THE POSSIBILITY OF A (c, s) VECTOR CURRENT AND $D \to K^* \ell \nu$

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The properties of the K* and charged lepton from the charmed particle decay $D \to K^* \ell \nu$ are used to give some model-independent tests for the presence of a purely vector (c, s) weak current. Present data on the electron energy spectrum may suggest that the (c, s) current is not purely vector. Models for the decay and general analysis techniques are also discussed

It has been suggested [1] that the charmed and strange quark appear not only in the usual V–A form $(c, s)_L = \bar{c}\gamma_\mu(1 - \gamma_5)s$, but also symmetrically in the V+A (right-handed) form, $(c, s)_R = \bar{c}\gamma_\mu(1 + \gamma_5)s$. Ignoring the Cabibbo angle, which would presumably occur as a factor $\cos\theta_c$ for the first of these and not for the second, the $c \to s$ transition would then be prely a vector one, treating left- and right-handed s quarks symmetrically.

Various places where such a possibility could be tested have been examined. Barger and Nanopoulos [2] have considered obtaining information from $\psi \to \nu\bar{\nu}$, and Sasaki [3] has examined F decays that are dominated by an axial current transition, such as $F \to \mu\nu$ and $F \to 3\pi$; then the rate is very sensitive to whether there is an axial part to the current. However, the above tests will be very difficult since all the rates involved are expected to be very small.

In this note the decay $D \to K^*\ell\nu$ is studied [4]. It has been considered already by Ali and Yang [5], and by Bletzacher et al. [6]; these groups have constructed models for the decay and compared V+A and V–A forms with the electron energy spectrum, concluding both that the K* mode is an important one for D semileptonic decay and that the conventional V–A form gives better agreement with the data. The total rate and lepton energy spectrum have also been estimated [7] in models by Hinchliffe and Llewellyn-Smith, Barger et al., and Kajantie. Rather than construct models, in the following I note that several tests can be given to decide whether the decay could be purely a vector one, as discussed above. Two completely model-independent tests are presented which involve observing the K*, which should not be too difficult if this is an important mode of D decay. Another essentially model-independent test can be made with the electron energy spectrum, and when compared with the data of ref. [8] suggests that the purely vector decay may be experimentally excluded, for much the same reasons as V–A is preferred in refs. [5] and [6].

When more data are available considerable additional information can be obtained from the decay $D \to K\pi\ell\nu\,(D_{\ell 4})$ of which $K^*e\nu$ is a special case. To a large extent the techniques familiar from $K_{\ell 4}$ analysis [9–11] can be directly taken over since the spin structure is the same, although the emphasis will be different here since the behavior of the $K\pi$ system is well known and it is the basic weak hadronic coupling which one wants to study. Similar techniques can be applied to $F \to \varphi\ell\nu$ when that data is available.

The models constructed in refs. [5–7] will be useful to study the details of the relative sizes of V, A couplings, the relative amount of S and D wave axial vector decay, and SU(4) symmetry breaking. I will mention several models and comparisons among them.

In the section "Model-independent tests" the problem will be stated in detail, and model-independent tests given. The electron energy spectrum is compared with data there. The section "Models" briefly discusses possible models. The emphasis of the present note is on model-independent tests for a vector (c, s) current; the discussion of models is included for completeness.

Model-independent tests. Eventually a complete study of

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$$D \to K\pi\ell\nu\,, \tag{1}$$

will be very fruitful. Tests are possible for most basic structural properties of the weak current, in analogy with the $K_{\ell 4}$ results. Here I consider only the case where the $K\pi$ system is in the K* region; even then the s-wave $K\pi$ may be present, which leads to one useful test:

(A) If the decay occurs through a vector interaction, the hadron matrix element $\langle K\pi|V_\mu|D\rangle$ can make a $K\pi$ system in a $1^- = J^P$ state (the K*) but not in an s-wave state. The simplest argument is to note that a vector current (1^-) and a 0^+ $K\pi$ state can make states with $J^P = 1^-; 0^+, 1^+, 2^+; ...$ but not a pseudoscalar with $J^P = 0^-$. If the transition is via an axial vector interaction, a 0^+ $K\pi$ state is allowed. If both 0^+ and 1^- $K\pi$ states are populated, a forward-backward asymmetry relative to the lepton pair direction (for example) will be present in the $K\pi$ decay, while if it is a purely vector interaction no asymmetry is allowed since a single partial wave is populated in the $K\pi$ system. Thus, in the absence of background not due to reaction (1), any forward-backward asymmetry is evidence against a purely vector interaction.

Since the $K\pi$ system is known [12] to have strong s-wave scattering in the region of the K*, this is likely to be a useful test in practice, so long as a fairly pure sample of reaction (1), can be isolated. Since the K* is fairly narrow, this may well be a practical test in the near future.

(B) The second test also involves observing the decay angular distribution of the $K\pi$ system. In the $K\pi$ rest frame, define a z-axis along the direction of the momentum of the D or of the current. Consider a purely vector interaction; according to (A) there will not be an s-wave, $K\pi$ state interfering with the K*. Then one has effectively a 0^- state (D) decaying to two 1^- states, the K* and the conserved weak vector current. To conserve J_z the two vector states will have z-components of angular momentum either (0, 0) or (+1, −1). To conserve parity they will be in a p-wave, so one must take the antisymmetric combination and (0, 0) is excluded. Therefore the K* must have $J_z = \pm 1$. This leads to a $\sin^2\theta$ decay distribution of the K or π relative to the above z axis. To the extent that a pure sample of (1) can be isolated, any deviation from $\sin^2\theta$ is an indication that the interaction is not vector.

Both (A) and (B) can be checked from eqs. (2)–(4) below if one desires. The simple arguments given above are completely correct in the stated reference frames. (One could also check the results from the $K_{\ell 4}$ formalism. For example, eq. (4) of ref. [9], with $f = g = 0$ to give purely a vector interaction, gives those results. Further tests can be read off there or in refs. [10] or [11]; for example, a purely vector interaction gives a $1 + 2\cos^2\varphi$ correlation between the hadron and lepton planes. By studying all the correlations one can deduce the relative amount of vector and axial vector interactions.)

(C) A third test can be made using available data for the electron energy spectrum. The full amplitude for the decay $D \to KK^*\ell\nu$ can be written

$$M = \frac{G_F}{\sqrt{2}} \langle K^*|V_\mu + A_\mu|D\rangle \bar{\nu}\gamma_\mu(1-\gamma_5)\ell\,, \tag{2}$$

and the hadron matrix element is (in general a fourth term is present but its contribution vanishes for zero lepton mass so it is ignored here)

$$\langle K^*|V_\mu + A_\mu|D\rangle = \mathrm{i}h\epsilon_{\mu\alpha\beta\gamma}p_\alpha K_\beta \epsilon^*_\gamma + f\epsilon^*_\mu + g(\epsilon^*\cdot p)K_\mu\,, \tag{3}$$

where p is the D momentum, and K and ϵ the K* momentum and polarization vector. To calculate rates and distributions in general one must make a model for f, g, and h. However, to test whether the transition is a vector one, the case of most immediate theoretical interest, we can set $f = g = 0$ (f and g correspond to axial vector transitions, s- and d-wave, and h corresponds to the vector transition). Then (metric $p^2 = m_D^2$)

$$\sum_{\text{spins}} |M|^2 = 8G_F^2 h^2 [K\cdot p(q'\cdot p\, q\cdot K + q'\cdot K\, q\cdot p) - m_{K^*}^2 p\cdot q' p\cdot q - m_D^2 K\cdot q' K\cdot q]\,, \tag{4}$$

where q and q' are the charged lepton and ν momenta. Integrating over K* energies, the electron energy spectrum is shown in the D rest frame in fig. 1, along with data from ref. [8]. The electron energy is taken between limits $(m_D^2 - m_{K^*}^2)/2m_D$ and 0, and no spreading is introduced for resolution or for motion of the D. (The equivalent dashed curve for $D \to K\ell\nu$ is also shown copied from ref. [6]; this is necessarily a purely vector transition. This curve takes account of the

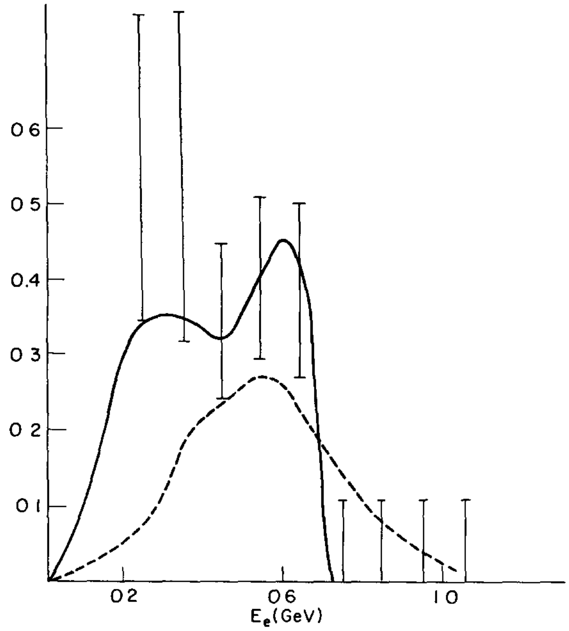

Fig. 1. The solid line is the electron energy spectrum from $D \to K^* e\nu$ for a purely vector (c, s) current, with no spreading for resolution or motion The data is taken from ref. [8] Note that while the data does not disagree statistically with the solid curve, they behave differently, the data peaking at low electron energy and the theory curve at higher electron energy. The dashed line shows the spectrum from $D \to K e\nu$, and is copied from ref. [6] where motion of the D and resolution are included consistent with experimental conditions. The dashed line is included here for completeness so the reader can subtract some amount of the dashed curve and consider what is left for the solid curve. Only the shapes of the spectra are relevant; the vertical scale is arbitrary.

motion of the D and resolution presumably in a manner consistent with the conditions of the experiment, and is included here for easy reference.)

While the solid curve does not seriously disagree with the data in a statistical sense, it shows the opposite systematic effect; the data is higher at lower electron mass but the theory is higher at higher electron mass. In addition, an undetermined amount from $D \to K e\nu$ contributes mainly at larger electron energy, leaving less room for the K* theory curve. Probably it is fair to conclude that (1) the data suggests that the $D \to K^*$ matrix element is not a pure vector one, and (2) data with somewhat smaller errors should settle the question fairly easily.

Two assumptions are being made here. First, it is assumed that only $K\ell\nu$ and $K^*\ell\nu$ semileptonic modes are important, so that the events at low E_ℓ are in fact due to the K* mode rather than to modes with excess pions There is no reason to doubt this, but it has to be checked; if excess pions are present they will show up in the charged multiplicity from the decay. Second, h is treated as a constant, independent of E_ℓ. Presumably there are actually form factor effects, with h something like $1/(m_{F^*}^2 - Q^2)$. Including such effects makes only small quantitative changes but will not affect any conclusions. (For example, assuming either a constant matrix element or one which vanishes as Q^2, the effect of a form factor is to multiply the curves of fig. 1 by a smooth curve which is approximately constant in the region of interest, peaking at about 0.47 GeV, and which reduces the high peak relative to the valley by about 3/4, the low peak relative to the valley by about 2/3.) Although these two assumptions reduce slightly the model-independence of test C, it seems likely they can both be ignored.

To conclude this section, two further remarks are of interest. First, arguments have been given [13] against a substantial V+A (c, d) current. If (c, s) also is not vector-like, it would impose a strong constraint on attempts to construct $SU(2) \otimes U(1)$ models. Second, it is worth noting that the tests (A)–(C) could be more valuable if essentially pure sources of D mesons were available. The $D^0\bar{D}^0$ and D^+D^- thresholds in e^+e^- collisions are at 3.73 and 3.74 GeV, while the heavy lepton and $D^*\bar{D}$ thresholds are above 3.8 GeV. If the bump reported [14] earlier at 3.75 GeV, which appears to take 1–2 units of R, were to turn out on closer examination to be a resonance giving substantial $D\bar{D}$ in its decay, then perhaps some extremely useful analyses of D semileptonic decays could be carried out by collecting D events at that energy.

Models. Assuming that the data used for comparison above are mainly due to D semileptonic decay, it seems that the (c, s) current is likely to contain a substantial axial vector part. This will be checked by the K* decay tests (A) and (B) above. The analyses of refs. [5, 6] have constructed models for the decay and conclude that the excess of low energy events implies the current is mainly a V–A one, which would be an important confirmation of the GIM mechanism [15].

Although the models are not unique, they give similar results, and can be understood qualitatively by a

helicity argument [16]. If the charged lepton energy is large, the K* and ν are mainly moving parallel. Since the ν and ℓ and non-strange quark in the K* can be treated as massless, conservation of angular momentum will favor a V+A or right-handed s quark. Conversely, a V−A current will give a left-handed s quark and favor a low lepton energy. The purely vector case can be thought of as the superposition of these.
At a more quantitative level the amount of flexibility in the models may be too large to permit simple conclusions to be drawn. Perhaps the most obvious model consists in directly writing

$$\langle K^* | \bar{s}\gamma_\mu (a + b\gamma_5) c | D\rangle = = ih\epsilon_{\mu\alpha\beta\gamma} p_\alpha K_\beta \epsilon^*_\gamma + f\epsilon^*_\mu + g(\epsilon^* \cdot p) K_\mu \quad (5)$$

and evaluating the left hand side with both K* and D non-relativistic. Then one finds $h = \sqrt{2}\sqrt{m_s/m_c}\, a/m_{K^*}$, $f = 2\sqrt{2b}\sqrt{m_s m_c}$, and $g = \sqrt{2}\sqrt{m_s/m_c}\, b/m_{K^*}$, where m_s and m_c are strange and charmed quark masses. An overlap integral is also contained in h, f, and g and has been set to unity here since our purpose is mainly qualitative in this section. Clearly, one can get quite different answers depending on whether one uses SU(4) symmetric masses or broken ones with $m_s \approx m_{K^*}$ (e.g. f/h varies by more than a factor of two). These results do confirm one's naive expectation that vector and axial vector transitions at the quark model level correspond to vector and axial vector in the hadron matrix element.

Further, none of the models of refs. [5–7] is equivalent to the simple quark model of eq. (5) or to each other. For example, Hinchcliffe and Llewellyn-Smith use $g = 0$, Barger et al. put $h = g = 0$, ref. [6] has the same g as eq. (5), and ref. [5] has g/h uncertain up to a factor $m_\rho/m_{F^*} \approx 1/3$ depending on how one introduces the symmetry breaking. Similarly, g/f varies by a factor of about 4 from eq. (5) to the value of ref. [6]. Clearly any conclusion based on the details of models is suspect. However, the helicity argument given above [16] suggest that V−A will always give a peaking at a lower lepton energy, so the conclusion of ref. [5, 6] that a V−A current is preferred may be more general than the models.

Conclusions. Some model such as those briefly described above is necessary at the present time to find what combination of V and A describes the (c, s) weak current, except for the case of a vector current in which case several feasible model independent tests exist. The present data on the electron energy spectrum suggests independent of the models that the current is not a vector one. The models of Ali and Yang [5] and Bletzacher, Nieh, and Soni [6] indicate that the current is a conventional left-handed one; simple helicity arguments ‡ suggest that this conclusion is likely to persist even though there is considerable ambiguity in choosing a model.

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‡ This argument was also known to M K. Gaillard, and discussions with her helped clarify its interpretation

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