TOTAL CROSS SECTIONS OF $\pi^{\pm}$, $K^{\pm}$, p AND $\bar{p}$ ON PROTONS AND DEUTERONS BETWEEN 23 AND 280 GeV/*c*

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New measurements are reported of total cross sections for $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ on protons and deuterons at 11 momenta between 23 and 280 GeV/*c*.

This paper describes measurements of high energy total cross sections which extend the momentum range reported earlier [1, 2] (referred to here as I and II) down to 23 GeV/*c* and up to 280 GeV/*c*. A description of the experiment, which was carried out in the M1 beam at the Fermi National Accelerator Laboratory, was given in I and II. We note here only several equipment refinements and additional checks of its performance: (i) Identification of muons in the incident beam was improved by requiring coincident counts between two scintillators placed behind 4.3 and 4.9 meters of steel, respectively, downstream of the transmission counters. (ii) Electron identification was improved by requiring large pulse heights in two consecutive lead glass Cerenkov counters of thickness 3 and 22 radiation lengths [3]. (iii) To improve incident particle identification above 200 GeV/*c*, the two differential Cerenkov counters were combined into one, increasing the radiator length from 15 to 30 meters, and reducing the Cerenkov angle from 15 to 7.5 mr. Corrections to the cross section for beam contamination were negligible except for K^+ at 240 and 280 GeV/*c* due to a K^+/p ratio which was as low as 2×10^{-4} at 280 GeV/*c*. The corrections were 0.04% and 1.7%, respectively. (iv) Cross sections were remeasured at 200 GeV/*c*. The new data agreed with I and II within the errors which were, for example, ±0.1% for the proton-proton cross sections. (v) The measurement procedure, described in I and II, makes use of partial cross sections measured by scintillation counters at several small values of $|t|$ down to $|t| = 0.016\ (\mathrm{GeV}/c)^2$. A fit to the partial cross sections is then used to extrapolate to $|t| = 0$. Three sets of proportional wire chambers, two in front of the target and one at the location of the transmission counters, has allowed us to make measurements down to $|t|$ as small as $0.004\ (\mathrm{GeV}/c)^2$ for a subset of the data. The PWC data for events with both single and multiple tracks show no rapid change in slope down to $|t| = 0.004$ and verify the validity and accuracy of our extrapolation procedure using the scintillation counter

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TABLE I. Total cross sections in millibarns measured in this experiment. See text for definitions of α and $\langle r^{-2}\rangle$.

	MOMENTUM IN GeV/c											
	23	35	50	70	100	120	150	170	200	240	280	α
σ_{pp}	39.39±.42	38.46±.05	38.20±.05	38.28±.04	38.46±.04	38.58±.04	38.69±.04	38.83±.04	38.97±.04	39.21±.04	39.38±.04	—
σ_{pd}	73.91±.69	73.57±.09	73.12±.08	73.15±.07	73.28±.07	73.44±.07	73.57±.07	73.78±.07	74.03±.07	74.40±.07	74.57±.07	—
σ_{pn}	38.52±.88	39.15±.10	38.96±.09	38.95±.07	38.96±.07	39.02±.07	39.07±.07	39.18±.06	39.32±.07	39.50±.07	39.52±.07	—
$\sigma_{\bar{p}p}$	—	45.46±.10	43.93±.10	43.05±.06	42.12±.08	41.70±.15	41.79±.17	41.69±.15	41.44±.18	—	—	—
$\sigma_{\bar{p}d}$	—	85.33±.20	82.45±.20	81.05±.16	79.42±.17	79.31±.23	78.41±.27	78.54±.26	78.16±.28	—	—	—
$\sigma_{\bar{p}n}$	—	45.64±.21	43.88±.21	43.18±.14	42.26±.16	42.54±.27	41.44±.33	41.69±.31	41.51±.34	—	—	—
σ_{K^+p}	—	17.82±.09	18.06±.08	18.52±.08	18.88±.07	19.14±.07	19.36±.07	19.64±.06	19.90±.11	20.28±.07	20.64±.40	—
σ_{K^+d}	—	35.11±.13	35.68±.13	36.06±.13	36.81±.11	37.23±.12	37.81±.11	38.18±.10	38.34±.16	39.32±.11	39.41±.62	—
σ_{K^+n}	—	18.29±.15	18.66±.14	18.60±.14	19.04±.11	19.23±.13	19.63±.12	19.74±.10	19.65±.18	20.31±.14	20.04±.78	—
σ_{K^-p}	—	20.54±.12	20.30±.10	20.38±.05	20.45±.06	20.59±.06	20.60±.07	20.65±.06	20.76±.05	21.02±.12	—	—
σ_{K^-d}	—	39.12±.16	38.91±.14	38.97±.09	39.15±.11	39.47±.10	39.44±.12	39.62±.10	39.97±.10	40.37±.15	—	—
σ_{K^-n}	—	19.84±.20	19.86±.16	19.83±.08	19.96±.11	20.16±.10	20.12±.12	20.25±.10	20.52±.09	20.69±.18	—	—
σ_{π^+p}	23.71±.06	23.21±.04	23.11±.06	23.22±.06	23.33±.06	23.42±.04	23.50±.04	23.68±.05	23.84±.06	24.12±.07	—	—
σ_{π^+d}	46.71±.10	45.87±.08	45.42±.12	45.62±.12	45.47±.12	45.73±.08	45.81±.08	46.09±.08	46.32±.10	46.90±.10	—	—
σ_{π^-p}	25.01±.06	24.37±.04	24.06±.06	24.00±.06	24.00±.06	24.06±.04	24.11±.04	24.21±.04	24.33±.04	24.58±.04	24.67±.08	—
σ_{π^-d}	46.83±.11	45.98±.08	45.59±.12	45.53±.12	45.59±.12	45.74±.07	45.93±.07	46.12±.07	46.36±.07	46.88±.07	46.81±.12	—
$\sigma_{\bar{p}p} - \sigma_{pp}$	—	7.00±.10	5.73±.11	4.76±.06	3.66±.08	3.12±.15	3.10±.17	2.86±.15	2.47±.18	—	—	0.39±.02
$\sigma_{\bar{p}d} - \sigma_{pd}$	—	11.75±.18	9.32±.18	7.90±.13	6.14±.14	5.87±.21	4.84±.25	4.76±.24	4.13±.27	—	—	0.40±.02
$\sigma_{\bar{p}n} - \sigma_{pn}$	—	6.49±.23	4.92±.23	4.23±.16	3.30±.18	3.52±.28	2.37±.33	2.51±.32	2.18±.35	—	—	0.39±.04
$\sigma_{K^-p} - \sigma_{K^+p}$	—	2.72±.15	2.23±.13	1.86±.09	1.57±.09	1.45±.09	1.24±.09	1.01±.08	0.86±.10	0.74±.14	—	0.40±.04
$\sigma_{K^-d} - \sigma_{K^+d}$	—	4.01±.19	3.22±.17	2.91±.13	2.34±.12	2.24±.13	1.63±.13	1.44±.11	1.64±.13	1.06±.18	—	0.41±.03
$\sigma_{K^-n} - \sigma_{K^+n}$	—	1.55±.25	1.20±.22	1.23±.16	0.92±.16	0.93±.16	0.49±.17	0.51±.14	0.87±.20	0.38±.23	—	0.38±.11
$\sigma_{\pi^-p} - \sigma_{\pi^+p}$	1.31±.08	1.16±.04	0.94±.06	0.78±.06	0.67±.06	0.64±.04	0.61±.04	0.54±.04	0.48±.06	0.46±.07	—	0.55±.03
$\sigma_{\pi^-d}/\sigma_{\pi^+d}$	1.003 ±.003	1.002 ±.002	—	—	—	1.000 ±.002	1.003 ±.002	1.001 ±.002	1.001 ±.003	1.000 ±.003	—	—
$\langle r^{-2}\rangle$ (mb^{-1})	0.042	0.037	0.038	0.037	0.040	0.039	0.039	0.039	0.040	0.038	—	—

data. The PWC resolution and multiple Coulomb scattering prevent measurements below $|t| = 0.004$.

(vi) Studies showed negligible variation of the measured cross section due to changes in beam spot size and transmission counter position; a variation with beam intensity required a small correction (~0.1%) which was also applied to the data of I and II. The revised data are also reported in table 1.

Data analysis was carried out essentially as in I and II. Based upon the reproducibility of the data, and upon the uncertainty in the extrapolation procedure, we estimate a momentum dependent systematic uncertainty for incident protons and antiprotons of ±0.1% in addition to the statistical error. For pions and kaons, the estimated systematic uncertainty was increased to between ±0.15% and ±0.25% as a result of uncertainties in the correction for muon and electron contamination. A momentum independent systematic scale error in the absolute magnitude of the cross section is introduced by uncertainties in the form of extrapolation and in the hydrogen and deuterium densities and contaminations. It is estimated to be ±0.4% for protons and ±0.5% for deuterons.

Results are given in table 1 and displayed in figs. 1 and 2 together with previous data [4–19]. Momentum dependent errors only are shown. For the cross sections of $K^{\pm}$, $\bar{p}$ and π^+ on protons and deuterons, we are in reasonable agreement with all of the previous measurements. In the region from 50 to 70 GeV/c the π^-p cross sections of this experiment are about 0.2 mb lower than those of Denisov et al. [8, 9]. However, we are in good agreement with the more recent measurements of Apokin et al. [10]. Our pp total cross sections join smoothly to the rising cross section from the CERN-ISR [13, 14]. There is a small difference only around 50 GeV/c from the data of Denisov et al. [7], and a larger difference from the 200 and 300 GeV/c data points of Gustafson et al. [17].

The cross sections for target neutrons have been obtained from those on protons and deuterons using the Glauber-Wilkin [20, 21] procedure. From the pion-proton and pion-deuteron cross sections we derive the values of the parameter $\langle r^{-2}\rangle$ given in table 1. $\langle r^{-2}\rangle$ is consistent with being momentum independent with an average equal to 0.039 mb^{-1}. For kaons we have used this value; for protons and antiprotons we have

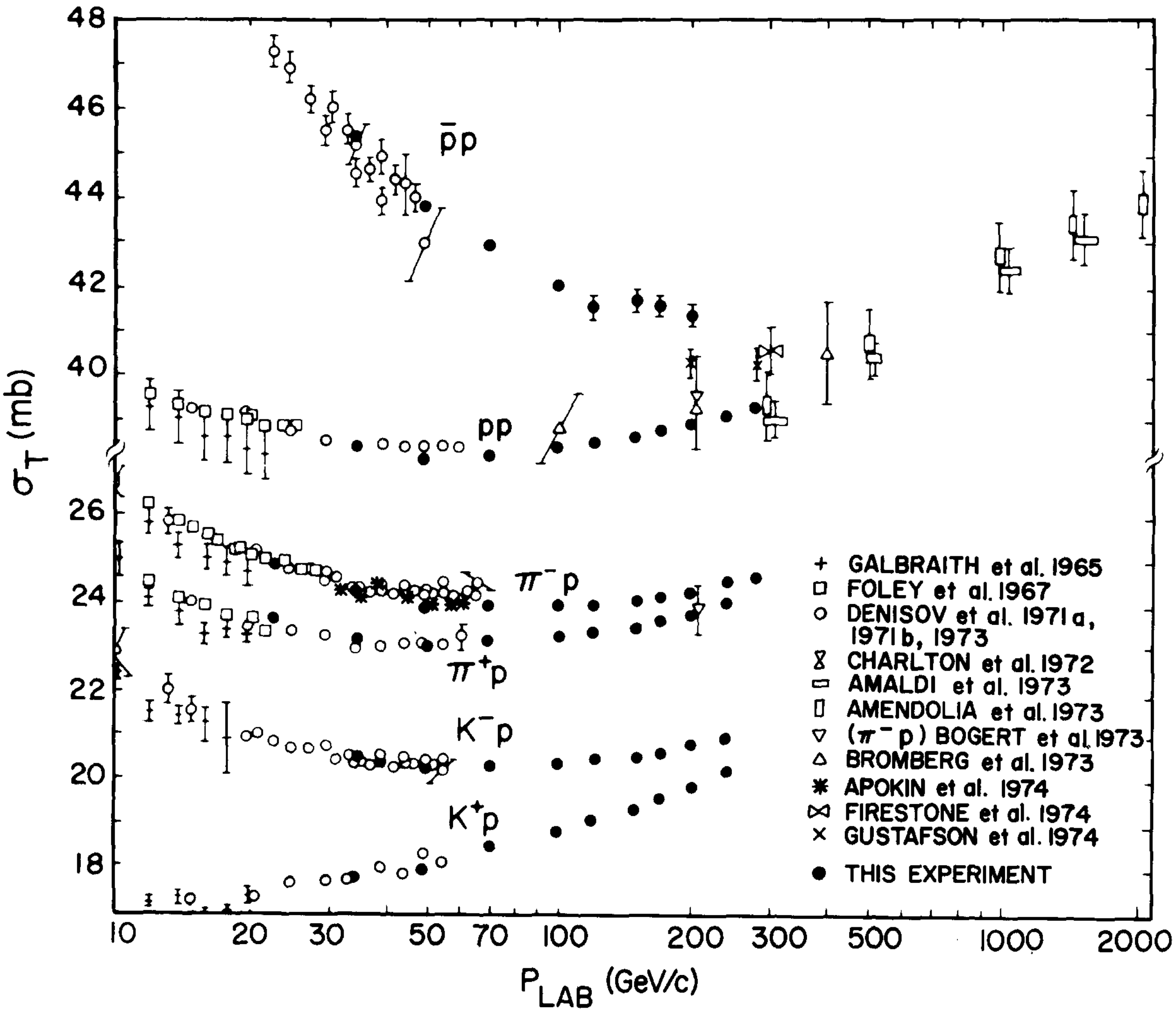

Fig. 1. Total cross sections on protons. Only momentum dependent errors are shown.

used the value 0.035 mb^{-1} for the reasons discussed in I and II. It is clear, however, that this procedure introduces uncertainties due to theoretical approximations which are large compared to the experimental errors of the data and the adequacy of the procedure has been frequently questioned [22–28]. For example, an uncertainty in the parameter $\langle r^{-2} \rangle$ of ± 0.004 mb^{-1} produces a ±1.5% uncertainty in the p-n cross section and ±0.7% in the kaon-neutron cross section. The dashed curves in fig. 2 illustrate this effect. Thus caution must be exercised in drawing conclusions concerning neutron cross sections from these data. We note, however, that reasonable changes in the parameter $\langle r^{-2} \rangle$ do not appreciably affect the momentum dependence of the neutron cross sections.

One of the striking regularities of the total cross section behavior is the simple power law dependence of the antiparticle-particle difference over our momentum range as shown in fig. 3. Fitting only our data with the form $As^{\alpha-1}$ we obtain the values of α given in table 1.

The results of this experiment, together with previous data, show that the cross sections of all incident particles except p̄ fall as the momentum increases, followed by a minimum and then a rise. The p̄p total cross section continues to fall with increas-

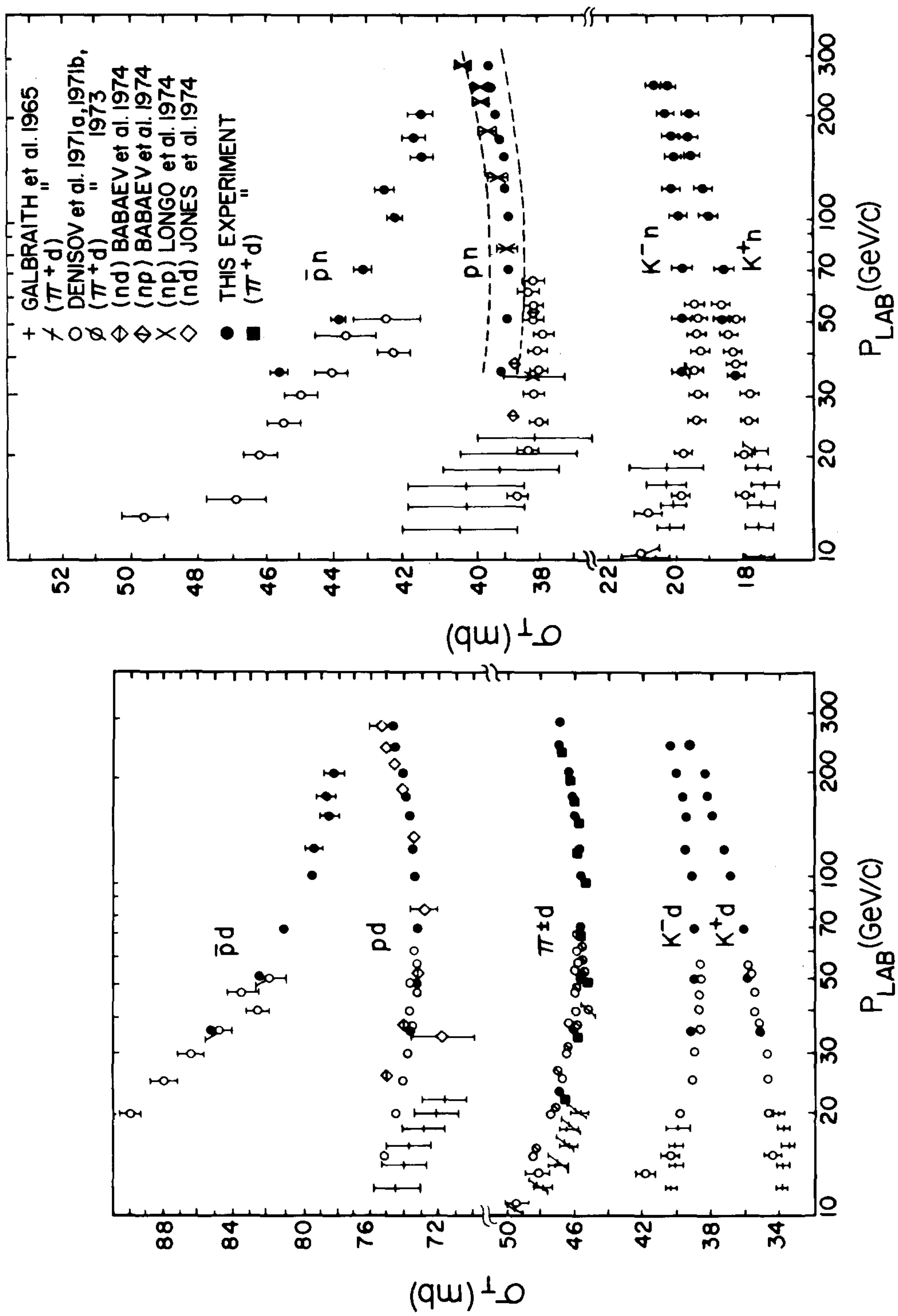

Fig. 2. Total cross sections on deuterons and neutrons. Only momentum dependent errors are shown. The upper and lower dashed curves represent the p-n cross sections obtained assuming $\langle r^{-2} \rangle = 0.039$ and $0.031\ \mathrm{mb}^{-1}$ respectively.

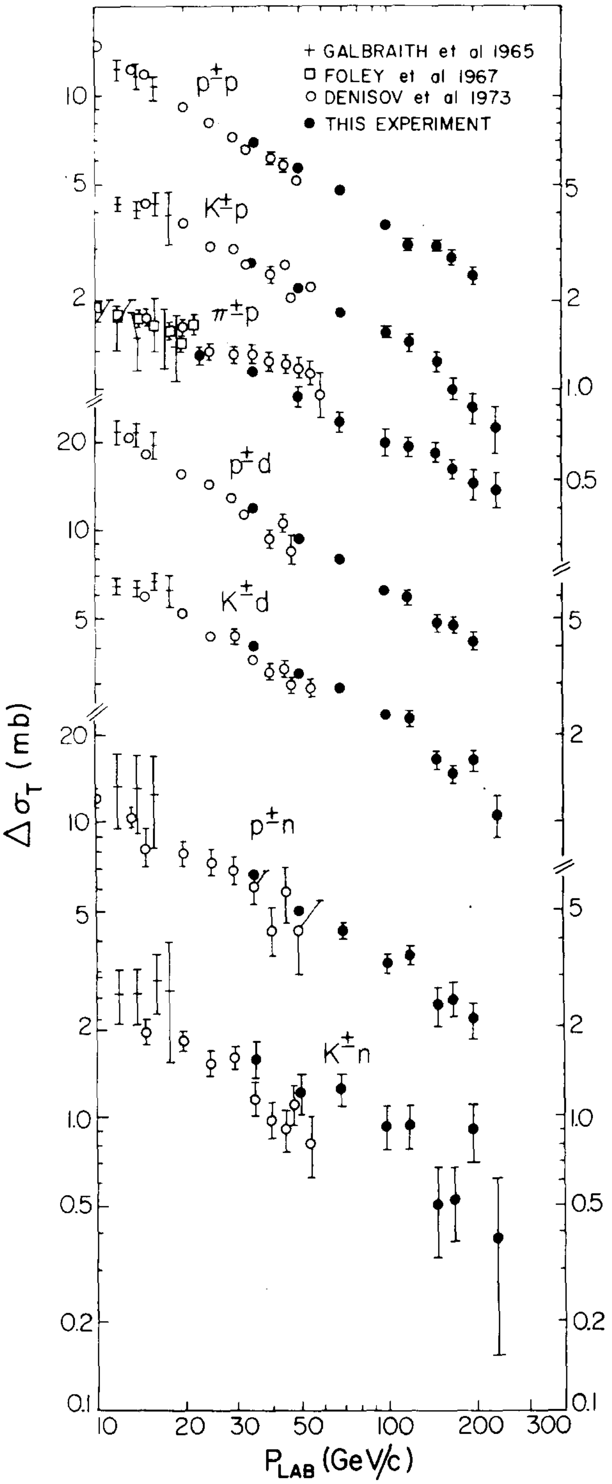

Fig. 3. Antiparticle-particle total cross section differences.

ing momentum, but the rate decreases markedly and above 120 GeV/c there is comparatively little variation. Considering the regular behavior of the p̄p-pp difference and the observed rise in the pp total cross section, it is very likely that the flat regions in the p̄p and p̄d cross sections represent minima before they also rise.

It is interesting also to note that the average of the K^+p and K^-p and the average of the π^+p and π^-p cross sections are slowly approaching one another. The data are consistent with a slower approach of the ratio of the average of the π^+p and the π^-p to the average of the p̄p and the pp cross sections to the value 2/3 predicted by the additive quark model.

The ratio $\sigma_{\pi^-d}/\sigma_{\pi^+d}$, which should be unity if charge symmetry is valid, is given in table 1 (for those momenta where it was not assumed in order to estimate uncertainties in electron contamination). The ratio is always consistent with unity, and the average is 1.0014 ± 0.0009. The $\pi^-p - \pi^+p$ total cross section differences agree within errors with the predictions from forward charge exchange measurements of Barnes et al. [29]. Several authors have compared total cross section data with the various relations given by quark and Regge Pole models [9, 30]. A comparison of our new data with such relations reinforces the conclusions of a similar comparison made to the data of I and II [e.g. 30].

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