Semileptonic Charm Decay at a Tau Charm Factory *

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Abstract

The full spectrum of $D_{\ell 3}$ and $D_{\ell 4}$ semileptonic decays can be precisely measured at a Tau Charm Factory. Sensitivety to rare semileptonic decays extends to branching fractions as small as 10^{-3}. Improved measurements of Cabibbo-Kobayashi-Maskawa matrix elements V_{cs} and V_{cd} can be obtained. With an improved theoretical understanding, semileptonic measurements can test the unitarity of the second row of the Cabibbo-Kobayashi-Maskawa matrix at the 1% level.

Semileptonic charm decays continue to play an important role in our understanding of the weak and strong interactions. The absence of interference between final state leptons and hadrons greatly simplifies the interpretation of these decays. Semileptonic decays proceed through simple spectator graphs. Since the dynamics of the weak interaction are well understood, both the weak couplings and the hadronic portion of the matrix element may be studied. Tau Charm Factory data will lead to a thousand-fold increase in the number of reconstructed events with greatly reduced backgrounds, and it will measure every $D_{\ell 3}$ and $D_{\ell 4}$ semileptonic decay. The complete picture is an important input to theoretical predictions of hadronic form factors. Better theoretical models in turn lead to an improved determination of Cabibbo-Kobayashi-Maskawa (CKM) matrix elements which can be used to test the unitarity of the CKM matrix.

The second row of the CKM matrix is the only row or column whose elements have all been measured in first order weak processes. The element V_{cd} is measured in semileptonic charm decay[1] and its inverse process, neutrino induced charm

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production.[2] The element V_{cs} is determined from semileptonic charm decay,[1][3] and V_{cb} has been determined from the weak decay of bottom mesons.[4] The most precise values for V_{cd} and V_{cs} are obtained in a fit which imposes unitarity and three generations in accordance with the Standard Model. The fit finds $0.217 < |V_{cd}| < 0.223$ and $0.9733 < |V_{cs}| < 0.9754$ at the 90% confidence level, and it reflects the precision with which V_{ud} and V_{us} are determined.[4] However, only direct measurements can test the model itself. The Particle Data Group direct measurement averages are $0.162 < |V_{cd}| < 0.230$ and $0.65 < |V_{cs}| < 0.98$. The large ranges are due to statistical errors and the theoretical uncertainty of form factor estimates.

Cabibbo-Kobayashi-Maskawa matrix elements are determined from $D_{\ell 3}$ decays using the relation

$$B(D \rightarrow Pe\nu)\Gamma_D = (G_F^2 M_c^5/192\pi^3)|V_{cx}|^2 \int |f_+(t)|^2 p^3 dt$$

where $D = D^0, D^+, D_S$ and $P = \pi, K$. The decay rate is denoted as Γ_D, V_{cx} is the appropriate CKM matrix element, p is the momentum of the pseudoscalar meson in the D rest frame, t is the square of the four-momentum transfer, and $f_+(t)$ is the vector form factor. A second form factor, $f_-(t)$ is suppressed by terms of order $(m_{lepton}/m_D)^2$ and may be neglected. The D^0, D^+, and D_S decay rates are currently measured with 3%, 3%, and 9% precision respectively,[4] and these measurements continue to improve. The Tagged Photon Spectrometer (TPS)[3] measures $B(D^0 \rightarrow K^- e^+ \nu_e)$ =(3.8 ± 0.5 ± 0.6)%, and Mark III[1][5] measures $B(D^0 \rightarrow K^- e^+ \nu_e) = (3.4 \pm 0.5 \pm 0.4)\%$, $B(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.39\, ^{+0.23}_{-0.11} \pm 0.04)\%$, and $B(D^+ \rightarrow \bar{K}^0 e^+ \nu_e = (7.1\, ^{+1.8}_{-1.0} \pm 1.0)\%$. A Tau Charm Factory would improve the precision of these branching fraction measurements by over an order of magnitude. Table I lists the number of reconstructed semileptonic events that are expected in one year of running (5000 hours with a luminosity $\mathcal{L}=10^{33} cm^{-2} s^{-1}$). All $D_{\ell 3}$ final states are experimentally accessible and nearly background free. With reconstructed samples of 10^4 to 10^5 events, the statistical error will be smaller than a systematic error in the reconstruction efficiency of order 1%. At this level of precision, a radiative correction due to bremsstrahlung from the electron is needed.

Theoretical input is essential to evaluate the $f_+(t)$ form factors. Current estimates predict $f_+(0)$ and assume a vector dominance-like t dependence with a pole at the $D_S^*(D^*)$ mass for Cabibbo favoured (suppressed) decays. The t dependence will be measured directly at a Tau Charm Factory. Figure 1 shows the effect in a vector dominance model of a second pole with a mass of 2.73 GeV corresponding to the first radially excited $^3S_1$ D_S state.[6] A coupling of 10% of the D_S^* pole's coupling was used. A second pole would be detectable for couplings as small as 1% of the principle pole's coupling.

The values for $f_+^K(0)$ and $f_+^\pi(0)$ are expected to deviated substantially unity due to SU(4) symmetry breaking. Estimates of $f_+^K(0)$ from potential models, QCD sum rules and lattice calculations vary from 0.58 to 0.75[7] . Some reduction of the theoretical uncertainty may be expected with current techniques combined with improved Tau Charm Factory data. However, new techniques are required for theoretical uncertainties to reach the 1% level possible of experimental data. One method being pursued are lattice calculations which calculate quark loops explicitly instead of using the quench approximation. Tau Charm Factory results will play an essential role in testing any new model. It is the only experiment capable of precision measurements for all nine $D_{\ell 3}$ decays and all seven $D_{\ell 4}$ decays plus the two leptonic decay constants, f_{D^+} and f_{D_S}. The leptonic decay constants are predicted by the same models that estimate the semileptonic form factors.

Ratios of semileptonic branching fractions give ratios of CKM elements with form factor uncertainties reduced to the level of SU(3) breaking (~ 5%). Mark III combines their branching fractions and reports[1]

$$|V_{cd}/V_{cs}|^2 = (0.057^{+0.038}_{-0.015} \pm 0.005)(f_+^K(0)/f_+^\pi(0))^2.$$

A recent lattice calculation[8] predicts $(f_+^K(0)/f_+^\pi(0)) = (0.74/0.70)$. A pair of decays that is of special interest is $D^+ \rightarrow \bar{K}^0 e^+ \nu_e$ and $D_S \rightarrow K^0 e^+ \nu_e$. The two decays have different CKM elements, but similar final states. The ratio of their branching fractions should further reduce the model dependence when determining $|V_{cd}/V_{cs}|$.[9]

The $D_{\ell 4}$ decays D (or D_s) $\rightarrow Ve\nu$, where V can be K^*, ρ, ϕ, or ω involves one vector form factor, $V(t)$ and three axial vector form factors, $A_0(t), A_1(t)$, and $A_2(t)$. The third, $A_2(t)$ is suppressed by terms of order $(m_{lepton}/m_D)^2$ and may be neglected. It is expected that $A_0(t)$ and $A_1(t)$ are dominated by a $J^P = 1^+$ pole and that $V(t)$ is dominated by a $J^P = 1^-$ pole. The relative strengths of $A_0(t), A_1(t)$, and $V(t)$ can be determined from the vector meson helicity angle, the $W^+ \rightarrow e^+ \nu_e$ "helicity angle", and the angle between the W and the vector meson decay planes as shown in figure 2. Branching fractions for vector decays are given by the TPS[10] and Mark III[5] groups with uncertainties of 20% or greater. TPS finds strong longitudinal polarization of the $K*$ in $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$ decays and report $\Gamma_L/\Gamma_T = 2.4^{+1.7}_{-0.09} \pm 0.2$. With the expected rates for a Tau Charm Factory of 10^4 to 10^5 per year (see Table 1), branching fractions will be again determined to a precision dominated by a systematic uncertainty of approximately 1%. Data sample of this size are large enough to unfold the ratio $V(t) : A_0(t) : A_1(t)$. Figure 3 shows the correlation of two of the angular variables with a Monte Carlo sample size of 5×10^4 events. The ratio of the three form factors is an important measurement for a detailed check of theoretical form factor predictions.

Many light quark resonances are found with masses between 1.0 to 1.8 GeV. They should also be produced in semileptonic decays. Decays occuring at a rate of a tenth of the $D_{\ell 4}$ decays typically give few thousand (hundred) reconstructed events per Cabibbo allowed (suppressed) D^0 or D^+ decay mode. Reconstructed samples for D_S decays will be a factor of ten smaller.

The Tau Charm Factory can also provide information on states not permitted by semileptonic spectator graphs such as $D \rightarrow gg\ell^+\nu_\ell$ and resonant $D \rightarrow (glueball)\ell^+\nu_\ell$. The couplings to the η', the θ and the iota in a semileptonic decay may provide new insights into their gluonic makeup. Branching fractions as small as 10^{-3} will produce tens of detected, background free events in these channels.

Semileptonic decays are best reconstructed in $c\bar{c}$ events produced at e^+e^- collisions at $\sqrt{s}$ of 3.77 and 4.03 GeV. These energies lie below the threshold for $D\bar{D}^*$ and $D_S\bar{D}_S^*$ production respectively. Therefore, a reconstructed hadronic decay can be used to tag $D\bar{D}$ or $D_S^+D_S^-$ events. If a recoiling D meson decays semileptonically, it is detected by identifying the lepton and hadrons and reconstructing the missing momentum and energy. A hermetic detector with good particle identification is essential. Kinematics provide and additional means of rejecting backgrounds from misidentified or undetected particles. The quantity U is defined as $E_{missing} - p_{missing}$, and it should be close to zero if the event has been correctly reconstructed.

There are two important backgrounds for any semileptonic decay. Adding a π^0 to the decay gives another semileptonic decay which can feed down if the π^0 is undetected. The worst hadronic background is obtained by swapping the lepton and neutrino with a charged and neutral pion. Generally, Cabibbo suppressed decays have Cabibbo suppressed backgrounds. The need for a cesium iodide crystal calorimeter to reject these backgrounds is demonstrated by figure 4. The shaded regions in figures 4a and 4c represents the $D^0 \rightarrow K^-\pi^+\pi^0\pi^0$ background to reconstructed $D^0 \rightarrow K^-\pi^0e^+\nu_e$ events. Figure 4a corresponds to a detector with a lead-proportional tube calorimeter and figure 4c corresponds to a detector with a CsI crystal calorimetry. The dramatic improvement is due to CsI's ability to veto events with extra low energy photons. This takes on an added importance when fitting the angular distributions in a form factor analysis. The "classic" mistake in this sort of analysis is that the angular distribution of the background is difficult to determine. The best solution is to avoid all backgrounds. The same effect for a Cabibbo suppressed decay can be seen in figures 4b and 4d . The shaded regions represent the $D^+ \rightarrow \pi^+\pi^0\pi^0$ background to reconstructed $D^+ \rightarrow \pi^0e^+\nu_e$ events.

Neutron albedo is another potential problem. Approximately a tenth of Mark

III's events contain "non-physics" neutral showers in its lead- proportional tube sandwich calorimeter. Crystal calorimeters which sample a larger fraction of a shower are less sensitive to albedo. If necessary, additional rejection can be obtained by timing the start of the CsI pulse. Albedo showers occur at late times. A resolution of ~1 ns would be sufficient to reject albedo.

The use of fully reconstructed $D\bar{D}$ events gives a Tau Charm Factory a special advantage over fixed target experiments or $B\bar{B}$ factories. Fixed target experiments and $B\bar{B}$ factories are unable to distinguish whether a photon comes from a fragmentation particle or a semileptonic candidate. This makes reconstruction of decays with neutrals problematic. They also lack the strong kinematic rejection of backgrounds which are possible only when the entire event is reconstructed. Neither can be expected to attain the small systematic errors possible at a Tau Charm Factory.

REFERENCES

1. J. Adler *et al*, Phys. Rev. Lett.62 (1989) 1821.
2. H. Abramowicz*et al*, Z, Phys, C15 (1982) 19;
   K. Kleinknecht and B. Renk, Z, Phys, C34 (1987) 209.
3. J.C. Anjos *et al*, Phys. Rev. Lett. 62 (1989) 1587.
4. Particle Data Group*et al*, Phys. Lett. 204B (1988).
5. J.M. Izen, SLAC-PUB-4753 (1988).
6. S. Godfrey and N. Isgur, Phys. Rev. D32 (1985) 189.
7. M. Crisafulli *et al*, Phys. Lett. 223B (1989) 90;
   A. Soni, *Proceedings of the Tau Charm Workshop*, SLAC-REPORT-343, Vol. 1;
   C. Bernard *et al*, Phys. Rev. D38 (1988) 3540;
   C. Dominguez *et al*, Phys. Lett. 207B (1988) 499;
   C. Dominguez *et al*, Phys. Lett. 197B (1987) 423;
   B.F.L. Ward *et al*, Nuovo Cimento 98A (1987) 401;
   B. Grinstein *et al*, Phys. Rev. D39 (1989) 799;
   B. Grinstein *et al*, Phys. Rev. Lett. 56 (1986) 298;
   B. Grinstein *et al*, CALTECH 68-1311 (1986);
   M. Bauer*et al*, Z, Phys. C29 (1985) 637.
8. M. Crisafulli, *ibid.*
9. B.F.L. Ward, *Proceedings of the Tau Charm Workshop*, SLAC-REPORT-343, Vol. 1.
10. J.C. Anjos *et al*, Phys. Rev. Lett.62 (1989) 722.

Figure Captions

1. Kaon momentum in the D^0 rest frame for $D^0 \to K^- e^+ \nu_e$ decays. The two histograms are vector dominance predictions for a simple pole and for the same pole plus a second pole coupling with one tenth the strength of the first.

2. Geometry of a $D_{\ell 4}$ decay. The kaon helicity angle with respect to the K^* is labelled θ_K, the positron helicity angle with respect to the W is labelled θ_e and the angle between the decay planes is labelled ϕ.

3. Correlation between $cos(\theta_K)$ and $|\phi|$ for $5 \times 10^4 D_{\ell 4}$ decays.

4. U distribution for Cabibbo allowed and Cabibbo suppressed semileptonic decays. The shaded regions represent background levels with (a-b) lead-proportional tube calorimetry and (c-d) Cesium iodide crystal calorimetry.

Table I. Number of Reconstructed Semileptonic Decays Per Year

$D^0 \rightarrow$	BR	$N_{Xe\nu_e}$	$N_{X\mu\nu_\mu}$	CKM
$K^-\ell^+\nu$	0.034	2.9×10^5	2.2×10^5	V_{cs}
$\pi^-\ell^+\nu$	0.004	3.7×10^4	3.0×10^4	V_{cd}
$K^{*-}\ell^+\nu$	0.06	1.5×10^5	1.2×10^5	V_{cs}
$\rho^-\ell^+\nu$	0.004	1.6×10^4	1.3×10^4	V_{cd}
$D^+ \rightarrow$				
$K^0\ell^+\nu$	0.07	1.1×10^5	8.6×10^4	V_{cs}
$\pi^0\ell^+\nu$	0.004	1.4×10^4	1.1×10^4	V_{cd}
$\eta\ell^+\nu$	0.0015	3.3×10^3	2.6×10^3	V_{cd}
$\eta'\ell^+\nu$	0.0005	9.2×10^2	6.2×10^2	V_{cd}
$\bar{K}^{*0}\ell^+\nu$	0.05	2.0×10^5	1.5×10^5	V_{cs}
$\rho^0\ell^+\nu$	0.0025	1.3×10^4	1.0×10^4	V_{cd}
$\omega\ell^+\nu$	0.0025	5.5×10^3	4.0×10^3	V_{cd}
$D_S \rightarrow$				
$\eta\ell^+\nu$	0.02	6.7×10^3	5.1×10^3	V_{cs}
$\eta'\ell^+\nu$	0.006	1.5×10^3	8.5×10^2	V_{cs}
$K^0\ell^+\nu$	0.002	4.7×10^2	3.6×10^2	V_{cd}
$\phi\ell^+\nu$	0.034	4.4×10^3	3.2×10^3	V_{cs}
$K^{*0}\ell^+\nu$	0.0013	4.5×10^2	3.4×10^2	V_{cd}

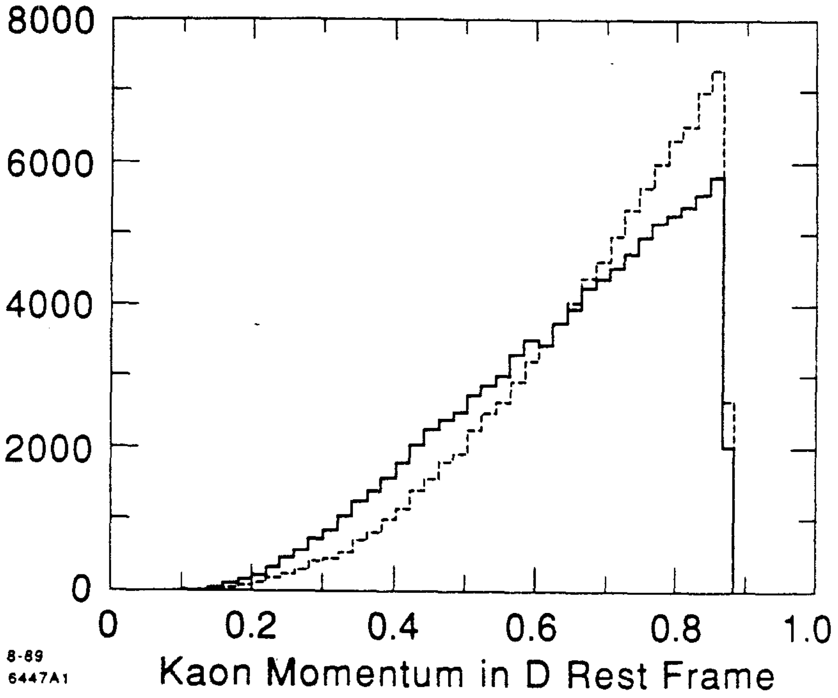

8000
6000
4000
2000
0
0
0.2
0.4
0.6
0.8
1.0
8-89
6447A1
Kaon Momentum in D Rest Frame

Fig. 1

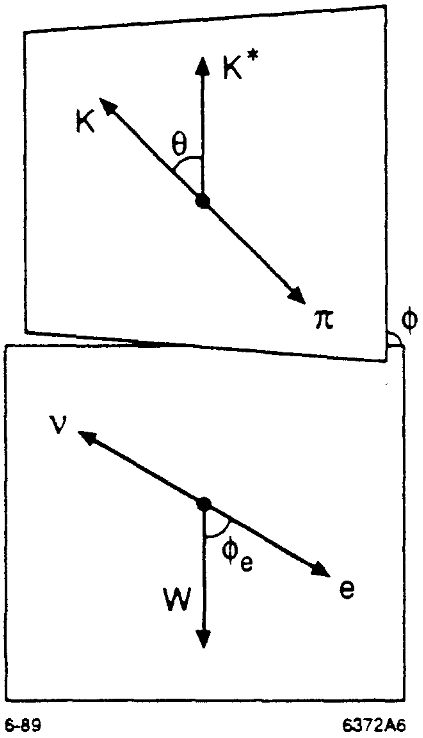
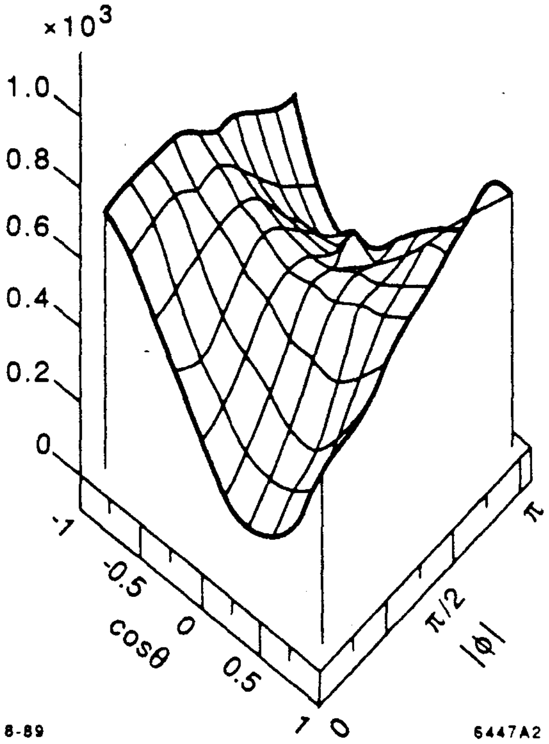
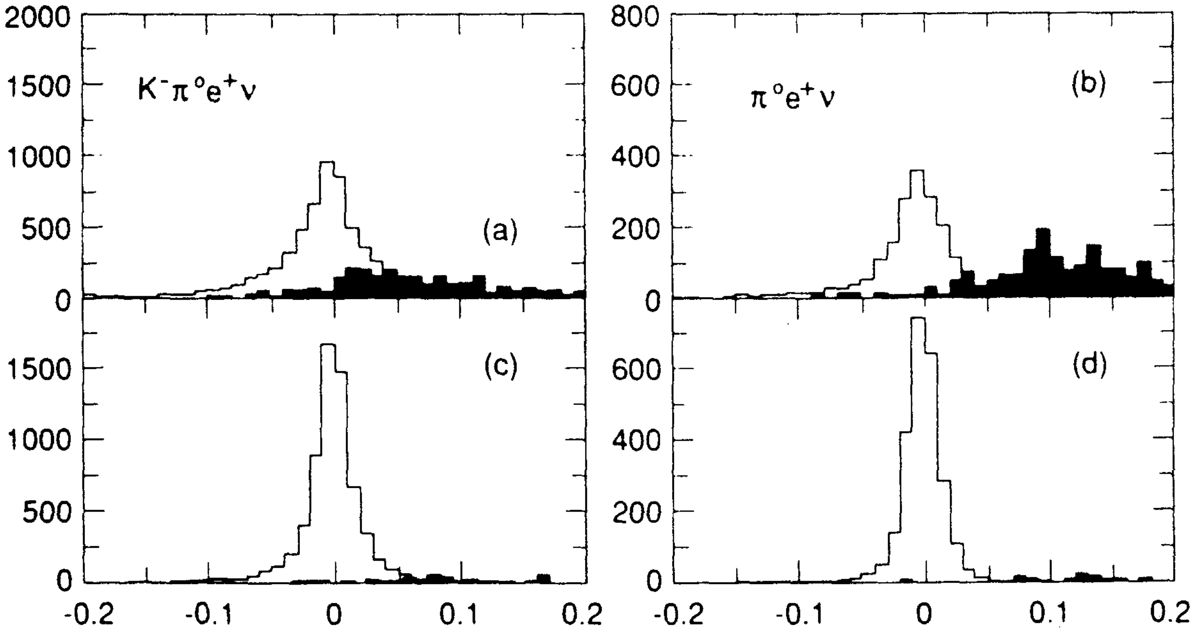

K*
K
θ
π
ϕ
ν
ϕe
W
e
6-89
6372A6

Fig. 2



×10^3
1.0
0.8
0.6
0.4
0.2
0
-1
-0.5
cosθ
0
0.5
1
0
π/2
|φ|
π
8-89
6447A2

Fig. 3



2000
1500
1000
500
0
K⁻π°e⁺ν
(a)
(c)
800
600
400
200
0
π°e⁺ν
(b)
(d)
-0.2
-0.1
0
0.1
0.2
6 89
6372A5
U = E missing − P missing (GeV)

Fig. 4