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ARE D^*-DECAYS ALL RIGHT?*

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ABSTRACT

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 in broken $SU(4)$ schemes.

The mass splitting between D^* and D mesons is such that the only hadronic decay modes available to D^* are $D\pi$ states. D^{*+} mass is such that it can decay to $D^+\pi^0$ and $D^0\pi^+$; however, D^{*0} can decay hadronically only into $D^0\pi^0$, $D^+\pi^-$ 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:

$$
\begin{aligned}
D^{*+}: \quad BR(D^0\pi^+) &= 49 \pm 8\% \\
BR(D^+\pi^0) &= 34 \pm 7\% \\
BR(D^+\gamma) &= 17 \pm 11\% \\
\Gamma_T(D^{*+}) &< 2.0\ MeV
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
D^{*0}: \quad BR(D^0\pi^0) &= 54 \pm 9\% \\
BR(D^0\gamma) &= 46 \pm 9\% \\
\Gamma_T(D^{*0}) &< 5.0\ MeV\ .
\end{aligned} \tag{2}
$$

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 Eq. (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]

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

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

$$
g_{ijk} = i\, f_{ijk}\, g_{VPP}\ . \tag{4}
$$

Applying formula (3) to $\rho \to \pi\pi$, with $\Gamma(\rho \to \pi\pi) = 154 \pm 5\ MeV$,[1] we obtain

$$\frac{g^2_{VPP}}{4\pi} = 2.98 \pm 0.10\ . \tag{5}$$

From $\Gamma(K^* \to K\pi) = 51.3 \pm 1.0\ MeV$,[1] we obtain

$$\frac{g^2_{VPP}}{4\pi} = 3.42 \pm 0.07\ . \tag{6}$$

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

$$\frac{g^2_{VPP}}{4\pi} = 3.20 \pm 0.22 \tag{7}$$

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 $|\vec{p}|$ for the various decay modes. We find,

$$\Gamma(D^{*+} \to D^+\pi^0) = (2.32 \pm 0.28)\ \frac{g^2_{VPP}}{4\pi}\ KeV \tag{8}$$

$$\Gamma(D^{*+} \to D^0\pi^+) = (5.0 \pm 0.19)\ \frac{g^2_{VPP}}{4\pi}\ KeV \tag{9}$$

$$\Gamma(D^{*0} \to D^0\pi^o) = (3.5 \pm 0.96)\ \frac{g^2_{VPP}}{4\pi}\ KeV \tag{10}$$

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

$$\Gamma(D^{*+} \to D^+\pi^0) = 7.4 \pm 1.0\ KeV \tag{11}$$

$$\Gamma(D^{*+} \to D^0\pi^+) = 16.0 \pm 1.3 \; KeV \tag{12}$$

$$\Gamma(D^{*0} \to D^0\pi^0) = 11.2 \pm 3.1 \; KeV \tag{13}$$

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

$$BR(D^{*+} \to D^+\pi^0) = 34 \pm 7\% \text{ yields } \Gamma_T(D^{*+}) = 22 \pm 6 \; KeV \tag{14}$$

$$BR(D^{*+} \to D^0\pi^+) = 49 \pm 8\% \text{ yields } \Gamma_T(D^{*+}) = 32 \pm 6 \; KeV \tag{15}$$

$$BR(D^{*0} \to D^0\pi^0) = 54 \pm 9\% \text{ yields } \Gamma_T(D^{*0}) = 21 \pm 7 \; KeV \; . \tag{16}$$

Again the individual errors on the two values of $\Gamma_T(D^{*+})$ in Eq. (14) and (15) are small and the central values are separated by almost 2 standard deviations. We choose to work with an average for some of the following calculations,

$$\Gamma_T(D^{*+}) = 27 \pm 5 \; KeV \tag{17}$$

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 Eq. (1) and (2) and the average total rate $\Gamma_T(D^{*+})$ from Eq. (17) we find that

$$BR(D^{*+} \to D^+\gamma) = 17 \pm 11\% \text{ yields } \Gamma(D^{*+} \to D^+\gamma) = 4.6 \pm 3.0 \; KeV \tag{18}$$

and

$$BR(D^{*0} \to D^0\gamma) = 46 \pm 9\% \text{ yields } \Gamma(D^{*0} \to D^0\gamma) = 9.7 \pm 3.7 \; KeV \tag{19}$$

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

$$\frac{\Gamma(D^{*+} \to D^+\pi^0)}{\Gamma(D^{*+} \to D^0\pi^+)} = 0.466 \pm 0.057 \ . \tag{20}$$

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

$$\frac{\Gamma(D^{*+} \to D^+\pi^0)}{\Gamma(D^{*+} \to D^0\pi^+)} = \frac{34 \pm 7}{49 \pm 8} = 0.694 \pm 0.178 \ . \tag{21}$$

We have propagated the errors as if the data sample were independent. The actual errors could well be smaller. Clearly theory and experiment are 1 standard deviation apart. Since this limited $SU(2)$ charm sector symmetry should not be broken (more than in the corresponding strangeness sector) $\Gamma(D^{*+} \to D^+\pi^0)$ would 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,

$$\frac{\Gamma(D^{*+} \to D^+\gamma)}{\Gamma(D^{*0} \to D^0\gamma)} = \frac{(17 \pm 11)}{(46 \pm 9)} \frac{\Gamma_T(D^{*+})}{\Gamma_T(D^{*0})} \ . \tag{22}$$

We can obtain three different values for this ratio depending upon what we use for $\Gamma_T(D^{*+})$ and $\Gamma_T(D^{*0})$.

$$(a): \ \frac{\Gamma_T(D^{*+})}{\Gamma_T(D^{*0})} = \frac{\Gamma(D^{*+} \to D^+\pi^0)}{\Gamma(D^{*0} \to D^0\pi^0)} \frac{BR(D^{*0} \to D^0\pi^0)}{BR(D^{*+} \to D^+\pi^0)} = 1.05 \pm 0.28 \ , \tag{23}$$

using Eq. (8) and (10) for the hadronic rates. Using Eq. (23) in Eq. (22) we obtain

$$\frac{\Gamma(D^{*+} \to D^+\gamma)}{\Gamma(D^{*0} \to D^0\gamma)} = 0.370 \pm 0.272 \ . \tag{24}$$

$$(b): \ \frac{\Gamma_T(D^{*+})}{\Gamma_T(D^{*0})} = \frac{\Gamma(D^{*+} \to D^0\pi^+)}{\Gamma(D^{*0} \to D^0\pi^0)} \frac{BR(D^{*0} \to D^0\pi^0)}{BR(D^{*+} \to D^0\pi^+)} = 1.56 \pm 0.4 \ , \tag{25}$$

using Eq. (9) and (10) for the hadronic rates, and results in

$$\frac{\Gamma(D^{*+} \to D^+\gamma)}{\Gamma(D^{*0} \to D^0\gamma)} = 0.576 \pm 0.415 \ . \tag{26}$$

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

$$\frac{\Gamma(D^{*+} \to D^+\gamma)}{\Gamma(D^{*0} \to D^0\gamma)} = 0.480 \pm 0.336 \ . \tag{27}$$

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,

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

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

$$g_{ijk} = d_{ijk} \ g_{VPP} \ . \tag{29}$$

Using the tabulation[4] of the symmetric symbol d_{ijk} and the fact that the $SU(4)$

label, k, of the photon is

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

we find that[2]

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

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 non-relativistic form

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

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

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

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 1/16. If we use m_c = 1500 MeV and m = 340 MeV we obtain,

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

Thus symmetry breaking through quark masses suppresses this ratio even further. Yet we expect that in $D^* \to D\gamma$ 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 non-charmed decays via pole-dominated duality sum rules. Due to large symmetry-breaking effects in $\phi \to \eta\gamma$ and $J/\psi \to \eta_c\gamma$, 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 non-relativistic 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 $\Gamma(\omega \to \pi\gamma)$ for normalization. Broken $SU(4)$ symmetry rates from the interaction (32) are also normalized to $\Gamma(\omega \to \pi\gamma)$. 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.

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Table 1

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

$\Gamma(D^{*+} \to D^+\gamma)(KeV)$	$\Gamma(D^{*0} \to D^0\gamma)(KeV)$	*Source*
4.6 ± 3.0	9.7 ± 3.7	Experimental B.R. plus $D^* \to D\pi$
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 $1/M_V^2$

REFERENCES

1. Particle Data Group, Rev. Mod. Phys. 56, S1 (1984). The data on D^* in the main body of this reference were revised in a separate sheet. We are quoting the revised data listing.

2. P. J. O'Donnell, Rev. Mod. Phys. 53, 673 (1981); R. L. Thews, Phys. Rev. D17, 3038 (1978); B. J. Edwards and A. N. Kamal, Phys. Rev. Lett. 39, 66 (1977); A. Kazi, G. Kramer and D. H. Schiller, Acta. Phys. Austriaca 45, 195 (1976).

3. This is also consistent with values from ϕ decays; from $\phi \to K^+K^-$, $g^2/4\pi = 3.17 \pm 0.13$, and from $\phi \to K_L K_S$, $g^2/4\pi = 3.43 \pm 0.14$.

4. Z. Maki, T. Maskawa and I. Umemura, Prog. Theor. Phys. 47, 1682 (1972).

5. R. L. Thews in Ref. 2, and to be published.