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Channel-coupling effects in high-energy hadron collisions

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The two-gluon model of the Pomeron predicts strongly size-dependent high-energy hadron cross sections. Yet experimental cross sections for radially excited mesons appear surprisingly close in value. The strong coupling of these mesons in hadron collisions also predicted by the model permits a qualitative understanding of this puzzling behavior in terms of eigenmode propagation with a common eigen-σ. A detailed semiempirical coupled-channel model of the Pomeron is constructed to elucidate this and other features of high-energy hadron cross sections. [S0556-2821(96)50219-5]

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The two-gluon model of the Pomeron (TGMP) has given a simple and rather successful picture of high-energy hadron-hadron scatterings [1,2]. Its most appealing feature is perhaps this: While accounting for the dependence on quark numbers emphasized so graphically by the additive quark model [3–5], it goes beyond the latter by giving a natural explanation of the flavor dependence of hadron cross sections as a size effect arising from the color separation inside colorless hadrons [6,7]. This model prediction seems consistent with meson-nucleon (mN) cross sections for ground-state mesons [8]. Theoretical support has come from nonperturbative QCD [9] and lattice calculations [10].

To account for other features such as the dependence of the cross sections on the squared c.m. energy s, this simple picture of the Pomeron must be improved by the inclusion of Fock-space components of the hadrons containing gluons [11] in a Balitskii-Fadin-Kuraev-Lipatov (BFKL) evolution equation [12,13]. These additional processes are also needed to achieve the cancellation of infrared divergences in the gluon-gluon scattering amplitude that would otherwise appear [13]. This means that the TGMP discussed here, which uses nonsingular gluon propagators, is only an effective model.

This paper is concerned with the puzzling prediction of this phenomenological TGMP that mN cross sections are much larger for radially excited mesons of larger radii. In the small-meson limit [6], these cross sections are proportional to the meson ms radii, so that $\sigma_{\psi'N}$ would be about four times larger than $\sigma_{(J/\psi)N}$.

Yet their experimental values appear to be similar: The older data on nuclear photoproduction, when analyzed in the vector-meson dominance (VMD) model [14] gives a cross-section ratio of 0.77 (uncertainty 14) for the SLAC data [15], 0.77 (9) for the NA14 data [16], and 0.78 (11) for the E401 data [17]. [When corrected with modern branching ratios [18], these numbers should be changed to 0.79(15) and 0.86(10) for the first two data.] For muon production, one finds the ratio 0.81 (19) for the European Muon Collaboration (EMC) data [19], updated to 0.76 (18) with modern branching ratios. For the E772 data on the proton production in nuclei [20], analyzed in the Glauber multiple-scattering formalism [21] with uniform nucleon densities fitting experimental nuclear radii [22], we get 9.0 mb/7.8 mb = 1.15. A more careful analysis of this rough equality, already noted in [23], has recently been made in [24].

Yet another piece of the puzzle comes from the nuclear production amplitudes of excited mesons relative to that of their ground state in mN scatterings. Hüfner and Kopeliovich (HK) [25] have recently deduced an experimental value of 0.46 for the production amplitude ratio $\psi'/(J/\psi)$ in p-nucleus (A) collisions [26,27]. They have tried to explain this ratio in terms of a two-channel model of meson produc-

tion using harmonic-oscillator (HO) wave functions and mN cross sections in the small-meson limit. We shall show below that this two-channel model is unstable, and that the generalization to many channels gives very poor results.

The purpose of this paper is to show that this channel-coupling (CC) idea, when properly applied, seems to provide a key to a qualitative understanding of these puzzling features. The essential ingredients seem to be: (1) using the full TGMP without making the small-meson approximation, (2) using more realistic meson wave functions, and (3) using many meson channels. A semiempirical CC model of the Pomeron is constructed to elucidate the many interesting features of mN cross sections.

Let us begin by pointing out that the coupling between different reaction channels of different hadron (h) excitations is unavoidable in hA scattering. What is not clear is whether the coupling is strong or weak in the TGMP. We shall see that it is strong for color-singlet mesons on nucleons, but weak for color-octet mesons.

For definiteness, we consider the simplified situation where the target hadrons are the nucleons in a nucleus and where only the projectile meson undergoes radial excitations. Channel coupling is in general a multiple-scattering phenomenon. Its physics becomes particularly transparent when described in the attenuation appoximation [28,25], where a multichannel wave is attenuated by the matrix $\exp(-\rho_0 L\sigma)$ in channel space. Here ρ_0 is the nucleon density, $L=\frac{3}{4}R(1-1/A)$ is the average attenuation length across a nucleus of radius R, and σ is the matrix containing both single- and cross-channel absorption cross sections. It is usefully expressed as the dimensionless matrix $M=\sigma/\sigma_0$, where $\sigma_0=\sigma_{11}$, so that $M_{11}=1$.

The attenuation of the multichannel hadron wave can then be understood in terms of the eigenvalues and eigenvectors of M. After a generally complicated transient, the wave will eventually decay into that eigenmode belonging to the smallest eigen-σ, hereafter called the ''lowest'' eigenmode. When produced in an eigenmode, the hadrons will propagate in that eigenmode over all distances, with the same eigen-σ, and therefore the same attenuation, in all channels. However, only the lowest eigenmode is stable against perturbations.

In the HK model [25], the nucleons remain unexcited, but the propagating J/ψ meson can be excited radially. In addition, the CC matrix M is calculated in the small-meson limit using HO wave functions. It is then a tridiagonal matrix in channel space.

The HK model is based on the observation that in the two-channel approximation, the theoretical ψ'/ψ ratio F of wave amplitudes in the lowest eigenmode agrees with the experimental value of 0.46 (6). This agreement is displayed in the first row of Table I, where Σ_i is the ith eigen-σ, and $\mathbf{v}_i(j)$ is the wave amplitude in the jth channel of its eigenvector.

However, as the number n of channels increases beyond 2, the amplitude ratio F increases rapidly to above 1, thus destroying the agreement with experiment. At the same time, Σ_1 decreases towards zero, making the nucleus increasingly transparent to meson propagation. This result also contradicts the well-known experimental fact that the effective ψN cross section in nuclei is larger than its value in free space [28].

TABLE I. The lowest eigenmode of the channel-coupling matrix M for J/ψ mesons in different models.

| Model | HO r^2 | | NP/HO | | NP/Hy | |
n	Σ_1/σ_0	F^a	Σ_1/σ_0	F^a	Σ_1/σ_0	F^a
2	0.61	0.47	0.66	0.53	0.92	0.142
3	0.44	0.68	0.49	0.72	0.89	0.153
4	0.35	0.80	0.40	0.83	0.88	0.158
15	0.10	1.10				
30	0.05	1.16				
∞	0.00	1.22	0.02	1.22	0.86	0.169

$^aF=\mathbf{v}_1(2)/\mathbf{v}_1(1)$

The table shows that in this HO r^2 model, stability in the ψ'/ψ amplitude ratio F requires the inclusion of at least 30 channels. The results numerically extrapolated to $n=\infty$ by using a ''diagonal'' rational approximant [29] are also given.

The situation is more interesting if the small-meson approximation is not used. We start with the full hN amplitude of the TGMP first derived by Low and others [1,2,6,7,9,30,31], using either perturbative or nonperturbative (NP or Cornwall) gluon propagators [32,33] with an effective gluon mass $m=m(q^2=0)$. Application of the optical theorem yields the total hN cross sections

$$\sigma_{ij}(h)=8n_h n_N \alpha_s^2 \int d^2\mathbf{k}D^2(k)\Phi_{ij}(h;k)\Phi_N(k), \quad (1)$$

where n_i is the number of quarks in hadron i, and

$$\Phi_N(k)\simeq 1-f_N(3k^2), \quad (2)$$

$$\Phi_{ij}([q\bar{q}]_1;k)=\delta_{ij}-f_{ij}(4k^2), \quad (3)$$

$$\Phi_{ij}([q\bar{q}]_8;k)=\delta_{ij}+\tfrac{1}{8}f_{ij}(4k^2), \quad (4)$$

$$\Phi_{ij}([(q\bar{q})_8 g]_1;k)\simeq\tfrac{9}{4}[\delta_{ij}-f_{ij}(4k^2)]. \quad (5)$$

Here f_{ij} is the diagonal or off-diagonal wave-function form factor. The proton and $[q\bar{q}]_8$ expressions are from [30], while the color factor for the hybrid is from [34,35]. The expression for hybrid mesons involves only the separation between g and $(q\bar{q})_8$ if the weak dependence on the $q\bar{q}$ separation is neglected.

Each hadron factor in Eqs. (2)–(5) contains two terms: (1) a one-body term diagonal in the channel index caused by the exchange of both Pomeronic gluons with the same body: q, $\bar{q}$, or the $(q\bar{q})_8$ of the hybrid treated as a single body, and (2) a two-body term arising from the gluons interacting with both parts of the hadron, dependent on form factors, and responsible for channel coupling. For a colorless hadron, these terms interfere destructively because the scattering amplitude vanishes for a point hadron [6]. This is why the cross sections are so sensitive to hadron sizes, and could be quite small even though each term is large. In color octets, however, the two-body term is much weaker and adds constructively to the one-body term. The result is much larger cross sections and much weaker channel couplings.

TABLE II. Pomeron-exchange contribution (in mb) to $\sigma_{hN} = X_{hN}s^{0.0808}$ at $\sqrt{s} = 20$ GeV using dipole form factors.

Hadron $D(k)$	$\langle r^2 \rangle^{\text{a}}$	Ref.	X_{hN} NP	Perturbative	σ_{hN} NP
p	0.67(2)	[43]	21.70[b]		35.21[b]
π	0.44(1)	[44,45]	13.63[b]		22.12[b]
K	0.31(5)	[45,46]	11.82[b]		19.18[b]
J/ψ	0.044	[36]	3.2(7)	3.7(5)	5.2(12)
	0.055	[38]	3.8(8)	4.3(6)	6.2(13)
ψ'	0.181	[36]	8.6(9)	8.8(7)	14.0(15)
Υ	0.013	[36]	1.1(3)	1.6(3)	1.9(6)
Υ'	0.063	[36]	4.2(9)	4.7(6)	6.8(14)
ρ,ω	0.54	[47]	14.90(12)	14.91(9)	24.2(2)
K^{a}	0.37	[47]	12.6(4)	12.6(3)	20.5(7)
ρ_8	0.54	[47]	28(8)		45(12)
$(J/\psi)_8$	0.044	[36]	29(8)		48(13)
Υ_8	0.013	[36]	29(8)		47(13)

[a]In fm.
[b]Experimental results from [5].

TABLE III. The lowest eigenmode in the 75%(HO)/25%(Hy) model and the GVMD input vector $\mathbf{v}_\gamma$ in different meson families. Meson ms radii used are those of Table II.

Mesons	Type	Σ_1/σ_0	$\mathbf{v}_1$ or $\mathbf{v}_\gamma$
ρ	$n=4$	0.69	(1,0.69,0.50,0.35)
	$n=\infty$	0.46	(1,0.90,...)
	γ		(1,0.35,...)
J/ψ	$n=4$	0.71	(1,0.40,0.19,0.09)
	$n=\infty$	0.65	(1,0.45,...)
	γ		(1,0.58,0.32,0.25,...)
Υ	$n=4$	0.74	(1,0.32,0.12,0.05)
	$n=\infty$	0.70	(1,0.35,...)
	γ		(1,0.64,0.58,0.40,0.45,0.29,...)

Ratios of these cross sections are theoretically simpler: They are independent of α_s in the perturbative treatment, and only weakly dependent on the QCD energy scale Λ_{QCD} in the NP treatment. We determine m by a best fit to the ratio $\pi N/pN$ and KN/pN of the experimental Pomeron-exchange cross sections at the experimental hadron matter radii, both given in Table II. (Matter radii are deduced from charge radii.) The result is $m = 0.08(10)$ GeV in the perturbative treatment, and 0.27(6) GeV in the NP treatment used below, the latter being at the lower end of the Cornwall estimate of 0.5(3) GeV [32]. These masses are obtained with dipole form factors and $\Lambda_{\text{QCD}} = 0.3$ GeV, but the results for Gaussian form factors and other values of Λ_{QCD} are practically the same. Note that the product $\alpha_s D(k)$ does not depend on α_s in the NP treatment, and that the estimated error in m comes only from the errors in the input hadron radii, since the errors in the Pomeron cross sections are unknown.

Meson wave functions are needed to calculate the CC matrix M. The effort is greatly reduced by using HO and the hydrogenic (Hy) wave functions. Neither turn out to be adequate, but they bracket more realistic wave functions, thereby allowing a simulation of the latter by the interpolation of their M matrices. As in Ref. [25], we have used σ_{total} instead of σ_{abs} in M.

As shown in Table I for J/ψ mesons, the results for HO wave functions, though improved over the HO r^2 model, are not yet convergent with four channels. On the other hand, the results for Hy wave functions are beginning to converge with four channels, because the off-diagonal matrix elements are much weaker. This difference is also responsible for the result, already noticeable in Table I, that channel mixing in the lowest eigenmode becomes much weaker in the Hy model. (The channel components in the lowest eigenmode are highly coherent and have the same sign because all the off-diagonal matrix elements of M have the same negative sign.)

The wave-amplitude ratio F for the first two channels turns out to be too large for the HO model, but too small for the Hy model, when compared to the experimental value of 0.46(6) quoted previously. To simulate more realistic wave functions, we take the linear combination of the two theoretical cross-section matrices that will reproduce the experimental value of F when the $n = 2,3,4$ results are numerically extrapolated to $n = \infty$ [29]. This gives the "75%(HO)/25%(Hy)" model shown in Table III. Obviously the fit would change with future changes in F, but the qualitative features of the model should be similar.

The lowest eigen-σ Σ_1, which controls the steady-state propagation, should be lower than the smallest single-channel cross section σ_0. It is about $0.64\sigma_0$ for J/ψ mesons in the 75/25 model. As channel-coupling decreases in going from the HO r^2 to the Hy model, the reduction of Σ_1 below σ_0 also becomes less and less.

The Pomeron-exchange parts σ_0 of ground-state hN cross sections are themselves of interest. These can be obtained from the theoretical cross-section ratios by multiplication into the empirical pN Pomeron contribution of $21.70(s/\text{GeV}^2)^{0.0808}$ mb fitted by Ref. [5]. In this way, we not only reduce the considerable sensitivity of each cross section to model parameters, but also recover the experimental s dependence. Using dipole form factors fitting theoretical meson ms radii, we obtain the TGMP predictions shown in Table II. The errors shown come from the uncertainty of the gluon mass m. In addition, the cross sections are smaller by about 5% for Gaussian form factors.

At $\sqrt{s} = 20$ GeV, we find $\sigma_0 \simeq 5.2$ mb for a J/ψ meson ms radius of 0.044 fm^2 [36]. This is about twice the value of 2.4 mb calculated in the short-distance QCD model of [37], and almost the same as the 6 mb obtained in [28], or the 8 mb reported here, both from nuclear suppression data. If the meson ms radius is 0.055 fm^2 [38], σ_0 would have been 6.2 mb.

Stable asymptotic propagation in nuclei on the other hand involves the lowest eigen-σ Σ_1. For J/ψ mesons, this is $\simeq 0.64\sigma_0 = 3.3(8)$ mb. The additional uncertainties from ΔF or the extrapolation to infinite matrix dimension probably does not exceed 0.3 mb each.

A number of conclusions can be drawn: (1) Colorless mesons of different radial excitations and sizes experience the *same* total mN cross section in nuclear suppression if they are propagating close to an eigenmode, usually the lowest

eigenmode. (2) The smallest eigen-σ Σ_1 is smaller than $\sigma_0 = \sigma_{11}$ of the meson ground state. (3) For colorless J/ψ mesons, Σ_1 is smaller than the effective mN cross section deduced from nuclear suppression. (4) The single-channel cross section σ_0 is about twice the 2.4 mb given by the short-distance QCD model [37]. Given the many uncertainties of our Pomeron model, it is not clear if the discrepancy is serious, and if so how it should be understood. Channel-coupling effects should also be present in the short-distance QCD model, but it is not known if they are strong or weak. (5) The nuclear propagation of hybrid mesons is quite similar to that for colorless mesons, but their cross sections are larger by the relative color factor $\frac{9}{4}$. On the other hand, color octets of different sizes tend to propagate independently in nuclei with roughly the same cross section. This is because the size-dependent, channel-coupling two-body term is only $-\frac{1}{8}$ of that in color singlets.

Concerning conclusion (3), it has been suggested that the the larger cross sections of the absorption model could arise from the appearance of J/ψ mesons in color octet forms, either together with a gluon in a hybrid [35], or as bare color octets [39]. A hybrid explanation of the increasing apparent nuclear absorption with increasing x_F discussed in [39] can readily be given in our TGMP, with the ms hybrid radius increasing from about 0.03 fm^2 at small x_F to about 0.25 (16) fm^2 at $x_F \simeq 0.6$.

Conclusions (1) and (2) have interesting implications in the generalized VMD model of meson photoproduction from nuclei. In this model, the photon appears as a coherent admixture of all possible virtual vector mesons. Progress in this problem in the past has been hindered by the lack of information on both the channel-coupling matrix and the incident meson amplitudes [14]. Our CC model gives very specific predictions, although limited to only a small number of channels in the present calculation. The lowest eigenvectors of our largest $n=4$ models, all with 75/25 mixing of wave functions, are shown in Table III for several meson families. The ground-state component $\mathbf{v}_1(1)$ has been taken to be 1 for ease of comparison. Each eigenvector can be compared with the GVMD input amplitude vector $\mathbf{v}_\gamma = (1, f_1/f_2, \dots)$, where f_i is the universal meson coupling constant to its source obtained from [18], and for ρ', from [40].

We see that the input amplitude vector for photoproduced mesons is rather close to the lowest eigenvector, especially for J/ψ's. Hence mesons are produced close to this eigenmode, and propagate in nuclei with roughly the same reduced cross section Σ_1 in different radial excitations. However, this reduction is not enough to explain why $\sigma_{(J/\psi)N}$ is only 1.8–1.9 mb at $\sqrt{s} = 18$–20 GeV when deduced from photoproduction data under traditional VMD [24] unless a smaller gluon mass is used.

The experimental ratio $\sigma(\psi')/\sigma(J/\psi)$ for production in pA collisions is also independent of A [26], meaning that the hadron production at a nucleon is also close to the lowest eigenmode when interpreted in the coupled-channel model. This idea of "eigenmode production," assumed both here and in [25], is roughly consistent with the color-evaporation model of quarkonium production [41,42] where the production amplitude appears in the coupled-channel form $\mathbf{v}_{\text{prod}} = (1, (f_1 M_1)/(f_2 M_2), \dots)$, where M_i is a meson mass.

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