Tests of QCD in Exclusive Reactions

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Phenomenology of simple exclusive reactions may help to show how QCD works for hadrons and pinpoint the right leading terms. QCD has reached the stage of condensed matter physics in QED. The basic theory and Lagrangian are known, but exact calculations from first principles of experimentally measurable quantities like the properties of a type II superconductor are impossible today. The "leading term syndrome" is used to calculate experimental predictions based on QCD hand-waving arguments and "nonleading effects" are blamed for any disagreement with experiment. We consider three examples: 1) OZI-forbidden transitions; 2) the reaction $\pi p \to \rho p$, and 3) the spin dependence of elastic proton-proton scattering.

1. The OZI Rule

QCD has not yet provided quantitative prescriptions for the suppression factors of OZI-forbidden "disconnected quark line diagrams".[1] Phenomenological analyses[1] of related processes with similar allowed and forbidden final states indicate that some are more forbidden than others. The well known $\phi \to \rho\pi$ and $f' \to \pi\pi$ decays are suppressed by factors of order 10^2 relative to the allowed $\omega \to \rho\pi$ and $f^0 \to \pi\pi$ transitions. In meson photoproduction the OZI-forbidden $\gamma \to \phi\pi\pi$ is comparable to the allowed $\gamma \to K^+K^-\rho^0$ and $\gamma \to K^+K^-\omega$ which also involve the creation of a strange quark pair and only a factor of ten smaller than $\gamma \to \omega\pi^+\pi^-$. All OZI-forbidden charmonium decays are suppressed by the enormous factor of 10^6 in comparison with allowed charmonium decays above the $D\bar{D}$ threshold, except for the $\psi'(3685) \to \psi\pi\pi$ decay which is only suppressed by a factor of order 10^3. The enormous signals which revealed the J/ψ decay were experimentally discovered by pure accident, because theorists erroneously overestimated its very narrow OZI-forbidden width by comparing it with $\phi \to \rho\pi$, and directed experimentalists to search for charm elsewhere.

These analyses suggest that some transitions are "semi-forbidden" and confirm a topological criterion defining semi-forbiddenness:[2]

1. Hairpin diagrams (strongly forbidden), in which the quark lines from a single hadron are disconnected from all other hadrons; e.g. $\phi \to \rho\pi$, $f' \to \pi\pi$ and all the strongly forbidden charmonium decays.

2. Ski-track diagrams (semi-forbidden), in which the disconnected piece can be a ski track. The quark lines from two hadrons are connected together and disconnected from the remaining part of the diagram, but there is no disconnected single hadron; e.g. $\gamma \to \phi\pi\pi$ and $\psi'(3685) \to \psi\pi\pi$. We discard the term "crossed-pomeron" diagrams previously used[1] because of its erroneous dynamical implications.[3]

QCD must provide a consistent theoretical description of these systematics and also explain the crucial role of nonet symmetry, exchange degeneracy and duality in suppressing OZI-violating two-step transitions, in which each step is OZI-allowed; e.g.[4-5]

$$\phi \to (K^+, K^{*+}) + (K^-, K^{*-}) \to \rho + \pi \tag{1.1}$$

$$f' \to (K^+, K^{*+}) + (K^-, K^{*-}) \to \pi + \pi \tag{1.2}$$

$$J/\psi \to (D^+, D^{*+}) + (D^-, D^{*-}) \to \rho + \pi \tag{1.3}$$

$$\pi^- + p \to (K^+, K^{**}) + (K^-, K^{**}) + n \to \phi + \phi + n \tag{1.4}$$

$$\pi^- + p \to (\eta, \eta') + n \to \phi + \phi + n \tag{1.5}$$

$$D^{**}(c\bar{d}) \to D^+ + (f^0, A2^0) \to D^+ + K^+ + K^- \tag{1.6}$$

where D^* denotes a high-mass charmed meson resonance.

This is illustrated in the comparison of the forbidden D^* decay mode (1.6) with the analogous OZI-allowed decay with a neutral kaon pair.

$$D^{*+}(c\bar{d}) \rightarrow D^+ + (f^o, A2^o) \rightarrow D^+ + K^o + \bar{K}^o \quad (1.7)$$

If the decay is dominated by the contributions from either the f^o or the $A2^o$ intermediate state the OZI rule is inconsistent with isospin invariance which requires the two decays (1.6)-(1.7) to be equal even though one overall transition (1.6) is OZI-forbidden and the other (1.7) is OZI-allowed. The OZI violation arises from terms in the transition amplitude involving $d\bar{d} \rightarrow u\bar{u}$ transitions in the propagators of the f^o and A2 mesons which are mixtures of the two flavors $d\bar{d}$ and $u\bar{u}$. The OZI rule is saved in the nonet symmetry limit where f^o and A2 mesons are exactly degenerate and their contributions to the forbidden reaction (1.6) exactly cancel.

Similar cancellations might save the OZI rule in the reactions (1.1)-(1.4) in a symmetry limit where the K and K^* and the D and D^* are degenerate. The symmetry is broken by mass differences, which are crucial in the reactions (1.1) and (1.2) as they leave the K^+K^- channel open and close all the others. The contribution from an on-shell K^+K^- intermediate state has been shown by a rough calculation[4] to explain completely the experimental widths. The observed $\phi \rightarrow \rho\pi$ width thus expresses the magnitude of this on-shell contribution which cannot be cancelled by other off-shell contributions. Its use as input for the J/ψ decay[1] where there are no on-shell contributions can easily give an erroneous overestimate of the OZI-violation. The J/ψ decay has been described by QCD as via a three-gluon intermediate state, with no justification for neglecting the hadronic contributions (1.3). Since all intermediate states in (1.3) are far off shell by an amount which is much larger than the D^* - D mass difference cancellations may well occur and drastically reduce this violation, but this has yet to be shown.

In the reaction (1.5), nonet symmetry is broken[4], the physical intermediate $I = Y = 0$ states are nondegenerate flavor mixtures like the η^* and η', and their contributions break the OZI rule because there are no degeneracies to produce cancellations.

There is no way with our present knowledge of hadron spectroscopy to estimate the strength of transitions like (1.4) and (1.5). The kaon pair may be either on shell or off shell and there can be contributions from many on-shell intermediate states involving K^* resonances. There are both off-shell contributions from the known physical η, η', ζ and ι mesons and on-shell contributions from radially excited states above the ϕ-ϕ threshold. The spectrum of radially excited states in the η-η' system is completely unknown, as well as their mixing angles and production cross sections.

2. Flavor and Spin Dependence of Meson-Baryon Reactions

Perturbative QCD suggests three different quark diagrams as leading terms for exclusive reactions:[6] multiple gluon exchange, quark exchange, and quark-antiquark annihilation. These diagrams have been shown to give very different predictions for the very similar reactions[7] $\pi^{\pm}p \to \rho^{\pm}p$, $\pi^-p \to \rho^o n$ and $\pi^-p \to \omega n$.

For multiple gluon exchanges which are flavor independent,

$$\left(\frac{\sigma(\pi^+p \to \rho^+p)}{\sigma(\pi^-p \to \rho^-p)}\right)_{GLUON} = 1 \tag{2.1}$$

$$[\sigma(\pi^-p \to \rho^o n)]_{GLUON} = [\sigma(\pi^-p \to \omega n)]_{GLUON} = 0 \tag{2.2}$$

The two models with quark exchange or annihilation involve a transition by a single "active" quark in the nucleon, with drastic differences between predictions arising from differences in the flavor of the active quark. In quark exchange the active quark is a u quark for the π^+ reaction and a d quark for the π^- reaction, while the reverse holds for annihilation. Some predictions are spin dependent and defined for two kinds of transitions, with the baryon transition described in one case by a spin independent (spin-scalar) operator and in the other by a spin-vector operator. The latter can give rise to spin-flip transitions.

In the model of quark exchange between the meson and the nucleon, the cross section ratios are:

$$\begin{aligned}&[\sigma_s(\pi^+p \to \rho^+p) : \sigma_s(\pi^-p \to \rho^o n) : \sigma_s(\pi^-p \to \rho^-p)]_{QEX} = \\ &= [\langle p|n_u|p\rangle : (1/\sqrt{2})\langle n|\sum_i t_{-i}|p\rangle : \langle p|n_d|p\rangle]^2 = 4:0.5:1\end{aligned} \tag{2.3}$$

$$\begin{aligned}&[\sigma(\pi^+p\downarrow \to \rho^+p\uparrow) : \sigma(\pi^-p\downarrow \to \rho^o n\uparrow) : \sigma(\pi^-p\downarrow \to \rho^-p\uparrow)]_{QEX} = \\ &= [\langle p\uparrow|S_{+u}|p\downarrow\rangle : (1/\sqrt{2})\langle n\uparrow|\sum_i s_{+i}t_{-i}|p\downarrow\rangle : \langle p\uparrow|S_{+d}|p\downarrow\rangle]^2 = 16:12.5:1\end{aligned} \tag{2.4}$$

where σ_s denotes the cross section for a spin independent transition induced by a spin scalar operator, n_u and n_d are the number of u and d quarks, $S_{\alpha u}$ and $S_{\alpha d}$ are the α-components of the total spins S_u and S_d of the u and d quarks respectively in the nucleon wave function, S is the total quark spin of the nucleon, $s_{\alpha i}$ and $t_{\alpha i}$ denote the spin and isospin operators respectively for the i-th quark in the nucleon, and S_α and T_α are the total spin and isospin. There is also the spin independent prediction

$$[\sigma(\pi^-p \to \rho^o n)]_{QEX} = [\sigma(\pi^-p \to \omega n)]_{QEX} \tag{2.5}$$

In the model of quark-antiquark annihilation and subsequent pair creation,

$$[\sigma_s(\pi^+p\to\rho^+p) : \sigma_s(\pi^-p\to\rho^0n) : \sigma_s(\pi^-p\to\rho^-p)]_{ANN} = \tag{2.6}$$
$$= [\langle p|n_d|p\rangle : (1/\sqrt{2})\langle n|\sum_i t_{-i}|p\rangle : \langle p|n_u|p\rangle]^2 = 1:0.5:4$$

$$[\sigma_s(\pi^+p\downarrow\to\rho^+p\uparrow) : \sigma(\pi^-p\downarrow\to\rho^0n\uparrow) : \sigma(\pi^-p\downarrow\to\rho^-p\uparrow)]_{ANN} = \tag{2.7}$$
$$=[\langle p\uparrow|S_{+d}|p\downarrow\rangle : (1/\sqrt{2})\langle n\uparrow|\sum_i s_{+i}t_{-i}|p\downarrow\rangle : \langle p\uparrow|S_{+u}|p\downarrow\rangle]^2 = 1:12.5:16$$

$$[\sigma(\pi^-p\to\rho^0n)]_{ANN} = [\sigma(\pi^-p\to\omega n)]_{ANN} \tag{2.8}$$

The standard SU(6) wave functions have been used to evaluate matrix elements, but the results are much more general.[7]

Recent experimental data[8] with 10 GeV/c pions incident on unpolarized protons at θ_{cm}=90°,$-t$=9 GeV^2/c^2 indicate that the ρ^- production cross section is very large, about half the elastic cross section, and that the ρ^- is aligned in the helicity ±1 state. If helicity is conserved at the quark level, this rules out the gluon exchange mechanism and implies that there must be a proton helicity flip. It will therefore be very interesting to examine the other charge states of this reaction.

3. High Transverse Momentum Transfer in pp Scattering

Two qualitatively different mechanisms for high transverse momentum transfer in hadron-hadron scattering are suggested by QCD. Hard gluon exchange between two quarks in two different hadrons is suppressed by powers of α_s. Constituent interchanges depending upon the high-momentum tail of the wave function are also suppressed; a minimum of five hard gluon exchanges is required to generate this high momentum tail in perturbative QCD. A simple three-gluon exchange without constituent interchange[9] would seem to be the dominant process with the minimum number of gluons. Sudakov form factors suppress hard gluon exchange when all quarks are on shell,[10-11] but not the gluon exchange involving off-shell quarks generating the high momentum tail of the wave function. There can also be combinations of hard gluon exchange with quark exchange.

In perturbative QCD a high transverse momentum transfer occurs via helicity-conserving vector interactions at the quark level. This predicts helicity conservation in hadron-hadron scattering in models with only gluon exchange. When constituents with opposite helicity are interchanged,[11] a double helicity flip can occur but not a single helicity flip. However, if the "spectator" quarks in the tail of the wave functions are non-relativistic, or they acquire a high transverse momentum in many small steps, it may be the quark spin direction in the center-of-mass system or some other Lorentz frame that is conserved, rather than helicity.[12-13]

Recent experiments show an unexpected polarization dependence in 28 GeV/c proton-proton elastic scattering at high transverse momentum, implying a single helicity flip in the scattering.[14] This suggests that perturbative QCD may not be valid and that there may be interesting physics in these spin effects.

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