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Mixtures of quarkonium and gluonium

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We study the 2γ decays of the light pseudoscalar mesons in a model that allows the isoscalar states to have a significant gluonium component, and show that the rates are in good agreement with experiment. The amount of radial mixing in η,η' states determines these decays completely. This makes it difficult to test for the presence of gluonium. The radiative decays of $\psi'(3685)$ might be a better way to test for the gluonium admixture. We give estimates for the branching ratios.

I. INTRODUCTION

The region between 1 and 2 GeV has become of great interest for the isoscalar pseudoscalar mesons. Unlike the isoscalar vector mesons (ω and ϕ), which are ideally mixed into a $|u\bar{u}+d\bar{d}\rangle$ and $|s\bar{s}\rangle$ quark structure, the pseudoscalars appear to contain nearly equal amounts of strange and nonstrange quarks in their wave functions,[1] i.e.,

$$\eta=-\cos\alpha_P\,|s\bar{s}\rangle-\sin\alpha_P\,|u\bar{u}+d\bar{d}\rangle/\sqrt{2}\ , \tag{1}$$

$$\eta'=-\sin\alpha_P\,|s\bar{s}\rangle+\cos\alpha_P\,|u\bar{u}+d\bar{d}\rangle/\sqrt{2}\ , \tag{2}$$

where experiment, for example, used to favor[2] the value $\alpha_P\simeq-45°$ from the ratio $\Gamma(\eta\to\gamma\gamma)/\Gamma(\pi^0\to\gamma\gamma)$.

The claim that we understand this mixing mechanism must be reexamined if radially excited states exist and have additional mixing with these mesons. Unfortunately, the existence of the radial excitations of the pseudoscalars seems to be unclear at present. In 1979 an experiment detected the $\eta(1275)$ in a π^-p reaction.[3] Its main decay mode appears to be $\delta\pi$ although only $\eta\pi\pi$ is seen. If the $\eta(1275)$ is part of the $2\,^1S_0$ nonet, along with the $\pi(1300)$ and $K(1400)$, then from mass considerations one might expect it to be made from nonstrange quarks. For consistency we might expect the radial partner of the $\eta'(958)$ to be made from strange quarks and have a mass of about 1500 MeV.[4] The discovery[5] of the $\iota(1440)$ has complicated the problem. The radiative decay of J/ψ to the ι has a branching ratio $(0.42\pm0.12)\%$, i.e., comparable to or greater than that to η' $[(0.36\pm0.5)\%]$ while the $\eta(1275)$ has not as yet been seen in J/ψ radiative decays. The branching ratio of $\iota\to\rho\gamma$ is of the order[6] of 3%, which would be surprising for a predominantly $s\bar{s}$ state, although this argument can be vitiated by the presence of mixing with other $q\bar{q}$ states.

A number of explanations have been put forward in which the ι might be a glueball,[7] a hybrid $q\bar{q}g$,[8] a giant nuclear resonance containing various degrees of radial excited states,[9] the nonstrange radial partner of the $\eta(549)$, assuming the $\eta(1275)$ does not exist[10] or a mixture of gluonium and quarkonium.[11] These are discussed more fully in Ref. 11.

II. COMPARISON WITH THE SIMPLE QUARK MODEL

In the present paper we want to expand on our interpretation of the $\iota(1440)$ as a mixture of quarkonium and gluonium states.[11] For readers unfamiliar with this model we review briefly the salient points.[12,13] The model is based on an analysis of the light mesons considered as bound states of u, d, and s quarks. Only S waves were considered and the ground state, together with the first two radially excited states formed the set of basis states. The model has a harmonic-oscillator potential with the mixing coming from a hyperfine (Fermi-Breit) interaction. The spectra of the known low-lying mesons together with their radiative decays were used to obtain a determination of the parameters. The masses and the decays of the radially excited mesons were then predicted since the composition of the physical states in terms of the (unperturbed) harmonic-oscillator states was available. The results of the complete fit were in good agreement with experiment and formed an improvement over the naive quark-model fits. In our model the π, η, and η' are all mixtures of ground and radial excited states. The situation is more complicated for η and η', which contain one ground and two radial excitations for both the octet and singlet parts, in addition to a gluonium component. We give some of the results for the composition of the physical states as mixtures of the ground state, the first and second radial excitations, and gluonium.[13] For example, the ground-state π and the first radial partner are

$$|\pi_1\rangle=0.836\,|N_0\rangle-0.446\,|N_1\rangle+0.319\,|N_2\rangle\ , \tag{3}$$

$$|\pi_2\rangle=0.533\,|N_0\rangle+0.800\,|N_1\rangle-0.277\,|N_2\rangle\ . \tag{4}$$

Here $|N\rangle=|u\bar{u}-d\bar{d}\rangle/\sqrt{2}$. The subscripts 0, 1, and 2 refer to ground, first, and second radial excitations on the right-hand side, while 1 and 2 on the left-hand side denote the physical ground state and the first radial excitation of the neutral pion. For the isoscalar sector, the composition of the physical states in terms of the radial components and gluonium are

$$|\eta_1\rangle = 0.856|N_0\rangle - 0.175|N_1\rangle + 0.220|N_2\rangle - 0.380|S_0\rangle + 0.129|S_1\rangle - 0.117|S_2\rangle - 0.117|G\rangle , \quad (5)$$

$$|\eta_1'\rangle = 0.327|N_0\rangle + 0.035|N_1\rangle + 0.062|N_2\rangle - 0.828|S_0\rangle - 0.068|S_1\rangle + 0.119|S_2\rangle - 0.429|G\rangle , \quad (6)$$

$$|\eta_2\rangle = 0.119|N_0\rangle + 0.630|N_1\rangle - 0.096|N_2\rangle - 0.260|S_0\rangle - 0.666|S_1\rangle + 0.102|S_2\rangle - 0.204|G\rangle , \quad (7)$$

$$|\iota\rangle = 0.308|N_0\rangle + 0.049|N_1\rangle - 0.019|N_2\rangle + 0.290|S_0\rangle - 0.312|S_1\rangle + 0.015|S_2\rangle + 0.849|G\rangle , \quad (8)$$

where on the right-hand side

$$|N\rangle = |u\bar{u} + d\bar{d}\rangle/\sqrt{2} ,$$

$$|S\rangle = |s\bar{s}\rangle ,$$

$$|G\rangle = |\text{gluonium}\rangle ,$$

and we keep the same convention for ground and radial states. In the standard model the mixing is, using $\alpha_P \simeq -45°$,

$$|\eta_1\rangle = 0.707|N_0\rangle - 0.707|S_0\rangle , \quad (9)$$

$$|\eta_1'\rangle = 0.707|N_0\rangle + 0.707|S_0\rangle . \quad (10)$$

Including the radial excitations our model gives

$$|\eta_1\rangle = +0.856|N_0\rangle - 0.380|S_0\rangle + \text{radial excitations} + \text{gluonium} , \quad (11)$$

$$|\eta_1'\rangle = 0.327|N_0\rangle + 0.828|S_0\rangle + \text{radial excitations} + \text{gluonium} . \quad (12)$$

The gluonium and radial excitations form between 12% and 20% of the η and η' wave functions. However, in radiative decays the effect of these "contaminations" is reduced by the fact that the matrix element between the ground and radial excited states is smaller than that among ground states alone; the effect is still strongly evident in the mixing angles.

In the deviation from standard mixing in our model we tend to have less $|s\bar{s}\rangle$ in η_1 and $|u\bar{u}+d\bar{d}\rangle$ in η_1', so we should expect to disagree with the naive quark model in those processes that measure the $|s\bar{s}\rangle$ content of the η_1 and the $|u\bar{u}+d\bar{d}\rangle$ content of η_1', namely, $\phi_1\to\eta_1\gamma$ and $\eta_1'\to\rho_1\gamma$, $\eta_1'\to\omega_1\gamma$. However, by including the mixing properly,[13] the complete fit to the light-meson radiative decays is significantly better that that of the naive quark model, particularly for $\phi_1\to\eta_1\gamma$; the quark model has great difficulty with this decay mode. This difference is common to all quark models with radial mixing and has little to do with the choice of the confining potential (harmonic oscillator in our case). The main difference between the harmonic oscillator and a linear potential, for example, is that for the harmonic oscillator there is equal spacing for radial states. As a result, a physical n radial excitation in the isoscalar sector will always get its biggest contribution from the same n radial eigenfunctions of the harmonic oscillator. The linear potential can mix different radial eigenfunctions into the same physical state in a different way;[14] the data are not yet sufficiently accurate to distinguish these effects.

In a previous paper we showed that it is hard to reconcile the notion that the ι is a pure radial excitation of η or η' particularly when the branching for radiative decay from charmonium is so large. Compared to $J/\psi\to\gamma\eta'$, the decay $J/\psi\to\gamma\iota$ goes down by a factor of 2 in phase space alone, and if the ι were simply a radial excitation we might expect the matrix element to be further reduced. Radiative decays of J/ψ are therefore a good way of finding states with significant gluonium components. On the other hand, if the ι were a pure gluonium state it would not decay radiatively. If, however, the gg state has the same quantum numbers as a $q\bar{q}$ state it will mix with it. The mechanism of this mixing has not yet been developed dynamically so we will take a simple mixing model with only one mixing parameter, using our previous results.[12] From Eqs. (5)—(8), we note that the effect of gluonium-quarkonium mixing in the isoscalar-pseudoscalar channel is that all the states in that sector (η and η' included) have a significant gluonium component,[13] in agreement with previous calculations based on QCD sum rules.[15]

The gluonium admixtures in the $q\bar{q}$ states do not affect the ground state much,[13] so that the deviation from the usual mixing angle can be considered mainly as a radial mixing effect. This is to be compared with an analysis done by Rosner[16] of the experimental radiative decays in which radial mixing is ignored and mixing angle differences are assumed to result purely from gluonic admixtures. He obtained the following values for the mixing angles:

$$\eta_1 = \pm(0.73\pm0.10)|N\rangle \pm (0.74\pm0.06)|S\rangle ,$$

$$\eta_1' = \pm(0.63\pm0.12)|N\rangle \pm y_{\eta'}|S\rangle ,$$

where $y_{\eta'}$ is to be fixed by the value of $\phi\to\eta'\gamma$ (expected to be small). This procedure allows the possibility that 16% of η_1 and more than half of η_1' could be gluonic.

III. TWO-PHOTON DECAY PROCESSES

To distinguish among these possibilities we first of all discuss the 2γ decays for the neutral light mesons. We use vector dominance to evaluate the 2γ decays, calculating the one-photon coupling with the ρ, ω, and ϕ. For example, in the standard model[2] the physical vector states can be written as

$$\phi = \omega_8 \cos\theta_V - \omega_1 \sin\theta_V , \quad (13)$$

$$\omega = \omega_8 \sin\theta_V + \omega_1 \cos\theta_V \quad (14)$$

(where the standard model has the ideal mixing angle $\theta_V = 35°$). The relation between 2γ couplings and radiative decays through vector dominance is

$$M_{\pi\gamma\gamma}=c_1 M_{\pi\rho\gamma}+c_2(\sin\theta_V M_{\pi\omega\gamma}+\cos\theta_V M_{\pi\phi\gamma}) , \tag{15}$$

where

$$\Gamma(\pi\to\gamma\gamma)=(\text{phase space})\,|\,M_{\pi\gamma\gamma}\,|^2$$

and

$$\Gamma(\rho,\omega,\phi\to\pi\gamma)=(\text{phase space})\,|\,M_{\rho,\omega,\phi\pi\gamma})\,|^2 .$$

Here $c_1=e/2\gamma_\rho$, $c_2=e/2\sqrt{3}\gamma_\omega$ appear in the definition of the electromagnetic current.

The $SU(3)_{\text{flavor}}$ limit is $\gamma_\rho=\gamma_\omega$ which holds well even when $SU(3)_{\text{flavor}}$ is broken. Our case is in fact more complicated since we should, in principle, add all contributions of the radial excitations to the radiative decays, such as $M_{\pi_1\rho_2\gamma}$, $M_{\pi_1\omega_2\gamma}$, $M_{\pi_1\phi_2\gamma}$ and also those from the higher states. We shall include these three in order to get an understanding of the effects of including ρ_2, ω_2, and ϕ_2 couplings to the pion. As will be seen the effect is small (5% or less) so we expect the radiative decays of the second radially excited states to give a negligible contribution to $\pi_1\to\gamma\gamma$. The other complication is that our ω and ϕ states are not just simple mixtures of singlet and octet SU(3) states but also contain radial excitations; that is, there is no single angle θ_V. We calculate the contribution to $\pi_1\to 2\gamma$ from our mixing scheme and insert it into the vector-dominance assumption. As in the naive quark model we shall keep approximate $SU(3)_{\text{flavor}}$ symmetry for γ_ρ, γ_ω with $\gamma_p{}^2/4=0.51$. This way the rates for the radiative decays completely determine the 2γ decays; care must be taken only with the sign of the amplitudes $M_{PV\gamma}$ (P = pseudoscalar, V = vector). In a similar way we can calculate the η-η' sector. Our results are as shown in Table I. In the second column are our results for $\pi_1\to 2\gamma$, $\eta_1\to 2\gamma$, $\eta_1'\to 2\gamma$, and the predictions of $\pi_2\to 2\gamma$, $\eta_2\to 2\gamma$, $\iota\to 2\gamma$ with only ground states coupling to the photon being included. The results do not change much on adding the contributions of the radial excited states (column 3). The experimental values are given in the last column and include a recent measurement of $\eta_1'\to 2\gamma$ by the TASSO collaboration.[19]

Our results are in reasonably good agreement with experiment; the $\eta'(958)$ decay to two photons, despite the large gluonium component, is within the experimental errors. The agreement with the more recent value for the decay $\eta\to\gamma\gamma$ gives a reason for α_P to deviate from the old value without giving up the annihilation picture.[1] The results reflect the accuracy of our fits[11,13] to the radiative decays; the worst cases contribute about 10 to the overall χ^2. This is contrasted with the simple quark model which fails miserably in accounting for $\phi\to\eta_1\gamma$ (Table II).

The conclusions we can draw from these results are the following.

(1) Inclusion of radial and gluonium excitations alter the standard mixing picture of the light mesons so that the mixing angle is no longer $\simeq -45°$. The new "effective angle" $\simeq -55°$ is in good agreement with recent experiments and with other theoretical predictions.[14] The naive quark model was in good agreement with the older measurement of $\eta\to 2\gamma$.

(2) The 2γ decays of the π, η, and η' can be well accounted for in this picture by the amount of radial mixing; this obscures the extent of gluonium mixing in the ground states. As a result, this is not a good way to ascertain the gluonium admixture. More generally, the composition and decays of light mesons are not an efficient way to determine this admixture.

IV. RADIATIVE $\psi'(3865)$ DECAYS

We have shown in the previous discussion that neither radiative nor 2γ decays of the isoscalar mesons could test for the presence of gluonium in that sector. In the search for reactions to test for the presence of gluonium, the radiative decay of the J/ψ to light isoscalars turns out to be important. Using the Okubo-Zweig-Iizuka (OZI) rule means this proceeds by $c\bar{c}\to gg, u\bar{u}, d\bar{d}, s\bar{s}$.

A further simplifying assumption would put the gg in a bound gluonium state (although this is not necessarily the only way[21]). This assumption does not introduce any new parameters into the theory and gives, in our current understanding, the main channel of J/ψ radiative decay to light pseudoscalars. Then $J/\psi\to\gamma P$, P a light pseudoscalar, measures the gluonium component of the pseudoscalar P (where P is our model is a mixed state of gluonium and quarkonium). Since $c\bar{c}\to u\bar{u}, d\bar{d}, s\bar{s}$ is OZI-rule suppressed the process $c\bar{c}\to gg$ is expected to be less suppressed (sometimes referred to as a square-root OZI suppression) and, in fact, should dominate. This would explain why $J/\psi\to\gamma\iota$ is so large (in particular larger than $J/\psi\to\gamma\eta_1'$) as well as giving the relative ratios of

$$B(J/\psi\to\gamma P)/B(J/\psi\to\gamma\eta_1')$$

with $P=\eta_1,\eta_2,\iota$ (Ref. 11).

TABLE I. Two-photon decays of pseudoscalar mesons. The experimental values are from the references quoted.

Decay	Vector dominance for ground states	Vector dominance for ground and first radial excitations	Experiment
$\pi_1\to 2\gamma$	7.9 eV	8.1 eV	7.86±0.54 eV (Ref. 17)
$\eta_1\to 2\gamma$	0.56 keV	0.56 keV	0.56±0.16 keV (Ref. 18)
$\eta'\to 2\gamma$	4.22 keV	4.28 keV	5.1±0.4±0.7 keV (Ref. 19)
$\iota\to 2\gamma$	2.9 keV	2.5 keV	<7 keV (Ref. 20)
$\pi_2\to 2\gamma$	8.6 keV	9.0 keV	
$\eta_2\to 2\gamma$	2.4 keV	2.5 keV	

TABLE II. Radiative decays in the isoscalar section. The experimental values are taken from Ref. 17. Only ground states are involved and the suffices have been dropped.

Decay	Predicted values in keV	Experimental values in keV
$\rho\to\eta\gamma$	97.1	55.4±14.0 (83.2±17.2)
$\omega\to\eta\gamma$	10.9	3.0±2.5 (28.7±7.0)
$\phi\to\eta\gamma$	30.1	50.6±8.6
$\eta'\to\rho\gamma$	37.4	87.0±15.7
$\eta'\to\omega\gamma$	5.6	8.1±2.0
$\phi\to\eta'\gamma$	0.6	

We can generalize this argument to any vector $c\bar{c}$ state below the charm threshold, and therefore to the $\psi'(3865)$ allowing a prediction of the rates for $\psi'\to\gamma P$ where $P=\eta_1$, η_1', η_2' and ι. The radiative decays of ψ' to light pseudoscalars will have the same mechanism as the radiative decays of J/ψ, so that we can predict the rates of ψ' with no additional parameters. This gives another test of the model and, in general, of any model that considers the ι to be predominantly gluonium.

We can expect the $\psi'(3865)$ radiative decays to follow from the $J/\psi(3100)$ radiative decays using the scaling relation[22]

$$\frac{B(\psi'\to\gamma P)}{B(\psi\to\gamma P)}=\frac{\Phi(\psi'\to\gamma P)}{\Phi(\psi\to\gamma P)}\frac{|\psi'(0)|^2}{|\psi(0)|^2}\frac{\Gamma_{\rm tot}(\psi)}{\Gamma_{\rm tot}(\psi')},$$

where Φ denotes phase space, and $\psi(0)$ ($\psi'(0)$) is the wave function at the origin of ψ (ψ'). The above relation is valid for any decay process X, in particular for γP. Comparison with experimental data yields

$$\frac{B(\psi'\to\gamma P)}{B(\psi\to\gamma P)}=(0.12\pm0.02)\frac{\Phi(\psi'\to\gamma P)}{\Phi(\psi\to\gamma P)},$$

where

$$\Phi(\psi'\to\gamma P)=[(m_{\psi'}{}^2-m_P{}^2)/2m_{\psi'}]^3$$

with a similar expression for $\Phi(\psi\to\gamma P)$. We can therefore scale all our results to $B(J/\psi\to\gamma\eta_1')$ and using the values given in Ref. 11 we obtain that shown in the second column of Table III. The Particle Data Group[17] gives only upper values for these processes which we list in the third column of Table III. Notice that all our results do well in comparison to experiment with the exception of the ι. There are several possibilities that arise which could explain why the ι does not do so well.

(a) The ι is not really a mostly gluonium state. If it were a normal radial excitation containing little admixture of gluonium, the branching ratio of ψ' radiative decay should be suppressed. This would of course make it difficult for us to understand why the J/ψ radiative decay to

TABLE III. Radiative decays of $\psi'(3865)$ to light isoscalars. Experimental values are from Ref. 17.

Decay	Predicted value	Experimental value
$B(\psi'\to\eta_1\gamma)$	0.002×10^{-2}	$<0.02\ \times10^{-2}$
$B(\psi'\to\eta_1'\gamma)$	$0.02\ \times10^{-2}$	$<0.02\ \times10^{-2}$
$B(\psi'\to\eta_2\gamma)$	0.007×10^{-2}	
$B(\psi'\to\iota\gamma)$	$0.07\ \times10^{-2}$	$<0.012\times10^{-2}$

the ι has such a large branching ratio since the mechanism should be similar.

(b) The assumption that $\psi'\to\gamma P$ and $\psi\to\gamma P$ scale as the wave function at the origin is wrong and there are in fact more complicated dynamical processes going on. The problem with this is that it works well for a variety of strong decays, so that it should be expected to do reasonably well for radiative decays.

(c) Alternatively, it may be related to some other anomalous ψ' decays. Neglecting phase space the ratio

$$R=\frac{B(\psi'\to X)}{B(\psi\to X)}=0.12\pm0.02$$

is independent of X; this is what was found[22] at SLAC (SPEAR) for

$$X=p\bar{p},p\bar{p}\pi^0,K^+K^-\pi^+\pi^-\ ,$$
$$2\pi^+2\pi^-\pi^0,\omega\pi^+\pi^-,3\pi^+3\pi^-\pi^0,e^+e^-\ .$$

However, this was not the case of $X=K^*\bar{K},\rho\pi$. Neglecting phase space for all of the above neglects a factor of order unity so we would expect the above relation to be approximately true. But for $X=K^*\bar{K}$

$$\frac{B(\psi'\to K^*\bar{K})}{B(\psi\to K^*\bar{K})}<1.96\times10^{-2}\ .$$

Since the ι is the only member of the $\eta_1,\eta_1',\eta_2,\iota$ group that can decay[23] to $K^*\bar{K}$, the lack of $\gamma\iota$ may be closely related to this.[23]

In conclusion, the interpretation of the ι is an interesting problem which may still need more experimental data particularly from J/ψ decays, but also from ψ' radiative decays. Although it seems certain that the ι has considerable mixing of radial excitations and gluonium,[11] at least in the conventional approach using J/ψ radiative decays, the complete solution for the mixing needs a better understanding of the problems of the $K^*\bar{K}$ final states.

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