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A Measurement of the p-p Total Cross Section at 200 and 300 GeV/c*

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Abstract

In a counter experiment, performed at the National Accelerator Laboratory, we have measured total cross sections for p-p scattering with the results $\sigma_T = 40.42 \pm 0.27$ mb at 200 GeV/c and 40.40 ± 0.28 at 300 GeV/c. Our 300 GeV/c result is significantly higher than published data from the ISR. Our data, taken together with the Serpukhov data, indicate that the cross section rises ≈ 2 mb between 60 and 250 GeV. The variation of the cross section with energy may be more complicated than the $(a+b \log^{\alpha} s)$ behavior commonly assumed for $E_{lab} \geqslant 50$ GeV.

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We have carried out a measurement of proton-proton total cross sections at 200 and 300 GeV/c in a proton beam at the National Accelerator Laboratory. The standard good geometry transmission technique was used with a liquid hydrogen target and scintillation counters.

The experimental arrangement is shown schematically in Figure 1. The proton beam was made by slightly modifying an existing neutral beam by the addition of two small bends, each about 0.7 mr. The beam was taken off at an angle of 1 mr from a beryllium target in an external proton beam. The beam line had a nominal momentum spread of ±7%. However, diffractively scattered protons completely dominated the spectrum, so that the actual momentum spread was less than 1%. Pulse height spectra from the total absorption calorimeter[1] showed no evidence for low energy particles in the beam. The beam size at the hydrogen target was about 2 mm diameter as defined by a collimator about 15 m upstream of the target. The beam at counters D_1 -D_7 was approximately 0.6 cm in radius. The beam intensity was generally kept below 10^4 protons per pulse so that accidentals were <<1%.

The target was a refrigerated liquid hydrogen target 121.41 ± 0.05 cm long at liquid hydrogen temperature. The target pressure was monitored continuously during the running and was approximately one atmosphere. The liquid hydrogen was essentially in equilibrium with hydrogen vapor, so that knowledge of the pressure was sufficient to determine the temperature, and

consequently the density. Sufficient time elapsed between filling the target and taking data to insure that the ortho-to-parahydrogen transition was complete. The hydrogen vessel was interchanged with an evacuated dummy target of similar construction about once a minute during data taking. The uncertainty in the final cross sections due to uncertainties in the target length and density are estimated to be <0.2%.

The beam transmitted by the hydrogen target was measured by the transmission counters D_1-D_7 and the calorimeter C . The transmission counters were circular scintillator discs, concentric with the beam, and ranged from 1.9 cm to 10.2 cm in radius. A total of 64 coincidences of various kinds were recorded. Most of these were of the type $[D_o \cdot D_j \cdot D_{j+1} \cdot C_i]$ where C_i represents a pulse from one of seven discriminators which were set to trigger only if the pulse height from the calorimeter exceeded some minimum δ_i . The δ_i corresponded to energies deposited in the calorimeter of approximately 40, 80, 130, 180, 215, 240 and 270 GeV. Thus, in effect, we were able to measure the apparent cross section vs. energy deposited in the calorimeter. This served as a useful check against beam contamination and also greatly facilitated the extrapolation to zero solid angle as discussed below.

The other scaler channels recorded the monitors, accidental coincidences of various kinds, singles rates, proton beam intensity, etc. The scaler counts were recorded on magnetic

tape after every beam pulse. This allowed later editing of occasional bad beam pulses.

The apparent cross section for any channel (corresponding to a calorimeter pulse height cut δ_i and a solid angle $\Delta\Omega_j$) is given by the usual expression

$$\sigma_{ij} = \frac{1}{nx} \log \frac{(C_{ij}/M)_{MT}}{(C_{ij}/M)_{Full}}$$

where (C_{ij}/M) is the ratio of counts in that channel to monitor counts with the target full or empty and nx is the target constant. As is well known, the cross sections are independent of the counter efficiencies provided they are the same for target empty and full.

The measured cross sections were corrected for Coulomb scattering. Corrections for multiple scattering were calculated following the technique of R.M. Sternheimer.[2] Only data points for which these corrections were <u>negligible</u> were used to obtain the final total cross sections. Corrections for single Coulomb scattering were also made.[3] These corrections were usually <0.2 mb. As a sensitive check on the Coulomb corrections, data taken when the beam spot was displaced 0.7 cm from the center of the transmission counters were compared to data taken with the beam centered properly. For counters for which the calculated multiple Coulomb corrections were negligible, no change was seen in the cross sections, even though large changes occurred

for the smaller counters.

The corrected cross sections were extrapolated to zero solid angle in the usual way. It was found that the slope of the extrapolation increased significantly for the lower calorimeter pulse height channels, due to the detection of inelastic events with low energy secondaries. As might be expected, the slope of the extrapolation approached $(d\sigma/d\Omega)_{elastic}$ when the pulse height cut was just below the incident proton energy. It was also found that the extrapolated total cross sections were essentially independent of the pulse height cut. Typically the extrapolation increased the cross section about 1% above the cross sections measured with the smaller counters. The error in the extrapolated cross section due to the uncertainty in the extrapolation was about 0.35%.

In the final data sample, only runs with accidental rates $\leq$0.4% were used. At 200 GeV/c, a group of runs with an average accidental rate of 3% yielded a cross section differing by +0.4 ± 0.3 mb from that of the lower rate data retained in the final sample. For each run the ratios (C_{ij}/M) were also plotted <u>vs</u> rate for each beam pulse. Typically the beam rate per pulse varied over an order-of-magnitude during each run, but no sign of any variation of the (C_{ij}/M) with rate was found. The pulse-to-pulse variations of these ratios were also studied and compared with variations expected due to statistical fluctuations.

For most runs the variations were consistent with statistics. For a few, slightly larger variations were found and the statistical errors in the cross sections were increased proportionately.

For the 300 GeV/c data there were 10 runs in the final sample. These gave a $\chi^2 = 7.6$, relative to their weighted average, for 9 degrees of freedom (56% confidence level). For the 200 GeV/c data there were 6 runs with a χ^2 of 2.0, corresponding to a confidence level of 83%.

Our result for the total cross section at 300 GeV/c is 40.40 ± 0.28 mb. The error corresponds to adding in quadrature the statistical error (±0.22 mb), the error in the extrapolation to zero solid angle (±0.15 mb), the error due to possible uncertainties in Coulomb scattering corrections (±0.06 mb), and the uncertainty in the target constant (±0.08 mb). Our result at 200 GeV/c is 40.42 ± 0.27 mb with very similar contributions to the error.

Our results are plotted in Figure 2 along with previous data from Serpukhov,[4] the NAL bubble chamber,[5] and the CERN ISR.[6,7] Our result at 300 GeV is significantly higher than the published ISR data[6,7a] and the NAL bubble chamber result.[5b] However, it does agree well with ISR data from the Pisa-Stony Brook group taken with lead converters in front of their counters[7b] (the dashed points in Fig. 2). Our data, together with the Serpukhov data, indicate a rise of approximately 2 mb in σ_T

between 60 and 250 GeV/c.[8] Pumplin, Henyey, and Kane have recently pointed out that a rise of several millibarns would be expected between ~30 and 500 GeV/c due to the effects of pion exchange.[9] With our results included, it is difficult to fit the data with the smooth $(a + b \log^{\alpha} s)$ energy dependence commonly assumed at high energies.[10] However a smooth rise starting just above P_{lab} = 60 GeV/c and continuing beyond 1500 GeV/c is not excluded.

We wish to express our sincere gratitude to the NAL staff whose hard work and devotion makes the entire experimental program there possible. We also wish to thank the many other members of the Michigan group who have worked on various aspects of the experiment, especially C. Ayre, J. Chanowski, C. DeHaven, D. Koch, P.V. Ramana Murthy, F. Ringia, P. Skubic and J. Stone.

References

1. For a complete discussion of the total absorption calorimeter see: L.W. Jones *et al.*, UMHE Report 73-24, December 1973.
2. R.M. Sternheimer, Rev. Sci. Instr. 25, 1070 (1954). Sternheimer assumes a Gaussian distribution for multiple Coulomb scattering. For a thin, low-Z target such as ours the actual distribution deviates significantly from a Gaussian. The Snyder-Scott distribution includes single and "plural" scattering and gives a more accurate description. We have used a technique like that used by Sternheimer in his treatment of single scattering (Sect. III) to estimate how sensitive the Coulomb corrections are to the distribution function. We find that the error in σ_T due to the neglect of plural scattering is $\leqslant 0.05$ mb.
3. The Coulomb-nuclear interference term was included, but was found to be negligible.
4. S.P. Denisov et al., Phys. Lett. 36B, 415 (1971).
5. (a) G. Charlton *et al.*, Phys. Rev. Lett. 29, 515 (1972).
   (b) F.T. Dao *et al.*, Phys. Rev. Lett. 29, 1627 (1972).
   (c) C. Bromberg *et al.*, Phys. Rev. Lett. 31, 1563 (1973).
6. U. Amaldi et al., Phys. Lett. 44B, 112 (1973).
7. (a) S.R. Amendolia *et al.*, Phys. Lett. 44B, 119 (1973).
   (b) G. Bellettini, invited paper at the 5th International Conference on High Energy Collisions, Stony Brook, August 1973 (to be published in the proceedings).

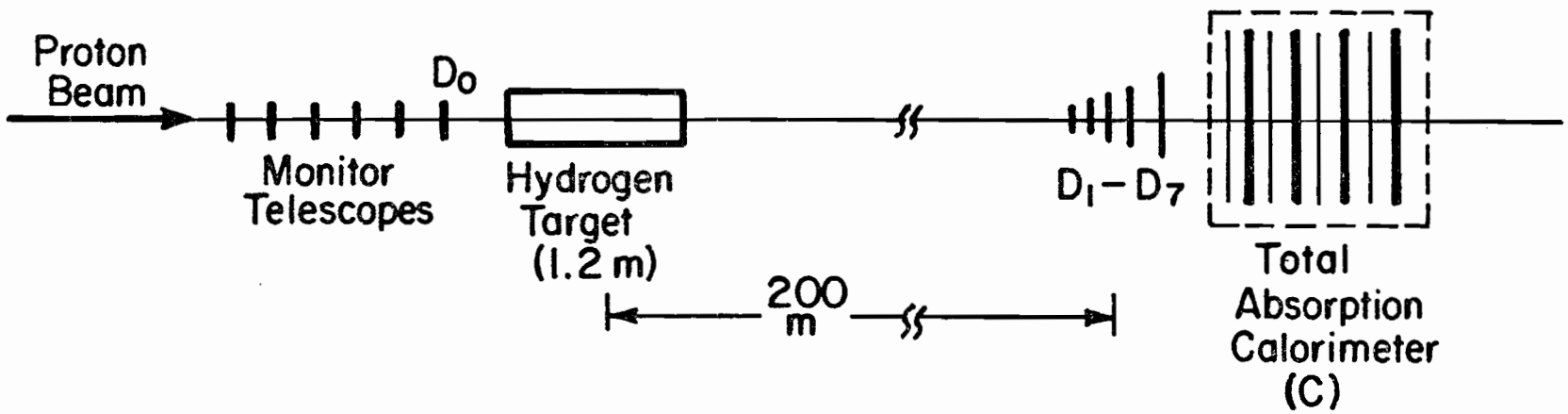
8. If the increase in σ_T is interpreted as a result of an increase in the effective radius of the nucleon, it should be accompanied by a proportionate increase in the slope of the forward peak, b. It is interesting to note that the data of Bartenev et al. [Phys. Rev. Lett. 31, 1088 (1973)] indicate that b increases from 10.84 ± 0.20 at 78 GeV/c to 11.56 ± 0.12 at 199 GeV/c.

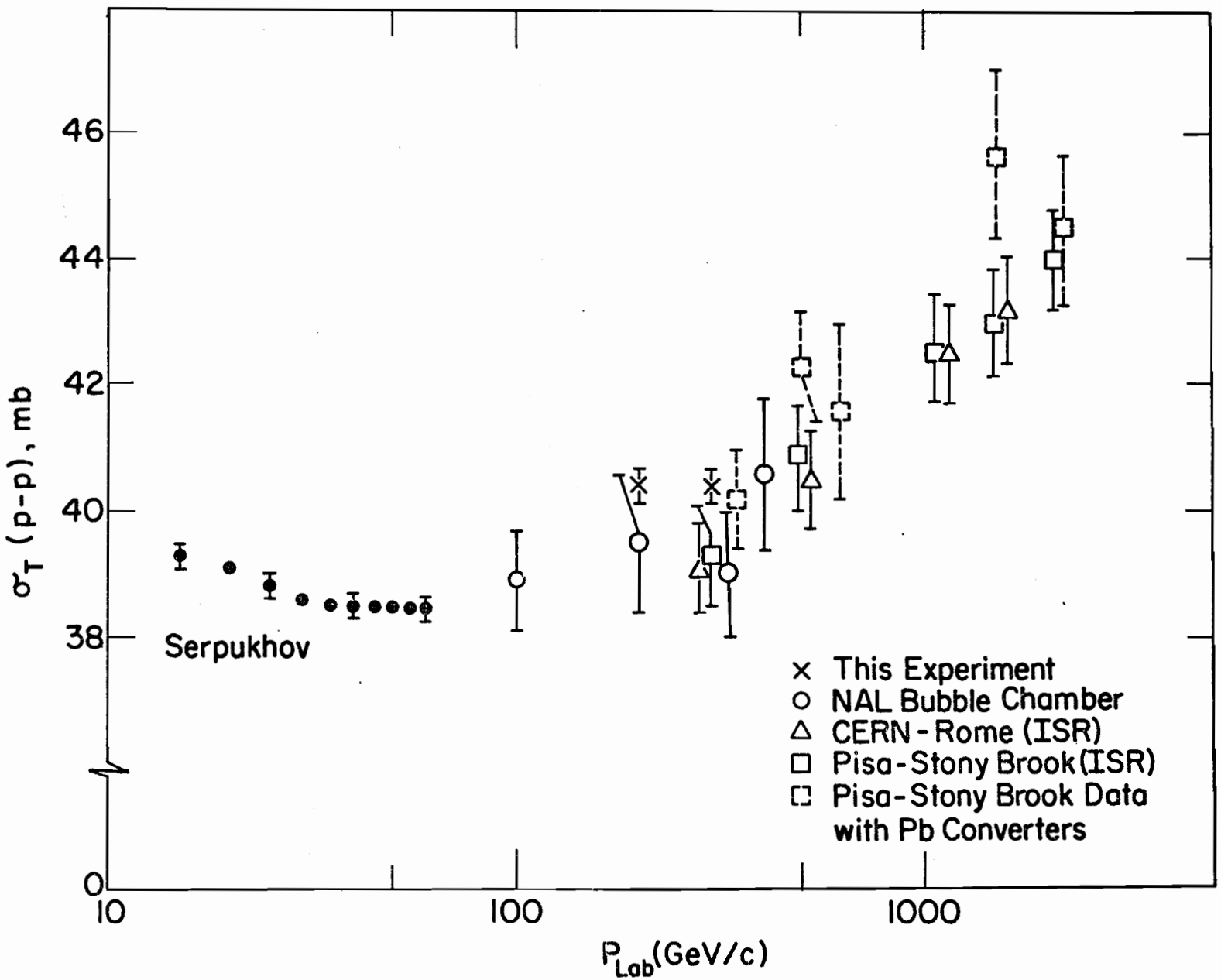
9. J. Pumplin, F. Henyey, and G. Kane, Michigan State University Preprint, December 1973 (submitted to Physics Letters). This rise in σ_T is on top of a "background" which is assumed to be slowly varying with energy. The "background" could include a logarithmic rise at high energy.

10. See, for example, Bartenev et al., Phys. Rev. Lett. 31, 1367, 1973.

Figure Captions

1. Schematic of the experiment.
2. pp total cross section data.


Proton
Beam
Monitor
Telescopes
D_0
Hydrogen
Target
(1.2 m)
200
m
$D_1 - D_7$
Total
Absorption
Calorimeter
(C)


46
44
42
40
38
0
σ_T (p-p), mb
10
100
1000
P_{Lab}(GeV/c)
Serpukhov
× This Experiment
○ NAL Bubble Chamber
△ CERN - Rome (ISR)
□ Pisa-Stony Brook(ISR)
Pisa-Stony Brook Data
with Pb Converters