PHYSICAL REVIEW D VOLUME 15, NUMBER 7 1 APRIL 1977

Observation of asymmetry in inclusive proton production by 6-GeV/c polarized protons*

D. S. Ayres, I. Ambats, R. Diebold, R. J. Jost,† S. L. Kramer, W. T. Meyer,‡ A. J. Pawlicki, C. E. W. Ward, A. B. Wicklund
Argonne National Laboratory, Argonne, Illinois 60439

R. R. Crittenden, H. A. Neal, and D. R. Rust
Indiana University, Bloomington, Indiana 47401

A. Lesnik and D. M. Schwartz§
Ohio State University, Columbus, Ohio 43210

E. C. Swallow‖
Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637
(Received 22 November 1976)

Left-right asymmetries of fast forward protons produced in the inclusive reaction $p_\uparrow p \to pX$ have been measured using a 6-GeV/c polarized proton beam and the Argonne Effective Mass Spectrometer. The experiment covers the kinematic range $p_T^2 \leq 0.72$ GeV^2 and $M_X \leq 2.6$ GeV with 1.6×10^5 inelastic events. The average asymmetry is 0.047 ± 0.010, with the same sign as the asymmetry in proton-proton elastic scattering and roughly half the magnitude. In order to facilitate comparison with future high-energy data in the triple-Regge region, finite-mass-sum-rule integrals are used to average over the low-M_X data of this experiment.

I. INTRODUCTION

The 6-GeV/c polarized proton beam from the Zero-Gradient Synchrotron (ZGS) at Argonne National Laboratory has been used to measure the left-right asymmetries of fast forward protons produced in the inclusive reaction

$$p_\uparrow p \to pX. \qquad (1)$$

The spectrum of the recoil-baryon system X is strongly influenced by nucleon resonances (N^*'s and Δ's) in the mass region $M_X < 2$ GeV, and has been well studied previously (see for example, Ref. 1). The asymmetries measured in this experiment depend on the interference between proton-vertex helicity-flip and non-helicity-flip production amplitudes, and provide new information on the amplitudes and their relative phases. The presence of a strong diffractive component in nucleon-resonance production suggests that the asymmetries in reaction (1) might be similar to those in pp elastic scattering, namely owing to the interference of the diffractive amplitude with Reggeon contributions (e.g., ρ and A_2 exchange).

Even in the framework of this simple diffractive picture, the behavior of the asymmetries in reaction (1) could *a priori* be quite complicated, since the relevant coupling constants can be arbitrary for the different N^* states produced. The Mueller-Regge picture, supplemented by finite-mass sum rules (FMSR's), economizes the description by constraining the mass dependence of the Reggeon (R) and Pomeron (P) exchanges.[2] In particular, the asymmetry (A) in reaction (1), owing to interference of two different Regge exchanges, $\alpha_i(t)$ and $\alpha_j(t)$, can be expressed in the limit $s\to\infty$, $M_X^2/s \ll 1$, and M_X^2 large, as[3]

$$A\frac{d^2\sigma}{dtdM_X^2} \approx \frac{1}{s^2}\left(\frac{s}{\nu}\right)^{\alpha_i(t)+\alpha_j(t)} \sum_k P_{ijk}(t)\nu^{\alpha_k(0)}, \qquad (2)$$

where $\nu = M_X^2 - M_p^2 - t$, $\alpha_k(0)$ is the trajectory describing forward Reggeon-proton scattering $ip \to jp$, and $P_{ijk}(t)$ includes the residue functions and signature factors. As indicated schematically in Fig. 1, and explained in detail in Ref. 3, $P_{ijk}(t) \propto \mathrm{Im}(A_f^* A_n)$, i.e., depends on the interference between proton helicity-flip and non-helicity-flip amplitudes A_f and A_n. $P_{ijk}(t)=0$ if Regge pole $i=j$, or if i and j have the same phase or have different naturalities.

In the triple-Regge picture, the unpolarized cross section has the same dependence on s and ν as Eq. (2), but the Regge poles which dominate the cross section are expected to be different from the interfering poles which cause the asymmetries. For example, if the asymmetries are due to Pomeron-Reggeon interference as in elastic scattering ($ijk = PRR$), Eq. (2) predicts [with $\alpha_k(0)=\frac{1}{2}$] that $Ad^2\sigma/dtdM_X^2 \propto s^{-1/2}\nu^{-1}$ for small t; if the cross section is dominated by Pomeron exchange ($ijk=PPP$), then $d^2\sigma/dtdM_X^2 \propto \nu^{-1}$ and $A \propto s^{-1/2}$, independent of ν.

Strictly speaking, Eq. (2) applies only in the lim-

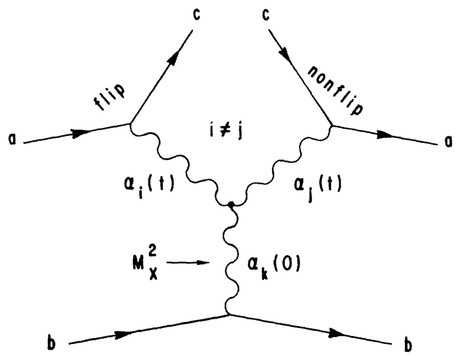

FIG. 1. Mueller-Regge diagram which describes the asymmetry in the process $ab \to cX$ in the triple-Regge region, where the large-M_X^2 behavior of the Reggeon-particle forward scattering is given by the exchange of a Regge pole $\alpha_k(0)$. In this experiment, a is the polarized beam proton, b is the target proton, and c is the proton measured by the spectrometer.

it of large M_X^2; however, FMSR's can be used to extend its range of validity into the N^* region by smoothing out local variations due to resonances. We emphasize that the applicability of the Mueller-Regge formalism at 6 GeV/c is somewhat doubtful, for both the asymmetry and the unpolarized cross section, because the criterion $M_X^2/s \ll 1$ is not well satisfied. But the Mueller-Regge description provides an economical asymptotic model with which our data and future measurements at high energy can be compared.

II. EXPERIMENTAL METHOD

The data for this experiment were acquired simultaneously with those for a measurement of the polarization parameter in small-angle proton-proton elastic scattering,[4] which utilized the same spectrometer configuration and trigger logic. The 6-GeV/c transversely-polarized proton beam[5] from the ZGS entered a 50-cm liquid-hydrogen target upstream of the Argonne Effective Mass Spectrometer (EMS).[6,7] Forward-scattered charged particles traversed the spectrometer, in which their angles and momenta were measured with magnetostrictive-readout wire spark chambers. In order to minimize systematic errors in the measured left-right asymmetries, the (vertical) beam polarization was reversed approximately every two hours, and data were taken with both directions of the field in the spectrometer magnet.

The trigger for the data reported here required one or more counts in a large scintillation-counter hodoscope downstream of the spectrometer magnet, and no count in a beam-veto counter just downstream of the hodoscope. This extremely loose trigger condition was necessary to provide an unbiased sample for the study of inclusive reactions, but it was also satisfied by some beam-halo particles and by interactions occurring outside the hydrogen target. Although such unwanted events were completely eliminated by cuts in the off-line analysis, their presence saturated the trigger and limited the number of inclusive events which could be accumulated.

A second trigger used, in addition to the hodoscope and beam-veto requirements, a recoil-proton signal from one of two scintillation counters placed on either side of the hydrogen target. This trigger provided a relatively rich source of forward elastic scatters ($-t \gtrsim 0.04$ GeV^2). The measured left-right asymmetry and the known polarization parameter[8] were used to obtain the incident-beam polarization, integrated over the course of the experiment. This gave an average beam polarization[9] of 0.50 ± 0.04, where the uncertainty is mainly due to the absolute normalization of Ref. 8.

The reconstructed events were subjected to a number of cuts to eliminate interactions originating outside the hydrogen target, beam-halo particles, and tracks which suffered secondary interactions or decays. In each event, a satisfactory χ^2 for the fit to the measured trajectory through the spectrometer was required for at least one positive track, along with an acceptable vertex position within the volume of the hydrogen target. Events consisting of single tracks with zero scattering angle and a momentum equal to that of the incident beam were also rejected.

Since the apparatus did not provide secondary-particle in identification, the highest-momentum positive track was taken to be the proton for each event. (The measured[10] π^+/p ratio at 6 GeV/c and $p_T^2 < 0.4$ GeV^2 is less than 0.1 for $p_\parallel \gtrsim 3.5$ GeV/c, corresponding to $M_X \lesssim 2.2$ GeV.) The missing mass M_X and transverse momentum p_T were then calculated using the measured momentum and angle of the proton, and the left-right scattering asymmetry was found for the events in each bin of M_X and p_T^2.

The left-right asymmetry A was calculated by comparing scatters from "up" and "down" beam polarization using the relation

$$AP_B = \frac{K}{2}\,\frac{L_\uparrow R_\downarrow - L_\downarrow R_\uparrow}{L_\uparrow R_\downarrow + L_\downarrow R_\uparrow}(1+\epsilon), \tag{3}$$

where P_B is the beam polarization, K is a constant determined by the range of azimuthal angles accepted, and $\epsilon = P_B^2 A^2$ is negligible in this experiment. The number of left (right) scatters observed for beam polarization up (down) is denoted by $L_\uparrow$ ($R_\downarrow$). This expression is appropriate[11] even for the case of unequal solid angles for left and right scatters and for unequal beam fluxes for the polarization-up and polarization-down data-taking. It does require that the effective solid angles be independent of beam polarization and that the same amount of beam be available for left and right scatters, conditions which are met automatically in our experiment. In the absence of systematic errors, Eq. (3) gives the same results as the more usual $(L-R)/(L+R)$ method which is, however, subject to systematic errors from apparatus asymmetries and beam-flux determinations. For our experiment an azimuthal-angle cut of $|\cos\phi| \geq 0.55$ was imposed, where ϕ is the angle between the scattering-plane normal and the beam spin direction. This leads to a value of $K=1.183$ in Eq. (3).

III. RESULTS

Figure 2 shows a typical missing-mass distribution for our data. The significance of resonance peaks above background is somewhat degraded by the poorer resolution of this experiment relative to the best published cross-section experiments, for example, at 1.5 GeV, $\sigma(M_X) \approx 34$ MeV for this experiment compared to $\sigma(M_X) \approx 14$ MeV for Edelstein *et al.*[1] When smeared by our resolution, the missing-mass spectra of Ref. 1 are very similar

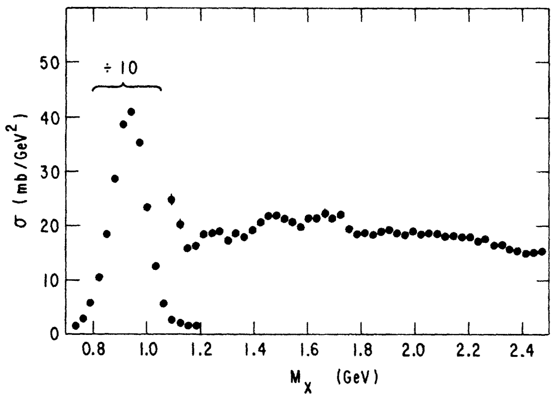

FIG. 2. Invariant cross section $\sigma=[(s^2-4sM_p{}^2)^{1/2}/\pi] \times(d^2\sigma/dtdM_X{}^2)$ for $p_\uparrow p \rightarrow pX$ at 6 GeV/c and $0.03 \leq p_T{}^2 \leq 0.24$ GeV^2. The points in the elastic-scattering peak have been divided by 10; the four points on the high side of the peak have been plotted both with and without this scale factor.

in shape to those which we observe. Although the purpose of the experiment was to measure spin dependence and not absolute cross sections, we note that the differential cross section for elastic scattering derived from these data agrees well with previous measurements.[7] Our inclusive cross sec-

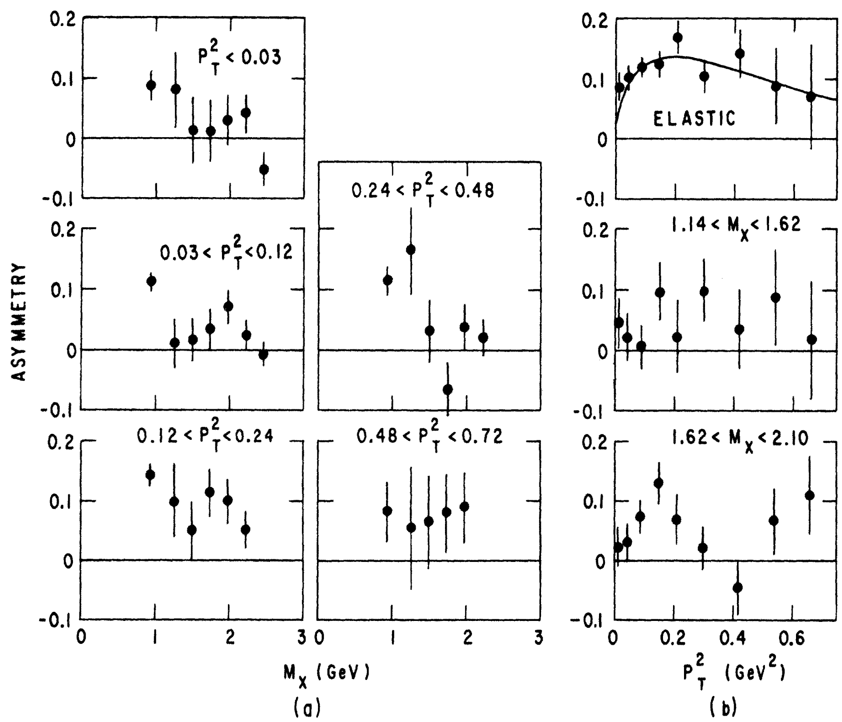

FIG. 3. Measured left-right asymmetry A of fast forward protons in $p_\uparrow p \rightarrow pX$ (a) as a function of M_X (240-MeV-wide bins) in the $p_T{}^2$ ranges given (in GeV^2), (b) as a function of $p_T{}^2$ in the M_X ranges given (in GeV). The curve through the elastic data is from Ref. 4.

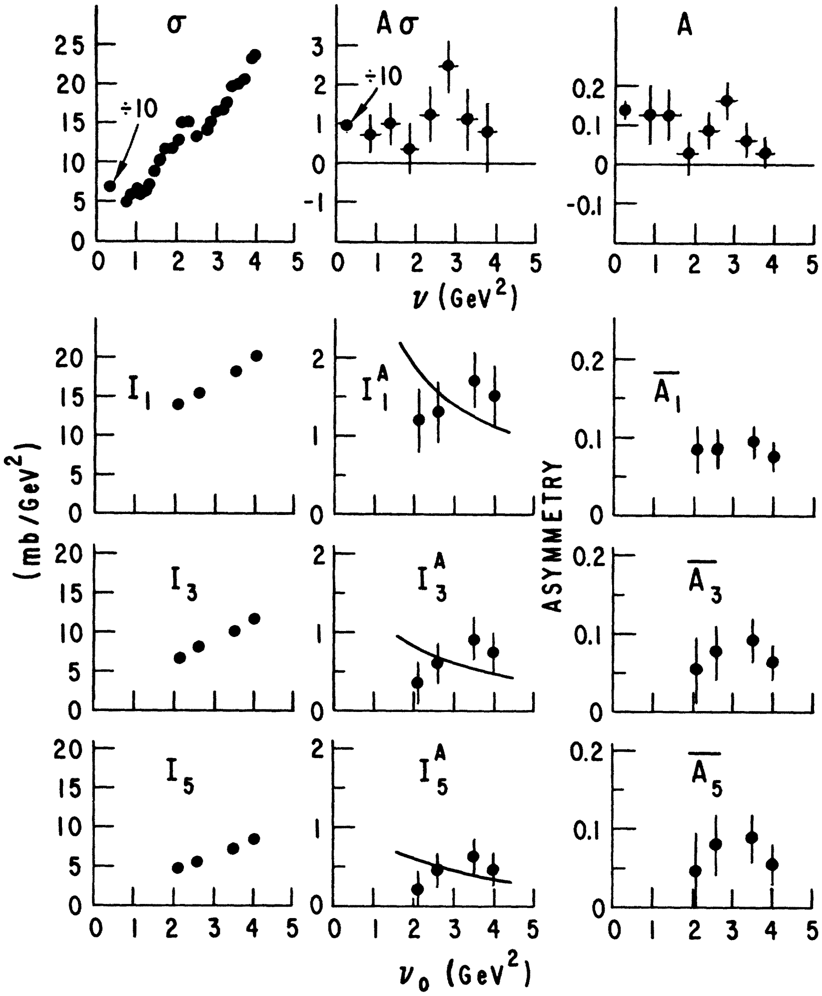

FIG. 4. FMSR integrands and integrals for $0.18 \leq -t \leq 0.36$ GeV^2, as functions of the dispersing-variable cutoff $\nu_0 = M_X^2$ (max) $- 0.61$ GeV^2. σ, $A\sigma$, I_n, and I_n^A are in units of mb/GeV^2. The curves on the I_n^A graphs show the $A\sigma \propto \nu^{-0.7}$ dependence expected for a triple-Regge *PRR* term at $-t = 0.3$ GeV^2. The elastic-scattering data have been divided by 10 and plotted as a single point in the cross-section plots.

tions agree within 10% with those measured by Edelstein *et al.*,[1] consistent within the absolute-normalization uncertainties of the two experiments.

Figure 3 shows the left-right asymmetry from our our data as a function of p_T^2 and M_X. The inclusive asymmetry has the same sign as in pp elastic scattering but is generally smaller in magnitude. Averaged[12] over the range $M_X \leq 2.1$ GeV, $p_T^2 \leq 0.72$ GeV^2, the inelastic asymmetry $A = 0.047 \pm 0.010$, giving a ratio of the inelastic to elastic asymmetries of 0.41 ± 0.09 for $p_T^2 \leq 0.72$ GeV^2.

Figure 4 shows the invariant cross section σ, the product $A\sigma$, and the FMSR integrals[3]

$$I_n = \frac{1}{\nu_0^{n+1}} \int_0^{\nu_0} \nu^n \sigma(s,t,\nu)\, d\nu, \tag{4}$$

$$I_n^A = \frac{1}{\nu_0^{n+1}} \int_0^{\nu_0} \nu^n A(s,t,\nu)\sigma(s,t,\nu)\, d\nu, \tag{5}$$

evaluated from our data for various values of the dispersing-variable cutoff, ν_0. Here $n = 1, 3, 5$ (higher values of n weight larger M_X^2 data more heavily),

$$\sigma(s,t,\nu) = \frac{(s^2 - 4sM_p^2)^{1/2}}{\pi} \frac{d^2\sigma}{dt\,dM_X^2}$$

is the invariant cross section, and $A(s,t,\nu)$ is the left-right asymmetry from Eq. (3). Notice that the FMSR relations require use of the variable t instead of the more convenient p_T^2 used in Figs. 2 and 3. The asymmetry A and quotient $\bar{A}_n = I_n^A / I_n$ are also shown in Fig. 4; the latter gives a measure of the averaged asymmetries with the effect of the absolute cross sections divided out. The upper end of the M_X^2 range chosen sets the lower end of the t range through the $t_{\min}$ value; for the integrals shown in Fig. 4, the range $0.18 \le -t \le 0.36$ GeV^2 allows data only for $M_X^2 \le 4.6$ GeV^2. The integrals were evaluated using M_X^2 bins of width 0.12 GeV^2, except for the elastic-scattering bin, which included all data below $M_X^2 = 1.26$ GeV^2 as the $M_X^2 = M_p^2$ point.

To check that the integrals were not overly influenced by the elastic contribution, they were also calculated with the elastic data omitted; I_n and I_n^A decreased by less than 25% for $n=1$, and were essentially unaffected for $n=3$ and 5.

The graphs in Fig. 4 show an approximately linear increase of both I_n and I_n^A with ν_0, directly mirroring the behavior of the raw cross sections and asymmetries before integration. The unpolarized cross sections do not resemble the triple-Pomeron expectation $\sigma \propto \nu^{-1}$, with $ijk = PPP$ in Eq. (2). Although this disagreement may arise because M_X^2/s is too large for Eq. (2) to apply, it can be qualitatively understood in terms of two effects. First, pion exchange is certainly important at 6 GeV/c and gives a $\pi\pi P$ contribution[13] with the dependence $\sigma \propto \nu^1$; the relations given in Ref. 2 indicate that pion exchange could account for as much as half of the small-t cross section. Second, slow protons from the decays of forward-produced N^*'s and Δ's tend to populate regions of high M_X^2.

The asymmetries given by the I_n^A integrals of Fig. 4 are compatible with the $A\sigma \propto \nu^{1/2}$ dependence predicted[13] by Eq. (2) for π-B interference ($ijk = \pi B\omega$). The behavior of the integrals is somewhat inconsistent with the $A\sigma \propto \nu^{-0.7}$ dependence (shown in Fig. 4) expected from Pomeron-Reggeon interference at $t = -0.3$ GeV^2 with $ijk = PRR$ (e.g., $P\rho\rho$ or PA_2A_2). The effect of decay protons from forward-produced N^*'s is much harder to predict for the asymmetries than for the cross sections, however.

In conclusion, we have presented new data on inclusive polarization effects in $p_{\uparrow} p \to pX$. The observed asymmetries are generally similar to those in pp elastic scattering except that they are about half as large. The inclusive cross sections, as interpolated by finite-mass sum rules, do not conform to the asymptotic expectation $\sigma \propto \nu^{-1}$, but this can be understood qualitatively in terms of pion exchange and N^*-decay effects. The inclusive asymmetry does not agree well with the triple-Regge behavior expected from Pomeron-Reggeon interference, which accounts for elastic-scattering asymmetries.

ACKNOWLEDGMENTS

We gratefully acknowledge several useful discussions with R. D. Field concerning the interpretation of our results. We thank T. A. Romanowski and R. Winston for their support and encouragement in the course of this work, and are indebted to R. Ely, L. Filips, E. Hayes, C. Klindworth, R. Rivetna, and E. Walschon for their technical help. The spectrometer was designed and constructed in collaboration with A. F. Greene and D. D. Yovanovitch. Finally, we thank the many people of the Argonne Accelerator Research Facilities Division who provided the polarized beam which made this experiment possible.

---

*Work supported in part by the U.S. Energy Research and Development Administration and by the National Science Foundation.

†Visitor at Argonne National Laboratory from Portland State University, Portland, Oregon. Present address: Space Physics and Astronomy, Rice University, Houston, Texas 77001.

‡Present address: Stanford Linear Accelerator Center, P.O. Box 4349, Stanford, California 94305.

§Present address: Zettler Software Co., Columbus, Ohio 43215.

‖Present address: Department of Physics, Elmhurst College, Elmhurst, Illionois 60126.

[1]R. M. Edelstein *et al.*, Phys. Rev. D 5, 1073 (1972).

[2]R. D. Field and G. C. Fox, Nucl. Phys. B80, 367 (1974).

[3]R. D. Field, in Proceedings of the Summer Study on High Energy Physics with Polarized Beams, Argonne National Laboratory Report No. ANL/HEP 75-02, 1975 (unpublished).

[4]D. R. Rust *et al.*, Phys. Lett. 58B, 114 (1975).

[5]E. F. Parker *et al.*, Phys. Rev. Lett. 31, 783 (1973); T. Khoe *et al.*, Part. Accel. 6, 213 (1975).

[6]D. S. Ayres, in *Proceedings of the International Conference on Instrumentation for High Energy Physics, Frascati, Italy*, 1973, edited by S. Stipcich (Laboratori Nazionali del Comitato Nazionale per l'Energia Nucleare, Frascati, Italy, 1973), p. 665.

[7]I. Ambats *et al.*, Phys. Rev. D 9, 1179 (1974).

[8]M. Borghini *et al.*, Phys. Lett. 31B, 405 (1970).

[9]The data for this experiment are a subset of those used in Ref. 4, and thus the average beam polarizations are slightly different for the two data samples.

[10]K. Ruddick, Minnesota-Rice-Argonne collaboration, private communication.

[11]The asymmetry defined in Eq. (3) is similar to the "geometric mean" discussed by G. G. Ohlsen and P. W.

Keaton, Jr., Nucl. Instrum. Methods 109, 41 (1973).

[12]The average asymmetry was obtained from Eq. (3) using the inelastic events in the single wide M_X-p_T^2 bin indicated. This is equivalent to an average of the narrow-bin results, weighted by the cross section.

[13]The Regge trajectories used to obtain the triple-Regge predictions for ν dependence from Eq. (2) are $\alpha(P) = 1$, $\alpha(R) = \alpha(\omega) = 0.5 + t$, and $\alpha(\pi) = \alpha(B) = 0$.