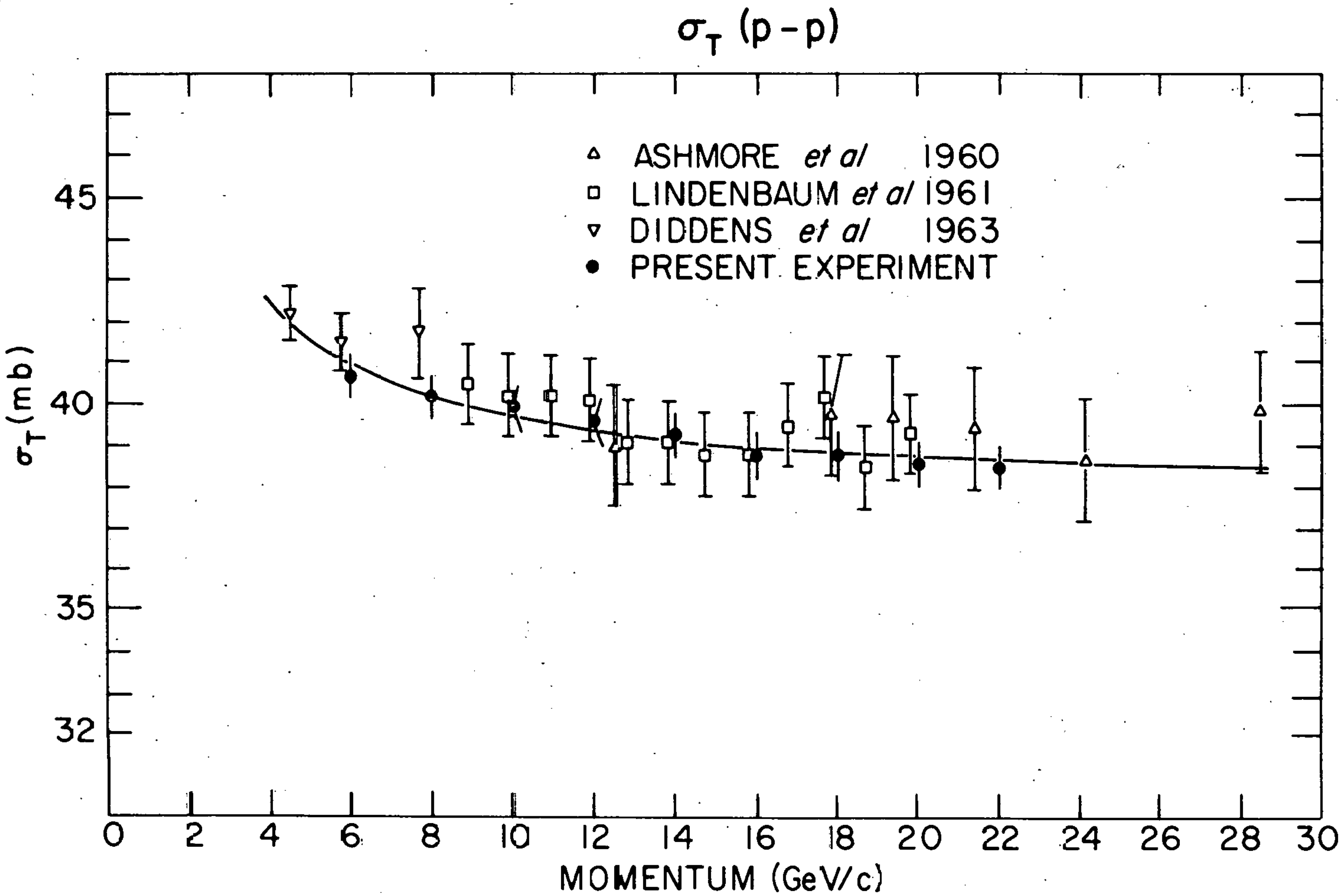
σ_T(π±-p) σ_T(π±-d)
50
40
30
20
σ_T (mb)
π±-d
△ (π⁻p) VON DARDEL et al
▲ (π⁺p) VON DARDEL et al
○ π⁺p LINDENBAUM et al
● π⁻p LINDENBAUM et al
■ π⁻p THIS EXPERIMENT
□ π⁺p THIS EXPERIMENT
π⁻-p
π⁺-p
0 2 4 6 8 10 12 14 16 18 20 22
MOMENTUM GeV/c

FIGURE 2



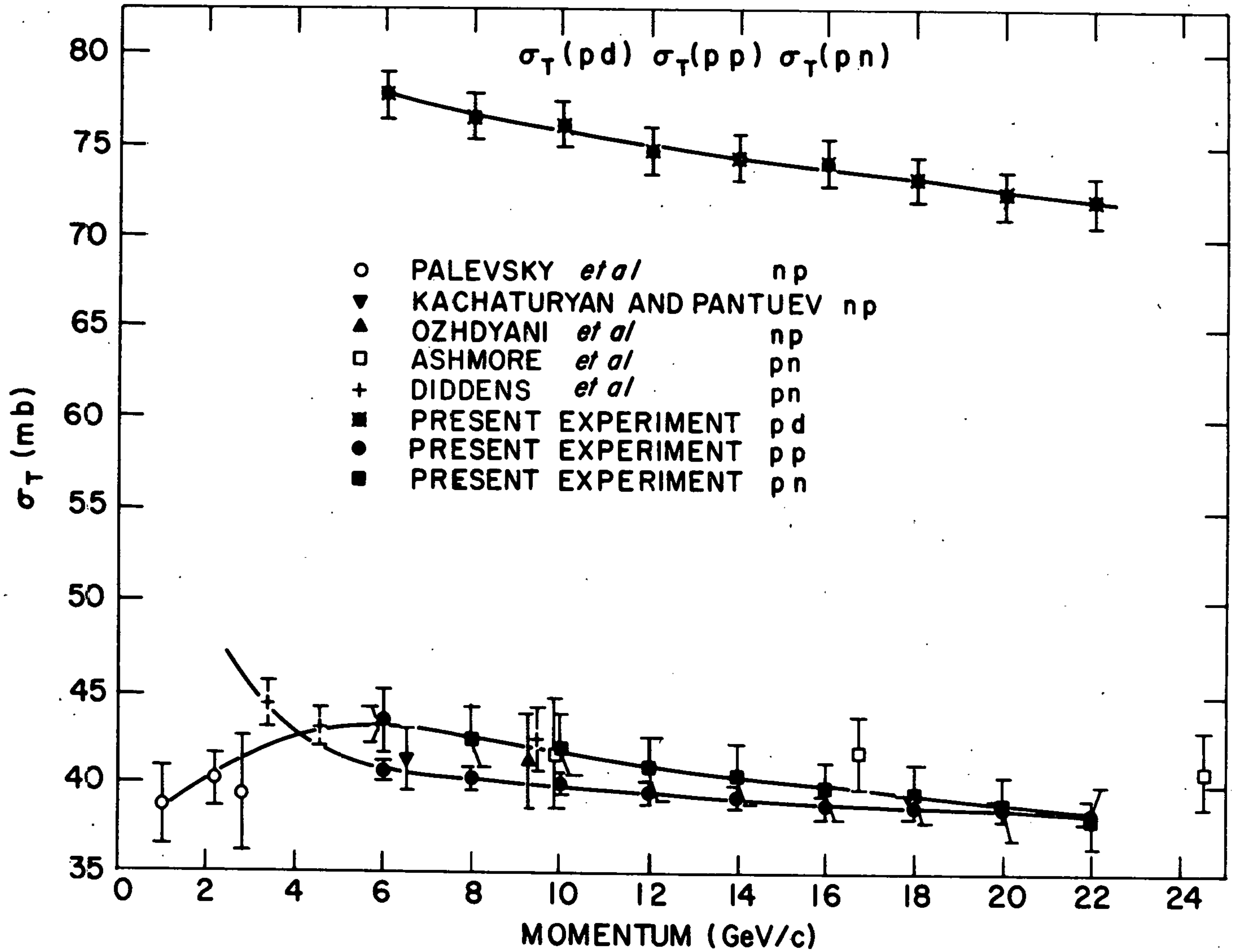
$\sigma_T(K^{\pm}-p)$ $\sigma_T(K^{\pm}-d)$
BAKER etalia (1963)
K⁻ d
K⁺-d
K⁻-p
K⁺-p
σ_T (mb)
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
20
MOMENTUM (GeV/c)

FIGURE 3



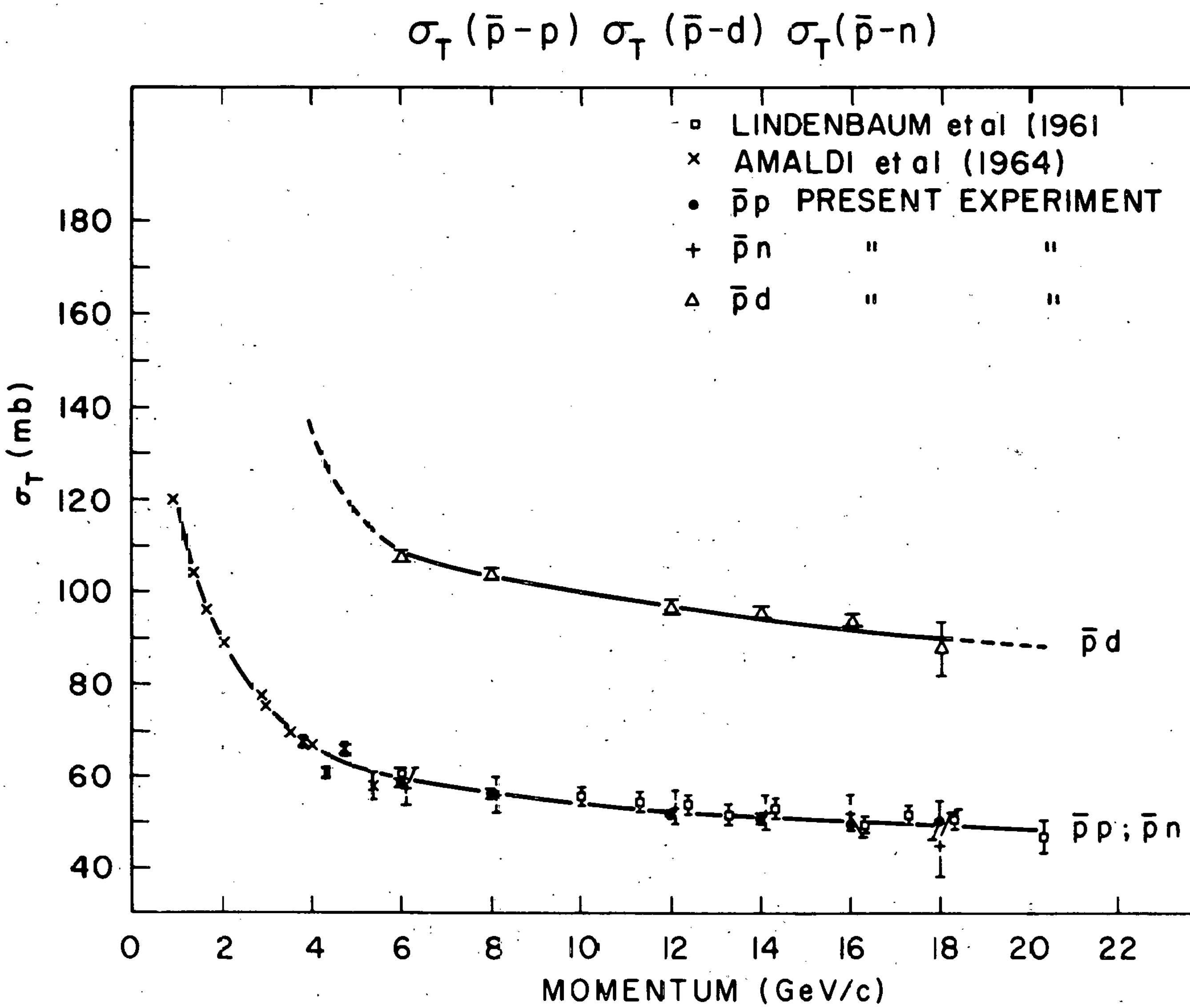
σT (p-p)
ASHMORE et al 1960
LINDENBAUM et al 1961
DIDDENS et al 1963
PRESENT EXPERIMENT
σT (mb)
45
40
35
32
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
MOMENTUM (GeV/c)

FIGURE 4



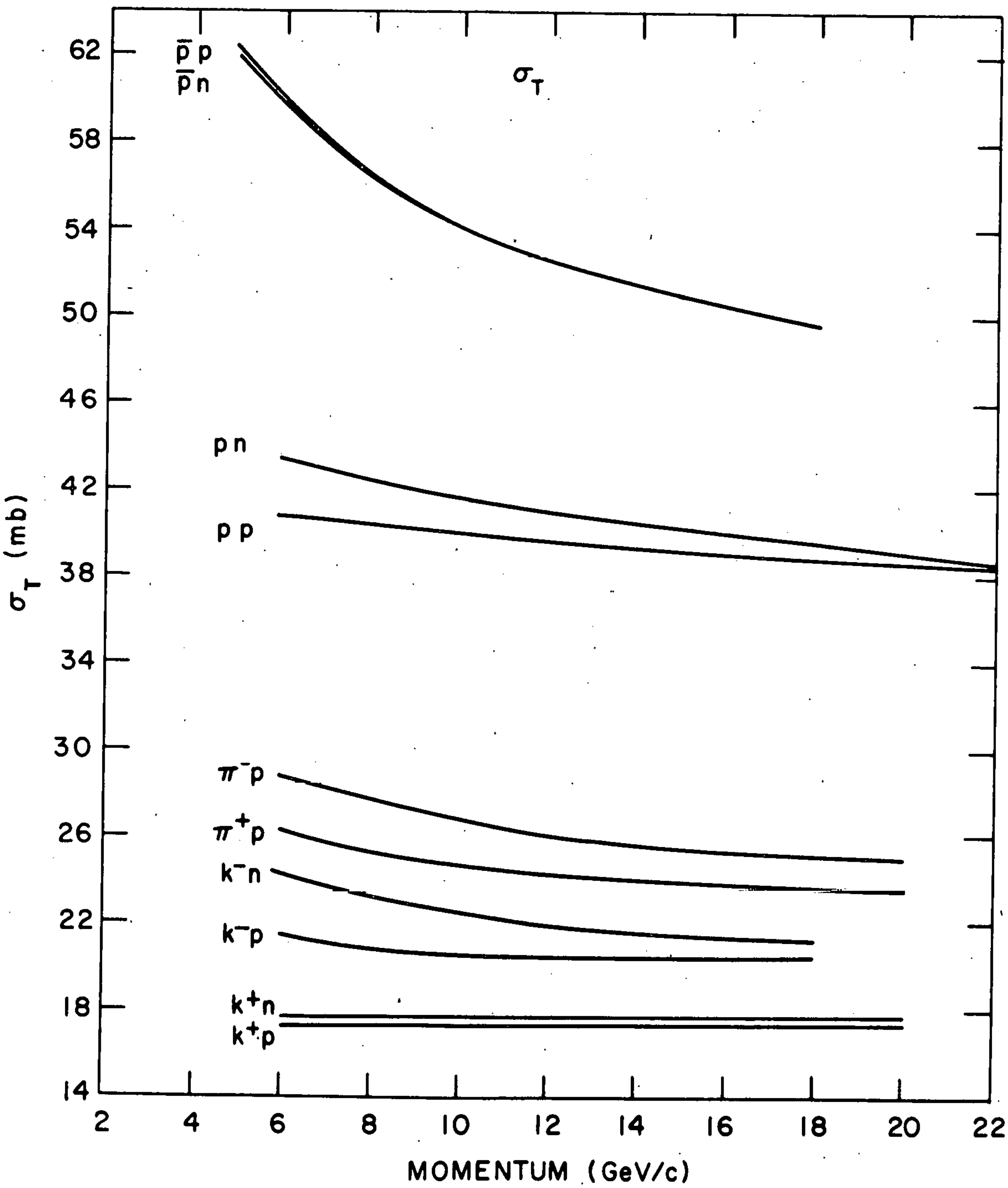
σ_T(pd) σ_T(pp) σ_T(pn)
○ PALEVSKY et al np
▼ KACHATURYAN AND PANTUEV np
▲ OZHDYANI et al np
□ ASHMORE et al pn
+ DIDDENS et al pn
PRESENT EXPERIMENT pd
● PRESENT EXPERIMENT pp
■ PRESENT EXPERIMENT pn
σ_T (mb)
MOMENTUM (GeV/c)

FIGURE 5



σT (p̄-p) σT (p̄-d) σT(p̄-n)
LINDENBAUM et al (1961
AMALDI et al (1964)
p̄p PRESENT EXPERIMENT
p̄n " "
p̄d " "
σT (mb)
180
160
140
120
100
80
60
40
p̄d
p̄p ; p̄n
0
2
4
6
8
10
12
14
16
18
20
22
24
MOMENTUM (GeV/c)

FIGURE 6



σ_T
$\bar{p}p$
$\bar{p}n$
pn
pp
π^-p
π^+p
k^-n
k^-p
k^+n
k^+p
62
58
54
50
46
42
38
34
30
26
22
18
14
σ_T (mb)
2
4
6
8
10
12
14
16
18
20
22
MOMENTUM (GeV/c)

FIGURE 7