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Mass spectra of the new particles and the ψ' radiative decays*

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A previously published light-quark elementary-particle model contains an excitation series for generating high-mass narrow-width meson resonances. Two terms in this excitation series accurately correspond to the $\psi(3095)$ and $\psi'(3684)$ resonances; these two terms also lead to quantitatively correct values for the χ_1, P_c, and χ_2 radiative decay levels of the $\psi'(3684)$. Several other new particle states also correspond to terms in this light-quark excitation series.

The details of a light-quark elementary-particle model which accurately reproduces the observed spectrum of low-mass baryon and meson resonances were published[1,2] prior to the appearance of the new particles. Table I summarizes the features of this light-quark model which apply to the low-mass meson resonances. With respect to the new particles, the most pertinent aspect of this light-quark model is the prediction[3] that the excitation series $(\dot{3}\dot{3}\dot{3})^n$ (see Table I), with $n = 1, 2, 3, \ldots$, serves as the generator of the higher-mass narrow-width meson resonances.[4]

Before the discovery of the new particles, meson resonances existed which matched the terms $n = 1$, 2, and 3 in the $(\dot{3}\dot{3}\dot{3})^n$ excitation series; some of these states are shown in Table I. When the $\psi(3095)$ and $\psi'(3684)$ new particles first appeared, it was clear that they matched the terms $n = 5$ and $n = 6$ in this series, and a paper to this effect was published.[5] Recently, other new-particle resonances have appeared which also match terms in this series, and which clarify the precise manner in which the excitations occur. The $(\dot{3}\dot{3}\dot{3})^n$ excitation levels which have been filled to date by new particle states are shown in Table II.[6-16]

Phenomenologically, one of the most useful aspects of the light-quark model stems from its accurate mass calculations.[1,2] Since the light-quark

TABLE I. Low-mass meson resonances in the light-quark model (Refs. 1 and 2). This model gives very accurate mass values for the narrow-width low-mass particles, and also for the high-mass new particles of Tables II and III. The excitation series $(\dot{3}\dot{3}\dot{3})^n$ is the generator of the high-mass resonances (see Table II).

Fundamental mass quanta:	$M^0, \bar{M}^0 = 70.0$ MeV; $M^+, M^- = 74.6$ MeV.
Spinless basis states[a]:	$1 \equiv M$, $3 \equiv 3M$, $4 \equiv 4M$, $7 \equiv 7M$.
Spinning basis states[b]:	$M_s^{\pm} = \mu^{\pm} = 105$ MeV, $3_s \equiv S \simeq 327.5$ MeV.
Binding energies:	matching state-antistate pairs ($\sim 4\%$); mixed states[c] or unpaired states ($\sim 0\%$).
Basis-state transitions:	$\dot{3}\dot{3}\dot{3}$(630 MeV) +25 MeV $\rightarrow$ $[\dot{3}]\dot{S}\dot{S}$(655 MeV),[d] $\dot{S}\dot{S}$(655 MeV) $\rightarrow$ $\{\dot{3}\}\dot{3}\dot{3}$(630 MeV) +25 MeV, where [ ] and { } denote annihilation and creation operators.
Pseudoscalar mesons:	$\pi = 1\bar{1}$, $\eta = 4\bar{4}$, $\eta' = 7\bar{7}$ (4% binding energy (B.E.)) $K = 7$, $\bar{K} = \bar{7}$ (0% B.E.).
Vector mesons:	$\dot{3}\dot{3}\dot{3} \rightarrow \dot{S}\dot{S} = \rho$, $^1P_1$, $\Gamma = 150$ MeV, $I = 1$[d,e]; $\dot{4}\dot{7} \rightarrow \dot{S}\dot{S}\pi = \omega$, $^3S_1$, $\Gamma = 10$ MeV, $I = 0$[d]; $\dot{4}7 \rightarrow \dot{S}S\pi = K^*$, $^1P_1$, $\Gamma = 50$ MeV, $I = \frac{1}{2}$[d,e]; $\dot{7}\dot{7} \rightarrow \dot{S}\dot{S}\dot{3}\pi = \phi$, $^3S_1$, $\Gamma = 4$ MeV, $I = 0$[d].
Higher-mass states:	$(\dot{3}\dot{3}\dot{3})^2 \rightarrow \dot{S}\dot{S}\cdot\dot{3}\dot{3}\dot{3} = D(1286)$ (0% B.E.); $(\dot{3}\dot{3}\dot{3})^3 \rightarrow \bar{S}S\bar{S}\cdot S\bar{S}S = \bar{p}n(1795)$ (4% B.E.).

[a] The masses for these states are additive.
[b] Fully-relativistic spinning quanta have $M_s/M_0 = \frac{3}{2}$ (see Ref. 1, Appendix B).
[c] Mixed states, denoted by an overdot contain both M and $\bar{M}$ subquanta.
[d] The $\dot{S}\dot{S}$ pair has spin and isotopic spin ($J = 1$, $I = 0$) or else ($J = 0$, $I = \frac{1}{2}$ or 1).
[e] These P states have rotational energies $E_{rot} \sim 110$ MeV.

TABLE II. New-particle and old-particle meson resonances which match the excitation sequence $(\dot{3}\dot{3}\dot{3})^n$, $n=1-10$. Note the accurate agreement in the mass values. $N\bar{N}$ excitations predominate in the region where $R \equiv \sigma(\text{hadrons})/\sigma(\mu^+\mu^-)$ has the value $R \simeq 2.5$, and $N\bar{N}N\bar{N}$ excitations probably predominate in the higher-mass region where $R \simeq 5$. The odd-n excitations contain only spinors, whereas the even-n excitations also contain spinless triplets $\dot{3}\dot{3}\dot{3}$ [rule (i) in the text]. A similar result occurs in the ψ' high-mass decay modes shown in Table III.

Excitation sequence	Calculated mass (MeV)[a]	Observed meson or baryon	Reference
Low-mass excitations			
$(\dot{3}\dot{3}\dot{3})^1 \rightarrow \dot{S}\dot{S}$ (P state)	$655 + E_{\text{rot}}{}^{\text{b}} \sim 765$	$\rho(770 \pm 10)$	6
$(\dot{3}\dot{3}\dot{3})^2 \rightarrow \dot{S}\dot{S} \cdot \dot{3}\dot{3}\dot{3}$	$655 + 630 = 1285$	$D(1286 \pm 2)$	6
$\rightarrow \dot{S}\dot{S}\dot{S}\dot{S}$	$655 + 655 = 1310$	$A_2\text{dip}(1310 \pm 3)$	7
$N\bar{N}$ excitations ($R \simeq 2.5$ region)			
$(\dot{3}\dot{3}\dot{3})^3 \rightarrow S\bar{S}S \cdot SS\bar{S} \equiv N\bar{N}$	$2 \times 939 - 4\%$ B.E. $= 1803$	$\bar{p}n\,(1794.5 \pm 1.4)$	6, 8
$(333)^4 \rightarrow N\bar{N} \cdot \dot{3}\dot{3}\dot{3}$	$1795 + 630 = 2425$	$\cdots$	$\cdots$
$(\dot{3}\dot{3}\dot{3})^5 \rightarrow N\bar{N} \cdot \dot{S}\dot{S}\dot{S}\dot{S}$	$1795 + 1310 = 3105$	$\psi(3095 \pm 4)$	9
$(\dot{3}\dot{3}\dot{3})^6 \rightarrow N\bar{N} \cdot (\dot{3}\dot{3}\dot{3})^3$	$1795 + 3 \times 630 = 3685$	$\psi'(3684 \pm 5)$	10
$(\dot{3}\dot{3}\dot{3})^7 \rightarrow N\bar{N} \cdot (\dot{S}\dot{S}\dot{S}\dot{S})^2$	$1795 + 2 \times 1310 = 4415$	$\psi'''(4414 \pm 7)$	11
$N\bar{N}N\bar{N}$ excitations ($R \simeq 5$ region)			
$(\dot{3}\dot{3}\dot{3})^6 \rightarrow N\bar{N} \cdot N\bar{N}$	$2 \times 1795 - 4\%$ B.E. $= 3445$	$\cdots$	$\cdots$
$(\dot{3}\dot{3}\dot{3})^7 \rightarrow N\bar{N}N\bar{N} \cdot \dot{S}\dot{S}$	$3445 + 655 = 4100$	$\psi''(4100)$	11, 12
$(\dot{3}\dot{3}\dot{3})^8 \rightarrow N\bar{N}N\bar{N} \cdot (\dot{3}\dot{3}\dot{3})^2$	$3445 + 2 \times 630 = 4705$	$\mu\mu(4700 \pm 160)$	13
$(\dot{3}\dot{3}\dot{3})^9 \rightarrow N\bar{N}N\bar{N} \cdot (\dot{S}\dot{S})^3$	$3445 + 3 \times 655 = 5410$	$\cdots$	$\cdots$
$(\dot{3}\dot{3}\dot{3})^{10} \rightarrow N\bar{N}N\bar{N} \cdot (\dot{3}\dot{3}\dot{3})^4$	$3445 + 4 \times 630 = 5965$	$\Upsilon(5970)$	14, 15
Λ excitation (neutrino-induced)			
$\nu + p \rightarrow \Lambda \cdot \dot{S}\dot{S}\dot{S}\dot{S}$	$1116 + 1310 = 2426$	$X(2426 \pm 12)$	16

[a] The mass values are from $\dot{S}\dot{S} = 655$ MeV, $\dot{3}\dot{3}\dot{3} = 630$ MeV, B.E. $= 0\%$ (Table I).
[b] See Table I.

TABLE III. High-mass decay modes of the $\psi'(3684)$. These are the decays which correspond to the annihilation of 1, 2, 3, 4, and 5 subquanta $M = 70$ MeV, respectively. The [1], [3], and [5] annihilations lead to the ψ, whereas the [2] and [4] annihilations do not. Since $\psi' \equiv N\bar{N} \cdot (\dot{3}\dot{3}\dot{3})^3$ and $\psi \equiv N\bar{N} \cdot \dot{S}\dot{S}\dot{S}\dot{S}$ (Table II), the basis-state transition $(\dot{3}\dot{3}\dot{3})^2 \rightarrow \dot{S}\dot{S}\dot{S}\dot{S}$ (Table I) evidently occurs only for odd-M annihilations [rule (ii) in the text]. Thus this transition occurs in the P_c decay mode, but it does not occur in the χ_1 and χ_2 decay modes (see Fig. 1).

No. of 70-MeV quanta annihilated	Observed decay modes	Observed level energies	Reference
1[a]	$\psi' \rightarrow \psi + \eta$		18
2[b]	$\psi' \rightarrow \chi_2 + \gamma,\ \chi_2 \not\rightarrow \psi$	$\chi_2(3545)$	19
3[a]	$\psi' \rightarrow P_c + \gamma,\ P_c \rightarrow \psi + \gamma$	$P_c\,(3507 \pm 7)$	20
4[b]	$\psi' \rightarrow \chi_1 + \gamma,\ \chi_1 \not\rightarrow \psi$	$\chi_1(3407 \pm 8)$	21
5[a]	$\psi' \rightarrow \psi + \pi\pi$		22

[a] $(\dot{3}\dot{3}\dot{3})^2 \rightarrow \dot{S}\dot{S}\dot{S}\dot{S}$ ($\Delta E = -50$ MeV).
[b] $(\dot{3}\dot{3}\dot{3})^2 \not\rightarrow \dot{S}\dot{S}\dot{S}\dot{S}$.

basis states shown in Table I are all much more massive than the calculational uncertainties, we can use the observed masses of the narrow-width resonances to deduce which basis states must be present. In particular, we can distinguish clearly between excitations which involve 4% binding energies and those which involve ~0% binding energies (see Table I). Also, we can use the mass values (and in some cases the spin values) to determine whether the spinless excitation group $\dot{3}\dot{3}\dot{3} = 630$ MeV or else the corresponding spinor pair $\dot{S}\dot{S} = 655$ MeV (see Table I) has been formed in a hadron excitation or deexcitation process. This last result is crucial for the present discussion because, as shown in Table II, the $\psi(3095)$ contains the spinor group $\dot{S}\dot{S}\dot{S}\dot{S} = 1310$ MeV whereas the $\psi'(3684)$ contains the corresponding spinless excitation group $\dot{3}\dot{3}\dot{3} \cdot \dot{3}\dot{3}\dot{3} = 1260$ MeV, and it is the transition between these two groups which shifts the P_c decay level of the ψ' by 50 MeV with respect to the χ_1 and χ_2 decay levels (as we show below).

Examining Table II in detail, we see that several prominent new-particle peaks occur as $N\bar{N}$ excitations over a region of energies where the ratio $R \equiv \sigma\,(\text{hadrons})/\sigma(\mu^+\mu^-)$ has a value[17] of about 2.5. Above the $N\bar{N}N\bar{N}$ threshold the ratio R increases, first showing considerable structure[17] and then leveling off at a value of about 5. Several of the higher-mass peaks seem identifiable as $N\bar{N}N\bar{N}$ excitations, as shown in Table II. In particular, the $\Upsilon(5970)$ peak[14,15] appears at just about twice the energy of the $\psi(3095)$ peak; this kind of a linear mass relationship is typical of a light-quark (weak binding energy) behavior for hadron resonances.[1,2] It is interesting to note that the Λ excitation at the bottom of Table II, which is a spin-$\frac{1}{2}$ baryon resonance, follows the same kind of excitation systematics as the integral-spin meson resonances in the rest of the table.

One of the most important results to emerge from Table II is the manner in which the spinless $\dot{3}\dot{3}\dot{3}$ triplets appear. As can be seen in Table II, the $(\dot{3}\dot{3}\dot{3})^n$ excitations for odd-n values ($n = 1, 3, 5, 7$) lead to resonances which contain only spinors, whereas the $(\dot{3}\dot{3}\dot{3})^n$ excitations for even-n values ($n = 2, 6, 8, 10$) lead to resonances which contain both spinors and spinless $\dot{3}\dot{3}\dot{3}$ triplets. Thus we have the following empirical rule for meson production processes:

(i) In the excitation sequence $(\dot{3}\dot{3}\dot{3})^n$ of Table II, odd-n excitations lead to fully-saturated $\dot{3}\dot{3}\dot{3} \to \dot{S}\dot{S}$ transitions, whereas even-n excitations do not. This empirical rule was deduced solely on the basis of fitting to the resonance mass values of Table II. However, as we now demonstrate, the $\psi \equiv N\bar{N} \cdot \dot{S}\dot{S}\dot{S}\dot{S}$ and $\psi' \equiv N\bar{N} \circ (\dot{3}\dot{3}\dot{3})^3$ light-quark basis-state assignments, which seem at first glance to be somewhat contrived, are precisely the assignments which are required to account for the energy levels and angular distributions of the ψ' radiative decays. Moreover, the empirical odd-even rule (i) carries over in an analogous manner to the dominant ψ' decay modes, which are shown in Table III.

In the light-quark picture of hadron decay processes,[1,2] the decay of a resonance is initiated by the annihilation of some of the $M = 70$ MeV subquanta contained in the resonance. The remaining subquanta then rearrange and form one or more final-state particles. Table III (Refs. 18–22) shows the ψ' decay modes which correspond to the annihilation of 1, 2, 3, 4, and 5 subquanta M, respectively. As can be seen in Table III, the annihi-

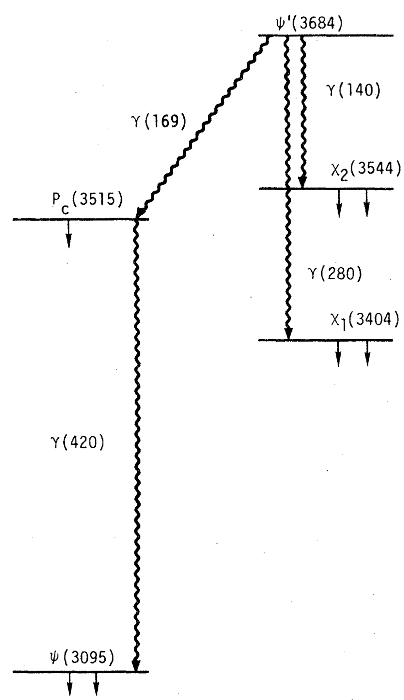

FIG. 1. The χ_1, P_c, and χ_2 radiative decay levels of the ψ' (3684). As shown in Table III, the χ_2 and χ_1 radiative levels correspond to the annihilation of 2 and 4 subquanta $M = 70$ MeV, respectively, so that they appear 140 MeV and 280 MeV below the ψ'. The P_c radiative level, on the other hand, corresponds to the annihilation of 3 subquanta M (+210 MeV) accompanied by the basis-state transition $(\dot{3}\dot{3}\dot{3})^2 \to \dot{S}\dot{S}\dot{S}\dot{S}$ (−50 MeV), so that it appears roughly 160 MeV below the ψ'; the P_c then decays via the annihilation of 6 subquanta M ($[\dot{3}\dot{3}\dot{3}] = 420$ MeV) down to the ψ. It is interesting to note that the decay $\psi' \to P_c + \gamma(169)$ [where the basis state transition $(\dot{3}\dot{3}\dot{3})^2 \to \dot{S}\dot{S}\dot{S}\dot{S}$ occurs] is anisotropic (Ref. 24), whereas the decay $P_c \to \psi + \gamma(420)$ is isotropic (Ref. 24). Experimentally determined values for the χ_1, P_c, and χ_2 level energies are shown in Table III. Also see note added in proof.

lation of 1, 3, or 5 subquanta M leads to final states which contain the ψ, whereas the annihilation of 2 or 4 subquanta M leads to final states which do not contain the ψ. Thus we have the following empirical rule for ψ' decay processes:

(ii) The annihilation of an odd number of subquanta M leads to the basis-state transition $(\dot{3}\dot{3}\dot{3})^2 \to \dot{S}\dot{S}\dot{S}\dot{S}$, whereas the annihilation of an even number of subquanta M does not lead to this transition.

As can be seen, the odd-even behavior observed in rule (ii) for ψ' decay processes is quite similar to the odd-even behavior observed in rule (i) for meson production processes.

The systematic results shown in Tables II and III, when taken together, are sufficient to account quantitatively for the high-mass radiative decays of the $\psi'(3684)$. From Table III, we see that the annihilation of 2 or 4 subquanta M does *not* lead to the $(\dot{3}\dot{3}\dot{3})^2 \to \dot{S}\dot{S}\dot{S}\dot{S}$ basis-state transition. Thus these decay levels, which are the χ_2 and χ_1 levels shown in Fig. 1, appear at energies which are 140 MeV and 280 MeV, respectively, below that of the ψ'; and their subsequent decays are into low-mass states which do not include the ψ. The annihilation of 3 subquanta M, on the other hand, *is* accompanied by the endoergic transition $(\dot{3}\dot{3}\dot{3})^2 \to \dot{S}\dot{S}\dot{S}\dot{S}$, which shifts the P_c level in Fig. 1 upwards by about 50 MeV from the position it would normally occupy (halfway between the χ_1 and χ_2 resonances); the P_c level decays by photon emission[23] down to the ψ. As additional experimental confirmation for these light-quark–basis state assignments, we note that the low-energy γ ray in the P_c decay process, $\gamma \sim 169$ MeV, which arises from a $[\dot{3}]$ annihilation accompanied by a $(\dot{3}\dot{3}\dot{3})^2 \to \dot{S}\dot{S}\dot{S}\dot{S}$ transition, is emitted anisotropically[24]; whereas the high-energy γ ray in the P_c decay process, $\gamma \sim 420$ MeV, which arises from a straight $[\dot{3}\dot{3}]$ annihilation, is emitted isotropically.[24]

Note added in proof. Recently other new particle resonances have been identified which are of interest here. A $\chi(3455)$ resonance,[25] seen in the decay sequence $\psi' \to \chi + \gamma$, $\chi \to \psi + \gamma$, closely parallels the P_c resonance of Fig. 1 and Table III; it should be placed about 70 MeV below the P_c level in Fig. 1. Also, a narrow peak has been observed at an energy of about 1870 MeV,[26,27] which appears in conjunction with a system of mass 2010 MeV (Ref. 27); the separation between these two masses is 140 MeV, which seems analogous to the 140-MeV ψ' decay intervals observed in Fig. 1. We call attention to the following sequence of observed narrow resonances: $\bar{p}n(1795)\Gamma \leq 8$,[6] $X(1870)\Gamma < 40$,[26,27] $\bar{p}p(1935)\Gamma = 9$,[28] and $X(2010)\Gamma < 40$,[27] which are separated from one another by accurate 70-MeV intervals.

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[21]G. J. Feldman *et al.*, Ref. 19. The value $\chi_1(3407 \pm 8)$ shown in Table III is from K. Pretzl, talk given at the 1976 Vanderbilt Conference, Ref. 13.
[22]The $\psi' \to \psi + \pi\pi$ decay mode of Table III, like the $\psi' \to \psi + \eta$ decay mode, is unexpectedly large; also, the final-state $\pi\pi$ mass distribution [see J. A. Kadyk *et al.*, LBL Report No. LBL-3687 (unpublished), Fig. 7] indicates that the final-state ψ is essentially at rest in the c.m. system, and the two emitted pions are ejected in opposite directions.
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