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IS THE IOTA A GIANT QUARKONIUM RESONANCE?

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ABSTRACT

Properties of the iota are explained by a radially mixed quarkonium state. Very different radial wave functions for the strange and nonstrange components arise from the near degeneracy of the first radially excited $s\bar{s}$ state and the second radially excited nonstrange state. The $K\bar{K}\pi$ decay is dominant; the $\eta\pi\pi$ decay suppressed and the SU(3) relation between the two decays naturally broken. Coherent effects analogous to those in nuclear giant resonances enhance production in radiative ψ decays by a considerable factor. One experimental test is a search for decays like D or F $\rightarrow \iota\pi \rightarrow K\bar{K}\pi\pi$ or $\psi \rightarrow \iota\phi \rightarrow \pi K\bar{K}\phi$.

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The controversy over the nature of the iota (1440) meson resonance [1,2,3]; i.e. whether it is an ordinary quarkonium state or a new exotic object like a glueball or a mixed state of quarks and gluons has been confused by the use of the standard nonet mixing formalism for the quarkonium state. It has been pointed out [4,5,6] that the standard nonet mixing pattern should not be expected to hold for pseudoscalar mesons and that different degrees of radial excitation should be mixed as well as the different flavor eigenstates [7,8,9].

We point out a new kind of mixing for the iota in which it is a mixture of different degrees of radial excitation with collective coherent effects [10] analogous to the giant resonant states observed in nuclear and condensed matter physics [11]. Such a state has very different properties from those of standard nonet mixing and seem to be consistent with the experimental data for the iota. The basic physics underlying this mixing description is: 1) Radial excitation spacings <u>decrease</u> at higher excitation as indicated by ψ and Υ spectra. 2) The same dynamical mechanism appears both in radiative ψ decays to pseudoscalar mesons and in the mixing of the different unperturbed pseudoscalar states; namely $q\bar{q}$ pair creation from gluons [12]. Radiative ψ decay is very sensitive to small coherent admixtures in meson wave functions.

In the language commonly used by nuclear physicists, the pseudoscalar mesons are "particle-hole excitations" of the vacuum. Radiative ψ decay is described by a summation of all bubble diagrams in which the excitation of a particle-hole pair by a gluonic probe is followed by a series of annihilations and pair creations. The contributions from diagrams of different order and from different excited configurations in the intermediate bubbles are all coherent and tend to push all the transition strength into a single "collective" or "giant resonant" state.

Let η_f, η'_f and η''_f denote the ground, first radially excited and second radially excited states of a quark-antiquark pair with flavor f analogous to the notation η_c, η'_c and η''_c used for charmonium. We use the conventional notation for the physical pseudoscalar meson η', but the ' denotes radial excitation in all other cases. The isospin scalar states in the u and d flavor sector are denoted by η_n, η'_n and η''_n, e.g.

$$|\eta_n\rangle = \frac{1}{\sqrt{2}} \{|\eta_u\rangle + |\eta_d\rangle\} \tag{1}$$

We assume that the lowest-lying pseudoscalar states with $I = Y = 0$ are mixtures of the six states η_n, η'_n, η''_n, η_s, η'_s and η''_s. A detailed dynamical model would define and diagonalize the mass matrix in this space of six states [8]. However such calculations are very sensitive to the values of parameters which are not known from first principles like unperturbed masses of the six states before the mixing is taken into account and the strengths of the mixing interaction and to the number of radially excited states included. For this reason it is difficult to obtain reliable quantitative results. However the qualitative features of the giant resonance phenomenon can be seen from the following reasonable assumptions regarding these parameters.

1. The unperturbed radial excitation splittings can be taken from the charmonium spectrum [8,13,14].

2. The difference between the unperturbed masses of the strange and nonstrange states with the same radial excitation is just due to the quark mass difference which can be taken from low-lying hadron spectra [8,13].

Then

$$M^0(\eta_n'') - M^0(\eta_n') \cong M(\psi'') \cong M(\psi') = 344 \text{ MeV} \tag{2a}$$

$$M^0(\eta_s') - M^0(\eta_n') \cong 2(m_s - m_u) \cong 2[M(\Lambda) - M(p)] = 355 \text{ MeV} \tag{2b}$$

$$M^0(\eta_n'') - M^0(\eta_s') \cong -11 \text{ MeV} \cong 0 \tag{2c}$$

where M^0 denotes the unperturbed mass in the absence of mixing and m_s and m_u denote the quark masses. The conventional nonet pattern is thus already destroyed at the fourth excited pseudoscalar state with the η_n'' approximately degenerate with and perhaps even lower than the η_s'.

The relations (2) suggest that the η_n'' and η_s' are much more strongly mixed with one another than either with the corresponding state in its own standard nonet and that the mixing should be treated by degenerate perturbation theory. In the lowest approximation the fourth and fifth states in the pseudoscalar meson spectrum are the linear combinations

$$|\iota\rangle = \cos\theta|\eta_s'\rangle + \sin\theta|\eta_n''\rangle \tag{3a}$$

$$|d\rangle = -\sin\theta|\eta_s'\rangle + \cos\theta|\eta_n''\rangle \tag{3b}$$

where θ is a mixing angle to be determined by the dynamics. One of these two states is a candidate for the physical iota which has been observed as the fourth pseudoscalar state in the spectrum of radiative ψ decays.

The transition matrix elements for the production of these states in rdiative ψ decays are then given by

$$\langle\iota\gamma|T|\psi\rangle = \cos\theta\langle\eta_s'\gamma|T|\psi\rangle + \sin\theta\langle\eta_n''\gamma|T|\psi\rangle \tag{4a}$$

$$\langle d\gamma|T|\psi\rangle = -\sin\theta\langle\eta_s'\gamma|T|\psi\rangle + \cos\theta\langle\eta_n''\gamma|T|\psi\rangle \tag{4b}$$

We now show how coherence and mixing can strongly enhance the $\psi\to2\gamma$ transition. The optimum mixing angle for this effect is the giant-resonance mixing angle defined by the relation

$$\tan\Theta_G = \frac{\langle\eta_n''\gamma|T|\psi\rangle}{\langle\eta_s'\gamma|T|\psi\rangle} \tag{5}$$

Substituting eq. (5) into eqs. (4) gives

$$\langle\iota_G\gamma|T|\psi\rangle = \langle\eta_s'\gamma|T|\psi\rangle/\cos\theta_G \tag{6a}$$

$$|\langle\iota_G\gamma|T|\psi\rangle|^2 = |\langle\eta_s'\gamma|T|\psi\rangle|^2 + |\langle\eta_n''\gamma|T|\psi\rangle|^2 \tag{6b}$$

$$\langle d_G\gamma|T|\psi\rangle = 0 \tag{6c}$$

where $|\iota_G\rangle$ and $|d_G\rangle$ denote the states (3) with the the mixing angle θ_G. Equations (6) show the characteristics of giant resonance mixing. All of the strength of the radiative ψ decay transition comes into the state $|\iota_G\rangle$ and the state $|d_G\rangle$ is decoupled.

A considerable additional enhancement is obtainable from very small mixing of the ι with the first three states in the pseudoscalar meson spectrum, the η, η' and ζ.

Let us write

$$|\iota_G^M\rangle = \cos\theta_G|\eta_s'\rangle + \sin\theta_G|\eta_n''\rangle + \varepsilon_1|\eta\rangle + \varepsilon_2|\eta'\rangle + \varepsilon_3|\zeta\rangle + O(\varepsilon^2) \tag{7a}$$

$$|\eta^M\rangle = |\eta\rangle - \epsilon_1 |\iota_G\rangle + O(\epsilon^2) \tag{7b}$$

where $|\iota_G^M\rangle$ and $|\eta^M\rangle$ denote the ι and η states with this additional mixing, ϵ_1, ϵ_2 and ϵ_3 are small parameters, and equations similar to (7b) hold for the η' and ζ. Then

$$\langle\iota_G^M\gamma|T|\psi\rangle = \langle\iota_G\gamma|T|\psi\rangle + \epsilon_1\langle\eta\gamma|T|\psi\rangle + \epsilon_2\langle\eta'\gamma|T|\psi\rangle + \epsilon_3\langle\zeta\gamma|T|\psi\rangle + O(\epsilon^2) \tag{8a}$$

$$\begin{aligned} |\langle\iota_G^M\gamma|T|\psi\rangle|^2 = {} & |\langle\iota_G\gamma|T|\psi\rangle|^2 + \\ & + 2\mathrm{Re}[\langle\iota_G\gamma|T|\psi\rangle(\epsilon_1\langle\eta\gamma|T|\psi\rangle + \epsilon_2\langle\eta'\gamma|T|\psi\rangle + \epsilon_3\langle\zeta\gamma|T|\psi\rangle + O(\epsilon^2))] \end{aligned} \tag{8b}$$

$$|\langle\eta^M\gamma|T|\psi\rangle|^2 = |\langle\eta\gamma|T|\psi\rangle|^2 - 2\mathrm{Re}[\epsilon_1\langle\iota_G\gamma|T|\psi\rangle\langle\eta\gamma|T|\psi\rangle] + O(\epsilon^2) \tag{8c}$$

This shows the large coherence effects characteristic of the giant resonance phenomenon. For a rough qualitative picture we take $\epsilon_1 = \epsilon_2 = \epsilon_3 = 0.1$, and set all the transition matrix elements equal. Then these 1% admixtures of each of the three low-lying states into the iota wave function (7) produce a 60% enhancement and a 20% suppression of the radiative transition probabilities (8b) and (8c) respectively, thus increasing the ratio of iota production to η production by a factor of 2.

In this description, the iota has a very strong transition matrix element for radiative ψ decays while the dominant component in its wave function is η'_s. This would explain why the dominant decay mode observed for the iota is $K\bar{K}\pi$ and the corresponding nonstrange state $\eta\pi\pi$ is not seen. All SU(3) predictions from the standard nonet model can be broken since the strange and nonstrange components of the wave function have different degrees of radial excitation and a different number of nodes. Giant resonant mixing thus provides a good qualitative description for the observed ι properties.

We now show that the giant resonance description not only describes the qualitative features of the physical iota but also arises naturally from the dynamics in any conventional model for radial mixing with unperturbed masses satisfying eqs. (2); e.g. with potentials that fit the charmonium spectrum.* The giant resonance mixing angle (5) and the phase coherence of the wave function (7) and the radiative ψ decay matrix element arise automatically. In such models the mass matrix has the form [8]

$$M = M^0 + A \tag{9}$$

The matrix elements of the unperturbed mass operator M^0 and the annihilation interaction A are given by

$$\langle \eta_f^i | M^0 | \eta_g^j \rangle = \delta_{fg} \delta_{ij} M^0_{fi} \tag{10a}$$

$$\langle \eta_f^i | A | \eta_g^j \rangle = g_{fi} g_{gj} \tag{10b}$$

where η_f^i denotes the unperturbed state of a quark-antiquark pair of flavor f and radial excitation i, f = n or s and i = 0,1 or 2 denotes the states η_f, η'_f and η''_f respectively. M^0_{fi} is the unperturbed mass eigenvalue and g_{fi} are constants specifying the interaction.

The key dynamical assumption is the factorized form of eq. (10b) where the constant g_{fi} depend only upon the properties of the η_f^i wave function. In the simple models, where the annihilation depends upon the wave function at the origin, g_{fi} is given by [13]

*In harmonic oscillator models [7] this degeneracy (2) does not appear and giant resonance mixing does not occur.

$$g_{fi} = g\, n_f^i(0) \tag{11}$$

where g is a constant specifying the strength of the interaction. The underlying physics behind the factorization (10b) is that the quark-antiquark annihilation and subsequent pair creation goes via an intermediate state of gluons which does not remember the quantum numbers of the initial state. We do not need the explicit form (11) for our purposes and can use any generalization having the factorized form (10b) such as including a finite range for the interaction.

The second essential dynamical assumption is that the radiative ψ decay depends upon the same property of the wave function as the annihilation interaction (10b) because the transition occurs via the same kind of gluonic intermediate state [10]. This is expressed formally by the relation

$$\langle n_f^i \gamma | T | \psi \rangle = G\, g_{fi} \tag{12}$$

where G is a constant specifying the strength of the transition.

The relation (2c) between the unperturbed masses becomes, in this notation,

$$M_{s1}^0 = M_{n2}^0 \tag{13}$$

The giant resonance mixing angle (5) is seen to be

$$\tan\theta_G = \frac{g_{n2}}{g_{s1}} \tag{14}$$

We now see that states (3a) and (3b) are the eigenvectors of the annihilation matrix (10b) in this two-dimensional subspace when the mixing angle is defined to be the giant resonance value (14). The decoupled state

$|d_G\rangle$ is indeed decoupled and is an eigenvector of A with the eigenvalue 0, and also an eigenvector of the mass operator (9)

$$A|d_G\rangle = 0 \tag{15a}$$

$$M|d_G\rangle = M^0_{s1}|d_G\rangle = M^0_{n2}|d_G\rangle \tag{15b}$$

Substituting eqs. (12) and (14) into eqs. (6) then gives

$$\langle\iota_G\gamma|T|\psi\rangle = G\ g_{s1}/\cos\theta_G = G\ g_G \tag{16a}$$

$$|\langle\iota_G\gamma|T|\psi\rangle|^2 = G^2[g^2_{s1} + g^2_{n2}] = G^2\ g^2_G \tag{16b}$$

where g_G is defined as

$$g_G = g_{s1}/\cos\theta_G \tag{16c}$$

The iota wave function to first order in standard degenerate perturbation theory is then

$$|\iota^M_G\rangle = |\iota_G\rangle + \frac{g_{n1}g_G}{\Delta M_{n1}}|n_n\rangle + \frac{g_{s1}g_G}{\Delta M_{s1}}|n_s\rangle + \frac{g_{n2}g_G}{\Delta M_{n2}}|n'_n\rangle \tag{17a}$$

where ΔM_{fi} denotes the unperturbed mass difference between the iota and the state n^i_f. These mass differences are always positive since the three admixed states all lie below the iota. We then obtain

$$\langle\iota^M_G\gamma|T|\psi\rangle = G\ g_G\{1 + \frac{g^2_{n1}}{\Delta M_{n1}} + \frac{g^2_{s1}}{\Delta M_{s1}} + \frac{g^2_{n2}}{\Delta M_{n2}}\} \tag{17b}$$

This is the analog of eq. (8a) and shows explicitly that the parameters ϵ_1, ϵ_2 and ϵ_3 are indeed all positive and that the coherence with the constructive interference of the giant resonance does come out of the dynamics.

The mass eigenvalue of the ι is above the d because the operator A is positive definite and has positive eigenvalues [10]. However the d by eq. (6c) is not expected to appear in radiative ψ decays. The iota in this formulation is indeed the fourth state in the spectrum appearing in radiative ψ decays.

A quantitative calculation of the properties of the iota depends on the exact values of the parameters g_{fi} and the unperturbed masses M^0_{fi}. It also must be corrected for the mixing with higher states which would tend to counteract the giant resonance effect since the higher states would be mixed in with a negative phase. However one would expect the qualitative features to remain. The approximate accidental degeneracy expected from eqs. (2) should not be far off, suggesting the use of nearly degenerate perturbation theory to describe these states. If the coefficients g_{fi} decrease reasonably rapidly with the degree of radial excitation, we can expect that the contributions from the higher states will not be very important. In any case the existence of the giant resonant state must be carefully considered in any analysis of the iota. Its description as a quarkonium state cannot be discarded simply because its properties are in disagreement with the standard nonet mixing model [15].

This model can be tested experimentally by a search for the iota in the decays of charmed and charmonium states. The $\iota\pi$ decay modes for decays of D or F mesons are s-wave and should have comparable branching ratios to $\eta\pi$ and $\phi\pi$ decays. They would be observed as

$$D^+ \text{ or } F^+ \to \iota\pi^+ \to K_s K^{\pm}\pi^{\mp}\pi^+ \tag{18a}$$

$$D^+ \text{ or } F^+ \rightarrow \iota\pi^+ \rightarrow K_s K_s \pi^0 \pi^+ \tag{18b}$$

$$D^+ \text{ or } F^+ \rightarrow \iota\pi^+ \rightarrow K^+ K^- \pi^0 \pi^+ \tag{18c}$$

$$D^0 \rightarrow \iota\pi^0 \rightarrow K\bar{K}\pi\pi^0 \tag{18d}$$

The kaon pair would be very close to threshold and the two pions would have very different energies in the center of mass system of the D or F. This might help reduce background. Although the D decays are Cabibbo suppressed, they might be enhanced by a factor similar to that in eq. (17b) if the ι is produced in both the $s\bar{s}$ and $d\bar{d}$ components with a strength proportional to the wave function at the origin.

The $\iota\phi$ decay mode might be seen in ψ decays with branching ratios comparable to $\eta\phi$ and $\eta'\phi$

$$\psi \rightarrow \iota\phi \rightarrow K\bar{K}\pi\phi \tag{19}$$

Another possible experimental test is in radiative decays of the iota to vector meson states. The strengths of these transitions are very sensitive to details of the radial wave functions and are not easily predicted. However, if the $\rho\,\gamma$ decay mode is seen, then the $\omega\gamma$ and $\phi\gamma$ decays should be investigated. The $\phi\gamma$ and $\rho\,\gamma$ decays are not related, since the strange and nonstrange components have very different radial wave functions. However the standard 9:1 ratio holds for the $\rho\,\gamma$ and $\omega\gamma$ decays which come from the same nonstrange component

$$\Gamma(\iota\rightarrow\omega\gamma) = (1/9)\Gamma(\iota\rightarrow\rho\gamma). \tag{20a}$$

The $\phi\gamma$ decay mode should be considerably larger than the $\omega\gamma$ decay

$$\Gamma(\iota\to\phi\gamma) > \Gamma(\iota\to\omega\gamma) \ . \tag{20b}$$

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