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Radiative decays of light- and heavy-flavor tensor mesons

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New data are used to reexamine $T \rightarrow V\gamma$ and $T \rightarrow \gamma\gamma$ decays. Their strength is determined from sum rules involving experimentally determined quantities. One of two models considered is in excellent agreement with the measured $f^0, A_2^0 \rightarrow \gamma\gamma$ transitions. The model is extended to calculate radiative decays of strange and charmed tensor mesons.

During the last few years, remarkable experimental progress has been made in the field of two-photon physics.[1] In particular, the 2γ partial decay widths of A_2^0, f^0, and η' have been determined from their production in γ-γ collisions and there is work in progress on additional exclusive channels. The measured $A_2^0 \rightarrow \gamma\gamma$ and $f^0 \rightarrow \gamma\gamma$ transitions turn out to be close to the values we anticipated[2] some years ago.

In this note we bring up to date the predictions[2] on various radiative decays of light-flavor tensor mesons. We then extend the model used in Ref. 2 and apply it to the calculation of radiative decays of strange and charmed tensor mesons. We use here the notation of Ref. 2, to which the reader is referred for details.

A dual amplitude for the scattering of pseudoscalar mesons on vector mesons[3] was used in Ref. 2 to relate the trilinear couplings of tensor and vector mesons (TVV) to the couplings of lower-spin mesons. The Veneziano-type amplitude developed in Ref. 3 for the process $\pi + V_1 \rightarrow \pi + V_2$ (V_i being an isosinglet, $C=-1$ vector meson) displays crossing symmetry and Regge asymptotic behavior in all channels and is gauge invariant in the limit $m_{V_i} \rightarrow 0$. The requirements imposed[3] on the amplitude lead to relations among the couplings of the leading contributions. Extending the construction to scattering amplitudes involving photons and isospin-carrying vector mesons, the following relations were obtained[2]:

$$g_{f\omega\gamma} = \frac{g_{\omega\rho\pi} g_{\rho\pi\gamma}}{4 g_{f\pi\pi}}, \quad g_{f\rho\gamma} = \frac{g_{\omega\rho\pi} g_{\omega\pi\gamma}}{4 g_{f\pi\pi}}, \quad g_{f\gamma\gamma} = \frac{g_{\omega\pi\gamma}^2 + g_{\rho\pi\gamma}^2}{4 g_{f\pi\pi}}, \tag{1}$$

$$g_{A_2\omega\gamma} = \frac{g_{\omega\omega\eta} g_{\omega\pi\gamma} + g_{\rho\eta\gamma} g_{\omega\rho\pi}}{8 g_{A_2\eta\pi}}, \quad g_{A_2\rho\gamma} = \frac{g_{\rho\rho\eta} g_{\rho\pi\gamma} + g_{\omega\eta\gamma} g_{\omega\rho\pi}}{8 g_{A_2\eta\pi}}, \quad g_{A_2\gamma\gamma} = \frac{g_{\rho\eta\gamma} g_{\rho\pi\gamma} + g_{\omega\pi\gamma} g_{\omega\eta\gamma}}{4 g_{A_2\eta\pi}}. \tag{2}$$

A confirmation on the consistency of the dynamical assumption made in the derivation of (1) and (2) may be found in the fact that, if SU(3) +nonet symmetry relations are assumed for respective couplings on the right-hand sides (RHS's) of these equations, the couplings given by the left-hand sides fulfill the correct symmetry relations among themselves. This holds also for the newly derived Eqs. (6) and (7) of the present paper, when SU(4) is considered.

Recently, $f^0 \rightarrow \gamma\gamma$ and $A_2^0 \rightarrow \gamma\gamma$ were measured in several experiments. An average of five experiments on $f^0 \rightarrow \gamma\gamma$ gives[1] $\Gamma(f^0 \rightarrow \gamma\gamma) = 3 \pm 0.8$ keV and an average of two experiments on $A_2^0 \rightarrow \gamma\gamma$ gives[1] $\Gamma(A_2^0 \rightarrow \gamma\gamma) = 1 \pm 0.4$ keV. The closeness of these values to those predicted gives credibility to the approach of Ref. 2. However, since these predictions were made[2] mainly on the basis of symmetry relations for the coupling constants in the RHS's of Eqs. (1) and (2), it is of obvious interest to reevaluate these sum rules by using recently determined experimental values for the couplings (e.g., $\rho\pi\gamma$, $\rho\eta\gamma$, $\omega\eta\gamma$, $K^* K\gamma$). Our results are presented in Table I. Experimental values[4] are used for the couplings in the RHS's of Eqs. (1) and (2), except for $g_{\omega\omega\eta}$, $g_{\rho\rho\eta}$ for which we use symmetry-determined values from $g_{\omega\rho\pi}$. For $\Gamma(\rho \rightarrow \pi\gamma)$ we use the latest[5] experimental value of 67 keV and for $\rho \rightarrow \eta\gamma$, $\omega \rightarrow \eta\gamma$ we use the positive-interference solution.[4]

The $T \rightarrow V\gamma$ ($T \rightarrow \gamma\gamma$) processes are described by three (two) independent amplitudes. The specific form of the effective Lagrangian used relates among independent amplitudes. We use for our calculations two alternative forms: Model I is the effective Lagrangian given in Eqs. (1) and (2) of Ref. 2. Model II is due to Renner[6] and was obtained in the framework of tensor-meson dominance. The form of the effective Lagrangian expressing Renner's model is

$$\mathcal{L}_{TVV}^{(\mathrm{II})} = \frac{g_{TV_1V_2}}{\mu} \tau^{\mu\nu} [(\epsilon^{(1)} \cdot p_2) \epsilon_\mu^{(2)} p_{1\nu} + (\epsilon^{(2)} \cdot p_1) \epsilon_\mu^{(1)} p_{2\nu} - (p_1 \cdot p_2) \epsilon_\mu^{(1)} \epsilon_\nu^{(2)} - (\epsilon^{(1)} \cdot \epsilon^{(2)}) p_{1\mu} p_{2\nu}]. \tag{3}$$

TABLE I. Partial decay widths in keV for one- and two-photon decays of tensor mesons. Model I is represented by the effective Lagrangian of Ref. 2 and model II by Eq. (3) of this paper. The second and third columns are obtained by using experimentally determined values in the RHS's of Eqs. (1), (2), and (6). Values in the fourth column are derived by using SU(4).

	Calculated decay widths			Average
Process	Model I (Ref. 2)	Model II [Eq. (3)]	Symmetry values (Model II)	experimental values (Ref. 1)
$f\to\omega\gamma$	39	41		
$f\to\rho\gamma$	527	551		
$f\to\gamma\gamma$	4.7	2.8		3 ± 0.8
$A_2\to\omega\gamma$	745	763		
$A_2\to\rho\gamma$	51	52		
$A_2\to\gamma\gamma$	1.7	1.0		1 ± 0.4
$K^{**+}\to K^{*+}\gamma$	88	94	82	
$K^{**0}\to K^{*0}\gamma$	104	111	323	
$D^{**+}\to D^{*+}\gamma$			102	
$D^{**0}\to D^{*0}\gamma$			1.62×10^3	

The structure of the two effective Lagrangians we use is different, while the g_{TVV} couplings are given in both cases by Eqs. (1), (2), (6), and (7). The decay widths resulting from (3) are

$$\Gamma^{(\mathrm{II})}_{T\to V\gamma}=\frac{g_{TV\gamma}{}^2}{4\pi}\frac{M_T{}^3}{80\mu^2}(1-x)^3\left(2+x+\frac{x^2}{3}\right),\quad x=\left(\frac{m_V}{M_T}\right)^2, \tag{4}$$

$$\Gamma^{(\mathrm{II})}_{T\to\gamma\gamma}=\frac{g_{T\gamma\gamma}{}^2}{4\pi}\frac{M_T{}^3}{80\mu^2}. \tag{5}$$

The appropriate expressions for model I are given in Eqs. (31) and (32) of Ref. 2.

Our next step is to estimate the radiative decays of strange and charmed tensor mesons. Such transitions are now becoming of increasing interest. Extending the prescription of Ref. 2, we derive from the amplitudes for $\pi K^*\to K\gamma$ and $\pi D^*\to D\gamma$ the following new relations:

$$g_{K^{**+,0}K^{*+,0}\gamma}=\frac{g_{K^{*+,0}K^{*+,0}\pi^0}\,g_{K^{*+,0}K^{+,0}\gamma}}{4g_{K^{**+,0}K^{+,0}\pi^0}}, \tag{6}$$

$$g_{D^{**+,0}D^{*+,0}\gamma}=\frac{g_{D^{*+,0}D^{*+,0}\pi^0}\,g_{D^{*+,0}D^{+,0}\gamma}}{4g_{D^{**+,0}D^{+,0}\pi^0}}, \tag{7}$$

where K^{**} is the strange tensor meson of mass 1434 MeV/c^2 and D^{**} is the yet undiscovered tensor meson, for which we assume a mass of 2511 MeV/c^2 as calculated by Eichten *et al.*[7]

The values we present in the second and third columns of Table I for $\Gamma(K^{**}\to K^*\gamma)$ are calculated with experimental data[4] for $g_{K^{**}K\pi}$ and $g_{K^*K\gamma}$, while for $g_{K^*K^*\pi}$ we use the symmetry value. For comparison, we give in the fourth column the decay rates obtained if we relate $g_{K^{**}K^*\gamma}$ to $g_{f\rho\gamma}$ by using SU(3) +nonet symmetry, with the effective Lagrangian of Eq. (3). Lacking any relevant experimental information, we can give for $D^{**}\to D^*\gamma$ only symmetry values. The rates are obtained by using the SU(4)-symmetry relations[8]

$$\tfrac{1}{3}g_{f\rho\gamma}=g_{K^{**+}K^{*+}\gamma}=g_{D^{**+}D^{*+}\gamma},$$

$$g_{D^{**0}D^{*0}\gamma}=4g_{D^{**+}D^{*+}\gamma},$$

and $\Gamma(f\to\rho\gamma)=551$ keV.

We make the following observations in connection with the results in Table I:

(1) The approach we use allows us to express the radiative decays of tensor mesons to vector mesons in terms of experimentally determined couplings. There is no need, in principle, to invoke symmetry relations or vector-meson dominance to relate among various transitions. If further experiments will continue to validate our predictions, one has a powerful tool for estimating a new class of radiative decays. Particularly gratifying is the possibility of estimating radiative decays of heavy-flavor mesons without resorting to symmetries, given the difficulties[9] in controlling their validity or the symmetry-breaking pattern.

(2) It is evident from Table I that model II agrees

very well with existing data. The experimental findings on $f^0 \to \gamma\gamma$ reveal[1] the dominance of the helicity state $\lambda=2$ over the helicity state $\lambda=0$. It is in the helicity ratios that different effective Lagrangians may differ from one another. While model I leads to comparable amplitudes for the two helicity states,[2] the effective Lagrangian of Eq. (3) gives only a $\lambda=2$ transition.[6,10] This Lagrangian was also shown[10] to be consistent with several $V \to T\gamma$ transitions in the charm sector. Its prediction[11] for the ratios of helicity amplitudes in $\psi/J \to f^0+\gamma$, consistent with a two-gluon-exchange QCD calculation,[12] was favored by an early experiment[13] but disagrees with a more recent one.[14] One may also remark that models in which $f^0 \to \gamma\gamma$ is derived[15,16] from finite-energy sum rules also predict the dominance of the $\lambda=2$ transition. They do not cover, however, the wide range of decays which can be analyzed with our approach. The q^2 dependence of the $T \to VV$ amplitude may also be used to distinguish among various models. We shall return to this in a separate publication.

(3) The $T \to V+\gamma$ processes are mainly $E1$ transitions with a smaller $M2$ component, their ratio depending on the exact form of the transition amplitude. The main experience so far has been with $M1$ transitions among mesons (i.e., $V \to P+\gamma$ or $P \to V+\gamma$), which have been studied extensively. In the treatment[17] of $M1$ transitions, the quark model and phenomenological Lagrangians have been employed successfully and the vector-meson dominance of the electromagnetic current proved to be a useful concept. There is much less experience with $E1$ mesonic transitions and, in fact, theoretical attempts[18] using explicitly this feature fail to account for the $f^0, A_2^0 \to 2\gamma$ rates, and there are difficulties[7] with the $E1$ transition rates in the hidden-charm sector. Rosner[19] has made a multipole analysis of these decays. In his approach, the $E1$ component of $f \to \rho\gamma$ is related to the axial-vector-meson decays $A_1 \to \pi\gamma$, $B \to \pi\gamma$, and the $M2$ component to $A_2 \to \pi\gamma$. The rate he predicts for $f \to \rho\gamma$ is larger by 2.5 than ours while his prediction for $f \to \gamma\gamma$, related by vector dominance to $f \to \rho\gamma$, is about 8 keV. In our treatment, the rates of the $E1$ $V \to T\gamma, \gamma\gamma$ transitions are determined by the strength of $M1$ transitions of type $V \to P\gamma$, and no use is made of vector-meson dominance.

(4) From the strong decays $A_2 \to \omega\pi\pi$ and $K^{**} \to K^*\pi\pi$ one can determine[2,20] the strong-interaction TVV coupling. When this value is used in conjunction with vector-meson dominance to calculate $T \to V\gamma$, $T \to \gamma\gamma$ transitions, one obtains[21] figures which are one order of magnitude larger than those in Table I. It appears therefore that vector-meson dominance fails in this instance. Nonetheless, it might still be useful in relating[19] $f \to \gamma\gamma$ to $f \to \rho\gamma$.

(5) The decays $K^{**+} \to K^{*+}\gamma$, $K^{**0} \to K^{*0}\gamma$ play an important role in connection with SU(3)-symmetry breaking. As is well known, the $M1$ transitions $K^{*0} \to K^0\gamma$ and $K^{*+} \to K^+\gamma$ are expected from SU(3) to occur at a 4:1 ratio, while experimentally[4] they are of equal strength. Although consistent[22] with the general form of SU(3) breaking in D-type couplings, there is yet no satisfactory understanding[17] of this phenomenon. If our sum rule (6) holds, this pattern will thus repeat itself in the rates for $K^{**+} \to K^{*+}\gamma$, $K^{**0} \to K^{*0}\gamma$, as predicted in the second and third columns of Table I. In the fourth column we list for comparison the values obtained if we relate these decays by SU(3) +nonet symmetry to $f \to \rho\gamma$, using Eq. (3). Needless to say, this is a very critical test of our approach, though it should be kept in mind that in our calculations we had to use the symmetry value for $g_{K^*K^*\pi}$, not having a direct determination for it.

(6) Charmed tensor mesons have not been discovered yet. It is even not clear what their mass is, estimates ranging[21] from 2.2–2.8 GeV/c^2 for D^{**}. The expected decay widths are sensitive to the actual mass value. It could well happen that these widths for strong decays are such[21] as to make the detection of charmed tensor mesons by the standard methods a very difficult task. One would have then to resort to more sophisticated techniques, such as photon-photon correlations from cascade radiative decays.[23] It is therefore important to have an estimate of the strength of the radiative transitions. The partial widths we present in the fourth column of Table I are obtained from relating by SU(4) to $f \to \rho\gamma$, as no experimental data are available yet for the RHS of Eq. (7). The figures we obtain indicate that $D^{**} \to D^*\gamma$ are probably the major radiative decays of D^{**}, the estimates[21] for $D^{**} \to D\gamma$ being lower by a factor of 3–5. There are no previous calculations, to the best of our knowledge, to which we may compare our predictions for $K^{**} \to K^*\gamma$ and $D^{**} \to D^*\gamma$ decays.

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