Primary electron spectrum in semileptonic B decays

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We calculate the inclusive and primary electron spectrum in B decay and determine the coupling parameters, including the size of the chiral anomaly in $B \rightarrow D\pi e\nu$.

In a recent paper,¹ we calculated semileptonic decay rates of K and D mesons in the channels $K \rightarrow \pi\pi e\nu$ and $D \rightarrow \pi e\nu$, $Ke\nu$, $K\pi e\nu$. These amplitudes were parametrized by the couplings of the weak current to pseudoscalars, couplings that obey current-algebra theorems at threshold, including effects of chiral anomalies.² Form factors were then introduced to represent the dominant dynamical enhancements in two-body channels (K^* , D^* , and ρ poles). This pole-enhanced current-algebra model gives an excellent description of K_{l4} decay,^{1,3} where the vector form factor affords a check of the Wess-Zumino² chiral anomaly in the strangeness-changing current.

When these methods are applied to semileptonic decays of the D meson, a good fit is obtained to the electron spectrum in $D \rightarrow eX$ if the contributions from the important channels are summed ($X = \pi, K, K\pi$). We note this is a zero-parameter fit if the couplings are determined by matching the amplitudes of threshold of their current-algebra value.^{1,3} The semileptonic decay width is also predicted and agrees well with the experimental result obtained from the lifetime and the semileptonic branching ratio. What is surprising here is that the pole-enhanced soft-meson results seem also to give a good description of D decays, where momentum transfers are so large and where pseudoscalar masses are not small compared to the scalar of strong interactions. However, it should be noted that the electron spectrum and semileptonic decay width are but two crude tests of the model; more detailed angular correlations are needed for a definitive test.

For several years, B -meson decay data have been reported from the Cornell Electron Positron Storage Ring.⁴ In this Brief Report, we will attempt to apply the above parametrization to semileptonic-decay data of the B meson. Among other things, we will show that the pole-enhanced current-algebra model fails miserably to describe these heavy-quark decays. However, a similar model, cast in terms of vector and axial-vector form factors, pole enhanced in two-particle channels, remains a convenient phenomenology when freed from the low-energy current-algebra constraints. The model is

more complete than those used to fit the data in Ref. 4.

At present the only detailed data we have for semileptonic B decays is the inclusive electron and muon spectrum. These data include secondary contributions from the cascade $B \rightarrow DX$, $D \rightarrow eX$. The authors of Ref. 4 have subtracted these from the complete spectrum by using a phenomenological fit to $D \rightarrow eX$. The result is the primary electron spectrum, $B \rightarrow eX$, which we will fit with our model for the dominant primary channels $B \rightarrow De\nu$ and $B \rightarrow D^*(D\pi)e\nu$. [We neglect the small contribution from $b \rightarrow u$ quark transitions, consistent with the CLEO (Ref. 4) and CUSB data.]

Previous fits⁴ to the primary spectrum have been more restrictive, two-parameter fits based on the naive quark model and a QCD-corrected quark model,⁵ and the meson-decay models of Ali⁶ and Bletzacker, Nieh, and Soni.⁷ Our interest is to determine a best fit to the data in terms of the minimum number of operators that are expected to contribute based on our experience at lower energies. This parametrization may be interpreted in a current-algebra framework; in particular we determine the size of the chiral-anomaly² term in the vector-matrix element of the decay $B \rightarrow D\pi e\nu$. The fit to the electron spectrum fixes our model, which then can be used to predict more detailed data, such as angular correlations.

All relevant formulae are contained in the Appendix and in Ref. 1, where we calculated the corresponding amplitudes for D decays, using a slightly different formulation. In Ref. 1 we calculated

$$\begin{aligned} D &\rightarrow K^*(K\pi)e\nu \quad (V \text{ and } A \text{ contributions}) , \\ D &\rightarrow Ke\nu \quad (V \text{ only}) . \end{aligned} \quad (1)$$

To obtain from Ref. 1 corresponding expressions for B decay, change masses appropriately, replace D by B , K by D , etc., and change the sign of the V - A interference term in $B \rightarrow D\pi e\nu$. (The interference term in $B \rightarrow D\pi e\nu$ decay has the same sign as K_{l4} decay.)

The parameters of our model are

X_1 = vector form factor at zero momentum transfer in $B \rightarrow D\pi e\nu$,

X_2 = axial-vector form factor at zero momentum transfer in $B \rightarrow D\pi e\nu$, (2)

X_3 = vector form factor at zero momentum transfer in $B \rightarrow De\nu$.

All three parameters have the value unity in the current-algebra model.

Before comparing our model with the measured electron spectrum, we boosted the B to the laboratory system to reflect effects of the decay in flight, and smeared the spectrum to reflect detector momentum resolution. This boosted and smeared

FIG. 1. (a) χ^2 contours for the parameters X_1 and X_2 , with X_3 fixed at best fit. The contours represent χ^2 's of 2.92, 5.92, and 10.92. (b) χ^2 contours for the parameters X_1 and X_3 , with X_2 fixed at best fit. The contours represent χ^2 's of 2.92, 5.92, and 10.92. (c) χ^2 contours for the parameters X_2 and X_3 , with X_1 fixed at best fit. The contours represent χ^2 's of 2.92, 5.92, and 10.92.

model was compared with the measured spectrum. The best fit is obtained with the parameters

$$\begin{aligned} X_1 &= 0.11 \pm 0.03, \\ X_2 &= 0.39 \pm 0.31, \\ X_3 &= 1.37 \pm 0.16. \end{aligned} \quad (3)$$

The contours of equal likelihood are shown in Figs. 1(a),

1(b), and 1(c). Our best fit has a χ^2 of 1.93 (six degrees of freedom). The contours shown have χ^2 's of 2.9, 5.9, and 10.9. The errors in Eq. (3) correspond to increases in χ^2 of 1 unit. Our best fit to the primary electron spectrum of Ref. 4 is given in Fig. 2, where both data (squares with error bars) and theory (bar graph) have been binned.

Further, more detailed data is needed to reduce fit uncertainties, but it is clear that the following models give unacceptable fits:

$$X_1=1, X_2=0, X_3=1 \text{ (pole-enhanced naive current-algebra model),}$$

$$X_1=1, X_2=1, X_3=1 \text{ (pole-enhanced current-algebra model with chiral-anomaly term).} \quad (4)$$

Note also that χ^2 increases significantly when the chiral-anomaly term is ignored ($X_2=0$), but we can find χ^2 's as small as 6 with this constraint.

Using our best-fit model, we determine the branching ra-

tios

$$\Gamma_{B \rightarrow Dev} = 0.331 \times 10^{-13} \text{ GeV} = 59\% (\Gamma_{B \rightarrow DeX}), \quad (5)$$

$$\Gamma_{B \rightarrow D^*(D\pi)ev} = 0.235 \times 10^{-13} \text{ GeV} = 41\% (\Gamma_{B \rightarrow DeX}).$$

Our fits are normalized to $\Gamma(B \rightarrow DeX) = 0.566 \times 10^{-13} \text{ GeV}$, which gives 11.9% for the semileptonic branching ratio if $\tau_B = (1.4 \pm 0.4) \times 10^{-12} \text{ sec}$. [The CLEO measurement for the branching ratio is $(12.0 \pm 0.7 \pm 0.5)\%$ (Ref. 4).]

In conclusion, we have constructed a model for semileptonic B decay, more general than ones considered previously, and fit it to the electron decay spectrum. The threshold values of the fit are far from those predicted by soft-meson methods. An anomaly term is required. The ratio of $B \rightarrow Dev$ to $B \rightarrow D^*ev$ is 3 to 2.

APPENDIX

The electron spectrum in B decay is given by

$$\frac{d\Gamma}{dE_l}(B \rightarrow lx) \simeq \frac{d\Gamma}{dE_l}(B \rightarrow l\nu D^*) + \frac{d\Gamma}{dE_l}(B \rightarrow l\nu D),$$

where

FIG. 2. Primary electron spectrum in B decay. The histogram represents the theoretical prediction normalized to data. The theoretical model has been boosted and smeared to take account of the effects of decay in flight and detector resolution.

$$\begin{aligned}
\frac{d\Gamma}{dE_l}(B \rightarrow l\nu_l D^*) &= \frac{3}{2} \frac{G_F^2 V_{cb}^2}{128\pi^6 m_B} \left(\frac{M_{D^*}^3 \pi}{\Gamma_{D^*}} \right) \left[\frac{\pi}{12} \frac{\lambda^{3/2}(M_{D^*}^2, M_D^2, M_\pi^2)}{M_{D^*}^6} \right] \\
&\times \int_{B(D^*)}^{A(D^*)} dE_\nu \left[X_1^2 \frac{M_{D^*}^2}{\pi^4 F_\pi^6} P^2(F_{(B)}^*) Q^2 \left[\frac{1}{4} \lambda(Q^2, M_{D^*}^2, M_B^2) + \frac{1}{2} M_B^2 Q^2 - 2M_B^2 E_l E_\nu \right] \right. \\
&\quad + X_2^2 \frac{8}{9F_\pi^2} P^2(F_{A(B)}^*) \{ (2M_B E_e - Q^2)(2M_B E_\nu - Q^2) + M_{D^*}^2 Q^2 \\
&\quad \quad + 3(M_D^2 - M_\pi^2)^2 [\lambda(M_{D^*}^2, M_D^2, M_\pi^2)]^{-1} \\
&\quad \quad \times [(2M_B E_e - Q^2)(2M_B E_\nu - Q^2) - M_{D^*}^2 Q^2] \} \\
&\quad \left. + X_1 X_2 P(F_{(B)}^*) P(F_{A(B)}^*) \frac{M_{D^*}^2}{\pi^2} \frac{8}{3F_\pi^4} Q^2 M_B (E_l - E_\nu) \right], \\
\frac{d\Gamma}{dE_l}(B \rightarrow l\nu_l D) &= X_3^2 \frac{G_F^2 V_{cb}^2}{8\pi^3} M_B \int_{B(D)}^{A(D)} dE_\nu [M_B^2 - M_D^2 + 4E_\nu E_l - 2M_B(E_\nu E_l)] P^2(F_{(B)}^*) .
\end{aligned}$$

In the above, by $\Gamma(B \rightarrow l\nu_l D^*)$ we really mean $\Gamma(B \rightarrow l\nu_l D\pi)$, summed over charge states, with a resonant D^* in each channel, in narrow-width approximation. We have used the notation

$$Q^2 = M_{D^*}^2 - M_B^2 + 2M_B(E_\nu + E_l) ,$$

$$A(x) = \frac{M_x^2 - M_B^2 + 2M_B E_l}{4E_l - 2M_B} ,$$

$$B(x) = -\frac{M_x^2 - M_B^2 + 2M_B E_l}{2M_B} ,$$

$$P(x) = \frac{M_x^2}{M_x^2 - Q^2} ,$$

$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + ac + bc) .$$

The value of the mixing angle was taken to be⁸

$$V_{cb}^2 = (0.053)^2 .$$

$F_{(B)}^*$ is the $J^P=1^-$ ($b\bar{s}$) state and $F_{A(B)}^*$ the $J^P=1^+$ ($b\bar{s}$) state. We take $M_{F_B^*} = M_{F_{A(B)}^*} = 6.5$ GeV.

The value of Γ_{D^*} was determined from the experimental $B(D^* \rightarrow D\pi)$ by calculating $\Gamma(D^* \rightarrow D\pi)$, with mass values $m_{D^*} = 2.01$ GeV, $m_D = 1.865$ GeV, and $m_\pi = 139.6$ MeV. [The factor of $\frac{3}{2}$ leading the spectrum formula accounts for the fact that one of the D^* channels has no phase space for subsequent decay into $D\pi$ ($D^* \rightarrow D^+\pi^-$)]. While the decay width Γ_{D^*} is sensitive to these masses, the spectrum itself is not sensitive, because of a similar canceling factor in the phase space for $B \rightarrow D\pi e\nu$.

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