Polarization of the χ_{c2} in $p\bar{p}$ annihilation: Massless QCD versus diquarks

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The measurement of the diagonal spin-density matrix elements ρ_{MM} of the χ_{c2} produced in exclusive $p\bar{p}$ annihilation, via its radiative decay into $J/\psi\gamma$, can discriminate between different nucleon models. Whereas perturbative massless QCD predicts the χ_{c2} to be entirely in $M=\pm1$ states (i.e., only $\rho_{11}=\rho_{-1-1}\neq0$), quark-diquark models of the nucleon allow also $M=0$ states ($\rho_{00}\neq0$). Predictions of a particular model are given.

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Charmonium decays into $p\bar{p}$ have been studied both experimentally [1–5] and theoretically [6–13]. Reliable data now exist on $J/\psi,\chi_{c1,2}\to p\bar{p}$; also $\eta_c\to p\bar{p}$ has been observed, although the actual data are still based on very few events and have large errors [3]; for $\chi_{c0}\to p\bar{p}$ only a large upper bound is given [1].

Perturbative QCD calculations are in good agreement with the data on J/ψ and $\chi_{c1,2}\to p\bar{p}$ [10]; these theoretical computations depend very strongly on the choice of the proton wave functions and on the different quark momentum distribution amplitudes. The choice suggested by QCD sum rules [13,14] is the one which best reproduces the data; this particular wave function shows a strong asymmetry in the sharing of the proton momentum by the three valence quarks, and it has been interpreted in terms of two-quark clusterings inside the proton [15]. Perturbative massless QCD, however, forbids, due to the helicity-conserving quark-gluon couplings, the $\eta_c,\chi_{c0}\to p\bar{p}$ decays.

To overcome the above problems, and similar ones appearing in many spin data in exclusive reactions [16], a quark-diquark model of the nucleon, which models some nonperturbative effects, has been developed and applied to the description of the $\eta_c,\chi_{c0,1,2}\to p\bar{p}$ decays [12]. Such a model agrees with the data on $\Gamma(\chi_{c1,2}\to p\bar{p})$, as well as perturbative QCD; it also gives a nonzero value for $\Gamma(\eta_c,\chi_{c0}\to p\bar{p})$, contrary to perturbative QCD. However, the numerical value found for $\Gamma(\eta_c\to p\bar{p})$ is much too small (a factor $\sim10^{-4}$) when compared with experiment. Even if the parameters of the model might still be tuned and refined by exploiting the latest, more precise, experimental data [5] (which were not yet available in Ref. [12]), it seems unavoidable to conclude that the quark-diquark model, similarly to perturbative QCD, fails to give a correct description of the $\eta_c\to p\bar{p}$ decay. The reason for such a failure might be traced in other unusually large decays of the η_c and a possible gluonic component [17–19]. Concerning $\Gamma(\chi_{c0}\to p\bar{p})$, the quark-diquark model gives results similar to those for $\Gamma(\chi_{c1,2}\to p\bar{p})$, and much bigger than $\Gamma(\eta_c\to p\bar{p})$, but the lack of definite experimental information does not allow one to draw any conclusion.

At this stage, and limitedly to the treatment of charmonium decays into $p\bar{p}$, both the pure (massless) quark perturbative QCD scheme and the quark-diquark one seem to perform equally well. New experimental information could, however, help in discriminating between the two schemes. The measurement of a sizable value of $\Gamma(\chi_{c0}\to p\bar{p})$, quantitatively similar to the values measured for $\Gamma(\chi_{c1,2}\to p\bar{p})$, would be a definite argument in favor of diquarks. Such a measurement, however, is rather difficult: The observation of large mass charmonium states in $p\bar{p}$ channels is achieved via the multistep reaction [3,5]

$$p\bar{p}\to\chi_c\to J/\psi\,\gamma\to e^+e^-\gamma \tag{1}$$

and the branching ratio $\chi_{c0}\to J/\psi\,\gamma$ is very small.

Here, we propose a different way of testing the validity of the quark-diquark model versus the pure quark scheme; the polarization of the χ_{c2}, created at rest in $p\bar{p}$ annihilation, turns out to be different in the two cases. The measurement of the χ_{c2} spin-density matrix elements would then result in a clear test of the two models. Such a measurement should be feasible with the data collected in the experiment in progress at Fermilab [5].

The spin-density matrix of a χ_{c2} produced in the annihilation of an unpolarized $p\bar{p}$ pair, $p\bar{p}\to\chi_{c2}$, is given by

$$\rho_{MM'}(\chi_{c2})=\frac{1}{N}\sum_{\lambda_p\lambda_{\bar p}} A_{M;\lambda_p\lambda_{\bar p}} A_{M';\lambda_p\lambda_{\bar p}} \quad (2)$$

where

$$N=\sum_{\lambda_p\lambda_{\bar p};M} |A_{M;\lambda_p\lambda_{\bar p}}|^2 . \quad (3)$$

In Eqs. (2) and (3) the $A_{M;\lambda_p\lambda_{\bar p}}$ are the amplitudes for the process $p\bar p\to\chi_{c2}$, and $\lambda_p,\lambda_{\bar p}$ are, respectively, the $p,\bar p$ helicities. M and M' denote the z component of the χ_{c2} spin, and p ($\bar p$) are chosen to move along the $\hat z$ ($-\hat z$) direction. From angular momentum conservation the only nonzero amplitudes are $A_{0;++}$, $A_{0;--}$, $A_{1;+-}$, and $A_{-1;-+}$. In perturbative massless QCD, however, the p and $\bar p$ only annihilate, via hard-gluon annihilations of $q\bar q$ pairs, if they have opposite helicities. Thus, in perturbative QCD (PQCD) only $A_{\pm1;\pm\mp}$ are different from zero, that is, the χ_{c2} is always produced in states with $M=\pm1$. Then, from Eqs. (2) and (3), we have that the only nonzero elements of $\rho(\chi_{c2})$ are

$$\rho_{11}=\rho_{-1-1}=\tfrac{1}{2} \quad \text{(PQCD)} . \quad (4)$$

In the quark-diquark model, instead, helicity flips are allowed, so that also the amplitudes $A_{0;\pm\pm}$ need not be zero. The explicit expressions of the amplitudes $A_{0;\pm\pm}$ and $A_{\pm1;\pm\mp}$ can be obtained by applying time reversal to the amplitudes for the process $\chi_{c2}\to p\bar p$, $A_{\lambda_p\lambda_{\bar p};M}(\chi_{c2}\to p\bar p)$, given in Ref. [12]:

$$A_{M;\lambda_p\lambda_{\bar p}}(p\bar p\to\chi_{c2}) =(-1)^{M+1-(\lambda_p-\lambda_{\bar p})} A_{\lambda_p\lambda_{\bar p};M}(\chi_{c2}\to p\bar p) . \quad (5)$$

By inserting the values of such amplitudes into Eqs. (2) and (3) one finds $\rho_{MM'}$ in the quark-diquark model. It turns out that the numerical values of $\rho_{MM'}$, being ratios of $|A|^2$, have very small dependence on the parameters of the model (including the quark-diquark momentum distributions). For the whole set of parameters that give a good description of $\Gamma(\chi_{c1,2}\to p\bar p)$ [12] one finds

$$\rho_{11}=\rho_{-1-1}\simeq0.42 , \quad \rho_{00}\simeq0.16 \quad \text{(quark-diquark)} , \quad (6)$$

while all other elements of $\rho(\chi_{c2})$ are zero.

Equations (4) and (6) show that, by measuring ρ_{11} and ρ_{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 $\chi_{c2}\to J/\psi\gamma$, given, assuming an electric-dipole-transition dominance, by [7,20,21]

$$W_\gamma(\theta)=\frac{\rho_{00}}{8}(5-3\cos^2\theta)+\frac{3\rho_{11}}{8}(3-\cos^2\theta) , \quad (7)$$

where θ is the angle between the z axis and the direction of the photon in the χ_{c2} rest frame, and an integration has been performed over the azimuthal angle.

Recalling that $\mathrm{Tr}\rho(\chi_{2c})=2\rho_{11}+\rho_{00}=1$, Eq. (7) can be rewritten as

$$W_\gamma(\theta)=\tfrac{1}{16}[9+\rho_{00}-3(1+\rho_{00})\cos^2\theta] . \quad (8)$$

Any measurement of the photon angular distribution $W_\gamma(\theta)$ which, when compared with Eq. (8), yields a value of ρ_{00} different from zero, would be in favor of the quark-diquark model.

In conclusion, we have shown that further, more detailed, data on charmonium decays might help in improving our modeling of nucleon structure; in particular, once more, spin data prove to be a precious source of information. A knowledge of the polarization of the χ_{c2}, produced in the annihilation of unpolarized $p\bar p$ pairs, would help in understanding if indeed two quark correlations inside nucleons, diquarks, play a crucial dynamical role in intermediate-energy hadronic interactions.

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