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TESTING QUANTUM CHROMODYNAMICS IN ANTI-PROTON REACTIONS*

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ABSTRACT

An experimental program with anti-protons at intermediate energy can serve as an important testing ground for QCD. Detailed predictions for exclusive cross sections at large momentum transfer based on perturbative QCD and the QCD sum rule form of the proton distribution amplitude are available for $\overline{p}p \to \gamma\gamma$ for both real and virtual photons. Meson-pair and lepton-pair final states also give sensitive tests of the theory. The production of charmed hadrons in exclusive $\overline{p}p$ channels may have a non-negligible cross section. Anti-proton interactions in a nucleus, particularly J/ψ production, can play an important role in clarifying fundamental QCD issues such as color transparency, critical length phenomena, and the validity of the reduced nuclear amplitude phenomenology.

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INTRODUCTION

Quantitative tests of Quantum Chromodynamics generally involve high momentum transfer where factorization theorems and asymptotic freedom allow detailed predictions based on perturbative quark and gluon subprocesses. The most challenging testing ground of the theory is now the intermediate (few GeV/c) momentum transfer domain where both perturbative and non-perturbative aspects of the theory are manifest. In this talk, I will focus on a class of exclusive and inclusive antiproton reactions which can test important and novel features of QCD even at moderate energy. Further discussion may be found in several recent reports (Brodsky, 1986 and 1987).

EXCLUSIVE PROCESSES

One of the most elegant applications of QCD is to exclusive processes at large momentum transfer such as $\overline{p}p \rightarrow AB$ where A and B can be photons, leptons, or hadrons. Such reactions can be factorized (Lepage and Brodsky, 1980; Brodsky, et.al., 1980; Efremov and Radyushkin, 1980; Duncan and Mueller, 1980; Chernyak and Zhitnitskii, 1984) into a convolution of factors: the distribution amplitudes $\phi_H(x, Q)$ - which contain the non-perturbative dynamics of each incident and outgoing hadron - multiplied by a perturbatively-calculable amplitude for the scattering of the quarks from the incident to final direction. The logarithmic dependence of the distribution amplitudes is controlled in leading order by gluon exchange and can be derived from evolution equations or renormalization group methods. In first approximation, one derives fixed angle scaling laws (Sivers, et. al.,1976), $d\sigma/dt = f(\theta_{cm})/s^{N-2}$, where according to QCD quark counting rules, (Brodsky and Farrar, 1973; Matveev, et. al. 1973) N is the total number of incident and final fields. In the case of $\overline{p}p \rightarrow \gamma\gamma$ and e^+e^- the explicit dependence of the angular function $f(\theta_{cm})$ has been worked out in detail. (See below.) In general, the angular dependence reflects the underlying duality graph (minimally-connected quark-gluon subprocess amplitudes). In some diagrams, pinch singularities arise (Landshoff,1974) where propagators can become nearly-on-shell, but this region is suppressed by Sudakov form factors (Mueller, 1981). This effect leads in some cases to a small change in the power-law fall-off. One wishes to check not only these predictions, but also the crossing behavior to related amplitudes such as that measured in proton Compton scattering at large momentum transfer. One also can check the consequences of hadron helicity conservation (Brodsky and Lepage, 1981) which is derived for the leading power contribution predicted by QCD. Exclusive $\overline{p}$ processes test not only the scaling and angular dependence of the elementary quark and gluon subprocesses, but also place experimental constraints on the form of the fundamental distribution amplitude of the anti-proton and other hadrons. Conversely, the perturbative QCD predictions provide important analytic constraints on the form of scattering amplitudes at any momentum scale.

The simplest exclusive channels accessible to a $\overline{p}p$ facility are $\overline{p}p \to e^+e^-$, $\mu^+\mu^-, \tau^+\tau^-$ which to leading order in α provide direct measurements of the Dirac and Pauli timelike proton form factors. The angular dependence can be used to separate F_2 and F_1 and to check the basic predictions, (Brodsky and Lepage, 1980) $s^2F_1(s) \sim f(\ell n\, s)$ and $F_2(s)/F_1(s) \sim M^2/s$. A high luminosity $\overline{p}$ facility could provide time-like measurements of both form factors well beyond those available from e^+e^- storage rings. Another important example is $p\overline{p} \to \gamma\gamma$. QCD factorization implies that to leading order in $1/p_T^2$,

$$\mathcal{M}_{p\overline{p}\to\gamma\gamma}(p_T^2,\theta_{CM}) = \int_0^1 [dx] \int_0^1 [dy] \phi_{\overline{p}}(x,p_T) \times T_H(qqq + \overline{qqq} \to \gamma\gamma)\phi_p(y,p_T)$$

where $\phi_{\overline{p}}(x,p_T)$ is the anti-proton distribution amplitude, and $T_H \sim \alpha_s^2(p_T^2)/(p_T^2)$ gives the scaling behavior of the minimally connected tree graph amplitude for the two-photon annihilation of three quarks and three antiquarks collinear with the initial hadron directions. QCD thus predicts

$$\frac{d\sigma}{d\Omega_{CM}}\,(p\overline{p} \to \gamma\gamma) \simeq \frac{\alpha_s^4(p_T^2)}{(p_T^2)^5}\, f(p_T,\theta_{CM},\ell np_T^2)\,.$$

Complete calculations of the Born diagrams for the $\gamma\gamma \to M\overline{M}$ (Brodsky and

Lepage, 1981; Chernyak and Zhitnitskii, 1984; Gunion, et. al; 1986) and $\gamma\gamma \to B\overline{B}$ (Farrar, et. al, 1985) amplitudes are now available. The predictions for meson pairs have been confirmed both in normalization and scaling behavior for center of mass energies in the 1 GeV to 3.5 GeV range by the Mark II and PEP/Two Gamma groups at PEP. (Boyer, et. al., 1986; Aihara, et. al., 1986). One can use crossing to compute T_H for $p\overline{p} \to \gamma\gamma$ to leading order in $\alpha_s(p_T^2)$ from the calculations reported by Farrar, Maina, and Neri (1985) and Millers and Gunion (1985). The calculations assume the QCD sum rule form for the proton distribution amplitude computed by Chernyak and Zhitnitskii, 1984). The region of applicability of the leading power-law results is presumed to be set by the scale where $Q^4 G_M(Q^2)$ is roughly constant. One can even study timelike photon production and probe the virtual photon mass dependence of the Compton amplitude; predictions for the q^2 dependence of the $p\overline{p} \to \gamma\gamma^*$ amplitude can be obtained by crossing the results of Millers and Gunion (1985). These predictions are particularly sensitive to the form of the proton's distribution amplitude.

INCLUSIVE PROCESSES

In the case of inclusive reactions, the essential test of QCD involving $\overline{p}$ reactions is the Drell-Yan reaction $\overline{p}p \to \ell^+\ell^- X$ and $\overline{p}p \to \gamma\gamma X$. Such reactions are fairly well understood at high momentum transfer in terms of the QCD factorization theorem for inclusive reactions (Bodwin, 1985; Collins, et. al.,1984). At low energies the physics is far less well understood because of breakdown of the "target length condition" required for the validity of QCD factorization (Bodwin, et. al., 1985): $E_{\overline{q}} > \mu^2 L$, where $E_{\overline{q}}$ is the energy of the anti-quark in the target rest frame, μ is a characteristic QCD mass scale, and L is the target length. Thus at sufficiently high energies, an annihilating anti-quark suffers no induced collinear radiation, and can interact without degradation of energy anywhere in the nucleus! This result is clearly necessary in order to have factorization of the anti-proton structure function independent of the target. The absence of significant initial state inelastic interactions is due to the fact that radiation from different scattering centers is cancelled by destructive interference when the processes are coherent over the target volume.

Nevertheless, *elastic* scattering of the incident $\overline{p}$ in the target is not prevented by the target length condition. Recent data by the NA-10 group at the SPS (Bordalo, et. al. 1987) for pion induced lepton pairs has now verified this rather surprising prediction of the theory: the transverse momentum distribution of the lepton pair grows with nuclear number, as expected from elastic initial state interactions, despite the absence of induced colinear radiation. Further measurements of low energy $\overline{p}$ Drell Yan reactions are needed to understand the limits of validity of QCD factorization and to explore the re-emergence of traditional Glauber inelastic scattering at low anti-quark energies.

COLOR TRANSPARENCY AND J/ψ PRODUCTION

Many fascinating aspects of QCD can be studied by measuring quasi-exclusive J/ψ production in a *nuclear* target. For example, the basic formation amplitude for exclusive $\overline{p}p \to J/\psi$ production involves three-gluon annihilation at small impact distances of order $1/M_c$. Hadron helicity conservation implies that the dominant amplitude has opposite p and $\overline{p}$ helicities, and short distance dominance implies that only the Fock state of the incident antiproton which contains three antiquarks at small impact separation can annihilate. Since this state has a small color dipole moment, it should have a longer than usual mean-free path in nuclear matter. This is the central idea of "color transparency". More generally, for any exclusive reaction at large momentum transfer Q, one expects that only the lowest particle-number "valence" Fock state wavefunction with all the quarks within an impact distance $b_\perp \leq 1/Q$ contributes to the amplitude. Such a Fock state component has a small color dipole moment and thus interacts only weakly with hadronic or nuclear matter (Mueller, 1982; Brodsky, 1982; Bertsch, et. al. 1980). Thus unlike traditional Glauber theory, QCD predicts that $\overline{p}p$ annihilation into charmonium inside a nucleus is not restricted to the front surface; i.e., one expects a volume rather than surface dependence in the nuclear number for the exclusive J/ψ production rate. Hadron decay channels will also reflect the J/ψ short distance decay dynamics and thus suffer less absorption than expected. The exception may be the vector+pseudoscalar channels such as $\rho\pi$ which may be due to mixing of the

J/ψ with a nearby gluonium resonance (Brodsky, et. al., 1987). In this case one expects normal final state absorption.

The cross section for exclusive J/ψ production on a nucleus involves the convolution with the nuclear distribution $G_{p/A}(y)$. Here $y = (p^0 + p^3)/(P_A^0 + P_A^3)$ is the boost invariant light-cone fraction for protons in the nucleus. Measurements above and below the single nucleon target threshold can thus determine the covariant nuclear Fermi-motion in a very clean way. The behavior of $G_{p/A}(y)$ for y well away from the Fermi distribution peak at $y \sim m_N/M_A$ is predicted by spectator counting rules (Blankenbecler and Brodsky, 1974; Schmidt and Blankenbecler, 1977; Brodsky and Chertok, 1976): for $y \rightarrow 1$, $G_{p/A}(y) \sim (1-y)^{2N_s-1} = (1-y)^{6A-7}$ where $N_s = 3(A-1)$ is the number of quark spectators required to "stop" ($y_i \rightarrow 0$) as $y \rightarrow 1$. This simple formula has been quite successful in accounting for distributions measured in the forward fragmentation of nuclei.

A test of "color transparency", has recently been carried out at BNL (Heppelmann, 1987) in large momentum transfer elastic pp scattering at $\theta_{cm} \simeq \pi/2$ in nuclear targets by a BNL-Columbia collaboration. The attenuation of the recoil proton as it traverses the nucleus and its momentum distribution dN/dp_y transverse to the x-z scattering plane were measured. In the latter case, the acceptance was restricted in energy so that only quasi-elastic events were selected. The preliminary results reported for incident proton momenta $p_{lab} = 10$ GeV/c ($\sqrt{s} = 4.54$ GeV), in aluminum with $\theta_{cm} \sim \pi/2$ shows strong peaking at small $| p_y | \leq 0.2$ GeV/c, consistent with Fermi smearing alone. In conventional multi-scattering theory, the dN/dp_y distribution reflects the Fermi motion of the bound nucleon plus the initial state interactions of the incoming proton and the final state interactions of the two outgoing protons. The apparent absence of significant elastic initial or final state interactions provides striking confirmation of the color transparency ansatz that only the valence wavefunction of the proton with small impact separation is involved in the scattering reaction. However the data at $p_{lab} = 12$ GeV/c, ($\sqrt{s} = 4.93$ GeV) show quite different behavior: the dN/dp_y out-of-plane momentum distribution shows almost no peaking and appears consistent with conventional elastic-Glauber initial and final state scattering. One can explain this surprising result if a di-baryon resonance exists with mass near 5 GeV (Brodsky and de Teramond, 1987), since a resonance couples to the full large-scale structure of the proton. If the resonance has spin $S = 1$, this can also explain the large spin correlation A_{NN} (Court, 1986) measured at the same momentum, $p_{lab} = 11.75\ GeV/c$.

CHARMONIUM PRODUCTION AND HADRON HELICITY CONSERVATION

The production of heavy quark resonances $p\overline{p} \rightarrow \psi, \chi, \eta_c$, etc. can be analyzed in a systematic way in QCD using the exclusive amplitude formalism of Lepage and Brodsky (1980). Since quark helicity is conserved in the basic subprocesses to leading order, and the distribution amplitude is the azimuthal angle symmetric $L_z = 0$ projection of the valence hadron Fock wavefunction, total hadron helicity is conserved for $A + B \rightarrow C + D$: $\lambda_A + \lambda_B = \lambda_C + \lambda_D$. This result is predicted to hold to all orders in $\alpha_s(Q^2)$. Thus an essential feature of perturbative QCD is the prediction of hadron helicity conservation up to kinematical and dynamical corrections of order m/Q and $\langle\psi\overline{\psi}\rangle^{1/3}/Q$ where Q is the momentum transfer or heavy mass scale, m is the light quark mass, and $\langle\psi\overline{\psi}\rangle$ is a measure of non-perturbative effects due to chiral symmetry breaking of the QCD vacuum. Applying this prediction to $p\overline{p}$ annihilation, one predicts $\lambda_p + \lambda_{\overline{p}} = 0$, i.e., $S_z = J_z = \pm 1$ is the leading amplitude for heavy resonance production. Thus the ψ is expected to be produced with $J_z = \pm 1$, whereas the χ and η_c cross sections should be suppressed, at least to leading power in the heavy quark mass. The analogous tests in e^+e^- annihilation appear to be verified for ψ' decays but not the ψ. Hou and Soni (1983) and Brodsky, Lepage, and Tuan (1987) have suggested this effect may be due to the ψ mixing with $J = 1$ gluonium states. Antiproton-proton production of narrow resonances should be able to help clarify these basic QCD issues.

EXCLUSIVE CHARM PRODUCTION

Open charm production in inclusive reactions is one of the few areas where there may be a discrepancy between QCD predictions and experiment. (See, e.g. Brodsky, Gunion, and Soper, 1987). Here I want to address the question of heavy flavor production in exclusive $p\overline{p}$ reactions, e.g. $\overline{p}p \to \overline{\Lambda}_{\overline{Q}}\Lambda_Q$ where $Q = s, c, b$. The following arguments are heuristic, but they may give a guide to the expected scaling laws and features of these reactions. If the Λ's are produced in the forward direction with $p_T^2 \lesssim \mu^2 \sim (300 \text{ MeV})^2$ then there is maximal kinematic overlap for the light quarks between the initial and final light wavefunctions. The hard subprocess cross section $\overline{u}u \to c\overline{c}$ would normally give cross sections of order

$$\frac{d\sigma}{d\Omega} \sim \frac{\alpha_s^2(s) f(\Omega)}{s} \sim \frac{\alpha_s^2(4m_Q^2)}{4M_Q^2}\, f(\Omega)$$

but the alignment restriction $p_T^2 < \mu^2$ gives an extra $\mu^2/4m_Q^2$ suppression in the angular integral. Therefore one predicts the scaling

$$\sigma(\overline{p}p \to \overline{\Lambda}_{\overline{Q}}\Lambda_Q) \sim \mu^2\, \frac{\alpha_s^2(4M_Q^2)}{m_Q^4}\, F\left(\frac{4m_Q^2}{s}\right)$$

i.e. $\overline{\Lambda}_{\overline{s}}\Lambda_s : \overline{\Lambda}_{\overline{c}}\Lambda_c : \overline{\Lambda}_{\overline{b}}\Lambda_b = 1 : (10^{-2} \text{ to } 10^{-3}) : (10^{-4} \text{ to } 10^{-6})$ for $s \gg 4m_Q^2$. Thus it may not be hopeless to actually measure exclusive pairs of heavy charmed baryons in $\overline{p}p$ collisions. The above analysis can be readily extended to other heavy flavor baryon and meson pair exclusive cross sections. The issues are important for clarifying the OZI rule in QCD and the connection between exclusive and inclusive production mechanisms.

REDUCED NUCLEAR AMPLITUDES

There are interesting tests of QCD using $\overline{p}$ beams in which the nuclear target itself plays an essential dynamical role. The basic observation is that for vanishing nuclear binding energy $\epsilon_d \to 0$, the deuteron can be regarded as two nucleons sharing the deuteron four-momentum. The $\overline{p}d \to \pi^- p$ amplitude then contains a factor representing the probability amplitude (i.e. form factor) for the proton to remain intact after absorbing momentum transfer squared $\hat{t} = (p - \frac{1}{2}pd)^2$ and the $\overline{N}N$ timelike form factor at $\hat{s} = (\overline{p} + \frac{1}{2}p_d)^2$. Thus $\mathcal{M}_{\overline{p}d \to \pi^- p} \sim F_{1N}(\hat{t})\, F_{1N}(\hat{s})\, \mathcal{M}_r$ where the "reduced" amplitude $\mathcal{M}_r$ has the same QCD scaling properties as the quark meson scattering amplitude (Brodsky and Hiller, 1983). We thus predict

$$\frac{\frac{d\sigma}{d\Omega}\,(\overline{p}d \to \pi^- p)}{F_{1N}^2(\hat{t})\,F_{1N}^2(\hat{s})} \sim \frac{f(\Omega)}{p_T^2}\ .$$

The analogous scaling of the deuteron's reduced form factor (Brodsky and Chertok, 1976; Brodsky, et. al., 1983)

$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_{1N}\left(\frac{Q^2}{4}\right)\,F_{1N}\left(\frac{Q^2}{4}\right)} \sim \frac{1}{Q^2}$$

is consistent with experiment for $Q = p_T \gtrsim 1$ GeV (Arnold et. al., 1975).

NON-PERTURBATIVE METHODS AND HADRON WAVEFUNCTIONS

Is it possible to make reliable predictions for low momentum transfer hadron reactions clearly controlled by non-perturbative dynamics? In recent years useful results on hadron spectra and couplings have been obtained from lattice gauge theory and spectral sum rule analyses. I also want to mention another non-perturbative method which shows promise as a means for obtaining not only the spectrum of the hadrons in QCD, but wavefunctions and scattering amplitudes. The essential idea of this method, (Pauli and Brodsky, 1986; Eller, et. al., 1987) "Discretized Light-Cone Quantization" (DLCQ) is to diagonalize the QCD Hamiltonian, quantized at fixed $\tau = t + z/c$, on the Fock basis of free quarks and gluons.

When a light-wave traverses a hadron, it probes the quark and gluon constituents in flight at a fixed time τ on the light-cone. In QCD this corresponds to the momentum space Fock state expansion $|\psi_P\rangle = \psi_{uud}(x_i, \mathbf{k}_{\perp i}, \lambda_i)\,|uud\rangle + \psi_{uudg}(x_i, \mathbf{k}_{\perp i}, \lambda_i)\,|uudg\rangle + \ldots$, with $\sum_i \mathbf{k}_{\perp i} = \mathbf{0}, \sum_i x_i = 1$. The wavefunctions ψ give the probability amplitude that the proton is in a particular Fock state with light-cone momentum fractions $x_i = (k_i^0 + k_i^z)/(P^0 + P^z)$, etc. The $|uud\rangle$, etc. are eigenstates of the free Hamiltonian. The sum over squares of the coefficient wavefunctions ψ_n (integrated over the $x_i \neq x_a$ and the $\mathbf{k}_{\perp i}$ up to the momentum scale Q) defines the structure functions $G(x_a, Q)$ measured in deep inelastic lepton scattering. The integral of the lowest "valence" wavefunction integrated over the $\mathbf{k}_{\perp i}$ up to the scale Q defines the distribution amplitude, $\phi(x_i, Q)$, the basic non-perturbative quantity which controls large momentum transfer exclusive reactions. Other physical observables such as form factors, magnetic moments, decay constants, and scattering amplitudes from, for example, quark interchange are also directly expressible in terms of the light-cone wavefunctions.

Solving for the color singlet hadron spectrum in QCD is equivalent to solving the eigenvalue problem $H_{LC}\,|\Psi\rangle = M^2\,|\Psi\rangle$ in the sector of fixed charge, baryon number, and total momentum P^+ and $P_\perp$. The free Hamiltonian is the sum of relativistic kinetic energies: $H_{free} = \sum_i a_i^\dagger a_i(\mathbf{k}_{\perp i}^2 + m_i^2)/x_i$ and the interaction Hamiltonian $H_{int} = H_{LC} - H_{free}$ consists of the usual 3 and 4 point vertices plus well-defined instantaneous gluon and quark exchange 4 point interactions. Detailed formulae are given in Lepage and Brodsky, (1980). The eigenvalues and eigenfunctions of H_{LC} then determine the complete spectrum and wavefunctions of the theory. By imposing periodic boundary conditions in $z_- = z - t/c$ on the free Fock basis (Pauli and Brodsky, 1986), the momenta become discrete and the eigenvalue problem reduces to the diagonalization of a finite Hermitian matrix. The continuum limit is reached as the dimension of the representation increases to infinity. The discrete representation has the same unitary, renormalizable, frame-independent properties as the continuum QCD with no fermion-doubling problem. The length of periodicity in z_- does not appear in physical quantities since it is effectively a Lorentz boost.

Recently Hornbostel (1987) has applied the DLCQ analysis to the color-singlet spectrum of QCD in one space and one time dimension for $N_C = 2, 3, 4$. The results for the lowest meson mass in the $SU(2)$ theory agree within errors with the lattice Hamiltonian results of Hamer (1984). The method also provides the first results for the baryon spectrum in a non-Abelian gauge theory as well as the meson and baryon structure functions. Eventually one hopes to obtain results of similar quality for the wavefunctions and spectra of QCD in physical space-time.

Although QCD in 3+1 dimensions has not been solved directly, important constraints on nucleon and meson wavefunctions have been obtained self-consistently using the ITEP QCD sum rule analysis (Chernyak and Zhitnitskii, 1984). This analysis predicts a surprising feature: strong flavor asymmetry in the nucleon's momentum distribution. The computed moments of the distribution amplitude imply that 65% of the proton's momentum in its 3-quark valence state is carried by the u-quark which has the same helicity as the parent proton. A recent comprehensive re-analysis by King and Sachrajda (1987) has now confirmed the Chernyak and Zhitnitskii (1984) form in its essential details. In addition, Martinelli and Sachrajda (1987) have shown that lattice gauge theory leads to a value for the second moment of the pion distribution amplitude consistent with the QCD sum rule results. The QCD sum rule form for the proton distribution amplitude together with QCD factorization gives a prediction for the proton form factor $G_M(Q^2)$ consistent in both normalization and sign with the measured proton form factor data at large momentum transfer (Chernyak and Zhitnitskii, 1984; Ji, et. al., 1986). Dziembowski and Mankiewicz (1987) have recently shown that the asymmetric form of the CZ distribution amplitude can effectively be derived from a rotationally-invariant center-of-mass wavefunction transformed to the light cone using a Melosh-type boost of the quark spinors. The transverse size of the valence wavefunction is found to be significantly smaller than the mean radius of the proton, averaged over all Fock states, as predicted by Lepage, et. al. (1981). This implies a small range of interaction for processes involving complete anti-proton annihilation, such as $\overline{p}p \to \phi\phi$. Dziembowski and Mankiewicz (1987) also show that the perturbative QCD contribution to the form factors dominates over the soft contribution (obtained by convoluting the non-perturbative wavefunctions) at a scale $Q/N \approx 1$ GeV, where N is the number of valence constituents. Similar criteria were also derived by Jacob and Kisslinger (1986). (Earlier claims by Isgur and Llewellyn Smith (1984) that a simple overlap of soft hadron wavefunctions could fit the form factor data were erroneous since they were based on wavefunctions which violate rotational symmetry.)

CONCLUSIONS

Where clear tests can be made, such as two-photon processes and the hadron form factors, perturbative QCD predictions for exclusive processes appear to be correct empirically in scaling behavior, helicity structure, and absolute normalization. There is now evidence for the remarkable color transparency phenomenon predicted by perturbative QCD for quasi-elastic scattering within a nucleus. This effect can be used to separate processes involving large and small distance amplitudes. I have also mentioned a possible explanation for the strong spin correlations in proton-proton elastic scattering and breakdown of color transparency in terms of relatively high mass di-baryon resonances. The general conclusion is that perturbative QCD will give reliable predictions for exclusive processes in the absence of nearby resonance or threshold phenomena.

QCD is usually studied at much higher energies than those considered in the AMPLE or Super-LEAR range. Nevertheless, as discussed above, there are interesting novel effects involving the interface between perturbative and non-perturbative dynamics and quark propagation in hadronic matter – all of which can be explored at $\overline{p}$ energies below 10 GeV. Eventually, such experimental and theoretical explorations could lead to a comprehensive theory of hadronic interactions.

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