MEASUREMENT OF ELASTIC SCATTERING IN ANTIPROTON-PROTON COLLISIONSAT 52.8 GeV CENTRE-OF-MASS ENERGY

M. Ambrosio², G. Anzivino², G. Barbarino²,
G. Carboni^{1,3}, V. Cavasinni^{3,*}, T. Del Prete³, P.D. Grannis⁴,
D. Lloyd Owen¹, M. Morganti³, G. Paternoster²,
S. Patricelli², and M. Valdata-Nappi³

[CERN¹-Napoli²-Pisa³-Stony Brook⁴ Collaboration]

ABSTRACT

We measured the differential cross-section for $\bar{p}p$ and pp elastic scattering in the momentum-transfer range $0.01 < |t| < 1.0 \text{ GeV}^2$ at the CERN Intersecting Storage Rings with centre-of-mass energy $\sqrt{s} = 52.8 \text{ GeV}$. Fitting the differential cross-section with an exponential ($A e^{bt}$), we found $b_{\bar{p}p} = 13.92 \pm 0.59 \text{ GeV}^{-2}$ for $|t| < 0.05 \text{ GeV}^2$, whilst for $|t| > 0.09 \text{ GeV}^2$, $b_{\bar{p}p} = 10.68 \pm 0.26 \text{ GeV}^{-2}$. Using the optical theorem, we obtained for the total cross-section $\sigma_{\text{tot}}(\bar{p}p) = 44.86 \pm 0.78 \text{ mb}$ and, by integrating the differential cross-section, we obtained for the total elastic cross-section $\sigma_{\text{el}}(\bar{p}p) = 7.89 \pm 0.28 \text{ mb}$. Calculations of σ_{tot} combining elastic-rate and total-rate measurements are also given. All of these measurements were also performed for pp scattering at the same energy, and the results for both reactions are compared.

(Submitted to Physics Letters B)

-
- 1) CERN, Geneva, Switzerland.
 - 2) Istituto di Fisica dell'Università, Napoli, and INFN, Sezione di Napoli, Italy.
 - 3) INFN, Sezione di Pisa and Istituto di Fisica dell'Università, Pisa, Italy.
 - 4) State University of New York, Stony Brook, NY, USA.
 - *) Scuola Normale Superiore, Pisa, Italy.

In an experiment performed at the CERN Intersecting Storage Rings (ISR) we measured the differential elastic cross-section $d\sigma/dt$, the total elastic cross-section σ_{el} , and, using the optical theorem, the total cross-section σ_{tot} for antiproton-proton interactions at the centre-of-mass energy $\sqrt{s} = 52.8$ GeV. The same quantities were also measured in proton-proton interactions at the same energy.

The method used to determine the differential cross-sections was that of measuring the elastic rate R_{el} into a detector cell of solid angle $(\Delta t \cdot \Delta \phi)$ as a function of the four-momentum transfer t , while simultaneously measuring the luminosity L of the colliding beams. The measured cross-section is then

$$\frac{d\sigma_{meas}}{dt} = 2\pi \frac{R_{el}(t)}{L \times (\Delta t \cdot \Delta \phi)} . \quad (1)$$

The Coulomb contribution to the scattering process was subtracted from this cross-section to yield the *nuclear* differential cross-section $d\sigma/dt$. A universal feature of high-energy hadronic scattering is that nuclear elastic scattering at small angles can be parametrized by an exponential function of t :

$$\frac{d\sigma}{dt} = A e^{bt} . \quad (2)$$

By fitting this expression to the data, we obtained the nuclear slope parameter b and the total elastic cross-section σ_{el} . The total cross-section was calculated by extrapolating $d\sigma/dt$ to $t = 0$ GeV² and applying the optical theorem. Neglecting spin effects, we can write

$$\sigma_{tot}^2 = (\hbar c)^2 \frac{16\pi}{(1 + \rho^2)} \left. \frac{d\sigma}{dt} \right|_{t=0} , \quad (3)$$

where ρ is the ratio of the real to the imaginary part of the forward scattering amplitude.

The $\bar{p}p$ data were collected in a run made in October 1981, during which a stochastically cooled $\bar{p}$ beam was circulating in Ring 2 with a current of ~ 2 mA. Two different proton beams, each of ~ 10 A, were consecutively circulating in Ring 1, and the resulting luminosity was $L \sim 7 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$. The pp data were

collected with currents of ~ 3 A in both rings, yielding a luminosity $L \sim 4 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$. Both sets of data were analysed using exactly the same techniques.

The experimental apparatus (fig. 1) has been fully described elsewhere [1-3]. Briefly, it consisted of sets of scintillation-counter hodoscopes covering the entire solid angle (except for two narrow forward cones totalling $1.9 \times 10^{-4} \text{ sr}$), supplemented by drift-tube hodoscopes at small angles and a set of drift chambers in the central region. The detector in one arm was the mirror image of that in the other arm.

Elastic scattering was studied in the t range $0.01 < |t| < 1.0 \text{ GeV}^2$ using different parts of the detector: for $0.01 < |t| < 0.05 \text{ GeV}^2$, the elastically scattered particles were detected by the TB hodoscopes; for $0.09 < |t| < 1.0 \text{ GeV}^2$, by the H_5 hodoscopes. We shall first discuss the smaller-angle measurement and then pass on to the larger-angle one.

The TB hodoscopes were located about 9.2 m from the intersection point, where the vacuum chamber containing the exiting beam was elliptical in cross-section with a vertical aperture of 56 mm. Each hodoscope (fig. 1b) comprised:

- i) two planes of scintillation counters (TB_A and TB_B), which provided the trigger;
- ii) two arrays of nine "finger" scintillators (TBy), each $25 \times 90 \text{ mm}^2$, which determined the horizontal coordinate y of the triggering particle; and
- iii) two arrays of drift tubes [4], each array consisting of two planes of twelve tubes staggered vertically to resolve up/down ambiguities. Each tube was a cylinder 10 mm in diameter and 300 mm in length, with 250 μm aluminium walls and a 40 μm sense wire along the cylindrical axis.

The fourfold coincidence

$$T = (TB_A \cdot TB_B)_{\text{left}} \cdot (TB_A \cdot TB_B)_{\text{right}}$$

provided the trigger for this measurement. When a trigger occurred, the presence of hits in all counters was recorded and the relative timings between a master

signal and the signals of each hodoscope were digitized and also recorded. All this information was transferred to magnetic tape for subsequent analysis.

In the off-line analysis, the timing difference between the TB trigger hodoscopes in the left and the right arm was formed, and events outside the beam-beam peak in the distribution of this difference were rejected. (By examining the wings of the distribution, the remaining number of spurious triggers, due to random coincidences of the TB counters, was found to be $< 0.2\%$ in both $\bar{p}p$ and pp data.) Next, events with hits in the large-angle hodoscopes ($CI \cdot CO$ to $H_3 \cdot H_4$) were rejected to reduce the inelastic contamination of the data. The number of elastic events rejected because of accidental signals in these hodoscopes was measured to be 0.72% in the $\bar{p}p$ case and 0.71% in the pp case, using the timing distributions of the hodoscope signals.

Each candidate event populated two sets of matrices, $\begin{pmatrix} L_{yz}^{up}, R_{yz}^{down} \end{pmatrix}$ and $\begin{pmatrix} L_{yz}^{down}, R_{yz}^{up} \end{pmatrix}$, describing the hit pattern observed on the Left and the Right side in the TBy and TBz hodoscopes above and below the vacuum chamber. The index y corresponded to individual elements of the TBy hodoscope ($1 \leq y \leq 9$); the index z corresponded to cells (5 mm high) formed by the overlap of pairs of adjacent drift tubes (one in each plane) of the TBz hodoscope ($1 \leq z \leq 25$). Owing to the asymmetry of the background in $\bar{p}p$ running (the current in Ring 1 was ~ 5000 times that in Ring 2), the level of accidentals was lower in the right arm than in the left, so the R^{up} and R^{down} matrices were used to determine the t of the elastic event (in pp as well as $\bar{p}p$ data).

Elastic events were selected by imposing the following criteria on the event:

- i) At least one hit was required in one of the R_{yz} within the limits $3 \leq y \leq 7$ and $2 \leq z \leq 10$. The limits in y and the lower limit in z were chosen to ensure that the elastically scattered particle in the opposing arm would impinge on the left-arm detector. The upper limit in z was necessary because of the presence of thick flanges in the vacuum chamber: particles encountering these flanges produced too many secondaries to be unravelled by the analysis.

ii) The right-arm hit, the interaction region, and the left-arm hit were required to be collinear. (To optimize the effectiveness of this criterion, the ISR was operated in the Terwilliger scheme [5], which reduced the dimensions of the interaction diamond in our intersection region.)

In both the $\bar{p}p$ and the pp data, 31% of the events passing criterion (i) had more than a single hit in either arm because of secondary interactions and δ -ray production, and because some inelastic events were not removed by the large-angle veto. Such events were retained if criterion (ii) was satisfied by a single pair of hits, all other hits being subsequently ignored in the analysis. Figure 2 shows the distribution of events in $\Delta y = y_{\text{right}} - y_{\text{left}}$ and $\Delta z = z_{\text{right}} - z_{\text{left}}$. In practice, an event was considered collinear if $|\Delta y| \leq 2$ and $|\Delta z| \leq 2$.

This procedure for handling multiple hits tended to cause the surviving inelastic background to cluster around $\Delta y = \Delta z = 0$ under the elastic peak. In order to obtain the shape of this background in the collinearity plot, we chose a sample of inelastic events having hits only in hodoscopes either above or below the vacuum chamber in *both* arms. The multiplicity detected by the hodoscopes for these events was found to be similar to that for the elastic data for observed multiplicity greater than three, and the sample was analysed in the same way as the elastic sample, except that the two sets of matrices were paired differently, i.e. $\begin{pmatrix} L_{yz}^{\text{up}}, R_{yz}^{\text{up}} \end{pmatrix}$ and $\begin{pmatrix} L_{yz}^{\text{down}}, R_{yz}^{\text{down}} \end{pmatrix}$. The pseudo-collinearity distribution thus obtained was normalized to the tails of the collinearity distribution of the elastic sample and subtracted from it. The amount of background removed was about 6% of the total sample and did not depend on t .

A further correction had to be applied for elastic events lost due to dead spaces in the left-arm hodoscopes. Such events, which produced no hit in either TBy or TBz, were analysed separately using a cut in coplanarity rather than in collinearity (i.e. a cut in one coordinate rather than two) to select elastic events. The inelastic contamination was subtracted from the coplanarity distributions in a manner analogous to that described above, and the surviving events (10% of the final sample) were added to the original sample with an error of $\pm 20\%$, taking into account the greater uncertainty in the background subtraction.

The mean value of t for a detector cell $\langle t \rangle$ was calculated by a Monte Carlo, taking into account the finite dimensions of the source. The indeterminacy in the definition of $\langle t \rangle$ for a given cell varied in the range $1.4\% < |\Delta\langle t \rangle / \langle t \rangle| < 2.8\%$ because of

- i) the uncertainty in the mean values of the beam momenta,
- ii) the uncertainty in the distance of the detector from the source,
- and
- iii) the uncertainty in the horizontal position of TBy and in the vertical position of TBz with respect to the source.

The latter was by far the most important contribution and the only one giving a t dependence to $\Delta\langle t \rangle / \langle t \rangle$. This indeterminacy contributed an error of $\pm 1.6\%$ to the determination of the slope parameter b and of $\pm 0.6\%$ to the determination of the nuclear intercept $d\sigma/dt|_{t=0}$.

The luminosity was obtained using as a luminosity monitor the fourfold coincidence of the TB trigger counters. The rate $R_{TB \cdot TB}$ yielded the luminosity directly:

$$L = \frac{R_{TB \cdot TB}}{\sigma_{TB \cdot TB}},$$

where $\sigma_{TB \cdot TB}$ is the inclusive cross-section for events that triggered the monitor. This parameter was measured repeatedly by the Van der Meer method [1,6] in special runs interleaved with the data taking, and was found to be $\sigma_{TB \cdot TB} = 8.43 \pm 0.13$ mb for $\bar{p}p$ and $\sigma_{TB \cdot TB} = 7.915 \pm 0.034$ mb for pp .

The $\bar{p}p$ data were collected over a period of time during which the background and the position of the source varied. Different sets of data corresponding to different conditions were analysed separately and a fit was performed on each set to extract b . The fitting process took account of the Coulomb correction through

the standard formula^{*)}. In Table 1, we list the slope parameters b and the nuclear intercepts $d\sigma/dt|_{t=0}$ obtained for each set of $\bar{p}p$ data. The errors quoted are statistical only, and the error in $d\sigma/dt|_{t=0}$ does not take into account the statistical error in the luminosity. The final values were obtained by taking the weighted means of the results for each data set. These values are also presented in Table 1 together with the results for the pp reaction.

The measured differential cross-sections are listed in Table 2 and displayed in fig. 3 for $\bar{p}p$ and pp . (In both the figure and the table the errors are statistical only.)

We now turn to the measurement made in the larger- t region. Elastic scattering in the range $0.09 < |t| < 1.0 \text{ GeV}^2$ was studied using the H_5 hodoscopes (fig. 1c), which consisted of:

- i) two planes of trigger scintillators (H_{5A} and H_{5B}), and
- ii) a finely divided hodoscope ($H_{5\theta}$) consisting of eight circular rings divided into four quadrants, i.e. a total of 32 scintillation counters in each arm.

The latter hodoscope was located 8.02 m from the intersection point and spanned the polar range $11.4 < \theta < 38 \text{ mrad}$.

Data were collected with the trigger:

$$T = (TB_A \cdot TB_B + H_{5A} \cdot H_{5B} + H_4 \cdot H_3)_{\text{left}} \cdot (H_3 \cdot H_4 + H_{5A} \cdot H_{5B} + TB_A \cdot TB_B)_{\text{right}} .$$

In the analysis, events producing more than one count in $H_{5\theta}$ in either arm were rejected, and the left-arm hit, the interaction region, and the right-arm hit were required to be collinear in polar angle and in azimuth to within the $\Delta\phi = 90^\circ$ resolution afforded by the quadrants. The multiplicity requirement had the effect

*) The formula used was [7]:

$$\frac{d\sigma_{\text{meas}}}{dt} = \frac{\sigma_{\text{tot}}^2 e^{bt}}{16\pi (\hbar c)^2} (1 + \rho^2) + \frac{4\alpha^2 \pi (\hbar c)^2 G^4}{|t|^2} \pm \frac{\alpha \sigma_{\text{tot}} G^2 e^{\frac{1}{2}bt}}{|t|} (\rho \mp \alpha\phi) ,$$

where $G(t) = 1 - 2.94|t|$ is the proton/antiproton electromagnetic form factor, and $\phi = \ln \{0.08/|t|\} - 0.577$ is the Coulomb phase factor. The value used for ρ was 0.078 ± 0.010 [8] for pp and 0.10 ± 0.05 [9,10] for $\bar{p}p$. The upper (lower) sign corresponds to $\bar{p}p$ (pp) scattering.

of rejecting the $\sim 50\%$ of genuine elastic events which produced multiple hits because of secondary interactions in the vacuum-chamber walls and in the H_3 and H_4 hodoscopes. Since we did not attempt to normalize these data, we applied no correction for this bias, but verified that the percentage loss did not depend on t .

In figs. 4a and 4b we present the unnormalized differential cross-sections for $\bar{p}p$ and pp elastic scattering in this t range. Assuming the t dependence of eq. (2), we extracted from fits to these cross-sections: $b = 10.68 \pm 0.20 \pm 0.06 \text{ GeV}^{-2}$ for $\bar{p}p$ ($\chi^2/\text{NDF} = 13.6/7$) and $b = 10.34 \pm 0.19 \pm 0.06 \text{ GeV}^{-2}$ for pp ($\chi^2/\text{NDF} = 8.0/7$). The errors in b are statistical and systematic respectively, the systematic error arising from the uncertainty in the position of the $H_5\theta$ counters.

All the results obtained are summarized in Table 3 and compared with the recent results of the Louvain-Northwestern Collaboration [11] and with earlier ISR results [12]. In this table and in the following discussion, wherever two errors are quoted on a result, the first is statistical and the second is systematic.

From our studies of $\bar{p}p$ and pp interactions, we elicited the following information.

1) Nuclear elastic slopes

Both $\bar{p}p$ and pp elastic data are well parametrized by the exponential form of eq. (2), yielding different values of the slope parameter b in the two different t ranges covered:

$$\left. \begin{aligned} b_1(\bar{p}p) &= 13.92 \pm 0.37 \pm 0.22 \text{ GeV}^{-2} \\ b_1(pp) &= 13.09 \pm 0.37 \pm 0.21 \text{ GeV}^{-2} \end{aligned} \right\} |t| < 0.05 \text{ GeV}^2$$

and

$$\left. \begin{aligned} b_2(\bar{p}p) &= 10.68 \pm 0.20 \pm 0.06 \text{ GeV}^{-2} \\ b_2(pp) &= 10.34 \pm 0.19 \pm 0.06 \text{ GeV}^{-2} \end{aligned} \right\} 0.09 < |t| < 1.0 \text{ GeV}^2$$

A change in slope has already been observed in the pp case at the ISR [13,14] for $|t| \approx 0.12 \text{ GeV}^2$. The values of both b_1 and b_2 in the pp case are in good agreement with previous ISR measurements [12] having greater statistics. The pp re-

sults in the smaller- t region confirm the observed shrinkage of the forward peak with increasing s [14]. When our $\bar{p}p$ result is compared with lower-energy data [15], however, the evidence for shrinkage is not so clear.

Since both the slope and the nuclear intercept of the $\bar{p}p$ differential cross-section are greater than those of the pp cross-section, the two cross-sections must cross over. From our data we calculated the position of this cross-over to be:

$$|t_x| = 0.088 \pm 0.054 \text{ GeV}^2 .$$

The cross-over is also present at lower energy, and, in absorption models [16,17], is generally connected with the observed difference in the particle/antiparticle total cross-sections. Our data suggest that the cross-over moves towards smaller $|t|$ with increasing s , as suggested by absorption models and geometrical models.

2) Total elastic cross-section

We integrated the fitted differential cross-sections, assuming the change in slope occurs at $|t| = 0.12 \text{ GeV}^2$ for both $\bar{p}p$ and pp , and obtained:

$$\sigma_{el}(\bar{p}p) = 7.89 \pm 0.17 \pm 0.11 \text{ mb}$$

$$\sigma_{el}(pp) = 7.79 \pm 0.13 \pm 0.11 \text{ mb} .$$

The two values are very close, as they are at lower energy [18], and both show a small rise over the ISR energy range.

3) Total cross-section

Using the optical theorem with $\rho = 0.10 \pm 0.05$, we derived

$$\sigma_{tot}(\bar{p}p) = 44.86 \pm 0.44 \pm 0.13 \pm 0.21 \text{ mb} .$$

The third error arises from the uncertainty in ρ . Using the measured value of ρ for the pp case, we obtained

$$\sigma_{tot}(pp) = 43.34 \pm 0.29 \pm 0.13 \text{ mb} .$$

These results may be compared with those we obtained using the total-rate method [3]: the agreement is good, and, in terms of the difference in the two cross-sections $\Delta\sigma = \sigma_{tot}(\bar{p}p) - \sigma_{tot}(pp)$, the two methods gave:

$$\Delta\sigma(\text{opt theor}) = 1.52 \pm 0.57 \text{ mb}$$

and

$$\Delta\sigma(\text{total rate}) = 1.44 \pm 0.45 \text{ mb} .$$

Since both the elastic and the total rates were measured close in time with the same beam conditions, the total cross-section could be computed in a luminosity-independent manner. Formally, this corresponds to eliminating L from the two expressions for the total cross-section. The values obtained in this manner are

$$\left. \begin{aligned} \sigma_{\text{tot}}(\bar{p}p) &= 45.02 \pm 0.71 \pm 0.26 \text{ mb} \\ \sigma_{\text{tot}}(pp) &= 43.42 \pm 0.56 \pm 0.27 \text{ mb} \end{aligned} \right\} \text{ luminosity-independent} .$$

The good agreement of the three techniques for computing the total cross-section is an indication of the accuracy of the luminosity measurement and of the validity of the optical theorem.

The three measured quantities -- the total rate, the elastic rate, and the luminosity -- were combined together to calculate a maximum-likelihood value of the total cross-sections:

$$\left. \begin{aligned} \sigma_{\text{tot}}(\bar{p}p) &= 44.77 \pm 0.30 \pm 0.18 \text{ mb} \\ \sigma_{\text{tot}}(pp) &= 43.28 \pm 0.17 \pm 0.13 \text{ mb} \\ \Delta\sigma &= 1.49 \pm 0.35 \text{ mb} \end{aligned} \right\} \text{ maximum-likelihood} .$$

These are to be considered as our best measurements of the two total cross-sections.

4) Ratios

In a measurement such as that reported, it is customary to quote the ratios $\sigma_{\text{el}}/\sigma_{\text{tot}}$ and b/σ_{tot} . Geometrical scaling implies that these ratios be constant as a function of energy, since σ_{tot} , σ_{el} , and b are all proportional to the mean interaction radius squared. From our results we derived:

$$\left. \begin{aligned} \frac{\sigma_{\text{el}}}{\sigma_{\text{tot}}} &= 0.176 \pm 0.004 \pm 0.003 \\ \frac{b}{\sigma_{\text{tot}}} &= 0.310 \pm 0.009 \pm 0.005 \text{ mb}^{-1} \text{ GeV}^{-2} \end{aligned} \right\} \bar{p}p$$

$$\left. \begin{aligned} \frac{\sigma_{\text{el}}}{\sigma_{\text{tot}}} &= 0.180 \pm 0.003 \pm 0.003 \\ \frac{b}{\sigma_{\text{tot}}} &= 0.302 \pm 0.009 \pm 0.005 \text{ mb}^{-1} \text{ GeV}^{-2} \end{aligned} \right\} \text{pp}$$

(The value used for σ_{tot} in these ratios is that obtained via the optical theorem.)

These ratios are in good agreement with those found at lower energy, and are equal within the errors for the two reactions. The equality of particle-particle and antiparticle-particle ratios has already been observed in other reactions at lower energies. In our case, this equality and the observed rise in σ_{tot} and σ_{el} are evidence that $\bar{p}p$ reactions are in agreement with an optical model based on a constant central opacity and an increasing mean interaction radius.

Acknowledgements

We are indebted to E. Gabathuler and A. Wetherell for their continued interest in and support of this experiment. We are grateful to the personnel of the Intersecting Storage Rings, the Proton Synchrotron, and the Antiproton Accumulator for the operation of the machines, and especially to G. Kantardjian and K. Potter for their many contributions to the experiment. We are also grateful to A. Donnini for his supervision of and help during the installation of the apparatus. We thank G. Barnini, L. Giacomelli, T. Regan, and all the technical staff of the Universities and the INFN Sections of Naples and Pisa for their excellent assistance. Finally, we gladly acknowledge the diligence and enthusiasm of Ms. C. Candelari, who worked with us during the summer months under the CERN Summer Student Program.

REFERENCES

- [1] G. Carboni et al., Phys. Lett. 108B (1982) 145.
- [2] M. Ambrosio et al., SUNY preprint SB/HECG/82-3 (1982).
- [3] G. Carboni et al., CERN preprint CERN-EP/82-20 (1982); to be published in Phys. Lett. B.
- [4] U. Becker et al., Nucl. Instrum. Methods 180 (1981) 161.
- [5] K.M. Terwilliger, Proc. Int. Conf. on High-Energy Accelerators, CERN, 1959 (CERN, Geneva, 1959), p. 53.
- [6] S. Van der Meer, CERN Internal Report ISR-PO/68-31 (1968).
- [7] G.B. West and D.R. Yennie, Phys. Rev. 172 (1968) 1413.
- [8] U. Amaldi et al., Phys. Lett. 66B (1977) 390.
- [9] R.E. Hendrick and B. Lautrup, Phys. Rev. D11 (1975) 529.
- [10] H.J. Lipkin, Phys. Rev. D17 (1978) 366.
- [11] N. Amos et al., Phys. Rev. Lett. 47 (1981) 1191.
- [12] A review of all ISR data can be found in U. Amaldi and K. Schubert, Nucl. Phys. B166 (1980) 301.
- [13] G. Barbiellini et al., Phys. Lett. 39B (1972) 663.
- [14] U. Amaldi, M. Jacob and G. Matthiae, Ann. Rev. Nucl. Sci. 26 (1976) 385.
- [15] L.A. Fajardo et al., Phys. Rev. D24 (1981) 46.
- [16] V. Barger, Proc. 17th Int. Conf. on High-Energy Physics, London, 1974 (Rutherford Lab., Chilton, Didcot, 1974), p. I-193.
- [17] J.G. Rushbrooke and B.R. Webber, Phys. Rep. 44 (1978) 1.
- [18] V. Flaminio et al. (HERA Group), CERN Report CERN-HERA 79-03 (1979).

Table 1

Measurements of nuclear elastic slopes and intercepts

$\bar{p}p$ data set	Proton stack	Elastic slope, b (GeV^{-2})	Elastic intercept, $d\sigma/dt _{t=0}$ (mb/GeV^2)	χ^2/NDF
1	1	14.4 ± 1.1	106.9 ± 3.7	26/30
2	1	14.2 ± 1.2	105.0 ± 4.0	25/23
3	1	15.2 ± 0.9	108.3 ± 3.3	40/28
4	1	12.7 ± 0.9	100.3 ± 2.9	33/28
5	2	14.4 ± 1.1	103.7 ± 3.8	40/30
6	2	14.3 ± 0.8	106.0 ± 2.8	32/28
7	2	12.4 ± 1.0	97.9 ± 3.3	33/29
Final $\bar{p}p$	1 + 2	13.92 ± 0.37 $\pm 0.22^{\text{a})}$	103.88 ± 1.26 $\pm 0.62^{\text{a})}$ $\pm 1.59^{\text{b})}$	
Final pp		13.09 ± 0.37 $\pm 0.21^{\text{a})}$	96.58 ± 1.21 $\pm 0.58^{\text{a})}$ $\pm 0.40^{\text{b})}$	

a) Error due to the uncertainty in the determination of t .

b) Error due to the statistical uncertainty in the determination of L .

Table 2

The differential elastic cross-sections

$\bar{p}p \rightarrow \bar{p}p$ at $\sqrt{s} = 52.8$ GeV					
$\langle t \rangle$ (GeV ²)	$d\sigma/dt$ (mb/GeV ²)	$\langle t \rangle$ (GeV ²)	$d\sigma/dt$ (mb/GeV ²)	$\langle t \rangle$ (GeV ²)	$d\sigma/dt$ (mb/GeV ²)
0.0109	97.4 ± 4.1	0.0271	77.5 ± 1.5	0.0383	56.0 ± 4.2
0.0140	88.2 ± 1.6	0.0282	72.1 ± 3.4	0.0390	56.2 ± 1.3
0.0145	90.3 ± 10.3	0.0300	71.6 ± 2.9	0.0399	62.3 ± 3.5
0.0153	95.4 ± 5.3	0.0305	70.5 ± 1.6	0.0408	60.2 ± 1.2
0.0162	89.0 ± 3.8	0.0309	69.3 ± 1.4	0.0415	57.8 ± 1.1
0.0176	83.0 ± 1.4	0.0315	65.9 ± 1.5	0.0418	62.7 ± 1.6
0.0185	84.0 ± 1.9	0.0320	67.6 ± 2.5	0.0425	57.0 ± 2.6
0.0194	81.5 ± 1.6	0.0325	67.2 ± 3.7	0.0430	55.5 ± 1.4
0.0205	87.8 ± 4.5	0.0333	70.9 ± 2.5	0.0437	55.4 ± 3.5
0.0216	77.4 ± 1.4	0.0339	68.2 ± 2.8	0.0448	55.8 ± 4.0
0.0221	77.4 ± 1.8	0.0346	64.9 ± 2.7	0.0455	55.2 ± 1.6
0.0227	80.5 ± 3.5	0.0353	65.7 ± 1.2	0.0464	60.2 ± 1.4
0.0232	69.7 ± 1.6	0.0360	61.4 ± 1.5	0.0470	54.4 ± 1.6
0.0241	78.7 ± 4.1	0.0364	63.8 ± 1.3	0.0475	54.5 ± 1.1
0.0254	71.3 ± 3.7	0.0370	63.7 ± 1.6	0.0479	53.2 ± 1.6
0.0260	73.4 ± 1.1	0.0378	56.6 ± 4.4	0.0483	57.3 ± 3.3
$pp \rightarrow pp$ at $\sqrt{s} = 52.8$ GeV					
$\langle t \rangle$ (GeV ²)	$d\sigma/dt$ (mb/GeV ²)	$\langle t \rangle$ (GeV ²)	$d\sigma/dt$ (mb/GeV ²)	$\langle t \rangle$ (GeV ²)	$d\sigma/dt$ (mb/GeV ²)
0.0110	85.3 ± 4.4	0.0272	69.8 ± 2.3	0.0377	57.1 ± 2.0
0.0141	84.1 ± 1.5	0.0305	66.5 ± 6.4	0.0385	57.2 ± 1.5
0.0156	83.7 ± 8.0	0.0310	61.9 ± 0.9	0.0389	51.3 ± 1.9
0.0160	82.8 ± 3.5	0.0316	60.6 ± 1.2	0.0411	54.2 ± 1.1
0.0178	70.6 ± 1.3	0.0320	68.8 ± 7.0	0.0418	56.8 ± 0.8
0.0189	80.5 ± 1.5	0.0337	64.6 ± 2.9	0.0427	57.1 ± 1.3
0.0195	78.6 ± 1.5	0.0341	68.8 ± 2.1	0.0459	51.8 ± 2.5
0.0218	74.0 ± 1.4	0.0349	62.9 ± 1.7	0.0463	51.7 ± 1.7
0.0225	70.8 ± 1.4	0.0353	60.0 ± 2.1	0.0467	53.5 ± 2.1
0.0230	67.5 ± 1.3	0.0358	61.5 ± 2.2	0.0471	55.1 ± 0.9
0.0262	67.7 ± 1.1	0.0362	61.2 ± 0.8	0.0475	49.7 ± 1.3
0.0268	69.4 ± 1.2	0.0374	57.7 ± 2.9	0.0480	51.0 ± 1.1

Table 3

The final results for $\bar{p}p$ and pp at $\sqrt{s} = 52.8 \text{ GeV}^a$

	Antiproton-proton		Proton-proton		
	This experiment	Ref. 11	This experiment	Ref. 11	Ref. 12
Elastic slope b for $ t < 0.05 \text{ (GeV}^{-2}\text{)}$	$13.92 \pm 0.37 \pm 0.22$	13.6 ± 2.2	$13.09 \pm 0.37 \pm 0.21$	12.7 ± 0.2	13.1 ± 0.2
Elastic slope b for $ t > 0.09 \text{ (GeV}^{-2}\text{)}$	$10.68 \pm 0.20 \pm 0.06$	-	$10.34 \pm 0.19 \pm 0.06$	-	10.7 ± 0.2
Elastic intercept $d\sigma/dt _{t=0}$ (mb/GeV ²)	$103.9 \pm 2.0 \pm 0.6$	-	$96.6 \pm 1.3 \pm 0.6$	-	-
σ_{tot} (optical theorem) (mb)	$44.86 \pm 0.44 \pm 0.13$ $\pm 0.21^b$	44.1 ± 2.9	$43.34 \pm 0.29 \pm 0.13$	42.1 ± 0.2	$42.38 \pm 0.27 \pm 0.22$
σ_{tot} (total rate) (mb)	$44.70 \pm 0.40 \pm 0.13$	-	$43.26 \pm 0.20 \pm 0.13$	-	$42.71 \pm 0.35 \pm 0.36$
σ_{tot} (luminosity independent) (mb)	$45.02 \pm 0.71 \pm 0.26$	-	$43.42 \pm 0.56 \pm 0.27$	-	$42.02 \pm 0.47 \pm 0.25$
σ_{tot} (maximum likelihood) (mb)	$44.77 \pm 0.30 \pm 0.18$	-	$43.28 \pm 0.17 \pm 0.13$	-	$42.67 \pm 0.19 \pm 0.25$
σ_{el} (mb)	$7.89 \pm 0.17 \pm 0.11$	-	$7.79 \pm 0.13 \pm 0.11$	-	$7.45 \pm 0.09 \pm 0.09$
$\sigma_{\text{el}}/\sigma_{\text{tot}}$ (optical theorem)	$0.176 \pm 0.004 \pm 0.003$	-	$0.180 \pm 0.003 \pm 0.003$	-	0.1746 ± 0.0016
b/σ_{tot} (optical theorem) (mb ⁻¹ GeV ⁻²)	$0.310 \pm 0.009 \pm 0.005$	-	$0.302 \pm 0.009 \pm 0.005$	-	-

a) Where two errors are quoted, the first is statistical and the second is systematic.

b) Error arising from the uncertainty in ρ .

Figure captions

Fig. 1 : The experimental apparatus.

- a) A plan view of the entire detector: CI, CO, H₁, H₂, H₃, H₄, H₅, and three planes of TB are scintillation-counter hodoscopes. Sandwiched between CI and CO there is a set of drift chambers.
- b) The TB hodoscopes. TB_A and TB_B are trigger counters. TB_y is a hodoscope of "finger" scintillators, and TB_z consists of two staggered planes of drift tubes.
- c) The H₅ hodoscopes. H_{5A} and H_{5B} are trigger counters. H_{5θ} is a scintillator hodoscope divided into eight polar rings and four azimuthal quadrants.

Fig. 2 : The collinearity distribution of hits in the TB hodoscopes. The horizontal coordinate y corresponds to cells of width 25 mm in the TB_y hodoscopes; the vertical coordinate z corresponds to cells of width 5 mm in the TB_z hodoscopes. In the case of multiple hits in either arm, it is the pair of hits that results in the best collinearity that is considered, the other hits being ignored.

Fig. 3 : The differential elastic cross-section in the momentum-transfer region $0.01 < |t| < 0.05$ for antiproton-proton and proton-proton collisions at $\sqrt{s} = 52.8$ GeV.

Fig. 4 : The unnormalized differential cross-section in the momentum-transfer range $0.09 < |t| < 1.0$ for a) antiproton-proton and b) proton-proton elastic scattering at $\sqrt{s} = 52.8$ GeV.

Fig. 1 a)

Fig. 1 b)

Fig. 1 c)

Fig. 2

Fig. 3

Fig. 4 a)

Fig. 4 b)