Color mixing in high-energy hadron collisions

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The color mixing of mesons propagating in a nucleus is studied with the help of a color-octet Pomeron partner present in the two-gluon model of the Pomeron. For a simple model with four meson-nucleon channels, color mixings are found to be absent for pointlike mesons and very small for mesons of small sizes. These results seem to validate the absorption model with two independent color components used in recent analyses of the nuclear absorption of J/ψ mesons produced in nuclear reactions. [S0556-2821(98)07015-5]

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The two-gluon model of the Pomeron (TGMP) [1–4] gives a simple if somewhat oversimplified [5–7] picture of high-energy hadron-hadron scatterings. It makes the interesting prediction that color-octet (C8) hadrons interact much more strongly with nuclei than color-singlet (C1) hadrons [8,4]. This color dependence of hadron-nucleon cross sections makes it possible to obtain information about the C8 fraction of meson precursors produced in nuclear reactions, a topic of considerable current interest.

Analyses of the absorption of J/ψ mesons produced in nuclei at high energies using an absorption model with both C1 and C8 precursors propagating independently have recently been made [9,10]. In one analysis [9], both the C8 fraction and its absorption cross section $\sigma_{\text{abs } 8}$ by a nucleon are fitted to the data for an assumed C1 cross section $\sigma_{\text{abs } 1}$. Fitting the 800 GeV data gives $\sigma_{\text{abs } 8}\approx 15$ (20) mb if $\sigma_{\text{abs } 1}$ is taken to be 0 (3.5) mb. The important change is in the fitted C8 fraction, which decreases from 0.7 to 0.5 when $\sigma_{\text{abs } 1}$ takes on the nonzero value. The data at 200 GeV are not as informative, but they seem to prefer smaller values of $\sigma_{\text{abs } 8}$.

In another analysis [10], the C8 fraction is first deduced from other production data, and only $\sigma_{\text{abs } 8}$ is fitted. A value of 11 mb is obtained by fitting data at 158–450 GeV, in rough agreement with the more empirical analysis of [9]. However, as first pointed out by Wong [11], the fitted cross sections disagree seriously with the theoretical C8 total cross section, which in the TGMP is about 50 mb [4,8].

Before discussing this discrepancy between theory and experiment, we shall first review an older picture of absorption based on a single precursor component [12]. The absorption data require an absorption cross section of about 7 mb [12,13], whatever the nature of the precursor. This cross section is somewhat larger than that expected of J/ψ mesons of normal size. However, the major problem is that the $c\bar{c}$ pair originally produced at a point may not have sufficient time to grow to full size before it interacts with another nucleon [14]. It has been proposed instead that the $c\bar{c}$ pair picks up a hard gluon soon after production and propagates in the nucleus as a $[(c\bar{c})_8 g]_1$ hybrid [14]. The hybrid cross section in the TGMP is known to be about 9/4 that of the C1 meson with the same mean square radius (between the gluon and the pair in the case of the hybrid) [14,15].

This hybrid picture is very attractive because the hybrid size can be chosen to fit any cross section. In fact, it has no trouble accommodating the two-precursor model where the unexpectedly small empirical value found for $\sigma_{\text{abs } 8}$ can simply be attributed to a precursor produced as a C8 pair but propagating as a hybrid of the right size. The hybrid model also addresses the conceptual question as to how the C8 pair could remain a free unfettered object as it propagates in the nucleus. However, it is fair to say that this very promising hybrid picture has not been established beyond reasonable doubt.

Let us now concentrate on models in which both C1 and C8 meson precursors are produced. If these precursors are not coupled by subsequent interactions with nucleons, they would propagate independently after production. This is the picture assumed in the two-precursor models used recently in data analysis [9,10]. The main purpose of this Brief Report is to determine if the assumption of independent propagation is justified. This is done by studying a model in which the C1-C8 mixing of these meson precursors is induced by a C8 partner of the usual C1 Pomeron. The coupled-channel problem is cast in the approximate form used in [16,4], and solved for four chosen meson-nucleon channels. The resulting color mixings are found to be absent for pointlike mesons, and are very weak for small mesons: The cross sections are practically unchanged, while the predominantly C1 meson eigenchannel has only 1% admixture of C8 states. These results seem to justify the assumption of independent propagation of the produced color precursors.

Let us begin by noting that although the C8 and C1 meson states can be connected by the exchange of single gluons, such Born amplitudes are real and do not contribute to the imaginary part of the forward scattering amplitude appearing in the optical theorem. This means that it is necessary to use the TGMP also for the cross-channel terms that cause color mixing in the interacting hadrons. This involves the exchange of a C8 version of the Pomeron.

To obtain these matrix elements, we simply use the same color operator of the TGMP with different channel wave functions. Only four different color channels are included in the present study: two overall C1 channels $|m_1N_1\rangle$ and $|(m_8N_8)_1\rangle$, and two overall C8 channels $|m_1N_8\rangle$ and $|m_8N_1\rangle$, where m_i (N_i) denotes a meson (nucleon) state of color C1 (C8) for $i=1$ (8). These states will be labeled 1 to 4, in the order presented.

The overall C1 channels do not mix with the overall C8 channels. The total cross section is thus described by a 4×4 matrix Σ, with the following nonzero matrix elements:

$$\Sigma_{11}=\sigma(1,1)-\sigma(2,1)-\sigma(1,2)+\sigma(2,2), \tag{1}$$

$$\Sigma_{12}=\Sigma_{21}=\frac{5}{8}\sqrt{2}\Sigma_{11}, \tag{2}$$

$$\Sigma_{22}=\frac{69}{16}\left\{\sigma(1,1)-\frac{4}{23}[\sigma(2,1)+\sigma(1,2)]+\sigma(2,2)\right\}, \tag{3}$$

$$\Sigma_{33}=\sigma(1,1)-\sigma(2,1)+\frac{1}{8}[\sigma(1,2)-\sigma(2,2)], \tag{4}$$

$$\Sigma_{44}=\sigma(1,1)+\frac{1}{8}\sigma(2,1)-\left[\sigma(1,2)+\frac{1}{8}\sigma(2,2)\right], \tag{5}$$

and

$$\Sigma_{34}=\Sigma_{43}=\frac{5}{16}\Sigma_{11}. \tag{6}$$

Here $\sigma(i,j)$ is the absolute value of the contribution when the number of quarks involved on the meson (nucleon) side of the interaction is $i(j)$. Thus

$$\sigma(2,2)=8n_m n_N \alpha_s^2 \int d^2\mathbf{k} D^2(k) \times f_m(4k^2) f_N(3k^2), \tag{7}$$

involves both meson and nucleon wave-function form factors, f_m and f_N, respectively [1–3,17,18,8,19,4]. In this expression, n_i is the number of quarks in hadron i, α_s is the strong interaction coupling constant, and $D(k)$ is the nonperturbative and nonsingular gluon propagator commonly used in the TGMP. On the other hand,

$$\sigma(1,1)=8n_m n_N \alpha_s^2 \int d^2\mathbf{k} D^2(k) \tag{8}$$

contains no wave-function form factor at all, while $\sigma(2,1)$ involves only the meson form factor, and $\sigma(1,2)$ involves only the nucleon form factor. Equation (6) is greater than the result reported in [8] by a factor of 5/2.

For pointlike mesons, $\sigma(2,j)=\sigma(1,j)$. Σ_{11} and all the channel-coupling terms then vanish. The C1 and C8 meson precursors then propagate independently of each other.

The color mixing does not vanish for mesons of finite size and therefore nonzero mixing matrix elements. The question is also interesting because of a minor complication: The mesons (including the C8 ones) see a C1 nucleon on approach, but leave it behind after scattering partially in C8 states. This means that the nucleons are not in color eigenmodes except in the trivial non-coupling limit.

With C1 (C8) mesons approaching in channels 1 (4) and exiting in channels 1 and 3 (4 and 2) at each nucleon site, one can construct a simple mixing problem with 2 meson channels for meson-nucleus scattering if one assumes that each pair of meson exit amplitudes add coherently. The mixing is then described by the 2×2 matrix

$$\begin{pmatrix} \Sigma_{11} & \Sigma_{34} \\ \Sigma_{21} & \Sigma_{44} \end{pmatrix}=\Sigma_{11}\begin{pmatrix} 1 & \frac{5}{16} \\ \frac{5}{8}\sqrt{2} & x \end{pmatrix}, \tag{9}$$

where

$$x=\frac{\Sigma_{44}}{\Sigma_{11}}\approx\frac{48\ \text{mb}}{5.7\ \text{mb}}=8.42. \tag{10}$$

This matrix is real, but not symmetric. It is diagonalized by a similarity transformation that is not unitary.

When expressed in units of Σ_{11}, only the matrix element x depends on the meson size. Using the numerical values from [4] shown in Eq. (10), the eigenvalues are found to be 0.96 Σ_{11} and 8.46 Σ_{11}, while the corresponding eigenvectors are (0.993, -0.118) and (0.042, 0.999). These color mixings are very weak; the mixing is stronger in the first state where the C8 fraction is only 1%.

Two conclusions could be drawn from these results. First, the meson precursors of different color structures, once produced, do appear to propagate quite independently of each other. Secondly, the weak color mixing found in our model does not match the picture sketched in [11] of 10–20 % admixture of C8 components in a single ''coherent'' meson precursor propagating in the nucleus with a single absorption cross section.

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