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DPNU-93-20

December 1993

Possible Existence of Topped Hadrons

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Abstract : We study possibilities of formation of the topped hadrons, the $t\bar{q}$, tqq , $t\bar{t}$ and $t\bar{t}q$ bound systems. We assume that the inverse of binding energy as the parameter of the formation time of the bound system and take the ratio $\Gamma_{\text{total}}/E_B$ as a criterion for the formation of these hadrons, where E_B and Γ_{total} are a binding energy and a total decay width of a topped system respectively. We take into account as the binding force caused by the Higgs scalar exchange as well as the one gluon exchange. It is shown that no possibility to form the single top quark hadrons before the top quark decay. In the standard model, where only one Higgs doublet contributes, among the topped hadrons only the toponium $t\bar{t}$ and the three-top-quark baryon $Qt\bar{t}$ with the top quark mass less than 140GeV and 130GeV have a possibility to form the bound states before their decay. In the case of the two Higgs-doublet model which is required in supersymmetric theories we show that there are possibility to form the topped hadrons, the toponium, Ξ_t and $Qt\bar{t}$ for the larger top quark mass if the ratio of vacuum expectation values of two Higgs scalars is large near to the unitarity bound.

§1 Introduction

In recent years, the effective theory of QCD for hadrons containing one heavy quark has been developed which exhibits a new flavor-spin symmetry[1-5]. The effective theory has been applied to hadrons with the b or c quark[6-12]. This theory successfully described the semileptonic decays of B mesons such as, $B \rightarrow D\ell\bar{\nu}$ and $B \rightarrow D^*\ell\bar{\nu}$, etc. by introducing a universal form factor. The heavy quark effective theory with quark mass corrections also applied to the mass splitting among hadrons with the b and c quark and derive the mass relations such as, $M_{A_1} - (M_B + 3M_{B^*})/4 = M_{A_2} - (M_D + 3M_{D^*})/4$.

The idea of the heavy quark symmetry is considered to be effective only for heavy quarks whose masses m_Q are significantly larger than the QCD scale $\Lambda_{QCD} (\cong 0.2\text{GeV})$. However, it has been suggested that the heavy quark effective theory may be still effective for the systems with the s quark if a constituent quark mass is employed for the s quark and the $1/m_s$ corrections are taken into account[13-15]. In ref.[14], it is shown that by use of the same universal functions, both of the experimental data for the semileptonic decays, $B \rightarrow D^{(*)}\ell\bar{\nu}$ and $D \rightarrow K^{(*)}\ell\bar{\nu}$ are well reproduced with the $1/m_c$ and $1/m_s$ corrections.

If there exists the hadron which is composed of the t quark and light quarks, the heavy quark effective theory is more effective to describe the phenomena concerning to these hadrons, since the t quark mass is much larger than the QCD scale. If this is realized, we can systematically study through the s , c , b and t quark systems by the heavy quark symmetry with the $1/m_Q$ corrections. From recent analyses of

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high precision experiments, it has been expected that the t quark mass lies between 120GeV and 200GeV. Then the t quark will decay rapidly via the process $t \rightarrow b + W$ before the t quark composes a hadron. In this case, there will be no room that the heavy quark effective theory describes topped hadron phenomena.

As a criterion for the composition of hadrons with the t quark, we examine the ratio $\Gamma_{\text{total}}/E_B$, where E_B and Γ_{total} are a binding energy and a total decay width of a topped system respectively. We assume that the inverse of the binding energy $1/E_B$ is a measure of formation time of the composite system. If $E_B < \Gamma_{\text{total}}$ for a system with the t quark the constituent top quark will decay before to form the bound system and we will have no possibility to observe this system as a bound state.

In this paper, by use of this criterion we examine the existence of the topped hadrons. We assume that the t quark mass m_t lies between 120GeV and 200GeV. In §2 we discuss possibility to construct the single t quark hadrons, the $t\bar{q}$ mesons and tqq baryons. In §3 we turn to toponium and the double topped baryons Ξ_t where the effect of Higgs-boson exchange becomes important. On the basis of the two Higgs-doublet model which is required in supersymmetric theories we show that there are possibility to form the toponium even for larger top quark mass if the ratio of vacuum expectation values of two Higgs scalars is large near to the unitarity bound. Summary and discussions are given in §5.

§2 Single t quark hadrons

Under the condition $m_t \gg m_W + m_b$, the weak decay of the t quark $t \rightarrow b + W$ dominates over all other electroweak contributions. Then the decay width for the t quark is given by[16]

$$\Gamma(t \rightarrow b + W) = \frac{\sqrt{2}}{16\pi} G_F |V_{tb}|^2 m_t^2 m_t \left[\left(1 + \frac{m_b^2 - m_W^2}{m_t^2} \right)^2 - \frac{4m_b^2}{m_t^2} \right]^{1/2} \times \left\{ \left(1 + \frac{m_b^2 - m_W^2}{m_t^2} \right) + \frac{m_t^2}{m_W^2} \left[\left(1 - \frac{m_b^2}{m_t^2} \right)^2 - \frac{m_W^4}{m_t^4} \right] \right\}. \quad (1)$$

The Kobayashi-Maskawa matrix element[17] $|V_{tb}|$ is assumed to be one. The decay width of free top quark increases more rapidly than proportional to m_t^3 . Calculated values of the decay width are $\Gamma(t \rightarrow b + W) \simeq 0.164\text{GeV}$, 0.337GeV and 0.566GeV for $m_t = 120\text{GeV}$, 140GeV and 160GeV , respectively.

We consider in this section the mesons and baryons which composed with one t quark and one light anti-quark or two light quarks, i.e., $t\bar{q}$ or tqq . The dominant interaction between these quarks is the strong interaction due to the gluon exchange. The contribution of the Higgs exchange interactions to the binding energy of the single topped hadrons are expected to be very small because of the small coupling between the Higgs scalar and the light quark and roughly estimated less than a few MeV. Then the binding energy of the single topped hadron due to the gluon interactions is $E_B \leq 0.2\text{GeV}$, which is much smaller than the decay width of the t quark. Therefore it is impossible to compose $t\bar{q}$ mesons and tqq baryons before the top quark decays.

§3 Toponium and the Ξ_u baryon with Higgs-boson exchange

Let us turn our attention to the toponium and baryons including two t quarks. For these hadrons, as pointed out by Inazawa and Morii[21] the effect of Higgs-boson exchange between two top quarks is very important. In the following we assume the two-Higgs-doublet model, which is required naturally in supersymmetric theories. In these theories, there are two neutral Higgs scalars ϕ_u and ϕ_d which are coupled to the up-type quarks and the down-type quarks, respectively. They are described as[18]

$$H = \sqrt{2}[(\text{Re}\phi_u - v_u)\cos\xi - (\text{Re}\phi_d - v_d)\sin\xi], \quad (2)$$

$$H' = \sqrt{2}[(\text{Re}\phi_u - v_u)\sin\xi + (\text{Re}\phi_d - v_d)\cos\xi]. \quad (3)$$

where ξ is an unknown mixing angle between ϕ_u and ϕ_d . The parameters v_u and v_d are vacuum expectation values of the unmixed Higgs scalar fields ϕ_u and ϕ_d , respectively and constrained by $v = \sqrt{v_u^2 + v_d^2} \simeq 246\text{GeV}$. Since we have no individual information about these parameters at present, we treat the ratio $\zeta \equiv (\tan\beta)^{-1} = v_d/v_u$ as a free parameter. The case of $\zeta = 0$ corresponds to the minimal standard model with a single Higgs doublet. The potential caused by the Higgs scalars $V_H(r)$ is given by[19]

$$V_H(r) = -\frac{G_F m_t^2}{2\sqrt{2}\pi}(1 + \zeta^2) \left[\frac{\exp(-m_{H'}r)}{r} \cos^2\xi + \frac{\exp(-m_H r)}{r} \sin^2\xi \right]. \quad (4)$$

For simplicity, we assume $m_H = m_{H'}$ so that the potential becomes independent on ξ . This choice $m_H = m_{H'}$ gives larger combined effect of Higgs scalars exchange compared to that of $m_H \neq m_{H'}$ case.

There exists the unitarity bound for the t quark mass which is given by neglecting the b quark mass[20]

$$m_t < \sqrt{\frac{4\sqrt{2}\pi}{3G_F(1 + \zeta^2)}} \simeq \frac{684}{\sqrt{1 + \zeta^2}} \text{ (GeV)}. \quad (5)$$

For example for $\zeta = 3, 4$ and 5 the top quark mass has to be smaller than 217GeV , 166GeV and 135GeV , respectively. Then we examine the cases with $\zeta = 0, 1, 2, 3$ and 4 .

The total decay width of toponium is given by

$$\Gamma_{\text{total}} = \Gamma(t\bar{t} \rightarrow t\bar{b} + W \text{ or } \bar{t}b + W) + \Gamma(t\bar{t} \text{ annihilation}), \quad (6)$$

where partial decay width $\Gamma(t\bar{t} \text{ annihilation})$ includes the decay modes $t\bar{t} \rightarrow HZ^0$, gg , γZ^0 , WW , $\gamma\gamma$, $q\bar{q}$, $\ell\bar{\ell}$, etc. The dominant term in Γ_{total} of the toponium is the first term which is the single decay of the t quark or the $\bar{t}$ quark. Since we assume that $m_t \geq 120\text{GeV} \gg m_W + m_b$, this decay width $\Gamma(t\bar{t} \rightarrow t\bar{b} + W \text{ or } \bar{t}b + W)$ is approximated by the sum of decay widths of the free t and $\bar{t}$ quarks so that the twice of Eq.(1). Estimated m_t dependence of the total decay width of the toponium is shown in Fig. 1.

In order to calculate the wave function and the binding energy of the $t\bar{t}$ system, we assume that the potential for this system:

$$V(r) = -\frac{G_F m_t^2}{2\sqrt{2}\pi}(1 + \zeta^2) \frac{\exp(-m_{H'}r)}{r} - \frac{4\alpha_s(m_t^2)}{3} \frac{1}{r}. \quad (7)$$

The first term is the potential caused by the Higgs scalar exchange. The factor $G_F m_t^2$ comes from the Yukawa coupling constant between Higgs scalar and the t quark. The experimental lower bound of m_H is 48GeV [22], so that we take two

cases with $m_H = 50\text{GeV}$ and 60GeV . The factor $G_F m_t^2$ comes from the Yukawa coupling constant between Higgs scalar and the t quark. The second term is the potential caused by the gluon exchange. For simplicity, we neglect the linear confining potential because in the heavy quark system the long-range part does not effect to binding energy. We use the variational method with the normalized trial wave function for toponium, $\psi(r) = 2a^{3/2} \exp(-ar)/\sqrt{4\pi}$, where a is a positive variational parameter which is related to the binding energy $E_{B(t)}$ by

$$E_{B(t)} = \frac{\sqrt{2} G_F m_t^2 a^3}{(m_H + 2a)^2 \pi} + \frac{4}{3} \alpha_s a - \frac{a^2}{m_t}. \quad (8)$$

We show in Fig. 1 the binding energy E_B of toponium obtained in terms of the variational method from the potential. In the case of pure gluon exchange as shown in Fig. 1 the binding energy increases more slowly with m_t than proportional to $\alpha_s^2 m_t$. Then for $m_t > 140\text{GeV}$ the total decay width of toponium becomes larger than the binding energy. For $\zeta = 0$ which corresponds to the standard model with single Higgs doublet the effects of the Higgs exchange on the binding energy E_B are rather weak. In the two Higgs doublet model cases with smaller values of parameter $\zeta < 2.5$, the effects of the Higgs exchange are not so strong to bind top quark and anti-top quark with mass larger than 150GeV before their decays. If $\zeta \geq 2.5$ the effect of the exchange of Higgs scalar with mass 50 and 60GeV become significant even for the top quark mass $m_t > 140\text{GeV}$.

In Fig. 2 we summarize the calculated results of the ratio $\Gamma_{\text{total}}/E_{B(t)}$ for varying m_t . For the top quark mass $m_t < 140\text{GeV}$ the ratio $\Gamma_{\text{total}}/E_{B(t)} < 1$ irrelevant from the Higgs exchange and the toponium will be formed before the top quark decay. On the other hand if $m_t > 140\text{GeV}$ the results are largely dependent on the value

of $\zeta = (\tan \beta)^{-1}$. For $\zeta < 2.5$ most of parameter $\Gamma_{\text{total}}/E_{B(t)} > 1$ and there is no possibility of the toponium formation. In the case with $\zeta = 3$, the t quark mass is constrained $m_t < 167\text{GeV}$ by the unitarity bound.

Next, we discuss the possibility of formation of double topped baryons, Ξ_{tt} . For a QQq baryon, Savage and Wise[23] suggested that one can look upon it as the bound state of a light quark and a heavy diquark system QQ since the Bohr radius of the QQ system is much smaller than the typical scale of a hadron

$$\frac{1}{\alpha_s(m_Q) m_Q} \ll \frac{1}{\Lambda_{QCD}}. \quad (9)$$

The diquark is color 3^* state and behaves as an axial vector particle A . Then a QQq baryon is considered as an Aq bound state which is a meson-like system concerning to color degree of freedom and we can deal with this baryon on the basis of the heavy quark effective theory. For the tt diquark system in this baryon, the effective interaction between two t quarks is important and it is given by a sum of the gluon and the Higgs-boson exchange interaction. While the effective interaction between the light constituent quark and the tt system is approximated by the gluon exchange interaction.

Now, let us examine the possibility of the Ξ_{tt} baryon formation. At first, we estimate the total decay width of the Ξ_{tt} baryon. Since the decay mode of the Ξ_{tt} baryon is dominated by only $ttq \rightarrow tbq + W$. Under the condition of $m_t \gg m_W + m_b$, the total decay width of this baryon is approximated by that of tt system:

$$\Gamma_{\text{total}}(\Xi_{tt}) \approx \Gamma(tt \rightarrow tb + W) \quad (10)$$

$$= 2\Gamma(t \rightarrow b + W), \quad (11)$$

In Fig. 3, the m_t dependence of estimated $\Gamma_{\text{total}}(\Xi_u)$ is shown. In order to estimate the binding energy of the Ξ_u baryon, we neglect the effect of the light quark in the Ξ_u baryon for the binding energy. Then the binding energy is approximated by one of the tt system $E_{B(tt)}$. We assume a potential for the tt dquark system is given by

$$V(r) = -\frac{G_F m_t^2}{2\sqrt{2}\pi}(1 + \zeta^2) \frac{\exp(-m_H r)}{r} - \frac{2\alpha_s(m_t^2)}{3} \frac{1}{r}. \quad (12)$$

The first term of Eq.(12) is the potential caused by Higgs scalar exchange which is the same in the toponium. The second term is the potential caused by the gluon exchange which is a half of that in the toponium case. We use the variational method with the normalized trial wave function for the tt system, $\psi(r) = 2a^{3/2} \exp(-ar)/\sqrt{4\pi}$, where a is a positive variation parameter again. Fig. 3 shows the binding energy $E_{B(tt)}$ obtained for the potential (12) with $m_H = 50\text{GeV}$ and 60GeV . Significant effect of Higgs scalar exchange appears for $m_t > 140\text{GeV}$ and $\zeta > 2.5$ as in the case of toponium. In Fig. 4 we plot m_t dependence of $\Gamma_{\text{total}}/E_B$ of the tt systems in the case of $m_H = 50\text{GeV}$ and $m_H = 60\text{GeV}$. Fig. 4 shows that $\Gamma_{\text{total}}/E_B > 1$ in all cases for all region of $m_t \geq 120\text{GeV}$ except for some special region of the ratio of vacuum expectation values of two Higgs scalars ζ near to the unitarity bound. Then we will have very rare chance to form the Ξ_u baryon. The essential difference between the toponium and the Ξ_u baryon is brought from the difference of the Coulombic potentials due to the gluon exchange in these two systems.

Are there possibilities to compose of the baryon of three t quarks Ω_{ttt} ? If we assume the binding energy of Ω_{ttt} is given by the sum of each top quark pair then

$E_{B(ttt)}$ is estimated about three times of that of tt system. On the other hand the decay rate of Ω_{ttt} is also approximated by three times of $\Gamma(t \rightarrow b + W)$ given by Eq.(1). Then the situations of formation of Ω_{ttt} are intermediate between the cases of toponium and of Ξ_u . If $m_t \leq 135\text{GeV}$ the binding energy of Ω_{ttt} is about 0.9GeV and larger than the total decay width of Ω_{ttt} . If m_t lies between 135GeV and 160GeV there is possibility to form Ω_{ttt} only for enough large ζ values.

§5 Summary and discussions

We have studied in the previous sections the possibility that the top quarks form the hadron before the top quark decay. As a criterion for the possibility of formation of hadrons, we examine the ratio of total decay rate and the binding energy of the composite system, $\Gamma_{\text{total}}/E_B$. It is shown that in the double topped quark hadrons the contributions from the Higgs-boson exchange interaction is significant as well as the gluon exchange as pointed out by Inazawa and Morii[21].

There is no possibility to form the single top quark hadron before the top quark decays. If the t quark mass is smaller than 140GeV the binding energy is larger than the total decay width of the toponium $t\bar{t}$ by the potential is given mainly from gluon exchange. There is enough possibility that the toponium can be formed if the top quark mass lies between 140GeV and 160GeV and if the mass of Higgs scalar m_H is less than 60GeV and the ratio ζ is larger than 2.5 . If the mass of Higgs scalar is larger than 70GeV there is no possibility to form the toponium.

For the Ξ_u baryons there is no possibility of formation for the top quark with

mass larger than about 110GeV except for the special region of the ratio of vacuum expectation values of two Higgs scalars $\zeta = v_d/v_u$ very near to the unitarity bound. The essential difference between the toponium and the topped baryon stems from the difference of the Coulombic potentials in the two systems. In the case of the minimal standard model with single Higgs model corresponds to $\zeta = 0$. Then in this case only the toponium can be formed if the Higgs mass $m_H \simeq 50\text{GeV}$.

In the case of Ω_{uu} if $m_t \leq 135\text{GeV}$ the binding energy of Ω_{tt} is larger than the total decay width of Ω_{tt} and there is possibility to form the Ω_{tt} baryon. If m_t lies between 135GeV and 160GeV there is possibility to form Ω_{tt} only for enough large ζ values.

For the topped hadrons $1/m_t$ corrections are extremely small, so that we can examine the Isgur-Wise symmetry with high accuracy if the Ξ_u and Ξ_u^* baryons are formed. Unfortunately, however, there is rather rare chance to observed hadrons which are described in terms of the heavy quark effective theory.

Acknowledgement

We are grateful to Professor H. Inazawa and Professor T. Morii for useful advice.

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Figure captions

Fig. 1. The binding energy $E_{B(n)}$ of toponium for the cases of Higgs exchange with $m_H = 50\text{GeV}$ (dashed lines) and $m_H = 60\text{GeV}$ (full lines) and with $\zeta = 0, 1, 2, 3$ and 4, respectively. The dot-dashed line shows the binding energy corresponding to pure gluon exchange. The dotted line shows the total decay width of toponium. In the case of $\zeta = 4$ the lines are terminated by the unitarity bound.

Fig. 2. The ratio $\Gamma_{\text{tot}}/E_{B(n)}$ of toponium for the cases of Higgs exchange with $m_H = 50\text{GeV}$ (dashed lines) and $m_H = 60\text{GeV}$ (full lines) and with $\zeta = 0, 1, 2, 3$ and 4, respectively. The dot-dashed line shows the ratio corresponding to pure gluon exchange.

Fig. 3. The binding energy $E_{B(n)}$ of the Ξ_u baryon for the case of Higgs exchange with $m_H = 50\text{GeV}$ (dashed lines) and $m_H = 60\text{GeV}$ (full lines) and with $\zeta = 0, 1, 2, 3$ and 4, respectively. The dot-dashed line shows the binding energy corresponding to pure gluon exchange. The dotted line shows the total decay width of this baryon.

Fig. 4. The ratio $\Gamma_{\text{tot}}/E_{B(n)}$ of the Ξ_u baryon for the case of Higgs exchange with $m_H = 50\text{GeV}$ (dashed lines) and $m_H = 60\text{GeV}$ (full lines) and with $\zeta = 0, 1, 2, 3$ and 4, respectively. The dot-dashed line shows the ratio corresponding to pure gluon exchange.

FIG. 1.

FIG. 2.

Fig. 3.

Fig. 4.