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RADIATIVE DECAYS OF HEAVY PARTICLES IN
THE GEOMETRODYNAMICAL APPROACH

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A B S T R A C T

We calculate the radiative decays of the new particles in the geometrodynamical theory of hadrons. Very good results are obtained for E1 transitions, while the M1 transitions fail in describing the J/ψ and ψ' transitions into the $X(2830)$ and the $X(3455)$ interpreted as pseudoscalar states. On this basis we speculate that the $X(2830)$ might be interpreted as non-relativistic bound states ("molecules") of $(D\bar{D})$ and the $X(3455)$ might be called $\eta_c(3340)$.

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In a recent paper ¹⁾ we have discussed in the framework of the geometrodynamical approach ²⁾⁻⁴⁾ the possibility of defining a "direct" current-particle coupling which obeys the necessary conservation or partial conservation conditions. As stressed in Ref. 1), the definition of such currents is necessarily not unique, nevertheless one can invoke the principle of simplicity to obtain an essentially unique choice.

In this paper we intend to take this problem up again and to show that in the case of the radiative decays of the newly found heavy particles not only our definition works remarkably well, but we can get interesting clues as to the nature of these particles.

The radiative transitions of the heavy mesons made out of $c\bar{c}$ pairs are the best possibility to test the structure of the matrix elements of the "direct" contribution to the electromagnetic current. In fact the normalization of the wave functions of the mesons should be determined ^{3),4)} by imposing that the charge of a given meson, as calculated from the "direct" and vector dominated terms, should come out correctly. It has been shown ⁴⁾ that while for low-mass mesons the vector-dominated term dominates over the direct contribution, in the heavy meson case the situation is reversed. Thus the calculated rates for radiative transitions of heavy mesons will depend only on the particular form assumed for the direct piece of the current.

The calculation of the rates is straightforward, even though it becomes quite tedious in practice. The relevant meson wave functions are given in Ref. 4). We identify the J/ψ as the $(L=0, n=1, S=1)$ state, the ψ' as a mixture of the $(L=0, n=2, S=1)$ and $(L=2, n=1, S=1)$ states (with the mixing angle φ taken as a parameter) and the X states with the usual spin assignment as the $(L=1, n=1)$ states. The $X(2.83)$ and the $X(3.455)$ shall be tentatively identified with the $(L=0, S=0, n=1)$ and $n=2)$ states, respectively ^{*}). Our input parameters are :

- the charmed quark mass $m_c = 1.86$ GeV ;
- the slope of Regge trajectories [which determines the spatial radii R_s of the bags as in Ref. 4)] ;
- the experimental meson masses ^{**)}.

^{*}) Note that our description is fully relativistic, thus orbital angular momentum and spin have only a limited sense.

^{**)} The fine structure of the spectrum is, however, calculable by the methods of Ref. 5).

The radii of the time-bags R_t are then determined by Eq. (4.10) of Ref. 4).

The matrix element of the electromagnetic current is given by ¹⁾

$$\begin{aligned} \langle p_1 \alpha | J_\mu^Q(0) | p_2 \gamma \rangle &= \text{Tr} (\lambda^Q [\lambda^\alpha, \lambda^\gamma]) k_1^{\frac{1}{2}} k_2^{\frac{1}{2}} \\ &\frac{1}{2} \int_{\mathcal{R}} d^4x e^{i \frac{x}{2} (p_1 - p_2)} \text{Tr} \left\{ \left[\left(\frac{\not{x}}{2} - i \not{\partial}_x - m_c \right) \bar{\psi}_1(x) \right] \gamma_\mu \psi_2(x) + \right. \\ &\left. + \bar{\psi}_1(x) \gamma_\mu [\psi_2(x) \left[\left(\frac{\not{x}}{2} + i \not{\partial}_x - m_c \right) \right]] \right\} + J_\mu^{\text{add}}, \end{aligned} \quad (1)$$

where ψ_1 and ψ_2 denote the particles' wave functions, k_1 and k_2 are simple factors occurring naturally in the current definition,⁴⁾ and the integration extends over the intersection $\mathcal{R}$ of the bag-domains of the two particles. The first term in (1) is the "naïve" definition of the current, while the second term represents the surface charge contribution necessary to ensure current conservation. It was shown in Ref. 1) that J_μ^{add} is given by

$$J_\mu^{\text{add}} = - \frac{\partial}{\partial q_\mu} \left(q^\alpha \frac{\partial}{\partial q^\alpha} \right)^{-1} S, \quad (2)$$

where q_μ is the momentum of the current and S is the scalar product of q^μ and the first term of (1). The arbitrariness in the definition of J_μ^{add} lies in the different ways in which S may be expressed as a function of q_μ . We choose the "simplest" possibility [discussed in Ref. 1] which consists in keeping in the covariant tensors of the invariant decomposition of S the smallest number of q_μ factors, and in considering the invariant functions to depend on q^2 only. For particles of unequal mass an additional factor $(p_1 + p_2)q/M_1^2 - M_2^2$ is attached to S , whenever the product of the intrinsic parities of the particles is $+1$.

It is easy to see that the $1^- \rightarrow 0^- + \gamma$ transitions (usually called $M1$) are not affected by J_μ^{add} , while the $1^- \rightarrow 0^+ + \gamma$, $1^+ + \gamma$, $2^+ + \gamma$ ($E1$) transitions are modified from their naïve expression.

Our results for the E1 transitions appear in the Table. The mixing angle φ of the $L=0$ and $L=1$ states building up the ψ' is determined with a small uncertainty to be $\varphi = -51^\circ \pm 3^\circ$ (very close to maximal mixing!). The reason why φ is so well determined is that the rate of $\psi' \rightarrow \chi(3414) + \gamma$ is quite sensitive to it. Taking $\varphi = -51^\circ$, we obtain $\Gamma(\psi' \rightarrow e^+e^-)/\Gamma(\psi \rightarrow e^+e^-) = 0.42$ to be compared with the experimental value 0.44 ± 0.12 . [A striking confirmation of the mixing scheme proposed in Ref. 4).]

State	J^{PC}	$\psi' \rightarrow \chi + \gamma$		$\chi \rightarrow J/\psi + \gamma$
		Γ^{calc} (keV)	$\Gamma^{exp 7)}$ (keV)	Γ^{calc} (keV)
$\chi(3552)$	2^{++}	18.9	18 ± 7	61
$\chi(3508)$	1^{++}	10.4	20 ± 7	184
$\chi(3414)$	0^{++}	18.7	18 ± 6	187

Table - E1 transitions of $\psi' \rightarrow \chi$'s and χ 's $\rightarrow J/\psi$.

Our results for the M1 transitions (which are independent of the ambiguity of the current definition) do not support the identification of $\chi(2.830)$ with the ($L=0$, $S=0$, $n=1$) $c\bar{c}$ state. We get $\Gamma^{calc}(J/\psi \rightarrow \chi\gamma) = 16.6 \text{ keV}^*)$, while the experimental upper limit is $1.3 \text{ keV}^6)$. An identification of $\chi(3.455)$ with the lowest lying ($L=0$, $S=0$) $c\bar{c}$ state [suggested in 7] does not lead to difficulties, in fact we get $\Gamma^{calc}(\psi' \rightarrow \chi(3.455) + \gamma) = 0.98 \text{ keV}$, the experimental upper limit on the other hand is $6 \text{ keV}^6)$.

In the Figure we plot the calculated radiative rates, assuming that the pseudoscalar (η_c) and its radial excitation lie below the J/ψ and ψ' , respectively, the mass difference between the vectors and the

*) Interpreting the $\chi(3.455)$ as the η_c' we get $\Gamma^{calc}(\psi' \rightarrow \chi(3.455) + \gamma) = 2.5 \text{ keV}$ (Exp $< 6 \text{ keV}^6)$).

pseudoscalars being denoted by ΔM . We note that while the situation is safe for the η'_c in view of the small radiative rates, one might be in trouble regarding $\Gamma(\psi' \rightarrow \eta_c + \gamma)$ whose upper limit has been estimated⁶⁾ around 4 keV.

We conclude with a few observations.

- i) The geometrodynamical approach works very well for the E1 transitions among $c\bar{c}$ states ; the results of the Table lend support to the correctness of the definitions of the "direct" current coupling of Ref. 1).
- ii) The failure of the calculated M1 transitions suggests that the $X(3455)$ and the $X(2830)$ have been misidentified as the η_c and its radial excitation. We propose that $X(2830)$ be interpreted as a $D\bar{D}$ "molecule"⁸⁾.
- iii) One can explain the failure to observe the η'_c by noticing that because of the mixed nature of the ψ' such a state is most likely to lie above the ψ' .
- iv) The puzzle of the η_c remains ; we cannot exclude that the η_c lies also above the J/ψ and that it must be identified with the state at 3340 (3455) MeV⁶⁾.

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FIGURE CAPTION

Calculated values of the radiative widths for J/ψ and ψ' into $\eta_c(M)$ and $\eta_c(M)'$ as a function of the mass differences $\Delta M = M_{J/\psi} - M_{\eta_c}$ and $\Delta M = M_{\psi'} - M_{\eta_c'}$.