CERN-EP/83-72
2 June 1983

COMPARISON OF SMALL-ANGLE $p\bar{p}$ AND pp ELASTIC SCATTERING
AT THE CERN INTERSECTING STORAGE RINGS

N. Amos^{a)}, M.M. Block^{a)}, G.J. Bobbink^{b,1)}, M. Botje^{c)}, D. Favart^{d)},
C. Leroy^{d,2)}, F. Linde^{c)}, P. Lipnik^{d)}, J-P. Matheys^{d)}, D. Miller^{a)},
K. Potter^{b)}, S. Shukla^{a)}, C. Vander Velde-Wilquet^{b,3)} and S. Zucchelli^{a)}

ABSTRACT

Antiproton-proton and proton-proton small-angle elastic scattering have been measured for centre-of-mass energies $\sqrt{s} = 30.7$ and 62.5 GeV at the CERN Intersecting Storage Rings (ISR). Antiproton-proton and proton-proton total cross-sections are obtained using the optical theorem. The measurement of the Coulomb scattering and its interference with the nuclear scattering allows a determination of the ratio of the real-to-imaginary part of the forward nuclear scattering amplitude. Also presented are measurements for the nuclear slope parameter at $\sqrt{s} = 62.5$ GeV. Our new results reinforce the conclusions drawn recently from our measurements at $\sqrt{s} = 52.8$ GeV. In particular, the $p\bar{p}$ total cross-section is rising at ISR energies and should continue to rise well beyond these energies.

(Submitted to Physics Letters B)

a) Northwestern University, Evanston, Illinois, U.S.A.

b) CERN, Geneva, Switzerland.

c) State University, Utrecht, The Netherlands.

d) Université Catholique de Louvain, Louvain-la-Neuve, Belgium.

1) Now at Physics Department, Carnegie-Mellon University, Pittsburgh, U.S.A.

2) Now at Physics Department, McGill University, Montreal, P.Q., Canada.

3) Now at IIHE, Université Libre de Bruxelles, Belgium.

The proton-proton total cross-section, $\sigma_{\text{tot}}(pp)$, has been shown to rise over the energy range of the CERN Intersecting Storage Rings (ISR) by Amaldi et al. [1] and Amendolia et al. [2]. As a result of these measurements, it was also expected that the antiproton-proton total cross-section, $\sigma_{\text{tot}}(p\bar{p})$, would start rising over that energy range. Indeed, from a dispersion-theory fit simultaneously performed on data for the ratio of the real-to-imaginary part of the forward pp nuclear amplitude, $\rho(pp)$, and on pp and $p\bar{p}$ total cross-section data available in 1977, Amaldi et al. [3] predicted that antiproton-proton and proton-proton total cross-sections should rise with centre-of-mass energy $\sqrt{s}$ with a rate near the Froissart bound ($\sigma_{\text{tot}} \propto \ln^2 s$) [4] to at least $\sqrt{s} = 300$ GeV.

In a previous letter [5] we have reported a measurement of the $p\bar{p}$ and pp small-angle elastic scattering at the ISR at $\sqrt{s} = 52.8$ GeV. Using the optical theorem, a fit to pp and $p\bar{p}$ differential cross-sections enabled us to determine the $p\bar{p}$ total cross-section, which was found to be higher by more than four standard deviations than the value measured at the highest Fermilab energy [6], leading to the conclusion that not only the pp but also the $p\bar{p}$ total cross-section is rising over the ISR energy range and thus confirming the prediction of Amaldi et al. The same conclusion had been reached by Carboni et al. [7], who measured the $p\bar{p}$ total interaction rate at $\sqrt{s} = 52.8$ GeV. The recent measurement of $\sigma_{\text{tot}}(p\bar{p})$ at the CERN SPS $p\bar{p}$ collider [8], has shown that this rise continues up to $\sqrt{s} = 540$ GeV.

The aim of the present letter is to report the results of our measurements of $p\bar{p}$ and pp small-angle elastic scattering at the ISR at $\sqrt{s} = 30.7$ and 62.5 GeV, the latter energy being the highest energy available today to make a direct comparison between pp and $p\bar{p}$ scattering. Our experiment is an extension to $p\bar{p}$ of the method of Amaldi et al. [1]. The apparatus consists of two pairs of scintillation counter hodoscopes, mounted symmetrically above and below the beam pipes, at 8.7 m downstream of the intersection region. The counter arrangement is shown schematically in fig.1. Each hodoscope consists of 24 horizontal "stack" counters, 2 mm high, to measure polar angles and 7 vertical "finger" counters, 4 mm wide, to measure azimuthal angles. The area of the stacks and fingers is covered by a single trigger counter. The hodoscopes are mounted in thin-walled (0.2 mm stainless steel) re-entrant sections ("Roman pots") of the ISR vacuum chamber. Both the hodoscopes and the "Roman pots" can be accurately positioned (± 0.02 mm) under remote control. In practice, they could be moved sufficiently close to the circulating beams to reach a minimum scattering angle of 1 mrad. A coincidence of the signals of the trigger counter of a hodoscope located above one of the beams and the trigger counter of the hodoscope located below the other beam was used to trigger

the recording of elastic events. Details on the event trigger, information recorded, and data reduction have been given previously [9].

The luminosity was measured with several combinations of large scintillation counters. Four telescopes, U_1 , U_2 , D_1 , and D_2 , each made of two scintillator counters (100×50 cm²), were located symmetrically above (U) and below (D) the beam pipes at 8.5 m downstream from the intersection region. Two independent luminosity monitors were formed by the $U_1.U_2$ and $D_1.D_2$ coincidences. In addition we used a monitor (H_3H_4), which was made of the coincidence of four large circular arrays of scintillation counters of diameter 1.8 m, positioned around the downstream vacuum pipes at 6 m from the intersection region. The signals of H_3H_4 were kindly provided by the CERN-Napoli-Pisa-Stony Brook Collaboration [7,10,11]. Finally a monitor MONI was formed by the combination $(U_2+D_2).H_3H_4$. The geometry of the $U_1.U_2$, $D_1.D_2$ and MONI monitors is efficient in rejecting the relatively high background in $p\bar{p}$ runs arising from interactions of the high-current proton beam with the residual gas and from the beam halo striking the vacuum pipe upstream of the intersection region.

The $p\bar{p}$ data at $\sqrt{s} = 62.5$ GeV were collected in a run when a $\bar{p}$ beam of 3 mA was stored for 4 days in one of the ISR rings. The $p\bar{p}$ data at $\sqrt{s} = 30.7$ GeV were taken in a later run when the $\bar{p}$ beam current was 4 mA and the beam was kept for 11 days. Vertical cooling was applied to the antiproton beams, reducing beam losses and growth to a negligible amount. At both energies, the other ring was filled with a proton beam of 10 A, resulting in an average luminosity of 7×10^{28} cm⁻²s⁻¹. This luminosity allowed 165,000 and 59,000 $p\bar{p}$ elastic scattering events to be collected at $\sqrt{s} = 62.5$ and 30.7 GeV, respectively. The pp data were obtained, at $\sqrt{s} = 62.5$ GeV, in a run preceding the $p\bar{p}$ run, whereas the $p\bar{p}$ run at $\sqrt{s} = 30.7$ GeV took place in between two pp runs at the same energy. In these pp comparison runs, both beam currents were around 5 A and an average luminosity of 5×10^{29} cm⁻²s⁻¹ was reached. Two to three million pp elastic scattering events were collected at each energy. In all runs the Terwilliger scheme [12] for momentum compaction was applied in order to minimize the size of the interaction region. At the beginning of a run the detectors were positioned close to the beams and were moved outwards later in order to extend the angular range.

The luminosity monitors were calibrated using the Van der Meer method [13] for both $p\bar{p}$ and pp, in special runs interleaved with the data taking. During these runs the beams were displaced with respect to each other in small accurate steps [14]; the beam currents, the counting rates, and the time-of-flight differences were measured for the various luminosity counter coincidences. The monitor constants were measured at $\sqrt{s} = 62.5$ GeV with

an accuracy better than 1% for both $p\bar{p}$ and pp . At $\sqrt{s} = 30.7$ GeV a similar accuracy was obtained for the pp data, but relatively poor background conditions affected the $p\bar{p}$ luminosity measurements and the accuracy was estimated to be no better than 3%.

After the collection of the data at $\sqrt{s} = 62.5$ GeV a deterioration of the surface of some trigger counters was discovered. This resulted in a variation of about a factor of two in light-collection efficiency from one end of the counter to the other. The discriminator-threshold settings used on these trigger counters, for the run at $\sqrt{s} = 62.5$ GeV, were such that a small trigger inefficiency had to be corrected for. A careful investigation of these inefficiencies was made and two independent methods were used to calculate the corrections, which were found to be negligible in the high $|t|$ region of the hodoscope but were between 2 and 5% in the low $|t|$ region. One method was based on a parametrization of the pulse-height distribution of particles detected in a region of the trigger counter where the detector inefficiency was negligible and scaling to the region where the discriminator threshold started to cut into this distribution. The other method was based on the measurement of these inefficiencies, using particles whose trajectories through the trigger counter were determined with other counters. The agreement between the two methods was satisfactory.

The measured $p\bar{p}$ and pp differential elastic cross-sections have been fitted to the parametrization [3]:

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

In eq. (1), f_c and f_n are the Coulomb and the nuclear scattering amplitudes respectively. The Coulomb amplitude is given by the expression:

$$f_c = \mp 2\alpha [G^2(t)/|t|] \exp(\pm i\alpha\phi), \quad (2)$$

where t is the momentum transfer squared, $G(t) = [1+|t|/0.71]^{-2}$ is the proton electromagnetic form factor, α is the fine-structure constant, and the Coulomb phase $\alpha\phi$ is that of West and Yennie [15]. In eq. (2), the upper sign is used for pp and the lower sign for $p\bar{p}$. The nuclear elastic scattering amplitude for small values of t approximates to:

$$f_n = [(i+p)/4\pi] \sigma_{tot} \exp(-b|t|/2). \quad (3)$$

In eq. (3), the total cross-section σ_{tot} is introduced through the optical theorem; p is the ratio of the real-to-imaginary part of f_n and b is the nuclear slope parameter, which is assumed to be constant over the small t -range explored in this experiment. The elastic scattering cross-section is defined by:

$$\sigma_{el} = \pi \int |f_n(t)|^2 dt,$$

and, using eq. (3), is given by:

$$\sigma_{el} = (1+p^2) \sigma_{tot}^2 / 16\pi b.$$

To these parameters we have to add an overall normalization factor N ,

multiplicative to eq. (1), which accounts for uncorrected inefficiencies (nuclear absorption, etc.) and a parameter Δh , which is the average deviation of the vertical position of the hodoscopes from the values obtained by optical survey measurements and provides essentially a calibration of the t -scale. The systematic errors due to counters where edge effects, efficiency correction errors, or counting-rate effects could be non negligible, have been investigated. It was observed that, in order to reduce these errors to a level small compared to the other sources of uncertainties, it was sufficient to remove from the fit cross-section points corresponding to the edge fingers and the first (lowest $|t|$), second and last stacks.

The measured pp and $p\bar{p}$ differential cross-sections at $\sqrt{s} = 30.7$ GeV are shown in figs. 2a and 2b, respectively. The data at this energy cover well the Coulomb and Coulomb-nuclear interference region of very low momentum transfer squared, $0.0007 \leq |t| \leq 0.02$ (GeV)², but do not extend deep into the nuclear region. The parameters N and Δh can best be determined from the pp data at $\sqrt{s} = 30.7$ GeV, where the Coulomb scattering, of which both the t -dependence and the absolute magnitude is known, prevails. We have therefore performed a fit to the pp differential elastic cross-sections using as input: $\sigma_{\text{tot}}(pp) = 40.26 \pm 0.20$ mb [3], $b(pp) = 12.2 \pm 0.3$ (GeV)⁻² [16], and obtained $N = 0.99 \pm 0.01$, $\Delta h = -0.11 \pm 0.04$ mm, and $p(pp) = 0.029 \pm 0.010$. The statistical errors have been added in quadrature with those arising from the errors on the input parameters. The values obtained for N and Δh agree with the values found at $\sqrt{s} = 52.8$ GeV [5] and have been used in the subsequent analysis. The $p\bar{p}$ data at this energy were fitted using as input $b(p\bar{p}) = 12.7$ (GeV)⁻² [17], on which an error of 0.3 (GeV)⁻² was assumed, to obtain $\sigma_{\text{tot}}(p\bar{p})$ and $p(p\bar{p})$. The pp data at $\sqrt{s} = 62.5$ GeV with the "Roman pots" in the retracted position cover the range $0.008 < |t| < 0.060$ (GeV)², where the nuclear amplitude dominates (see fig. 2c); they were used to extract $\sigma_{\text{tot}}(pp)$ and $b(pp)$. The pp data with the detectors closer to the beam cover the range $0.002 < |t| < 0.040$ (GeV)⁻² (see fig. 2d) and were used to determine $p(pp)$. Finally the $p\bar{p}$ data, covering the range $0.003 < |t| < 0.040$ (GeV)⁻² (see fig. 2e), were used to extract $\sigma_{\text{tot}}(p\bar{p})$, $p(p\bar{p})$ and $b(p\bar{p})$. Table 1 contains a summary of the results. The errors quoted are the statistical errors added in quadrature with those arising from the uncertainties in the input parameters, the measurement of the integrated luminosity, the setting of the hodoscopes, and, for the data at $\sqrt{s} = 62.5$ GeV, the inefficiency correction. As the same apparatus was used to measure both pp and $p\bar{p}$ elastic scattering, some systematic errors tend to cancel in the differences $\Delta\sigma = \sigma_{\text{tot}}(p\bar{p}) - \sigma_{\text{tot}}(pp)$ and $\Delta b = b(p\bar{p}) - b(pp)$.

Our measurement of $\sigma_{\text{tot}}(pp)$ at $\sqrt{s} = 62.5$ GeV is consistent with the

value deduced from the dispersion relation fit of Amaldi et al. $\{\sigma_{\text{tot}}(pp)=43.9 \text{ mb}\}$ [3] and slightly higher than the average value of previous ISR measurements $\{\sigma_{\text{tot}}(pp) = 43.34 \pm 0.24 \text{ mb}\}$ [18]. Our results for $\sigma_{\text{tot}}(p\bar{p})$ reinforce our previous conclusion [5] that $\sigma_{\text{tot}}(p\bar{p})$ is rising over the ISR energy range. Our results for $\Delta\sigma_{\text{tot}}$ at $\sqrt{s} = 30.7$ and 62.5 GeV are presented in fig. 3 together with our earlier measurement at 52.8 GeV [5], the measurement at $\sqrt{s} = 52.8$ GeV by the CERN-Napoli-Pisa-Stony Brook Collaboration [10], and lower energy results. The solid curve represents the Regge fit of Bartel and Diddens [19] and the dot-dashed line the two-component model of Lipkin [20]. These two models assume that $\Delta\sigma_{\text{tot}}$ vanishes at very high energy and are fitted only to the lower energy data. The extrapolations based on these fits, as well as the more recent fit by Block and Cahn [21], are in good agreement with our results. However, it has been pointed out by Nicolescu and coworkers [22] that the presence of an amplitude odd under crossing, the so-called "odderon", which would cause $\Delta\sigma$ to approach a constant or even to increase like $\ln s$ at high energies, cannot be excluded.

We show our measured values for $\rho(p\bar{p})$ and $\rho(pp)$ together with a survey of high-energy data [23] in fig.4. The solid line represents the dispersion-relation fit of Amaldi et al. [3]. Our results for $\rho(pp)$ are in agreement with the values measured by Amaldi et al. [3]. It is seen that $\rho(p\bar{p})$ is positive and rising over the ISR energy range and that there is good agreement between the dispersion relation fit, for which no $\rho(p\bar{p})$ measurements were used, and the $\rho(p\bar{p})$ data. The large values observed for $\rho(p\bar{p})$ and $\rho(pp)$ are typical of models in which the $p\bar{p}$ and pp total cross-sections are rising with rates near the Froissart bound.

We take pleasure in congratulating the staffs of the Antiproton Accumulator, the ISR, and the Proton Synchrotron Divisions at CERN for their achievement in providing us with the special beams required for these measurements. We are indebted to the CERN-Rome Collaboration for making available to us part of the equipment they used. We further thank the technical staffs of Louvain and Northwestern Universities and of the CERN ISR and DD Divisions for their support. We gratefully acknowledge the contribution to this experiment of the late J. Debaisieux who designed most of the monitoring programs for our data acquisition computer.

This work was supported in part by the Institut Interuniversitaire des Sciences Nucléaires, Belgium, and in part by a U.S. Department of Energy grant.

References

- [1] U. Amaldi et al., Phys. Lett. 44B (1973) 112.
- [2] S.R. Amendolia et al., Phys. Lett. 44B (1973) 119.
S.R. Amendolia et al., Nuovo Cimento 17A (1973) 735.
- [3] U. Amaldi et al., Phys. Lett. 66B (1977) 390.
- [4] M. Froissart, Phys. Rev. B123 (1961) 1053.
- [5] N. Amos et al., Phys. Lett. 120B (1983) 460.
- [6] A.S. Carroll et al., Phys. Lett. 80B (1979) 423.
- [7] G. Carboni et al., Phys. Lett. 113B (1982) 87.
- [8] R. Battiston et al., Phys. Lett. B117 (1982) 126.
- [9] D. Favart et al., Phys. Rev. Lett. 47 (1981) 1191.
- [10] M. Ambrosio et al., Phys. Lett. 115B (1982) 495.
- [11] G. Carboni et al., Phys. Lett. 108B (1982) 145.
- [12] K.M. Terwilliger, Proc. Int. Conf. on High-Energy Accelerators, CERN, 1959 (CERN, Geneva, 1959), p.53.
- [13] S. van der Meer, CERN Internal Report ISR-PO/68-31, (1968).
- [14] P. Bryant and K. Potter, CERN Internal Report ISR-ES-BOM/82-15 (1982).
- [15] G.B. West and D.R. Yennie, Phys. Rev. 172 (1968) 1413.
A recent calculation by R. Cahn, Z. Phys. C15 (1982) 253, using an eikonal approach, has yielded a result for the Coulomb phase that is close to that of West and Yennie.
- [16] U. Amaldi et al., Nucl. Phys. B145 (1978) 367.
- [17] M.M. Block and R. Cahn, Phys. Lett. 120B (1983) 229.
- [18] U. Amaldi and K.R. Schubert, Nucl. Phys. B166 (1980) 301.
- [19] W. Bartel and A.N. Diddens, CERN NP Internal Report 73-4, (1973).
- [20] H.J. Lipkin, Phys. Rev. D17 (1978) 366.
- [21] M.M. Block and R. Cahn, Phys. Lett. 120B (1983) 224.
- [22] P. Gauron and B. Nicolescu, Phys. Lett. 124B (1983) 249.
K. Kang and B. Nicolescu, Phys. Rev. D11 (1975) 2461.
- [23] Data for $p(pp)$: K.J. Foley et al., Phys. Rev. Lett. 19 (1967) 857;
G.G. Beznogikh et al., Phys. Lett. 39B (1972) 411;
V. Bartenev et al., Phys. Rev. Lett. 31 (1973) 1367;
U. Amaldi et al., see ref. [3];
J.P. Burq et al., Phys. Lett. 109B (1982) 124.
Data for $p(p\bar{p})$: L.A. Fajardo et al., Phys. Rev. D24 (1981) 46.

Table 1

Results of the fits to the $p\bar{p}$ and pp differential cross-sections at $\sqrt{s} = 30.7$ and 62.5 GeV. Inputs to the fits are shown in parenthesis.

	$\sqrt{s} = 30.7$ GeV		$\sqrt{s} = 62.5$ GeV	
	pp	$p\bar{p}$	pp	$p\bar{p}$
σ_{tot} [mb]	(40.26 $\pm$ 0.20)	42.0 $\pm$ 0.5	43.7 $\pm$ 0.3	43.9 $\pm$ 0.6
ρ	0.029 $\pm$ 0.010	0.065 $\pm$ 0.025	0.08 $\pm$ 0.02	0.12 $\pm$ 0.03
b [GeV $^{-2}$]	(12.2 $\pm$ 0.3)	(12.6 $\pm$ 0.3)	13.0 $\pm$ 0.3	13.1 $\pm$ 0.6
σ_{el} [mb]	-	7.14 $\pm$ 0.17	7.56 $\pm$ 0.08	7.62 $\pm$ 0.19
$\Delta\sigma = \sigma_{\text{tot}}(p\bar{p}) - \sigma_{\text{tot}}(pp)$ [mb]	1.7 $\pm$ 0.5		0.2 $\pm$ 0.6	
$\Delta\rho = \rho(p\bar{p}) - \rho(pp)$	0.036 $\pm$ 0.027		0.04 $\pm$ 0.03	
$\Delta b = b(p\bar{p}) - b(pp)$ [GeV $^{-2}$]	-		0.1 $\pm$ 0.6	

Figure captions

Fig. 1. Top and side views of the intersection region showing the location of the "Roman pots", the scintillation counter hodoscopes and the scintillation counter telescopes used for the luminosity measurement.

Fig. 2. Differential elastic scattering cross-sections $d\sigma/dt$ versus $|t|$:
(a) pp at $\sqrt{s} = 30.7$ GeV obtained with 3,100,000 events,
(b) $p\bar{p}$ at $\sqrt{s} = 30.7$ GeV obtained with 59,000 events,
(c) pp at $\sqrt{s} = 62.5$ obtained with 340,000 events,
(d) pp at $\sqrt{s} = 62.5$ obtained with 780,000 events,
(e) $p\bar{p}$ at $\sqrt{s} = 62.5$ obtained with 120,000 events.
In each case, the curve represents the best fit to the data as described in the text.

Fig. 3. The difference $\Delta\sigma = \sigma_{\text{tot}}(p\bar{p}) - \sigma_{\text{tot}}(pp)$ versus laboratory momentum p_{lab} . The curves represent the fits of Bartel and Diddens [19] (full line) and Lipkin [20] (dashed line) to the lower energy data.

Fig. 4. Summary of high-energy data [23] for $p(pp)$ and $p(p\bar{p})$. The full line represents the dispersion relation fit of Amaldi et al. [3]. Not shown are two early data points for $p(pp)$ of Amaldi et al. and the $p(pp)$ data of Fajardo et al., which lie above the other pp data.

Fig. 1

Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d

Fig. 2e

Fig. 4