Form factor analysis and unitarity effects in D→K*ℓν

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The large polarization recently reported by Fermilab experiment E691 in D→ K*ℓν casts doubt on quark model form factors. We investigate whether unitarity corrections can make the standard quark model consistent with the E691 data. Despite significant corrections, we show that the quark model still cannot achieve the high polarization of the E691 data. Unitarity corrections, including *CP*-odd effects, will be visible in the next generation experiments.

Experimental and theoretical study of weak semileptonic (s.l.) decays has recently been important for extracting mixing parameters of the weak hadronic currents, particular those connecting light and heavy quarks. To obtain these parameters from branching ratios, lepton spectra or other observables of D and B decays, theoretical input [1] is needed to determine the weak current matrix elements between initial D or B states and the final hadron systems they decay into. Recently, two of us [2] have shown that model dependence of the theoretical input can involve factors of two in the determination of the amplitude $|V_{bu}|$.

Conventional experimental and theoretical analysis of s.l. heavy meson decays relies for the most part on a single resonance in zero width approximation to the final hadronic state. For example, the decay $D\to K\pi\ell\nu_l$ is saturated by the single resonance K* in the Kπ system and is described by three basic form factors $F^V(q^2)$, $F_1^A(q^2)$ and $F_2^A(q^2)$ where q is the momentum transfer to the final leptonic system. In quark models the axial form factors F_1^A, F_2^A and the vector form F^V are determined by matching free quark or bound state wave functions at some q^2 to the hadronic current's spin properties. For D→K*ℓν the distinction between $q^2=0$ and $q^2=q^2_{max}$ is not significant. The q^2 evolution is usually assumed to be governed by a single pole dominance of the form $F(q^2)=F(0)/(1-q^2/M^2)$ where M represents the mass of the nearest resonance with the appropriate quantum numbers [#1]. In the Körner–Schuler (KS) model [1] matched at $q^2=0$,

$$F_0^A(0)=I(m_1+m_{K^*}),$$

$$F_2^A(0)=R_{12}\frac{-2I}{m_1+m_{K^*}},$$

$$F^V(0)=R_V\frac{2I}{m_1+m_{K^*}}. \tag{1}$$

The overlap factor I stands for deviations from the matching to the free quark model. In the "standard" quark model of KS the overlap factor is assumed to be universal, i.e. $R_V=R_{12}=1$. With this choice the relations of the form factors F_1^A, F_2^A and F^V at $q^2=0$ agree with the Isgur–Wise relations [3] found in the limit of infinite quark masses in the initial and final states. Although these relations are usually thought to be applicable only for s.l. B→D, D* transitions it is not impossible that they are approximately valid for s.l. D→K, K* transitions also.

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[#1] For D-decays the results are not very sensitive to the assumed q^2 dependence because the range of q^2 is only about 1 GeV^2.

Recent and ongoing experimental work on s.l. D-decays by the Fermilab experiments E691 [4] and E653 [5] is providing detailed angular correlations between the electron and decay fragments of the K*, which afford precise tests of the hadron dynamics underlying the models of the weak matrix elements. The outcome of E691 measurements are [4]

$$R_V=2.0\pm0.70\,,\quad R_{12}=0.0\pm0.50\,. \tag{2}$$

These values for R_{12} and R_V imply, in particular, a rather large ratio of longitudinal to (unpolarized) transverse polarization of the $\bar{K}^{*0}$ meson, $L/U=1.8^{+0.7}_{-0.5}$, compared to a value of 1.2 in the standard quark model. Thus these data cast doubt on the traditional quark model form factor estimates in the decay $D\to K\pi\ell\nu$. Note, however, that this conclusion is based on analysis of the data using a single resonance approximation to the K* region of the Kπ mass spectrum.

In this letter we investigate the possibility that the underlying $D\to K^*$ traditional quark model form factors could be correct but other expected unitarity effects not included in the E691 analysis were interfering with the basic form factors and significantly contributing to the high polarization observed by E691. To this end we include other processes which can contribute to the four-body final state. We improve the simple form factor model by augmenting the single (zero width) resonance approximation by additional terms required by unitarity or crossing symmetry we generically label "unitarity effects" associated with: finite width of the K*, cross channel pole in πD invariant mass system, another partial wave in the Kπ system, and current algebra inspired backgrounds of a magnitude roughly the size observed by E691 [4]. We will analyse the joint angular distribution of the lepton and the K in the four-body decay $D\to K\pi\ell\pi$ for the following four cases: the traditional form factor quark model for the two choices (I) [#2]: $R_{12}=0$, $R_V=1.86$, and (II): $R_{12}=1=R_V$. Both models will then be improved with the unitarity terms.

For definiteness we consider the decay $D(p_1)\to K(p_2)+\pi(p_3)+\ell^+(k)+\nu_\ell(k')$ where the symbols in brackets denote the particle momenta. We denote by θ and χ the polar and azimuth angles of the electron in the dilepton center of mass system, respectively. In ref. [6] it was shown that the dependence on the lepton angles θ and χ is completely trivial and factors out. The fully differential decay distribution is given by [6]

$$\frac{2\pi\,d^5\Gamma}{dq^2\,d\cos\theta\,d\chi\,ds_{23}\,d\cos\theta^*}=\sum_i \ell_i(\cos\theta,\xi)\frac{d^3\Gamma_i}{dq^2\,ds_{23}\,d\cos\theta^*} \tag{3}$$

with the lepton coefficients

$$\ell_U=\tfrac{3}{8}(1+\cos^2\theta)\,,\quad \ell_L=\tfrac{3}{4}\sin^2\theta\,,$$
$$\ell_F=\frac{3}{2\sqrt{2}}\sin 2\theta\sin\chi\,,\quad \ell_I=-\frac{3}{2\sqrt{2}}\sin 2\theta\cos\chi\,,$$
$$\ell_T=\tfrac{3}{4}\sin^2\theta\cos 2\xi\,,\quad \ell_V=-\tfrac{3}{4}\sin^2\theta\sin 2\chi\,,$$
$$\ell_N=\frac{3}{\sqrt{2}}\sin\theta\sin\chi\,,\quad \ell_A=-\frac{3}{\sqrt{2}}\sin\theta\cos\chi\,,$$
$$\ell_P=\tfrac{3}{4}\cos\theta\,. \tag{4}$$

The dynamics of the decay is contained in the partial decay rates Γ_i. They depend on the (Kπ)-invariant mass squared s_{23}, the momentum transfer to the lepton system $q=k+k'$, and the polar angle θ^* of the K meson in the Kπ rest frame. The Γ_i can be calculated from the decomposition of the hadronic matrix element. This has an axial–vector and a vector part and depends on four form factors f, g, r, and h in the following way

$$J_\mu\equiv\langle p_2,p_3|A_\mu+V_\mu|p_1\rangle=\frac{1}{m_1}\Big(f(p_2+p_3)_\mu+g(p_2-p_3)_\mu+rq_\mu+\frac{ih}{m_1^2}\epsilon_{\mu\nu\alpha\beta}q^\nu(p_2+p_3)^\alpha(p_2-p_3)^\beta\Big)\,, \tag{5}$$

where f, g, r, and h depend on s_{23}, q^2, and $\cos\theta^*$. Consider now the helicity projections of the current, $F_\lambda=\epsilon^*(q,\lambda)J^\mu$ for $\lambda=0,\pm1$ in the Kπ rest frame. They have the following partial wave expansion:

$$F_\lambda(s_{23},q^2,\cos\theta^*)=\sum_j(2j+1)d^j_{\lambda,0}(\theta^*)F^j_\lambda(s_{23},q^2)\,. \tag{6}$$

This means that the expansion of F_0 starts with $j=0$

[#2] Our analysis is based on the preliminary E691 values.

whereas for $F_{\pm 1}$ the lowest partial wave is $j=1$. The partial wave amplitude F^j_λ depend only on s_{23} and q^2. According to the Watson theorem they have the final state interaction phases δ_j for $I=\frac{1}{2}$ Kπ scattering:

$$F^j_\lambda(s_{23},q^2)=|F^j_\lambda(s_{23},q^2)|\exp(\mathrm{i}\delta_j) . \quad (7)$$

The phase shifts δ_j depend on the single variable s_{23}.

The main contribution to F_λ comes from the intermediate state K*(892) resonance which is purely elastic. In the zero width approximation we parameterize the form factors [#3] f, g and h in terms of the basic form factors (1) conventionally used in the narrow width, single resonance approximation, which depend only on q^2 [6]:

$$f\to F^{\mathrm{A}}_1(q^2)\,,F^{\mathrm{A}}_2(q^2)\,,\quad g\to F^{\mathrm{A}}_1(q^2)\,,$$
$$h\to F^{\mathrm{V}}(q^2)\,. \quad (8)$$

We take I in (1) to be I in (1) to be $I=0.5$ to account for the correct total decay rate for Model I where we take $R_{12}=0$, $R_{\mathrm{V}}=1.86$. We maintain $I=0.5$ for simplicity for Model II, although this can easily be adjusted to match the total decay rate [7]. The q^2 dependence of the form factors in (8) is given by single resonance poles with masses as in ref. [6].

Besides the dominant K*(892) resonance state there are other contributions to the Kπ final state. If we restrict the expansion (6) to s- and p-waves only, the form factors g and h are independent of θ^* whereas f is at most linear in $\cos\theta^*$. The s-wave is resonant at $\sqrt{s_{23}}=1.429$ GeV yielding the $\mathrm{K}^*_0(1430)$ state which also decays dominantly into Kπ. It has a rather large width of (0.287±0.023) GeV. From threshold the phase shift δ_0 grows monotonically with energy until it reaches 90° near the resonance mass [8]. In ref. [6] it was shown that there are strong interference terms between $j=0$ and $j=1$ contributions for those partial decay rates Γ_i which involve F_0, i.e. Γ_i for $i=$L, F, I, A, N [see (4) for the definition of L, F, I, etc.]. Therefore these cross sections are ideal for studying the phase difference $\delta_0-\delta_1$ in isodoublet Kπ scattering. Other resonances that might contribute are K*(1415), which however decays dominantly into K*π, and $\mathrm{K}^*_2(1430)$ with $j=2$. We notice that as long as we restrict the partial wave expansion (6) to s- and p-waves the cross sections Γ_{U}, Γ_{T}, Γ_{V} and Γ_{P} depend on θ^* only through the characteristic multiplicative factor $\sin^2\theta^*$ and give information on the $J^P=1^-$ states only. All the other cross sections involve s–p interference. Furthermore Γ_{L}, Γ_{I} and Γ_{A} depend on the s–p phase shift difference in the form $\cos(\delta_0-\delta_1)$ whereas Γ_{F} and Γ_{N} are proportional to $\sin(\delta_0-\delta_1)$.

In ref. [6] we illustrated how to extend the simple single resonance model with the above mentioned contributions. We constructed a model with K*(892) and $\mathrm{K}^*_0(1430)$ resonant states, and non-resonant background required by cross channel processes in the Dπ system or inspired by chiral lagrangians. The expressions for the functions f, g, and h can be found in ref. [6]. In ref. [6], the unknown coupling of $\mathrm{K}^*_0(1420)$ to the weak current was parameterized by a strength $\epsilon=1, 0, -1$. Here we take $\epsilon=-1$ which gives a good fit to preliminary data from E653 [5] for low q^2 $(0<q^2<0.3\ \mathrm{GeV}^2)$ versus high q^2 $(0.3<q^2<0.9\ \mathrm{GeV}^2)$ events. The hadron invariant mass

$$830<\sqrt{s_{23}}<950\ \mathrm{MeV} \quad (9)$$

corresponds to the K*(893) region, within which there are also contributions from the $\mathrm{K}^*_0(1420)$ tail and other backgrounds. In addition to the work of ref. [6] we have unitarized the s- and p-waves by multiplying the projected background amplitudes with the s- and p-wave phase shifts as represented by the Breit–Wigner formulas. Since the formulas are cumbersome and lengthy, we have not written them down. This way we fulfill the Watson theorem (7) for the partial wave and not just for the resonance term as we did in ref. [6].

Our approach allows to calculate the combined θ^*–θ–χ correlations with coefficients which depend on s_{23} and q^2. In this letter we want to illustrate the kind and size of the unitarity effects. We therefore present results in terms of the coefficients of the one dimensional decay distributions

$$2\pi\frac{\mathrm{d}\Gamma}{\mathrm{d}\chi}=\Gamma_{\mathrm{U+L}}(1+a_1\sin\chi+a_2\sin 2\chi$$
$$+b_1\cos\chi+b_2\cos 2\chi)\,,$$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta^*}=c(1+\beta\cos\theta^*+\alpha\cos^2\theta^*)\,,$$

[#3] The form factor r does not contribute to the rate for massless leptons.

$$\frac{d\Gamma}{d\cos\theta}=\tfrac{3}{8}(\Gamma_U+2\Gamma_L)(1+c_1\cos\theta+c_2\cos^2\theta)\,. \tag{10}$$

The results for each form factor model (I, II) with or without unitarity terms are given in tables 1-4. We also present results for the case of the E653 cut (9) on the hadron invariant mass, both for the whole q^2-range and separately for the low q^2 and high q^2 contributions. All our results are for $(\ell^+\nu_\ell)$ emission. The $(\ell^-\bar{\nu}_\ell)$ emission case is obtained by changing the sign of ℓ_P, ℓ_N and ℓ_A and changing the sign of the form factor h. Therefore the angular coefficients of the *CP*-odd terms, V, F and N change sign. Γ_V and Γ_N are reflected in the odd terms in the χ distribution [#4] ($\sin\chi$, $\sin 2\chi$) which are a measure of "direct" *CP*-violation [9] or unitarity phases arising from final state interactions. These odd terms in the χ distribution cancel if the decays of D and $\bar{D}$ are averaged.

Unitarity effects contribute to the total Kπ decay rate Γ_{U+L} when integrated over the entire Kπ invariant mass, increasing its value. However, within the narrow K* resonance region (9), the interference is destructive in both models I and II, lowering the total decay rate, relative to the rate calculating without the corrections. Yet, the total rate can always be accounted for by adjusting the overall normalization factor I. Model I populates the low q^2 more copiously than model II. The ratio $\Gamma_{low}/\Gamma_{high}$ of low q^2 events to high q^2 events is 0.61 in model I and 0.41 in model II, essentially independent of the unitarity effects (0.56 and 0.38, respectively).

An important aspect of our unitarity analysis concerns the relationship of the $\cos\theta^*$ distribution to the polarization. For pure resonance models $\beta=0$, and the ratio of longitudinal to transverse polarization of the $\bar{K}^{*0}$ meson is given by $L/U=\frac{1}{2}(1+\alpha)$. This relation no longer holds true if unitarity terms are included. Unitarity effects change the polarization parameter $\frac{1}{2}(1+\alpha)$ appreciably as compared to the pure resonance models. In both, models I and II, $\frac{1}{2}(1+\alpha)$ is smaller, especially in the low q^2 region, as compared to the pure resonance models. *However, the polarization parameter* $\frac{1}{2}(1+\alpha)$ *is much smaller in II (the standard model with* $R_{12}=1=R_V$*), whether or not unitarity effects are included. Unitarity effects can therefore not account for the high polarization observed by E691* [4]. This fact is confirmed by fig. 1 where we show the $\cos\theta^*$ distributions in the low q^2 region. The dotted line gives the result of a conventional, single resonance-zero width, form factor model with factor ratios as measured by E691 (model I: $R_V=1.86$, $R_{12}=0$). The question we have been asking is: can this result be reproduced by the standard quark model (model II: $R_V=1=R_{12}$) if augmented by unitarity terms (dashed line in fig. 1). The answer is clearly no: the discrepancy between these two lines is largest. In contrast, model II in single resonance approximation resembles model I augmented by unitarity terms. *In any case, it is difficult to escape from the conclusion*

[#4] Γ_F is only measurable in the fully differential distribution (3).

Table 1
Results for the coefficients of eq. (10) for model I ($R_V=1.86$, $R_{12}=0$) including unitarity terms.

	No cuts	$830<\sqrt{s_{23}}<950$ MeV		
		all q^2	low q^2	high q^2
$U+L$	3.17	2.37	0.851	1.52
L/U	1.45	1.43	3.72	0.913
$\frac{1}{2}(1+\alpha)$	1.13	1.37	3.38	0.884
α	1.25	1.74	5.75	0.767
β	−0.0918	−0.0307	−0.0356	−0.0296
c_1	0.445	0.437	0.232	0.577
c_2	−0.486	−0.483	−0.763	−0.292
a_1	0.0771	0.110	0.0991	0.117
a_2	-1.0×10^{-5}	-8.0×10^{-6}	-1.3×10^{-7}	-9.9×10^{-6}
b_1	0.0462	0.00750	0.00391	0.00952
b_2	−0.0690	−0.0941	−0.0193	−0.136

Table 2
Results for the coefficients of eq. (10) for model I ($R_V=1.86$, $R_{12}=0$) in single resonance, zero width approximation.

	No cuts	$830<\sqrt{s_{23}}<950$ MeV		
		all q^2	low q^2	high q^2
$U+L$	3.15	3.15	1.19	1.96
L/U	1.78	1.78	5.16	1.09
$\frac{1}{2}(1+\alpha)$	1.78	1.78	5.16	1.09
α	2.56	2.56	9.26	1.16
β	0	0	0	0
c_1	0.301	0.300	0.154	0.408
c_2	−0.562	−0.563	−0.824	−0.371
a_1	0	0	0	0
a_2	0	0	0	0
b_1	0	0	0	0
b_2	−0.125	−0.125	−0.0396	−0.176

of E691 that standard quark models such as model II cannot fit their data. To achieve their high polarization, form factors are needed which populate the low q^2 region and have a more pronounced $\cos^2\theta^*$ dependence than the traditional quark model form factors. The main conclusion of our analysis, therefore, supports the E691 conclusion that standard quark model form factors even when augmented by unitarity corrections cannot fit their data.

The $\cos\theta^*$ component measured by the parameter β arises from a deviation of Γ_L from its canonical $\cos^2\theta^*$ dependence due to the unitarity terms. It remains, however, quite small in both models I and II and is most visible at low q^2 in model I.

The recoil electron spectrum is measured by c_1, c_2. Both coefficient are of order 0.2–0.4 for pure resonance models. The coefficient c_2 differs somewhat between models I and II, whereas c_1 is more sensitive to unitarity effects.

The azimuth distribution is described by the four coefficients a_1, a_2, b_1, and b_2. Only b_2 is nonzero for pure resonance models. Its value depends somewhat on the choice of model I or II but shows clearly a sensitivity to the unitarity effects. The coefficient a_2 is very small in both models, with or without the unitarity terms. This results from the fact that a_2 originates from the partial cross section Γ_V which is proportional to $\mathfrak{I}\{h^*g\}$. Other partial waves than the dominant p-wave originate only from the πD channel which is real [6] and apparently do not interfere with the p-wave. The contribution from the p-wave alone vanishes because of (7). This makes the asymmetry a_2 particularly useful to detect *CP*-violation in s.l. D-decays [9].

By far the greatest unitarity effect is seen in the coefficients a_1 and b_1. The coefficient a_1 measures the asymmetry $\ell^\pm(\chi)-\ell^\pm(-\chi)$ where $\ell^\pm$ is the number of leptons with indicated charge. The χ-asymmetry measures the strong phase (plus any non-standard model weak *CP*-violation phase). Since $\ell^+(\chi)=\ell^-(-\chi)$ if *CP* is valid, these asymmetries average to zero when $\ell^\pm(\chi)$ data are added. In the experimental analysis, they should be looked at separately. The $\pm\chi$ asymmetry is strong in both models I and II at high and low q^2, but stronger in model II. The contribu-

Table 3
Results for the coefficients of eq. (10) for model II ($R_V=1=R_{12}$) including unitarity terms.

	No cuts	$830<\sqrt{s_{23}}<950$ MeV		
		all q^2	low q^2	high q^2
$U+L$	2.36	1.66	0.461	1.20
L/U	1.10	0.972	2.22	0.716
$\frac{1}{2}(1+\alpha)$	0.747	0.901	1.88	0.683
α	0.495	0.803	2.75	0.365
β	−0.0616	−0.0257	−0.0174	−0.0278
c_1	0.464	0.467	0.317	0.535
c_2	−0.375	−0.321	−0.632	−0.178
a_1	0.103	0.156	0.181	0.147
a_2	-1.44×10^{-5}	-1.22×10^{-5}	-2.63×10^{-7}	-1.33×10^{-5}
b_1	0.0567	0.00943	0.00637	0.0105
b_2	−0.128	−0.174	−0.0760	−0.121

Table 4
Results for the coefficients of eq. (10) for model II ($R_V=1=R_{12}$) in single resonance, zero width approximation.

	No cuts	$830<\sqrt{s_{23}}<950$ MeV		
		all q^2	low q^2	high q^2
$U+L$	2.18	2.18	0.629	1.55
L/U	1.16	1.16	2.98	0.824
$\frac{1}{2}(1+\alpha)$	1.16	1.16	2.98	0.824
α	1.31	1.32	4.91	0.644
β	0	0	0	0
c_1	0.249	0.249	0.164	0.290
c_2	−0.399	−0.400	−0.714	−0.246
a_1	0	0	0	0
a_2	0	0	0	0
b_1	0	0	0	0
b_2	−0.201	−0.201	−0.102	−0.252

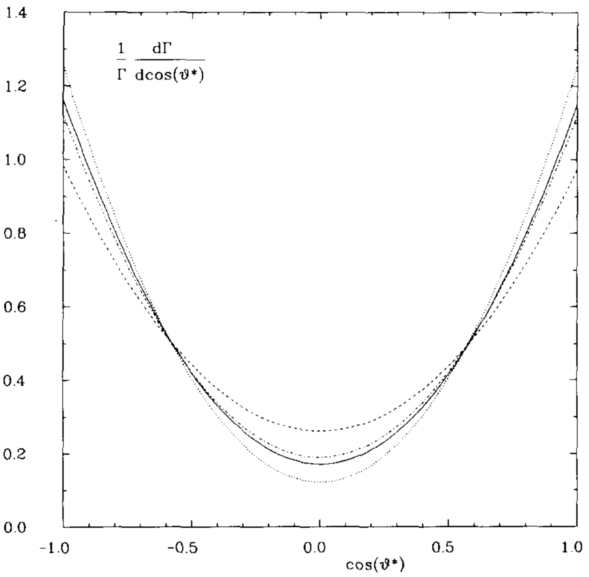

Fig. 1. Distributions in cos θ^* for the different models: full line: model I ($R_V=1.86$, $R_{12}=0$) including unitarity terms, dotted line: model I in single resonance, zero width approximation, dashed line: model II ($R_V=1=R_{12}$) including unitarity terms, dash-dotted line: model II in single resonance, zero with approximation.

tion to b_1 is less pronounced in both unitarity corrected models I and II but might be visible at high q^2.

Generally we have found that unitarity effects are small but not negligible and should be visible in current generation experiments. They appear most conspicuously in the longitudinal decay width at small q^2. This implies that the polarization parameter $\frac{1}{2}(1+\alpha)$ no longer equals the longitudinal to transverse polarization ratio L/U. Unitarity effects also contribute to the CP-odd decay correlations Γ_i, $i=$F, N at a level of several percent, i.e. to a_1 in (10) and to Γ_F in (3). CP-odd effects cancel in general when both sign lepton data are added. Thus data should be analysed separately when statistics permit. The asymmetry coefficient a_2 (Γ_V) turned out to be extremely small so that this coefficient is particularly useful to search for CP-violation.

In this note we have relied heavily on the E691 quoted value for the polarization parameter $\frac{1}{2}(1+\alpha)$. Much more information resides in the full angular correlation data, not accessible to us because of the need for Monte Carlo calculations including detector acceptance and efficiency corrections. This Monte Carlo calculation should be applied not simply to the basic form factor models but to extended models including the unitarity effects we have described. The next generation experiments (Fermilab experiments E687 and E791), with one or two orders of magnitude better statistics than current experiments, should be able to make this analysis, definitively pin down the basic form factors, and observe CP-odd effects in the electron azimuth χ.

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