STRUCTURE OF HIGH-ENERGY, LARGE-MOMENTUM-TRANSFER COLLISION PROCESSES*

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It was first argued by Wu and Yang[1] in 1965 that there should be a qualitative connection between high-energy ($s \gg m_N^2$), large-momentum-transfer ($-t \gg m_N^2$), proton-proton scattering (or more generally hadron-hadron scattering) and the structure of the proton as revealed in elastic electron-proton scattering at large momentum transfers. We would like to pursue this idea with a suggestion of an origin for this connection and a remark about how it will exhibit itself in the differential cross section for p-p elastic scattering. We also present some implications of our suggestions for future experiments.

Our starting point is Fig. 1 which shows the normalized differential cross section for p-p elastic scattering,[2]

$$X(s,t) \equiv \frac{d\sigma/dt}{(d\sigma/dt)_{t=0}}$$

plotted together with the fourth power of $G_{Mp}(t)$, the magnetic form factor measured in e-p scattering,[3] normalized to $G_{Mp}(0)=1$. Earlier attempts to correlate the p-p scattering data at large s and $-t$ with $G_{Mp}^4(t)$ have proceeded by searching for a suitable universal function which would represent all the p-p data. These efforts have yielded forms such as

$$\frac{d\sigma}{d\Omega}_{cm} \sim \exp(-ap_\perp)$$

(due to Orear[4]),

$$\frac{d\sigma}{d\Omega}_{cm} \sim e^{-as\,\sin\theta}$$

(Allaby et al.[2]), and

$$\frac{d\sigma}{dt} \sim \exp(-a\beta_\perp^{\,2}p_\perp^{\,2})$$

(Krisch[5]). It is not very transparent, however, how to map these proposed data fits alongside the form factor $G_{Mp}(t)$, since they depend on special kinematical constructs of energy and angle that differ from the invariant momentum transfer t. In particular, the form proposed by Allaby et al. vanishes as $s\to\infty$ for fixed t.

We would like to suggest here the following correlation and interpretation of these data: In the amplitude for p-p scattering there is a piece, the "diffractive tail," which dies precipitously for fixed t as s grows and, in addition, a point interaction of current-current form[6] which depends on t alone and emerges as s becomes asymptotic. The differential cross section then appears as

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{t=0} [aG_{Mp}^{\,2}(t) + R(s,t)]^2,$$

where a is independent of s and t and $R(s,t)$ vanishes as $s\to\infty$ for large, fixed $-t$.

For concreteness we have chosen for $R(s,t)$

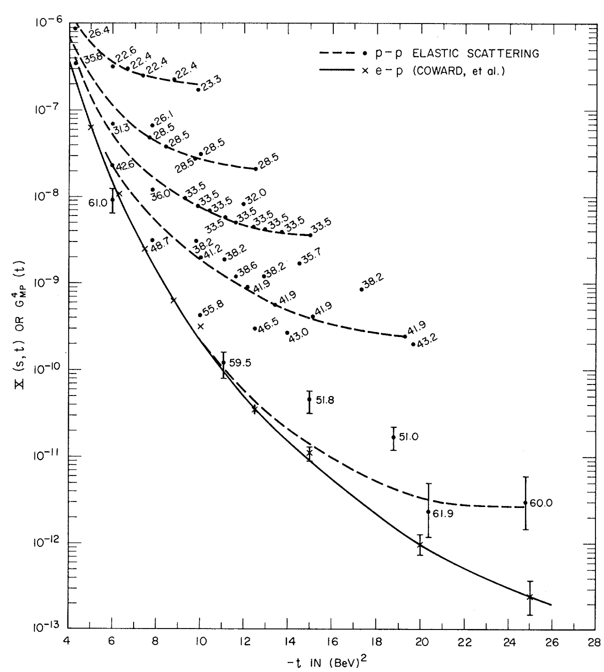

FIG 1. The normalized differential cross section

$$X(s,t) = \frac{d\sigma/dt}{(d\sigma/dt)_{t=0}}$$

for p-p scattering and the fourth power of $G_{Mp}(t)/G_{Mp}(0)$ plotted against t. The experimental points are labeled by the corresponding value of s, the square of the c.m. energy, and are taken from Ref. 2. Equal-s contours are shown by dashed lines.

the canonical "Regge form,"

$$R(s,t)=\beta(t)\frac{(1+e^{-i\pi\alpha(t)})}{\sin\pi\alpha(t)}s^{\alpha(t)-1}$$

although our ideas are weakly coupled to any special model for R. In a Reggeized world, of course, $\alpha(t)$ refers here to the usual vacuum trajectory. The experimental basis for choosing such an $R(s,t)$ is the observed dramatic drop in $X(s,t)$ by a factor of $\gtrsim 2$ for each 20% increase in s in the range 20-60 BeV^2. It is tempting to propose that $s^{\alpha(t)}$ accurately describes the approach to the high-energy limit. Not only is this in accord with the data shown in Fig. 1 and more transparently by the straight line segments of Fig. 2 whose slopes measure $\alpha(t)$ at the labeled values of t, but it is also theoretically appealing. If one particular Regge trajectory has a slightly smaller slope than all others, then by the time we move out to large values of both s and $-t$ it will dominate the others and a simplified parametrization of the elastic-scattering amplitude such as proposed for $R(s,t)$ is a natural consequence. The small slope for the Pomeranchuk or vacuum trajectory, compared with other known trajectories,[7] which is suggested by p-p and π-p data at small t, is in agreement with this behavior. We repeat, however, that our main point of comparison between the e-p and p-p scattering is not rigidly tied to a specific Regge model. More broadly stated, as $s\to\infty$, $R(s,t)$, which may be interpreted as the decreasing tail of the diffractive or unitarity contribution from the inelastic channels, falls below the postulated s-independent contact term revealing the $G_{Mp}{}^4(t)$ structure.

How might such a contact interaction originate? Consider the reaction nucleon (p_1) + nucleon $(p_2)\to$ nucleon (p_1') + nucleon (p_2') in the region where $s\gg -t\gg m_N{}^2$. Writing out the T matrix in terms of the Fermi invariants, we find that the pseudoscalar and scalar contributions are of order t/s or $m_N{}^2/s$ compared with V, A, and T. If we imagine that in this kinematic region, where all masses are negligible, the scattering occurs with no flip of the nucleon helicities, the amplitude becomes to order t/s

$$T_{NN}=F_V\bar{u}(p_2')\gamma_\alpha u(p_2)\bar{u}(p_1')\gamma_\alpha u(p_1)$$
$$+F_A\bar{u}(p_2')\gamma_\alpha\gamma_5 u(p_2)\bar{u}(p_1')\gamma_\alpha\gamma_5 u(p_1).$$

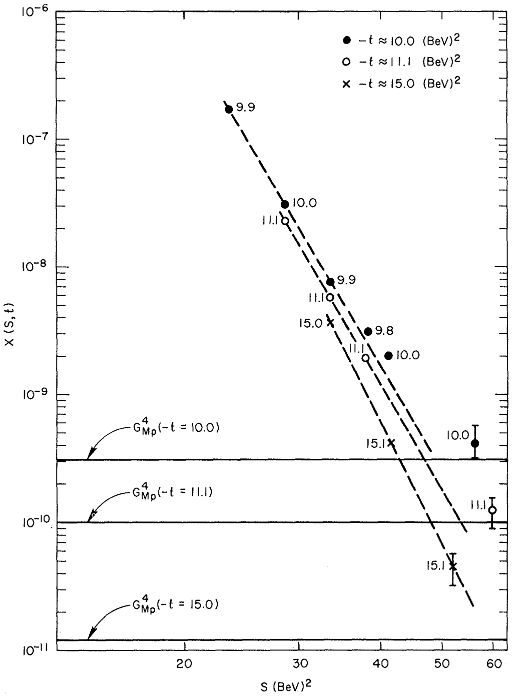

FIG 2. The normalized differential cross section $X(s,t)$ for p-p scattering and the fourth power of $G_{Mp}(t)/G_{Mp}(0)$ plotted against s for $-t=10.0$, 11.1, and 15.0 BeV^2. If $X(s,t)$ were purely of the form $\beta(t)s^{\alpha(t)}$, the plotted points for given $-t$ would lie on the straight lines. The deviations from these lines we attribute to the emergence of the form factor term.

This resembles one vector density probing another plus an axial density interacting with another. We propose to take this resemblance seriously and suggest that the proper statement of the "contact interaction" which is exhibited in the p-p data is that for $s\gg -t\gg m_N{}^2$, F_V and F_A become proportional to the squares of the vector and axial-vector form factors one measures in the weak[8] and electromagnetic interactions.[9] The contact terms enter $d\sigma/dt$ as

$$|F_V|^2+|F_A|^2+4\,\mathrm{Re}(F_V{}^*F_A)t/s.$$

If, further, the vector and axial-vector form factors become similar for large t, or if the contact interaction cannot distinguish between right-handed and left-handed protons so that the contact interaction is purely of the vector type and $F_A=0$, then the structure $a^2G_{Mp}{}^4(t)$ for $X(s,t)$ emerges.

Our picture of the large-s, large-t proton-proton scattering is now drawn. The differential cross section is written[10]

$$\frac{d\sigma}{dt}=\left(\frac{d\sigma}{dt}\right)_{t=0}\left[a^2G_{Mp}^{\;4}(t)+\gamma(t)\left(\frac{s}{s_0}\right)^{2[\alpha(t)-1]}+\text{interference terms}\right].$$

The magnitude of the interference terms depends on the relative phases of the contact terms and $R(s,t)$, given by the signature factor in the Regge case, as well as on the spin structure of the diffractive contributions.[11] We need only consider the interference terms in the limited range of s and t where $R(s,t)$ and $G_{Mp}(t)$ are of comparable magnitude, and in our preliminary fits we have ignored them. Turning our attention again to the data we find that it is possible to fit the conjectured approach of the p-p scattering data to $G_{Mp}(t)$ with the following representative set of parameters:

$$\alpha(t)=1+\alpha'(0)t+\tfrac{1}{2}\alpha''(0)t^2,\quad \alpha'(0)=0.5\pm0.1,$$

$$\alpha''(0)=+0.02\pm0.005,\ \text{and}\ a\approx0.85\pm0.15.$$

The small value of $\alpha'(0)$ is consistent with our earlier remarks. Within the uncertainties permitted by the unknown interference term, more complicated guesses are possible for these parameters.

There is an appealing simplicity to the idea that, in hadron processes, under a "diffractive tail" there should emerge a contact interaction of a current-current nature with the same currents whose transition form factors are being measured in weak and electromagnetic processes. Let us proceed by supposing that this is, in fact, what we are being told by the existing p-p data and ask where we might seek critical tests and verification of this behavior as well as where we expect corrections to it.

(1) In higher energy p-p experiments[12] (such as will be performed soon at Serpukhov and before long at CERN and Weston) we expect $d\sigma_{p\text{-}p}/dt$ to follow the $G_{Mp}^{\;4}(t)$ curve out to higher values of $-t$ before departing from it near, say, $-t\approx\frac{1}{4}s$. This makes it important to reduce the size of the present experimental errors on the e-p data at large $-t$ as well as on the corresponding p-p data at the highest values of s presently attainable. Larger-s data can rapidly confirm or shoot down the whole idea since we enjoy a welcome dearth of parameters.

(2) In the region where t and s are of the same order of magnitude, we expect contributions in p-p scattering from possible interference terms if both F_A and F_V are present, u-channel current-current interactions, and other t- and u-channel processes which are negligible in the kinematic limit we considered. Similarly, for small t, we do not attempt to use our form for $d\sigma/dt$ since the contact term is buried under a manifold of diffractive phenomena.[10]

(3) If the Regge structure for $R(s,t)$ is correct, then the absence of polarization correlations in the region where $R(s,t)$ dominates $aG_{Mp}^{\;2}(t)$ is expected. Another consequence of our assumption that one trajectory dominates $R(s,t)$ is that the s dependence for fixed t is completely determined up to corrections from the interference terms, and thus a larger number of accurate data points checking this behavior would be of great importance. In particular, experimental evidence confirming or destroying the straight lines in Fig. 2 would be very interesting at high s and $-t$ values.

(4) The structure of $\bar{p}$-p elastic scattering should be the same as for p-p scattering in the $s\gg -t\gg m_N^2$ kinematic limit, up to those correction terms of order t/s that are of opposite sign in the two collisions. Processes such as $\bar{p}+p\rightarrow\bar{n}+n$, $\bar{p}+p\rightarrow\bar{\Sigma}+\Sigma$, etc., are very important for determining the isotopic and unitary spin structure of the currents in the proposed contact interaction.

(5) In inelastic processes such an $N+N\rightarrow N+N^*$ we expect to see emerge, in the same limit, the product of the nucleon vector (or axial-vector) form factor times the appropriate NN^* transition form factor. If it is indeed the vacuum trajectory that is dominating the unitarity tail at large s and t, as we have earlier suggested, the form-factor term should emerge at lower energies since the vacuum trajectory will not contribute to the N^* excitation.

(6) For $\pi^{\pm}p$ elastic scattering and for πN charge exchange, we expect in the given kinematic region that $d\sigma/dt$ will take the form

$$d\sigma_{\pi N}/dt=[a'F_{\pi}(t)G_M^{\;V}(t)+R'(s,t)]^2,$$

where a' is independent of s and t, $F_{\pi}(t)$ is the pion electromagnetic form factor, and $G_M^{\;V}(t)$, the isovector nucleon magnetic form factor. The absence of the vacuum trajectory in πN charge exchange means that the contact interaction should show up more quickly than in p-p or $\pi^{\pm}$-p scattering, analogously to the case above for N^* production.

We thank the members of the electron-scattering group at Stanford Linear Accelerator Center (see Ref. 3) for discussions of their data before publication.

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[1]T. T. Wu and C. N. Yang, Phys. Rev. 137, B708 (1965). A discussion of how such a connection might arise in the quark model has been given by J. J. J. Kokkedee and L. Van Hove, Nuovo Cimento 42A, 711 (1966); L. Van Hove, in Lectures at 1966 Scottish Universities Summer School in Physics, edited by T. Preist and L. Vick (Oliver and Boyd Publishers, London, England, 1967). See also H. Schopper, CERN Report No. CERN 67-3, 1967 (unpublished).

[2]G. Cocconi et al., Phys. Rev. 138, B165 (1965); J. V. Allaby et al., Phys. Letters 23, 389 (1966); J. V. Allaby et al., Phys. Letters 25B, 156 (1967).

[3]D. H. Coward et al., Phys. Rev. Letters 20, 292 (1968) (this issue).

[4]J. Orear, Phys. Letters 13, 190 (1964).

[5]A. D. Krisch, Phys. Rev. Letters 19, 1149 (1967).

[6]An especially inspirational passage on this idea has been given by R. P. Feynman, in Proceedings of the Thirteenth International Conference on High Energy Physics, Berkeley, 1966 (University of California Press, Berkeley, California, 1967), p. 98.

[7]The data of A. M. Boyarski et al., Phys. Rev. Letters 20, 300 (1967) (this issue), strongly indicate that one may be a bit hasty in including the pion among "other known trajectories."

[8]At this point the isotopic and unitary spin properties of the current in the contact interaction are not specified beyond saying that its diagonal matrix element in the proton state exists.

[9]Specifically we mean the form factors $F_1(t)$ and $g_A(t)$ which are the coefficients of γ_α and $\gamma_\alpha\gamma_5$, respectively. If the scaling law $G_{Ep}(t)=G_{Mp}(t)/G_{Mp}(0)$ holds, as assumed by Coward et al., Ref. 3, then $F_{1p}(t)$ becomes proportional to $G_{Mp}(t)$ for large t.

[10]With $a=1$ our conjectured form for $d\sigma/dt$ if applicable at $t=0$, which we specifically do not propose, leads to equal real and imaginary amplitudes in conflict with experiment. Among the many arguments against applying our considerations elsewhere than in the region of large s and $-t$ is the observation that iterations of the contact interaction at small t lead to increasing contributions from higher order terms containing at least logs.

[11]For the Regge model one may consult D. H. Sharp and W. G. Wagner, Phys. Rev. 131, 2227 (1963).

[12]The observation that the 30-BeV p-p data already reveal the asymptotic behavior of the optical model for large s has been made earlier by Serber in analyzing the t dependence of the data in Ref. 2. See R. Serber, Rev. Mod. Phys. 36, 649 (1964).

ZERO-DEGREE PRODUCTION OF HIGH-MOMENTUM π^+ MESONS BY π^- MESONS INCIDENT ON NUCLEI*

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We have studied π^+ production at 0° by 2- to 6-BeV/c π^- incident on beryllium, carbon, copper, lead, and polyethylene. The experiment was done in the 17° negative pion beam at the zero-gradient synchrotron (ZGS) at Argonne National Laboratory.

The experimental setup is shown in Fig. 1. The arrangement consists of a two-stage beam spectrometer followed by a detection system. The first section of the spectrometer uses the fringe field of the ZGS followed by a system of two quadrupoles and a bending magnet. A momentum slit is placed at the focus of this first section. The second section is a symmetric system consisting of four quadrupoles and a bending magnet. Our target material was placed just after the momentum slit, a choice dictated by the physical arrangement of the

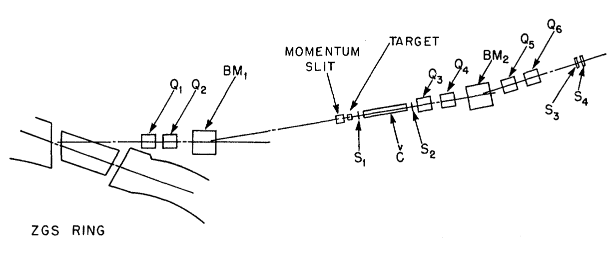

FIG. 1. The ZGS 17° beam. The π^- of the desired momentum were focused on the momentum slit by quadrupoles Q_1 and Q_2 and bending magnet BM_1. Q_3, Q_4, BM_2, Q_5, and Q_6 were tuned to select π^+ of given momenta from the target.