Spin and mass effects in charmonium decays

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Abstract

The description of two-body charmonium decays in QCD cannot be entirely based on lowest order perturbation theory; the modest $Q^2$ values involved make higher order and non perturbative corrections still sizeable and, in some cases, indeed leading. The separate experimental evaluation of such corrections, according to the available data, is difficult. Two different spin measurements are suggested in $p \bar{p} \rightarrow \chi_{c2}$ and $\chi_{c2} \rightarrow \rho \rho$ processes, which are sensitive to the presence of two quark correlations inside protons and to constituent mass corrections respectively.

Introduction

Exclusive charmonium decays into meson or baryon pairs are extensively discussed in the literature [1-10]; the perturbative QCD scheme [1-4] shows both good agreement [10] with the experimental data and severe difficulties [11-13]. Most problems arise from the helicity conserving coupling of current quarks and gluons which forbids many processes [6]. As an example, let us consider $\eta_c$ and $\chi_{c0} \rightarrow p\bar{p}$ decays. According to the perturbative QCD scheme, the initial heavy quarks annihilate into hard gluons, which then create $q\bar{q}$ pairs with the $q$ helicity always opposite to the $\bar{q}$ one. The final quarks $q_f$ then hadronize collinearly into a final hadron with helicity $\lambda_h = \sum_i \lambda_{q_i}$; similarly do the antiquarks, $\lambda_{\bar{h}} = \sum_i \lambda_{\bar{q}_i}$. We are thus led to final states with only opposite helicity particles, $\lambda_h = -\lambda_{\bar{h}}$, which immediately forbids many charmonium decays. In particular, the decays $\eta_c$, $\chi_{c0} \rightarrow p\bar{p}$ should not occur.

* Talk delivered at the 10th International Symposium on High Energy Spin Physics, Nagoya, November 9-14, 1992
because a spin zero particle cannot decay into two opposite helicity fermions

Similarly forbidden, also due to the collinear configuration of the final quarks, are the \( \eta_c \rightarrow VV \) decays (where \( V \) is a vector meson, \( V = \rho, K^*, \phi \)) [12] and \( J/\psi \rightarrow \pi \rho, K^*K \) decays [11]. All the processes we have mentioned, with the only possible exception of \( \chi_{c0} \rightarrow pp \), have been experimentally observed to occur with large branching ratios; for \( \chi_{c0} \rightarrow pp \), data only give us a large upper bound for its decay rate, \( \Gamma(\chi_{c0} \rightarrow pp) < 12 \text{ KeV} \).

These failures show the limits of the perturbative QCD approach in describing exclusive hadronic charmonium decays. The most obvious consideration at this stage is that of admitting that, in this energy region, non perturbative, higher order effects or even new decay mechanisms can still be at work and cannot be neglected. We shall now briefly discuss some possible corrections to the massless perturbative QCD calculations, which we expect to play a rôle in the few (GeV)\(^2\) region, and show how spin measurements could help in evaluating their importance.

Two quark correlations in nucleons

In one attempt to overcome the difficulties encountered by the massless perturbative QCD scheme in describing many charmonium decays, a quark-diquark model of the nucleon has been proposed and applied to many physical processes [14,15]. Two quark correlations, induced by colour forces, are indeed present inside baryons [16]; in intermediate energy regions these correlations might behave as actual particles, scalar or vector diquarks, participating as single entities to the underlying dynamics. Vector diquarks, in particular, might help with the spin problems: the coupling of gluons to spin 1 diquarks may change their helicity, thus avoiding the troublesome helicity conservation rule.

The quark-diquark model of the nucleon has been consistently applied to the description of several charmonium decays, in order to fix the parameters of the model and the properties of diquarks [14,15]: it gives a correct description of \( \chi_{c1,c2} \rightarrow pp \) decays; it also yields a value of \( \Gamma(\chi_{c0} \rightarrow pp) \) as big as, or even bigger than, the values measured for \( \Gamma(\chi_{c1,c2} \rightarrow pp) \) [17]; such value is larger than the value supplied by mass corrections (see next paragraph) and is in agreement with the generous experimental upper bound previously mentioned.

The quark-diquark model of the nucleon describes \( \chi_{c1,c2} \rightarrow pp \) decays as well as perturbative QCD; both schemes have troubles in explaining \( \eta_c \rightarrow pp \) [14] and, it seems [15,18], \( J/\psi \rightarrow \gamma pp \) decays. The real discrimination between the quark-diquark and the massless pQCD models would come from good data on \( \Gamma(\chi_{c0} \rightarrow pp) \), predicted to be zero in the latter. However, lacking these experimental data, a further different prediction of the two schemes can be tested by measuring the polarization of the \( \chi_{c2} \) produced in \( pp \) annihilations [19].

The spin density matrix of a \( \chi_{c2} \) produced in the annihilation of an unpolarized \( pp \) pair, \( pp \rightarrow \chi_{c2} \), is given by:

\[
\rho_{MM'}(\chi_{c2}) = \frac{1}{N} \sum_{\lambda_p,\lambda_{\bar{p}}} A_{M;\lambda_p\lambda_{\bar{p}}} A_{M';\lambda_p\lambda_{\bar{p}}}'
\]
where

\[ N = \sum_{\lambda_p, \lambda_{\bar{p}}; M} |A_{M; \lambda_p, \lambda_{\bar{p}}}|^2 \]  

and the \( A_{M; \lambda_p, \lambda_{\bar{p}}} \) are the amplitudes for the process \( p\bar{p} \rightarrow \chi_{c2} \); \( \lambda_p, \lambda_{\bar{p}} \) are, respectively, the \( p, \bar{p} \) helicities, \( M \) and \( M' \) denote the \( z \)-component of the \( \chi_{c2} \) spin and \( p (\bar{p}) \) are chosen to move along the \( \hat{z} (-\hat{z}) \)-direction.

In perturbative massless QCD the \( \chi_{c2} \) is always produced in states with \( M = \pm 1 \). Then, from Eqs. (1,2), we have

\[ \rho_{11} = \rho_{-1-1} = \frac{1}{2}; \quad \rho_{00} = 0 \quad \text{(pQCD)} \]  

In the quark-diquark model, instead, helicity flips are allowed, so that also the amplitudes \( A_{0;\pm\pm} \) need not be zero and one obtains \[ 19 \]

\[ \rho_{11} = \rho_{-1-1} \simeq 0.42; \quad \rho_{00} \simeq 0.16 , \quad \text{(quark – diquark)} \]  

Eqs. (3) and (4) show that, by measuring \( \rho_{11} \) and \( \rho_{00} \), one could differentiate between pure quark and quark-diquark schemes. Such spin density matrix elements can be measured via the photon angular distribution in the decay \( \chi_{c2} \rightarrow J/\psi \gamma \), given, assuming an electric-dipole-transition dominance, by \[ 7,20,21 \]:

\[ W_\gamma (\theta) = \frac{1}{16} \left[ 9 + \rho_{00} - 3(1 + \rho_{00}) \cos^2 \theta \right] \]  

where \( \theta \) is the angle between the \( z \)-axis and the direction of the photon in the \( \chi_{c2} \) rest frame, and an integration has been performed over the azimuthal angle. We have also used the normalization relation, \( 2\rho_{11} + \rho_{00} = 1 \).

Any measurement of the photon angular distribution \( W_\gamma (\theta) \) which, when compared with Eq. (5), yields a value of \( \rho_{00} \) different from zero, would be in favour of the quark-diquark model. Mass corrections might also give \( \rho_{00} \neq 0 \), but we expect their contribution to \( \rho_{00} \) to be very small.

**Mass corrections**

In perturbative QCD calculations the light quarks are assigned their *current* masses, \( m_q \), of few MeV, which makes any helicity flip of a quark of energy \( E_q \), which couples to a gluon, proportional to \( m_q/E_q \), in practice negligible; hence, the helicity conservation rule with all the problematic consequences discussed above. One might, however, assume that, at the \( Q^2 \) values involved in charmonium decays, the *constituent* quarks, that is the current quarks surrounded by their cloud of \( q\bar{q} \) pairs and gluons, still act as single particles; the elementary interactions then involve, rather than the (almost) massless current quarks, the massive constituent ones, which, as shown by Weinberg \[ 22 \], can be treated as bare Dirac particles with the same couplings as for current quarks in the standard SU(3) \( \otimes \) SU(2) \( \otimes \) U(1) Lagrangian. It is then natural, in the small \( Q^2 \) region, to assign the quarks an effective mass \( x m_h \), like in the naive parton model, where \( x \) is the fraction of the four-momentum of the hadron \( h \) (with mass \( m_h \)) carried by the quark. The different values of \( x \)
are weighted by the hadron wave function. The massive quarks thus allow helicity flips in the elementary amplitudes proportional to $m_h/m_c$, where $m_c$ is the charm quark mass.

The "forbidden" $\eta_c \rightarrow VV$, $p\bar{p}$ and $\chi_{c0} \rightarrow p\bar{p}$ decays have been studied in such a scheme [12,13]. Mass contributions to $\Gamma(\chi_{c0} \rightarrow p\bar{p})$ are interesting: they turn out to be sizeable, leading to results a factor $\sim 2$ to $10$ smaller than data on the analogous decays $\chi_{c1,c2} \rightarrow p\bar{p}$ and the values found in the quark-diquark model. Mass corrections, however, do not help at all with $\eta_c \rightarrow VV$ and very little with $\eta_c \rightarrow p\bar{p}$; in the former case the model keeps predicting, even with massive quarks, $\Gamma(\eta_c \rightarrow VV) = 0$, and, in the latter, the actual value obtained for $\Gamma(\eta_c \rightarrow p\bar{p})$, although different from zero, is several orders of magnitude smaller than the data.

Mass corrections have also been evaluated to allowed decays, $\chi_{c0,c2} \rightarrow \rho\rho$, where diquarks cannot contribute, and shown to be relevant [23]; once more, measurements of spin effects, like the helicity density matrix elements of the produced $\rho$, could help in testing their importance. Quark mass effects have also been considered to study the angular distributions of $B\bar{B}$ pairs produced in the decay of polarized $J/\psi$ [24]; agreement with the data is found using a very simple quark-parton model where each constituent quark is assumed to have an effective mass about a third of the baryon mass.

Let us consider in some more details how the measurement of the helicity density matrix elements of $\rho$ mesons produced in the process

$$p\bar{p} \rightarrow \chi_{c2} \rightarrow \rho\rho$$

(6)

could help in testing the importance of mass effects [23]. The helicity density matrix elements are defined in terms of the decay amplitudes as

$$\rho_{\lambda\lambda'}(\rho) = \frac{1}{N} \sum_{\lambda_1,M,M'} A_{\lambda\lambda_1;M} A'_{\lambda\lambda';M'} \rho_{MM'}(\chi_{c2})$$

(7)

where $N$ is the normalization factor such that $\text{Tr} \rho = 1$ and $\rho_{MM'}(\chi_{c2})$ is the spin density matrix of the decaying $\chi_{c2}$. It describes the $\chi_{c2}$ polarization as it emerges from $p\bar{p}$ annihilation and it has been given in Eqs. (3,4); it differs according to whether or not we assume the $p\bar{p}$ annihilation to occur via pQCD alone. However, the results found for $\rho_{\lambda\lambda'}(\rho)$ show almost no difference when choosing the values of $\rho_{MM'}(\chi_{c2})$ given by Eq. (3) or (4).

$\rho_{\lambda\lambda'}$ can be measured through the polar and azimuthal angular distribution of the decay $\rho \rightarrow \pi\pi$ in the $\rho$ helicity rest frame

$$W(\Theta) = \frac{3}{2}[\rho_{00} + (\rho_{11} - \rho_{00}) \sin^2 \Theta]$$

$$W(\Phi) = \frac{1}{2\pi}[1 - 2\rho_{1,1} + 4\rho_{1,-1} \sin^2 \Phi]$$

(8)

The values of $\rho_{\lambda\lambda'}$ turn out [23] to be sizeably different when taking massless or massive quarks and this reflects in different angular distributions of the pions emitted by the $\rho$, Eqs. (8), difference which should be detectable experimentally. In
particular, when neglecting quark masses all non diagonal elements of $\rho_{\lambda\lambda'}$ are zero, whereas they are different from zero with constituent quarks. Detailed numerical results can be found in ref. [23].

Conclusions
It is clear that pQCD alone with current quarks cannot explain all charmonium decays and non perturbative corrections are necessary. Both quark correlations and mass corrections seem to be relevant and give sizeable contributions. The quark-diquark model can easily explain all $\chi_c$ decays into $p\bar{p}$, including an eventual large value of $\Gamma(\chi_{c0} \rightarrow p\bar{p})$, which could not be explained by massless perturbative QCD. Mass corrections alone could also provide a reasonable value of $\Gamma(\chi_{c0} \rightarrow p\bar{p})$, somewhat smaller than the diquark model. The available experimental data, mainly unpolarized decay rates, do not allow yet a precise separate evaluation of these corrections.

Spin data could help in discriminating between the different contributions. The polarization of $\chi_{c2}$ produced in $p\bar{p}$ annihilations should be sensitive to diquark correlations, whereas the polarization of $\rho$ mesons produced in $\chi_{c2}$ decays shows mass effects. Good spin data, once more, would increase our knowledge of the hadron structure.

We conclude by recalling that the $\eta_c$ decays, instead, keep defeating any attempt of explanation and appear then to be somewhat special: they might require new decay mechanisms and unconventional explanations [25].

REFERENCES

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