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F-meson production rate in bottom-meson decays

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The inclusive production rate of the F meson in bottom-meson decays is estimated as accurately as possible in the standard theory. In branching ratio, $B(B^- \rightarrow F^+ + X) + B(B^- \rightarrow F^- + X) = 0.09 \pm 0.02$ and $B(B_s{}^0 \rightarrow F^+ + X) + B(B_s{}^0 \rightarrow F^- + X) = 0.86^{+0.08}_{-0.13}$. Semileptonic B_s decays always produce F mesons either directly or through radiative cascading.

The F meson was detected at mass ~ 1970 MeV first by the CLEO Collaboration,[1] and then by several other groups[2–5] in e^+-e^- annihilation. While most of these groups measured the F mesons in the region of high z $(=E_F/E_e)$, which are presumably fragmented from primary charmed quarks, the High Resolution Spectrometer (HRS) Collaboration[4] observed very copious F production in the low-z region ($z < 0.4$). The only known source of F with such low z values is the weak decay of primary b quarks. The magnitude of the F production observed by HRS appears to exceed any reasonable expectation of F production through b decays. If this excess F production is established, its implication will be profound. Having this experimental data in mind, we try to compute here the inclusive F production rate in bottom-flavored-meson decays with the best accuracy attainable within the present theoretical understanding.

There have been many theoretical works on different aspects of B decays.[6,7] Since we are interested here in inclusive production of a heavy meson, we will use, whenever possible, the impulse approximation or the quark-decay picture. The total decay rate is given by the dominant spectator processes since the annihilation processes are less than 1% in rate for theoretically reasonable values of the B decay constant, $f_B \lesssim 100$ MeV. The magnitude of the total rate depends on choice of quark masses. Motivated by the D^+ and D^0 lifetimes, we choose[7]

$$m_c = 1.6 \text{ GeV}, \quad m_s = 0.3 \text{ GeV}, \quad m_{u,d} = 0.15 \text{ GeV} . \tag{1}$$

These values are halfway between the current quark masses and the constituent quark masses. The b-quark mass is chosen to be 5.0 GeV. The spectator-quark mass is defined as $m_{\text{spec}} = m_D(m_F) - m_c$. This definition leads us to slightly different mass values for a given quark, depending on whether it is a spectator or a quark produced by W. However, this choice of spectator masses ensures correct kinematical constraints when phase-space effects are important. The short-distance gluon corrections of 10%–15% are included for nonleptonic decays, but the $b \rightarrow u$ transition is ignored altogether. Hereafter, B stands generically for B^+, B^-, B^0, and $\bar{B}^0$, while B_s stands for B_s and $\bar{B}_s$. Similarly, F means F^+ and F^-.

I. SEMILEPTONIC DECAYS

One striking feature is that the invariant mass of the hadron system (c and a spectator quark) is constrained kinematically into a very narrow region. The mass is given by

$$M_h{}^2 = (p_c + p_{\text{spec}})^2 = m_c{}^2 + m_{\text{spec}}{}^2 + 2E_c m_{\text{spec}} , \tag{2}$$

when the Fermi motion of a spectator is ignored. We find with

$$E_c < (E_c)_{\max} = (m_b{}^2 + m_c{}^2)/2m_b$$

that M_h is in the range

$$\begin{aligned} &1.87 \text{ GeV} < M_h < 2.02 \text{ GeV} \quad \text{for } B , \\ &1.97 \text{ GeV} < M_h < 2.18 \text{ GeV} \quad \text{for } B_s . \end{aligned} \tag{3}$$

In case of B, M_h is well below the FK threshold (2.47 GeV), so F production is forbidden in semileptonic B decays,

$$B(B \rightarrow F + l + \nu + X) = 0 . \tag{4}$$

In case of B_s, too, M_h is below the threshold of DK (2.37 GeV), so the c quark must always pick up the spectator s quark to form F or its excited states, all of which cascade down to F radiatively. Therefore,

$$B(B_s \rightarrow F + l + \nu + X) = B(B_s \rightarrow l + \nu + X) . \tag{5}$$

We have $B(B_s \rightarrow l + \nu + X) = 0.30 \pm 0.03$ after the logarithmic corrections due to hard gluons are made. The conclusions (4) and (5) are insensitive to the choice of spectator masses and little affected by inclusion of the Fermi motion of $\langle \mathbf{p}^2 \rangle^{1/2} \simeq 300$ MeV.

II. NONLEPTONIC DECAYS

A. F production from $b \rightarrow c(\bar{u}d_c)$

The invariant mass M_h of c and a spectator is equally small in nonleptonic decays as in semileptonic decays, but the argument made for the semileptonic decays cannot be applied to the nonleptonic decays. Four quarks in a final state are connected by three strings of gluon field, as shown in Fig. 1. Each string beyond a certain length can break up to create quark pairs. When it breaks, however, energy may be transferred from one string to another through final-state interactions. Therefore, there is no need for each string to obey strict energy conservation by itself. We learned from inclusive hadron spectra in electron-positron annihilation[8] that a string of gluon field breaks up into pieces of a little

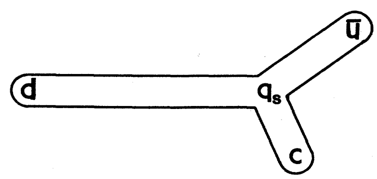

FIG. 1. Strings of gluon field formed in nonleptonic decays. The quark q_s at the center stands for a spectator.

less than one unit of rapidity length. With this knowledge, we are able to estimate how likely the string between c and a spectator is to break off in bottom decays. Since the string between c and a spectator does not extend for more than about one rapidity length in b decays, the chance for this string to break into two pieces is less than 50%. Detailed numerical study can be performed by introducing the probability that a string of rapidity length Δy breaks off. Let us choose for this probability the function

$$P(\Delta y)=N\int_0^{\Delta y}\exp[-(y-a)^2/b^2]dy \ , \tag{6}$$

where N is the normalization factor to make $P(\infty)=1$. A string of rapidity length $\Delta y \gtrsim a+b$ breaks off most likely, but not often a string of $\Delta y \lesssim a$. The function $P(\Delta y)$ looks like the one in Fig. 2 for $a=1$ and $b=\frac{1}{2}$, our choice of parameter values: Strings break up into pieces of $\Delta y \simeq 0.7$ on average. One can compute with this $P(\Delta y)$ the average multiplicity of charged pions in nonleptonic B decays. Assuming that all the nonstrange s-wave $q\bar{q}$ states are created with statistical weight, we have found that our $P(\Delta y)$ reproduces correctly the experimental observation[9]

$$B\to(D \text{ or } D^*)+(3.8\pm0.2\pm0.2)(\pi^+ \text{ or } \pi^-)+\text{ neutrals} \ .$$

The probability for the $c\bar{s}$ string not to break is given by

$$p=\frac{1}{\Gamma(b\to c(\bar{u}d))}\int\frac{d\Gamma(b\to c(\bar{u}d))}{d(\Delta y)}\times[1-P(\Delta y)]d(\Delta y) \ , \tag{7}$$

where Δy is the rapidity along the $c\bar{s}$ string. We obtain from (7)

$$p=0.65 \ . \tag{8}$$

This number is insensitive to choice of $P(\Delta y)$ as long as the average breaking length of strings is fixed. When the string does not break, c picks up the spectator $\bar{s}$ unless it captures a quark created on another string. Such capture can happen when the $\bar{u}$ (d) quark in $b\to c(\bar{u}d)$ is thrown into the same general direction as the c quark. However, we have found from the energy and angular distributions of the $b\to c(\bar{u}d)$ decay that this capture probability is small enough to be ignored in our present accuracy of quantitative estimate. Therefore, approximately with 65% of probability, c forms D or D^* with a spectator in B decays, and F or F^* with the spectator s (or $\bar{s}$) in B_s decays. When the string breaks (with 35% of probability), the c quark picks up a sea quark from vacuum. The probability to pick up an s quark rather than a u quark or a d quark is the parameter often denoted by $f(s\bar{s})$. Following the conventional wisdom, we choose

$$f(s\bar{s})=0.15\text{–}0.17 \ . \tag{9}$$

Putting all together, we obtain

$$B(B\to F+X)_{c\bar{u}d}=(1-p)f(s\bar{s})B(b\to c(\bar{u}d_c)) \ ,$$
$$=0.35\times0.16\times0.54=0.03\pm0.01 \ , \tag{10}$$

$$B(B_s\to F+X)_{cud}=[p+(1-p)f(s\bar{s})]B(b\to c(\bar{u}d_c))$$
$$=[0.65+0.35\times0.16]\times0.54$$
$$=0.38^{+0.05}_{-0.12} \ . \tag{11}$$

The errors are mostly due to the uncertainties involved in the estimate of p and in the $b\to c(\bar{u}d_c)$ branching ratio.

B. Forming F in $b\to c(\bar{c}s)$

The $c\bar{s}$ produced by W can form F, F^*, F^{**}, . . . (Fig. 3). Computation of the production rate is straightforward once the decay constants are known.[10] Theoretically, f_F (corresponding to $f_\pi=93$ MeV) has been determined to be[10] 120 ± 20 MeV. With this value for f_F, we obtain

$$B(B\to F+X)=B(B_s\to F+X)=0.06\pm0.02 \ . \tag{12}$$

We add to (12) the probability for c, instead of $\bar{c}$ from W, to form F. It is practically zero for B because the lack in phase space forbids $s\bar{s}$ creation from vacuum. For B_s, the c quark can capture the spectator $\bar{s}$. The same string picture as in Sec. II A leads us to

$$0.90\times B(b\to c(\bar{c}s_c))=0.12\pm0.04 \ .$$

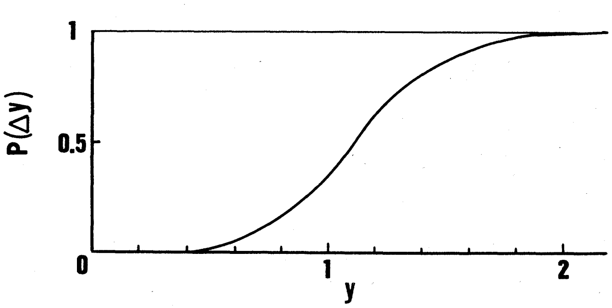

FIG. 2. Probability function $P(\Delta y)$ with $a=1$ and $b=\frac{1}{2}$.

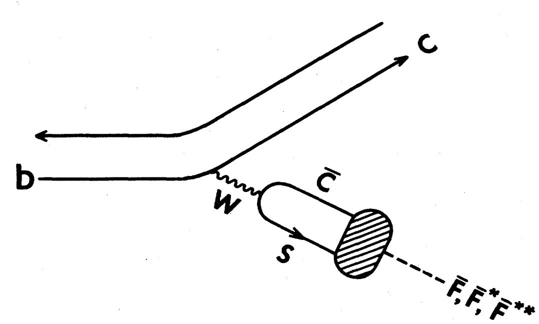

FIG. 3. Formation of F and its excited states by the quark pair from W.

TABLE I. Inclusive decay branching ratios of B and B_s into $F+$ anything.

		$B\to F+X$	$B_s\to F+X$
Semileptonic	$b\to c(l\bar{\nu})$	0	0.30 ± 0.03
Nonleptonic	$b\to c(\bar{u}d_c)$	0.03 ± 0.01	$0.38^{+0.05}_{-0.12}$
	$b\to c(\bar{c}s_c)$	0.06 ± 0.02	0.18 ± 0.05
Total		0.09 ± 0.02	$0.86^{+0.08}_{-0.13}$

We thus obtain for $b\to c(\bar{c}s_c)$

$$B(B\to F^+ +X)_{ccs}+B(B\to F^- +X)_{ccs}=0.06\pm0.02\ , \quad (13)$$

$$B(B_s\to F^+ +X)_{ccs}+B(B_s\to F^- +X)_{ccs}=0.18\pm0.05\ . \quad (14)$$

III. SUMMARY

Summing all the contributions up, we finally obtain (see Table I)

$$B(B\to F+X)=0.09\pm0.02\ , \quad (15)$$

$$B(B_s\to F+X)=0.86^{+0.08}_{-0.13}\ . \quad (16)$$

Equation (15) is to be compared with the experimental value[11]

$$B(B\to F+X)\leq[1-B(B\to D^0+X)]=0.2\pm0.2\pm0.2\ .$$

No positive identification of B_s has been reported.

The simplest and most striking results of the present analysis are not only that the inclusive F production from B_s is very high, but also that semileptonic B_s decays always produce F in one way or another. If there is no new source of F, a good half of the F's produced in the low-z region are due to B_s and a third of the F's from B_s are accompanied by energetic prompt leptons. It may turn out in the near future that tagging F is one of the most efficient ways to search for the illusive B_s meson. Meanwhile, a theoretical estimate of the F yield in the region of $z<0.4$, based on our F production rate and the decay branching ratio $B(F^+\to\phi\pi^+)=4.4\%$ of CLEO, is roughly one order of magnitude smaller than that observed by HRS. Even if one accepts the high value by TASSO for $B(F^+\to\phi\pi^+)$, the F mesons at low z by HRS are about four times larger than a theoretical prediction. Therefore, an experimental confirmation of the HRS observation will have a profound impact on the search for possible new particles.

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[1]CLEO Collaboration, A. Chen *et al.*, Phys. Rev. Lett. **51**, 634 (1983).

[2]TASSO Collaboration, M. Althoff *et al.*, Phys. Lett. **136B**, 130 (1984).

[3]ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. **146B**, 111 (1984).

[4]HRS Collaboration, M. Derrick *et al.*, in Proceedings of the XXII International Conference on High Energy Physics, Leipzig, 1984 (unpublished); Report No. HRS-CP-84-6 (unpublished).

[5]Time Projection Chamber (TPC) Collaboration, H. Aihara *et al.*, Phys. Rev. Lett. **53**, 2465 (1984).

[6]V. Barger, J. P. Leveille, P. M. Stevenson, and R. J. N. Phillips, Phys. Rev. Lett. **45**, 83 (1980); S. P. Rosen, Phys. Lett. **93B**, 492 (1980); J. H. Kühn, S. Nussinov, and R. Rückl, Z. Phys. C **5**, 117 (1980); I. I. Y. Bigi and M. Fukugita, Phys. Lett. **91B**, 121 (1980); B. Guberina, R. D. Peccei, and R. Rückl, *ibid.* **90B**, 169 (1980); V. Barger and S. Pakvasa, Phys. Rev. Lett. **43**, 812 (1979); V. Barger, W. F. Long, and S. Pakvasa, Phys. Rev. D **21**, 174 (1980); M. Wise, Phys. Lett. **89B**, 229 (1980); N. Cabbibo and L. Maiani, *ibid.* **79B**, 109 (1978); N. Cabbibo, L. Maiani, and G. Corbo, Nucl. Phys. **B155**, 93 (1979); G. Altarelli, N. Cabbibo, G. Corbo, L. Maiani, and G. Martinelli, *ibid.* **B208**, 365 (1982); M. Suzuki, *ibid.* **B145**, 420 (1978); **B177**, 413 (1981).

[7]See, R. Rückl, Phys. Rep. (to be published) for an extensive review.

[8]TASSO Collaboration, R. Brandelik *et al.*, Phys. Lett. **89B**, 418 (1980); S. L. Wu, Phys. Rep. **107**, 60 (1984).

[9]G. Kalmus, in *Proceedings of the 21st International Conference on High Energy Physics, Paris, 1982,* edited by P. Petiau and M. Porneuf [J. Phys. (Paris) Colloq. **43**, C3-431 (1982)].

[10]M. Suzuki, Phys. Lett. **142B**, 207 (1984), and references therein.

[11]S. Stone, in *Proceedings of the 1983 International Symposium on Lepton and Photon Interactions at High Energies, Ithaca, New York,* edited by D. G. Cassel and D. L. Kreinick (Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, 1984), p. 203.