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REVIEW OF SEMILEPTONIC CHARM DECAYS

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ABSTRACT

The experimental status of D^0 and D^+ semileptonic decays is reviewed and compared to model predictions. Topics covered are the form factor pole mass and decay rate for $D \to K\ell\nu$, the decay rate and form factor ratios for $D \to K^*\ell\nu$, and, finally, the issue of modes other than $K\ell\nu$ and $K^*\ell\nu$.

Interest in the 3-body semileptonic decays of charm mesons stems in part from their relative simplicity. These decays proceed only via the spectator model Feynman diagram, and all strong interaction effects can be described in terms of form factors, which can be calculated in several different ways. By contrast, hadronic weak decays can include interfering diagrams at the parton level, and c_n be also be affected by final state interactions.

Semileptonic charm decays are also important in the determination of K-M matrix element $|V_{bu}|$. In heavy quark effective theory, measurements of the decay modes $D \to \rho\ell\nu$ and $B \to \rho\ell\nu$, for example, would allow extraction of the ratio $|V_{bu}|/|V_{cd}|$. Currently, these measurements are unavailable, and model input is required to determine $|V_{bu}|$ from measurements of the lepton momentum spectrum in inclusive semileptonic beauty decays. The semileptonic decays of charm particles provide a testing ground for the models used in this method.

The $K\ell\nu$ mode is the simplest semileptonic charm decay. In the zero mass lepton limit, the differential decay rate can be written as,

$$d\Gamma \sim G_F^2|V_{cs}|^2K(q^2)|f_+(q^2)|^2,$$

where G_F is the Fermi constant, $|V_{cs}|$ is the K-M matrix element, q^2 is the mass squared of the virtual W, $K(q^2)$ is a known kinematic factor, and $f_+(q^2)$ is the form factor. The "monopole ansatz", in which the coupling of the virtual W is analogous to that of the photon in the vector dominance hypothesis, is frequently used to describe the q^2 dependence of the form factor. With this assumption, the form factor is,

$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/M_{POLE}^2},$$

where M_{POLE} equals the mass of the D_S^* meson, the nearest pole with the correct quantum numbers. Several experiments have measured M_{POLE} by fitting to the q^2 dependence of the decay. Table 1 shows the results, along with the ansatz value and a prediction (BBD)[1]. The monopole ansatz appears to describe the data; however, some models use other equally valid descriptions of the q^2 dependence.

Table 1: Pole mass for the form factor f_+.

EXPT	M_{POLE} (GeV/c^2)
MARK III[2]	$1.8 ^{+0.5}_{-0.2} {}^{+0.3}_{-0.2}$
E691[3]	$2.1 ^{+0.4}_{-0.2}$
CLEO[4]	$2.0 ^{+0.1}_{-0.2} {}^{+0.3}_{-0.2}$
D_S^*	2.11
BBD[1] (thy)	1.8 ± 0.1

Table 2 shows measurements and predictions for $\Gamma(K\ell\nu)$. The experimental results are generally in good agreement with one another, and all three types of models are able to describe the data. It should be noted, however, that the experimental results for the D^0 may be systematically higher than those for the D^+. Since the Cabibbo favored weak current conserves strong isospin, this effect would presumably be due to a statistical fluctuation, or to some common systematic problem. Most of the measurements in Table 2 are normalized to Mark III branching ratios[5], and the average takes into account the common systematic errors.

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Table 2: Results for $\Gamma(K\ell\nu)$ and $\Gamma(K^*\ell\nu)$ in units of $10^{10} sec^{-1}$. For the $K\ell\nu$ mode, the charged lepton, ℓ, is identified by (e) or (μ).

EXPT	$D^+ \to \overline{K^0}\ell^+\nu$	$D^0 \to K^-\ell^+\nu$	$D^+ \to \overline{K^{*0}}e^+\nu$	$D^0 \to K^{*-}e^+\nu$
MARK III[2]	$5.6^{+2.0}_{-1.2} \pm 0.65(e)$ $6.6\ ^{+2.6}_{-1.5} \pm 1.1(\mu)$	$8.1 \pm 1.2 \pm 1.0(e)$	$5.0^{+1.8}_{-1.0} \pm 0.6$	$10.4^{+4.5}_{-2.4} \pm 1.6$
E653[6]		$5.6 \pm 0.9 \pm 1.2(\mu)$		
E691[3]	$5.6 \pm 0.8 \pm 1.5(e)$	$9.1 \pm 0.7 \pm 1.7(e)$	$4.2 \pm 0.6 \pm 0.5$	
CLEO[4]		$8.8 \pm 0.7 \pm 1.4(e)$ $7.8 \pm 0.9 \pm 1.4(\mu)$		$4.5 \pm 1.4 \pm 1.1$
ARGUS[7]		$10.5 \pm 0.7 \pm 2.6(e)$ $10.2 \pm 1.2 \pm 2.9(\mu)$	$4.7 \pm 0.7 \pm 0.9$	$5.2 \pm 0.9 \pm 1.4$
AVERAGES	$K\ell\nu$:	7.0 ± 0.7	$K^*\ell\nu$:	4.7 ± 0.6
		PREDICTIONS		
GROUP	$D \to K\ell\nu$		$D \to K^*\ell\nu$	
		QUARK MODELS		
WSB[8]	8.3		9.5	
KS[9]	10.		9.8	
ISGW[10]	8.4		9.6	
GS/AW[11]	7.1		9.5	
		LATTICE QCD CALCULATIONS		
CMHS[12]	$9.5 \pm 4.$			
BKS[13]	$14. \pm 6.$			
LMS[14]	4.9 ± 0.7		5.2 ± 2.0	
		QCD SUM RULES		
AOS[15]	$11. \pm 5.$			
DP[16]	9.7 ± 1.3			
BBD[1]	$6.4 \pm 3.$		3.8 ± 1.5	

Table 3: Form factor ratios and Γ_L/Γ_T for the decay mode $D \to K^*\ell\nu$. The units for $g(0)/f(0)$ are GeV^{-2}; other ratios are dimensionless.

EXPT	$a_+(0)/f(0)$	$g(0)/f(0)$	Γ_L/Γ_T
E653[17]	-0.09 ± 0.03	0.26 ± 0.04	1.2 ± 0.2
E691[18]	0.0 ± 0.06	0.26 ± 0.08	1.8 ± 0.5
MARK III[2]			$0.5^{+1.0+0.1}_{-0.1-0.2}$
	PREDICTIONS		
GROUP			
	QUARK MODELS		
WSB[8]	-0.17 (FREE)	0.14 (FIXED)	0.9
KS[9]	-0.13 (FIXED)	0.13 (FIXED)	1.2
ISGW[10]	-0.13 (± 0.4)	0.18 (± 0.5)	1.1
GS/AW[11]	-0.10	0.25	1.2
	LATTICE QCD CALCULATIONS		
BKS[13]	$-0.09 \pm .02^{+0.03}_{-0.02}$	$0.26 \pm 0.03^{+0.04}_{-0.05}$	
LMS[14]	-0.01 ± 0.09	0.21 ± 0.03	1.7 ± 0.6
	QCD SUM RULES		
AOS[15]	-0.12 ± 0.04	0.25 ± 0.09	
BBD[1]	-0.16 ± 0.03	0.29 ± 0.03	0.86 ± 0.06

Despite the problem mentioned above, the $K\ell\nu$ mode is quite well understood. Several different theoretical approaches, and four very different experimental techniques were used. Due to the missing neutrino, the analyses of the experimental results were difficult and systematic errors large. Considering the variety of theoretical and experimental approaches employed and the difficulties involved, the agreement among the entries for the $K\ell\nu$ mode in Table 2 is impressive.

In the $K^*(892)\ell\nu$ mode, the weak current flips the spin of the heavy quark, and therefore this mode is considerably more complicated than the $K\ell\nu$ mode, in which there is no spin flip. The differential decay rate can be written as[11],

$$d\Gamma \sim G_F^2 |V_{cs}|^2 K(q^2) \left[|H_+|^2 + |H_-|^2 + |H_0|^2\right],$$

where $H_{+,-,0}$ are helicity amplitudes, and the remaining quantities are defined as for the $K\ell\nu$ mode. Apart from known kinematic factors, the amplitudes H_+ and H_- are linear combinations of two form factors $g(q^2)$ and $f(q^2)$, and H_0 is a linear combination of $a_+(q^2)$ and $f(q^2)$. Predictions for these three form factors are believed to be less reliable than those for the $K\ell\nu$ form factor, f_+, which is "nearly"[10, 8] an overlap between intial and final state mesonic wave functions.

Table 2 shows measurements and predictions for $\Gamma(K^*\ell\nu)$. Although the measurements are generally in good agreement with one another and with the lattice and QCD sum rule predictions, they are a factor of two smaller than the quark model predictions. Some of the models have attempted to accomodate to this discrepancy, but a more stringent requirement is that they be able to predict correctly the three form factors.

Two form factor ratios, $a_+(0)/f(0)$ and $g(0)/f(0)$, can be determined by fitting to the 4 quantities that define the kinematics of the decay; these are q^2, the polar angle between the π and the D in the K^* rest frame, the polar angle between the ν and the D in the rest frame of the virtual W, and the azimuthal angle between the K^* and W decay planes in the D rest frame. Since current data do not have adequate statistics to determine the q^2 dependence of the form factors, the monopole ansatz is used, and the ratios are expressed at $q^2 = 0$. Table 3 lists the results of three measurements, as well as several predictions. The last column, Γ_L/Γ_T, is the ratio of the longitudinal to transverse polarization of the K^*. For E653[17] and E691[18], this ratio is computed from the form factor ratios, but for MARK III[2] it is measured from angular distribution of the K^* decay. The three experiments are in acceptable agreement. Entries in Table 3 for the quark models include the original predictions along with any later modifications or error estimates (in parentheses) made in response to disagreements with the measured value of $\Gamma(K^*\ell\nu)$.

The form factor ratios provide a clean test of some of the models. As indicated in the table, the model of WSB[8] fixes $g(0)/f(0)$, while that of KS[9] fixes both $a_+(0)/f(0)$ and $g(0)/f(0)$. Neither WSB nor KS agrees very well with the measured value of $g(0)/f(0)$, despite the fact that both have the flexibility to accomodate the decay rate. The model of ISGW[10] appears to be consistent with the measurements; however, the predicted values for the three form factors have uncertainties of $\sim 20\%$, which is inadequate for agreement with both rate and ratio measurements. The GS/AW[11] model agrees very well with the ratio measurements; rescaling the three form factors by a factor of 0.7 would result in good agreement with the rate measurement as well. In the lattice and QCD sum rule predictions, some of the theoretical uncertainties for the form factors cancel in the ratios. In general, these two techniques predict a higher value for $g(0)/f(0)$ than do the quark models, and most are in good agreement with the measurements.

Modes other than $K\ell\nu$ and $K^*\ell\nu$ are difficult to measure, but their existence is an important theoretical concern. The Veloshin-Shifman[19] limit for semileptonic decays of heavy quark-light quark mesons provides a guide for what to expect. In this limit, the recoil energy of the final state heavy quark is sufficiently small that the spatial wave function is the same for the initial and final state mesons and depends only on the light spectator quark. If applied to D decays, the Veloshin-Shifman limit would predict that $K\ell\nu$ and $K^*\ell\nu$ saturate the Cabibbo allowed modes. Although D decays don't explicitly satisfy the conditions for the Veloshin-Shifman limit, the prediction does agree with that of the ISGW quark model, and the physical picture invoked by the limit is relevant. For the Cabibbo suppressed modes, the situation is more complex, since the weak current now no longer conserves strong isospin. The Veloshin-Shifman limit (and the quark models) would have D^0 decays saturated by $\pi\ell\nu$ and $\rho\ell\nu$, and D^+ decays saturated by $\pi\ell\nu$, $\rho\ell\nu$, $\eta\ell\nu$, $\eta'\ell\nu$, and $\omega\ell\nu$.

Table 4 lists all measured exclusive three body semileptionic decay rates (entries are the averages from Table 2, and the MARK III measurement of $\Gamma(D^0 \to \pi\ell\nu)$[2]), and compares the sum to the inclusive rate computed by the Particle Data Group (PDG)[20]. The shortfall may or may not be significant. If the entries in the table for the exclusive modes were recalculated using PDG instead of MARK III branching ratios for normalization, the shortfall would be $\sim 4\sigma$. If, on the other hand, the MARK III inclusive semileptonic branching ratio[21] were used instead of the PDG value, the shortfall would be only $\sim 2\sigma$. Missing from the table is the unmeasured $\rho\ell\nu$ mode, for which the rate is expected to be comparable to that for the $\pi\ell\nu$ mode.

Table 4: Comparison of exclusive and inclusive semileptonic rates.

MODE	Γ ($10^{10} sec^{-1}$)
$K\ell\nu$	7.0 ± 0.7
$K^*\ell\nu$	4.7 ± 0.6
$D^0 \to \pi\ell\nu$[2]	$0.9^{+0.6}_{-0.3} \pm 0.1$
TOTAL	12.6 ± 1.0
INCLUSIVE S.L.[20]	18.1 ± 1.3
SHORTFALL	5.5 ± 1.6

Table 5 displays some experimental results for semileptonic decays with more than one hadron in the final state. Modes in which $(K\pi)_{NR}$ appears exclude the $K^*(892)$, but not necessarily low mass tails of higher mass $K\pi$ resonances. From the entries in Table 5, it is clear that there is no solid evidence for multihadron modes, and, if they are present at all, it is only at the level of 5% of the total semileptonic rate. Decays with more than one hadron in the final state would be subject to some of the same problems as hadronic weak decays, such as final state interactions, and the models used for the $K\ell\nu$ and $K^*\ell\nu$ modes cannot handle these more complex decays. Thus, the absence or strong suppression of these modes is necessary to retain a simple understanding of semileptonic decays.

Table 5: Modes with more than one hadron in the final state.

EXPT	MODE	Γ ($10^{10} sec^{-1}$)
E691[3]	$(K\pi)_{NR}\ell\nu$	0.4 ± 0.4
MARK III[2]		$1.2^{+1.5}_{-1.0}$
E653[17]		< 1.3 (prelim)
E691[22]		< 1.1
CLEO[4]	$K^*\pi\ell\nu$	2.2 ± 1.6
E691[22]	$(K\pi)_{NR}\pi\ell\nu$	< 0.6

In summary, for the $K\ell\nu$ mode, the form factor pole mass and the decay rate have been measured by several experiments and agree with the predictions of lattice calculations, QCD sum rules, and quark models. For the $K^*\ell\nu$ mode, the decay rate has been measured by several experiments, and the form factor ratios by two. The results are in agreement with lattice and QCD sum rule predictions, but not with those of the quark models. It is unclear whether $K\ell\nu$, $K^*\ell\nu$, and the corresponding Cabibbo suppressed modes saturate the inclusive semileptonic rate, but experimental searches have not yet turned up convincing evidence for other modes. The experimental situation for semileptonic charm should improve significantly in about two years when Fermilab experiments E687 and E791 provide data samples an order of magnitude larger than currently available.

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