the primary target. The reason the synchrotron signal had so little background is that T_1 was retracted for synchrotron runs. Tests indicated that the background was probably caused by bremsstrahlung radiation directly exciting the photocathode. The PM was masked so that the signal could excite only the central portion of the photocathode, whereas the background could excite all parts of the photocathode resulting in early background pulses due to transit time differences.

[8] The optical delay consisted of a 1-in. Lucite window which could be inserted after S_4, delaying optical light by 40 psec.

[9] The background limitations on the present experiment could perhaps be eliminated by better shielding or by adding a 10-nsec delay to the optical signal path to allow the PM to recover from the background radiations. Limitations due to resolution and drift of perhaps 5 psec with the present data system seem reasonable.

[10] Z. Bay and J. P. White, Phys. Rev. D 5, 796 (1972); G. Feinberg, Science 166, 879 (1969); J. M. Rawls, Phys. Rev. D 5, 487 (1972).

[11] J. E. Grindlay, Astrophys. J. 174, L9 (1972); J. V. Jelley, in *The Crab Nebula,* edited by R. D. Davies and F. G. Smith (Springer, Berlin, 1971), p. 32; T. C. Weeks *et al.*, Astrophys. J. 174, 165 (1972).

[12] B. C. Brown, Nature (London) 224, 1189 (1969); T. C. Pavlopoulos, Phys. Rev. 159, 1106 (1967), and Nuovo Cimento 60B, 93 (1969).

Study of the Inclusive Reaction $p+p\rightarrow p+X$ between 40 and 260 GeV/*c* Using an Internal H_2 Jet Target[*][†]

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We have measured the relative energy dependence of the invariant cross section for the inclusive reaction $p+p\rightarrow p+X$ for $0.05\leq M_X^2/s\leq 0.22$ at $t=-0.33$ and -0.45 GeV^2. The energy range from $s=80$ to 480 GeV^2 was covered continuously by taking data during the acceleration ramp of the National Accelerator Laboratory machine. The data are compared with the diffractive-excitation and Regge models.

We have measured the s and M_X^2 dependence of the invariant cross section for the single-particle inclusive reaction

$$p+p\rightarrow p+X \quad (1+2\rightarrow 3+X) \qquad (1)$$

(X = anything) at the National Accelerator Laboratory (NAL) using the acceleration ramp from $P_{\text{lab}}=40$ to 260 GeV/*c* and the internal H_2 jet[1] target. Recoil protons from Reaction (1), with $55^\circ<\theta_3<65^\circ$ in the lab, exit the main accelerator beam pipe through a 3-mil Ti window and are detected in a counter-range telescope (Fig. 1). Two recoil momentum bites are selected simultaneously by means of three Al absorbers, the trigger logic being $C_1C_2C_3C_4C_5\bar{C}_6$ and $C_1C_2C_3C_4C_5C_6\bar{C}_7$. The protons of interest have $560<P_3<660$ MeV/*c* and $660<P_3<780$ MeV/*c* and are $\simeq 2.5$ and $\simeq 2.0$ times minimum ionizing, respectively. They are distinguished from π's of the same ranges by means of time of flight between counters C_1 and C_4 and pulse height in counters C_1–C_5.

The H_2 jet target is essentially a vertical cylinder of ~10 mm diameter. It is pulsed for 250 msec twice during the 2.5-sec acceleration ramp of the machine. The H_2 jet density is roughly 2×10^{-7} g/cm^3, and may vary up to a factor of 2 over a period of a few hours. Above 40 GeV/*c* the circulating beam profile is an ellipse with ap-

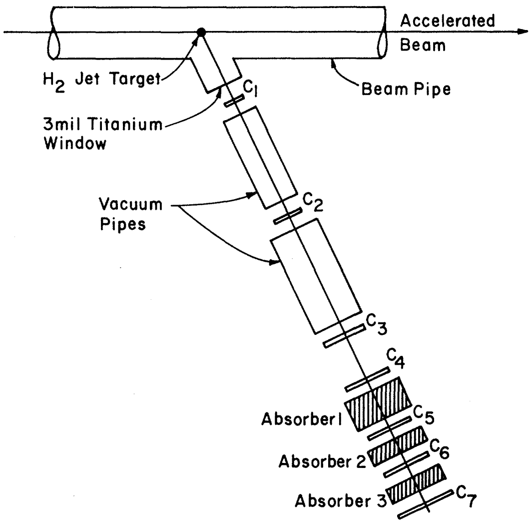

FIG. 1. Spectrometer setup inside the NAL main ring (not to scale). The spectrometer angle to the beam can be varied between 55° and 65°. The defining counter C_4 is 2.5 m from the target and subtends 5×10^{-4} sr.

proximate dimensions 2×3 mm^3 in the vertical and radial directions, respectively.

This mode of operation requires that the beam-target luminosity be monitored continuously during each run. To do this we use elastically scattered protons reaching an 8-mm-diam solid-state detector[2] situated at a lab angle of 86° to the beam. At this angle, the kinetic energy $T=11.6$ MeV of the elastic recoil proton and the momentum transfer $|t|=2mT=0.022$ GeV^2 are almost independent of the incident beam energy. By using the optical theorem, the forward differential cross section can be related to the total cross section. To the extent that the total cross section is constant over our energy range,[3,4] the number of elastic events at $t=-0.022$ GeV^2 is proportional to the luminosity provided we apply a small shrinkage correction. For this we use the parameters determined in Ref. 3 which lead to a shrinkage correction of 2.2% between the two extreme energy values of our experiment. The uncertainty in our relative normalization is dominated by the uncertainty in the total cross section which is about ± 2.5%. Target-out rates in the recoil spectrometer are less than 1% of the target-in rates, and corrections for accidental vetoes introduced by counters C_6 and C_7 are also less than 1%.

We describe the kinematics of Reaction (1) by the three invariants s, t, and M_X^2/s. We have

$$s=(P_1+P_2)^2\simeq 2mE_1, \tag{2a}$$

$$t=(P_2-P_3)^2=-2m(E_3-m), \tag{2b}$$

$$M^2=(P_1+P_2-P_3)^2\simeq s[1-(E_3-P_3\cos\theta_3)/m], \tag{2c}$$

where m is the proton mass. Equations (2) imply that, for P_3 and θ_3 fixed, t is fixed and M_X^2/s is nearly fixed for all s. The variation of M_X^2/s at fixed θ_3 as P_1 goes from 40 to 260 GeV/c is less than 1%. We collect data in such a way that all but one of the variables in Eqs. (2) are fixed. In the first mode we vary s and fix θ_3 at the values 55.6° and 64.3°. These angles, together with the two recoil momentum bites given earlier, define the values $M_X^2/s=0.18$ and 0.09 at $t=-0.33$ GeV^2 and $M_X^2/s=0.17$ and 0.07 at $t=-0.45$ GeV^2. In the second mode we fix s at 100 and 360 GeV^2 and vary θ_3 so that we obtain data in the range $0.06\leq M_X^2/s\leq0.21$.

Our results are presented in Figs. 2 and 3 in terms of the invariant cross section $s\,d^2\sigma/dt\,dM_X^2$. For fixed recoil momentum P_3 this quantity is measured directly by our apparatus since we have

$$\frac{d^2\sigma}{d\Omega\,dP_3}=P_3^2\frac{d^3\sigma}{d^3P_3}=\frac{1}{\pi}\frac{P_3^2}{E_3}\frac{s\,d^2\sigma}{dt\,dM_X^2}. \tag{3}$$

The statistical errors on each point are less than ± 2% to which we have added quadratically relative normalization errors of ± 2.5%.

The absolute normalization is obtained by extrapolating our data to lower energies. Experiments at CERN[5] and Brookhaven National Laboratory (BNL)[6] have measured Reaction (1) at $s=46.8$ and 56 GeV^2 with overall normalization uncertainties of about ± 20%. We have used the average[7] between the CERN and BNL results which is 17.5 mb/GeV^2 at $t=-0.33$ GeV^2, $M_X^2/s=0.18$ and 10.5 mb/GeV^2 at $t=-0.45$ GeV^2, $M_X^2/s=0.17$. The extrapolation was made using a function of the form (4) below, and we estimate the resulting uncertainty in the overall normalization of our data to be ± 25%.

The most prominent features of our data are (i) the presence, in Fig. 2, of an energy-dependent component in the invariant cross section at fixed t and M_X^2/s; (ii) in Fig. 3 the presence of a minimum in the invariant cross section plotted against $x=1-M_X^2/s$ at fixed t and s; (iii) the position of this minimum near $x\simeq0.9$ does not change with s. More generally, the shape of the entire x distribution depends very little on s.

In order to compare qualitatively our results

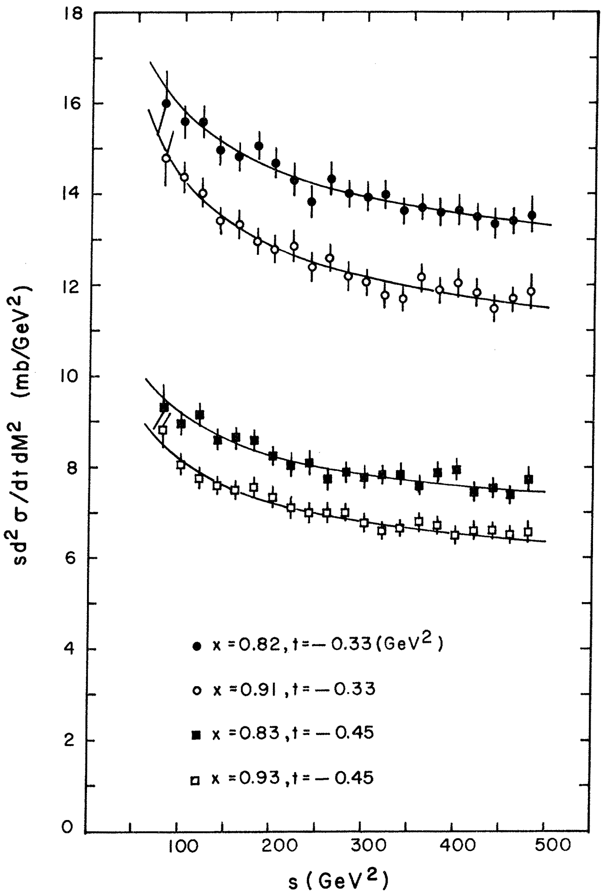

FIG. 2. Our data plotted as a function of s at fixed t and $x = 1 - M^2/s$. The curves are fits to the data of the form $A(1 + Bs^{-1/2})$.

with theoretical predictions, we fit our data on the s dependence with the form

$$s\,d^2\sigma/dt\,dM_X^2 = A(t,M_X^2/s)[1 + B(t,M_X^2/s)s^{-1/2}]. \quad (4)$$

The results are given in Table I, and as can be seen from Fig. 2 we obtain excellent fits. It is interesting to note that at $s = 480$ GeV^2 the invariant cross section is within 20% of its asymptotic limit. This is in agreement with recent CERN Intersecting Storage Rings measurements[8] which, within the 10% normalization uncertainties, show no variation between $s = 960$ and 1995 GeV^2.

Diffractive-excitation models[9,10] predict a pure $s^{-1/2}$ dependence in the quasielastic region $x > 0.9$ (but not near 1). This prediction is obtained naturally in these models when one assumes[10] (a) small transverse momenta for the fireball decay products, (b) average particle multiplicity increasing logarithmically with s, and (c) isotropic decay in the fireball rest frame. These assumptions lead to a distribution $d\sigma/dM \propto 1/M^2$ for the fireball mass which coincides with the missing mass in the quasielastic region where

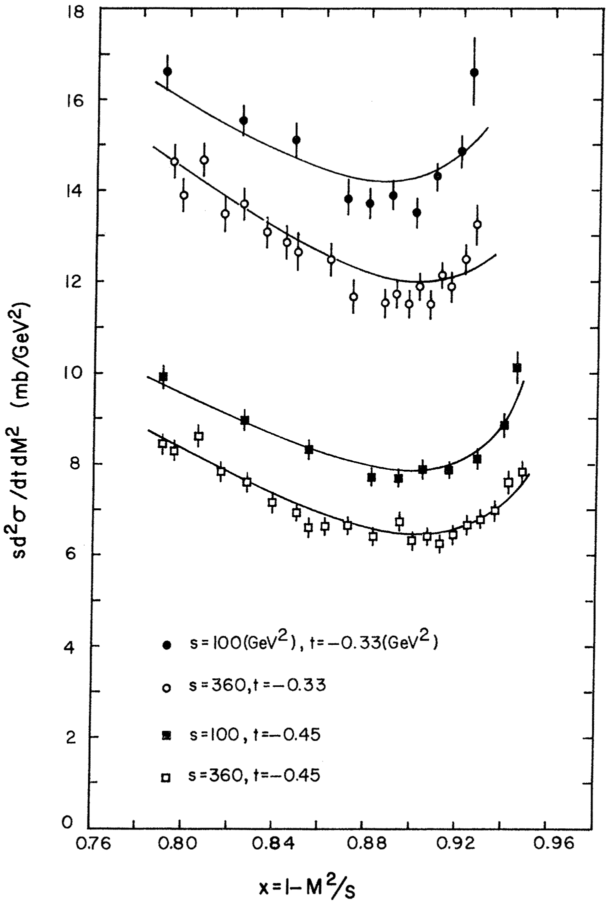

FIG. 3. The measured x distributions at two values of s and t. The curves are the best fits, at each t separately, to all the data of Figs. 2 and 3 by a four-term triple Regge formula. The respective values of the couplings G_{PPP}, G_{PPR}, G_{RRP}, and G_{RRR} are 0.21, 0.87, 33.7, 30.4 mb/GeV^2 at $t = -0.33$ GeV^2 and 0.14, 0.56, 27.7, 31.5 mb/GeV^2 at $t = -0.45$ GeV^2. For both fits we get $\chi^2 \simeq 1.2$ per degree of freedom.

TABLE I. The coefficients A and B of Eq. (4) for the four t and M^2/s values of this experiment.

$x = 1 - \frac{M^2}{s}$	t (GeV^2)	A (mb/GeV^2)	B (GeV)
0.82	− 0.33	11.4	3.8
0.91	− 0.33	9.2	5.4
0.83	− 0.45	6.1	4.9
0.93	− 0.45	5.0	6.1

the through-going proton is observed. At fixed t the invariant cross section then becomes $s\,d^2\sigma/dt\,dM_X{}^2 \propto (s/M_X{}^2)^{3/2}s^{-1/2}$. This is contradicted by the presence of a large energy-independent component A in our data at $x = 0.91$ and 0.93. As (a) and (b) have experimental support, our results, within the framework of this model, may imply anisotropic fireball decays.

Regge theory for inclusive reactions predicts,[11] in the single Regge limit ($s, M_X{}^2 \to \infty$ and t small), an s dependence of the form (4) provided only the Pomeranchukon and leading meson trajectories are considered. The fact that we obtain a good fit with Eq. (4) implies that lower-lying trajectories are not needed. The functional dependence on t and M^2/s of A and B in Eq. (4) can be calculated in the triple Regge limit[12] where, in addition to $s, M_X{}^2 \to \infty$, t small, one also requires $s/M^2 \to \infty$. We have fitted simultaneously the s and x dependence of the data with the triple Regge formula[13]

$$\frac{s\,d^2\sigma}{dt\,dM_X{}^2} = \frac{s_0}{s}\sum_{ijk} G_{ijk}(t)\left(\frac{s}{M_X{}^2}\right)^{\alpha_i(t)+\alpha_j(t)}\left(\frac{M_X{}^2}{s_0}\right)^{\alpha_k(0)}, \qquad (5)$$

where $s_0 = 1\ \mathrm{GeV}^2$. In general, all possible combinations ijk [where i, j, k are the Pomeranchukon ($\alpha_{\mathrm{P}} = 1$) or leading meson trajectories ($\alpha_{\mathrm{R}} = \frac{1}{2} + t$)] can contribute to Eq. (5), and there have been many theoretical conjectures concerning the relative importance of these contributions.[13] We find that we need at least four terms: PPP, PPR, RRP, and RRR. The resulting best fits to the 140 data points of Figs. 2 and 3 simultaneously, but at each t separately, are shown in Fig. 3.

Summarizing, we have measured the energy dependence of the reaction $p + p \to p + X$ over the range $s = 80-480\ \mathrm{GeV}^2$ with about ± 2.5% uncertainty in the relative normalization between different energies. We establish that the approach to scaling follows an $s^{-1/2}$ law, and that at $s = 480\ \mathrm{GeV}^2$ the invariant cross section is about 20% above its asymptotic limit. Finally, the shape of the x distribution over the range $0.79 \leq x \leq 0.94$ depends only very weakly on the incident energy.

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[1] V. Bartenev *et al.*, to be published.

[2] The signal from the elastic monitor was provided by the U.S.A.-U.S.S.R. collaboration at NAL (V. Bartenev *et al.*), authors of Refs. 1 and 3.

[3] V. Bartenev *et al.*, Phys. Rev. Lett. 29, 1755 (1972).

[4] S. Denisov *et al.*, Phys. Rev. Lett. 36B, 415 (1971); G. Charlton *et al.*, Phys. Rev. Lett. 29, 515 (1972); M. Holder *et al.*, Phys. Lett. 35B, 361 (1971).

[5] J. V. Allaby *et al.*, in *Proceedings of the Fourth International Conference on High Energy Collisions, Oxford, England, 1972* (Rutherford High Energy Laboratory, Chilton, Didcot, Berkshire, England, 1972); see also CERN Report No. 72-1380 (unpublished).

[6] E. W. Anderson *et al.*, Phys. Rev. Lett. 19, 198 (1967).

[7] We have multiplied the 30-GeV/c data of Ref. 6 by 1.28. This is suggested by the authors of Ref. 6 in R. M. Edelstein *et al.*, Phys. Rev. D 5, 1073 (1972).

[8] M. G. Albrow *et al.*, to be published.

[9] R. K. Adair, Phys. Rev. D 5, 1105 (1972); K. Gottfried and O. Kofoed-Hansen, Phys. Lett. 41B, 195 (1972).

[10] M. Jacob and R. Slansky, Phys. Lett. 37B, 408 (1971).

[11] Chan H.-M. *et al.*, Phys. Rev. Lett. 26, 672 (1971); H. D. I. Abarbanel, Phys. Lett. 34B, 69 (1971).

[12] R. D. Peccei and A. Pignotti, Phys. Rev. Lett. 26, 1076 (1971); C. E. DeTar *et al.*, Phys. Rev. Lett. 26, 675 (1971).

[13] For further discussion see S. D. Ellis and A. I. Sanda, Phys. Rev. D 6, 1347 (1972); M. B. Einhorn *et al.*, Phys. Lett. 37B, 292 (1971).