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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ

R.A. ALANAKYAN, S.G. GRIGORYAN, S.G. MATINYAN

ON THE QUESTION OF HIGGS BOSON PRODUCTION IN HEAVY QUARKONIUM DECAYS

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Р.А.АЛАНАКЯН, С.Г.ГРИГОРЯН, С.Г.МАТИНЯН

К ВОПРОСУ О РОЖДЕНИИ ХИГГСОВСКОГО БОЗОНА В РАСПАДАХ ТЯЖЕЛОГО КВАРКОНИЯ

Изучен механизм рождения H^0- бозона в адронных распадах тяжелого $\eta(^1S_0)$ - кваркония. Показано, что для малых масс хиггсовского бозона ($m_H <$ [illegible] ГэВ) вероятность его рождения в адронных распадах кваркония выше, чем в радиационных распадах, а для m_H в интервале [illegible] ГэВ вероятности этих распадов сравнимы. Исследованы дифференциальные характеристики рождения H^0- бозона в рассматриваемом механизме.

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R.A. ALANAKYAN, S.G. GRIGORYAN, S.G. MATINYAN

ON THE QUESTION OF HIGGS BOSON PRODUCTION IN HEAVY QUARKONIUM DECAYS

The mechanism of production of H^0-boson in hadronic decays of the heavy $\eta(^1S_0)$-quarkonium is studied. It is shown that the probability of production of a light Higgs boson (with $m_H < 10$ GeV) in the hadronic decay of quarkonium is higher than in radiative decays, while for m_H in 10-[illegible] GeV range the probabilities of these decays are comparable. The differential characteristics of the H^0-boson in the mechanism under consideration are studied.

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Decays of hadrons containing heavy quarks are one of the best sources of information on the production and the nature of the Higgs bosons, the constant of the interaction of which with quarks is proportional to the quark mass m . So, there is only one neutral H^0-boson in the minimal model of electroweak interaction [1-3] and its coupling constant with the quarks is of the order of $(G_F\sqrt{2})^{1/2}\cdot m$, that in the case of the heavy quarkonia $Q\bar{Q}$ gives quite intensive source of Higgs boson production with a mass of $m_H < 2m$. A restriction to the lower limit of m_H resulting from the standard model of $m_H \geqslant 6\div7$ GeV [4,5] should be noted (one must bear in mind that the supersymmetry requires the existence of at least two Higgs doublets and one of the neutral Higgs bosons may have rather small mass, of the order of some GeV).

In [6], the radiative decays of J/Ψ , Υ , T (the states $Q\bar{Q}$ with $J^{PC} = 1^{--}$) vector quarkonia with the production of H^0-boson were studied in the framework of non-relativistic potential model. So, for the width of their decays is obtained (see reviews [7,8]):

$$\frac{\Gamma(V_{Q\bar{Q}} \to H^\circ\gamma)}{\Gamma(V_{Q\bar{Q}} \to \mu^+\mu^-)} = \frac{G_F M_V^2}{4\sqrt{2}\pi\alpha}\left(1 - \frac{m_H^2}{M_V^2}\right), \tag{1}$$

where M_V and m_H are the masses of the vector quarkonium and H^0-boson, respectively. At $m_H^2/M_V^2 \ll 1$ we obtain from the formula (1) (when M_V : M_Υ = 9.5 GeV and M_T = 80 GeV):

$$\frac{\Gamma(\Upsilon \to H^\circ\gamma)}{\Gamma(\Upsilon \to \mu^+\mu^-)} \simeq 8\cdot 10^{-3}, \quad \frac{\Gamma(T \to H^\circ\gamma)}{\Gamma(T \to \mu^+\mu^-)} \simeq 0{,}56\,;$$

This gives for a bottonium quite detectable value. It should be noted that the estimation of the width ratio for a toponium was made without the contribution of Z^0-boson to the width of the decay $T \to \mu^+\mu^-$, which becomes considerable at M_T = 80 GeV.

In this work we have studied the mechanism of H^0-boson production in hadronic decays of quarkonia

$$Q\bar{Q} \to H^\circ + X\;, \tag{2}$$

where X stands for hadrons not containing heavy quarks. On the quark-gluon level the width of this decay is determined by the decay:

$$Q\bar{Q} \to H^\circ + 2g\,, \tag{3}$$

where two gluons turn into quark-antiquark pairs forming ordinary (light) hadrons. Fig.1 shows the diagrams corresponding to the process we study.

The final system ($2g\,H^\circ$) is C-even, so the production of H^0 in hadronic decays may proceed only through C-even states of quarkonium, such as

$$\eta(J^{PC}=0^{-+}), \quad \chi_J(J^{PC}=0^{++},\ 1^{++},\ 2^{++}).$$

The amplitude of the process shown in Fig.1 has the form:

$$M = 4\pi\alpha_s \cdot m (G_F\sqrt{2})^{1/2} \cdot \frac{1}{\sqrt{3}} Sp\left(\frac{\lambda^b}{2}\cdot\frac{\lambda^a}{2}\right)\cdot \varepsilon^a_\mu(K_1)\varepsilon^b_\nu(K_2)H(K_3)\times$$
$$\times \bar{U}(-K_5)\frac{\hat{K}_3-\hat{K}_5+m}{(K_3-K_5)^2-m^2}\gamma_\nu \frac{\hat{K}_4-\hat{K}_1+m}{(K_4-K_1)^2-m^2}\gamma_\mu U(K_4) \qquad (4)$$

plus the contributions of diagrams with permutations, where $a,b=1,2,\ldots 8$; λ^a – are the Gell-Mann SU(3) matrices; $\varepsilon^a_\mu(K_1)$, $\varepsilon^b_\nu(K_2)$ – are the gluon polarization vectors; $H(K_3)$ is the wave function of the H^0-boson; α_s – is the strong interaction coupling constant. The factor $\frac{1}{\sqrt{3}}$ is connected with the averaging by the color.

For the differential characteristics of the decay under study, in the framework of non-relativistic potential model (in the rest system of quarkonium $\vec{K}_4=-\vec{K}_5$, so $\vec{K}_4=-\vec{K}_5\simeq 0$) we obtain:

$$d\Gamma(Q\bar{Q}\to 2gH^0)=\frac{2}{3}(G_F\sqrt{2}m^2)\frac{\alpha_s^2}{\pi}\cdot\frac{2}{m^2}|\Psi(0)|^2\cdot$$
$$\cdot\left[\left(\frac{m_0-\omega_3}{\omega_1\omega_2}\right)^2+\left(\frac{m_0-\omega_2}{\omega_1\omega_3}\right)^2+\left(\frac{m_0-\omega_1}{\omega_2\omega_3}\right)^2-\right.$$
$$-2\frac{(m_0-\omega_2)(m_0-\omega_3)}{\omega_1^2\omega_2\omega_3}-2\frac{(m_0-\omega_1)(m_0-\omega_3)}{\omega_1\omega_2^2\omega_3}- \qquad (5)$$
$$\left.-2\frac{(m_0-\omega_1)(m_0-\omega_2)}{\omega_1\omega_2\omega_3^2}+4\frac{m_0(m_0-\omega_3)}{\omega_1\omega_2\omega_3^2}\right]d\omega_1 d\omega_2=$$
$$=\frac{16}{3}\frac{G_F\sqrt{2}\alpha_s^2}{\pi}|\Psi(0)|^2\left[\frac{m_0(m_0-\omega_3)}{\omega_1\omega_2\omega_3}\right]^2 d\omega_1 d\omega_2$$

where ω_1 , ω_2 are the gluon energies; $\omega_3 = \varepsilon - 2m\xi$, ε - is the energy of the H^0-boson, $\xi = m_H^2/4m^2$; $m_0 = m(1-\xi)$; $\Psi(0)$ - is the wave function of quarkonium at the origin; $\frac{2}{3}$ - is the color factor The range of variables ω_1 and ω_2 is the following:

$$m_0 - \omega_1 \leqslant \omega_2 \leqslant \frac{m}{m-\omega_1}(m_0 - \omega_1),$$

$$0 \leqslant \omega_1 \leqslant m_0 .$$

It is interesting to compare (5) with the differential width of positronium decay into three photons [9] (Ore-Powell formula, see also [10,11]). The massiveness of one of the particles (namely the H^0-boson) leads to the fact that in (5) the role of energy is played by quantity $\omega_3 = \varepsilon - 2m\xi$, while $m_0 = m(1-\xi)$ plays the role of the quark mass in the quarkonium. The scalar nature of H^0-boson-quark interaction leads to new terms, one of which (the last term in square brackets in (5)) breaks the symmetry with respect to cyclic permutations of ω_1 , ω_2 , ω_3 at all. The mentioned scalar nature of interaction as well as the H^0-boson massiveness gives a characteristic behaviour for the spectral distribution of the decaying gluons (i.e. for $d\Gamma/d\omega_1$). So, integrating (5) over ω_2 we have:

$$d\Gamma(Q\bar{Q} \to 2gH^0) = \frac{8\alpha_s^2}{3\pi}(G_F\sqrt{2}\,m^2)\frac{1}{m^2}|\Psi(0)|^2 \cdot F(x,\lambda)\,dx, \qquad (6)$$

$$F(x,\lambda) = \frac{2(1-x)}{\lambda x(2-x)^2}\left[\frac{2\lambda - 2x + x^2}{\lambda - 2x + x^2} + \right.$$

$$\left. + \frac{2\lambda}{x(2-x)}\ln\left\{\lambda^{-1}(\lambda - 2x + x^2)\right\}\right],$$

where $x = \omega_1/m_0\ (0 \leqslant x \leqslant 1)$, $\lambda = m/m_0$.

One can see from (6) that the spectral distribution $F(x,\lambda)$ at the boundaries of the variable x is equal to zero (in the analogous expression for Ore-Powell formula [9,11] the spectral function monotonously grows from zero (at $x = 0$) to unity (at $x = 1$)) and rather strongly depends on the parameter λ (see Fig.2), i.e. on the mass of the H^0-boson . In Fig.2 the dependence of $F(x,\lambda)$ for different values of the mass of the H^0-boson is shown. One can see that in the region of large x we have a peak in the differential distribution and the height of that peak strongly depends on the mass of the Higgs particle. So, for m_H = 20 GeV the peak is approximately six times as high, and at m_H = 8 GeV 25 times as high as that at m_H = 40 GeV (all the curves are plotted for m = 40 GeV).

It is interesting to study the distribution in the invariant mass of the produced pair of gluons $\Delta^2 = (K_1 + K_2)^2$. The differential distribution in Δ^2 has the form:

$$d\Gamma(Q\bar{Q} \to 2gH^0) = \frac{8\alpha_s^2}{3\pi}(G_F\sqrt{2}m^2)\frac{1}{m^2}|\Psi(0)|^2 R(z,\lambda)dz,$$

$$R(z,\lambda) = \frac{4z}{\lambda(1-z^2)^2}\Big[\{(1+z)^2 - 4\lambda z\}^{1/2} + \qquad (7)$$

$$+ \frac{2\lambda z}{1+z}\ln\frac{1+z+\{(1+z)^2-4\lambda z\}^{1/2}}{1+z-\{(1+z)^2-4\lambda z\}^{1/2}}\Big],$$

Here $z = \Delta^2/(4mm_0)$.

The range of variable Δ^2 is the following:

$$0 \leqslant \Delta^2 \leqslant (2m - m_H)^2,$$

hence $0 \leqslant z \leqslant (\sqrt{\lambda} - \sqrt{\lambda - 1})^2$.

One can see from (7) that the function $R(z,\lambda)$ turns into zero both at $Z=0$ and at the upper limit of the variable Z depending on the H^0-boson mass. In Fig.3 the dependence of the distribution on the invariant mass is shown. One can see that here also the differential distribution is sensitive to the mass of the Higgs boson (all the curves are plotted for $m = 40$ GeV).

For the total decay width of quarkonium into the $2g\,H^0$ system we have:

$$\frac{\Gamma(Q\bar{Q} \to 2gH^0)}{\Gamma(Q\bar{Q} \to 2g)} = \frac{1}{8\pi^2}\left(G_F\sqrt{2}\,M^2_{Q\bar{Q}}\right)\int_0^1 F(x,\lambda)\,dx, \qquad (8)$$

where $M_{Q\bar{Q}}$ is the mass of quarkonium ($M_{Q\bar{Q}} = 2m$).

This width is normalized to the quarkonium decay width into $2g$, as the decay into $2g$ takes place for the C-even state of quarkonium as well. Note that we have neglected the quark momenta in quarkonium, so the discussed expressions refer only to the C-even states with [illegible] orbital momentum [illegible]-quarkonium).

The [illegible] situation with orbital momentum equal to unity (χ -states) will be considered elsewhere.

In Table [illegible] the values of the ratios of widths (8) for different H^0-boson masses [illegible].

Table [illegible]

[illegible]							
[illegible]	[illegible]	8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\frac{\Gamma(Q\bar{Q} \to 2gH^0)}{\Gamma(Q\bar{Q} \to 2g)}$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

It is obvious that the total width of $Q\bar{Q} \to 2gH^0$ [illegible] sensitive to the mass of the H^0-boson. In the course of our consideration [illegible] we always took the mass of the quark equal to 40 GeV, i.e. studied the decay of toponium into $2g\ H^0$, which allowed one, in contrast to the bottonium case, to discriminate the hadronic jets from gluons for not very large H^0-boson masses.

Let us compare the width of quarkonium decay into $2g\ H^0$ with the one into $H^0\gamma$ (it must be noted again that these decays stem from different C-even states of quarkonium).

$$\frac{\Gamma(Q\bar{Q} \to 2gH^0)}{\Gamma(V_{Q\bar{Q}} \to H^0\gamma)} = \frac{2\alpha_s^2}{3\pi\alpha \cdot Q_q^2} \int_0^1 \lambda F(x,\lambda)\, dx \qquad (9)$$

In Table 2 the values of ratios of these widths are given.

Table 2

m_H, GeV	1	8	20	30	40	56.5	75
$\frac{\Gamma(Q\bar{Q} \to 2gH^0)}{\Gamma(V_{Q\bar{Q}} \to 2H^0\gamma)}$	4.0	1.5	0.6	0.3	0.15	3.6 10^{-2}	1.2 10^{-3}

One can see that for small masses of the Higgs boson ($m_H < 10$ GeV) it is produced more frequently in hadronic decays than in the radiative decays of quarkonium. In the range of $m_H = 10 \div 30$ GeV these widths are comparable. The further increase of the H^0-boson mass leads to a sharp reduction of this ratio down to fractions of a per cent of H^0-boson production widths in the radiative decays (for estimations. $\alpha_s(2m)$ is taken equal to ~ 0.1).

As it has been shown, the considered mechanism of H^0-boson production in the hadronic decays of quarkonium is of interest from the viewpoint of the behaviour of the differential characteristics (see Figs 2 and 3) as well as of the total width of the decay (see formulae (8), (9) and Tables 1, 2). In the final state we have along with H^0-boson two hadronic jets in this mechanism. This can help one in the identification of the Higgs particles in the decays of heavy quarkonium. One should bear in mind that the production of the Higgs particles accompanied with two hadronic jets may proceed only through C-even states of quarkonium. That is why in e^+e^- annihilation, the mechanism of the H^0-boson production in the radiative decays of C-odd states of the vector quarkonium $V_{Q\bar{Q}} \to H^0 + \gamma$ is more effective.

The situation is different when one deals with the hadron-hadron interactions. It is known that the heavy quarkonium in the hadron-hadron interactions is produced through the gluon-gluon fusion mechanism (the available experimental data are well described by this mechanism for C-odd charmonium and bottonium, see, e.g. [11]). In such a mechanism the production of the considered C-even states must dominate [11] over the formation of the vector quarkonia which require an emission of an additional gluon jet ($gg \to \eta$, χ_0 , χ_2 , but $gg \to V_{Q\bar{Q}}\, g$).

It follows from the aforesaid that the Higgs boson production mechanism we have considered is of particular interest for the study in hadron-hadron interactions where it is more effective, as we have seen, than the mechanism of the radiative production of the H^0-boson in quarkonium decays.

It is worthwhile to note finally that the total cross section of the H^0-boson production in the hadronic decay of the η_t -state which is produced in $p\bar{p}$ (pp)-collisions, is at least of the same order of magnitude as those of the known associated mechanisms of Higgs particle production in $p\bar{p}$ (pp)-collisions [7,8,13] for not very large masses of the H^0-boson ($m_H \lesssim$ 30 GeV).

The authors are indebted to I.G.Aznauryan for interesting and helpful discussions.

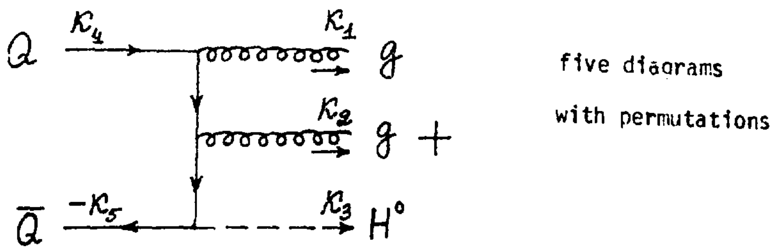

Fig.1. Diagrams referring to hadronic mechanism of the H^0-boson production in the heavy quarkonium decays.

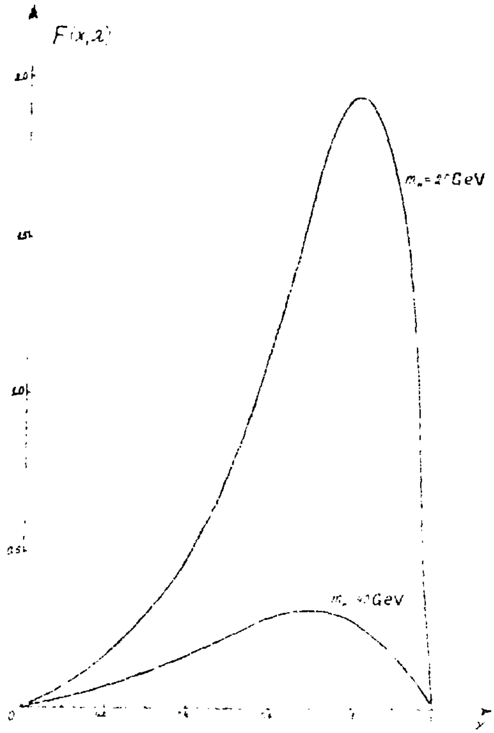

Fig.2. The spectral distribution $F(x,\lambda)$ as a function of $x = \omega_1/m_0$. Curves are plotted at the heavy quark mass m = 40 GeV and refer to m_H = 20 and 40 GeV.

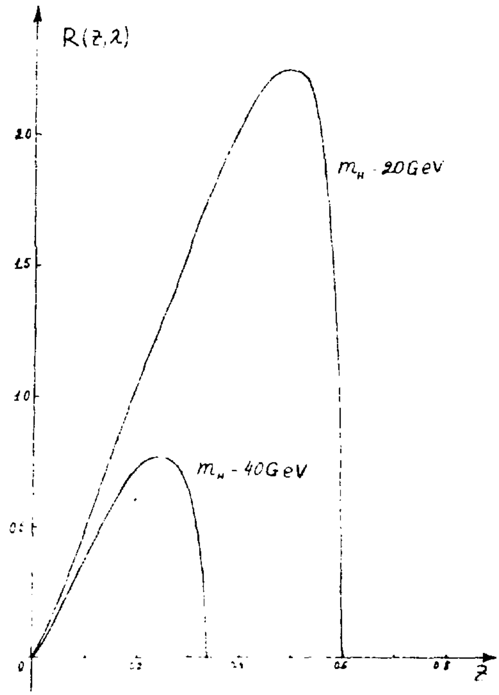

Fig.3. Behaviour of differential distribution $R(z,\lambda)$ of the reaction $Q\bar{Q} \to 2gH^{\circ}$ as a function of $z = \Delta^2/(4mm_0)$ Curves are plotted for the heavy quark mass m = 40 GeV and m_H = 20 and 40 GeV.

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Р.А.АЛАНАКЯН, С.Г.ГРИГОРЯН, С.Г.МАТИНЯН

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