Measurement of $\bar{p}p$ Elastic Scattering at $\sqrt{s} = 52.8$ GeV at the CERN Intersecting Storage Rings

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The small-angle elastic scattering for pp at $\sqrt{s} = 23.5$, 30.7, and 52.8 GeV and for $\bar{p}p$ at $\sqrt{s} = 52.8$ GeV are measured. The data are normalized on Coulomb scattering. Using the optical theorem and the best estimate of the real part of the forward scattering amplitude, $\rho(p\bar{p}) = 0.1$, we obtain $\sigma_{\text{tot}}(\bar{p}p) = 44.1 \pm 2.9$ mb for the total cross section and $b(\bar{p}p) = 13.6 \pm 2.2$ GeV⁻² for the nuclear slope parameter. This supports the dispersion relation prediction that $\sigma_{\text{tot}}(\bar{p}p)$ will start to rise above $E_{\text{lab}} \approx 200$ GeV.

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The dramatic rise in pp total cross section above c.m. energy $\sqrt{s} = 10$ GeV was discovered in the early seventies by Amaldi *et al.*¹ and Amendolia *et al.*² working at the CERN Intersecting Storage Rings (ISR). Amaldi *et al.*³ extended their measurements of pp differential cross sections through the region of Coulomb-nuclear interference. They used the standard parametrization of the elastic-scattering cross section,

$$d\sigma/dt = \pi |f_c + f_n|^2, \quad (1a)$$

where

$$f_c = -2\alpha[G^2(t)/|t|] \exp(i\alpha\Phi), \quad (1b)$$

and

$$f_n = [(i + \rho)/4\pi]\sigma_{\text{tot}} \exp(-b|t|/2). \quad (1c)$$

The Coulomb phase $\alpha\Phi$ is that of West and Yennie,⁴ where α is the fine-structure constant, $G(t) = [1 + |t|/(0.71)]^{-2}$ is the proton electromagnetic form factor, σ_{tot} is the total cross section, b is the nuclear slope parameter, ρ is the ratio of the real to the imaginary part of the forward nuclear scattering amplitude, and t is the square of the four-momentum transfer.

Amaldi *et al.* extracted ρ from a fit to their data and used dispersion theory to relate ρ to an integral over pp and $\bar{p}p$ total cross sections. Under the assumption that $\sigma_{\text{tot}}(pp)$ and $\sigma_{\text{tot}}(\bar{p}p)$ approach

the same value for $\sqrt{s} \rightarrow \infty$, they were able to predict (i) that $\sigma_{\text{tot}}(pp)$ will continue to rise with energy up to at least equivalent laboratory energies $E_{\text{lab}} \simeq 40$ TeV; and (ii) that $\sigma_{\text{tot}}(\bar{p}p)$ will stop decreasing near $E_{\text{lab}} \simeq 200$ GeV and start to rise to approach the pp total cross section. With the successful operation of the CERN antiproton accumulator and subsequent injection and storage of antiprotons in the ISR, it has now become possible to study the asymptotic behavior of the $\bar{p}p$ system and test the latter prediction.

The present experiment represents an extension of the method of Amaldi *et al.* to $\bar{p}p$ collisions with use of the known Coulomb-scattering cross section for absolute normalization of the data.⁵ The apparatus consists of two pairs of scintillator hodoscopes; the first hodoscope of each pair (arm 1) is above (below) the beam and the second (arm 2) is below (above). Each hodoscope consists of 24 "stack" counters, 2 mm high, for position measurement in the vertical (x) direction, and 7 "finger" counters, 4 mm wide, for position measurement in the horizontal (y) direction, all covered by a single trigger counter. The four hodoscopes are placed in thin-walled movable sections of the ISR vacuum chamber ("Roman pots") at a distance 8.7 m from the diamond (intersecting beam region). When a coincidence occurs in any pair of trigger counters, the pulse

height of all counters and the time difference between the trigger counters are recorded.

We have had pp runs of $\approx 500\,000$ events each, with ISR beam momenta of 11.8, 15.4, and 26.6 GeV/ c ($\sqrt{s} = 23.5, 30.7, \text{ and } 52.8$ GeV), and a $p\bar{p}$ run of ≈ 5000 events at 26.6 GeV/ c . For all runs, the beam emittance was limited by scraping and the Terwilliger scheme of momentum compaction was used to minimize the size of the interaction region. In this way we achieved adequate angular resolution and were able to operate routinely with the inner edges of the scintillators within 10 mm (~ 1 mrad) of the center of stored beams of up to 10 A.

After examination of analog-to-digital convert-

er and time-to-digital converter distributions, software cuts were imposed. Events were accepted as elastic-scattering candidates when (i) both stacks and fingers had one, two, or three pulses above threshold with multiple pulses in adjacent counters (hits were assigned to the largest pulse, which must occur in the center counter for triples); (ii) the time interval between trigger pulses fell within the window (± 3 nsec) for beam-beam events; and (iii) there was no in-time pulse from the external luminosity monitor which would identify the event as inelastic. Accepted events were assigned to a matrix element N_{ijkl} . The overlap between any stack (i) and finger (j) defines a cell; the number of coincidences between cell (ij) in arm 1 and cell (kl) in arm 2 is given by

$$N_{ijkl} \propto \int n_1(x_{D_1}, y_{D_1}; \Delta\alpha_{x_1}, \Delta\alpha_{y_1}) n_2(x_{D_2}, y_{D_2}; \Delta\alpha_{x_2}, \Delta\alpha_{y_2}) \frac{d\sigma}{dt} (\alpha_x^2 + \alpha_y^2) \\ \times dx_D dy_{D_1} dy_{D_2} d\Delta\alpha_{x_1} d\Delta\alpha_{y_1} d\Delta\alpha_{x_2} d\Delta\alpha_{y_2} d\alpha_x d\alpha_y, \quad (2)$$

where n_1 (n_2) is the particle density distribution in beam 1 (2); $\Delta\alpha_{x_1}, \Delta\alpha_{y_1}$ ($\Delta\alpha_{x_2}, \Delta\alpha_{y_2}$) are the initial betatron angles for a particle in beam 1 (2); $x_{D_1}, y_{D_1}, y_{D_2}$ define the interaction point within the diamond. The c.m. scattering angle θ equals $(\alpha_x^2 + \alpha_y^2)^{1/2}$ in the small-angle approximation. The domain of integration is such that the elastically scattered particle from beam 1 enters cell (ij) and the struck particle from beam 2 enters cell (kl). All cells in arm 2 associated with a given cell in arm 1 (and vice versa) form a pattern whose population can be predicted by analytically carrying out the nine-dimensional integration in (2). The agreement between the observed and predicted populations is excellent.

Small subtractions were needed for background events; these were estimated from out-of-pattern events in the matrices (inelastic scattering, $\lesssim 0.5\%$), and from events falling outside the time-to-digital converter window. In addition, corrections were applied for the small inefficiencies introduced by the software thresholds of the analog-to-digital converter spectra. Each cell is then used to calculate $d\sigma/dt$ at the point corresponding to its geometric center. Symmetric cells are averaged, and then symmetric hodoscopes averaged to obtain 96 differential cross sections.

The pp data have been used to check both the apparatus and the analysis method. The data were fitted with known values of σ_{tot} and b to obtain best values for ρ and Δh (mean deviation of the hodoscope vertical positions from survey measurements), and an overall normalization constant. The ρ values so obtained are in excel-

lent agreement with the fit based on dispersion relations.³ The values for Δh were well within the estimated error of the direct optical measurements (± 0.1 mm) and were averaged ($\Delta h = -0.06 \pm 0.03$ mm) for later use.

To test for systematic errors in measuring σ_{tot} and b , the pp data were refitted using Δh and the ρ values obtained from dispersion relations as input, and σ_{tot} , b , and the overall normalization constant were extracted. As a typical example, Fig. 1 shows 26.6-GeV/ c data, together with the best-fit curve. The results for σ_{tot} and b are

FIG. 1. The pp differential elastic scattering cross section $d\sigma/dt$, at $\sqrt{s} = 52.8$ GeV, vs $|t|$. The curve is the best fit to these data, where σ_{tot} , b , and normalization are fitted parameters and ρ and Δh are input parameters in Eq. (1).

TABLE I. Fits to $p\bar{p}$ data using as input $\Delta\bar{h}$ and ρ values obtained from dispersion-relation predictions.

ISR energy $\sqrt{s}$ (GeV)	Present experiment		Accepted values ^a		ρ_{input}	$ t _{\text{min}}$ (GeV ²)	$ t _{\text{max}}$ (GeV ²)
	σ_{tot} (mb)	b (GeV ⁻²)	σ_{tot} (mb)	b (GeV ⁻²)			
23.5	39.4 ± 0.3	15.5 ± 2.7	38.94 ± 0.17	11.8 ± 0.2	0.002	0.3 × 10 ⁻³	6.7 × 10 ⁻³
30.7	40.1 ± 0.2	12.9 ± 1.1	40.14 ± 0.17	12.2 ± 0.2	0.037	0.5 × 10 ⁻³	11.2 × 10 ⁻³
52.8	42.1 ± 0.2	12.7 ± 0.3	42.67 ± 0.19	13.1 ± 0.2	0.080	1.0 × 10 ⁻³	31.3 × 10 ⁻³

^aRef. 6.

compared with earlier measurements⁶ in Table I; the agreement is satisfactory. It is important to note that the data extend deep into the Coulomb region for $\sqrt{s}=23.5$ GeV; in this case the fitted cross section is insensitive to the input ρ value and the t range is too small to make a good determination of b . This is no longer true at $\sqrt{s}=52.8$ GeV, where the data extend from the nuclear region only through the region of Coulomb-nu-

clear interference.

Our 5000 $\bar{p}p$ events were obtained over a 40-h period with two different settings for t_{min} . The antiproton current was ≈ 0.4 mA and the proton current was 10 A, giving a luminosity of $\approx 1 \times 10^{26}$ cm⁻² s⁻¹. The data were analyzed with use of acceptance criteria and analysis procedures identical to those used for the $p\bar{p}$ data, except that α was replaced by $-\alpha$ in (1b).

To fit the $\bar{p}p$ data for σ_{tot} and b , it is necessary to have independent knowledge of the ρ value; this may be obtained by extrapolation of measurements at lower energies. Lipkin⁷ has proposed universal (quark model) parametrizations for σ_{tot} and ρ when hadrons are incident on proton targets; they are in remarkable agreement with existing high-energy data. Using dispersion relations, Hendrick and Lautrup⁸ predict ρ values for

FIG. 2. The $\bar{p}p$ differential elastic scattering cross-section $d\sigma/dt$, at $\sqrt{s}=52.8$ GeV, vs $|t|$. The figures represent two independent runs at different $|t|_{\text{min}}$. In both, the curves are the best fit to the data, where σ_{tot} , b , and normalization are fitted parameters and ρ and $\Delta\bar{h}$ are input parameters in Eq. (1).

FIG. 3. Reproduction of the world survey of $\sigma_{\text{tot}}(\bar{p}p)$ and $\sigma_{\text{tot}}(pp)$ data vs $\sqrt{s}$, along with a fit based on dispersion relations, from Ref. 3. Appended is our measured value, $\sigma_{\text{tot}}(\bar{p}p) = 44.1 \pm 2.9$ mb, at $\sqrt{s}=52.8$ GeV.

$\bar{p}p$ in essential agreement with those of Lipkin at high energies. Experimental support for these predictions is provided by the recent measurements of Fajardo *et al.*⁹ up to $\sqrt{s} = 19.4$ GeV.

We have used $\Delta\bar{h} = -0.06$ mm and the value $\rho = +0.10$ predicted by Hendrick and Lautrup and by Lipkin for $\sqrt{s} = 52.8$ GeV in fitting our $\bar{p}p$ data to extract $\sigma_{\text{tot}}(\bar{p}p)$, $b(\bar{p}p)$, and the normalization constant. The data with the best-fit curves are shown in Fig. 2. Averaging the two runs we obtain $\sigma_{\text{tot}}(\bar{p}p) = 44.1 \pm 2.9$ mb and $b(\bar{p}p) = 13.6 \pm 2.2$ GeV⁻². The uncertainty in $\Delta\bar{h}$ of ± 0.03 mm gives $\Delta\sigma_{\text{tot}} = \mp 0.2$ mb and $\Delta b = \mp 0.04$ GeV⁻², and an uncertainty $\Delta\rho = \pm 0.01$ gives $\Delta\sigma_{\text{tot}} = \pm 0.20$ mb and $\Delta b = \mp 0.15$ GeV⁻², which are small compared with the statistical errors.

If we further constrain the fit by fixing σ_{tot} at the value predicted from the dispersion-relation fits [$\sigma_{\text{tot}}(\bar{p}p) = 43.55 \pm 0.23$ mb], we obtain a slightly different value, $b(\bar{p}p) = 13.1 \pm 1.6$ GeV⁻² at $\sqrt{s} = 52.8$ GeV. These may be compared with the value $b(pp) = 13.1 \pm 0.2$ GeV⁻² at the same energy. These results are consistent with the "Pomeranchuk" theorem of Cornille and Martin¹⁰ which predicts that the ratio of the inverse diffractive widths b for pp and $\bar{p}p$ will approach unity at very high energies.

The value for $\sigma_{\text{tot}}(\bar{p}p)$ is plotted in Fig. 3, together with the dispersion-relation fit of Amaldi *et al.*³ for $\sigma(pp)$ and $\sigma(p\bar{p})$; the agreement is within experimental error and suggests that the $\bar{p}p$ total cross section is indeed rising.

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