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CONSISTENCY CHECKS ON THE SUGGESTED SPINS OF THE $\chi(3415)$, $\chi(3510)$ AND $\chi(3555)$

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In this note a method for the consistency checks on the spin assignment for the non-diffractive mesons of well defined G parities has been discussed. This method rules out the values 1 and 2 for the spins of the $\chi(3510)$ and $\chi(3555)$, respectively, suggested by the SLAC–LBL group and confirms the value 0 for the spin of the $\chi(3415)$ also suggested by the same group. It has also been shown that all the χ-particles so far observed must be spin-zero mesons.

Recently the spins of the $\chi(3415)$, $\chi(3510)$ and $\chi(3555)$ have been suggested [1] by the SLAC–LBL group to be 0, 1 and 2, respectively. However, in a very recent paper [2] we have shown that the $\chi(3510)$ cannot be a spin-one boson. One of our motivations in this note is to show that the $\chi(3555)$ is not a spin-two meson. For our purpose we have employed a method, discussed in this note, for the consistency checks of the assigned values for the spins of the non-diffractive mesons of well defined G parities (i.e. the mesons which do not carry any strangeness or charm quantum number). The method concerned utilizes the pseudo-dimension rule [3] which is a kind of spin selection rule for decaying particles. The method concerned also takes advantage of the following relation (*not* valid for the diffractive mesons like, A_1) [2]:

$$G(-1)^J = \pm C, \tag{1}$$

where J is the actual spin and C is the charge conjugation parity. In Eq. (1) the + sign holds for the G-even and the − sign for the G-odd mesons, respectively. It will be evident from the discussions given below that the pseudo-dimension rule [3] along with Eq. (1) imposes some restrictions on the probable values for the spin of an unstable non-diffractive meson which is nonstrange as well as uncharmed. This fact enables one to check the consistency of the suggested value for the spin of a meson for which Eq. (1) is valid. It has been shown in this note that all the χ-particles so far observed are spin-zero mesons.

The pseudo-dimension, denoted by d, of a free field carrying the actual spin J is defined

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[3] by the relation $d = -KJ$ where K is a positive odd integer. Using the properties of negative integers for assigning a non-zero value of d to a spin-zero field (since a field cannot be a dimensionless quantity) and also utilizing the fact that the photon, unlike the massive gauge fields, has only two states of polarization, the following relations are obtained [3]:

$$d(\text{magnitude}) = 3J \text{ for } J \neq 0, \tag{2a}$$

$$d(\text{magnitude}) = 1 \text{ for } J = 0, \tag{2b}$$

$$d(\text{magnitude}) = 2 \text{ for the photon.} \tag{2c}$$

The pseudo-dimension rule [3] reads: All the allowed decays (*not* occurring through subreactions) of an unstable particle must be governed by *one and only one* of the following two constraints:

$$d_u \geqslant D, \tag{3a}$$

$$d_u \leqslant D, \tag{3b}$$

where d_u is the magnitude of the pseudo-dimension of the field of the unstable particle and D is the sum of the magnitudes of the pseudo-dimensions of the fields of the particles constituting a decay mode (*not* occurring through a subreaction). It is emphasized here that as Eqs. (2a)–(2c) refer to free fields, therefore, the quantity D appearing in relations (3a) and (3b) refers to decay modes *not* occurring through subreactions. This is so because for free fields subreactions cannot occur even in principle. In relations (3a) and (3b), d_u is fixed foı a given unstable particle whereas D can take, in general, a finite spectrum of discrete values.

It is emphasized here that the pseudo-dimension rule reduces to the spin selection rule for a decaying particle by virtue of Eqs. (2a)–(2c) if the spins of the particles constituting the decay modes are known. This is so because, as implied by the pseudo-dimension rule, only one of the two relations (3a) and (3b) can be valid in the decays of an unstable particle. This fact imposes some restrictions on the probable values of d_u and as such on the spin of a decaying particle. It is to be noted, however, that the pseudo-dimension rule can be regarded as a spin selection rule for a decaying particle if, and only if, we know which one of the two relations (3a) and (3b) is valid in the decays of the particle concerned. Phenomenological considerations suggest that the constraint $d_u \leqslant D$, i.e. relation (3b), will be valid in the decays of a nonstrange as well as uncharmed *meson* if any one of the following conditions is satisfied: (*i*) if the decaying meson is an *abnormal* boson or it exhibits a non-resonant behaviour; (*ii*) if the decaying meson undergoes dominantly strong decays but its two-body strong decay modes are found to be suppressed relative to its higher-body strong decay modes; (*iii*) if the decaying meson suffers dominant electromagnetic or weak decays. If none of these conditions is found to be valid in the decays of a meson, then, for its decays the appropriate constraint should obviously be $d_u \geqslant D$. We have already mentioned that the probable values for the spin J of a non-diffractive meson of a well defined G-parity is further restricted by Eq. (1). It is worth mentioning that one of the important applications of the pseudo-dimension rule is to explain the suppressions [3] of some decay modes of unstable particles. Therefore, for the consistency checks for the spins assigned to mesons (of well defined G parities) only their *dominant* decay modes should be considered. What have been discussed so far is illustrated below.

(*i*) $\eta'(958)$: This particle is an abnormal meson as the $\pi\pi$ and $K\bar{K}$ modes are absent in its decays. Therefore, one of the conditions for the validity of the constraint $d_u \leqslant D$ is satisfied in η'-decay. Obviously, then, the decays $\eta' \to \eta\pi\pi(D = d_\eta + d_\pi + d_\pi = 1+1+1 = 3)$, $\varrho\gamma(D = d_\varrho + d_\gamma = 3+2 = 5)$, $\omega\gamma(D = d_\omega + d_\gamma = 3+2 = 5)$, $\gamma\gamma(D = d_\gamma + d_\gamma = 2+2 = 4)$ are controlled by the constraint $d_u \leqslant D$. For the reasons discussed above we shall consider only the modes $\eta\pi\pi$ and $\varrho\gamma$ which are *dominant*. It may be recalled that the equality sign in the non-sharp inequality $d_u \leqslant D$ can only occur for D_{min}, the minimum value of D which must be consistent with Eq. (1). For η-decay $D_{min} = 3$ associated with the $\eta\pi\pi$ mode. Clearly, $d_u = D_{min} = 3$ implies, through Eq. (2a), that $J = 1$ for η'. But the value $J = 1$ is disallowed by Eq. (1) as the meson concerned has even G and even C. This has the implication that the equality sign does not occur in the constraint for the decays of η' for which the appropriate constraint takes the form $d_u < D$ and *not* $d_u \leqslant D$. Needless to mention that all the observed modes must have to satisfy the inequality $d_u < D$ which, therefore, must also be satisfied for the mode $\eta\pi\pi(D = 3)$. Therefore, the inequality $d_u < 3$ indicates that $d_u = 1$ as $d_u = 2$ is true for the photon only which is evident from Eq. (2c). Now, $d_u = 1$ implies, through Eq. (2b), that $J = 0$ which is also consistent with Eq. (1). Obviously, then, the assigned [1] value $J = 0$ for η' is consistent with the pseudo-dimension rule and Eq. (1) as well.

(*ii*) $S^*(980)$: The phase shift analysis reveals that the S^* does not exhibit a resonant behaviour [1] and as such in its decays the constraint $d_u \leqslant D$ is valid. The observed decays $S^* \to \pi\pi(D = 2)$, $K\bar{K}(D = 2)$ indicate that the equality sign cannot occur in the constraint S^*-decay since the spectrum of the values of d for the *massive* bosons does not include the value 2 as evident from Eqs. (2a) and (2b). Obviously, then, the constraint for S^*-decay is $d_u < D$ which, as $D = 2$, implies that $d_u = 1$ which in turn suggests, through Eq. (2b), that $J = 0$ which is consistent with Eq. (1) as the S^* has $G = +$ and $C = +$.

(*iii*) $\varrho'(1600)$: It is well known that this particle suffers strong decay but its 2π mode is found to be suppressed relative to the 4π mode which is dominant. In its decays, therefore, the constraint $d_u < D$ is valid, the equality sign is not occurring because Eqs. (2a) and (2b) suggest that *the spectrum of d values of massive bosons include* 3, 6, 9, ... *and also* 1. It may be noted that the 2π mode fraction shown in Ref. [1] for ϱ'-decay is "an educated guess". Further, the 1976-edition of Ref. [1] contains the remark "possibly seen" for the 2π mode for ϱ'-decay. Since we are interested in dominant mode(s) and as the 2π mode for ϱ'-decay cannot be regarded as one of the dominant modes and as such we need to consider only the decay $\varrho' \to 4\pi(D = 4)$. Clearly, the inequality $d_u < 4$ is consistent with the values $d_u = 1, 3$ as the value $d_u = 2$ is inadmissible since it is true for the photon only. But $d_u = 1$ implies that $J = 0$ which is disallowed by Eq. (1) as for ϱ', $G = +$ and $C = -$. Obviously for ϱ', $d_u = 3$ which in turn suggests that $J = 1$ which is consistent with Eq. (1).

(*iv*) $\pi^0(135)$: This particle suffers dominant electromagnetic decays $\pi^0 \to 2\gamma(D = 4)$ and as such in its decays the constraint is $d_u < D$ the equality sign not occurring for the reasons already discussed. Clearly, $d_u < 4$ is consistent with the values $d_u = 1,3$ as the value 2 is true for the photon only. Furthermore, $d_u = 3$ is ruled out as it implies $J = 1$

which is disallowed by Eq. (1) as the π^0 has $G = -$ and $C = +$. Therefore, the particle concerned has $d_u = 1$ which means $J = 0$ which is consistent with Eq. (1).

(*v*) g(1680): In its decays *none* of the conditions for the validity of the constraint $d_u \leqslant D$ is satisfied and, therefore, in its decays the constraint is $d_u \geqslant D$ in which the equality sign can only occur for the maximum value of D, denoted by D_{max}, subject to the condition that the value of D_{max} is equal to one of the allowed values of d for bosons and is consistent with Eq. (1). The decays $g \to 2\pi(D = 2)$, $4\pi(D = 4)$ indicate that the maximum value of D is 4 and, therefore, the constraint in g-decay is $d_u > D$ which must be satisfied by all the observed modes. The inequality $d_u > 4$ is satisfied for $d_u = 6$ which, through Eq. (2a), means $J = 2$ which, however, is not allowed by Eq. (1) as for the g-meson $G = +$ and $C = -$ suggesting that for it the minimum value of J consistent with Eq. (1) is 3. It is emphasized here that the method discussed in this note does *not*, in general, uniquely specify the spin of a nonstrange (as well as uncharmed) meson but it rules out some of the probable values for the same. We shall elaborately discuss this point in a future communication.

(*vi*) $\chi(3415)$: This particle suffers dominantly strong decays as evident from its decay modes [1]. However, its two-body strong decay modes $\pi\pi$ and $K\bar{K}$ are suppressed relative to the higher-body strong decay modes [1] and, therefore, in its decays the constraint is $d_u < D$ where the equality sign does not occur for the reasons already discussed. This constraint, needless to mention, must necessarily be satisfied by the minimum values of D which are 2 associated with the $\pi\pi(D = 2)$ and $K\bar{K}(D = 2)$ modes [1] which are, unlike ϱ'-decay, not highly suppressed compared to higher-body strong decay modes. Clearly, $d_u < 2$ demands $d_u = 1$ which suggests, through Eq. (2b), that $J = 0$ which is also consistent with Eq. (1) as the $\chi(3415)$ has $G = +$ and $C = +$.

(*vii*) $\chi(3510)$: This particle is an *abnormal* meson and as such the constraint in its decays is $d_u < D$ where the equality sign does not occur as in this case the minimum value of D is 4 associated with the $4\pi(D = 4)$ and $\pi\pi K\bar{K}(D = 4)$ modes [1]. Obviously $d_u < 4$ is consistent with the values $d_u = 1,3$ but the value 3 will mean $J = 1$ which is not allowed by Eq. (1) as $G = +$ and $C = +$ for this particle. Clearly, $d_u = 1$ indicate that $J = 0$.

(*viii*) $\chi(3555)$: The fraction modes [1] indicate that this particle suffers dominantly electromagnetic decays and, therefore, in its decays the constraint is $d_u < D$ the equality sign not occurring as the minimum values of D are 2 associated with the $\pi\pi(D = 2)$ and $K\bar{K}(D = 2)$ modes. Clearly, $d_u < 2$ demands that $d_u = 1$ which means $J = 0$ which is consistent with Eq. (1) as for this particle $G = +$ and $C = +$. A similar conclusion holds for the $\chi(2830)$ which suffers electromagnetic decays $\chi(2830) \to 2\gamma(D = 4)$ described by the constraint $d_n < D$ where the equality sign does not occur for the reasons discussed above. The inequality $d_u < 4$ is consistent with the values $d_u = 1, 3$ but the value 3 (which implies $J = 1$) is inadmissible as a vector-boson cannot decay into two photons. Hence $d_u = 1$ i.e. $J = 0$.

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