D^* decays: Do theory and experiment agree?

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(Received 10 December 1984)

We study the hadronic and radiative decays of D^{*+} and D^{*0}. Using SU(4) symmetry for the hadronic decays, we convert the branching ratios into total rates for D^{*+} and D^{*0}. We point out a potential problem with the ratio $\Gamma(D^{*+}\to D^+\pi^0)/\Gamma(D^{*+}\to D^0\pi^+)$. Finally, using the measured branching ratios for radiative decays, we extract the "experimental" radiative rates. We find these radiative rates puzzling as they are difficult to understand in an SU(4) or broken-SU(4) scheme.

The mass splitting between D^* and D mesons is such that the only hadronic-decay modes available to D^* are $D\pi$ states. The D^{*+} mass is such that it can decay to $D^+\pi^0$ and $D^0\pi^+$; however, D^{*0} can decay hadronically only into $D^0\pi^0$; the $D^+\pi^-$ channel is not allowed kinematically. In the following we summarize what is known[1] about the branching ratios and the total rates for the D^*'s:

$$\begin{aligned} D^{*+}:\ & B(D^0\pi^+)=(49\pm8)\% \ ,\\ & B(D^+\pi^0)=(34\pm7)\% \ ,\\ & B(D^+\gamma)=(17\pm11)\% \ ,\\ & \Gamma_T(D^{*+})<2.0 \text{ MeV} \ , \end{aligned} \tag{1}$$

$$\begin{aligned} D^{*0}:\ & B(D^0\pi^0)=(54\pm9)\% \ ,\\ & B(D^0\gamma)=(46\pm9)\% \ ,\\ & \Gamma_T(D^{*0})<5.0 \text{ MeV} \ . \end{aligned} \tag{2}$$

We believe that the total rates for D^{*+} and D^{*0} decays can be calculated with reasonable accuracy. In this paper we calculate $D^*\to D\pi$ rates and then using the branching ratios given in Eqs. (1) and (2) we estimate the total rates for D^{*+} and D^{*0}. We then use the branching ratios for the radiative modes to estimate $\Gamma(D^{*+}\to D^+\gamma)$ and $\Gamma(D^{*0}\to D^0\gamma)$. Finally we discuss the theoretical implications of our results.

We compute $D^*\to D\pi$ rates from an SU(4)-invariant interaction:[2]

$$\Gamma(V_i\to P_jP_k)=\frac{2}{3}\frac{(g_{ijk})^2}{4\pi}\frac{|\mathbf{p}|^3}{M_V{}^2} \ , \tag{3}$$

where i, j, and k are SU(4) indices and

$$g_{ijk}=if_{ijk}g_{VPP} \ . \tag{4}$$

Applying formula (3) to $\rho\to\pi\pi$, with[1] $\Gamma(\rho\to\pi\pi)=154\pm5$ MeV, we obtain

$$\frac{(g_{VPP})^2}{4\pi}=2.98\pm0.10 \ . \tag{5}$$

From[1] $\Gamma(K^*\to K\pi)=51.3\pm1.0$ MeV, we obtain

$$\frac{(g_{VPP})^2}{4\pi}=3.42\pm0.07 \ . \tag{6}$$

The ratio of the last two numbers is 1.15 ± 0.05, representing about a 15% SU(3)-breaking effect. As the individual errors in (5) and (6) are small, we choose to work with a mean value[3]

$$\frac{(g_{VPP})^2}{4\pi}=3.20\pm0.22 \ , \tag{7}$$

where the errors connect the two central values of (5) and (6).

In applying Eq. (3) to $D^*\to D\pi$ one has to be very precise in computing the phase space as it depends very sensitively on the masses. We used the mass-difference measurements for $m_{D^+}-m_{D^0}$, $m_{D^{*+}}-m_{D^0}$, and $m_{D^{*0}}-m_{D^0}$ quoted in Ref. 1 to compute $|\mathbf{p}|$ for the various decay modes. We find

$$\Gamma(D^{*+}\to D^+\pi^0)=(2.32\pm0.28)\frac{(g_{VPP})^2}{4\pi}\text{ keV} \ , \tag{8}$$

$$\Gamma(D^{*+}\to D^0\pi^+)=(5.0\pm0.19)\frac{(g_{VPP})^2}{4\pi}\text{ keV} \ , \tag{9}$$

$$\Gamma(D^{*0}\to D^0\pi^0)=(3.5\pm0.96)\frac{(g_{VPP})^2}{4\pi}\text{ keV} \ . \tag{10}$$

If we use $(g_{VPP})^2/4\pi$ from Eq. (7) we obtain

$$\Gamma(D^{*+}\to D^+\pi^0)=7.4\pm1.0\text{ keV} \ , \tag{11}$$

$$\Gamma(D^{*+}\to D^0\pi^+)=16.0\pm1.3\text{ keV} \ , \tag{12}$$

$$\Gamma(D^{*0}\to D^0\pi^0)=11.2\pm3.1\text{ keV} \ . \tag{13}$$

The experimental branching ratios shown in Eqs. (1) and (2) can then be used to estimate the following total rates:

$$B(D^{*+}\to D^+\pi^0)=(34\pm7)\% \quad \text{yields } \Gamma_T(D^{*+})=22\pm6\text{ keV} \ , \tag{14}$$

$$B(D^{*+}\to D^0\pi^+)=(49\pm8)\% \quad \text{yields } \Gamma_T(D^{*+})=32\pm6\text{ keV} \ , \tag{15}$$

$$B(D^{*0}\to D^0\pi^0)=(54\pm9)\% \quad \text{yields } \Gamma_T(D^{*0})=21\pm7\text{ keV} \ . \tag{16}$$

Again the individual errors on the two values of $\Gamma_T(D^{*+})$ in Eqs. (14) and (15) are small and the central values are

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separated by almost 2 standard deviations. We choose to work with an average for some of the following calculations,

$$\Gamma_T(D^{*+})=27\pm5\text{ keV} \quad , \tag{17}$$

where the error is chosen to connect the two central values.

We are now in a position to estimate the radiative rates. Using the branching ratios for the radiative modes from Eqs. (1) and (2) and the average total rate $\Gamma_T(D^{*+})$ from Eq. (17) we find that

$$B(D^{*+}\to D^+\gamma)=(17\pm11)\%$$

$$\text{yields } \Gamma(D^{*+}\to D^+\gamma)=4.6\pm3.0\text{ keV} \tag{18}$$

and

$$B(D^{*0}\to D^0\gamma)=(46\pm9)\%$$

$$\text{yields } \Gamma(D^{*0}\to D^0\gamma)=9.7\pm3.7\text{ keV} \quad . \tag{19}$$

We now discuss the theoretical implications of the experimental data and our calculations.

Application of the symmetry in the SU(2) sector of the charm subspace results in

$$\frac{\Gamma(D^{*+}\to D^+\pi^0)}{\Gamma(D^{*+}\to D^0\pi^+)}=0.466\pm0.057 \quad . \tag{20}$$

This is to be compared with the experimental ratio,[1]

$$\frac{\Gamma(D^{*+}\to D^+\pi^0)}{\Gamma(D^{*+}\to D^0\pi^+)}=\frac{34\pm7}{49\pm8}=0.694\pm0.178 \quad . \tag{21}$$

We have propagated the errors as if the data sample were independent. The actual errors could well be smaller. Though the absolute rates computed by us depend on SU(4) invariance, we expect that even in a SU(4)-broken scheme, SU(2) symmetry in the charm sector will be preserved. $\Gamma(D^{*+}\to D^+\pi^0)$ would then be expected to come down to its lowest value, $\approx 27\%$, and $\Gamma(D^{*+}\to D^0\pi^+)$ would have to rise to its highest value, $\approx 57\%$. We may remark that the branching ratios in Ref. 1 before the revision were in better agreement with the theory.

We now turn our attention to the radiative decay. The ratio of the radiative widths is

$$\frac{\Gamma(D^{*+}\to D^+\gamma)}{\Gamma(D^{*0}\to D^0\gamma)}=\frac{(17\pm11)}{(46\pm9)}\frac{\Gamma_T(D^{*+})}{\Gamma_T(D^{*0})} \quad . \tag{22}$$

We can obtain three different values for this ratio depending upon what we use for $\Gamma_T(D^{*+})$ and $\Gamma_T(D^{*0})$. (a) Using Eqs. (8) and (10) for the hadronic rates, we have

$$\frac{\Gamma_T(D^{*+})}{\Gamma_T(D^{*0})}=\frac{\Gamma(D^{*+}\to D^+\pi^0)}{\Gamma(D^{*0}\to D^0\pi^0)}\frac{B(D^{*0}\to D^0\pi^0)}{B(D^{*+}\to D^+\pi^0)}$$

$$=1.05\pm0.28 \quad . \tag{23}$$

Using Eq. (23) in Eq. (22) we obtain

$$\frac{\Gamma(D^{*+}\to D^+\gamma)}{\Gamma(D^{*0}\to D^0\gamma)}=0.370\pm0.272 \quad . \tag{24}$$

(b) Using Eqs. (9) and (10) for the hadronic rates, we obtain

$$\frac{\Gamma_T(D^{*+})}{\Gamma_T(D^{*0})}=\frac{\Gamma(D^{*+}\to D^0\pi^+)}{\Gamma(D^{*0}\to D^0\pi^0)}\frac{B(D^{*0}\to D^0\pi^0)}{B(D^{*+}\to D^0\pi^+)}$$

$$=1.56\pm0.4 \quad , \tag{25}$$

which results in

$$\frac{\Gamma(D^{*+}\to D^+\gamma)}{\Gamma(D^{*0}\to D^0\gamma)}=0.576\pm0.415 \quad . \tag{26}$$

If we use the average value for $\Gamma(D^{*+})$ given in Eq. (17) and $\Gamma(D^{*0})$ from Eq. (16), we obtain

$$\frac{\Gamma(D^{*+}\to D^+\gamma)}{\Gamma(D^{*0}\to D^0\gamma)}=0.480\pm0.336 \quad . \tag{27}$$

All the three ways of obtaining $\Gamma(D^{*+}\to D\gamma)/\Gamma(D^{*0}\to D^0\gamma)$ yield a central value ≈ 0.5. Given the large errors this ratio could be as low as ≈ 0.1. Does this pose a problem?

If we assume that the radiative decays $V\to P\gamma$ can be described by an SU(4)-symmetric interaction,[2] then

$$\Gamma(V_i\to P_j\gamma_k)=\frac{1}{3}\frac{(g_{ijk})^2}{4\pi}|\mathbf{p}|^3 \quad , \tag{28}$$

where i, j, and k are SU(4) labels and

$$g_{ijk}=d_{ijk}g_{VP\gamma} \quad . \tag{29}$$

Using the tabulation[4] of the symmetric symbol d_{ijk} and the fact that the SU(4) label k of the photon is

$$k=\frac{\sqrt{2}}{3}(0)+(3)+\frac{1}{\sqrt{3}}(8)-\frac{\sqrt{2}}{\sqrt{3}}(15) \quad , \tag{30}$$

we find that[2]

$$\frac{\Gamma(D^{*+}\to D^+\gamma)}{\Gamma(D^{*0}\to D^0\gamma)}=\frac{1}{16} \quad , \tag{31}$$

which is certainly not consistent with the estimates from the experimental branching ratios (27).

A simple way of breaking SU(4) symmetry is to write the $M1$ transition operator for $1^-\to 0^-\gamma$ transition in the nonrelativistic form

$$H(M1)=\sum_q \frac{e_q}{2m_q}\boldsymbol{\sigma}\cdot(\boldsymbol{\epsilon}\times\mathbf{k}) \quad , \tag{32}$$

where the sum is over the quark flavors, e_q and m_q are the quark charge and the mass, respectively, and $\boldsymbol{\epsilon}$ and $\mathbf{k}$ are the photon polarization vector and momentum, respectively. Use of Eq. (32) in D^* radiative decays leads to

$$\frac{\Gamma(D^{*+}\to D^+\gamma)}{\Gamma(D^{*0}\to D^0\gamma)}=\frac{1}{4}\left(\frac{m_c-2m}{m_c+m}\right)^2 \quad , \tag{33}$$

where m_c = charmed-quark mass and m = up- (or down-) quark mass. Constituent quarks are used in this naive quark model. If we set $m_c=m$ we recover the suppression factor of $\frac{1}{16}$. If we use $m_c=1500$ MeV and $m=340$ MeV we obtain

$$\frac{\Gamma(D^{*+}\to D^+\gamma)}{\Gamma(D^{*0}\to D^0\gamma)}\simeq\frac{1}{20} \quad . \tag{34}$$

Thus, symmetry breaking through quark masses suppresses this ratio even further. Yet we expect that in $D^* \rightarrow D\gamma$ the naive quark model should work well since the photon momentum is small compared to the D or D^* mass.

Another possibility is to relate these widths directly to noncharmed decays via pole-dominated duality sum rules. Owing to large symmetry-breaking effects in $\phi \rightarrow \eta\gamma$ and $J/\psi \rightarrow \eta_c\gamma$, one can predict large deviations from symmetry values for the ratio (31) and the corresponding quantity in the strangeness sector.[5] We note that the symmetry-breaking mechanisms which deal with nonrelativistic corrections (p/M_V) or overall mass-dependent factor [e.g., $M_V^2(g_{VP\gamma})^2$ obeys SU(4)] all primarily effect absolute rates only, and do not alter conclusions on the ratios within a heavy-quark sector.

We now turn to the absolute radiative decay widths for the D^*'s. We take as "experimental" values (18) and (19), based on SU(4) symmetry for strong decays plus the experimental branching ratios. In Table I we list the theoretical predictions. The SU(4)-symmetry predictions are obtained from (28) and (29), using $\Gamma(\omega \rightarrow \pi\gamma)$ for normalization. Broken-SU(4)-symmetry rates from the interaction (32) are also normalized to $\Gamma(\omega \rightarrow \pi\gamma)$. Finally , values based on SU(4) symmetry for the dimensionless coupling $M_V^2(g_{VP\gamma})^2$ are also tabulated.

It is clear from Table I that the problem of explaining the ratio (27) remains in all cases, so that a consistent set of rates cannot be obtained in any of these schemes.

In summary, it should be emphasized that we regard the new data on ratios of D^* decays as possibly indicative of some theoretical puzzles. If the ratio of strong decays continues to diverge from SU(2) symmetry in the charm sector as in (20) and (21), this would indicate a qualitatively new behavior for heavy-quark systems. Theoretical prejudice, however, would be strongly in favor of SU(2) symmetry and one would suspect the experimental data. That the ratio of D^* radiative widths (22) does not obey SU(4) symmetry (again in a restricted sense) may not be totally due to problems in the heavy-quark sector. However, straightforward ways of breaking the symmetry do not improve agreement with present experimental indications.

TABLE I. Radiative rates for D^{*+} and D^{*0}.

$\Gamma(D^{*+} \rightarrow D^+\gamma)$ (keV)	$\Gamma(D^{*0} \rightarrow D^0\gamma)$ (keV)	Source
4.6 ± 3.0	9.7 ± 3.7	Experimental branching ratio plus $D^* \rightarrow D\pi$
4.4 ± 0.3	70 ± 5	SU(4) for $g_{VP\gamma}$
1.3 ± 0.1	27.0 ± 1.8	Broken SU(4) by $M1$ quark transition
0.67 ± 0.05	10.6 ± 0.8	Broken SU(4) by $1/M_V^2$

In a recent work[6] the hadronic and the radiative rates for D^* decay are calculated in a bag model with an infinitely heavy charm quark. The hadronic widths obtained in Ref. 6 are considerably higher than those obtained by us by factors of 5–8. These authors also obtain a value of $\frac{1}{4}$ for the ratio of radiative rates defined in (22). This result is readily obtained from (3) in the limit $m_c/m \rightarrow \infty$.

Note added in proof. We regret that Ref. 7 had escaped our attention. These authors discuss hadronic and radiative decays of D^*.

We thank Mike Scadron for several discussions. A. N. K. wishes to thank the theory group at SLAC and the Department of Physics, University of Arizona, Tucson, for their hospitality and a research grant from the Natural Sciences and Engineering Research Council of Canada. This work was supported in part by the Department of Energy through Contracts No. DE-AC03-76SF00515 and No. DE-AC02-80ER10663.

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