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Abstract

We argue in favor of an identification of the $\chi(3.55)$ as the paracharmonium 2^1S_o, η_c'. We predict the masses of the charmonium 2^{++} and 1^{+-} states and give estimates for the radiative decays of the ψ' via η_c and η_c'.

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Studying the $\psi' \longrightarrow \psi + 2\gamma$ chain decays, the DASP Collaboration [1] at DESY detected two narrow intermediate states, denoted as P_c, with masses of 3.41 (or 3.35) and 3.51 (or 3.26) GeV. The LBL-Group at SLAC [2], measuring the decays $\psi' \longrightarrow \gamma$ + hadrons, found two resonances in the same mass region, a narrow one at 3.41 GeV and a broader one at 3.53 $\pm$ .02 GeV, denoted as χ. The existence of such intermediate states was predicted by the charmonium picture [3]. It is plausible to assume that the $\chi(3.41)$ and the $P_c(3.41)$ are identical. If the mass of the second P_c is 3.26 GeV, we would have the three states 3.26, 3.41 and 3.53 GeV. But the more attractive alternative is, that the broad bump χ (3.53) is a superposition of two narrow resonances, the $P_c(3.51)$ and a new narrow resonance $\chi(3.55)$[2,4].

Within the charmonium model it is almost established that the $P_c/\chi(3.41)$ and the $P_c/\chi(3.51)$ are the $j^{PC}=0^{++}$ and the $j^{PC}=1^{++}$ $c\bar{c}$ states [2,4]. So far the possible $\chi(3.55)$ has been presumed to be the $j^{PC} = 2^{++}$ state, expected roughly at this mass [3].

In this letter we want to argue in favor of an identification of the χ (3.55) as the paracharmonium 2^1S_o state η_c'. The $\chi(3.55)$ would then be the radial excitation of the already observed 1^1S_o state $\eta_c(2.8)$ [5]:

i) Assuming that the S-wave ortho-para splitting can be described mainly by a term in the Hamiltonian[6]

$$c\,\delta^3(\vec{r}_1-\vec{r}_2)\,\vec{s}_1\cdot\vec{s}_2 \;+\; V_T\cdot S_{12} \quad ; \quad V_T \ll c \tag{1}$$

with the constant c, we are led to the following ratio

$$\frac{M(2^3S) - M(2^1S)}{M(1^3S) - M(1^1S)} \approx \left|\frac{\Psi(2^3S;r=0)}{\Psi(1^3S;r=0)}\right|^2 = \left(\frac{3.7}{3.1}\right)^2 \frac{\Gamma_{e^+e^-}(\Psi')}{\Gamma_{e^+e^-}(\Psi)} = 0.65 \tag{2}$$

where the last equality follows from the experimental values [7] $\Gamma_{e^+e^-}(\Psi) = 4.8$ keV and $\Gamma_{e^+e^-}(\Psi') = 2.2$ keV. Using (2) and taking $M(\Psi) - M(\eta_c) = 0.3$ GeV as input, we obtain

$$M(\eta_c') = M(\Psi') - 0.65\cdot 0.3\ \text{GeV} = 3.5\ \text{GeV} \tag{3}$$

In view of the crude estimate it is not unreasonable to identify the $\chi(3.55)$ with the η_c'.

ii) Our identification would imply that the DASP Group cannot observe the $\chi(3.55)$ in the decay $\Psi' \to \Psi + 2\gamma$. The radiative decay of $\eta_c' \to \Psi + \gamma$ is highly suppressed, since this would be a magnetic dipole transition between orthogonal wave functions. In contrast, an identification of $\chi(3.55)$ as 2^{++} meson would lead to a ratio of $\frac{\Gamma(\Psi' \to 2^{++} + \gamma)}{\Gamma(\Psi' \to 1^{++} + \gamma)} = \frac{5}{3}\left(\frac{k'}{k}\right)^3 \approx 1$ and together with the assumption of comparable branching ratios[8] of $2^{++} \to \Psi + \gamma$ and $1^{++} \to \Psi + \gamma$ one should see the 2^{++} and the 1^{++} with roughly the same probability in $\Psi' \to \Psi + 2\gamma$.

iii) The ratio of the P level splittings

$$R_1 := \frac{M(2^{++}) - M(1^{++})}{M(1^{++}) - M(o^{++})} \tag{4}$$

depends on the strength of the tensor forces. Without tensor forces, i.e. $V_T = o$ in (1), the pure $\vec{L}\vec{S}$ term gives $R_1 = 2$. If tensor forces are deduced from Coulomb-like potentials, similar to the Breit approximation in electrodynamics, one obtains $R_1 = 0.8$ as in the positronium.[9] This lower bound would give a mass of 3.59 GeV for the 2^{++}, which would still be higher than the assumed $\chi(3.55)$. If one applies the same approximation to the harmonic oscillator potential one obtains no tensor forces and therefore $R_1 = 2$.

no ¶ We would like to assume in this letter that ψ' is an almost pure 2^3S_1. Therefore, it is necessary to assume small tensor forces, which lead to $R_1 \lesssim 2$. Another argument which supports our assumption of $R \lesssim 2$ follows from the analogy to the ordinary P wave mesons, $A_2(1310)$, $A_1(1100)$ and $\delta(976)$, where

$$R_1 = \frac{M(A_2) - M(A_1)}{M(A_1) - M(\delta)} \approx 1.7 \quad , \tag{5a}$$

or, if we use a quadratic equation,

$$R_1' = \frac{M^2(A_2) - M^2(A_1)}{M^2(A_1) - M^2(\delta)} \approx 2 \tag{5b}$$

These splittings, especially (5b), are described better by an ordinary $\vec{L}\cdot\vec{S}$ term than by the analogy to the positronium. Employing the same ratios as in Eqs. (5a,b), with $P_c(3.41) = 0^{++}$ and $P_c(3.51) = 1^{++}$, we get the following predictions for the $c\bar{c}$ 2^{++} meson

$$M(2^{++}) = 3.68 \text{ GeV} \tag{6a}$$

$$M(2^{++}) = 3.70 \text{ GeV} \tag{6b}$$

In both cases the transitions $\psi' \longrightarrow 2^{++} + \gamma$ (or $2^{++} \longrightarrow \psi' + \gamma$) are suppressed by phase space.

We can also use the above analogy to A_2, A_1, δ to predict the mass of the $1^1P_1(j^{PC} = 1^{+-})$ state which corresponds to the B(1235) meson. Using

$$\frac{M^i(1^{+-}) - M^i(0^{++})}{M^i(2^{++}) - M^i(0^{++})} = \frac{M^i(B) - M^i(\delta)}{M^i(A_2) - M^i(\delta)} \quad , \ i=1,2$$

we get for i=1

$$M(1^{+-}) = 3.62 \text{ GeV} \tag{7a}$$

and for i=2

$$M(1^{+-}) = 3.63 \text{ GeV} \quad . \tag{7b}$$

We note that the center of gravity (c.o.g.) of the 2^3S and 2^1S states (which corresponds to c=0 in eq. (2)) is 3.62 GeV. The c.o.g. of the 2S and the 1P states are almost degenerate, just as in the case of a Coulomb potential. However, a spin-independent Coulomb potential would in a nonrelativistic calculation give a ratio of 1/8 instead of 0.65 in eq. (3).

The M1 transition $\psi' \to \eta_c + \gamma$ is suppressed, because of the orthogonality of the radial wave functions. However, the M1 transition $\psi' \to \eta_c' + \gamma$ is allowed, and we would like to estimate the radiative decay widths of ψ' via η_c'. In the absence of a reliable theory, we shall use rough analogy arguments to obtain ratios of these decay widths relative to $\Gamma(\psi \to \eta_c + \gamma \to 3\gamma)$. In spite of its narrowness, the cascade $\psi' \to \eta_c + \gamma \to 3\gamma$ has been observed experimentally, and one finds $\Gamma(\psi' \to \eta_c + \gamma \to 3\gamma) \approx 10$ eV [5]. Therefore, the comparison with this width should be useful as a guide for the feasibility of measuring the radiative decay modes of ψ' via η_c'. The above ratios depend crucially on the quantity

$$R := \Gamma_{tot}(\eta_c) / \Gamma_{tot}(\psi) \quad . \tag{8}$$

Experimentally, it has only been possible to ascertain that the width of η_c is smaller than the mass resolution of the DESY experiments [5], i.e. $\Gamma_{tot}(\eta_c) \leq 100$ MeV. This gives the upper bound $R \leq 5000$. It seems safe, very safe, to assume a lower bound of $R \geq 1$; according to asymptotic-freedom arguments, R is roughly equal to 100 [10].

And now to our analogy arguments: Assuming $\Gamma(\eta_c' \to 2\gamma) \approx \Gamma(\eta_c \to 2\gamma)$ [11], we get [12]

$$\frac{\Gamma(\psi' \to \eta_c' + \gamma \to 3\gamma)}{\Gamma(\psi \to \eta_c + \gamma \to 3\gamma)} \approx \frac{\Gamma(\psi' \to \eta_c' + \gamma)}{\Gamma(\psi \to \eta_c + \gamma)} \cdot \frac{\Gamma_{tot}(\eta_c)}{\Gamma_{tot}(\eta_c')} \approx \tag{9}$$

$$\approx \left(\frac{145}{300}\right)^3 \cdot \frac{2}{3} \cdot \frac{R}{1+R} \approx 4 - 8 \ \%$$

Similarly, assuming $\Gamma(\eta_c' \to \eta_c + 2\pi) \simeq \Gamma(\psi' \to \psi + 2\pi)$, gives [12]

$$\frac{\Gamma(\psi' \to \eta_c' + \gamma \to 2\pi + \eta_c + \gamma \to 2\pi + 3\gamma)}{\Gamma(\psi \to \eta_c + \gamma \to 3\gamma)} = \frac{\Gamma(\psi' \to \eta_c' + \gamma)}{\Gamma(\psi \to \eta_c + \gamma)} \cdot BR(\eta_c' \to \eta_c + 2\pi) \approx \tag{10}$$

$$\approx \left(\frac{145}{300}\right)^3 \cdot BR(\psi' \to \psi + 2\pi) \cdot \frac{\Gamma_{tot}(\psi')}{\Gamma_{tot}(\eta_c')} \approx$$

$$\approx \left(\frac{145}{300}\right)^3 \cdot \frac{1}{2} \cdot \frac{2}{R+1} \approx 0.002 - 6\ \%$$

Note that $R \gg 1$ corresponds to the upper bound in (9), but to the lower bound in (10). Note also that the width

$$\Gamma(\psi' \to \eta_c' + \gamma \to 2\pi + \eta_c + \gamma \to all + \gamma) = \frac{\Gamma(\psi' \to \eta_c' + \gamma \to 2\pi + \eta_c' + \gamma \to 2\pi + 3\gamma)}{BR\ (\eta_c \to 2\gamma)}$$

will also be suppressed [10] if $R \gg 1$.

To conclude, if the SLAC experiment with better statistics will split the broad $\chi(3.53)$ into two resonances $\chi(3.51)$ and $\chi(3.55)$ and if the DESY experiment $\psi' \to \psi + 2\gamma$ even with better statistics will fail to see the $\chi(3.55)$, then it will be worth to look for the $\chi(3.55)$ in $\psi' \to 3\gamma$ or $\psi' \to 3\gamma + 2\pi$. If our assignment of the $\chi(3.55)$ proves to be correct, the charmonium spectrum will look as in Fig. 1. If, however, it turns out experimentally, that no η_c' exists in the mass region 3.5-3.6 GeV, it would be necessary to explain why. One possibility would be the existence of strong tensor forces [6], i.e. V_T is no longer small compared to c in (1), which would in turn imply that ψ' is not a pure S wave but a mixture of $^3S_1$ and $^3D_1$.

References and Footnotes

1. DASP Collaboration, Phys. Lett. 57B, 407 (1975)

2. SLAC-LBL Group, Phys. Rev. Lett. 35, 821 (1975)

3. C.G. Callan et al., Phys. Rev. Lett. 34, 52 (1975)
   T. Appelquist et al., ibid., 365 (1975)
   E. Eichten et al., ibid., 369 (1975)

4. Talks given by G. Goldhaber and F. Vanucci at DESY, Hamburg

5. J. Heintze, DESY 75/34 (1975)
   B.H. Wiik, DESY 75/37 (1975)

6. A strong tensor interaction $V_T(r)\, S_{12}$ where $S_{12} := 3(\vec{S}_1 \cdot \hat{r})\cdot(\vec{S}_2\cdot\hat{r}) - \vec{S}_1\cdot\vec{S}_2$ would lead to an S-D mixing for the ψ', and also to a reduction of the ratio R_1 of the P level splittings (see eq. (4)) from the value $R_1 = 2$ expected for zero tensor force. In this paper however we want to assume that ψ' is a pure or almost pure 2^3S_1, so $V_T(r) \ll c$.

7. V. Lüth, Invited paper presented at the Int. Conf. on High Energy Physics, Palermo (1975)
   and the review given by G. Feldman, SLAC-PUB 1647

8. Assuming $\Gamma(2^{++}) \approx \Gamma(1^{++})$, we get
   $$\frac{BR(2^{++}\to\psi+\gamma)}{BR(1^{++}\to\psi+\gamma)} \approx \frac{\Gamma(2^{++}\to\psi+\gamma)}{\Gamma(1^{++}\to\psi+\gamma)} \cdot \left(\frac{0.46}{0.41}\right)^3 \approx 1.4$$

9. See, for example, H.J. Schnitzer, Brandeis Preprint (July 1975)

10. Because of charge conjugation, η_c and η_c' can decay into hadrons made up of non-charmed quarks via 2 gluons, whereas the ψ and ψ' need at least 3 gluons. Using Table I of Appelquist et al.[3], we get $R \approx 100$ and $BR(\eta_c \to 2\gamma) \approx 0{,}02$

11. This assumption holds, if the increase in phase space is roughly compensated by the spreading of the wave function.

12. Assuming $\Gamma_{\eta_c}(\eta_c') := \Gamma(\eta_c' \to \eta_c + 2\pi) \approx \Gamma_\psi(\psi')$ and $\Gamma_{hadr}(\eta_c')/\Gamma_{hadr}(\eta_c) \approx \Gamma_{hadr}(\psi')/\Gamma_{hadr}(\psi)$ gives together with the experimental result[7] $\Gamma_\psi(\psi') \approx \Gamma_{hadr}(\psi')$
    $$\frac{\Gamma_{tot}(\eta_c')}{\Gamma_{tot}(\psi')} \approx \frac{\Gamma_{\eta_c}(\eta_c') + \Gamma_{hadr}(\eta_c')}{\Gamma_{tot}(\psi')} \approx \frac{\Gamma_\psi(\psi') + \Gamma_{hadr}(\eta_c')}{2\,\Gamma_{hadr}(\psi')} \approx \frac{1+R}{2}$$

Using this result and the experimental ratio[7] $\Gamma(\psi')/\Gamma(\psi) \approx 3$ we get

$$\frac{\Gamma(\eta_c)}{\Gamma(\eta_c')} \approx \frac{\Gamma(\eta_c)}{3\Gamma(\psi)} \frac{\Gamma(\psi')}{\Gamma(\eta_c')} \approx \frac{R}{3} \cdot \frac{2}{R+1} .$$

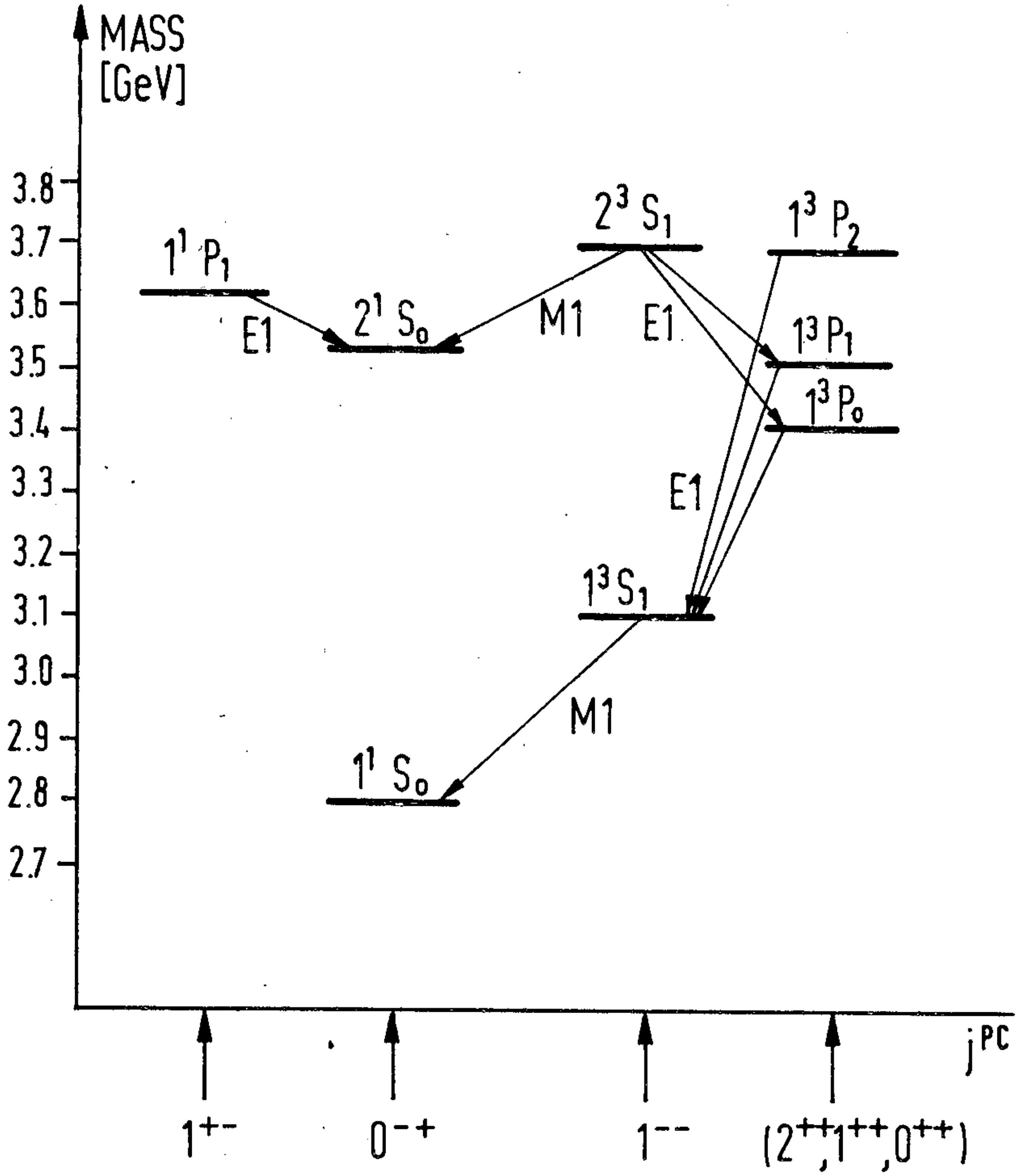

Figure 1. Masses and not suppressed radiative transitions of charmonium