Работа поступила - 25 декабря 1979 г.

Ответственный за выпуск - С.Г.ПОПОВ
Подписано к печати 18.I-1980г. МН 06545
Усл.0,8 печ.л., 0,6 учетно-изд.л.
Тираж 290 экз. Бесплатно
Заказ № 28.

Отпечатано на ротапринте ИЯФ СО АН СССР

СИБИРСКОЕ ОТДЕЛЕНИЕ АН СССР
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ

11

V.N.Baier, A.G.Grozin

THE DECAYS OF B AND B_S MESONS WITH PRODUCTION OF CHARMONIUM STATES

ПРЕПРИНТ 80 - 28

Новосибирск

THE DECAYS OF B AND B_S MESONS WITH PRODUCTION OF CHARMONIUM STATES

V.N.Baier, A.G.Grozin

Institute of Nuclear Physics,
Novosibirsk 630090, U.S.S.R.

A b s t r a c t

The heavy meson decay $B \to \psi + X$ is considered. The angular and polarization correlations for decay products are analysed.

The relative probability of the heavy meson decay $B \to \psi + X$, according to Fritzsch's estimate /1,2/ is comparatively high (of the order of 3%). This process is convenient to discover and study the B-meson, since it is practically backgroundless. The B-meson decay (quark composition ($b\bar{u}$), or ($b\bar{d}$)), or the B_s-meson decay (quark composition ($b\bar{s}$)) can be examined in terms of quantum chromodynamics and the standard 6-quark model of weak interaction /3/. The diagram of the decay is presented in Fig.1. The process is assumed to be mainly determined by the decay of the heavy b-quark. The quarks c and $\bar{c}$ are formed at the single point ($m_W \gg m_c$) and the relative momenta of the c and $\bar{c}$ quarks are comparatively low so that it is rather likely that the bound states $c\bar{c}$: ψ or η_c - mesons can be formed, which can be identified by the typical decays $\psi \to \mu^+\mu^-(e^+e^-)$, or $\eta_c \to 2\gamma$. The production of a bound state of the $c\bar{c}$ pair occurs at the distance which is short as compared to the radius of confinement $\frac{1}{\mu}$ $(m_c \gg \mu)$ and can be characterized by a parameter $|\psi(0)|^2$ (cf.Ref./4/ where the inclusive production of the states of charmonium is investigated). There is a problem concerning the colour state of the quarks. If the pair $c\bar{c}$ is produced in the colour neutral state, the production probability, as it has been mentioned, is described by a $|\psi(0)|^2$. If the pair is formed in the colour state, there exists a possibility that at the output from the confinement region the system $c\bar{c}$ becomes colour neutral and forms bound states with the help of the "soft colour neutralization" mechanism. The probability of this will be characterized by a parameter $|\psi^{col}(0)|^2$. Then the total probability of producing a bound state of charmonium will be proportional to

$|\Psi(0)|^2 + 8|\Psi^{col}(0)|^2$ (as a matter of fact, in Refs./1,2/ it was assumed that $\Psi^{col}(0) = \Psi(0)$).

The decay $b \to \Psi + s$ occurs at the distances much shorter than the sizes of the confinement region. For this reason, the interaction between the light antiquark composing the B-meson and the remaining participants of the process during the production time can be neglected.

Thus the investigation of the process at its first stage can be limited to the level of free heavy quarks. The direct calculation of the decay width of the b-quark with production of Ψ-meson, or η_c-meson (see Fig.1) gives

$$\Gamma_\Psi = A p F_\Psi \quad , \quad \Gamma_\eta = A p F_\eta \tag{1}$$

where

$$A = \frac{8}{\pi} a_{c\bar{c}s} G^2 \Psi_0^2 m_c^2 , \quad \varepsilon = \frac{m_b^2 + 4m_c^2 - m_s^2}{2m_b} ,$$

$$p = \sqrt{\varepsilon^2 - m_\Psi^2}, \quad F_\Psi = \varepsilon^2 - 6\frac{m_c^2}{m_b}\varepsilon + 2m_c^2, \quad F_\eta = \varepsilon^2 - 2\frac{m_c^2}{m_b}\varepsilon - 2m_c^2 \tag{2}$$

$$\Psi_0 = \int \frac{d^4q}{(2\pi)^4} \frac{\chi(q)}{\left[\left(\frac{p}{2}+q\right)^2 - m_c^2\right]\left[\left(\frac{p}{2}-q\right)^2 - m_c^2\right]}$$

Here $a_{c\bar{c}s}$ is the mixing angle function corresponding to the channel $b \to c\bar{c}s$, ε is the energy of Ψ in the rest frame of the B-meson, $\chi(q)$ is the Bethe-Salpeter amplitude of the Ψ-meson. Alongside with the states considered in (1) only the $^3P_1$ and $^3D_1$ states of charmonium could be produced in the used approximation and $\Gamma_{^3P_1} \simeq \Gamma_{^3D_1} \approx \Gamma_\Psi$. But the $^3P_1$ state doesn't decay into $\mu^+\mu^-$ (e^+e^-) or $\gamma\gamma$ and for the $^3D_1$ state the branching ratio for $\mu^+\mu^-$ decay is very small. The quantity Ψ_0 is determined from the decay $\Psi \to e^+e^-$:

$$\Gamma_{\Psi \to e^+e^-} = 48\pi\alpha^2 Q_c^2 m_\Psi \Psi_0^2 , \quad Q_c = \frac{2}{3} \tag{3}$$

One can calculate the total width of the decay of B-meson under the usual assumption that the transition of quarks into hadrons does not change the total probability of the process. It is equal to (see Appendix and Table)

$$\Gamma = \frac{G^2 m_B^5}{192\pi^3} \sum_{i=1}^{14} a_i F_i c_i \tag{4}$$

Here F_i is the suppression factor of the i-th channel with respect to the phase volume in comparison with the decay into massless particles, a_i the combination of mixing angles, $c_i = 1$ for lepton channels, $c_i = 3$ for hadron channels. For branching ratios $B_{\Psi,\eta}$ from Eqs.(1) and (3) we have

$$B_\Psi = \beta\lambda(1-\lambda)^2(1+2\lambda)\mathcal{D}, \quad B_\eta = \beta\lambda(1-\lambda)^2\mathcal{D} \tag{5}$$

where

$$\beta = \frac{9\pi}{4}\frac{\Gamma_{\Psi \to e^+e^-}}{m_\Psi \alpha^2}, \quad \lambda = \left(\frac{m_\Psi}{m_b}\right)^2, \quad \mathcal{D} = \frac{a_{c\bar{c}s}}{\sum_i a_i F_i c_i} \tag{6}$$

Taking into account the fact that the mixing angles are small and keeping the leading terms of expansion, we have

$$\mathcal{D} = \frac{0{,}17}{1 + 1{,}3\, s_1^2 \frac{s_3^2}{(s_2+s_3)^2} + 0{,}8\, s_1^2 + 0{,}6\,(s_2 - s_3)^2} \tag{7}$$

We shall suppose that there is no strong compensation in the sum $s_2 + s_3$, so that $|s_2 + s_3| \gtrsim s_3$. Since for the Cabibbo angle $s_1^2 \simeq \frac{1}{15}$, the denotator can not significantly differ from unity. Therefore, the quantity $\mathcal{D}$ actually does not depend on unknown mixing angles. Assuming $\mathcal{D} = 0.17$ and $\Psi^{col}(0) = \Psi(0)$, we have the values $B_{\Psi,\eta}$ suitable for orientation: $B_\psi \approx 5\%$ and $B_2 \approx 3\%$.

If there exists a resonance-generator $B\bar{B}$ (the analog of $\psi''(3770)$ for c-quarks), then under the assumption that $\Delta R \sim 0.4$ for this resonance we have $\sigma(e^+e^- \to B\bar{B} \to \underset{\underset{\mu^+\mu^-}{\longrightarrow}}{\psi + X}) \sim 1$ picobarn.

Fritzsch /2/ presents the arguments in favour of the fact that the main exclusive channel of the B-meson decay with production of ψ is $\psi K\pi$. It is explained by the fact that in the case of neglecting the motion inside the B-meson, the invariant mass of the system $s\bar{u}$ (or $s\bar{d}$) is $m_{s\bar{u}} \sim 1.1$ GeV. Similarly, for the B_s-meson decay we have $m_{s\bar{s}} \sim 1.4$ GeV, so that the main exclusive channel is a $\psi K\bar{K}$ (the mass of the system $K\bar{K}$ is larger than that of the ϕ-meson).

As to the kinematics of the process, when the motion inside the B-meson is neglected, in its rest frame, the ψ-meson and s-quark fly away in opposite directions with momentum $p \approx 1.5$ GeV/c and in this case the angular distribution is isotropic and the light antiquark (the observer) remains resting. For the B_s-meson the $\bar{s}$-quark is in rest. In transition to hadrons the transverse momentum of the catched up $q\bar{q}$ pair is not higher than μ. Then the collinearity of the decay is not disturbed with an accuracy of up to the terms $\sim \frac{\mu}{p}$, the π-meson being much slower than the K-meson. Likewise, for the B_s-meson, it is the $\bar{K}$-meson that is slow.

With no doubt, of interest is the polarization properties of the produced ψ-meson. It is a partially polarized meson with the density matrix

$$\rho^{\mu\nu} \sim g_\perp^{\mu\nu} + \frac{1}{\lambda} \ell^\mu \ell^\nu + i\varepsilon^{\alpha\beta\mu\nu} n_\alpha \ell_\beta \tag{8}$$

where $n^\mu = p^\mu_\psi / m_\psi$ (the unit vector over the momentum of ψ), ℓ^μ is the unit vector along the decay axis: $\ell^\mu = \frac{n^\mu(nk) - k^\mu}{|n^\nu(nk) - k^\nu|}$ (see Fig.1); $g_\perp^{\mu\nu} = n^\mu n^\nu - \ell^\mu \ell^\nu - g^{\mu\nu}$ is the projector onto the plane which is orthogonal to the decay plane. It is follows from Eq.(8) that the helicity of the ψ-meson is -1 with probability $\frac{2\lambda}{2\lambda+1}$ and its helicity is 0 with probability $\frac{1}{2\lambda+1}$. The appearance of the circular polarization of ψ is a consequence of the parity violation in the weak decay of B. The polarization state of the ψ-meson can be studied, basing upon the angular distribution of $\mu^+\mu^-$ pairs relatively to the direction of motion of ψ. This angular distribution is of the form

$$1 - \frac{1-\lambda}{1+\lambda} \cos^2 \vartheta \tag{9}$$

where ϑ is the angle between the direction of motion ψ and momentum of μ in the ψ rest frame.

To observe the effects of parity violation, it is necessary to measure the polarization of one of the produced muons. This polarization is longitudinal and its degree* is

$$\zeta = - \frac{2\lambda \cos\vartheta}{1+\lambda - (1-\lambda)\cos^2\vartheta} \tag{10}$$

Thus, the study of the polarization effect in the ψ-meson decay is an important instrument for studying the weak current $b \to c$.

Our analysis is mainly devoted to the colour neutral state of the $c\bar{c}$ pair. However, in the case when the quark helicity

---

* At $\lambda \to 0$ the helicity of ψ would be equal to 0 and the P-odd effects would disappear. It is due to the fact that c and $\bar{c}$ would fly out in parallel with opposite helicities.

is not changed under the soft colour neutralization, the results obtained hold.

We would like to present a few remarks.

1. In addition to ψ and η_c, the radially-excited S-wave states can also be produced. In particular, $B_{\psi'} \sim 0.4\, B_{\psi}$. About a half of the ψ'-mesons decays in the channel $\psi' \to \pi\pi\psi$ and the full S-wave dominates here. Then the polarization of the secondary ψ coincides with the polarization of ψ', which is also described by the formula (8).

2. If one uses the mechanism described here for the qualitative description of the $\mathcal{D}$-meson decay reaction $\mathcal{D} \to \varphi + X$, then $B_{\mathcal{D} \to \varphi + X} \simeq (0.3 \div 1.0)\%$. In this case, the φ-meson density matrix is given by the formula (8) with $\lambda = \left(\frac{m_\varphi}{m_c}\right)^2$ and the angular distribution of the K-meson in the φ rest frame will be of the form $1 + \frac{1-\lambda}{\lambda} \cos^2 \vartheta$.

3. Gluon corrections have to be taken into account. The main logarithmic corrections to the weak vertex are known for the time being. With these corrections taken into account, we have

$$|\psi(0)|^2 + 2|\psi^{col}(0)|^2 \to (2f_+ - f_-)^2 |\psi(0)|^2 + \left(\frac{f_+ + f_-}{2}\right)^2 2|\psi^{col}(0)|^2 \quad (11)$$

where

$$f_+ = \left(\frac{\alpha_s(m_W^2)}{\alpha_s(m_t^2)}\right)^{\frac{6}{21}} \left(\frac{\alpha_s(m_t^2)}{\alpha_s(m_b^2)}\right)^{\frac{6}{23}}, \quad f_- = \frac{1}{f_+^2} \quad (12)$$

If $\alpha_s(m_c^2) = 0.2$, $m_W = 79$ GeV, $m_b = 5$ GeV, $m_t = 20$ GeV (the dependence on m_t is very weak), then $f_+ = 0.90$, $f_- = 1.24$ and $(2f_+ - f_-)^2 = 0.31$, $\left(\frac{f_+ + f_-}{2}\right)^2 = 1.14$. The corrections for production of a colourless state of $c\bar{c}$ were discussed in /5/. It should be noted that the corrections considered here are only a part of the total gluon corrections.

APPENDIX

For the weak decay of a heavy quark $1 \to 2+3+4$ (see Fig.1), when all the final particles have nonvanishing mass, one should take into account the phase space suppression factor which is determined as

$$F = \frac{\Gamma_{m_1 \to m_2 m_3 m_4}}{\Gamma_{m_1 \to 000}}$$

where m_2, m_3, m_4 are the masses of the particles. The explicit form of the factor F is

$$F = 2 \int_{(m_3+m_4)^2}^{(m_1-m_2)^2} \Big\{ -2\omega + m_1^2 + m_2^2 + m_3^2 + m_4^2 + \frac{1}{\omega}\left[(m_1^2 - m_2^2)^2 + (m_3^2 - m_4^2)^2 - 2(m_1^2 + m_2^2)(m_3^2 + m_4^2)\right] + \frac{1}{\omega^2}\left[(m_1^2 + m_2^2)(m_3^2 - m_4^2)^2 + (m_3^2 + m_4^2)(m_1^2 - m_2^2)^2\right] - \frac{2}{\omega^3}(m_1^2 - m_2^2)^2 (m_3^2 - m_4^2)^2 \Big\} \times$$
$$\times \sqrt{\left[(m_1+m_2)^2 - \omega\right]\left[(m_1-m_2)^2 - \omega\right]\left[\omega - (m_3+m_4)^2\right]\left[\omega - (m_3-m_4)^2\right]}\, d\omega$$

Table

Channel	C	a	F
$ce\bar{\nu}$	1	$\left.\begin{matrix} \\ \\ \end{matrix}\right\}\ \lvert c_1 c_2 s_3 + s_2 c_3 e^{i\delta}\rvert^2$	0.63
$c\mu\bar{\nu}$	1		0.63
$c\tau\bar{\nu}$	1		0.18
$c\bar{c}s$	3	$\lvert c_1 c_2 s_3 + s_2 c_3 e^{i\delta}\rvert^2 \lvert c_1 c_2 c_3 - s_2 s_3 e^{i\delta}\rvert^2$	0.35
$c\bar{c}d$	3	$\lvert c_1 c_2 s_3 + s_2 c_3 e^{i\delta}\rvert^2\, s_1^2 c_2^2$	0.35
$c\bar{u}d$	3	$\lvert c_1 c_2 s_3 + s_2 c_3 e^{i\delta}\rvert^2\, c_1^2$	0.63
$c\bar{u}s$	3	$\lvert c_1 c_2 s_3 + s_2 c_3 e^{i\delta}\rvert^2\, s_1^2 c_3^2$	0.63
$ue\bar{\nu}$	1	$\left.\begin{matrix} \\ \\ \end{matrix}\right\}\ s_1^2 s_3^2$	1.00
$u\mu\bar{\nu}$	1		1.00
$u\tau\bar{\nu}$	1		0.39
$u\bar{c}s$	3	$s_1^2 s_3^2 \lvert c_1 c_2 c_3 - s_2 s_3 e^{i\delta}\rvert^2$	0.63
$u\bar{c}d$	3	$s_1^4 s_3^2 c_2^2$	0.63
$u\bar{u}d$	3	$s_1^2 s_3^2 c_1^2$	1.00
$u\bar{u}s$	3	$s_1^4 s_3^2 c_2^2$	1.00

Here we put m_c = 1.25 GeV and m_s = 0.15 GeV. If one takes into account the final-state interaction in the channel $b \to c\bar{c}s$, then one obtains F = 0.75 instead of F = 0.35 (free particles). The former was used for calculation of $\mathcal{D}$.

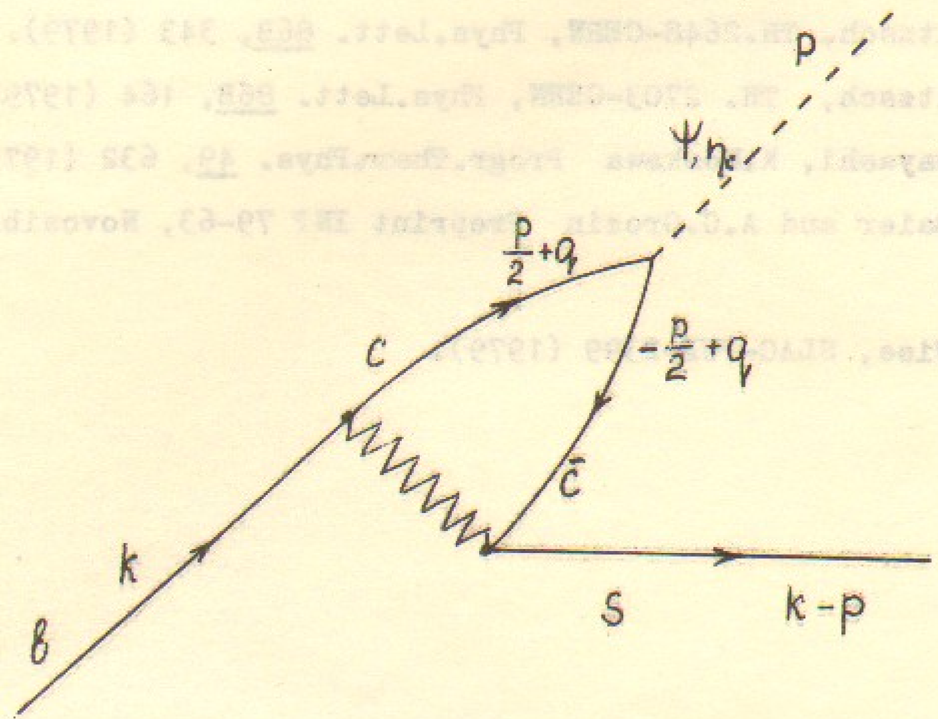

Fig.1

R e f e r e n c e s

1. H.Fritzsch, TH.2648-CERN, Phys.Lett. 86B, 343 (1979).

2. H.Fritzsch, TH. 2703-CERN, Phys.Lett. 86B, 164 (1979).

3. M.Kobayashi, K.Moskawa Progr.Theor.Phys. 49, 632 (1973).

4. V.N.Baier and A.G.Grozin Preprint INP 79-63, Novosibirsk, 1979.

5. M.B.Wise, SLAC-PUB-2399 (1979).