in the polarization. The average over our range of t is 0.12 ± 0.06, where the error includes statistics only. The polarization gives us a measure of the ratio $2\,\mathrm{Re}(F)/\mathrm{Im}(N)$, where F is the nucleon helicity-flip amplitude and N represents the diffractive part of the amplitude.

We are indebted to the staff of the Cambridge Electron Accelerator where we performed preliminary experiments. We wish to thank the staff of the Cornell Wilson Laboratory for their kind hospitality and efficient assistance in conducting this experiment. We are grateful to Robert DiGrazia for invaluable assistance throughout the experiment.

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Small-Angle Elastic Proton-Proton Scattering from 25 to 200 GeV

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We have measured the differential cross section for small angle p-p scattering from 25 to 200 GeV incident energy and in the momentum transfer range $0.015 < |t| < 0.080$ $(\mathrm{GeV}/c)^2$. We find that the slope of the forward diffraction peak, $b(s)$, increases with energy and can be fitted by the form $b(s) = b_0 + 2\alpha' \ln s$, where $b_0 = 8.3 \pm 1.3$ and $\alpha' = 0.28 \pm 0.13$ $(\mathrm{GeV}/c)^{-2}$. Such dependence is compatible with the data existing both at higher and lower energies. We have also obtained the energy dependence of the p-p total cross section in the energy range from 48 to 196 GeV. Within our errors which are ± 1.1 mb the total cross section remains constant.

We have measured the differential cross section for p-p elastic scattering at small angles for incident energies from 25 to 200 GeV, in the momentum-transfer range from 0.015 to 0.080 $(\mathrm{GeV}/c)^2$. The data have been fitted by the form $d\sigma/dt = Ae^{-b|t|}$, and we have determined the coefficient

b as well as the energy dependence of the elastic differential cross section extrapolated to $t = 0$.

The experimental method[1] makes use of the fact that the kinetic energy T of the recoil proton from elastic p-p scattering is directly related to the momentum transfer $|t|$ through $|t| = 2mT$ where m is the mass of the proton. Furthermore, for a fixed value of $|t|$ the angle of emission of the recoil proton is almost independent of the incident beam energy. We have measured the energy and angle of the recoil protons by using lithium-drifted silicon solid-state detectors. Eight such detectors were placed so as to cover the angular range from 90° to 80° in the laboratory. The detectors were collimated to an area of 0.6 cm^2 and were located 3.5 m from the scattering target. The energy response of the detection system was linear and had a resolution of 0.5%. The energy calibration was continuously monitored using 5.47-MeV α particles from an americium source.[2]

The measurements were performed at the National Accelerator Laboratory using a polyethylene target in the internal beam of the accelerator. The target consisted of a thin (typically 3 μm) strip of polyethylene foil which rotated at 60 Hz through the internal beam. The axis of rotation was oriented at an angle of 20° from the beam direction. The tip of the foil was 6 mm wide at the tip. The foil was cut radially so as to render the interaction rate independent of beam position. The thickness of the foil was uniform to ± 4%.

The detectors were mounted on a carriage so that their angular position could be changed. Data were obtained at six different carriage positions which provide (1) for cross calibration of detector acceptance and efficiency, and (2) for a measurement of the shape of the background under the peaks. It was observed that the background is independent of detector position to a high degree of accuracy. One of the detectors was kept at a fixed angle to serve as a normalization monitor. The beam intensity was also monitored using a toroidal coil encircling the beam pipe.[3] The signals from each detector were routed through appropriate circuitry to a single analog-to-digital converter and then written on magnetic tape. The signals were gated in synchronism with the foil passing through the beam; an asychronous gate provided simultaneous target-out data. Each event recorded on tape contained information on detector position, the recoil proton energy, the primary beam energy, and the target status. In addition, events occuring during the analog-to-digital convertor readout time were

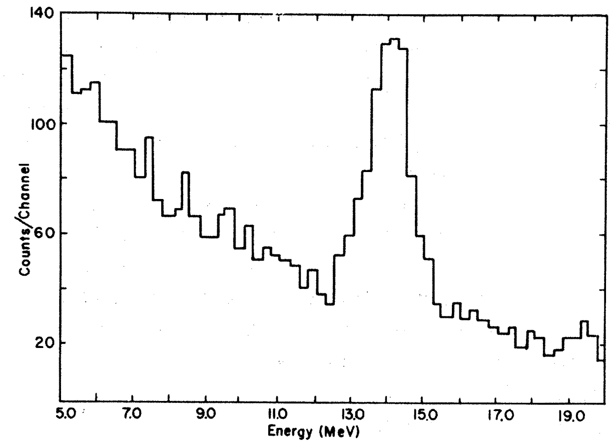

FIG. 1. Typical pulse-height spectrum from a 5-mm-thick solid-state detector. The elastic peak appears at an energy of 14.1 MeV and is due to protons stopping in the detector.

counted and recorded for use in correcting for dead-time losses. Clear peaks corresponding to elastic scattering were observed in the energy spectrum of each detector, a typical spectrum being shown in Fig. 1. At low values of $|t|$ the peak is due to protons stopping in the detector, whereas at high $|t|$ values the peaks were due to the energy loss ($\int dE/dx$) of protons traversing the detector. The elastic peaks were superimposed on a background arising mainly from the proton-carbon interactions in the target. To extract the yield of elastic events a background envelope, obtained from several positions of the same detector (but separately for each given energy), was subtracted from the data histogram. That this procedure selects only elastic events from p-p interactions in the target was verified by comparing data for the same $|t|$ value (and same energy), but obtained from different detectors as their angular position was varied. Finally, the elastic yield was corrected for the following effects: (a) nuclear interactions in the detector,[4] 0.2 to 2.6%; (b) interference of the Coulomb and nuclear amplitudes, 1.7 to 7.0%[5]; (c) geometric acceptance correction, 2.5 to 12.3%.

The differential cross sections extracted from the data in the interval $0.015 < |t| < 0.080$ were fitted by a functional form

$$\frac{d\sigma}{dt}(s, t) = \frac{d\sigma}{dt}(s, t=0)e^{-b(s)|t|}, \tag{1}$$

and the slope parameter $b(s)$ was determined for eight different energy intervals. The width of the energy bins was 10 GeV centered at 25-GeV intervals. Data from all detectors and all positions

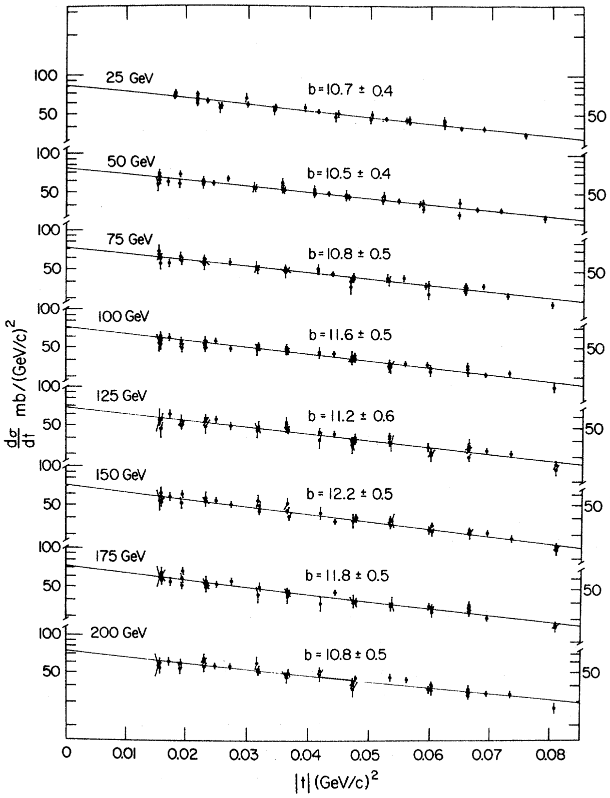

FIG. 2. The elastic p-p differential cross section $d\sigma/dt$ at the eight measured energy intervals. The data points have been corrected as discussed in the text. The normalization of the data is based on the value of σ_T at an energy of 48 GeV given in Ref. 10.

were combined, with appropriate errors to account for the statistical fluctuations of the peak and background. Typically, the fits gave χ^2 per degree of freedom in the range 0.7–1.5; the error on $b(s)$ was incremented by (χ^2 per degree of freedom)$^{1/2}$ when the χ^2 exceeded 1.0 in order to account for the systematic errors. The differential cross sections are shown in Fig. 2 and contain approximately 60 000 elastic events at each energy.

The values of $b(s)$ obtained are shown in Fig. 3 where data from other experiments are also included.[1,6-9] Our data are, in general, in agreement with those of the other authors. If $b(s)$ is parametrized in the usual way as

$$b(s)=b_0+2\alpha' \ln s, \tag{2}$$

we find, using *only our data*,

$$b_0=8.3\pm1.3, \quad \alpha'=0.28\pm0.13\ (\mathrm{GeV}/c)^{-2}.$$

When high-energy elastic scattering in the forward direction is interpreted as due mainly to

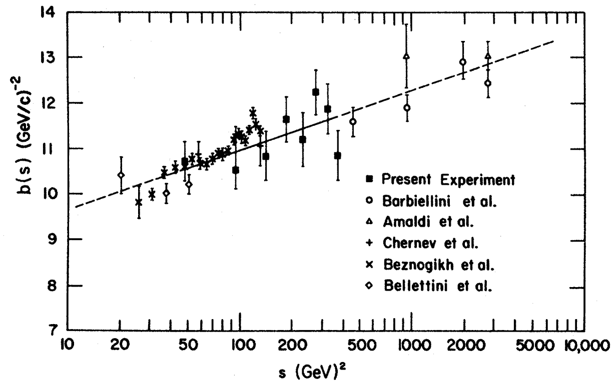

FIG. 3. The slope of the diffraction peak, $b(s)$, as a function of the square of the c.m. energy. The straight-line fit is made only to the eight points measured in this experiment.

diffraction, $b(s)$ is a measure of the proton's interaction radius, and our measurements indicate that this radius increases with energy. On the other hand, models of high-energy interactions predict $b(s)$ and its energy dependence. The parametrization we have used is based on a Regge-pole model where α' corresponds to the slope of the vacuum trajectory (Pomeranchukon). Our result indicates that this trajectory has a drastically different slope than the trajectories on which the known particles and resonances are presumed to lie [in that case the slope is ~1 $(\mathrm{GeV}/c)^{-2}$].

We refitted the data with Eq. (1) using the best-fit values of $b(s)$ to determine $(d\sigma/dt)(s,t=0)$. We note that the forward cross section depends only weakly on $b(s)$; a 10% variation in $b(s)$ results in a 3% change in $(d\sigma/dt)(s,t=0)$. The data were examined for possible variations with target position, target deterioration, and beam intensity; within statistical uncertainties no effects of this kind were observed. We have scaled the statistical error by a factor of 2 to allow for possible systematic effects.

Using the optical theorem and the usual assumption about spin independence of the p-p interaction, the forward differential cross section can be related to the total cross section:

$$\sigma_T(s)=\left(\frac{d\sigma}{dt}(s,t=0)\right)^{1/2}\frac{4\sqrt{\pi}}{1+\alpha^2/2}.$$

Our data on the energy dependence of σ_T are presented in Table I where the values of $\alpha=\mathrm{Re}(f)/\mathrm{Im}(f)$ are taken from Ref. 5. Finally, if the total cross section at $E=48$ GeV is normalized to the value $\sigma_T=38.5$ mb given by Denisov *et al.*,[10]

TABLE I. Energy dependence of p-p total cross section.

E_{lab} [a] (GeV)	$b(s)$ [b] $(\mathrm{GeV}/c)^{-2}$	$\alpha = \frac{\mathrm{Re}A}{\mathrm{Im}A}$ [c]	$(d\sigma/dt)_{t=0}$ [d] (Relative units)	$(d\sigma/dt)^{1/2}/(1+\alpha^2/2)$ (Relative units)	σ_{tot}
48	10.9	-0.16	(1.03)	(1.00)	(38.5 ± 0.1)
73	11.1	-0.09	0.96 ± 0.06	0.98 ± 0.03	37.7 ± 1.1
98	11.3	-0.09	0.96 ± 0.06	0.98 ± 0.03	37.7 ± 1.1
122	11.5	-0.09	0.93 ± 0.06	0.96 ± 0.03	37.0 ± 1.1
147	11.6	-0.09	0.96 ± 0.06	0.98 ± 0.03	37.6 ± 1.1
172	11.7	-0.09	0.95 ± 0.06	0.97 ± 0.03	37.4 ± 1.1
196	11.7	-0.09	1.01 ± 0.06	1.00 ± 0.03	38.5 ± 1.2

[a] The energy bins are 10 GeV wide centered at the indicated energies.

[b] The slope parameters are obtained from the fit shown in Fig. 3.

[c] The values of α are taken from Ref. 5 for the lowest energy and assumed to be -0.09 for $E \geq 73$ GeV. Note that if $\alpha = 0$, the change in σ_T is 0.5%.

[d] The forward cross section is given in relative units with the 48-GeV point having been set equal to 1.03.

[e] The total cross section at 48 GeV was normalized to the point given by Denisov *et al.*, Ref. 10.

we obtain the p-p total cross section at the remaining six energies.[11] The error on each point is ± 1.1 mb, and within these errors the total cross section remains constant in the energy interval from 48 to 196 GeV. This observation is in agreement with total-cross-section data reported by Holder *et al.*[12] at an equivalent energy of $E = 500$ GeV and by Charlton *et al.*[13] at $E = 200$ GeV.

We are indebted to many individuals who have contributed at various stages of this experiment, and in particular we wish to acknowledge the assistance and support given us by the National Accelerator Laboratory accelerator operations staff. We thank Mr. T. Haelan and Mr. C. Wilson for the construction of the target and vacuum chamber.

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†Work supported in part by the U. S. Atomic Energy Commission under Contract No. AT(11-1)-3065.

[1] This technique was first successfully used by G. Beznogikh *et al.*, Phys. Lett. 30B, 274 (1969).

[2] The detectors were also calibrated using proton beams from the Princeton cyclotron. We are indebted to E. Cecil for his assistance in these runs.

[3] We thank Dr. D. Sutter for designing and providing the beam-intensity monitor. This instrument had a time constant of 500 μsec and its linearity and stability were better than 1% at a circulating beam current of 5 mA.

[4] The correction for nuclear interactions in the silicon detectors was taken from D. F. Measday and C. Richard-Serre, CERN Report No. CERN 69-17, 1969 (unpublished).

[5] To perform the correction for the contribution of Coulomb interference to the nuclear scattering, the data of G. Beznogikh *et al.*, Phys. Lett. 39B, 411 (1972), were used and extrapolated up to 200 GeV/c.

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[10] S. Denisov *et al.*, Phys. Lett. 36B, 415 (1971).

[11] The internal-beam intensity varied considerably in the first energy bin (centered at 23 GeV); therefore, this point has been excluded from the data.

[12] M. Holder *et al.*, Phys. Lett. 35B, 316 (1971). These authors quote $\sigma_T = 40.3 \pm 2$ mb at a center-of-mass energy of 30 GeV.

[13] G. Charlton *et al.*, Phys. Rev. Lett. 29, 515 (1972).