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GENERAL CHARACTERISTICS OF B_c-MESONS. PRODUCTION MECHANISMS AND DECAYS

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Abstract

Gershtein S.S. et al General Characteristics of B_c-Mesons. Production Mechanisms and Decay: IHEP Preprint 89-214. - Protvino, 1989. - p. 26, tables 5, figs. 16, refs.: 25.

Using Martin's potential, independent of b- and c-quark flavour, we calculate the mass spectrum of $B_c(b\bar{c})$-mesons and widths of electromagnetic transition between them. We obtain the estimates of the production cross-section at e^+e^- colliders, in hadronic and neutrino interactions. A real possibility to observe B_c-mesons at LEP (up to 500 B_c per 10^6 Z^0) and also at hadron colliders ($\sigma(B_c)/\sigma(b\bar{b}) \sim 10^{-3}$) has been pointed out. The importance of observing the annihilation decay channels of B_c-mesons: $B_c \to \tau\nu_\tau$ ($Br(B_c \to \tau\nu_\tau)=1.5 \div 2\%$), and $B_c \to \phi D_s$, $D\bar{K}$ etc, has been emphasized.

Аннотация

Герштейн С.С. и др. Общие характеристики B_c-мезонов. Механизмы рождения и распадов: Препринт ИФВЭ 89-214.- Протвино, 1989. - 26 с., 5 табл., 16 рис., библиогр.: 25.

Используя потенциал Мартина (не зависящий от аромата кварков b и c) вычислен спектр масс состояний $B_c(b\bar{c})$-мезонов и ширины электромагнитных переходов между ними. Приведены оценки рождения B_c-мезонов на e^+e^- коллайдерах, в адронных и нейтринных взаимодействиях Указано на реальную возможность наблюдения B_c-мезонов в условиях LEP (до 500 B_c на 10^6 Z^0), а также адронных коллайдерах ($\sigma(B_c)/\sigma(b\bar{b}) \sim 10^{-3}$). Обращено внимание на важное значение наблюдения аннигиляционных каналов распада B_c-мезонов: $B_c \to \tau\nu_\tau$ ($Br(B_c \to \tau\nu_\tau)=1.5 \div 2\%$) а также $B_c \to \phi D_s$, DK и др.

1. INTRODUCTION

Presently, a great progress has been reached in the description of the properties (mass spectrum, decay width) of hadrons with heavy quarks and also of their production mechanisms. The best agreement with experiment has been achieved in describing, within the frames of the potential models, the properties of heavy onia $(Q\bar{Q})$: J/ψ- and Υ-families[1]. In the potential model the whole flavour-dependence of Q-quarks is determined by their mass and the potential parameters fitting while describing the masses and widths of $(Q\bar{Q})$-families. Therefore, the consideration of the mesons, consisting of quarks of different flavours $(b\bar{c}$, $b\bar{t}$, $c\bar{t}, \ldots)$ will be quite natural in this case. Very interesting are the predictions for the lightest family of B_c $(b\bar{c}$ or $\bar{b}c)$-mesons because the B_c holds the "intermediate" position between J/ψ- and Υ-families[2-5]. Consequently, the accuracy in predicting the B_c-meson properties is actually determined by that of describing J/ψ- and Υ-families, in which no need to introduce new parameters arises. Therefore the observation and study of the properties of the B_c-mesons is a very good test to verify of the applicability of the potential approach for the description of heavy onia.

In contrast with the J/ψ- and Υ-families, B_c-mesons have no annihilation decay channels (of the $Q\bar{Q} \to gg(ggg) \to$ hadrons type), and after emitting γ-quanta or light mesons they transform into a $B_c(0^-)$-meson which, in its turn, decays weakly. A specific feature of the B_c decays is the precence of either usual $B(b\bar{u}$, $b\bar{d}$, $b\bar{s})$-mesons or D-mesons[6], as well as of J/ψ, η_c, χ_c mesons[7] among the decay products. An interesting thing about these decay channels is that the probability of the $B_c \to J/\psi X$ decay may be large, $\leqslant 15\%$. Such a decay may be a trigger in the search for B_c-mesons[7,8].

The description of B_c-meson production in various interactions also of some interest. The most definite estimates have been obtained in e^+e^--annihilation[9], in νN-collisions[10] and in the $B_c B_c$ pair production in hadron collisions[11]. The minimal number of B_c-meson production events is expected in ν (or $\bar{\nu}$) beams. For example, for the generally accepted number of $\nu(\bar{\nu})N$-collisions, $\sim 10^6(10^7)$ per year, only a small number of B_c-mesons, $\leqslant 10(100)$, will be produced. The largest number of these events is expected to occure in hadron-hadron interactions because $(\sigma(B_c)/\sigma(b\bar{b}) \sim 10^{-3})$ but the separation of B_c's againts the background of usual hadrons must be a problem hardly manageable. Therefore the search for B_c-mesons in e^+e^--annihilation will be the most realistic. For example, one may expect up to 500 B_c's produced in the of Z^o-bosons peak for the total statistics of $\sim 10^6$ Z^o.

The paper is organized as follows. Section 2 is concerned with spectroscopy of B_c-mesons; Section 3 presents the calculation of the widths of radiation transitions in B_c-family; Section 4 considers the weak decays of B_c-mesons; the total and differential cross-sections for the B_c-meson production in different interactions are given in Section 5; the results obtained are summarised in Section 6.

2. B_c-MESON SPECTROSCOPY

As noted above, a meson consisting of quarks b and $\bar{c}$(or $\bar{b}$ and c), takes an "intermediate" state between J/ψ and Υ. Consequently, it is natural to use the potential model for describing B_c-mesons. The mass spectrum of $(b\bar{c})$-system was calculated in[2,3,5], where the quark-type-dependent potentials were used. However, these potentials demand the extrapolation of their parameters into the $(b\bar{c})$ family region, which introduces uncertainties into theoretical predictions. So, it is preferable to use a potential independent of the quark type. These calculations were made in our work[4], in which we used Martin's potential[12]:

$$V(r) = -8.064 + 6.869\, r^{0.1}, \qquad (1)$$

where all parameters are in GeV. The values of c- and b-quark masses were put to be

$$m_c = 1.8 \text{ GeV}, \; m_b = 5.174 \text{ GeV}, \qquad (2)$$

respectively[12].

Solving the Schrodinger equation with potential (1) and parameters (2), we obtain the B_c mass spectrum and the characteristics of the wave functions $\Phi(0)$ and $\Phi'(0)$ given in Tables 1 and 2, respectively[4].

Table 1. The masses of Bc-mesons calculated using different potentials (* are the level masses, calculated without relativistic corrections).

State	[4]	[2]	[3]	[5]
1 S *	6.301	6.315	-	-
2 S *	6.893	7.009	-	-
3 S *	7.237	-	-	-
1 P *	6.728	6.735	-	-
2 P *	7.122	-	-	-
3 P *	7.395	-	-	-
1 D *	7.008	7.145	-	7.021
2 D *	7.308	-	-	-
3 D *	7.532	-	-	-
1^1S_0	6.246	6.243	6.27	6.319
2^1S_0	6.863	6.969	6.85	6.884
1^3S_1	6.329	6.339	6.34	6.370
2^3S_1	6.903	7.022	6.89	6.907
1^1P_0	6.645	6.697	-	-
1^1P_1	6.682	6.719	-	-
1^1P_1	6.741	6.740	-	6.76
1^3P_1	6.760	6.750	6.77	6.784

Table 2. Wave functions characteristics $\Phi(0)$ and $\Phi'(0)$ obtained from the Schrodinger equation using potential (1).

nS	$\Phi(0)$, $GeV^{3/2}$	nP	$\Phi'(0)$, $GeV^{5/2}$
1S	0.369	1P	0.157
2S	0.275	2P	0.158

Note, that using of $\Phi_{1S}(0)$ (see Table 2), one can calculate the constant f_{B_c} of $B_c(0^-)$-meson weak decay[4]

$$f_{B_c} = \sqrt{6/M}\,\Phi(0) = 360\ \text{MeV}, \qquad (3)$$

which is in agreement with estimates obtained by other methods, for instance, that in[13], where f_{B_c}=350 MeV. Basically, the constant f_{B_c} and, consequently, $\Phi(0)$ can be measured in the decay $B_c \to \tau\nu_\tau$ (see Section 4).

To take into account spin-orbital and spin-spin interactions leading to the splitting of nL-levels (n is the main quantum number, L is the orbital momentum) one has to introduce, following the results from[2], the supplement to potential (1) in the form

$$V_{SD}(r) = \left(\frac{\mathbf{LS}_1}{2m_1^2} + \frac{\mathbf{LS}_2}{2m_2^2}\right)\frac{1}{r}\frac{dV}{dr} + \frac{4}{3}\alpha_s\frac{1}{m_1m_2}\frac{\mathbf{LS}}{r^3} + \frac{4}{3}\alpha_s\frac{2}{3m_1m_2}\mathbf{S}_1\mathbf{S}_2 4\pi\delta(\mathbf{r}) +$$

$$+ \frac{4}{3}\alpha_s\frac{1}{m_1m_2}\left(3(\mathbf{S}_1\mathbf{n})(\mathbf{S}_2\mathbf{n}) - \mathbf{S}_1\mathbf{S}_2\right)\frac{1}{r^3},\quad \mathbf{n} = \mathbf{r}/r. \qquad (4)$$

Here $V(r)$ is the quark-confining phenomenological potential (1); the first term takes into account the relativistic corrections to potential $V(r)$; the second, third and fourth terms are the perturbation theory corrections arising when taking into account one-gluon exchange between quarks b and $\bar{c}$, α_s is an effective gluon-quark coupling constant in $(b\bar{c})$.

A detailed discussion of these calculations can be found in[2,4]. The final results are shown in Table 1 and Fig.1. As one can see (from Table 1 and Fig.1) there is a larger number of levels (~15), lying below the threshold of B- and D-mesons production.

In Table 1 we also show the results of $(b\bar{c})$ mass spectrum calculations, using other potentials[2,3,5]. As one can see from Table 1, the calculated mass spectra are close enough to each other. This is naturally explained by the fact that all potentials used, describe fairly well J/ψ- and Υ-families, and B_c-family occupies an "intermediate" state between them. Note, however, that predictions for the states lying a little above the threshold of the decay into $B^+D^o(B^oD^-)$ mesons, can, in principle, tested in experiment quite reliably[4]. For instance, the state 2^+ (see Fig.1) has the mass 7.143 GeV, which is 1-2 MeV exceeding the threshold (M_{th}=7.142 GeV). So, the state 2^+ will decay into low-lying B_c-states with γ emission. But, a small increased the mass of 2^+ will cause the sharp increase of its probability to decay into the $B\bar{D}$-channel (see Section 3). The same prediction follows for the states from the 1D level.

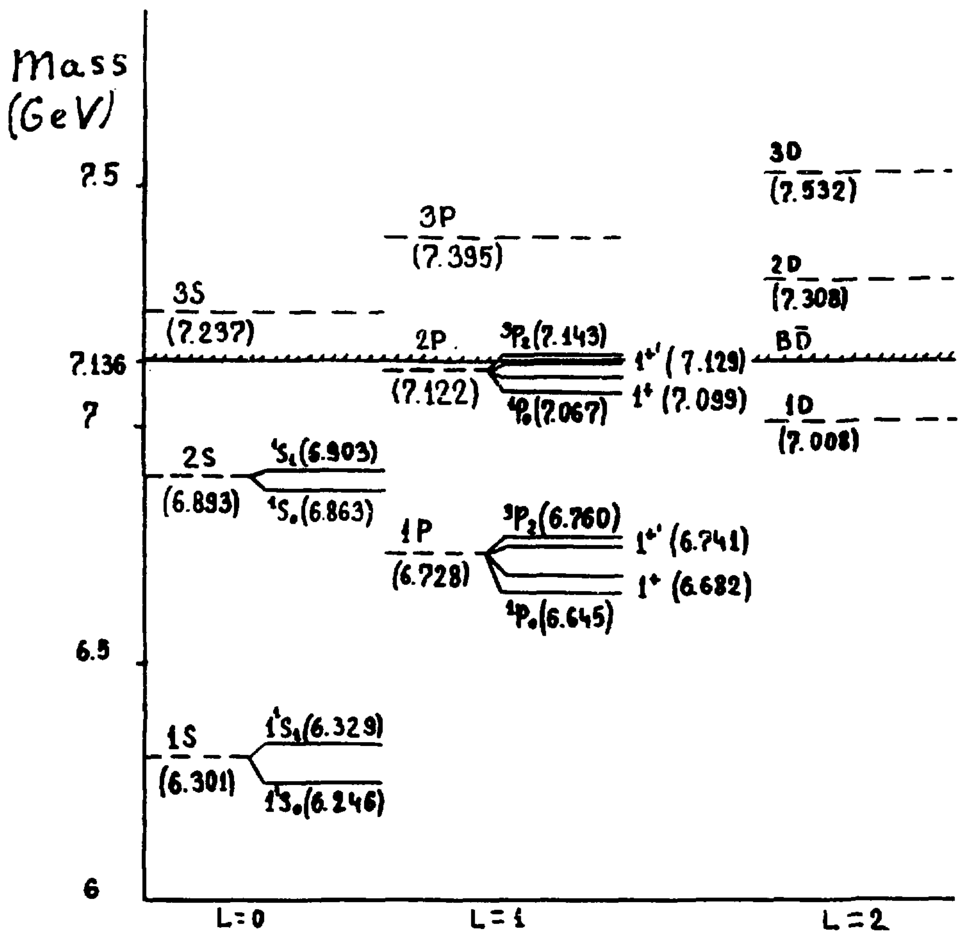

Fig. 1. B_c-meson state mass spectrum.

3. ELECTROMAGNETIC TRANSITIONS IN B_c FAMILY

As differed from "symmetrical" onia ($J/\psi(c\bar{c})$ and $\Upsilon(b\bar{b})$), B_c mesons have no annihilation decay channels due to QCD and electromagnetic interactions. So mesons lying below B and $\bar{D}$-mesons production threshold will decay into $0^-(1S)$-state with emission of γ-quanta or light mesons.

Formulae for the radiation transitions have the form[4]

$$\Gamma(nP \to n^3S + \gamma) = \frac{4}{9}\,\alpha Q^2_{eff}\omega^3 I^2 q, \tag{5}$$

$$\Gamma(n^3S_1 \to (n-1)P_J + \gamma) = \frac{4}{27}\,\alpha Q^2_{eff}\omega^3 I^2 q(2J+1),$$

where ω is photon energy, α is a fine structure constant, q is the probability that spin is S=1 in the state nP_J, for four states 1P with the growth of their masses we have q=1; 0.5; 0.9; 1. The quantity I is expressed through radial wave functions

$$I = |\int R_p(r)R_s(r)r^3dr|$$

and for the transition 2S → 1P and 1P → 1S we have

$$I(2S,\ 1P) = 2.02\ \mathrm{GeV}^{-2},\quad I(1P,\ 1S) = 1.56\ \mathrm{GeV}^{-2},$$

$$Q_{eff} = (m_1Q_2 - m_2Q_1)/(m_1 + m_2),$$

where m_i and Q_i are mass and electrical charge of the i-th quark. For B_c system with parameters from (2) one obtains Q_{eff}=0.41. For dipole magnetic transitions we have[14]

$$\Gamma(n^3S_1 \to n^1S_0 + \gamma) = \frac{16}{3}\,\mu_{eff}\omega^3, \tag{6}$$

where we consider the space wave functions of $^3S_1$ and $^1S_0$ states to be identicaly, and

$$\mu_{eff} = 1/2(e/2m_1m_2)(Q_1m_2 - Q_2m_1).$$

The calculation results of the radiation transitions[4] are given in Table 3.

Table 3. Radiation transition width in B_c family (ω_γ is the γ quantum energy).

P_J	$1P_J \to 1S_J\gamma$		$2S \to 1P_J\gamma$	
	ω_γ, GeV	Γ, keV	ω_γ, GeV	Γ, keV
2^+	0.441	113.0	0.143	11.0
$1^{+'}$	0.413	93.0	0.161	2.3
1^+	0.363	63.0	0.221	19.3
0^+	0.326	46.0	0.258	12.6

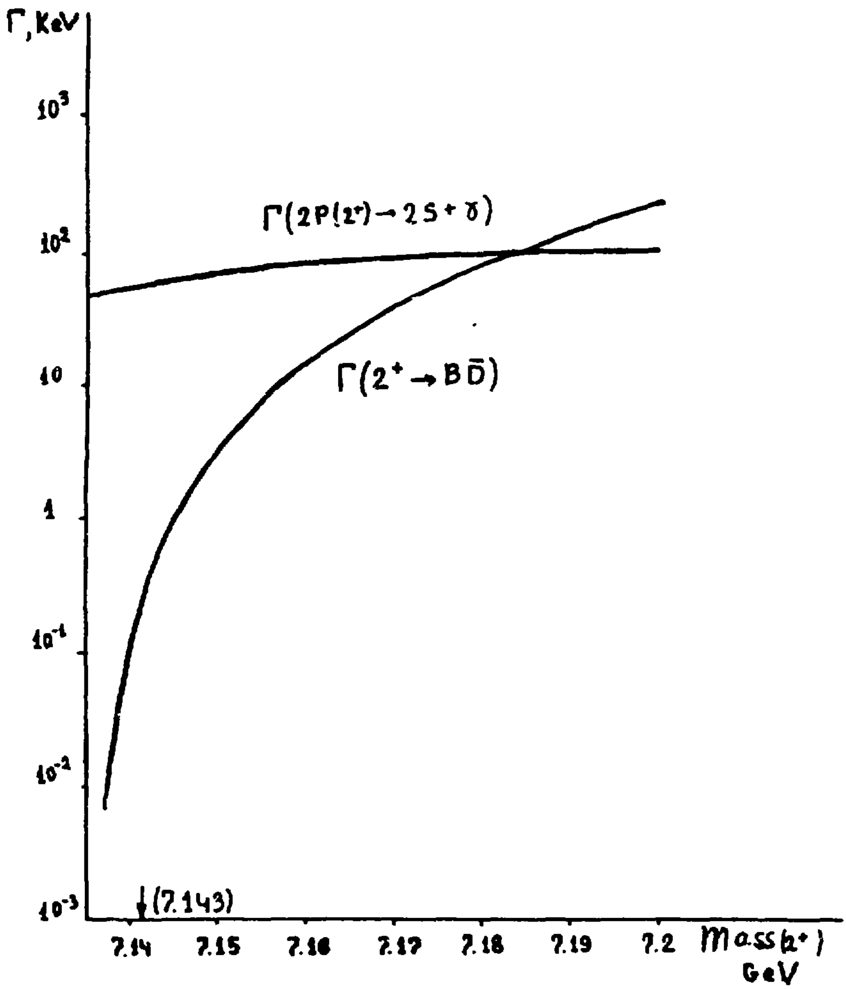

Fig. 2. Behaviour of width $\Gamma(2P(2^+) \to 2S+\gamma)$ and $\Gamma(2^+\to B\bar{D})$ versus 2^3P_2-state mass.

Note, that for $2P(2^+)$-state lying below the threshold of B and D-mesons production the width of electromagnetic transition into 2S-state is equal to $\Gamma(2^3P_2 \to 2^3S_1+\gamma)$=50 keV, which appears to be much larger than the decay width into mesons ($\Gamma(2^3P_2 \to BD)$= 0.6 keV[4]). However, as was noted in Section 2, ever small increase of 2^+ mass leads to a sharp increase of the width of $2^+ \to B\bar{D}$ (see Fig.2).

So, knowing the potential, describing J/ψ- and Υ-families, we predict the mass spectrum and widths of transition of $B_c(b\bar{c})$-family, without introducing new parameters. And the accuracy of our predictions is the same as for J/ψ- and Υ-families. Therefore, the observation of B_c-mesons and study of their properties is a very good test of the applicability of the potential approach to the description of heavy onia.

4. WEAK DECAYS OF B_c-MESONS

The total width of $B_c(0^-)$-meson is determined by decays of b(c spectator)-quark, c(b spectator)-quark and "annihilation" channels: $B_c \to W \to l\nu$ (cs, ud,...) (see Fig.3), i.e.,

$$\Gamma(B_c \to X) = \Gamma(b \to X) + \Gamma(c \to X) + \Gamma(\text{annihil}).$$

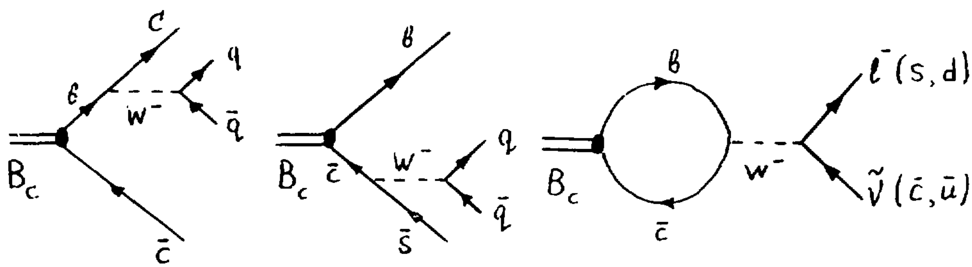

Fig. 3. Diagrams describing of weak decay $B_c \to$ anything.

The formulae for the widths of b and c quark decays are well known (see, for example,[6,15]). For the case of the annihilation channel its width is equal[17] to

$$\Gamma(B_c \to ab) = C \frac{G_F^2}{8\pi} |V_{bc}|^2 f_{B_c}^2 M_{B_c} m^2 (1 - m^2/M_{B_c}^2)^2, \quad (7)$$

where $ab=(l\nu)$ or $(q_1\bar{q}_2)$; C=1(3) for leptons (quarks); m is the mass of massive fermion (when the second fermion is massless); V_{bc} is a KM matrix element/18/.

In Table 4 the numerical values of respective contributions to the total width of B_c-meson for different masses of b- and c-quarks are shown.

Table 4. Width of the B_c-meson weak decays, the masses are given in GeV, width in $10^{10}\ s^{-1}$.

m_c	m_b	$\Gamma_{\tau\nu}$	Γ_{cs}	Γ_b	Γ_c	Γ_{tot}
1.4	4.6	4.1	7.5	124.2	115.8	252.0
1.7	4.9	4.1	11.1	161.1	311.9	489.0

Since B_c-meson decays are determined primarily by b- and c-quark decays, the following two groups will be singled out among the final states:

$B_c \to b\bar{s}q\bar{q}$ (c decay) ~50%

and

$B_c \to c\bar{c}q\bar{q}$ (b decay) ~50%.

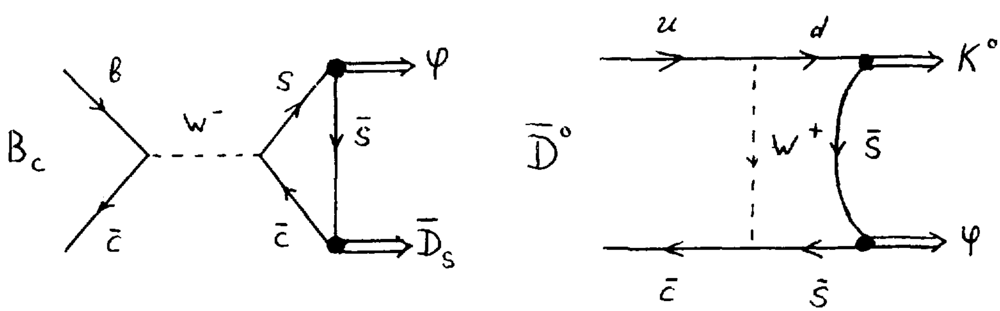

Fig. 4. Diagrams describing of weak "annihilation" decays of B_c and $\bar{D}^0$-mesons.

The last channel is very interesting, since a $(c\bar{c})$-pair of charmed quarks can produce a bound state of the type J/ψ, η_c, χ_c,... (see Fig. 4).

In[6-8] the partial widths of various channels of B_c-decay were calculated in the frame of the spectator model. In particular, the $B_c \to \psi X$ ($X=l\nu$, ρ, π, all)[7,8] decay was studied in detail. The results of calculations are presented in Table 5. As one can see, the probability of $B_c \to \psi X$ decay, $\leq 15\%$, is larger than the one for the decay of usual beauty B-mesons ($\sim 1\%$[18]). This allows to use J/ψ as a trigger to search for B_c-meson production (see below).

Table 5. Partial width of some weak decays of B_c-mesons (the width is in $10^{10}\ s^{-1}$).

$B_c \to$	Γ[7,8]	Γ[6]
$\to \psi e\nu$	$2\div13$	$0.3\div4.1$
$\to \psi\tau\nu$	$1.5\div5$	-
$\to \psi\bar{c}s$	$2\div8$	-
$\to \psi\pi^+$	$0.45\div3$	$0.005\div0.07$
$\to \psi\rho^+$	$1.8\div5$	$0.07\div1.0$
$\to \psi X$	$8\div33$	$0.5\div7.0$

Among the weak decays of B_c-mesons it is worth to note the importance of "annihilation" decay channels (see Fig.4). The most reliable is the prediction for $B_c \to \tau\nu_\tau$ decay, which equals $\sim 2\%$ (see Table 4). It is this decay in which one can measure directly the f_{B_c}, or $\psi(0)$, whose value is predicted in the potential model (see (3)). The hadronic channels of annihilation decays can make up about $3\div5\%$. The final states such as $D_s\phi$ and DK are typical among them. The estimate of their probabilities can be obtained from the experimentally measured probability for the $D^0 \to \phi\bar{K}^0$ decay (see Fig.4)

$$\frac{\Gamma(B_c \to D_s\phi)}{\Gamma(B_c \to \bar{c}s)} \simeq \frac{\Gamma(D^0 \to \bar{K}^0\phi)}{\Gamma(D^0 \to s\bar{d})} \simeq 0.5 \text{ with } m_s \simeq 0.5 \text{ GeV}. \qquad (8)$$

So, we obtain $Br(B_c \to D_s\phi) \leq (1.5\div2)\%$.

5. B_c-MESON PRODUCTION

The cross-section of the B_c-meson production will obviously be suppressed considerably in comparison with that of beauty (and charm) hadron production. This small cross-section embarrasses their search and study against usual hadronic background. We propose a few triggers for B_c-meson production[8]:

a) hard γ-quanta ($E_\gamma \sim 100$ MeV in the B_c rest frame), weak decay vertex and a noticeable partile track;

b) J/ψ-particle inclusive production with high p_t due to $B_c \to J/\psi X$ decay;

c) J/ψ-particle production with high transverse momentum in respect to the b-quark jet.

The set of such triggers is explained by the following reasonings. B_c-particles have no annihilation channels of decay into gluons, so, as mentioned above, all states lying below the threshold of the decay into B- and D-mesons will transit into the lowest states with emission of γ-quanta or light mesons (see Section 3). Hence, the $b\bar{c}$-system will transit into the 0^--state, which will weakly decay, i.e., with a noticeable decay pass of charged B_c-meson. This, the detection of a hard photon (as a result of $B_c(2S) \to \gamma B_c(1S) \to \gamma\gamma\gamma$...decays) and the vertex of weak decay can serve an indication of B_c-meson production.

One of the characteristic properties of $B_c(0^-)$ is a large decay probability $Br(B_c \to \psi X) \leqslant 15\%$ (Table 5). Therefore B_c-mesons make a large contribution into the production of J/ψ with $p_t > 5$ GeV (see below).

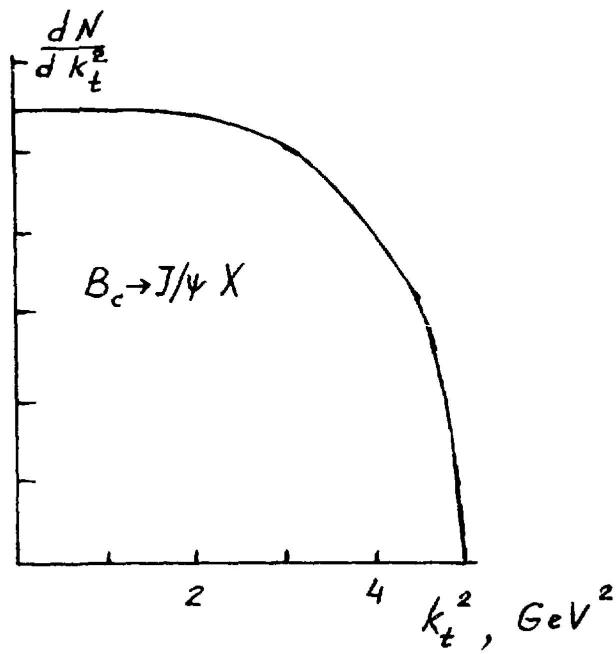

Fig. 5. The J/ψ-particle spectrum against their transverse momenta in the decay $B_c \to \psi X$.

Since B_c mass is 6.2 GeV and exceeds that of a usual B-meson (m_B=5.2 GeV), J/ψ-particles from B_c decay can have the transverse momentum k_t>1.5 GeV (Fig.5) w.r.t b-quark jet not allowed by the kinematics of usual B-meson's decay.

5.1. B_c-Meson Production in e^+e^--Annihilation

In e^+e^--annihilation, b- and c-quark production can be due to production of the $b\bar{b}(c\bar{c})$-pair with "cathing" a pair of heavy quarks from the quark sea (see Fig.6). In this case, the inclusive cross-section for $B_c(b\bar{c})$-meson production can be estimated as follows/4/:

$$\sigma(B_cX) = K(b\bar{c} \to B_c)[\lambda_b\sigma_c + \lambda_c\sigma_b], \tag{9}$$

where $K(b\bar{c}\to B_c)$ is the probability that b- and c- quarks will go into B_c-meson (we assume K=0.1); λ_q is the probability of catching a quark from the sea; $\sigma_{c(b)}$ is the cross-section for c(b)-quark production. The quantity λ_c is unknown, and only experimental limitations exist on λ_c/19/:

$$\lambda_c < 0.04. \tag{10}$$

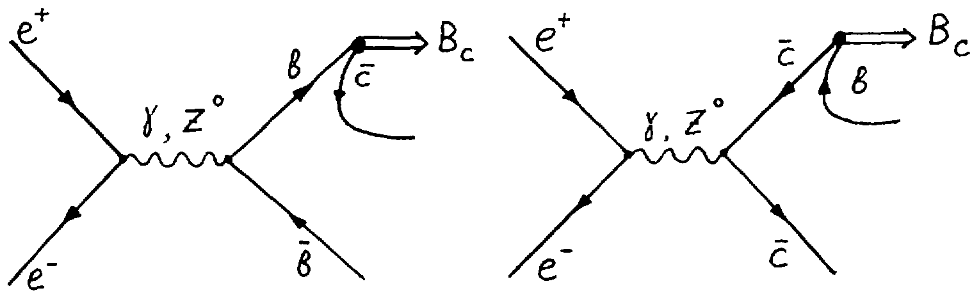

Fig. 6. Diagrams describing B_c-meson production in e^+e^--annihilation.

Assume the probability of catching a quark from the sea to be inversly proportional to a quark mass squared, then one obtains from (10)

$$\lambda_b = (m_c/m_b)^2\lambda_c < 0.004. \tag{11}$$

Putting the estimates for λ_b, λ_c and K into (9) we obtain the following limitations/4/:

$$\left.\begin{array}{l}\sigma(e^+e^- \to B_cX)/\sigma(e^+e^- \to \text{hadrons}) < 5\cdot10^{-4} \\ \sigma(e^+e^- \to B_c\bar{B}_c)/\sigma(e^+e^- \to \text{hadrons}) < 5\cdot10^{-5}\end{array}\right\}. \qquad (12)$$

The cross-section for B_c-meson production estimated within the frames of the perturbative QCD[9] yields also $\sigma_{B_c}/\sigma_h=10^{-4}$, which argees with (12). The values obtained give us the possibility of searching B_c-mesons in e^+e^- annihilation. The study of B_c in the Z^0-boson peak seems to be the most attractive, where having the statistics of $10^6$of Z^0's/year one may expect up to 500 events of B_c-meson production.

5.2. B_c-Meson Production in Hadronic Collisions

The cross-section of B_c-meson production in hadron collisions can be estimated as in the case of e^+e^--annihilation[4,8]

$$\sigma(hh \to B_cX) = K(b\bar{c} \to B_c)[\lambda_c\sigma(b\bar{b}X) + \lambda_b\sigma(c\bar{c}X)]\Big|_{M_{Q\bar{Q}} \geq 2M_{B_c}} , \qquad (13)$$

where the parameters K and λ are determined above (see (9)). The estimations of the relevant cross-sections are given in Table 6.

Table 6. The total cross-sections for B_c-meson production in pp-scattering at different energies and the secondary J/ψ-particle cross-sections from B_c decays (the J/ψ transverse momentum is p_t>5 GeV). The cross-section is given in nb, the energy - in GeV.

$\sqrt{s}$, GeV	$\sigma(b\to B_c)$	$\sigma(c\to B_c)$	$\sigma(b\to B_c\to\psi)$	$\sigma(b\to B\to\psi)$
.75	0.024	0.008	0.0008	0.02
1800	30	8.0	0.8	20
6000	160	50	4.6	100

To estimate the inclusive spectra and cross-sections for B_c-meson production in the framework of the parton model and QCD one should know the differential cross-sections for the subprocesses at the parton level: $gg\to B_c\bar{b}c$, $q\bar{q}\to B_c\bar{b}c$. Such calculations were made in[11], where the formulae for the cross-sections of the subprocesses $q\bar{q}\to B_c\bar{B}_c$ (see Fig.7) were obtained. In this work it was obtained[11], that

$$\sigma(pp \to B_c(1^-)\bar{B}_c(1^-)X) = 10\div20 \text{ pb at } \sqrt{s} = 100 \text{ GeV}.$$

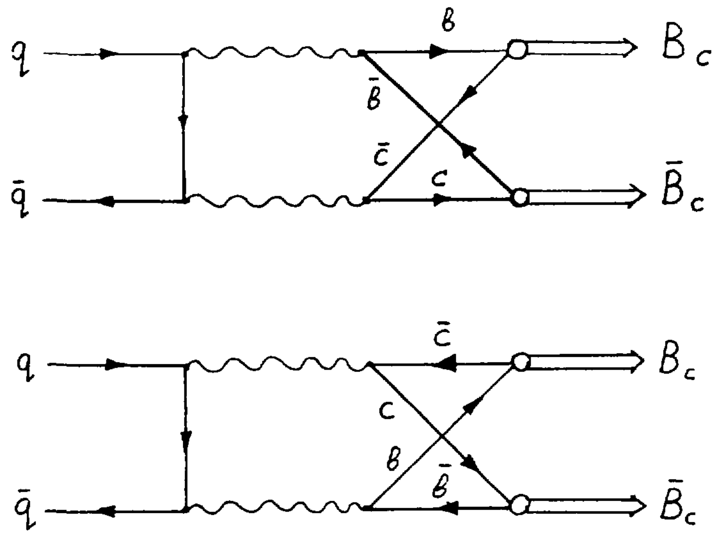

Fig. 7. Diagrams describing quark-antiquark annihiation into B_c-meson pair.

In[8] to estimate the total and differential inclusive cross-sections of B_c-meson production in pp-collisions the phenomenological model of the heavy quark fragmentation into hadrons was used. This model describes quite accurately B- and D-meson production, without the leading component caused by the interaction of heavy quarks with the valence ones from incident hadrons (see, e.g.,[20]). In such an approach, the fragmentation function of the i-th quark into meson, consisting of i- and j-quarks, has the form[8]

$$D_{i\to ij}(z) = \lambda_j K(ij \to B_c) N z^{-\alpha_i} (1-z)^{\gamma-\alpha_j},$$

where λ and K were determined in (9); α_i is the leading Regge trajectory intercept, connected with the quark of the i-type; $\gamma=1\div1.5$;

$$N = \Gamma(2 + \gamma - \alpha_i - \alpha_j)/\Gamma(1 + \gamma - \alpha_j)\Gamma(1 - \alpha_i).$$

With $\alpha_c=-(2\div2.5)$, $\alpha_b=-(8\div9)$ one obtains/8/

$$\left.\begin{aligned} D_{b\to B_c}(z) &= 6435\ \lambda_c K z^8 (1-z)^4 \\ D_{c\to B_c}(z) &= 858\ \lambda_b K z^2 (1-z)^{10} \end{aligned}\right\} \qquad (14)$$

In Fig.8 the behaviour of fragmentation functions $c\to D$, $c\to B_c$, $b\to B$, $b\to B_c$ is shown. With the help of the fragmentation functions the inclusive spectrum of B_c-meson, produced in b- and c-quark fragmentation, can be presented in the form/8,21/

$$E\frac{d^3\sigma}{d^3p} = \frac{1}{\pi}\sum\int_{\varepsilon}^{1} dx_1 \int_{\varepsilon/x_1}^{1} dx_2 L(x_1,\ x_2)\frac{d\hat{\sigma}_Q}{d\hat{t}} D_{Q\to B_c}(z)\ h_+/(h_+ - \mu^2\tau) \ , \quad (15)$$

where $(E,\ p)$ is the meson momentum; summation is carried out over the types of partons, whose interaction leads to the production of Q-quarks. The cross-section for the Q-quark production $d\hat{\sigma}/d\hat{t}$, is calculated in the QCD/22/:

$$L(x_1,\ x_2) = x_1 f(x_1) x_2 f(x_2),$$

$x_{1,2}$ are momentum fractions carried by partons from the incident hadrons h_1 and h_2. $f(x)$ is the distribution of these partons in the relevant hadrons (see Fig.9). Kinematical variables h_+, μ and τ were determined in/21/.

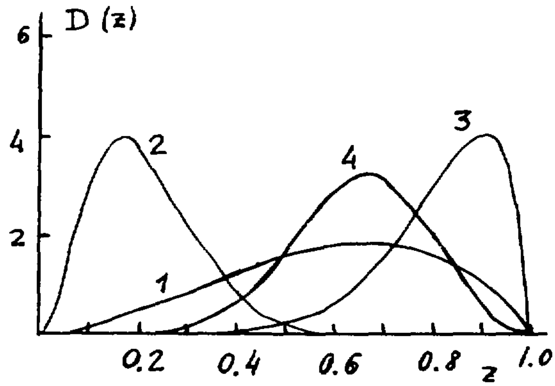

Fig.8.
The fragmentation functions D(z) for the processes: 1 - $c\to D$, 2 - $c\to B_c$, 3 - $b\to B$, 4 - $b\to B_c$.

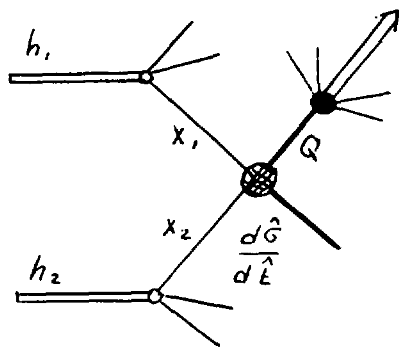

Fig.9.
The Q-quark production process in scattering of hadrons h_1 and h_2 with the following Q-quark fragmentation into meson.

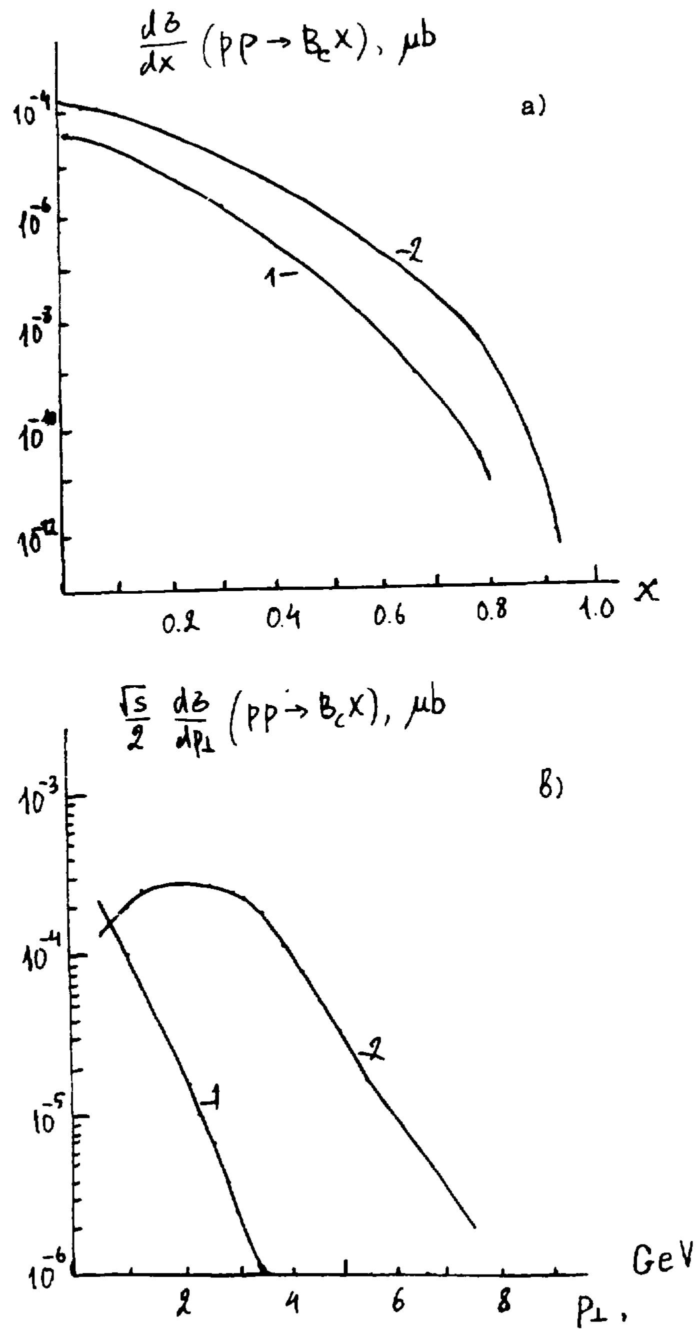

Fig. 10. The B_c-meson production spectra at $\sqrt{s}$=75 GeV; 1 - the contribution from c-quark fragmentation; 2 - the contribution from b-quark fragmentation; a) - $d\sigma/dx$, b) - $(\sqrt{s}/2)(d\sigma/dp_T)$.

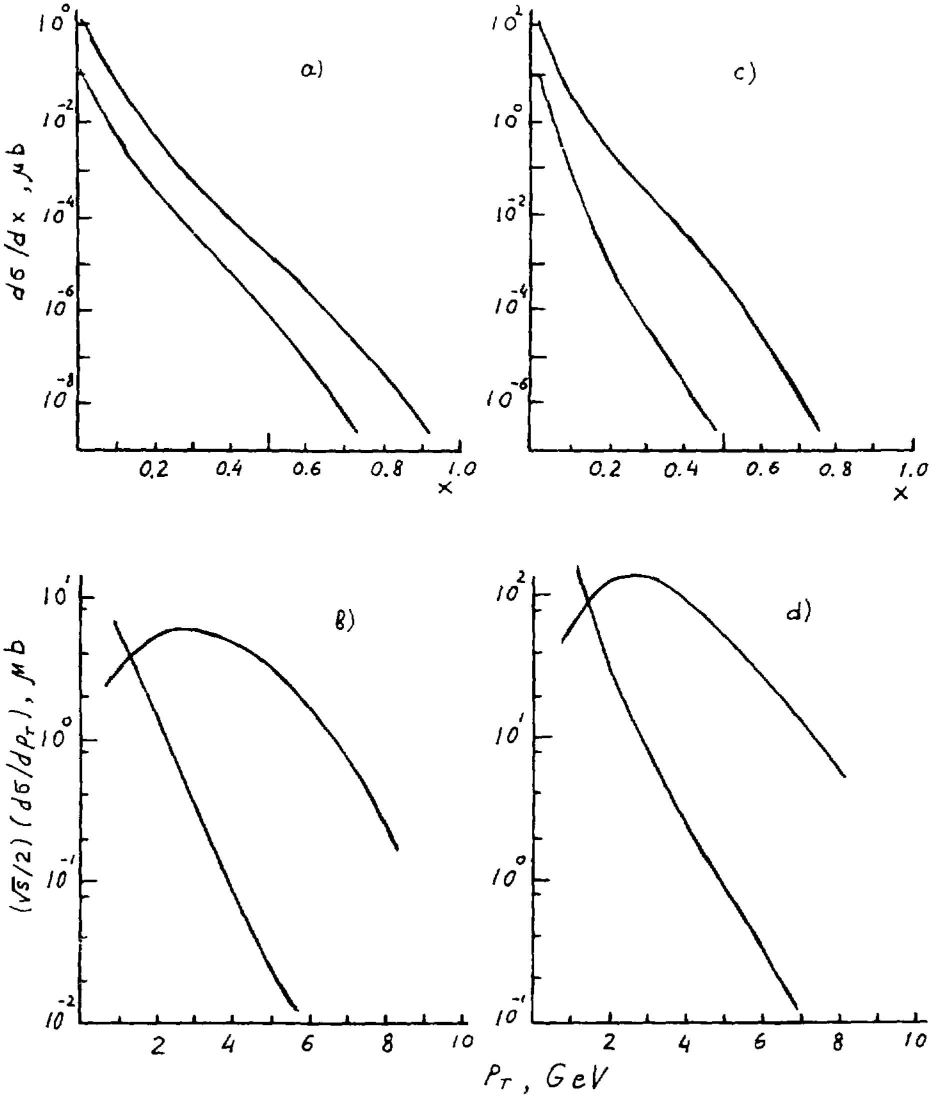

Fig. 11. The B_c-meson production spectra at different energies: a) and b) at $\sqrt{s}$=1800 GeV, c) and d) at $\sqrt{s}$=6000 GeV.

As it was mentioned above, B_c-meson is produced as a result of fragmentation of c- and b-quarks. In Fig.10 and Fig.11 we present the production spectra for B_c-meson at $\sqrt{s}$=75 GeV (for the UNK fixed target) separately for b and c quark fragmentation/8/. As is seen, the fragmentation of b-quark yields a harger spectrum for B_c as compared with c-quark fragmentation both in the distribution over $x=2p_l/\sqrt{s}$ and over B_c transverse momentum.

The detection of the J/ψ-particles from B_c decay can be a trigger for B_c-meson production. With the help of functions (14) and J/ψ distribution from B_c decay one can calculate the "cascade" fragmentation function of b- or c-quarks into J/ψ-meson (see, Fig.12/8/). As one can see from Fig.12, the form of fragmentation functions $b \to B_c \to J/\psi$ and $b \to B \to J/\psi$ is practically the same (to an accuracy of ~10%). Therefore, the spectra of secondary J/ψ from B_c- and B-mesons in hadron collisions should coincide. In order to extract B_c one must impose additional requirements. It can be the requirement of the presence of γ from B_c^* decays, or taking into account the distributions of J/ψ-particles on their transverse momentum k_t in of b-quark jet/8/.

In Fig.13, the spectra $d\sigma/dp_t$ of secondary J/ψ-particles from B_c-meson are shown.

4.3. B_c Meson Production in Neutrino-Hadron Interactions

B_c-Meson Production in the Vector Meson Dominance Model

Let us consider the production of particles containing b- and $\bar{c}$-quarks in neutrino (or antineutrino) beams in the processes with vector B_c-meson exchange in t-channel (Fig.14). A coupling of B_c with lepton current l_α has the form/23/

$$L = (G/\sqrt{2})M^2 B V^\alpha l_\alpha,$$

where G is a Ferm constant, M is the B_c mass, V_α is B_c vector field, B is the constant of the coupling of lepton current with B_c-meson. One can express this parameter through the value of the B_c wave function:

$$B = 2\sqrt{3}|\Phi(0)||V_{bc}|M^{-3/2},$$

with V_{bc}=0.45/18/one obtains $B^2=1.6 \cdot 10^{-5}$. For the cross-section of the process $\bar{\nu}N \to \mu^+ bcX$ we have /23/

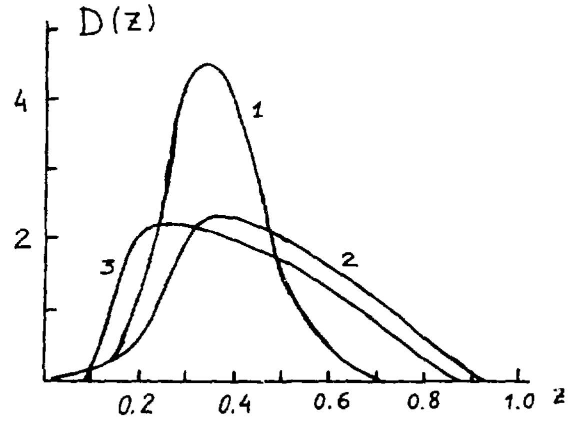

Fig. 12. The cascade fragmentation functions D(z) of b-quark into J/ψ-meson for processes: 1 - $b \to B \to \psi l \nu$, 2 - $b \to B \to \psi X$, 3 - $b \to B_c \to \psi \rho$.

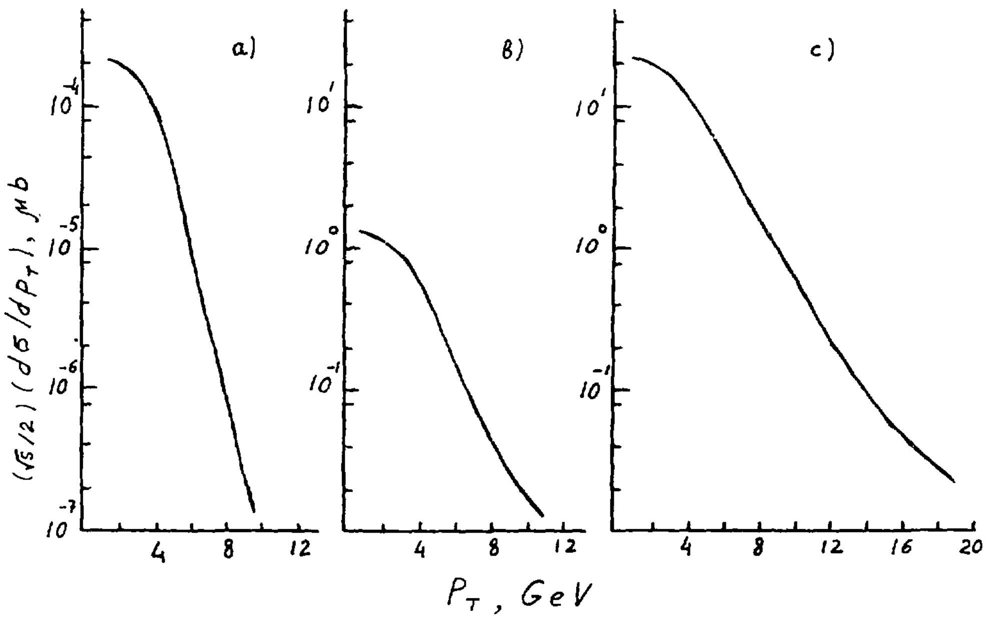

Fig. 13. The secondary J/ψ-particle spectra $d\sigma/dp_t$ at different energies: a) $\sqrt{s}$=75 GeV, b) $\sqrt{s}$=1800 GeV, c) $\sqrt{s}$=6000 GeV.

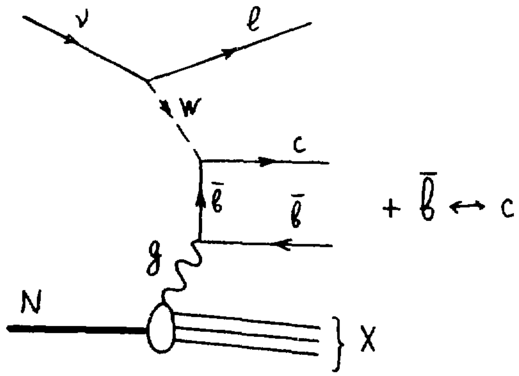

Fig. 14. Diagrams describing b and c quarks production in reaction $\nu N \to \bar{b} c X$ in parton model.

$$\frac{d^2\sigma}{dq^2 dW^2} = \frac{3G^2 M^4 B^2}{8\pi^2} \frac{q^2}{(M^2-q^2)(W^2-q^2)} [1+(1-\frac{W^2-q^2}{s})^2] \sigma_{B_cN}(q^2), \quad (16)$$

where W^2 is the invariant mass squared of the final hadrons q^2 is the transverse momentum squared. The cross-section of the reaction $B_cN \to b\bar{c}X$ for virtual B_c with momentum q $(q^2<0)$ has the form

$$\sigma_{B_cN}(q^2<0) = \sigma_{B_cN}(0)(M^2/(M^2-q^2)), \quad \sigma_{B_cN}(0) = \sigma^{tot}_{B_cN} \quad (17)$$

To estimate $\sigma^{tot}_{B_cN}$ we shall suppose two variants:

$$\frac{\sigma^{tot}_{B_cN}}{\sigma^{tot}_{\psi N}} = \begin{cases} M_\psi/M_{B_c} \\ (M_\psi/M_{B_c})^2 \end{cases}.$$

Using the estimate for the total $J/\psi N$-interaction cross-section $\sigma^{tot}_{\psi N}$=1.26±0.2 mb we will obtain

$$\sigma^{tot}_{B_cN} = \begin{cases} 0.62 \pm 0.1 \text{ mb} \\ 0.31 \pm 0.05 \text{ mb} \end{cases} \quad (18)$$

Assuming B_cN scattering to be of a diffractive type, one may get[24], for elastic B_cN scattering cross-section

$$\sigma^{el}_{B_cN} = (\sigma^{tot}_{B_cN})^2/(16\pi b),$$

where b=2 GeV^{-2}, then

$$\sigma^{el}_{B_cN} = \begin{cases} 9.5 \pm 1.5\ \mu b \\ 2.3 \pm 0.7\ \mu b \end{cases} \tag{19}$$

Integration of (16) gives for the total ($b\bar{c}$)-system production cross-section

$$\sigma = (3G^2M^4B^2/8\pi^2)\sigma_{B_cN}f(x_o), \quad x_o = M^2_{B_c}/s, \tag{20}$$

where

$$f(x) = -(1 - 2x + x^2/2)\ln x - (1 - x)(9 + 5x + 2x^2)/4.$$

The total and elastic cross-sections for neutrinoproduction of the ($b\bar{c}$)-system versus E_ν, which are calculated according to (20), are shown on Fig.15. The dashed regions are intermediate values between the variants in (18) and (19).

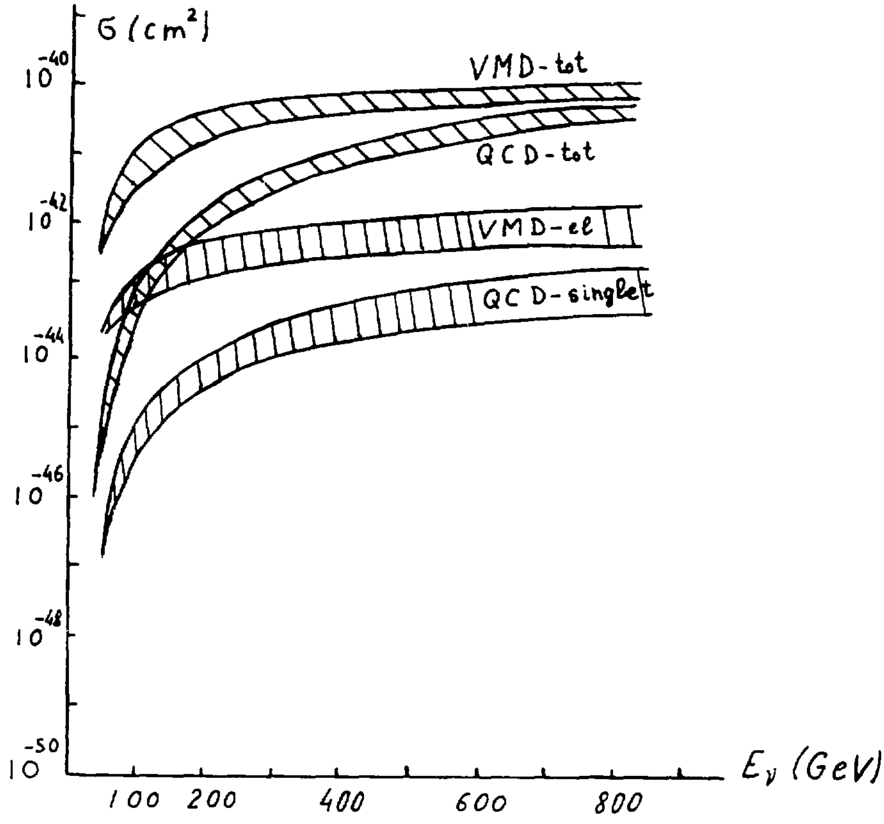

Fig. 15. Behaviour of inclusive cross-sections for B_c-meson, b- and c-quark production in νN reaction versus beam energy. "QCD-singlet" and "VMD-el" corresponds to B_c-meson production; "QCD-tot" and "VMD-tot" correspond to b and c quark production.

Neutrinoproduction of (bc)-system in parton model

In the framework of parton model $(b\bar{c})$-system may be produced as a result of interaction with gluons (Fig.14). This process is considered in ref.[25], where the expression for the crss-section of the process $lg \to l'Q_1Q_2$ is given.

The cross-section of the process $\nu N \to \mu b\bar{c}X$ is shown on Fig.15. In calculation we supposed m_c=1.25 GeV, m_b=4.5 GeV and α_s=0.2. Uncertainty in these parameters and account of radiative corrections, may change the estimate by a factor of two.

In order to calculate the cross-section of $(b\bar{c})$ bound state production it is necessary to consider the diagrams of the type given on Fig.16 with gluon emission. This emission allowed the $(b\bar{c})$-system to be singlet in colour. The calculatin of pseudoscalar B_c-meson production cross-section according to the diagram of Fig.16 was carried out in[10].

The obtained estimates must be considered as the minimal values of the cross-sections for $(b\bar{c})$-system production. The upper limit may be obtained in the following way.

In the lower order of the perturbation theory over α_s the system $(b\bar{c})$ is produced in the colour state (see Fig.14). On emitting gluons, the $(b\bar{c})$ system may transform into a singlet state with the invariant mass less than that of B- and D-mesons. Then the relevant cross-section may be equated to that of the production of all possible resonances in the $(b\bar{c})$. Figure 15 shows the behaviour of the cross-section versus E_ν[4]. Note that the cross-section for the production of B_c-mesons corresponds to $10^{-6\div-5}$ of the total cross-section of νN-interactions, $\sigma(\nu N \to B_cX)$ = $=10^{-43\div-42}cm^2$, which is next to beyond the experimental feasibilities ($1\div10$ B_c-meson/year) for the statistics of 10^6 events.

6. DISCUSSIONS

We have considered the properties and mechanisms of the B_c-meson production, i.e., the lightest representatives of the onium family, composed of quarks of different flavours. The system of b- and $\bar{c}$-quarks may produce a large number, comparable with J/ψ- or Υ-families, of narrow bound states. We consider the

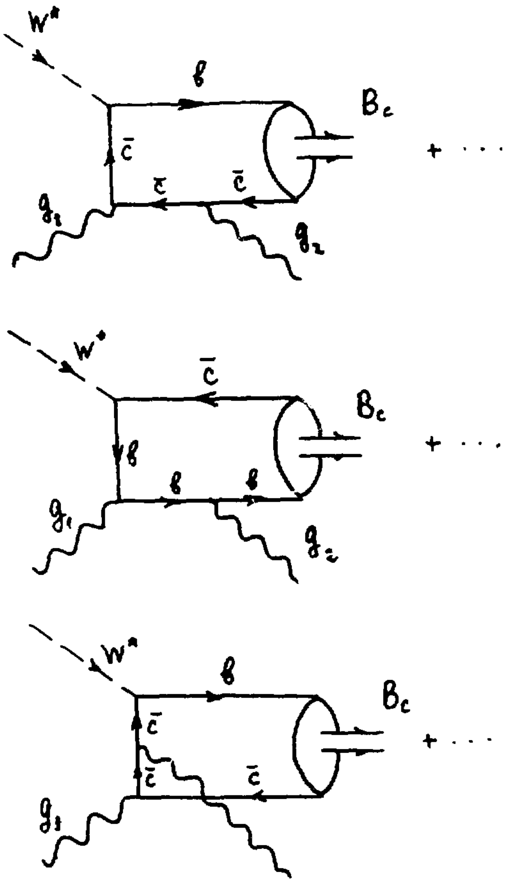

Fig. 16. Diagrams describing b- and c-quark production in reaction $\nu N \to \bar{b}cX$ in parton model.

calculations (which take into account the relativistic corrections) of the mass spectrum as well as widths of transition between various B_c-mesons. We compare the predictions of various potentials (in particular, potential/12/, independent of quark type). Since the B_c-family, as viewed from the potential approach, holds the "intermediate" position between the J/ψ- and Υ-families, the accuracy of predicting the properties of B_c's is the same as that of J/ψ- and Υ-particles. With different potentials/2-5/ applied this leads to close values of the B_c-meson masses. The difference in the predictions must be essential for the states lying somewhat higher than the threshold of decay into B- and D-mesons. This means that the study of the properties of B_c-mesons is a very good tool to verify the applicability of the potential models for the description of heavy quarkonia $(Q_1\bar{Q}_2)$

The weak decays of B_c-mesons have also been considered. Remaining within the frames of the spectator model, one may calculate the partial width of different channels of weak B_c decays. The presence of annihilation mechanism leads to noticeable probabilities of decays $B_c \to D_s\phi$ and $\to D\bar{K}$ ($\sim$3%) and $B_c \to \tau\nu_\tau$ ($\sim$1%). The measurement of the width of the latter decay is particularly interesting because it allows one to determine the quantity f_{B_c} calculated in the potential model directly. B_c is shown to decay into $J/\psi X$ with a high probability ($\lesssim$15%). This decay may serve as a trigger in the search for B_c-mesons.

The mechanisms of B_c-mesons production in different interactions (e^+e^-, hh and νN) have been considered. Search for B_c-mesons in the Z^o-boson peak (where one may expected up to 500 B_c-mesons for 10^6 Z^o) seems the most realistic. Having an accessible number of events of neutrino-nucleon interactions (10^6/year), one may expect just few events of B_c-meson production (<10). The largest number of events must be expected in hadron-hadron collisions, (for example, $\sigma(B_c)/\sigma(b\bar{b}) \sim 10^{-3}$). The differential spectra of B_c-meson production in pp-collisions as well as spectra of J/ψ-particles produced from B_c decays at large transverse momenta have also been calculated. Detection of J/ψ-particles with a large p_t in the b-quark jet and also the presence of a hard γ-quantum and of the weak decay vertex may be the most reliable indication to the production of B_c^*.

One may therefore conclude that the search for and study of the new family of mesons B_c ($b\bar{c}$ or $\bar{b}c$) seems to be very interesting and important high energy physics problem.

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