namely, that $g_0 \to 0$ when $\epsilon \to 0$.

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[1]G. B. West, Los Alamos Scientific Laboratory Report No. LA-UR-79-1690 (to be published), and in the Erice Lectures on Physics of Excited Atoms, 25 March–5 April, 1979, Erice, Italy; for an update and general review, see G. B. West, Los Alamos Scientific Laboratory Report No. LA-UR-80-913 (to be published), and invited talk, in "Orbis Scientiae, Recent Developments in High Energy Physics," January 1980, Coral Gables, Florida (Plenum, New York, to be published), Vol. 17.

[2]J. C. Collins, Nucl. Phys. B149, 90 (1979).

[3]S. J. Brodsky, G. F. de Téramond, and I. A. Schmidt, Phys. Rev. Lett. 44, 557 (1980).

[4]See the review of A. Zee, Phys. Rep. 3C, 129 (1972); Some of the previous work that should be mentioned includes: J. M. Cornwall and R. E. Norton, Phys. Rev. 173, 1637 (1968); D. G. Boulware and S. Deser, Phys. Rev. 175, 1912 (1968); R. Jackiw, R. van Royen, and G. B. West, Phys. Rev. D 2, 2473 (1970); J. Gunion, Phys. Rev. D 8, 517 (1973); J. Gasser and H. Leutwyler, Nucl. Phys. B94, 269 (1975).

[5]S. Weinberg, Phys. Rev. Lett. 29, 388 (1972).

[6]For a good review of this technique, see the Les Houches lectures of D. J. Gross, in *Statistical Theory of Turbulence*, edited by R. Balian (North-Holland, Amsterdam, 1976).

Spin Dependence of High-$p_\perp$ Elastic Nucleon-Nucleon Scattering: Evidence for Quark Interchange?

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High-$p_\perp$ elastic NN scattering is analyzed in terms of two quark-interchange amplitudes, which conserve and depend on quark helicities. Resulting relations between spin observables are compared with polarization data. Predictions are made for np scattering at $p_L = 12$ GeV/c, and for pp scattering at higher momenta, where the rise of A_{NN}^{pp} ($\theta_{\text{c.m.}} = 90°$) changes into a turn over. A sharp transition marks the onset of hard scattering.

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The use of a polarized target and beam in elastic nucleon-nucleon scattering experiments at laboratory momenta p_L up to 12 GeV/c has led to unexpected results. The spin-correlation parameter A_{NN}^{pp} for doubly polarized pp scattering rises sharply[1] from about 0.1 to 0.6, when $p_\perp^2$ (transverse momentum squared) increases from 3.6 to 5.1 (GeV/c)^2. For np scattering at $p_L = 6$ GeV/c, $p_\perp = 1$ GeV/c it was found[2] that A_{NN}^{np} is negative, about -0.2, while at the same momenta $A_{NN}^{pp} = 0.06$. No spin-spin data are available at higher momenta for np scattering. Most recently[3] new results for pp scattering have become available for p_L up to 12.75 GeV/c and $p_\perp^2$ up to 5.56 (GeV/c).[2] These indicate a leveling off in the behavior of A_{NN}^{pp} for $p_\perp^2$ larger than 5 (GeV/c)^2. Negative values of this parameter have not been found.[2] Experimental features of pp scattering suggest that the $\theta_{\text{c.m.}} = 90°$ scattering mechanism undergoes a drastic change[1,3] at about $p_\perp^2 = 3.6$ (GeV/c)^2, where it appears that constituent scattering starts being dominant. Accordingly a hard-scattering region may be defined, which begins at that transverse momentum.

It is the purpose of this note to point out that salient features in the hard-scattering region are understandable in a quark-interchange model (QIM), if corresponding amplitudes have the properties which may be expected from backward quark-quark scattering via one-gluon exchange. At the momentum transfers ($\hat{u}$) involved here the strength of the quark-gluon coupling is not well known, and the mentioned scattering mechanism cannot be rejected on the basis of the argument[4] that the resulting interchange amplitude(s) would be too small by about two orders of magnitude. All consequences for observables to be discussed will be independent of amplitude normalization. They depend crucially on other properties of interchange amplitudes implied by the mechanism indicated. These properties are (I) independence of quark flavor, (II) absence of transitions in which interchanging quarks flip their helicity, (III) dependence on whether interchanging quarks carry equal or opposite helicities, and (IV) positivity of the interchange amplitudes modulo an overall phase. Simultaneous implementation of properties (I)–(IV) has been lacking so far.

The $pp \to pp$ and $np \to np$ s-channel helicity amplitudes are computed by projecting the possible quark-interchange amplitudes on appropriate nucleon wave functions, keeping track of properties (I)–(IV). The basic diagram, indicated in Fig. 1(a), suggests that use be made of quark-diquark wave functions.[5] The noninterchanging quarks conserve their net helicity and net isospin. As far as these quantum numbers are concerned, one deals with spectator diquarks,[6] or perhaps more complicated "cores"[7] containing partons, but carrying the same quantum numbers. Quark counting is then simplified compared to the techniques employed in the original proposal of QIM[8] or in Ref. 4, and different interchange amplitudes can be dealt with more conveniently. Moreover, analysis of the spin dependence which is based on the quark-parton model[9] can then be compared with a limiting case of the present analysis. The following expressions are obtained for the helicity amplitudes[10]:

Proton-proton scattering,

$$\varphi_1 = 2\alpha s_1,$$
$$\varphi_3 = (\alpha - \beta)(s_1 + a_1) + \beta(s_4 - s_4), \qquad (1)$$
$$\varphi_4 = -(\alpha - \beta)(s_1 - a_1) - \beta(s_4 + a_4);$$

neutron-proton scattering,

$$\varphi_1 = \alpha s_1 + (\alpha - 2\beta)a_1,$$
$$\varphi_3 = (\alpha - \beta + \epsilon)(s_1 + a_1) + (\beta + \epsilon)(s_4 - a_4), \qquad (2)$$
$$\varphi_4 = \epsilon(s_1 - a_1 + s_4 + a_4).$$

Coefficients are defined by

$$2\alpha = (1 - \tfrac{8}{9}\gamma)^2 + \tfrac{8}{27}\gamma^2,$$
$$2\beta = (1 - \tfrac{10}{9}\gamma)^2 + \tfrac{4}{81}\gamma^2, \qquad (3)$$
$$2\epsilon = \tfrac{4}{9}\gamma(1 - \tfrac{10}{9}\gamma),$$
$$\gamma = \sin^2\Gamma.$$

Symmetric and antisymmetric parts of interchange amplitudes[8] have been denoted by s_i and a_i, respectively. For $i = 1$ (4) the initial quark helicities are equal (opposite).[11] The parameter γ is a measure for the SU(6)-symmetry breaking in the nucleon wave function.[5] All amplitudes contained in Eqs. (1) and (2) correspond to c.m. scattering angle $\theta_{\text{c.m.}}$. If one lets $s_1 = s_4$, $a_1 = a_4$, and $\gamma = \frac{1}{2}$, the original QIM amplitudes[8] are reproduced.

Restrictions for observables implied by Eqs. (1) and (2) are considered next. Observables are well-known bilinear forms in the φ_i's,[8] which have been used.

(a) For pp as well as np scattering and independently of $\theta_{\text{c.m.}}$ and γ one should have, as in original QIM, $d\sigma_{\uparrow\uparrow} = d\sigma_{\downarrow\downarrow}$ for parallel spins normal to the scattering plane ($\varphi_5 = 0$); $P = A_{SL} = 0$ ($\varphi_5 = 0$); $A_{NN} = -A_{SS}$ ($\varphi_2 = \varphi_5 = 0$).

(b) For pp scattering at $\theta_{\text{c.m.}} = 90°$, the requirement[10] $\varphi_3 = -\varphi_4$ holds, and correspondingly $A_{NN}^{pp} - A_{LL}^{pp} - A_{SS}^{pp} = 1$, which is model independent. For the spin-spin asymmetry in the normal direction (N) at this scattering angle ($\theta_{\text{c.m.}} = 90°$) the special forms in Eq. (1) lead to

$$r_{NN}^{pp} \frac{1 + A_{NN}^{pp}}{1 - A_{NN}^{pp}} = 1 + \left|1 - \frac{\beta}{\alpha}(1 - \bar{s}_4)\right|^2, \qquad (4)$$

where the reduced amplitude is defined as $\bar{s}_4 = s_4/s_1$. Hence the nontrivial bound is predicted to hold:

$$A_{NN}^{pp} \geq 0 \quad (r_{NN}^{pp} \geq 1). \qquad (5)$$

This bound should not only be satisfied at $\theta_{\text{c.m.}}$

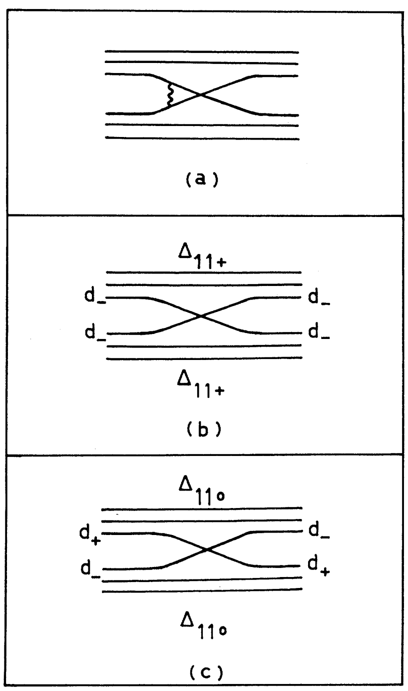

FIG. 1. Quark line diagrams for elastic nucleonic scattering via one-gluon exchange in the $\hat{u}$ channel, corresponding to (a) quark interchange, and some of the contributions to the pp amplitudes (b) φ_1 and (c) φ_4. $\Delta_{i,i_z,\lambda}$ denotes a core with isospin quantum numbers i and i_z, and helicity λ.

$=90°$ but also at different angles since the antisymmetric parts a_i of interchange amplitudes are expected to be relatively small.[4,8] It is no longer required in QIM that A_{NN}^{pp} is fixed at the value $\frac{1}{3}$.

(c) Considering $\bar{s}_4$ as unknown, its dependence on A_{NN}^{pp} and γ may be considered as due to Eq. (4) and property (IV). Figure 2 shows this function for some values of A_{NN}^{pp}. Dashed parts of curves correspond to $\bar{s}_4<0$ and are ignored. The large spin effect[1] in pp scattering can be accounted for by a moderate increase of $\bar{s}_4$ up to values of about 2. Such values are considered to be plausible.

(d) The spin-correlation parameters for np scattering at $\theta_{\text{c.m.}}=90°$ can be discussed on the basis of Eq. (2), or

$$A_{NN}^{np}=-1+2r_{NN}^{pp}/d, \quad A_{LL}^{np}=1-4/d, \qquad (6)$$
$$d=1+r_{NN}^{pp}+|1-(\beta/\alpha)(1-\bar{s}_4)+(2\epsilon/\alpha)(1+\bar{s}_4)|^2.$$

(e) For the spin-averaged differential cross sections at $\theta_{\text{c.m.}}=90°$, one finds

$$\sigma^{pp}=\alpha^2|s_1|^2(1+r_{NN}^{pp}), \quad \sigma^{np}=\tfrac{1}{4}\alpha^2|s_1|^2 d. \qquad (7)$$

After combining Eqs. (4), (6), and (7), two sum

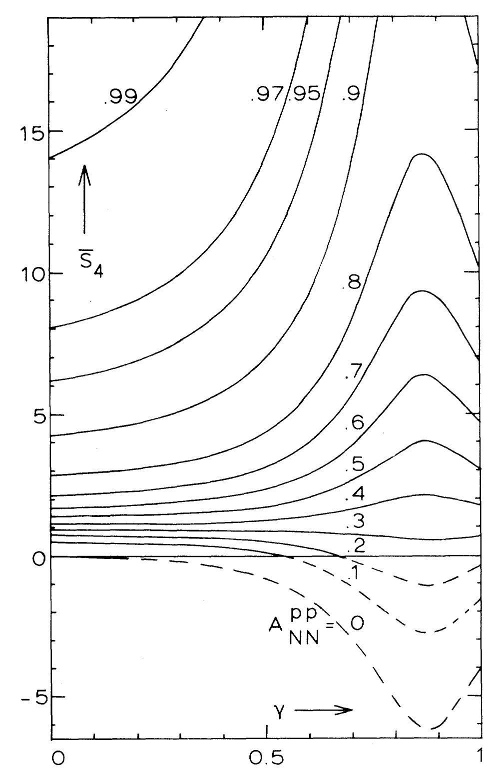

FIG. 2. Solutions for the reduced amplitude $\bar{s}_4$ plotted as functions of γ for the A_{NN}^{pp} values indicated.

rules follow:

$$4\sigma^{np}(1+A_{NN}^{np})=\sigma^{pp}(1+A_{NN}^{pp}),$$
$$2\sigma^{np}(1-A_{LL}^{np})=\sigma^{pp}(1-A_{NN}^{pp}). \qquad (8)$$

These hold independently of $\bar{s}_4$ and γ.

(f) From the sum rules (8) and identities mentioned in points (a) and (b) all spin-correlation parameters $A_{ii}(\theta_{\text{c.m.}}=90°)$ are seen to be determined once A_{NN}^{pp} and the ratio $r_\sigma=\sigma^{np}/\sigma^{pp}$ are known at a given momentum. For example, at $p_L=12$ GeV/c it follows that A_{NN}^{np} must be negative, at a value of about -0.2, if $A_{NN}^{pp}=0.6$ and $r_\sigma=0.5$[12] are used as input. A more detailed analysis, taking into account experimental accuracy, yields the predictions $A_{NN}^{np}=-0.22\pm0.22$ and $A_{LL}^{np}=0.57\pm0.22$ at this momentum. Moreover it is then found that $\gamma=0.2\pm0.2$. The very different behavior of A_{NN}^{pp} and A_{NN}^{np} is to be noted: When p_L increases from 6 to 12 GeV/c, the last-mentioned correlation parameter will not change drastically in contrast with A_{NN}^{pp}. The prediction of negative A_{NN}^{np} values is a typical one, valid at all momenta where the proposed quark-interchange mechanism applies. If this is the case down to the limit $\gamma=0$, one should find $A_{NN}^{np}=0$ in this limit. This may apply at momenta p_L much larger than 12 GeV/c, and is in agreement with parton-model expectations.[9]

(g) The definite predictions obtained above remain to be verified experimentally to a major part. The strongest support of this approach comes perhaps from the bound (5), and the plausible $\bar{s}_4$ value found in point (c), while the results of point (f) seem reasonable.[2] In view of the lack of np data for $p_\perp^2\geq3.6$ (GeV/c)^2 these results and the sum rule (8) cannot be used at present to carry out conclusive tests. It is a fortunate circumstance that pp data alone are sufficient to perform one more test. This test is based on the relation (7) for pp scattering. The p_L dependence of the quantity $\alpha^{-2}|s_1|^{-2}\sigma^{pp}$ and the $p_\perp$ dependence of A_{NN}^{pp} are directly related in this approach. With $s=4(p_\perp^2+m_p^2)$ and the dimensional counting rule[7] in order to fix the s dependence of $|s_1|^{-2}\sim s^{10}$, it follows that fluctuations[7] of $s^{10}\sigma^{pp}$ in the hard-scattering region are simply reflections of the structure occurring in $A_{NN}^{pp}(p_\perp^2)$. As a test, data for $s^{10}\sigma^{pp}(\theta_{\text{c.m.}}=90°)$, which are available for p_L values up to 21 GeV/c at least,[7] have been plotted versus $p_\perp^2$ in Fig. 3, which also contains the A_{NN}^{pp} data of Ref. 1 and the new point of Ref. 3 at the highest momentum reached for doubly polarized scattering.[13] The first-mentioned set

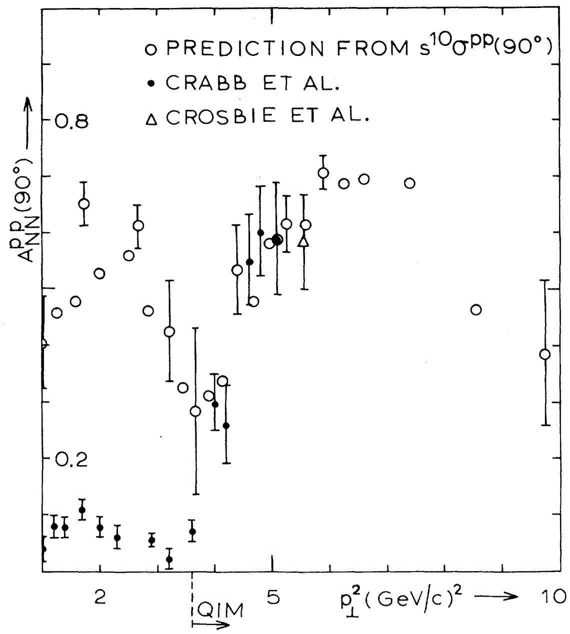

FIG. 3. Data for $s^{10}\sigma^{pp}$ and A_{NN}^{pp} plotted vs $p_\perp{}^2$, using Eq. (7) of text. The point at 5.1 (GeV/c)^2 has been taken to normalize the first-mentioned set of data to the second set.

of data has been transformed by use of Eq. (7), keeping α fixed.

Figure 3 reveals some striking features. First of all the sharp rise[1] of A_{NN}^{pp} is indeed contained in the (transformed) cross-section data, including the leveling off at about $p_\perp{}^2 = 5.5$ (GeV/c)^2. Furthermore a turn over is predicted for A_{NN}^{pp} at higher transverse momenta. This could mean that the parton-model prediction[9] $A_{NN}^{pp}(\theta_{\text{c.m.}} = 90°) \approx \frac{1}{9}$ is feasible at momenta p_L above 30 GeV/c. On the other hand, at transverse momenta below the hard-scattering region large discrepancies are observed, showing that here the validity of Eq. (7) completely breaks down. The value $p_\perp{}^2 = 3.6$ (GeV/c)^2 seems to mark a sharp transition from soft to hard scattering. This confirms an earlier mentioned indication.[1] The onset of hard scattering should shed light on the confinement problem. This problem has been brought into connection with a phase transition, which may occur in Z_3 gauge theories with triality confinement.[14] The spin effect may thus have a special significance. Further experimental consolidation of the approach presented above would help in clarifying this matter. Neat possibilities for carrying out experimental tests have been indicated. It is noted that Eq. (7) is not obtained in hard-scattering models with quark helicity flip.

In conclusion, it is proposed that the large spin effect in pp scattering almost trivially reflects an analogous effect, which takes place at the quark level, in terms of helicity-dependent quark interchange. This is qualitatively in agreement with lowest-order quantum chromodynamics.

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[1]D. G. Crabb *et al.*, Phys. Rev. Lett. 41, 1257 (1978).
[2]D. G. Crabb *et al.*, Phys. Rev. Lett. 43, 983 (1979).
[3]E. A. Crosbie *et al.*, University of Michigan Report No. UM-HE-80-2, March 1980 (to be published).
[4]S. Brodsky *et al.*, Phys. Rev. D 20, 2278 (1979).
[5]J. Carroll *et al.*, Phys. Rev. 174, 1681 (1968).
[6]J. C. Kluyver *et al.*, Nucl. Phys. B140, 141 (1978); J. C. Kluyver, Z. Phys. C 2, 351 (1979).
[7]D. Sivers *et al.*, Phys. Rep. 23, 1 (1976).
[8]G. Farrar *et al.*, Phys. Rev. D 20, 202 (1979).
[9]C. K. Chen, Phys. Rev. Lett. 41, 1440 (1978); K. Hidaka *et al.*, Phys. Rev. D 19, 1503 (1979).
[10]The notation and convention for NN amplitudes φ_i ($i = 1, \dots, 5$) are the same as used in Ref. 8, and in M. Goldberger *et al.*, Phys. Rev. 120, 2250 (1960).
[11]Two independent interchange amplitudes exist because of properties (I)–(IV) and with the condition that these obey the same symmetry relations with respect to space inversion and time reversal as the φ_i's. The last statement does not hold with respect to the Pauli principle.
[12]J. Stone *et al.*, Phys. Rev. Lett. 38, 1315 (1979).
[13]Most of the analysis described in the text has been performed prior to the circulation of Ref. 3.
[14]G. 't Hooft, Nucl. Phys. B138, 1 (1978), and B153, 141 (1979); A. M. Polyakov, Phys. Lett. 72B, 477 (1978).