**PRECISE COMPARISON OF ANTIPROTON-PROTON AND PROTON-PROTON
FORWARD ELASTIC SCATTERING AT $\sqrt{s} = 24.3$ GeV**

(UA6 Collaboration)

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ABSTRACT

We report results from a measurement of antiproton-proton and proton-proton small-angle elastic scattering at $\sqrt{s} = 24.3$ GeV in the range $0.001 \leq |t| \leq 0.06$ (GeV/c)². The measurement was performed at the CERN $p\bar{p}$ Collider by using silicon detectors to observe protons recoiling from a hydrogen cluster-jet target intercepting the stored p and $\bar{p}$ beams. Fits to the measured differential cross-sections yield the ratio of the real to the imaginary part of the forward nuclear scattering amplitude ρ and the nuclear slope parameter b for both $\bar{p}p$ and pp . We find that the difference $\Delta\rho = \rho(\bar{p}p) - \rho(pp) = 0.031 \pm 0.010$ agrees with conventional fits and disagrees with the 'odderon' fit designed to accommodate the recent UA4 measurement of $\rho(\bar{p}p)$ at 546 GeV.

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Measurements of small-angle elastic scattering provide a testing ground for such fundamental principles as unitarity, analyticity, and crossing symmetry, and for models predicting the energy dependence of the total cross-section. These principles are applied through the optical theorem, which relates the imaginary (absorptive) part of the elastic scattering amplitude to the total cross-section, and by dispersion relations, which connect the real part of the amplitude to the imaginary part. By measuring the strength of the interference between the Coulomb and nuclear parts of the scattering amplitude, the real part is determined, which may then be compared, through these relations, to model fits to the total cross-section.

We have performed a high-statistics measurement of the forward differential cross-sections for pp and $\bar{p}p$ elastic scattering at $\sqrt{s} = 24.3$ GeV. Fits to the measured differential cross-sections yield values for the ratio ρ of the real to the imaginary part of the forward nuclear scattering amplitude and for the nuclear slope parameter b . The measurement, which was performed as part of Experiment UA6 at the CERN $\bar{p}p$ Collider, used an internal hydrogen cluster-jet target intercepting the p and $\bar{p}$ stored circulating beams. Elastic scattering was studied in the range $0.001 \leq |t| \leq 0.06$ (GeV/c)², where t is the square of the four-momentum transfer, by observing recoil protons in an array of silicon detectors positioned at angles close to 90° to the beams.

Previously, the pp and $\bar{p}p$ low- $|t|$ elastic scattering differential cross-sections were compared at the ISR for $\sqrt{s} = 30.5$, 52.7, and 62.3 GeV in an experiment [1] using the ‘Roman pot’ method [2]. The ratio ρ was found to be positive and rising over ISR energies for both pp and $\bar{p}p$, with $\rho(\bar{p}p)$ somewhat larger than $\rho(pp)$. Our measurements are consistent with these results. However, the greater precision of our data provides a more stringent constraint to the models which may be used to fit the ρ -values and the total cross-sections simultaneously as a function of energy. Such fits are of great current interest in view of the recent UA4 measurement of an unexpectedly high $\rho(\bar{p}p)$ at $\sqrt{s} = 546$ GeV [3].

Our measurement [4] employed the recoil technique, which makes use of the relation between the kinetic energy T of the elastically scattered recoil proton and the four-momentum transfer $|t| = 2m_p T$, where m_p is the proton mass. The recoil technique using an internal target was pioneered at JINR [5] and was later used at Serpukov [6] and Fermilab [7, 8]. The UA6 apparatus is located in a 13 m straight section of the CERN Super Proton Synchrotron (SPS) and consists of a cluster-jet target and recoil arm of solid-state detectors followed by a double-arm magnetic spectrometer [9]. The latter played no part in the elastic scattering measurement. The jet, the first to be used in a colliding-beam environment, consists of clusters of about 10^5 hydrogen molecules. It is operated at densities of up to 4×10^{14} protons per cm³, which, with a typical beam of 4.0×10^{10} stored antiprotons circulating in three bunches, gives a luminosity of 5.5×10^{29} cm⁻² s⁻¹. The pp luminosity is about ten times higher owing to the larger number of stored protons. Because of the low density of the target, multiple Coulomb scattering is negligible and the detection of low-energy recoil protons is possible. The interaction region, which is determined by the intersection of the jet with the p and $\bar{p}$ beams, is small, typically 8 mm along the beam, 3 mm in the transverse horizontal direction, and 1 mm in the vertical direction. Since the experiment operates with the SPS in collider mode, the beams are particularly clean and the background due to interactions of the beam halo is negligible. The pumping system of the jet keeps the level of residual gas pressure to at most 10^{-7} Torr in the vicinity of the jet, and the background due to beam-gas interactions is therefore small. The experiment is not located at a beam intersection point, so the colliding bunches pass at different times, the $\bar{p}$ bunch following the p bunch by 907 ns.

Recoil protons emerging from the jet were recorded by an array of silicon solid-state detectors positioned at a distance of ~ 85 cm from the jet/beam intersection within the SPS vacuum (see fig. 1). Recoil protons of energy up to 10 MeV were detected by a 7×47 mm² position-sensitive detector (PSD), which in addition to measuring the energy of an incident particle could also locate

the point of entry into the detector to about ± 1 mm. This type of detector was first used for a measurement of this sort at Fermilab [8]. Higher-energy recoil protons up to 30 MeV were stopped by the ‘stack’ detectors: three sandwiches of two transmission-mount surface barrier detectors, each with an area of ~ 100 mm². A fourth stack was positioned for measuring background particles. The array could be rotated by 180° to intercept recoil protons from either pp or $\bar{p}p$ scattering; in fig. 1, the array is shown in the $\bar{p}p$ position. The relative acceptance of the stacks was determined by rotating the array by 90° to a vertical position where the detectors could simultaneously intercept recoils at the same $|t|$. The entire array was mounted in a vacuum chamber attached to the SPS vacuum pipe by a flexible bellows. The chamber could be moved on a carriage by remote control so that its angular position could be changed. Four silicon detectors, mounted at fixed positions at the opposite side of the beams, were used to monitor the luminosity.

POSITION-SENSITIVE DETECTOR ANALYSIS

The resolution and thickness (0.8 mm) of the PSD limited the acceptance of recoil protons to energies of $0.5 < T < 10$ MeV, corresponding to recoil angles in the range $16 < \omega < 73$ mrad as measured from 90°, and time of flight (TOF) between 30 and 120 ns. Because the elastic recoil angle is related to the energy by $T = 2m_p \sin^2 \omega$, the simultaneous measurement of energy, angle, and TOF allowed excellent background control. The resistive entrance window of the PSD was an evaporated palladium film 100–150 Å thick, giving an energy loss equivalent to approximately $20 \mu\text{g}/\text{cm}^2$ of silicon, for which the energy calibration was adjusted (significant only for $T < 1$ MeV). The impact point position x of an incident particle along the detector length ℓ is given by $x = \ell(q_p/q_e)$, where $q_p(q_e)$ is the charge pulse from the position (energy) electrode converted to a voltage level by a preamplifier.

A scan across the entrance window with an alpha source collimated to 0.5 mm showed the energy measurement varied across the detector by $< 0.5\%$. Throughout the data-taking period, the calibration was stable to within 0.8% and the energy-scale drift between calibrations was negligible. A small non-linearity in the position scale (up to 2 mm) was corrected, using a polynomial function obtained by a fit to the position spectrum of a uniform exposure to the uncollimated source. Figure 2 shows how this correction improved the accuracy of the measured collimated source positions; the diagonal is drawn to indicate what one would expect for true linearity. The position correction was performed to increase the reliability of the background subtraction. The PSD energy signal—and therefore the t -scale—was unchanged by this correction.

The PSD measured $d\sigma/dt$ over the range $0.001 < |t| < 0.014$ (GeV/c)², where the Coulomb-nuclear interference is maximal. Data were collected at four chamber positions and were combined using measured integrated luminosities. Events were binned in t , and recoils were selected with TOF cuts for each Δt interval. Figure 3 presents the distribution of surviving events from one chamber position corresponding roughly to the scattering angles $0.8 \leq \omega \leq 4.0^\circ$, and the inset shows the position spectrum of events within a typical Δt interval. The relation between the energy and position signals of the PSD further isolates the elastic recoils, which are constrained by kinematics to follow a band along $|t| = 4m_p^2 \sin^2 \omega$. The width of the band is mainly due to the size of the jet along the beam. Except for the very low energy bins, which required additional handling as described below, there were two backgrounds subtracted on the basis of position information. The first originated mostly from the scattering of recoil protons by residual jet gas in the vacuum system and had a constant level across the face of the PSD. This background was estimated, for each Δt interval, from the average rate over the kinematically forbidden small-angle area of the PSD and was generally found to be $< 1\%$. A second background extending beneath the elastic peak affected the larger-angle region of the PSD, as seen in the inset of fig. 3. This background was attributed to (inelastic) recoil protons from single diffraction dissociation, $p(\bar{p}) + p \rightarrow X + p$. A parametrization of inelastic data from

Fermilab available in the range $0.001 \leq |t| \leq 0.017$ (GeV/c)² [10] provided good agreement with the data in each Δt interval. An example is shown as the dotted line in the figure. The same parametrization was used for pp and $\bar{p}p$. The subtraction of the small tail of inelastics extending beneath the elastic peak was typically $< 1\%$.

In addition, a correction was made for the fraction of the approximately Gaussian elastic peak that was lost beyond the edge of the PSD. If this correction was greater than 5%, the data from that bin for that angle of the recoil arm were not included in the final rate distribution.

At each angle of the chamber, the elastic peak of the lower Δt bins was too close to the low-angle edge of the PSD to permit accurate background subtraction using the position signal. Therefore, for these very low energies, only the timing information could be used for background subtraction. The lowest $|t|$ -value data are shown in fig. 4. The large peak in the figure represents high-energy secondaries that penetrated the detector leaving only a small signal; the smaller peak contains the recoil protons. The background was well fitted with a Gaussian, and the extrapolation beneath the elastic TOF peak was subtracted. The correction in this case amounted to about 5%. As the $|t|$ -value increased, the background decreased rapidly, resulting in a smaller correction. A constant background level due to electronic noise was estimated by averaging over a TOF interval that was higher than the elastic peak range, and was subtracted from the data prior to making the fit shown in fig. 4.

The total integrated luminosity available for the PSD analysis for pp was 366 nb^{-1} and for $\bar{p}p$ it was 526 nb^{-1} , yielding respectively about 260,000 and 355,000 measured elastic recoils.

STACK DETECTOR ANALYSIS

Only data collected at angles where the recoils came to rest in the rear detector of a stack were used in the analysis. In this way, energy loss (dE/dx) was measured by the front ~ 1.5 mm detector, which together with the rear ~ 3.0 mm detector recorded recoils of total kinetic energy in the range $15.4 \text{ MeV} < T < 29.2 \text{ MeV}$. From knowledge of charged-particle energy loss in silicon, the measurement of both T and dE/dx allowed the determination of the mass of the recoil particle. Recoil protons were selected by requiring that the ratio of the recoil mass to the proton mass of the event be within the peak centred on unity. After subtracting the recoils due to single diffraction dissociation, as in the example shown in fig. 5, the rates in the stacks were corrected for cut inefficiencies and nuclear interaction losses using a Monte Carlo simulation. Corrections were also necessary for the variation of the stack acceptance with angle. The value of $|t|$ for each stack position was determined using the simulation program, taking into account the variation of $|t|$ and $d\sigma/dt$ over the acceptance coverage of the stack. About 277,000 pp and 256,000 $\bar{p}p$ elastic events were recorded for stack positions at several different angles.

FITTING FOR ρ AND b

The measured pp and $\bar{p}p$ differential cross-sections were fitted by the formula

$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2}{t^2} G^4(t) - \frac{\pm \alpha(q \pm \alpha\phi)}{|t|} \sigma_{\text{tot}} G^2(t) e^{bt/2} + \frac{(1 + q^2)}{16\pi} \sigma_{\text{tot}}^2 e^{bt}, \quad (1)$$

where the upper (lower) sign is for pp ($\bar{p}p$) scattering; $G(t)$ is the proton electromagnetic form factor for which a dipole form $(1 + |t|/0.71)^{-2}$ was used, and ϕ is the Coulomb-hadronic phase [11] (we used the form calculated by Cahn [12]). The overall normalization factors were allowed to be different for the PSD and the stack data, but were found to be consistent with expectation. In fitting eq. (1) for the ratio q and the nuclear slope b , we used as input for the total cross-section, at our centre-of-mass energy, values based on fits [13] to existing data [$\sigma_{\text{tot}}(\text{pp}) = 39.46 \pm 0.04 \text{ mb}$ and

$\sigma_{\text{tot}}(\bar{p}p) = 41.40 \pm 0.10 \text{ mb}$]. The fits are shown in fig. 6 and the results presented in table 1. The data used in these fits are listed in tables 2 and 3.

In table 1, the lines in which the b-slopes appear in brackets give the results of fits to the PSD data only, where instead of leaving b as a free parameter we used, as input, b-slopes obtained from global fits [13] to world data. The sources contributing to the errors for ρ and b are divided into two categories:

- i) The error on the measured values of $d\sigma/dt$, including the statistical error on the data and on the background subtraction. This error is the first listed in the table.
- ii) The uncertainty of the t-scale and of the total cross-section values used as input to the fit. For a t-scale uncertainty of 0.6%, as estimated conservatively from the collimated α -source scan over the full length of the PSD, the corresponding errors in ρ and b are ± 0.006 and $\pm 0.07 \text{ GeV}^{-2}$, respectively. Varying σ_{tot} within the errors of the fitted values quoted above results in a change to ρ of less than 0.003, which is small compared to the uncertainty due to the t-scale.

The quantity $R(t) = (d\sigma/dt)/(d\sigma/dt)_{\rho=0} - 1$, showing the proportion of the real part of the amplitude, is plotted for the PSD data in fig. 7. It can be seen that the measurement of $d\sigma/dt$ extends below the point where the interference term is maximal, which at 23.4 GeV occurs at $|t| = 0.0017 (\text{GeV}/c)^2$. In figs. 8 and 9 our values for b and ρ are shown plotted together with measurements at other energies.

The values of ρ and b are strongly correlated, with $\Delta\rho/\Delta b$ being approximately 0.013 GeV^2 for pp and 0.016 GeV^2 for $\bar{p}p$. Thus any systematic shift in b will cause a corresponding shift to the ρ -value. However, in this experiment, the difference $\Delta\rho = \rho(\bar{p}p) - \rho(pp)$ is not sensitive to systematic uncertainties. From the fits in which b was treated as a free parameter, we find $\Delta\rho(b_{\text{free}}) = 0.039 \pm 0.014$; the fits in which the b's were fixed to their world-data average values yield $\Delta\rho(b_{\text{fixed}}) = 0.031 \pm 0.010$. These results may be compared with expectations from models that attempt to fit the ρ -values and total cross-sections of pp and $\bar{p}p$ simultaneously as a function of energy. A conventional fit of the type given in ref. 13, in which the difference $\Delta\sigma = \sigma_{\text{tot}}(\bar{p}p) - \sigma_{\text{tot}}(pp)$ is assumed to vanish as $s \rightarrow \infty$, yields the value $\Delta\rho = 0.046$ for $\sqrt{s} = 24.3 \text{ GeV}$, in agreement with our results. However, this fit does not predict correctly the recent UA4 value [3] of $\rho(\bar{p}p) = 0.24 \pm 0.04$ at $\sqrt{s} = 546 \text{ GeV}$, which lies 3σ above the fit. The UA4 value, however, can be accommodated by an unconventional fit which assumes a significant odd-under-crossing amplitude [14] dubbed the 'odderon'. But at our energy, the odderon fit gives $\Delta\rho = 0.061$, a value 3σ larger than our $\Delta\rho(b_{\text{fixed}})$. Thus it appears that this odderon model cannot accommodate both the UA4 ρ -value and the UA6 result for $\Delta\rho$ [15].

We take pleasure in congratulating the staff of the CERN PS and SPS Divisions for the splendid operation of the antiproton source and the SPS Collider. It is with great sadness that we report the death of Professor Rodney Cool, who conceived this project and whose grace and style will be sorely missed. We gratefully acknowledge the technical assistance of R. Heidecker, D. Sceanovic, W. Huta, R. Gros and A. Kupferschmid, and the data management services of M.-A. Huber.

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Table 1

Results of fits to the differential cross-sections

	a	b (GeV ⁻²)	χ^2/DOF
pp	$0.009 \pm 0.010 \pm 0.006$	$11.4 \pm 0.5 \pm 0.07$	1.45
	$0.014 \pm 0.007 \pm 0.006$	[11.76 $\pm$ 0.04]	1.36
$\bar{p}p$	$0.048 \pm 0.011 \pm 0.006$	$12.3 \pm 0.5 \pm 0.07$	1.02
	$0.045 \pm 0.007 \pm 0.006$	[12.51 $\pm$ 0.08]	1.02

Table 2

Differential cross-sections measured by the position-sensitive detector (PSD)

$ t $ (GeV/c) ²	$d\sigma/dt$ (mb/GeV ²)	
	pp	$\bar{p}p$
0.00108	292.9 $\pm$ 3.0	313.0 $\pm$ 3.5
0.00126	234.9 $\pm$ 2.5	252.4 $\pm$ 2.6
0.00146	190.4 $\pm$ 2.2	210.5 $\pm$ 2.1
0.00168	163.1 $\pm$ 1.9	183.0 $\pm$ 1.8
0.00191	142.5 $\pm$ 1.4	160.9 $\pm$ 1.6
0.00216	127.8 $\pm$ 1.2	143.9 $\pm$ 1.2
0.00242	117.6 $\pm$ 1.1	132.0 $\pm$ 1.1
0.00269	108.2 $\pm$ 1.0	121.3 $\pm$ 1.0
0.00298	103.0 $\pm$ 1.0	116.0 $\pm$ 0.9
0.00329	96.7 $\pm$ 0.9	109.6 $\pm$ 0.9
0.00361	93.7 $\pm$ 0.9	105.5 $\pm$ 0.8
0.00394	89.8 $\pm$ 0.9	101.1 $\pm$ 0.8
0.00429	87.7 $\pm$ 0.8	99.4 $\pm$ 0.8
0.00466	84.5 $\pm$ 0.8	96.4 $\pm$ 0.8
0.00504	84.4 $\pm$ 0.8	94.0 $\pm$ 0.7
0.00543	82.0 $\pm$ 0.8	92.1 $\pm$ 0.7
0.00584	81.1 $\pm$ 0.7	90.2 $\pm$ 0.7
0.00626	78.7 $\pm$ 0.8	89.8 $\pm$ 0.8
0.00670	78.4 $\pm$ 0.8	87.8 $\pm$ 0.8
0.00716	78.2 $\pm$ 0.7	86.5 $\pm$ 0.7
0.00763	76.6 $\pm$ 0.8	85.3 $\pm$ 0.7
0.00811	75.7 $\pm$ 0.8	83.7 $\pm$ 0.8
0.00861	74.3 $\pm$ 0.8	82.9 $\pm$ 0.8
0.00912	74.7 $\pm$ 0.8	82.5 $\pm$ 0.8
0.00965	72.6 $\pm$ 1.0	82.0 $\pm$ 0.8
0.01019	72.2 $\pm$ 1.0	81.2 $\pm$ 0.8
0.01075	70.9 $\pm$ 1.0	79.5 $\pm$ 0.9
0.01132	70.2 $\pm$ 1.0	79.1 $\pm$ 0.9
0.01191	70.4 $\pm$ 0.9	78.9 $\pm$ 0.9
0.01251	70.7 $\pm$ 0.9	76.4 $\pm$ 0.8
0.01313	68.5 $\pm$ 0.9	75.8 $\pm$ 0.8
0.01376		75.8 $\pm$ 0.8

Table 3

Stack detector differential cross-sections

$ t $ (GeV/c) ²	$d\sigma/dt$ (pp) (mb/GeV ²)	$ t $ (GeV/c) ²	$d\sigma/dt$ ($\bar{p}p$) (mb/GeV ²)
0.0344	53.7 ± 0.5	0.0370	55.8 ± 0.6
0.0351	53.0 ± 0.3	0.0372	55.8 ± 0.5
0.0388	52.1 ± 0.4	0.0372	55.5 ± 0.6
0.0457	47.2 ± 0.4	0.0415	53.2 ± 0.7
0.0457	47.7 ± 0.4	0.0417	52.9 ± 0.6
0.0496	46.1 ± 0.5	0.0496	47.6 ± 0.4
0.0540	42.2 ± 0.5	0.0497	49.3 ± 0.7
		0.0497	47.9 ± 0.4
		0.0523	45.6 ± 0.7
		0.0546	44.6 ± 0.6

Figure captions

Fig. 1: Schematic layout of the moveable solid-state detector array and fixed luminosity monitors. The array is shown in its nominal position for recording $\bar{p}p$ scattering.

Fig. 2: Results of the collimated α -source scan of PSD: test of position linearity. The curved line is the polynomial correction function as explained in the text; the straight line is expected for perfect linearity.

Fig. 3: Position versus $|t|$ for a sample of pp PSD data after time cuts. The inset is a projection of the position spectrum of events in the interval $0.0078 \leq |t| \leq 0.0084$ (GeV/c)².

Fig. 4: Time-of-flight spectrum of a sample of $\bar{p}p$ data at the lowest $|t|$ -value used in the analysis. The curve represents a Gaussian fit to the background peak.

Fig. 5: Kinetic energy distribution of $\bar{p}p$ events from a stack at $\theta = 6.8^\circ$. The dotted line shows subtracted Monte Carlo simulation of inelastic recoils.

Fig. 6: The differential cross-sections for pp and $\bar{p}p$ shown along with superimposed fits. The PSD points represent averages over runs at all angles.

Fig. 7: Proportion of real amplitude in the differential pp and $\bar{p}p$ cross-sections.

Fig. 8: Our results (UA6) for ρ (open circles) compared with measurements at other energies. The pp plot was adapted from ref. 13.

Fig. 9: Our slope parameter values (UA6) compared with other results. Points marked 'x' are $\bar{p}p$, circles are pp . (Plot adapted from ref. 13.)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9