Exclusive versus inclusive semileptonic $\overline{B}$ decays in the quark model: A reply

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(Received 25 July 1996)

Some emerging difficulties in the theoretical description of exclusive semileptonic $\overline{B}$ decays are discussed in the context of the quark model. While there are no unambiguous problems at this time, I discuss physics beyond the valence quark model which should eventually be probed by precision measurements of B semileptonic decays. [S0556-2821(96)04921-1]

PACS number(s): 13.20.He, 12.39.Ki

Wolfenstein [1] has commented on an emerging discrepancy between the measured rate of inclusive semileptonic B decay and the sum of the rates to the exclusive channels considered in the Isgur-Scora-Grinstein-Wise (ISGW) quark model [2]. While calling attention to this issue is very valuable, I disagree with Wolfenstein's interpretation of its implications. In particular, I will argue that if there is rate missing from the sum over exclusive channels, then the most likely origins are nonresonant decays and highly excited resonances that lie outside the scope of the ISGW model, and not in a problem with the model itself.

We should begin these considerations by recognizing that the ISGW quark model should not in general be expected to be able to make predictions with better than typical quark model accuracy since, among other things, it is grounded in the $1/N_c$ expansion, so it assumes valence quark dominance, and, while it respects relativistic kinematics, it calculates the form factors for semileptonic decays using nonrelativistic valence quark wave functions. At the same time, we note that in its updated version as ISGW2 [2], this model respects the constraints of heavy-quark symmetry [3] and so in some cases its model-dependence appears only in $1/m_Q$ terms.

Let me next address the issue of the theoretical consistency between the ISGW2 model and QCD-corrected inclusive $b\rightarrow c\ell\overline{\nu_\ell}$ calculations. The latter calculations give $\Gamma_{sl}=(4.6\pm0.3)|V_{cb}|^2\times10^{13}$; the theoretical error I have assigned to this result will be discussed below. ISGW2 gives $\Gamma(\overline{B}\rightarrow D\ell\overline{\nu_\ell})=1.2|V_{cb}|^2\times10^{13}$, $\Gamma(\overline{B}\rightarrow D^*\ell\overline{\nu_\ell})=2.5|V_{cb}|^2\times10^{13}$, and a rate to the three lowest-lying excited heavy quark spin multiplets with $s_\ell^{\pi_\ell}=1/2^-$, $3/2^-$, and $1/2^+$ of $0.4|V_{cb}|^2\times10^{13}$. These exclusive modes correspond to $26\pm2\%$, $54\pm4\%$, and $8\pm1\%$ of Γ_{sl} leaving $12\pm6\%$ of the rate unaccounted for *theoretically*.

Note that the $1/N_c$ valence approximation is irrelevant to the issue of the consistency between ISGW and inclusive calculations since within that approximation a complete exclusive calculation and the inclusive calculation should agree. So where is the missing rate? It can be in three places.

(1) Without explicitly calculated matrix elements to yet more highly excited states, ISGW is unable to quantitatively address the completeness of their truncated sum over exclusive channels for $b\rightarrow c\ell\overline{\nu_\ell}$ transitions. However, from the convergence they see with excitation energy in B decays and the increasing shortfall with respect to the inclusive rate they see in B_s and B_c, it would not be surprising if the $\overline{B}$ decay rate to all yet higher spin multiplets were equal to that to the three excited spin multiplets they explicitly compute, namely about another 8%. If so, the exclusive-inclusive discrepancy would be an insignificant $4\pm6\%$. Note that the rate of convergence of the sum over exclusive channels is controlled by how close $b\rightarrow c\ell\overline{\nu_\ell}$ decays are to the Shifman-Voloshin limit [4].

(2) The inclusive rates have explicit QCD radiation in them. Such radiation is consistent with the $1/N_c$ valence approximation, but corresponds to the excitation of hybrid mesons which are ignored in ISGW. From the contribution of radiative corrections to the recoil dependence of the D and D^* rates, one can estimate using Bjorken's sum rule [5,6] about a 4% contribution of such states. The exclusive-inclusive discrepancy would now be $0\pm6\%$.

(3) The reliability of the inclusive rate calculation is still unclear. The theoretical error we have assigned was intended to be adequate to cover the uncertainty in QCD radiative corrections, but the total error could be considerably larger given how incompletely $1/m_Q$ effects (associated with both mass shifts $\overline{m_B}=m_b+\Lambda$ and the accuracy of quark-hadron duality) are understood [7].

In summary, there is no clear indication that the ISGW model is theoretically inconsistent as gauged by its correspondence to inclusive calculations.

Let us now turn to the experimental situation. We first note that experiment [8] gives D and D^* semileptonic rates of $19\pm5\%$ and $45\pm3\%$, each somewhat smaller than the ISGW2 predictions. Wolfenstein focuses on the fact that these measurements imply that $36\pm6\%$ of the rate goes to other states, versus the $8\pm1\%$ explicitly taken into account by ISGW2. Based on the preceding discussion, one could instead take the point of view that ISGW2 expected $20\pm6\%$ of the decays to be to excited states (a 2σ discrepancy), and that it explicitly calculated the rate to about half of these excited state decays.

Recent experimental findings lend support to this view. Wolfenstein's Comment depends to some extent on the 1995 publication by the OPAL Collaboration [9] reporting very large branching ratios to the $D_1(2420)$ and $D_2^*(2460)$ states of the $s_\ell^{\pi_\ell}=3/2^-$ multiplet. These reports, if confirmed, would have neatly accounted for the ''missing'' $36\pm6\%$ of the semileptonic rate. However, such a large strength to those states seemed to be in conflict with the observed [10] slope $\rho^2=0.84\pm0.14$ of the Isgur-Wise function, which strongly suggests *via* Bjorken's sum rule a much smaller $s_{\ell}^{\pi\ell}=3/2^-$ strength closer to that of ISGW2 (where $\rho^2=0.74$). Recent measurements have indeed changed matters substantially: ALEPH [11] reports $7\pm2\%$ of the semileptonic rate to the $D_1(2420)$ and CLEO [12] reports $<9\%$ at the 90% confidence limit, to be compared to OPAL's $20\pm6\%$. Moreover, measurements [8] of the decay $\bar{B}\to D_1(2420)\pi$, coupled with the apparent validity of factorization for such decays, would imply a semileptonic $D_1(2420)$ fraction of $5\pm2\%$. Thus the ISGW2 prediction that this fraction is 4% does not seem to be far off the mark. For the $D_2^*(2460)$, ALEPH reports $<4\%$ at the 90% confidence limit to be compared to OPAL's $22\pm9\%$. ISGW2 predicts this rate to be 2%. At the same time, ALEPH reports that the final states $D\pi\ell\bar{\nu}_\ell$ and $D^*\pi\ell\bar{\nu}_\ell$ account for $21\pm5\%$ of the $36\pm6\%$ of the B semileptonic rate that was not D or D^*. Recall that ISGW2 has $20\pm6\%$ non-$D+D^*$ decays, of which $8\pm1\%$ is in explicitly summed channels. The ALEPH observations are thus consistent with ISGW2 if it is indeed the case that $12\pm6\%$ of the semileptonic decays go into highly excited D mesons (both quarkonia and hybrids). I would conclude that it is premature to declare that there is a serious discrepancy between ISGW2 *per se* and experiment.

I would nevertheless like to agree with Wolfenstein that there *are* probably more than just the ISGW2 processes contributing to the inclusive rate. We have indeed already seen that theoretical consistency requires $12\pm6\%$ more rate, and have identified highly excited D mesons not in ISGW2 as certain sources of uncalculated rate. However, there are both theoretical and experimental indications that nonresonant processes, which are outside of ISGW2 since they correspond to N_c^{-1} effects, may be at least as important as these uncalculated parts of processes that are of leading order in N_c.

As a prelude to discussing nonresonant processes, we note that there are, in addition to direct measurements [10], many indirect indications that the prediction of ISGW2 for ρ^2 is too small: the predicted $\bar{B}\to D\ell\bar{\nu}_\ell$ and $\bar{B}\to D^*\ell\bar{\nu}_\ell$ rates are somewhat too high, the predicted production of all excited states is somewhat too low, and ISGW2 predicts all of the measured analogs to ρ^2, namely the form factor slopes for $\pi\to\pi$, $K\to\pi$ and $D\to K$ transitions, to be too small by about 30% [2]. These experimental problems are all consistent with an acknowledged [2] theoretical defect of ISGW: its neglect of nonvalence effects. This defect can be addressed by ''unquenching the quark model'' [13], i.e., by turning on the effects of $q\bar{q}$ pairs (or equivalently of a complete set of meson loop graphs). When the b quark decays from a $b\bar{q}q\bar{q}$ configuration inside the $\bar{B}$, it simply makes a corresponding configuration of the D or D^* at $w=1$ (in the heavy-quark limit), but as $w-1$ is increased such configurations make increasingly small contributions to ''elastic'' scattering relative to the $b\bar{q}$ configuration. That is to say, they will make a net positive contribution to ρ^2 after renormalization. By Bjorken's sum rule, this contribution will be dual not to the production of the $c\bar{q}$ resonances, but rather to a $c\bar{q}+q\bar{q}$ continuum. In such an ''unquenched'' version of ISGW one would in fact naturally expect an additional contribution of order 10% to the semileptonic rate from nonresonant states corresponding to a conjectured 30% increase in ρ^2. With additional $c\bar{q}$ excited states and hybrids as well as such nonresonant decays, the total rate to exclusive excited states could easily be of order 30%.

In summary, we believe the foregoing suggests that careful study of B semileptonic decays could answer some old and very important physics questions concerning quark-hadron duality. To extract this physics, it will be important to have more accurate measurements of the ''elastic'' D and D^* fractions, but especially to delineate the strength and nature of the non $D+D^*$ contributions. We anticipate not only somewhat more resonant strength, but also a substantial nonresonant continuum. Theoretically, these latter decays appear to provide a clear testing ground for the accuracy of the valence approximation. In particular, the large energy release in a $b\to c$ transition will allow a probe of the nonvalence components of the ''brown muck'' out to high relative momentum.

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