PHYSICAL REVIEW D VOLUME 46, NUMBER 9 1 NOVEMBER 1992

What color transparency measures

P. Jain and John P. Ralston
Department of Physics and Astronomy, University of Kansas, Lawrence, Kansas 66045-2151
(Received 30 June 1992)

Color transparency is commonly accepted to be a prediction of perturbative QCD. However it is more a phenomenon probing the interface between the perturbative and nonperturbative regimes, leading to some intricacy in its theoretical description. In this paper we study the consequences of the impulse approximation to the theory in various quantum mechanical bases. We show that the fully interacting hadronic basis, which consists of eigenstates of the exact Hamiltonian in the presence of the nucleus, provides a natural basis to study color transparency. In this basis we can relate the quark wave function at a small transverse separation distance $b^2 < 1/Q^2$ directly to transparency ratios measured in experiment. With the formalism, experiment can be used to map out the quark wave function in this region. We exhibit several loopholes in existing arguments predicting a rise in transparency ratios with energy, and suggest alternatives. Among the results, we argue that the theoretical prediction of a rising transparency ratio with energy may be on better footing for heavy-quark bound states than for relativistic light-quark systems. We also point out that transparency ratios can be *constant* with energy and not at variance with perturbative QCD.

PACS number(s): 12.38.Qk, 12.38.Bx, 24.85.+p, 25.30.Fj

Color transparency, namely, the reduced attenuation of hadrons in nuclear matter under certain circumstances [1], has recently received much theoretical study [2]. It is commonly understood to be a prediction of QCD, so that most work concentrates on calculating the magnitude of the effect in specific reactions, rather than questioning its foundations. On the other hand, it should be emphasized that color transparency is interesting precisely because it combines perturbative and nonperturbative physics. Therefore it is useful to reexamine the strength of the prediction, to become the devil's (or doubter's) advocate, especially since there is still no conclusive support for color transparency from data. Toward this purpose, our goal will be to give as thorough a discussion as possible of conceptual issues that are often swept under the rug.

Our primary concern is the correct use of the impulse approximation in hard exclusive reactions. For definiteness, we consider the $ee'p$ reaction in a nucleus of atomic number A, namely, $e+A \rightarrow e'+p+(A-1)$. A virtual photon knocks the proton elastically out of the nucleus. This reaction is to be compared with the analogous one in free space, namely, $e+p \rightarrow e'+p'$, which proceeds through the electromagnetic form factors. We assume that the momentum transfer Q^μ has large $Q^2 \gg \mathrm{GeV}^2$ and that the experimental setup selects quasiexclusive kinematics, so that the energy of the fast outgoing proton is close to $Q^2/2m$. Much of our analysis can also be applied to quasielastic hadron-initiated reactions such as $pA \rightarrow p'p''(A-1)$. We outline some distinctions between these reactions involving relativistic quark bound states and those involving nonrelativistic bound states such as charmonium production.

In the impulse approximation, a sudden perturbation applied to a system is represented by finding the overlap of the "before impulse" or initial state $|i\rangle$ onto the "after impulse" or final state $|f\rangle$, which then time evolves according to the Hamiltonian. If a system has a Hamiltonian $H_<$ for time $t<0$ and Hamiltonian $H_>$ for time $t>0$, then the time evolution after the sudden perturbation is approximately given by

$$|f(t)\rangle = \sum_n \exp(-itE_{>n})|E_{>n}\rangle\langle E_{>n}|i\rangle ,$$

where $|E_{>n}\rangle$ are the eigenstates of $H_>$. So long as the impulse approximation applies, the suddenness of the perturbation is irrelevant, and the system does not depend on the duration of the sudden impulse Δt_I. This is an important point, potentially at odds with the $\Delta E\,\Delta t > 1$ uncertainty principle, which one might think would give a range to the final-state energies of order $1/\Delta t_I$. The reason this would be incorrect is that the system is not really prepared, in the quantum-mechanical sense, by a measurement with a time scale Δt_I, but instead has no time to react to the sudden change.

Let us elaborate on this crucial point. Quantum dynamics is Hamiltonian and first order in time, exactly as classical dynamics; so the impulse approximation applies to both. If we represent the state immediately after the impulse as $|i'\rangle$ and expand its difference from the initial state as

$$|i'\rangle = |i\rangle + \sum_n c_n(\Delta t_I)|E_{n<}\rangle e^{-i\Delta t_I E_{n<}} ,$$

then a short calculation of the coefficients resulting from the impulse Hamiltonian $\delta H_I(t)$ gives

$$c_n(\Delta t_I) = -i\left\langle E_{n<} \left| \int_{\Delta t_I} dt'\,\delta H_I(t') e^{it'E_{n<}} \right| i \right\rangle .$$

The integral is of order Δt_I, showing that the impulse approximation becomes exact as $\Delta t_I \rightarrow 0$. (There is a possible loophole, however, if the sum over n, weighted by the matrix elements, diverges like $1/\Delta t_1$. In Feynmandiagram language, there could potentially be a problem with ultraviolet divergences, which physically react faster than any probe. This might be aggravated by the singularities of the infrared interplaying with the ultraviolet. But, in fact, the perturbative theory is safe, as shown by more than ten years of study, dedicated to just the issue of justifying the impulse approximation. Ultimately, we can use the impulse approximation because no detailed properties of the renormalized theory upset it. The considerations of the uncertainty principle are a puny worry in comparison and a red herring for this reason.)

Now, in more detail, the perturbative description of hard scattering is actually a three-step process. There is the long-time evolution of the soft wave function before the process, then the hard scattering, and then the long-time evolution after the scattering. The impulse approximation is used twice, in decoupling the hard scattering from the "before" and "after" hard-scattering time evolution. The approximations to the time evolution are represented mathematically by

$$\begin{aligned}|f(t)\rangle = \exp(-iE_{n>}t_{>})|E_{n>}\rangle\langle E_{n>}|3q'\rangle \\ \times\langle 3q'|S_{\text{hard}}(\Delta t_I)|3q\rangle \\ \times\langle 3q|\exp(-iE_{0<}t_{<})|E_0\rangle ,\end{aligned}$$

assuming we begin with a proton as a ground-state eigenvector $|E_0\rangle$. Here S is the hard scattering, a time-dependent process which couples for dynamical reasons predominantly to the lowest (three-quark) state $|3q\rangle$. S is calculated perturbatively, and except for the fact that only leading-order pieces are retained, the impulse approximation is not specifically invoked for S. Naturally, the perturbative calculation is consistent, and the uncertainty principle does not have to be applied again. Yet it is to the intermediate states while S is acting that the uncertainty principle is useful. In fact, in an inclusive experiment at large Q^2 and energy ν, we can experimentally measure all of the states ranging up to the maximum energy indicated by the uncertainty principle (or dimensional analysis). In contrast, color transparency refers to an exclusive experiment. Then the experiment kinematically selects a particular term among all the amplitudes generated. All of the complexity of the hard scattering just turns into a calculable matrix element. The uncertainty principle is true, but *incapable of saying anything about the size of the matrix element needed.* We conclude that, where the uncertainty principle applies, it is irrelevant to the coupling of the soft and hard time evolution.

Let us examine the approximations in more microscopic detail. In a free-space $ee'p$ experiment (namely, $e+p\to e'+p'$), we want the amplitude for the hard-struck initial proton carrying momentum p to look like three quarks and then look like an outgoing proton with momentum $p+Q$. This can be appreciated with a "cartoon" [Fig. 1(a)] showing the scattering of pancakes in a frame where both the initial- and final-state protons move fast, and the virtual photon delivers no energy and a large momentum Q. (Since in this reference frame the photon has no energy, we do not have a definite time for the event to occur. But the internal dynamics of the quarks absorbing the photon give energy denominators determining the duration of the event, Δt_I.) Since the proton states are used as eigenstates for the impulse approximation, they have a typical size of 1 fm.

The crucial perturbative step is replacing the true amplitude M by a product of hard-scattering kernel and distribution amplitudes [3]:

$$\begin{aligned}M = \int \prod_{i,j} dx_i dx_j \delta\left[\sum_i x_i - \sum_j x_j\right] d^2k_{T,i} d^2k_{T,j} \psi_f^*(k_{T,j},x_j) H(k_T;x;Q^2)\psi_i(k_{T,i},x_i) \\ \to \int \prod_{i,j} dx_j \delta\left[\sum_i x_i - \sum_j x_j\right] \phi_f^*(x_j,Q^2) H(Q^2,k_T=0,x)\phi_i(x_i,Q^2) ,\end{aligned}$$

where

$$\begin{aligned}\phi(x,Q^2) &= \int_0^Q d^2k_T \psi(k_T,x) \\ &= 2\pi Q\int_0^\infty db\, J_1(bQ)\tilde{\psi}(x,b) \\ &\cong \tilde{\psi}(x;b^2\le 1/Q^2) . \qquad (1)\end{aligned}$$

The last two lines (abstracted from Ref. [4]) illustrate the point that inspired much of the study, namely, that the important part of the wave function is the part with transverse separation $b^2<1/Q^2$. Assuming that the wave function near the origin is smooth, this is just a number, like a "coupling constant," fixing the normalization of the process. [We neglect slow logarithmically varying corrections to the wave functions near the origin. With our convention, the hard scattering is put into the perturbative quark dynamics (S) and is not a part of the wave function.]

The distribution amplitude onto the proton state is the perturbative QCD version of the overlap used in the impulse approximation. The "complete set" whose time evolution must be well followed is seen to be three quarks, integrated over x^-, with any momentum fraction x, and within a specified distance of the origin. We do *not* overlap this with a complete set of hadrons: In fact, the kinematics were selected to overlap onto an on-shell final-state proton and nothing else.

There is a popular semiclassical notion that the entire system actually becomes small, as if the multicomponent soft wave function had been compressed (or "prepared") into the region $b^2<1/Q^2$. The mathematics shows that the concept of "small" applies only during the hard scattering (S) and indeed only to the three-quark component selected by the hard scattering. The instant the

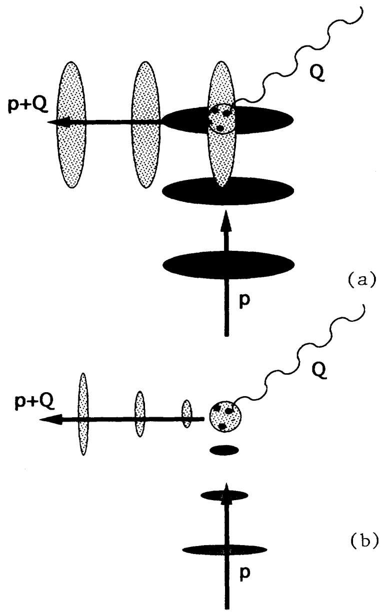

FIG. 1. Cartoons of different approximations. (a) In the impulse approximation, we need the overlap from an initial-state pancake onto a hard scattering (small circle) and then onto a final-state pancake. (b) In the adiabatic approximation, the system is gradually prepared to a small size which can interact with the hard scattering and then expand.

hard scattering is over, we want the overlap onto the energy eigenstate, which is "big," namely, a normal hadron. The popular picture of compressing all the soft components into a small system, by superposition, would, however, apply in the *adiabatic* limit, a case in which the system has unlimited time to react [Fig. 1(b)]. But in the impulse approximation the system itself does not have time to react, and it would not be right to invoke an uncertainty principle such as $\Delta x\ \Delta p_x > 1$ to estimate the size of the eigenstates. Although our presentation of the impulse approximation implicitly contradicts some of the "uncertainty principle" logic dominating discussions, we think it is correct. As mentioned above, the uncertainty principle can lead to unreliable conclusions.[1]

Now we turn to the color-transparency experiment deep in a nuclear target. Our goal is to see what can be learned from the transparency ratio, which is the ratio of reaction rates inside the nucleus to the corresponding free-space rate. The hard scattering and impulse approximation are the same as in free space. However, the distribution amplitude knows about the nucleus and should be different [4]. Models of color transparency are models for the distribution amplitude in interaction with the nucleus.

The physical picture of what is happening depends on the quantum-mechanical basis. There are three relevant choices for the basis to use. (1) One can use the Fock-space basis of the perturbative theory. This is the good basis for the hard scattering and, in fact, the only one in which we know the hard scattering. However, it is not a good basis for the subsequent time evolution of a relativistic light-quark system, which is nonperturbative. (2) One can use the free-space basis of noninteracting hadronic asymptotic states. Here we need the overlap of three quarks separated by a distance of order $1/Q$ onto the free-space proton and all other free-space states with the right quantum numbers that evolve into a proton at infinity. (3) One can use the fully interacting basis. By the interacting proton we mean the exact energy eigenstate that becomes a proton at infinity in interaction with the nucleus. (We do not mean the eigenstates in infinite nuclear matter, because these would have to be patched onto outgoing states. We mean the exact scattering eigenstates with finite-size nuclear effects and all.) In this basis we need the overlap of three quarks separated by a distance of order $1/Q$ onto the interacting proton.

A conventional choice of basis for modeling transparency is (2), the free-space one. Jennings and Miller [6], for example, show that for the proton and a few excited states, destructive interference of nuclear forces among the outgoing states can lead to color transparency. As implemented so far, this procedure can be interpreted as a "proof-of-principle" transcription of the expected result onto the hadronic basis: The off-diagonal couplings between states and phase relations leading to destructive interference of the outgoing protons' interactions are not so much predicted, but rather constructed to give the desired result. In the same basis, the Ralston-Pire approach [2,4] uses the few-quark perturbative cross section to estimate the survival amplitude of a free-space proton upon crossing the nucleus and being filtered by interaction with it. In this way one can confirm the semiclassical intuition predicting color transparency in the very-high-energy (frozen) limit. In the frozen limit, any coupling and mixing of channels becomes negligible because of time dilation.

On the other hand, it is very interesting to consider the calculation in the exact eigenstate basis, case (3). *A priori*, little is known about the energy eigenstates of objects with baryonic quantum numbers crossing the nucleus and carrying many GeV of energy. (It is not safe to claim their energy splittings $\Delta E = \Delta m^2/2E$, because this is an approximation assuming the interacting dispersion relation is known, namely, $E^2 = p^2 + m^2$. Perhaps the true dispersion relation interacting with the nucleus is not too far from this, but there is a problem of applying the approximation with a long "lever arm" far out on an uncertain mass-shell hyperbola.)

The main advantage of the true eigenstate basis is that there is no mixing of states. The concept of "expansion" disappears in this basis. Plus, the impulse approximation applies with a vengeance: we pay the price of coupling the struck quarks onto the interacting states only once (per leg), and the final-state evolution, filtering, and all other interactions are included.

[1]For example, certain estimates of the expansion time used in Ref. [5] actually violate causality, inasmuch as the quarks expand at a speed greater than light in the hadron rest frame and in a broad family of boosted frames. Careful definitions need to be made to obtain reliable estimates.

The exact eigenstate basis allows us to state a result. Consider the "transparency ratio" T, which is the ratio of the measured rate in a nuclear target to the rate in free space. (If there is an issue of oscillations or non-short-distance contributions in the denominator [7], we assume this has been taken out.) For definiteness, we are assuming that the rate measured is the number of quasielastic protons, which depends on the photon Q^2. From our analysis we can relate the measured transparency ratio T directly to the relative probability of quarks to be at small separation, namely,

$$T=\frac{|\langle \tilde{\psi}_{p/A}(b^2<1/Q^2)\rangle_x|^2}{|\langle \tilde{\psi}_{p}(b^2<1/Q^2)\rangle_x|^2}\ , \tag{2}$$

where $\langle\ \rangle_x$ indicates the convolution over the x variables with the initial distribution amplitude and the known hard-scattering kernel. Note that the leading power of Q^2 of the hard scattering cancels out in the ratio. All effects of color transparency, then, are coded into the only available matrix element, namely, the wave function for quarks to have $b^2<1/Q^2$. The experiment measures what is basically a ratio of probabilities for quarks to be found near the origin in the nuclear target, compared with free space.

Equation (2) is one of the main results of this paper. Suppose, for simplicity, we also consider a factorized model of the x and b dependence of the wave function

$$\tilde{\psi}_{p/A}(x,b)=\tilde{\psi}_{p/A}(b)\xi(x)\ .$$

This is not entirely compatible with detailed renormalization-group predictions [3,8], but since logarithmic effects will undoubtedly not dominate at the low energies of the data, this is an acceptable ansatz. Then the convolutions over x cancel out to some constants, giving

$$T=\text{const}\times\frac{|\tilde{\psi}_{p/A}(b^2<1/Q^2)|^2}{|\tilde{\psi}_{p}(b^2<1/Q^2)|^2}\ . \tag{3}$$

It says that if the transparency ratio increases by a factor of 2 going from Q_0^2 to Q_1^2, say, then the ratio of wave functions squared, namely, the probabilities of the interacting eigenstates, has increased by a factor of two over the spatial region of $b^2<1/Q^2$. By taking ratios of ratios, one can map out the wave function near the origin, up to the uncertainties caused by the x dependence. To a good approximation, the region mapped out is $b=\frac{1}{5}$ fm(GeV$/Q$). Equation (3) depends on the factorization ansatz $\psi(x,b)=\psi(b)\xi(x)$, but Eq. (2) is an "exact" result of the impulse approximation, inasmuch as we have not made further approximations. It is quite simple, but a point that has not received serious attention.

We now turn to what data can teach us.

(a) *If transparency increases with energy.* From Eq. (2) we can make a surprising *deduction* about the exact interacting eigenstates. Consider the region of energies $1<E<20$ GeV, where every theoretical model (so far) of relativistic quark systems predicts that the transparency ratio rises approximately like a power of the energy. Suppose, moreover, that this prediction is correct. Then the quark overlap wave function near the origin of the *exact* eigenstates is a strong function of the energy, rising like a power.

This is a rather strange and unprecedented phenomenon in a relativistic bound state. One would ask whether the flow of probability toward the origin occurs because the probability in the three-quark sector is approximately conserved, while flowing to the origin, and the system is truly becoming "mini." Another possibility is that the system is full sized and the central region simply rises. A third possibility is that the average size does not change, but that the three-quark wave function develops a "spike." These possibilities are sketched in Fig. 2; the transparency ratio itself cannot distinguish between them.

This brings up the distinction between the relativistic quark system and the heavy-quark meson. For a heavy-quark system such as charmonium or upsilon, the fully interacting state may be a simple nonrelativistic few-body system. The reduced attenuation predicted by perturbative decoupling then applies to a dominant part of the wave function. Thus we find that the prediction of transparency [9] is much more reliable here. As remarked by others the observation of transparency phenomena in QED [10] adds weight to the prediction, without adding information about the issues of relativistic bound states. Nevertheless, there are currently several predictions, including decreasing transparency, when all possible resonant states are brought into the problem [11].

Other measures of the transverse size of the hadron could possibly settle the question of the smallness of the interacting state. For one thing, the transverse spread of the detected final-state momentum distribution is a measure of final-state interactions, convoluted with Fermi motion. If the proportion of processes obeying the hadron helicity conservation rule [12] increases with Q^2, then the system is likely becoming more "small" [13]. All of this is in accord with conventional thinking, in which nuclear filtering plays a role of reducing the size of the in-

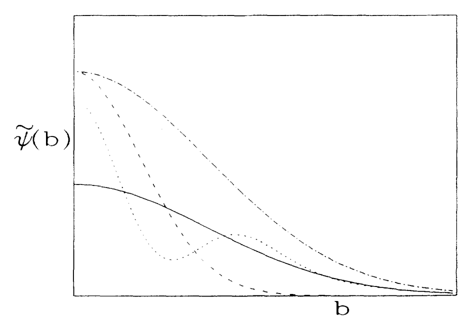

FIG. 2. Illustrations of possible nonperturbative few-quark b space wave functions that could lead to color-transparency ratios that rise with energy. Long-dashed line: a normalized wave function, showing probability flow toward the origin with increasing energy, compared with the conventional hadron (solid line). Dot-dashed line: a wave function for a full-sized system with a rise in the central region. Short-dashed line: development of an increase in the wave function at the origin by a spike at the origin.

teracting system and enriching the three-quark component. It would confirm that the concept of nuclear filtering is inseparable from color transparency. However, contrary to cherished belief, it is not the only possibility.

(b) *If transparency is constant with energy.* If transparency ratios are constant, it is telling us that the three-quark wave function at the origin is constant. There are a number of logical loopholes so that this might happen.

Recall the motivation for transparency: The small perturbative cross section of the small-b region of a few-quark color singlet allows one to relate the nuclear distribution amplitude to the free-space one [1,4]. By following this perturbative logic, one comes to a nonperturbative conclusion about the interacting wave functions. The conclusion is very reasonable, because the region of the color singlet near the center is not filtered away. *But this does not precisely say that the interacting state is ever small* because the rest of the fully interacting proton may not be specified by the three-quark component. Nor does high energy save us: The time scale for forming the interacting proton energy eigenstate is not the nuclear crossing time, but infinity.

Indeed, nonperturbative properties are not necessarily dependent on *any* perturbative result. Energy eigenstates, in particular, require infinite time to define. A small perturbation acting over a long enough time can usually upset a perturbative result. Back in the free-space (1) basis, this same long-time problem also appears, because superposition is responsible for so much in this basis: not only is mixing complicated, but multiple reflections from the nuclear edges, expansion, reshrinking, and probability back flow from excited states needs to be included *coherently,* all the way out to infinity. Such effects have been mentioned [2,11], but are not yet well controlled by calculations on the market. Simply put, it may not be important to the interacting system that the lowest quark projection has a small cross section.

If transparency were constant with energy, we would find that the transmission of eigenstates through nuclear media is not affected by the reduced interaction of the three-quark part. In fact, we already know that the total cross sections of hadrons are fairly constant with energy over the region of interest. The total cross sections are dominated by the multiquark components. After dividing out the oscillations, the data of Carroll *et al.* [14] show a *flat* energy dependence of $pp \rightarrow pp$ scattering in a nucleus, consistent with this (Fig. 3). Moreover, both the data of Carroll *et al.* and the preliminary data of SLAC NE18 [15] measure the transverse momentum distribution (of outgoing proton momenta about the measured Q vector), which is interpreted as originating in the Fermi motion of the target. The data show the puzzling phenomenon of scaling with Q^2; that is, the data lie close to the same curve when one goes from one Q^2 to another. Actually, these data represent the convolution of the Fermi motion with final-state interactions of the outgoing proton. Why apparently don't final-state interactions depend on Q^2? Naive transparency predicts decreased interactions and no scaling. A constant transparency might be expected, and perhaps has already been seen, if the three-quark component is not autonomously evolving in nuclear interactions, but instead is a mere slave driven by the interactions of the proton with itself.

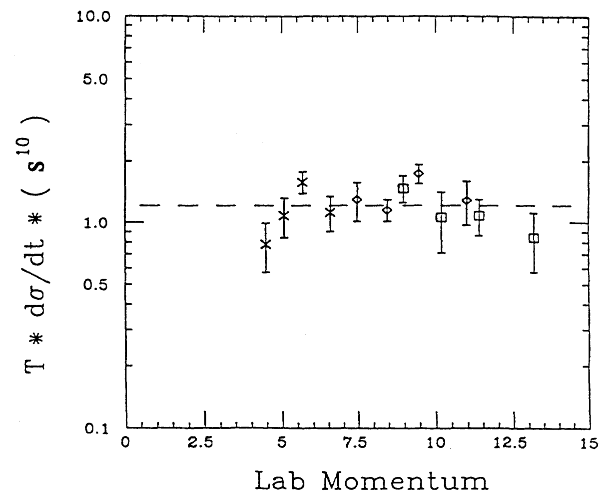

FIG. 3. Data from the Brookhaven experiment of Carroll *et al.* (Heppelmann [14]) showing the energy dependence of s^{10} $d\sigma_A/dt$ for proton nucleus quasielastic scattering [$pA \rightarrow p'p''(A-1), A=27$]. The plot shows that the cross section in the nuclear target scaled by s^{10}, which is the transparency ratio (T) times the free space cross section $d\sigma/dt$ with the same scaling, is rather flat with energy.

(c) *If transparency decreases with energy.* This is an unusual possibility, but we list it to emphasize that the relation (2) remains useful even if there are disappointing surprises. One can easily come up with scenarios to interpret a decrease of the wave function at the origin. In the case of nonrelativistic systems such as charmonium, transparency decreasing with energy has been obtained [11] as a result of strong mixing of resonances in the free-space eigenstate basis. This translates to a prediction that the exact interacting eigenstate is strongly mixed, if correct. For light-quark systems, nuclear filtering should decrease the multiparton components, perhaps destabilizing the unknown processes which feed the three-quark amplitude. Since so little is known, we just give an example to make the point: In diagonalizing the interacting proton, suppose we found the coupling of the three-quark plus multigluon sectors made a huge difference for the three-quark amplitude at the center. This sort of thing is not impossible, and as long as we have no reliable theory of the relativistic three-quark amplitude, it should be considered. Then, disturbing the balance of these components by filtering, the energy eigenstate reflects the change by reducing the amplitude at the origin, with apparently catastrophic results.

From the list above, one sees that one can use perturbative QCD, require the reduced interaction of a small three-quark color singlet, *and yet doubt* the prediction that the wave function at the origin grows rapidly with energy. Color transparency is not so much a prediction of QCD, but rather a prediction of imperfect models of QCD. The most positive thing that can happen is increasing transparency, because it would allow us to continue with the belief that the three-quark component of the proton is an important part.

However, one could equally well surmise, on the basis of cross-section data, that the interacting wave functions near the origin will be fairly independent of the energy. Given the current theoretical attitude, this can be considered speculative and bizarre, but it is a view by which Glauber theory might be vindicated in the end. What is needed is data, which we claim will measure something of value regardless of the predictions.

We thank Al Mueller, Stan Brodsky, and Byron Jennings for useful conversations. Some of the results of this paper stem from many earlier conversations with Bernard Pire. This research was supported in part under DOE Grant No. DE-FG02-85-ER-40214.A008.

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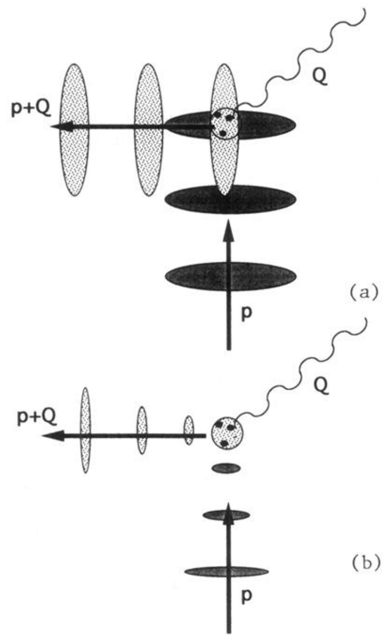

FIG. 1. Cartoons of different approximations. (a) In the impulse approximation, we need the overlap from an initial-state pancake onto a hard scattering (small circle) and then onto a final-state pancake. (b) In the adiabatic approximation, the system is gradually prepared to a small size which can interact with the hard scattering and then expand.