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EXCLUSIVE PROCESSES IN QCD AND SPIN–SPIN CORRELATIONS*

GUY F. DE TÉRAMOND

Stanford Linear Accelerator Center,
Stanford University, Stanford, California 94309, USA

and

Escuela de Fisica, Universidad de Costa Rica,
San José, Costa Rica†

ABSTRACT

The unexpected spin behavior observed in hard proton-proton collisions is described in terms of new degrees of freedom associated with the onset of strange and charmed thresholds. The deviation from dimensional scaling laws, the anomalous broadening of angular distributions, and the unusual energy dependence of *pp* quasielastic scattering in nuclear targets are also consistent with the onset of highly inelastic contributions to elastic *pp* amplitudes interfering with a perturbative QCD background. The model predicts significant charm production above 12 GeV/c and a relaxation of the spin correlation parameters to their scaling values at higher energies.

INTRODUCTION

The recent measurement of the longitudinal muon-proton spin asymmetry by the EMC collaboration[1] would suggest that most of the proton spin is not carried by the light quarks. This surprising result is not incompatible, however, with our current view of hard proton-proton exclusive reactions where the spin information is carried by valence quarks. A deep inelastic process measures the spin dependent quark and gluon structure functions, where all the components of the proton wave function are present. On the other hand, in an exclusive process, a collection of parallel quarks suffers a hard scattering and is deflected through a large angle. In doing an exclusive measurement a particular state is selected, in the sense of the quantum theory of measurement, and only the valence quarks participate in the hard collision.

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† Permanent address.

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Using the language of QCD, the light-cone proton wave function is expanded in a Fock-state basis with an infinite number of components $\langle qqq|P\rangle$, $\langle qqqg|P\rangle$, $\langle qqqq\bar{q}|P\rangle, \ldots$ In a high-momentum transfer exclusive reaction only the lowest order particle number, the valence state, contributes to leading order. This simple result has immediate consequences. If the kinematic invariants s and t are large compared to any masses or intrinsic scales in the problem, the only length scale is $1/\sqrt{s}$ (the proton has fluctuated to a region of small transverse dimension) and the differential cross section obeys the dimensional scaling law[2]

$$\frac{d\sigma}{dt} \sim \frac{1}{s^{n-2}} \quad ,$$

where n is the total minimum number of elementary fields of the initial and final states. In a theory with underlying scale-invariant interactions (excluding pinch singularities), the binding of the structureless constituents does not modify the power-law scaling predictions, and the wave function determines the absolute normalization. Fixed-angle scaling laws are thus a fundamental consequence of the scaling properties of QCD, and constitute a remarkable test of QCD ideas as applied to exclusive processes at high energies.[3]

The spin-spin correlation parameter A_{NN} measured in large-angle proton-proton collisions at high energy[4] exhibit a structure as a function of large s and p_T^2. This behavior defies a simple explanation based on the scale-invariant nature of the fundamental constituent interactions. As a result, numerous theoretical models have been proposed in an attempt to explain this striking behavior. I have chosen to classify the various models into three categories, according to their predictions for the large-angle behavior of A_{NN} above 12 GeV/c (where the spin effects have not been measured yet).[5] They are the following:

I Models where A_{NN} grows to large values,[6]

II Oscillatory models,[7]

III Models where A_{NN} relaxes to the PQCD predictions.[8]

In the first type I have included models with strong quark correlations, massive quark models, diquark models or models which incorporate other large-distance effects.[6] The oscillation of the pp elastic scattering data about the s^{-10} power law has been inspirational for type II models, where an oscillatory behavior of A_{NN} is also expected.[7] As an example, in the model of Pire and Ralston, one would expect coherent effects in the pp system to arise from the imaginary part of the double log Sudakov corrections. In the third category, I include models such as the present one, based on perturbative QCD (PQCD) which incorporate the onset of new effects due to the opening of a heavy quark threshold at 12 GeV/c. Available data suggest a strong correlation of the spin behavior with other anomalous pp data at 12 GeV/c. The new effect, characteristic of threshold phenomena, would die away at higher energies, the system relaxing to its

PQCD behavior. A complete QCD calculation has never been done, however, the Constituent Interchange Model (CIM),[9] gives a form which is believed to be representative of the full calculation. The CIM–inspired PQCD model gives $A_{NN} = 1/3$ and

$$\left(\frac{d\sigma}{dt}\right)_{\rm PQCD} \sim \frac{F^2(t)F^2(u)}{sp^2}$$

where $F(t)$ is the helicity-conserving proton form factor.

If we examine the pp elastic data at 90°, factoring out the CIM–PQCD differential cross section $(d\sigma/dt)_{\rm PQCD}$ (which behaves as s^{-10} at very large s), we find a strict correlation with the A_{NN} data as shown in Fig. 1: a very rapid increase in the total cross section in the 8–12 GeV/c region which tails off at higher energies. This behavior is reminiscent of a threshold effect due to the introduction of new degrees of freedom. The pp elastic angular distribution exhibits the same trend: a rapid anomalous broadening which is maximum at 12 GeV/c. This effect also dies away at higher energies. If we take seriously the correlation of anomalous A_{NN} with pp elastic data, this is not encouraging news for the type I models. Finally, the "color-transparency" effect,[10] recently discovered at BNL by measuring the energy dependence of absorptive corrections to quasielastic pp scattering in various nuclear targets, exhibits an anomalous behavior with respect to the QCD predictions. Since in large-angle exclusive processes only the valence Fock state is important, all the quarks are within an impact distance $1/\sqrt{|t|}$. It is expected that such a small proton configuration remains small for some time as it propogates within the nucleus before and after the hard scattering, resulting in reduced attenuation in the nuclear medium. At 12 GeV/c, however, the QCD transparency disappears and normal attenuation is observed.

The above considerations led Stan Brodsky and myself to propose a simple model based on the opening of new degrees of freedom in the s-channel, associated with charmed hadroproduction, which accounts for the observed structure in the pp system.[8] It has been pointed out[11] that the Landshoff–Sudakov interference mechanism could explain the transparency effects. At higher energies the model based on Landshoff pinch singularity diagrams predicts that the transparency should oscillate with a geometrically increasing period.[11] It has not been demonstrated, however, that this model could explain the large spin effects observed in A_{NN}.

The observed anomalous structure can be explained if the pp system has a resonance response near $p_{\rm lab} = 12$ GeV/c. What is the physical origin of a resonance structure at $\sqrt{s} = 5$ GeV? This energy value corresponds to the $c\bar{c}$ threshold where the light quarks would slow down to match the $c\bar{c}$ pair pulled out of the sea, and move with the same velocity. One can expect a resonance or threshold enhancement, since the system has a large time scale to interact.

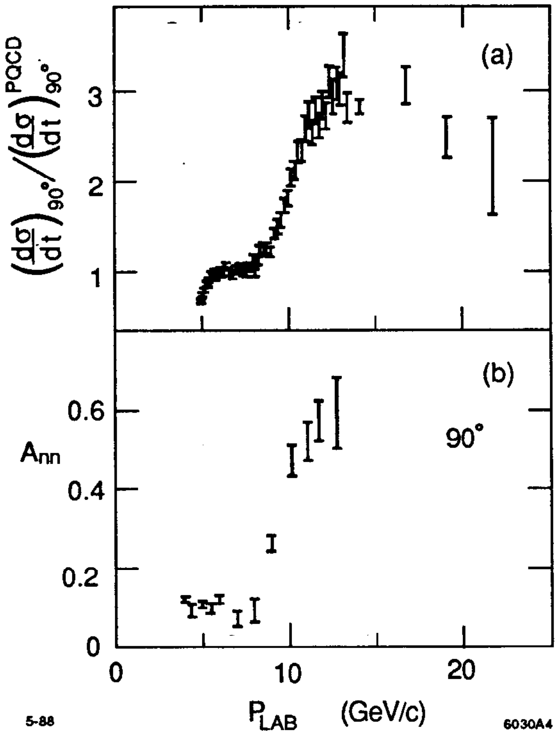

Fig. 1. Onset of threshold effects in $d\sigma/dt$ and A_{NN} at 90° near 12 GeV/c.

Furthermore, since at threshold this process can be considered as a low-impact parameter collision, it will affect only some low partial waves and dominate at large angles over the hard scattering amplitudes.

The PQCD component of the model is the CIM model,[9] which is the dominant mechanism at large momentum transfer.[12] We do not include diffractive contributions and our model is only valid at large angles where hard scattering is important. To describe the observed structure in a large energy region, we need to introduce two broad ($J = L = S = 1$) resonant amplitudes centered at $\sqrt{s} = 2.55$ GeV and 5.08 GeV and a sharp $^3F_3$ resonance at $\sqrt{s} = 2.17$ GeV, with widths of 1.6, 1.0 and 0.04 GeV, respectively. These amplitudes interfere with the CIM amplitude to reproduce the experimental data. The required $\sqrt{s}$ values correspond to the $pp \to K^+\Lambda p$, $pp \to D^\circ\Lambda_c p$, and $pp \to \Delta p$ thresholds, respectively. Because of higher-order corrections from loops, the hard QCD amplitudes are expected to have a phase (for example, when the hadron wave function is incorporated). We have allowed for a constant phase δ in the PQCD amplitudes which turns out to be very important (of the order of a radian). Other details of the model are described in Ref. 8.

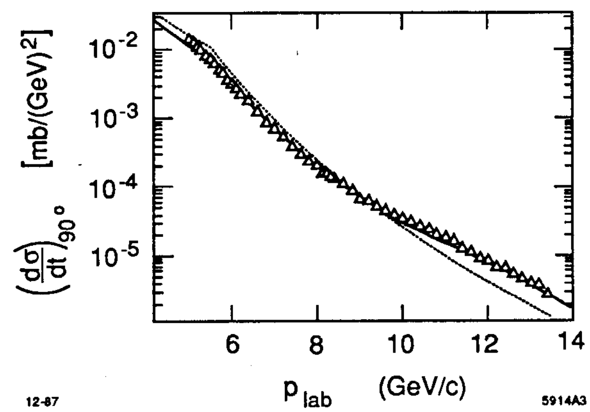

Fig. 2. *pp* elastic cross section.

MODEL PREDICTIONS

Some predictions of the model and comparison with experiment are shown in Figs. 2 and 3. As shown in Fig. 2, the deviations from the simple scaling predicted by the PQCD amplitudes are readily accounted for by the resonance structures. In Fig. 2 the solid curve is the prediction of the model and the dotted line is the background PQCD prediction. The angular distribution (normalized to the data at $\theta_{\rm cm} = \pi/2$) is predicted to broaden relative to the steeper perturbative QCD form, when the resonance dominates. This is also consistent with experiment. The narrow peak which appears near 1.3 GeV/c in Fig. 3 corresponds to the onset of the $pp \rightarrow p\Delta(1232)$ channel. The model is also consistent with the recent high-energy data point for A_{NN} at $p_{\rm lab} = 18.5$ GeV/c and $p_T^2 = 4.7$ GeV^2. 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 $p_{\rm lab} \approx 6$ GeV/c shown in Fig. 3. References for the data are given in Ref. 8.

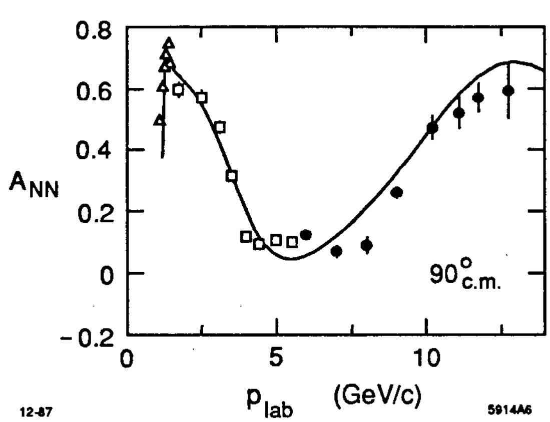

Fig. 3. A_{NN}.

The most striking test of the model is its prediction for the spin correlation A_{NN} shown in Fig. 3. The rise of A_{NN} to $\simeq 60\%$ at $p_{\rm lab} = 11.75$ GeV/c is correctly reproduced by the high energy $J = 1$ resonance interfering with a PQCD background. If the structure observed in A_{NN} at $p_{\rm lab} = 12$ GeV/c is indeed associated with the onset of heavy quark degrees of freedom, we predict, using unitarity, total charm production cross section of 1 μb near threshold. This value is just below the preliminary limits set by the BNL experiment E766 studying np collisions in the 15–28 GeV region.[13]

CONCLUSIONS

I have given a brief account of various possible explanations of the anomalous spin-spin correlation data, and how different models can be classified according to their prediction of A_{NN} at large angles above 12 GeV/c. Measurements of A_{NN} in this energy region are crucial. At $p_{\rm lab} = 18.5$ GeV/c we predict an increase in A_{NN} from 10% at $p_T^2 = 7$ (GeV/c)^2 to 40% at $p_T^2 = 8.2$ (GeV/c)^2, and a relaxation of A_{NN} to its CIM–PQCD value of 1/3 at 90° at higher energies. The model also predicts that the QCD color transparency in quasielastic pp scattering in nuclear targets should reappear at higher energies ($p_{\rm lab} > 16$ GeV/c) and also at smaller angles $\sim 60°$ at $p_{\rm lab} = 12$ GeV/c.

The anomalous pp elastic data is consistent with the onset at 12 GeV/c of a threshold effect due to the opening of new degrees of freedom. The data are well reproduced by the interference of two broad and highly inelastic resonance structures at $\sqrt{s} = 2.55$ GeV and 5.08 GeV. These energies correspond to the threshold value for open strangeness ($pp \rightarrow \Lambda K^+ p$) and open charm ($pp \rightarrow \Lambda_c D^\circ p$) respectively. The model may be interpreted in terms of actual "hidden-flavor" resonances near the respective thresholds. On the other hand, the successful description of a wide range of data may simply reflect an adequate parametrization of the threshold effects in the NN system arising from the opening of new (heavy flavor) inelastic channels. A search for charm production in pp collisions with higher statistics is underway, and results may soon be available.[13]

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