Spin Correlations, QCD Color Transparency, and Heavy-Quark Thresholds in Proton-Proton Scattering

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The strikingly large spin-spin correlation A_{NN} observed in pp elastic scattering at $p_{\text{lab}}=2.5$ and 11.75 GeV/c and the unexpected energy dependence of absorptive corrections to quasielastic proton-proton scattering in a nuclear target can be interpreted in terms of two $J=L=S=1$, $B=2$ resonance structures associated with the strange- and charmed-particle production thresholds, interfering with a perturbative QCD background. The results provide support for the "color-transparency" phenomenon predicted in perturbative QCD away from resonances or heavy-quark thresholds.

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One of the most serious challenges to quantum chromodynamics is the behavior of the spin-spin correlation asymmetry

$$A_{NN}=\frac{d\sigma(\uparrow\uparrow)-d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow)+d\sigma(\uparrow\downarrow)}$$

measured in large-momentum-transfer pp elastic scattering.[1] At $p_{\text{lab}}=11.75$ GeV/c and $\theta_{\text{c.m.}}=\pi/2$, A_{NN} rises to $\simeq 60\%$, corresponding to 4 times more probability for protons to scatter with their incident spins both normal to the scattering plane and parallel, rather than normal and opposite. Moreover, the data show a striking energy and angular dependence not expected from the slowly changing perturbative QCD predictions.[2] The onset of this apparently new phenomenon[3] at $s\simeq 23$ GeV^2 appears to signal new degrees of freedom or exotic components in the two-baryon system. In this Letter we propose an explanation of (1) the observed spin correlation, (2) the deviations from fixed-angle scaling laws, and (3) the anomalous energy dependence of absorptive corrections to quasielastic pp scattering in nuclear targets,[4] in terms of a simple model based on two $J=L=S=1$ broad resonances (or threshold enhancements) interfering with a perturbative QCD quark-interchange background amplitude. The structures in the $pp\to pp$ amplitude may be associated with the onset of strange and charmed thresholds. If this view is correct, large-angle pp elastic scattering would have been virtually featureless for $p_{\text{lab}}\gtrsim 5$ GeV/c, had it not been for the onset of heavy-flavor production. As a further illustration of the threshold effect, we also show the effect in A_{NN} due to a narrow $^3F_3$ pp resonance at $\sqrt{s}=2.17$ GeV ($p_{\text{lab}}=1.26$ GeV/c) associated with the $p\Delta$ threshold.

The perturbative QCD analysis[5] of exclusive amplitudes assumes that large-momentum-transfer exclusive scattering reactions are controlled by short-distance quark-gluon subprocesses, and that corrections from quark masses and intrinsic transverse momenta can be ignored. The main predictions are fixed-angle scaling laws[6] (with small corrections due to evolution of the distribution amplitudes, the running coupling constant, and pinch singularities), hadron-helicity conservation,[7] and a novel phenomenon described below called "color transparency."[8] The power-law scaling quark-counting predictions for form factors, two-body elastic hadron-hadron scattering,[9] and exclusive two-photon reactions[10] are generally consistent with experiment at transverse momenta beyond a few gigaelectronvolts. In leading order in $1/p_T$, only the lowest-particle-number "valence" Fock-state wave function with all the quarks within an impact distance $b_\perp\lesssim 1/p_T$ contributes to the high-momentum-transfer scattering amplitude in QCD. Such a Fock-state component has a small color dipole moment and thus interacts only weakly with hadronic or nuclear matter.[8] This minimally interacting proton configuration can retain its small size as it propagates in the nucleus over a distance which grows with energy. Thus, unlike traditional Glauber theory, QCD predicts that large-momentum-transfer quasielastic reactions occurring in a nucleus suffer minimal initial- and final-state attenuation; i.e., one expects a volume rather than surface dependence in the nuclear number. This is the QCD "color-transparency" prediction.

A test of color transparency in large-momentum-transfer quasielastic pp scattering at $\theta_{\text{c.m.}}\simeq\pi/2$ has recently been carried out with use of several nuclear targets (C, Al, Pb).[4] The attenuation at $p_{\text{lab}}=10$ GeV/c in the various nuclear targets was observed to be, in fact, approximately half of that predicted by traditional Glauber theory. This appears to support the color-transparency prediction. However, at $p_{\text{lab}}=12$ GeV/c, normal attenuation was observed, in contradiction to the expectation from perturbative QCD that the transparency effect should become even more apparent! Our observation is that one can explain this surprising result if the scattering at $p_{\text{lab}}=12$ GeV/c ($\sqrt{s}=4.93$ GeV) is dominated by an s-channel $B=2$ resonance (or resonancelike structure) with mass near 5 GeV, since unlike a hard-scattering reaction, a resonance couples to the fully interacting large-scale structure of the proton. If the resonance has spin $S=1$, this can also explain the large spin correlation A_{NN} measured nearly at the same momentum, $p_{\text{lab}}=11.75$ GeV/c. Conversely, in the momentum range $p_{\text{lab}}=5$ to 10 GeV/c we predict that the perturbative hard-scattering amplitude is dominant at large angles. The experimental observation of diminished attenuation at $p_{\text{lab}}=10$ GeV/c thus provides support for the QCD description of exclusive reactions and color transparency.

There are several possible sources for resonance structure at $\sqrt{s}=5$ GeV, more than 3 GeV beyond the pp threshold: (a) a multigluonic excitation such as $|qqqqqqggg\rangle$, (b) a "hidden-color" color-singlet $|qqqqqq\rangle$ excitation, or (c) a "hidden-flavor" $|qqqqqqQ\bar{Q}\rangle$ excitation, which is the most interesting possibility, since it is so predictive. As in QED, where final-state interactions give large enhancement factors for attractive channels in which $Z\alpha/v_{\text{rel}}$ is large, one expects resonances or threshold enhancements in QCD in color-singlet channels at heavy-quark production thresholds since all the produced quarks have similar velocities.[11] One thus can expect resonant behavior at $M^*=2.55$ GeV and $M^*=5.08$ GeV, corresponding to the threshold values for open strangeness, $pp\to\Lambda K^+p$, and open charm, $pp\to\Lambda_c D^0 p$, respectively. In any case, the structure at 5 GeV is highly inelastic: We find that its branching ratio to the proton-proton channel is $B^{pp}\simeq 1.5\%$.

We now proceed to a description of the model. We have purposely attempted not to overcomplicate the phenomenology; in particular, we have used the simplest Breit-Wigner parametrization of the resonances, and we have not attempted to optimize the parameters of the model to obtain a best fit. It is possible that what we identify as a single resonance is actually a cluster of resonances, or a threshold enhancement.

The background component of the model is the perturbative QCD (PQCD) amplitude. Although complete calculations are not yet available, many features of the QCD predictions are understood, including the approximate s^{-4} scaling of the $pp\to pp$ amplitude at fixed $\theta_{\text{c.m.}}$ and the dominance of those amplitudes that conserve hadron helicity.[7] Furthermore, recent data[9] comparing different exclusive two-body scattering channels show that quark-interchange amplitudes[12] dominate quark-annihilation or gluon-exchange contributions. With the assumption of the usual symmetries, there are five independent pp helicity amplitudes: $\phi_1=M(++,++)$, $\phi_2=M(--,++)$, $\phi_3=M(+-,+-)$, $\phi_4=M(-+,+-)$, $\phi_5=M(++,+-)$. The helicity amplitudes for quark interchange have a definite relationship.[2] For definiteness, we will assume the following form:

$$\phi_1^{\text{PQCD}}=2\phi_3^{\text{PQCD}}=-2\phi_4^{\text{PQCD}}=4\pi CF(t)F(u)[(t-m_d^2)/(u-m_d^2)+(u\leftrightarrow t)]e^{i\delta}.$$

The hadron helicity-nonconserving amplitudes, ϕ_2^{PQCD} and ϕ_5^{PQCD}, are zero. This form is consistent with the nominal power-law dependence predicted by perturbative QCD[5] and also gives a good representation of the angular distribution over a broad range of energies.[13] Here $F(t)$ is the helicity-conserving proton form factor, which, for simplicity, we take as the standard dipole form, $F(t)=(1-t/m_d^2)^{-2}$, with $m_d^2=0.71$ GeV^2. As shown in Ref. 2, the PQCD quark-interchange structure alone predicts $A_{NN}\simeq\frac{1}{3}$, nearly independent of energy and angle.

Because of the rapid fixed-angle s^{-4} falloff of the perturbative QCD amplitude, even a very weakly coupled resonance can have a sizable effect at large momentum transfer. The large empirical values for A_{NN} suggest a resonant $pp\to pp$ amplitude with $J=L=S=1$ since this gives $A_{NN}=1$ (in absence of background) and a smooth angular distribution. Because of the Pauli principle, an $S=1$ diproton resonance must have odd parity and thus odd orbital angular momentum. We parametrize the two nonzero helicity amplitudes for a $J=L=S=1$ resonance in Breit-Wigner form:

$$\phi_3^{\text{res}}=12\pi\frac{\sqrt{s}}{p_{\text{c.m.}}}d_{1,1}^{1}(\theta_{\text{c.m.}})\frac{(1/2)\Gamma^{pp}(s)}{M^*-E_{\text{c.m.}}-\frac{1}{2}i\Gamma},$$

$$\phi_4=-\phi_3(\cos\theta\to-\cos\theta).$$

(The $^3F_3$ resonance amplitudes have the same form with $d_{\pm1,1}^{3}$ replacing $d_{\pm1,1}^{1}$.) As in the case of a narrow resonance like the Z^0, we expect that the partial width into nucleon pairs is proportional to the square of the timelike proton form factor:

$$\Gamma^{pp}(s)/\Gamma=B^{pp}|F(s)|^2/|F(M^{*2})|^2,$$

corresponding to the formation of two protons at this invariant energy. The resonant amplitudes then die away by one inverse power of $E_{\text{c.m.}}-M^*$ relative to the dominant PQCD amplitudes. (In this sense, they are higher-twist contributions relative to the leading-twist perturbative QCD amplitudes.) The model is thus very simple: Each pp helicity amplitude ϕ_i is the coherent sum of PQCD plus resonance components: $\phi=\phi^{\text{PQCD}}+\sum\phi^{\text{res}}$. Because of pinch singularities and higher-order corrections, the hard QCD amplitudes are expected to have a nontrivial phase[14]; we have thus allowed for a constant phase δ in ϕ^{PQCD}. Because of the absence of the ϕ_5 helicity-flip amplitude, the model predicts zero single-spin asymmetry A_N. This is consistent with the large-angle data at $p_{\text{lab}}=11.75$ GeV/c.[15]

At low transverse momentum, $p_T\le 1.5$ GeV, the power-law falloff of ϕ^{PQCD} in s disagrees with the more slowly falling large-angle data, and we have little guidance from basic theory. Our interest in this low-energy region is to illustrate the effects of resonances and threshold effects on A_{NN}. In order to keep the model tractable, we have simply extended the background quark interchange and the resonance amplitudes at low energies using the same forms as above but replacing the dipole form factor by a phenomenological form $F(t) \propto e^{-(1/2)\beta\sqrt{|t|}}$. We have also included a kinematic factor of $\sqrt{s}/2p_{\text{c.m.}}$ in the background amplitude. The value $\beta = 0.85\ \text{GeV}^{-1}$ then gives a good fit to $d\sigma/dt$ at $\theta_{\text{c.m.}} = \pi/2$ for $p_{\text{lab}} \leq 5.5$ GeV/c.[16] The normalizations are chosen to maintain continuity of the amplitudes.

The predictions of the model and comparison with experiment are shown in Figs. 1 and 2. The following parameters are chosen: $C = 2.9\times10^3$, $\delta = -1$ for the normalization and phase of ϕ^{PQCD}. The masses, widths, and pp branching ratios for the three resonances are $M_d^* = 2.17$ GeV, $\Gamma_d = 0.04$ GeV, $B_d^{pp} = 1$; $M_s^* = 2.55$ GeV, $\Gamma_s = 1.6$ GeV, $B_s^{pp} = 0.65$; and $M_c^* = 5.08$ GeV, $\Gamma_c = 1.0$ GeV, $B_c^{pp} = 0.0155$. As shown in Fig. 1, the deviations from fixed-angle scaling are readily accounted for by the resonance structures. The angular distribution is predicted to be broader relative to the steeper perturbative QCD form. This is consistent with experiment when we compare data at $p_{\text{lab}} = 7.1$ and 12.1 GeV/c.

The most striking test of the model is its prediction for the spin correlation A_{NN} shown in Fig. 2(a). The rise of A_{NN} to $\simeq 60\%$ at $p_{\text{lab}} = 11.75$ GeV/c is correctly reproduced by the high-energy $J=1$ resonance intefering with ϕ^{PQCD}. The narrow peak which appears in the data of Fig. 2(a) corresponds to the onset of the $pp \to p\Delta$ (1232) channel which can be interpreted as a $uuuddq\bar{q}$ resonant state. Because of spin-color statistics, one expects in this case a higher orbital momentum state, such as a pp $^3F_3$ resonance. The model is also consistent with the recent high-energy datum point for A_{NN} at $p_{\text{lab}} = 18.5$ GeV/c and $p_T^2 = 4.7\ \text{GeV}^2$ [see Fig. 2(b)]. The data show a dramatic decrease of A_{NN} to zero or negative values. This is explained in our model by the destructive interference effects above the resonance region. The same effect accounts for the depression of A_{NN} for $p_{\text{lab}} \approx 6$ GeV/c shown in Fig. 2(a). The comparison of the angular dependence of A_{NN} with data at $p_{\text{lab}} = 11.75$ GeV/c is shown in Fig. 2(c). The agreement with the data[17] for the longitudinal spin correlation A_{LL} at the same p_{lab} is somewhat worse.

Our goal in this paper has not been a global fit to all the pp elastic scattering data, but rather to show that many features can be naturally explained with only a few ingredients: a perturbative QCD background plus resonant amplitudes associated with rapid changes of the inelastic pp cross section. The model provides a good description of the s and t dependence of the differential cross section, including its "oscillatory" dependence[18] in s at fixed $\theta_{\text{c.m.}}$, and the broadening of the angular distri-

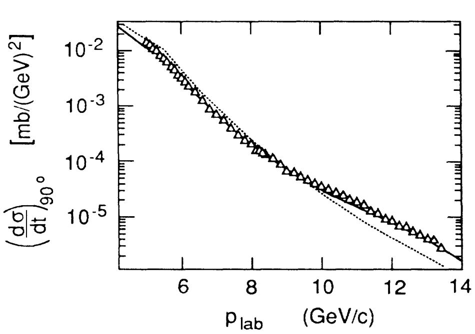

FIG. 1. Prediction (solid curve) for $d\sigma/dt$ compared with the data of Akerlof *et al.* (Ref. 16). The dotted line is the background PQCD prediction.

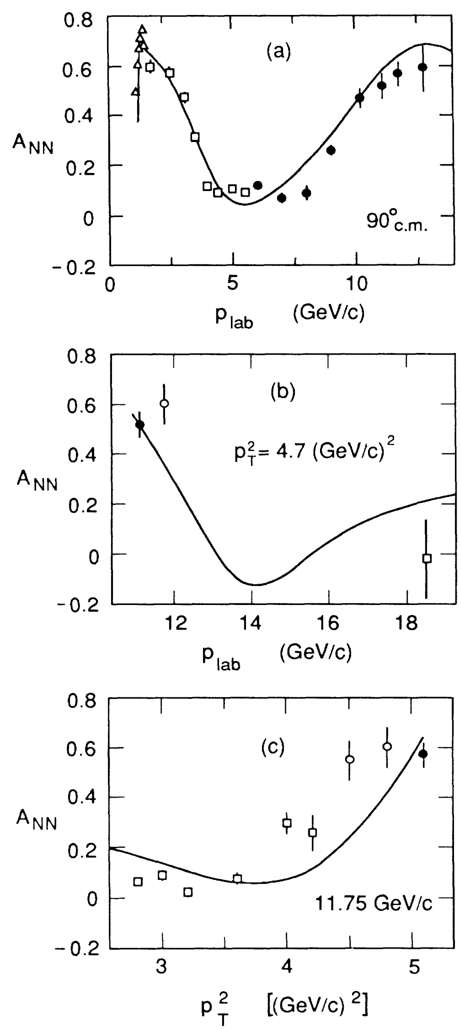

FIG. 2. (a) A_{NN} as a function of p_{lab} at $\theta_{\text{c.m.}} = \pi/2$. The data (Ref. 1) are from Crosbie *et al.* (solid dots), Lin *et al.* (open squares), and Bhatia *et al.* (open triangles). The peak at $p_{\text{lab}} = 1.26$ GeV/c corresponds to the $p\Delta$ threshold. The value of A_{NN} from PQCD alone is $\frac{1}{3}$. (b) A_{NN} at fixed $p_T^2 = 4.7$ (GeV/c)^2. The data point (Ref. 1) at $p_{\text{lab}} = 18.5$ GeV/c is from Court *et al.* (c) A_{NN} as a function of transverse momentum. The data (Ref. 1) are from Crabb *et al.* (open circles) and O'Fallon *et al.* (open squares). Diffractive contributions should be included for $p_T^2 < 3\ \text{GeV}^2$.

bution near the resonances. Most important, it gives a consistent explanation for the striking behavior of both the spin-spin correlations and the anomalous energy dependence of the attenuation of quasielastic pp scattering in nuclei. We predict that the color transparency should reappear at higher energies ($p_{\rm lab} \gtrsim 16$ GeV/c), and also at smaller angles ($\theta_{\rm c.m.} \approx 60°$) at $p_{\rm lab}=12$ GeV/c where the perturbative QCD amplitude dominates. If the $J=1$ resonance structures in A_{NN} are indeed associated with heavy-quark degrees of freedom, then the model predicts inelastic pp cross sections of the order of 1 mb and 1 μb for the production of strange and charmed hadrons near their respective thresholds.[19] Thus a crucial test of the heavy-quark hypothesis for explaining A_{NN}, rather than hidden-color or gluonic excitations, is the observation of significant charm-hadron production at $p_{\rm lab} \gtrsim 12$ GeV/c. Other elastic reactions such as $\pi p \rightarrow \pi p$ should also display structures at the corresponding heavy-quark thresholds.

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