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HOW TO DISCOVER THE B MESONS^{*)}

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ABSTRACT

We suggest to look for the production of $\psi(J)$ mesons in the weak decays of the B particles in order to measure the masses and other properties of the B particles. We estimate $B(B \rightarrow \psi(J) + X)$ to be of the order of 3%. The decay modes $B \rightarrow \psi(J) + K(K^*)$ may be most suitable for the determination of the B mass.

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If the b quark as the constituent of the $\Upsilon(9.46)$ meson is a heavy color triplet quark of charge $-1/3$, one expects the existence of new mesons carrying the new b flavor. The lightest new mesons are B^- (quark composition $\bar{u}b$) and B^0 (quark composition $\bar{d}b$). The masses of B^- and B^0 are expected to be between 5.0 and 5.3 GeV. The B mesons will be produced in e^+e^- -annihilation above $\sqrt{s} \gtrsim 10.5$ GeV. In analogy to the situation in the charm case one may expect the existence of relatively narrow 1^{--} resonances in the region of $11 \text{ GeV} \gtrsim \sqrt{s} \gtrsim 10.4$ GeV which decay exclusively into $\bar{B}B$ pairs.

Since the B mesons will decay typically via the weak interaction into many particles, it will be extremely difficult to detect the B mesons and to measure their masses. In this paper we shall consider a possibility to do just that, which to us seems the only realistic method to discover the B mesons.

As far as the weak interaction properties of the b quark are concerned, we assume that it forms together with the new t quark a new doublet of the weak isospin. The b quark can decay weakly only via mixing with the s and d quarks¹⁻³. Furthermore we shall assume that the weak current responsible for the b decay is dominantly of the type $(\bar{c}b)$ (and not $\bar{u}b$). Such a situation is obtained, for example, in theories where the weak mixing angles are related to the quark masses⁴. The B mesons decay in weak interaction cascades ($b \rightarrow c \rightarrow s \rightarrow u$). In addition we shall suppose that the inclusive decay rate for the B mesons is given by the decay rate for the b quark which is treated as a free spin 1/2 object. This assumption can be justified within QCD and works to a reasonable approximation in the case of the charmed particles⁵.

Let us consider the weak decay of a b quark. The b quark will emit a virtual W^- -boson and turn into a c quark. The W^- -boson disintegrates into a fermion-antifermion pair (either $\bar{\nu}_e e^-$, or $\bar{\nu}_\mu \mu^-$, or $\bar{\nu}_\tau \tau^-$, or $\bar{u}d'$ ($d' = d \cos \theta_c + s \sin \theta_c$, $\theta_c \sim$ Cabibbo angle) or $\bar{c}s'$ ($s' = -d \sin \theta_c + s \cos \theta_c$). Subsequently we shall set $\theta_c = 0$, i.e. $d' = d$, $s' = s$.

Of course, the decay modes involving a $(\bar{c}s)$ pair will be somewhat suppressed compared to the decay modes involving a $(\bar{u}d)$ -pair, due to phase space. Nevertheless we would like to argue that the decay modes involving a $(\bar{c}s)$ -pair are by far the most interesting decay modes, and in particular the ones which allow for a realistic possibility to find the B mesons and to determine their masses.

Our argument goes as follows. If the virtual W-boson disintegrates into a $(\bar{c}s)$ pair, the $c\bar{c}$ -pair in the final state can give a $\bar{c}c$ -charmonium state (e.g. $\Psi(J)$, see Fig. (1)). Thus e.g. the B^- meson will have a certain chance to break up as follows: $B^- \rightarrow \Psi(J) + K^-$, $\Psi(J) + K^{*-}$, $\Psi' + K^-$ etc. Since the $\Psi(J)$ meson has a sizeable branching ratio to decay into $\mu^+ \mu^-$, decay modes like $\Psi(J) + K^-$ are somewhat easy to identify. Furthermore the $\Psi(J)$ state is very heavy, and the amount of multiparticle phase space available in the B decay is greatly reduced in case of a $\Psi(J)$ emission. For this reasons we believe that the B decay modes involving a $\Psi(J)$ meson are the only ones which can be used to determine the masses of the B meson. Of course, it makes sense to look for such decay modes only if the branching ratios for them are not tiny. In this note we shall present arguments that the branching ratios for those decay modes of the B mesons involving a $\Psi(J)$ state are relatively large, at least large enough to be measurable.

At first we estimate how often the b quark is expected to decay weakly by emitting a $\bar{c}s$ -system. If we neglect the c quark mass and the τ -mass and use the free quark approximation, we obtain $\Gamma(b \rightarrow c + \bar{c} + s) / \Gamma(b \rightarrow \text{all}) = 1/3$, taking into account the possible decay modes $b \rightarrow c + \bar{c} + s$, $b \rightarrow c + \bar{u} + d$, $b \rightarrow c + \bar{\nu}_e + e^-$, $b \rightarrow c + \bar{\nu}_\mu + \mu^-$, $b \rightarrow c + \bar{\nu}_\tau + \tau^-$ (note, that the $\bar{q}q$ -decay modes count three times because of the color quantum number).

There will be a kinematical suppression of the $\bar{c}s$ -decay modes due to the large c quark mass. In order to take into account the quark mass and τ lepton mass effects, we use the results of ref. (6), which were derived for heavy lepton decays, and use the values $m_b = 4.8$ GeV, $m_c = 1.5$ GeV, $m_s = 0.5$ GeV. One finds:

$$\frac{\Gamma(b \rightarrow c + \bar{c} + s)}{\Gamma(b \rightarrow c + \text{all})} \approx 13 \% . \quad (1)$$

Furthermore the nonleptonic B decays are expected to be somewhat enhanced compared to the semileptonic decays. It is well-known that there exists a non-leptonic enhancement in case of the D meson decays, which are in agreement with the theoretical calculations based on QCD radiative corrections ⁷⁾. This non-leptonic enhancement is of the order of 1.15 (in amplitude) and leads to

$$\frac{\Gamma(c \rightarrow s + \text{leptons})}{\Gamma(c \rightarrow \text{all})} \approx 0.2, \quad (2)$$

in agreement with observation.

In case of the B mesons we expect the nonleptonic enhancement factor to be reduced compared to the one relevant for charm particle decay. Typical estimates are in the range of 1.05 ... 1.10. One finds

$$\frac{\Gamma(b \rightarrow c + \bar{c} + s)}{\Gamma(b \rightarrow c + \text{all})} \approx 14 \% . \quad (3)$$

Since the nonleptonic enhancement affects both the $(\bar{c}s)$ and $(\bar{u}d)$ decay modes, the ratio (3) is rather insensitive to the nonleptonic enhancement. We conclude that about 14 % of all b quark decays should lead to a final state containing a $\bar{c}c$ pair.

The next question we try to answer is the following one: How often does the $\bar{c}c$ pair lead to the production of a charmonium state, as compared to the production of a final state consisting of charmed particles? In order to answer this question, we use a method similar to the one employed in order to estimate the rate of charm and charmonium production in hadronic reactions⁸⁾. One expects the production of a charmonium state if the invariant mass of the $\bar{c}c$ -subsystem is less than $(2 M_D) \approx 3.7$ GeV. Otherwise the final state will contain a pair of charmed particles.

The invariant mass of the $\bar{c}c$ subsystem in the b quark decay is a function of the momentum of the s-quark emitted in the decay. One has

$$M^2(\bar{c}c) = (m_b - \sqrt{m_s^2 + p_s^2})^2 - p_s^2. \quad (4)$$

Using the "constituent quark masses" $m_b = 4.8$ GeV, $m_s = 0.5$ GeV, $m_c = 1.5$ GeV we can calculate $M(\bar{c}c)$. For $p_s < 0.8$ GeV one has $M(\bar{c}c) > 3.7$ GeV. Note that p_s can vary from 0 ($M(\bar{c}c) = 4.3$ GeV) to its maximum value of 1.4 GeV ($M(\bar{c}c) = 3$ GeV). The details of the momentum spectrum of the emitted s quark depend, of course, on details of the decay mechanism (in particular on uncalculable strong interaction effects). However, one may expect that the momentum spectrum is roughly of the form given in the free quark model. Here the momentum spectrum is such that relatively large s-quark momenta are favored (the spectrum is similar to the electron momentum spectrum in the μ -decay, which increases monotonically with the electron momentum⁹⁾). In this case about 60 % of all b quark decays proceed-

ing via a $\bar{c}s$ emission will lead to the production of a $\bar{c}c$ meson, and only about 40 % lead to the production of charmed particles. We shall assume that this is the case.

We mention the following decay modes of the B mesons involving $\bar{c}c$ mesons.

$$\begin{aligned} \text{I. } B &\rightarrow \eta_c K \\ &\eta_c K^* \\ &\eta_c K^* (1,430) \\ &\text{etc.} \end{aligned}$$

$$\bullet \quad \text{II. } B \rightarrow \psi(J)K, \psi(J)K^*, \psi(J)K^*(1,430), \text{ etc.}$$

$$\begin{aligned} \text{III. } B &\rightarrow \chi K, \chi K^*, \chi K^*(1,430) \text{ etc.} \\ &(\chi \text{ stands for } \chi(3,415), \chi(3,508), \text{ or } \chi(3,555)). \end{aligned}$$

$$\text{IV. } B \rightarrow \psi'K, \psi'K^*, \psi'K^*(1,430), \text{ etc.}$$

$$\begin{aligned} \text{V. } B &\rightarrow \hat{\chi} K, \hat{\chi} K^*, \hat{\chi} K^*(1,430), \text{ etc.} \\ &(\hat{\chi} : 1^{-+} \text{ p wave } \bar{c}c \text{ state, expected mass about } 3.35 \text{ GeV}). \end{aligned}$$

Of course, we cannot calculate exactly how often a $\psi(J)$ meson is produced in the B decay. However, it seems reasonable to assume that all charmonium states below charm threshold are produced with probabilities which are roughly equal (note that a similar assumption works successfully in predicting the magnitude of $\psi(J)$ production in hadronic collisions⁸⁾). In this case one expects about 30 % of all decays involving a $\bar{c}c$ meson to lead to a $\psi(J)$ state (either directly or via a sequential decay like $\psi' \rightarrow \psi(J) + \pi\pi$). Thus we obtain finally:

$$\frac{\Gamma(B \rightarrow \psi(J) + X)}{\Gamma(B \rightarrow \text{all})} \approx 3 \% . \quad (5)$$

The only way to observe a $\psi(J)$ meson in the B decay is to look for its $\mu^+ \mu^-$ decay mode. The probability to observe a $\mu^+ \mu^-$ state with the invariant mass of the $\psi(J)$ in a $\bar{B}B$ production event is of the order of 0.5 %.

Since the production of a $\Psi(J)$ state leads to a very clean signal, it seems feasible to use the $\Psi(J)$ production events in order to investigate the details of the B decay.

The momentum of the $(\bar{c}c)$ system emitted in the b decay is equal in magnitude to the momentum of the emitted s quark in the weak system of the b quark. The latter can vary between 0.8 GeV and 1.4 GeV. Thus we expect the momentum of the $\Psi(J)$ meson emitted in the B decay to be of the order of 1 GeV (in the rest system of the B particle).

Thus far we have concentrated on the inclusive production of $\Psi(J)$ mesons in the B decay. In order to determine the mass of the B meson, it would be most suitable to investigate a two-body decay like $B \rightarrow \Psi(J) + K$ or $B \rightarrow \Psi(J) + K^*$. The branching ratio for these decays is certainly much smaller than the inclusive branching ratio for $B \rightarrow \Psi(J) + X$, and depend on unknown details of the strong interactions (e.g. form factors). Nevertheless we expect that the two-body decay modes $B \rightarrow \Psi(J) + K$ and $B \rightarrow \Psi(J) + K^*$ constitute together a non-negligible fraction of all decays of the type $B \rightarrow \Psi(J) + X$, at least 20 %. For this reason we believe that the mass of the B meson can be measured by investigating these decays. We expect

$$B(B \rightarrow \Psi(J) + K(K^*)) \approx 0.6 \% . \quad (6)$$

In ref. (10) it was argued that decays like $B \rightarrow \Psi(J) + K$ should be strongly suppressed due to the color selection rules¹¹⁾. Indeed in a free quark model this decay is suppressed by a factor of three in amplitude, since only one color component can be active in order to lead to a color singlet K meson in the final state. The color selection rule is a consequence of the assumption that the following matrix element vanishes:

$$\langle B | \sum_{i=1}^8 (\bar{b}s)_i \cdot (\bar{c}c)_i | \Psi(J)K \rangle. \quad (7)$$

Here $(\bar{q}q)_i$ stands for the color octet operator $\bar{q} \frac{\lambda_i^c}{2} q$ (λ^c : $SU(3)^c$ matrix). We see no convincing reason why the color selection rule should be valid. In a nonleptonic weak decay like $B \rightarrow \Psi(J) + K$ the colors of the various quarks can always be changed by the emission or absorption of soft gluons. For this reason we doubt that the color selection rules for the nonleptonic decays are correct. An experimental test would be to measure the ratio

$$\frac{\Gamma(D^0 \rightarrow K^- \pi^+)}{\Gamma(D^0 \rightarrow \bar{K}^0 \pi^0)} \quad (8)$$

This ratio is expected to be large (~ 18) if the color selection rules are valid. Otherwise the ratio (8) is expected to be of order 2.

Finally we summarize our conclusions. The inclusive $\psi(J)$ production can be used as a clean signal to investigate the B decay. Since the $\psi(J)$ meson itself is a heavy system, two body decays like $B \rightarrow \psi(J) + K(K^*)$ are not negligible compared to the inclusive $\psi(J)$ production rate in the B decay which we estimate to be of the order of 3 %. We believe that the B mesons can only be discovered by looking for the decay modes $B \rightarrow \psi(J) + X$ discussed here.

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Figure caption

Fig. 1 : The b decay, resulting in a $\bar{c}c$ pair and an s -quark.

FIG.1