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THE FORGOTTEN 1D_2 LEVEL OF CHARMONIUM

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A B S T R A C T

The standard "charmonium" picture predicts four $C=+1$ states ($^3P_0, ^3P_1, ^3P_2, 2^1S_0$) between ψ and ψ' . If these are identified with the four experimentally observed levels, serious difficulties arise. We remark that a "forgotten" 1D_2 level ($J^{PC}=2^{-+}$) is likely to be around 3.5 GeV. It may be identified with $\chi(3.45)$ or $\chi(3.50)$, avoiding the above difficulties. The 2^1S_0 level has then yet to be discovered.

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The standard "charmonium" picture ¹⁾ predicts four $C=+1$ states between $\psi(3100)$ and $\psi'(3700)$. Three of these states are $L=1$ $c\bar{c}$ configurations, denoted by 3P_0 , 3P_1 , 3P_2 . The fourth is the pseudoscalar companion of ψ' , sometime called η'_c . It is a 2^1S_0 state.

Since four $C=+1$ states were indeed found ^{2),3)} at 3.41, 3.45, 3.50 and 3.55 GeV, it is only natural to associate them with the four predicted states. We are then led to the following conclusions ^{3),4)}:

i) $\chi(3.41)$ and $\chi(3.55)$ decay into $\pi\pi$ and/or $K\bar{K}$ ⁵⁾. Hence, they both have $P(-1)^J = +1$. The decay $\psi' \rightarrow \gamma + \chi(3.41)$ exhibits ⁵⁾ a photon angular distribution which is consistent with the $(1+\cos^2\theta)$ expected from an E1 transition between 2^3S_1 and 3P_0 . It is therefore reasonable to assume ^{3),4)} :

$$\chi(3.41) = ^3P_0$$

Since the only other predicted state with natural parity is 3P_2 , it follows that

$$\chi(3.55) = ^3P_2$$

The two remaining states, $\chi(3.45)$ and $\chi(3.50)$, are not seen to decay into $\pi\pi$ and/or $K\bar{K}$. This is consistent with $P(-1)^J = -1$, as required by the two remaining predicted states 3P_1 and 2^1S_0 .

ii) The photon angular distribution for $\psi' \rightarrow \gamma + \chi(3.50)$ is inconsistent with a $J=0$ χ state ^{3),5),6)}. If we assume that $\chi(3.50)$ and $\chi(3.45)$ are indeed the two remaining predicted states ($^3P_1, 2^1S_0$), only one solution survives :

$$\chi(3.45) = 2^1S_0 (?) \quad \chi(3.50) = ^3P_1 (?)$$

This solution is extremely unpleasant ⁴⁾. An educated guess for the decay modes of 2^1S_0 tells us that :

$$\Gamma(2^1S_0 \rightarrow \text{ordinary hadrons}) \sim \text{few MeV} \quad (1)$$

$$\Gamma(2^1S_0 \rightarrow \pi + \pi + 1^1S_0) \sim 100 \text{ keV} \quad (2)$$

$$\Gamma(2^1S_0 \rightarrow \gamma + \psi) < 1 \text{ keV} \quad (3)$$

The estimate (1) is based on the standard two-gluon decay picture for an $1S_0$ state ¹⁾. The rate (2) is assumed to be similar to $\Gamma(\psi' \rightarrow \pi + \pi + \psi)$. Finally, the reaction in (3) is suppressed by the same mechanism ¹⁾ which allegedly suppresses $\Gamma(\psi' \rightarrow \gamma + 1^1S_0)$, namely, the orthogonality between the $1S$ and $2S$ wave functions. Using the upper limit on $\Gamma(\psi' \rightarrow \gamma + 1^1S_0)$ and the relative k_γ^3 factors, we obtain (3). The estimates (1)-(3) give ⁴⁾:

$$\frac{\Gamma(2^1S_0 \rightarrow \gamma \psi)}{\Gamma(2^1S_0 \rightarrow \text{all})} \lesssim 10^{-3} \quad (4)$$

Within the conventional "charmonium" wisdom, this rough estimate could be wrong by, at most, a factor 10. Experimentally, however ³⁾

$$\frac{\Gamma(\chi(3.45) \rightarrow \gamma \psi)}{\Gamma(\chi(3.45) \rightarrow \text{all})} > 25\%$$

Unless the data are wrong, it is hard to see how the (otherwise successful) charmonium picture can live with such a discrepancy.

At this point we come to the rescue by recalling an entirely forgotten level of "charmonium" - the $1D_2$ level (with $J^{PC} = 2^{-+}$).

This is a $C=+1$ level which undoubtedly communicates with $\psi'(3700)$ via a γ transition. Where is it located? We do not know for sure. However, the $3D_1$ level (which has $J^{PC} = 1^{--}$ and can mix with the ψ states) is predicted by most model calculations to lie between 3.75 and 3.8 GeV ^{7),8)}. The $3D-1D$ splitting is unknown, but it could easily be as large as the $3S-1S$ splitting. In fact, the $1D_2$ state is the first Regge recurrence of the 1^1S_0 state, which is presumably identified with $\chi(2.85)$. If the $3D-1D$ splitting is similar to the $\psi-\chi$ splitting, the $1D_2$ level could easily be around 3.5 GeV. Our "forgotten" level could then be identified either with $\chi(3.50)$ or with $\chi(3.45)$, leaving the $3P_1$ assignment to the other level. Note that the troublesome assignment $\chi(3.45) = 2^1S_0(?)$ was not based on any positive arguments. It was simply a matter of associating the fourth remaining predicted level with the fourth remaining experimental state. Now that we have five predicted levels, there is no need to assume $\chi(3.45) = 2^1S_0$.

If we now associate $\chi(3.50)$ and $\chi(3.45)$ with $3P_1$ and $1D_2$ (or vice versa), we immediately understand why both of these levels have a large branching fraction into $\gamma + \psi$. Both $3P_1$ and $1D_2$ have a highly suppressed hadronic decay rate, because of the vanishing wave functions at the origin ¹⁾.

Both can decay into $\gamma + \psi$. The decays $\psi' \rightarrow \gamma + {}^1D_2$ and ${}^1D_2 \rightarrow \gamma + \psi$ proceed by M1, E2 or M3 transitions. The relative importance of these transitions is model dependent, but there is no reason to assume that the total transition rates are particularly small. The decay ${}^1D_2 \rightarrow \pi + \pi + {}^1S_0$ requires an $L=2$ angular momentum in the final state and is probably suppressed. Hence, a branching ratio ³⁾

$$\frac{P(\chi \rightarrow \gamma\psi)}{P(\chi \rightarrow \text{all})} \sim 25\% - 50\%.$$

is perfectly reasonable for both 3P_1 and 1D_2 . In fact, both the assignment :

$$\chi(3.50) = {}^3P_1 \quad \chi(3.45) = {}^1D_2$$

and the assignment :

$$\chi(3.45) = {}^3P_1 \quad \chi(3.50) = {}^1D_2$$

are consistent with the standard "charmonium" picture. The second assignment is even consistent with the Schnitzer bound ⁹⁾.

These assignments still leave the 2^1S_0 level to be discovered. It should not be seen in $\psi' \rightarrow \gamma + 2^1S_0$ followed by $2^1S_0 \rightarrow \gamma + \psi$, because of its small decay fraction into $\gamma + \psi$. It could be seen as a fifth line in the inclusive spectrum for $\psi' \rightarrow \gamma + \text{anything}$. However, the 1^1S_0 level is not yet seen in $\psi \rightarrow \gamma + \text{anything}$. Why should $\psi' \rightarrow \gamma + 2^1S_0$ be more detectable than $\psi \rightarrow \gamma + 1^1S_0$?

The transition $\psi' \rightarrow \gamma + 2^1S_0$ followed by $2^1S_0 \rightarrow \gamma + \gamma$ is allowed. This might be a good way to detect this state. However, the difficulties encountered in fully establishing the $\chi(2.85)$ state ³⁾, teach us that it is not an easy task.

Regardless of the validity of our detailed arguments, it is clear that five $C=+1$ levels are likely to exist between ψ and ψ' . The assignment $\chi(3.45) = 2^1S_0$ as well as the conclusion that the "charmonium" picture is in difficulty, are both premature.

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R E F E R E N C E S

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