

Measurement of the Slope of the Diffraction Peak for Elastic p - p Scattering from 8 to 400 GeV

V. Bartenev, A. Kuznetsov, B. Morozov, V. Nikitin, Y. Pilipenko, V. Popov, and L. Zolin
The State Committee for Utilization of Atomic Energy of the U.S.S.R., Moscow, U.S.S.R.

and

R. A. Carrigan, Jr., E. Malamud, and R. Yamada
*National Accelerator Laboratory, Batavia, Illinois 60510**

and

R. L. Cool and K. Goulianos
Rockefeller University, New York, New York 10021†

and

I-Hung Chiang,‡ A. C. Melissinos, D. Gross, and S. L. Olsen§
University of Rochester, Rochester, New York 14627||

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The slope $b(s)$ of the forward diffraction peak of p - p elastic scattering has been measured in the momentum-transfer-squared range $0.005 \lesssim |t| \lesssim 0.09$ (GeV/c)² and at incident proton energies from 8 to 400 GeV. We find that $b(s)$ increases with s , and in the interval $100 \lesssim s \lesssim 750$ (GeV)² it can be fitted by the form $b(s) = b_0 + 2\alpha' \ln s$ with $b_0 = 8.23 \pm 0.27$, $\alpha' = 0.278 \pm 0.024$ (GeV/c)⁻².

In the course of the recent operation of the 400-GeV accelerator at the National Accelerator Laboratory, we have studied the distribution of large-angle recoil protons from an internal hydrogen-gas-jet target for incident proton energies varying from 8 to 400 GeV in order to determine (i) the slope $b(s)$ of the diffraction peak of the elastic p - p scattering in the momentum-transfer-squared region $|t| < 0.1$ (GeV/c)², (ii) the ratio of the real to the imaginary part of the forward p - p nuclear scattering amplitude, and (iii) the differential cross section for the diffraction excitation of the proton to the low-mass isobars at small t and large s . In this paper, we report on the slope parameter $b(s)$. Results on parts (ii) and (iii) of the experiment will be presented in future publications.

Small-angle p - p elastic scattering has been investigated at every existing high-energy proton accelerator. Most recently, extensive measurements were performed at Serpukhov¹ and at the CERN Intersecting Storage Rings (ISR).^{2,3} The results for $|t| \lesssim 0.12$ (GeV/c)² can be fitted by the form

$$d\sigma/dt = A(s)e^{-b(s)|t|} \quad (1)$$

and show that b increases with s . In an optical model with constant opacity, b is related to the radius R of the interaction, $b = R^2/4$, and the results indicate that R increases with energy. The

exact form of the variation of b with s is of particular significance in models of high-energy interactions of elementary particles. For example, the frequently used parametrization

$$b(s) = b_0 + 2\alpha' \ln(s/s_0) \quad (2)$$

is based on a simple Regge-pole model, where α' corresponds to the slope of the vacuum trajectory (Pomeron). Although the ISR experiments extended the measurement of $b(s)$ from the Serpukhov interval of $26.2 < s < 133$ GeV² to the much higher s values of $460 < s < 2800$ GeV², no clear conclusion about the validity of Eq. (2) over the entire range covered by these experiments can be drawn from the combined results. The present experiment tests Eq. (2) over a large range of s ($17 < s < 745$ GeV²), which partially overlaps both the Serpukhov and the ISR data. In an earlier experiment⁴ at the National Accelerator Laboratory, we obtained results on $b(s)$ in the interval $47 < s < 375$ GeV². The present experiment is more accurate primarily because of the use of a gas-jet target.

The experimental method of studying small-angle p - p scattering by measuring the energy T and the angle θ of the recoil protons⁵ can be appreciated by examining the recoil kinematics. For the reaction

$$p + p \rightarrow p + X, \quad (3)$$

the relationship $|t| = 2M_b T$ holds exactly and, for incident proton momentum $p_0 \gg M_X$, the recoil angle near 90° in the laboratory is given approximately by

$$\cos\theta \approx \frac{1}{\beta} \frac{|t|^{1/2}}{2M_b} + \frac{M_X^2 - M_b^2}{2p_0 |t|^{1/2}}, \quad (4)$$

where $\beta = p_0 / (E_0 + M_b)$ is the c.m. velocity. For elastic scattering, θ is a function of t and only a weak function of p_0 . For example, at a fixed angle the recoil energy changes by at most 2% for incident energies between 50 and 400 GeV, an ideal condition for measuring the variation of $b(s)$ with s .

The experimental setup consisted basically of a hydrogen-gas-jet target which was pulsed to intercept the beam at predetermined times during the acceleration cycle, thus selecting the desired incident beam momenta, and a set of ten Si(Li) solid-state detectors spanning the angular range from 80.8° to 87.8° at a distance 2.5 m from the target. These detectors were used to measure the kinetic energy of the recoil proton.

The jet target had the following characteristics⁶: pulse duration, ~ 200 msec; density, $\sim 5 \times 10^{-7}$ g/cm³; and full width at half-maximum diameter at the beam axis, ~ 12 mm. The beam, accelerated at the rate of 100 GeV/sec, was ~ 5 mm in diameter at the target and, circulating with a period of 20 μ sec, traversed the target $\sim 10^4$ times during the jet pulse. Thus, with 10^{12} protons per machine pulse and a 5-sec repetition period, the effective luminosity was $\sim 6 \times 10^{32}$ cm⁻² sec⁻¹.

The detectors, collimated down to circular areas of 1 cm diam, were mounted on a movable carriage so that their angular position could be changed. Since the energy of the recoil protons of interest was in the range $0.25 < T < 50$ MeV, and our thickest detectors (5 mm) were capable of stopping protons up to only 30 MeV, copper degraders were placed in front of the five detectors on the high- $|t|$ side of the apparatus so that the elastic protons would stop in the detectors. In this way, inelastic protons from Eq. (3) always appeared on the low-energy side of the elastic peak in the pulse-height spectra of all detectors. One such spectrum is shown in Fig. 1. The elastic peak is superposed on a background which, mainly, was not produced in the immediate vicinity of the target. This "room" background was measured by running for five out of every fifteen pulses with the detector carriage moved to a position 56 mrad closer to 90° , where the elastic peaks were either completely eliminated or con-

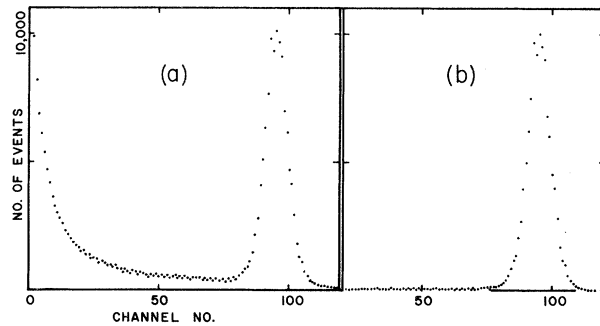


FIG. 1. Typical pulse-height spectrum from a 2-mm-thick solid-state detector at 50 GeV incident energy; the proton energy is approximately 20 MeV. (a) Original spectrum; (b) spectrum after correction for "room" background.

siderably shifted towards lower energies. Two extra detectors were mounted at fixed positions and served as normalization monitors together with two threefold scintillation counter telescopes. Figure 1(b) shows the same spectrum appearing in Fig. 1(a), but with the "room" background subtracted by this procedure. The width of the peak is consistent with the kinematic spread over the angular acceptance determined by the sizes of target and detector. The small remaining background of 1% in the spectra for $p_0 \lesssim 50$ GeV/c, such as the one in Fig. 1(b), is attributed to tails of the hydrogen gas jet. In one method of analysis, this background was removed by interpolation under the peak. In another approach, limits were placed on the pulse-height spectra to correspond to a definite interaction region in the gas jet, thus insuring that the events in all detectors came from the same amount of hydrogen gas. As p_0 is increased, the energy of recoil protons from diffractively produced low-mass isobars increases. For $p_0 \lesssim 50$ GeV/c, the energy of the recoil from $N(1470)$ production is much lower than the elastic peak energy. Above $p_0 \sim 100$ GeV/c, some inelastic recoil protons could contribute background events within our resolution for the elastic peak. Anticipating this inelastic contribution, we pulsed the jet twice during the acceleration ramp, once at ~ 50 GeV and the second time at the higher energy. For each detector, the 50-GeV spectrum was subtracted from that of the higher incident energy, after normalizing the spectra with the elastic peaks, yielding the inelastic events in the vicinity of the elastic peak. These data were transformed to $d^2\sigma/dt dM_X^2$, fitted by resonance formulas, and the results⁷ were used to make a correction for the inelastic

TABLE I. Energy dependence of $b(s)$. The momentum bins are ~ 20 GeV/c wide centered at the given p_{lab} except for the 9- and 12-GeV/c points which have widths of ~ 1 and 4 GeV/c, respectively. $\Delta b(\text{syst}) = \pm 0.2$, independent of s . The errors in $b(s)$ reflect both the statistical and background subtraction uncertainty.

p_{lab} (GeV/c)	$b(s)$ [(GeV/c) $^{-2}$]	p_{lab} (GeV)	$b(s)$ [(GeV/c) $^{-2}$]
9	8.72 ± 0.38	175	11.52 ± 0.11
12	9.03 ± 0.30	199	11.56 ± 0.12
50	10.70 ± 0.18	239	11.61 ± 0.19
58	10.83 ± 0.07	270	11.69 ± 0.10
78	10.84 ± 0.20	312	11.90 ± 0.28
102	11.24 ± 0.13	348	11.96 ± 0.15
128	11.30 ± 0.20	371	11.87 ± 0.15
150	11.57 ± 0.23	396	11.77 ± 0.10

contribution. This correction amounts to at most 4%. The obtained elastic yields were then corrected for nuclear interactions in the detector,⁸ at most a 3% correction.

About 8 million elastic events were collected in ~ 100 runs distributed over sixteen different incident proton energies. The differential cross sections calculated from the data in the interval $0.005 \leq |t| \leq 0.09$ were corrected for the Coulomb contribution⁹ and fitted by Eq. (1). The fits yielded typically a χ^2 per degree of freedom of 1.0 to 1.2; higher-order terms in the exponent did not improve the fit. The errors for $b(s)$ reflect both the statistical and background subtraction uncer-

tainty. However, we estimate that s -independent errors, such as collimator sizes and angle calibration, lead to an overall systematic uncertainty of ± 0.2 (GeV/c) $^{-2}$ in the absolute normalization of $b(s)$.

The results for $b(s)$ are shown in Table I and plotted in Fig. 2 along with data from other experiments.^{1-3,10,11} In examining this figure, one must keep in mind the s -independent systematic normalization uncertainties of ± 0.2 (GeV/c) $^{-2}$ for all b values of this experiment and of ± 0.3 (GeV/c) $^{-2}$ for the values of Baznogikh *et al.*¹ We observe that $b(s)$ increases with energy, and a fit of our data with Eq. (2) above $s \approx 100$ GeV 2 yields $b_0 = 8.23 \pm 0.27$ and $\alpha' = 0.278 \pm 0.024$ (GeV/c) $^{-2}$ with $\chi^2 = 0.44$ per degree of freedom, where we have taken $s_0 = 1$ GeV 2 ; this fit is compatible with the existing data at higher energies.

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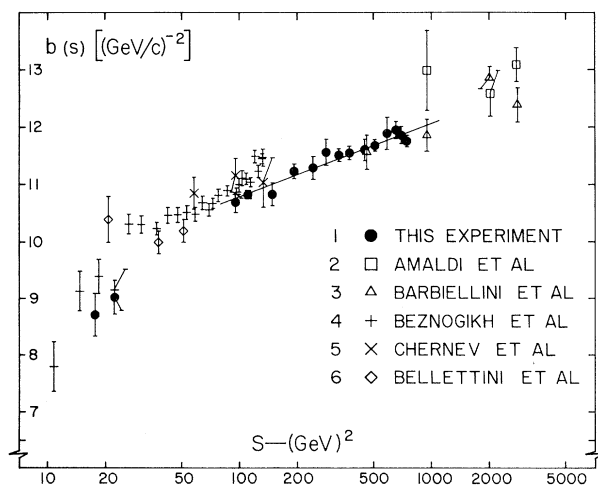


FIG. 2. Slope of the diffraction peak, $b(s)$, for $|t| \leq 0.12$ (GeV/c) 2 , as a function of the square of the c.m. energy. Solid line, fit of $b(s) = b_0 + 2\alpha' \ln(s/s_0)$ only to our data points for $s \gtrsim 100$ GeV 2 .

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‡Present address: Brookhaven National Laboratory, Upton, N.Y. 11973.

[§]A. P. Sloan Fellow.

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Muon Charge-Ratio Measurement and Comparison with Prediction from Hadronic Scaling*

G. K. Ashley, II, J. W. Elbert, J. W. Keuffel, M. O. Larson, and J. L. Morrison

Physics Department, University of Utah, Salt Lake City, Utah 84112

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The cosmic-ray muon charge ratio has been measured for muon momenta 0.7–4.5 TeV/c. It has also been calculated for a constant primary composition by applying scaling to nuclear-target data. The measurements, together with those at lower energies, are in good agreement with our predictions for primary collision energies up to 40 TeV.

Muon charge-ratio measurements provide an experimental constraint on acceptable models of the cosmic-ray primary spectrum and of hadronic interactions. We report here a set of measurements which extends this constraint to primary collision energies of 40 TeV. Predictions obtained with the specific assumptions of constant primary composition and scaling^{1,2} of nuclear-target data are presented for comparison.

The basic principle of the measurement is unique in that the muon momentum at production in the atmosphere is determined by the slant range of rock traversed by the muon on its way to the underground detector. The sign of the muon charge may then be determined by magnetic analysis of the underground muons, which are of relatively low energy: The *local* muon momentum spectrum is given to good approximation by $N(P) \sim \exp(-P/P_0)$, with $120 < P_0 < 160$ GeV/c for the entire range of depths in this experiment.³

The upper limit on the energy at production accessible to the present technique is set simply by the flux of muons, which falls off roughly as E^{-3} . The aperture of the University of Utah detector (~ 100 m² sr) is $\sim 10^3$ times larger than those of

the existing surface spectrometers, which makes it possible to extend the measurements about a decade beyond the limits set by flux for the latter.

The detector, which has been described elsewhere,⁴ is designed to accept muons with zenith angles $> 40^\circ$. It consists of 600 cylindrical spark counters arrayed in fifteen vertical planes, each 6×10 m², together with two vertical planes of magnetized iron, each 5×8 m² \times 60 cm thick, and four Cherenkov counters for triggering. The angular deflection of muons traversing the magnet planes is determined by a spark sonic-ranging system. Coulomb scattering, due almost entirely to the iron, is $\sim 30\%$ of the magnetic bending for all momenta of interest.

The direction of the magnet current was reversed at regular intervals; field direction alternates from leg to leg in the seven vertical legs which make up each magnet plane; and muons from both east and west contribute to most data points. Corrections for average systematic shifts in bending angles (~ 0.5 mrad) were made by comparing data for muons which encountered up and down fields; since the numbers of such muons were nearly equal, the effect of bending-angle