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Physics of Superheavy Onia †

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PHYSICS OF SUPERHEAVY ONIA

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The properties of quark-antiquark bound states made up with a superheavy quark (mass $\gtrsim m_W$) are discussed along with their production and decay at super-high-energy proton-proton colliders. Various aspects of superheavy onia go beyond the naïve extrapolation from known light and heavy onium systems. The empirical "constant" law for the leptonic width no longer holds; The pseudoscalar is the predominantly produced state in pp collisions.

Three categories of onia are described: (1) Nonexistent quarkonia, which literally do not exist as bound states; An important example is the superheavy toponium. (2) Heteronia, made of a quark with a mass generated by the SU(2)×U(1) breaking. A typical example is the fourth-generation quarkonium with a small KM mixing. (3) Homonia, whose mass is unrelated to the weak scale. An example is the state made of an extra charge-$\frac{1}{3}$ "quark" in the E_6 model.

The second category is phenomenologically the most interesting: Dominant decay modes include the final states with weak gauge bosons and/or Higgs bosons, specific mode being different for each onium state. At super pp colliders this kind of onia can be a rich source of Higgs bosons, which can be tagged by weak bosons.

Related topics of the extra Z boson as a source of the Higgs and the production of gluinonium and technipionium are also discussed.

INTRODUCTION

A proton-proton collider is a difficult machine for the physics of the future. Our recent experience tells us that it is hard to discover or exclude a new particle at hadron machines, even if it would be copiously produced. On the other hand, it is much easier to give a definite statement on the existence of a new particle in the clean environment of electron-positron colliders, something which we can see already from the long list of negative results of new particle searches.

However, if we look back to the recent history of new particle discoveries in the 1970's, we observe that the two new quark flavors (charm and bottom) were found in hadron reactions no later than at e^+e^- storage rings. For charm, the discovery was made simultaneously with

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Table I. Quarks.

Category	Definition	Example
Light	$m_q \lesssim \Lambda_{QCD}$	u, d, s
Heavy	$\Lambda_{QCD} \lesssim m_q \lesssim m_W$	$c, b, t(?)$
Superheavy	$m_Q \gtrsim m_W$	$t(?), \ldots (?)$

πp and e^+e^- reactions (hence the name J/ψ), and for bottom, the discovery in pp interactions preceded its confirmation at an e^+e^- machine by a year. The moral is that hadron machines can do well if there is a distinctive signature of the new phenomena (lepton pairs in the two examples). This was of course the case for the recent discovery of the W and Z bosons at the CERN $p\bar{p}$ collider.

One more point which emerges from the above example is that hidden-flavor states were found before the discovery of open-flavor states. In other words, quarkonia preceded flavored mesons. This is also related to the fact that a quarkonium can provide a clearer trace (decay modes) of its existence.

So, in considering the physics possibility at future super-high-energy proton colliders, it seems worthwhile to study* the production and decay of a new onium, the bound state of a quark and its antiquark (or the bound state of more exotic particles).

Actually, it turns out that the properties of onia changes drastically when the mass of its constituent quark exceeds the W mass. In contrast to light quarks (u, d, s) and heavy quarks (c, b), we call such a heavy quark ($m_Q \gtrsim m_W$) a *superheavy* quark. It is on these aspects which I will concentrate in this talk.

HETEROQUARK *vs* HOMOQUARK

The first qualitative novelty we encounter is that one should really distinguish two types of superheavy quarks. Although this distinction applies to lighter quarks also, there occurs significant phenomenological difference in the onia properties *only* if the quark is superheavy. We shall call these two classes of quarks *heteroquarks* and *homoquarks*. More precisely we define them as follows:

(1) A heteroquark is massless if the weak SU(2)×U(1) symmetry is not broken, and acquires mass through the weak symmetry breaking. In a formal language, the left-handed and right-handed counterparts are in different SU(2)×U(1) representations. All the quarks we know belong to this category. A fourth-generation quark is by definition a heteroquark.

(2) A homoquark, on the other hand, can be massive before the weak symmetry breaking. The left- and right-handed quarks are in the same SU(2)×U(1) representation and can have an invariant mass term at the Lagrangian level. Some examples include the exotic "d quark"

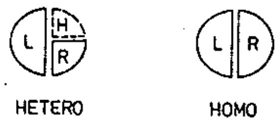

Fig. 1. Heteroquark and homoquark.

* A large part of this talk is based on the collaboration with V. Barger, E.W.N. Glover, W.-Y. Keung, M. G. Olsson, C. J. Suchyta III, and X. Tata. For details I refer to Ref. 1. See also Ref. 2 for a related work.

present in the superstring-inspired E_6 model. Broadly speaking, the gluino, the supersymmetric partner of the gluon, belong to this category, although it is not a color triplet but an octet and it is a Majorana fermion.

UPPER LIMITS ON THE QUARK MASS

As we are considering very heavy quarks, it is natural to ask how heavy a quark can one tolerate. For a homoquark the answer is simple: There is no limit on its mass. This is because the origin of the quark mass is totally unrelated to the weak interaction. Of course, at the aesthetic level, one is faced with the heralded problem of hierarchy and naturalness. In a renormalizable theory, however, one may choose any value of the quark mass, without referring to "bare" quantities which are the source of the problem. The resulting theory is healthy after proper renormalization is done.

On the other hand, the situation is totally different for a heteroquark. The mass comes from the Higgs mechanism, so the Yukawa coupling of a heteroquark with the Higgs is proportional to the mass. If we want to make the quark mass larger, we are forced to go to a strong-coupling regime. Thus the limit of large quark masses is singular here and many strange phenomena can happen.

There are some theoretical "limits" on heteroquark masses:

ρ parameter: The neutral-to-charged current coupling ratio ρ is shifted from the canonical value $\rho = 1$ if there is a split weak multiplet.[3] A generous bound $|\rho - 1| < 0.02$ would give a limit $|m_{t'} - m_{b'}| \lesssim 200$ GeV for any pair of quarks.† There is no limit for a degenerate doublet, however, even if the mass is very large.

Breakdown of perturbation theory: The Yukawa coupling exceeds unity for a very heavy quark. To be quantitative, partial-wave unitarity for tree scattering amplitudes is violated if $m_Q \gtrsim 500$ GeV.[5] This is not a *real* limit; it tells us only that above this value we are dealing with a strongly interacting theory, in which higher order contributions are no longer negligible and we cannot (as yet) make any reliable prediction.

Vacuum stability: From the stability of the broken vacuum, derived from the one-loop effective potential, one gets $m_Q \lesssim 100$ GeV if $m_H \sim 0$.[6] However the limit goes away if there exist heavy scalar particles (heavy Higgs, supersymmetry, *etc.*).

Renormalization group limits: Because the Yukawa coupling is not asymptotically free, one may deduce a limit on the coupling at the weak scale by demanding that the coupling does not diverge (or become bigger than unity) up to some scale, which can be the GUT scale,[7] the Planck mass,[8] *etc.** This kind of limit is always better than the simple perturbation limit because one can take advantage of the renormalization-group evolution to push down the allowed Yukawa strength *at the weak scale.* These limits are, however, rather prejudice-dependent, since one has to assume a desert between the weak scale and the high scale.

One may conclude that there is no rigorous upper limit on the heteroquark mass. I will, however, restict myself to the mass range $m_Q < 500$ GeV, because otherwise one cannot rely on predictions based on perturbation theory at all.

SPECTRUM OF ONIA

I will discuss only the lowest-lying states of the quarkonium system, the S- and P-wave

† In a recent global analysis of the "neutral current" data, Amaldi *et al.*[4] claim that $m_t < 180$ GeV (at 90% CL and if $m_H < 100$ GeV).

* The so-called "triviality" bound should be in this category. In my opinion this bound is more than questionable because it is obtained by requiring the validity of the gauge-Higgs theory itself far above the Planck mass, where gravity should certainly play an important role.

Table II. Spectrum of onia. There are, of course, radial and higher orbital excitations.

J^{PC}	$S=0$	$S=1$
$L=0$	0^{-+}	1^{--}
$L=1$	1^{+-}	$0^{++}, 1^{++}, 2^{++}$

Names	$S=0$	$S=1$
$L=0$	η	ψ
$L=1$	h	χ_0, χ_1, χ_2

ground states. The spectrum is predicted by a simple quark model as is well known (see Table II).

In this talk I will use the simplified names for these states, as given in Table II. If one has to be more specific, one can add a subscript to indicate the flavor content, *e.g.*, η_c, ψ_b ($= \Upsilon$), *etc.* Please remember that "η" is not *the* η meson, connected to the U(1) problem! Note that for the gluinonium, there are no $C = -$ states (ψ, h), due to the Majorana nature of gluinos.

NOVEL FEATURES OF SUPERHEAVY ONIA

I summarize now some of the new features of superheavy onia, which may lie beyond a simple extrapolation from known quarkonia. Each of these properties will be explained below in more detail.

(1) The empirical "constant law" ($\Gamma_{ee}/e_q^2 \sim$ const.) for the leptonic width no longer holds. Eventually one expects that this quantity scales linearly with the quark mass (up to a logarithmic correction).

(2) Quarkonium production cross section in hadronic interactions is only a tiny fraction of the quark-pair production cross section of the same flavor, in contrast to the charmonium and bottomonium cases.

(3) There is a strong hierarchy in the production cross section of states with different quantum numbers. The pseudoscalar η accounts for most of the onium cross section. The vector ψ production is much suppressed, and P-wave χ states are even more suppressed.

(4) For the heteronia (onia made of heteroquark), "weak" decay modes are enhanced and they actually become the dominant modes of annihilation decays. It is important here to discriminate heteronia from homonia, for there is no enhancement at all for the latter.

ANNIHILATION STRENGTH

To give a detailed discussion of the points mentioned above, it is convenient to introduce the concept of "annihilation strength," which has the dimension of mass and is defined as follows: For an S-wave state

$$F_S = \frac{|R_S(0)|^2}{M^2} ,$$

and for a P-wave state

$$F_P = \frac{|R'_P(0)|^2}{M^4} .$$

Here M is the mass of the onium (also used throughout the paper), $R_S(0)$ is the (nonrelativistic) radial wave function of the S state at the origin, and $R'_P(0)$ is the derivative of the radial wave function of the P state at the origin. The merit of introducing the quantity F is that the annihilation decay width Γ of a state can be estimated simply as the annihilation strength multiplied by some appropriate coupling factor

$$\Gamma \sim (\text{coupling})^2 \cdot F ,$$

where "coupling" is, for instance, g_s^2 for the two-gluon decay, and e^2 for leptonic decays.

An important relation for superheavy onia is

$$F_S \gg F_P ,$$

which should be contrasted with $F_S \sim F_P$ for light onia. The latter can be inferred from $f_\rho \sim f_{A_1}$ for up/down quarks, and $\Gamma(\eta_c) \sim \Gamma(\chi_0)$ for charm. (In the charmonium case the P-wave annihilation is actually beginning to be suppressed.)

It is easy to understand the above inequality by remembering that for a very heavy onium the one-gluon exchange approximation for the potential becomes appropriate (for the ground states at least; the confining interaction is still important for higher excitations). In this approximation, the annihilation strengths can be read off any elementary quantum mechanics textbook, with appropriate insertion of color factors and substitutions:

$$F_S = \frac{4}{27}\alpha_s^3 M ,$$

$$F_P = \frac{1}{5832}\alpha_s^5 M ,$$

$$F_P/F_S = \frac{1}{864}\alpha_s^2 \sim 10^{-5} .$$

The reason for the large ratio above is that for a Coulomb potential the shape (wave function) of a bound state is essentially determined by the Bohr radius $\sim (\alpha_s M)^{-1}$, and therefore F_P is smaller than F_S by a factor of α_s^2. The additional small numerical factor ($\frac{1}{864}$) is in part due to the somewhat inadequate definition of F_S and F_P (the onium mass is four times the reduced mass).

For a realistic potential, which agrees with the expected asymptotic behaviors and reproduces the charmonium and bottomonium spectra, such as the Richardson[9] and the Wisconsin[10] potentials which I will use to estimate the rates in this talk, F_P is somewhat larger than the Coulomb result but the overall tendency remains correct.

In Fig. 2 the S-wave annihilation strength F_S of heavy quarkonia is plotted. The region sandwiched by the Richardson and Wisconsin curves should give a rather realistic estimate. Included in the same figure are the experimental data of the "reduced" leptonic widths of the ground-state vector mesons. The plotted quantity $\Gamma/(4\alpha^2 e_q^2)$ is equal to F_S in the quarkonium calculation in the lowest order. One should remember that the QCD correction factor to the rate $(1 - \frac{16}{3\pi}\alpha_s)$ is not at all small; Actually it amounts to $\sim 50\%$ for charmonium and $\sim 30\%$ for bottomonium.

A conclusion one can draw from the figure is that the empirical "constant law," which is quite good for the five known states, cannot continue to hold for heavier quarkonium (in particular for toponium). The rate should eventually scale as $\Gamma \sim M$, with a logarithmic correction due to asymptotic freedom.

The P-wave annihilation strength F_P is shown in Fig. 3. Realistic values are larger than the Coulombic estimate, because the P-wave state is more extended than the S state and is thus more sensitive to the confining part of the potential. Still, they are much smaller than the corresponding F_S values.

There are two important implications of the fact that $F_S \gg F_P$.

(1) The annihilation decay of the P states is much slower than that of the S states. This makes the P-wave annihilation decay less competitive to the other decay mechanisms, notably the constituent decay, even when the S state annihilation is dominating (see later).

(2) The production cross section of the P states will be much less than that of the S states, as we discuss in some detail below.

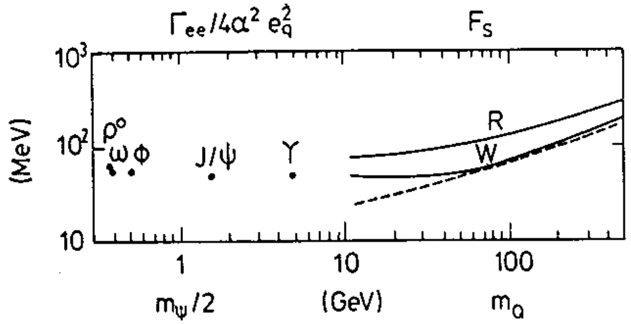

Fig. 2. Annihilation strength F_S for the ground S state of a quarkonium. Solid curves: Richardson (R) and Wisconsin (W) potentials. Dashed curves: Coulomb potential approximation. Also shown are the corresponding experimental data extracted from the leptonic width of known vector mesons, which displays the empirical "constant" law.

ONIA PRODUCTION IN HADRON COLLISIONS

I will now turn to the discussion of the production of onia in pp collisions. Before going to the specific production processes, I note that the cross section of superheavy onia is much smaller than the corresponding cross section of the open-flavored quark. This may be explained with a duality argument for the dominant production process $gg \to Q\bar{Q}$, for which the part below the flavor threshold is supposed to turn into the quarkonia states. Although this kind of calculation cannot be trusted quantitatively (there is an ambiguity in the selection of the quark mass value, and also a problem of the division into each onium state), it can provide a qualitative understanding of the relative suppression of the onia production.

To be specific, let me contrast a superheavy onium with charmonium. For charmonium, the resonance region extends from 2.98 GeV to 3.73 GeV, which is not a small interval compared

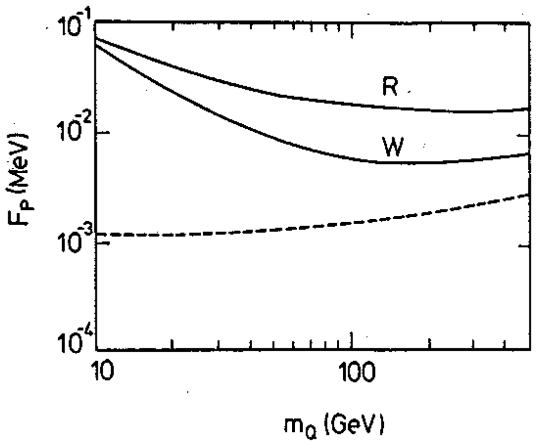

Fig. 3. Annihilation strength F_P for the ground P state of a quarkonium. Curves are the same as in Fig. 2. Notice the difference in the scale.

Table III. Production of onia in pp collisions.

State	Mechanism	Cross section
η	$gg \to \eta$	1(Normalization)
ψ	$gg \to \psi g$	10^{-2}
	$gg \to \chi_{0,2} \to \psi\gamma$	$< 10^{-3}$
	$q\bar{q} \to \psi$	10^{-4}
	$WW \to \psi$	$< 10^{-5}$
h	$gg \to hg$	10^{-4}–10^{-5}
	$gg \to \eta' \to h\gamma$	10^{-3}
χ_0, χ_2	$gg \to \chi_0, \chi_2$	10^{-3}
χ_1	$gg \to \chi_1 g$	10^{-4}–10^{-5}
	$gq \to \chi_1 q$	10^{-4}–10^{-5}
	$q\bar{q} \to \chi_1 g$	$< 10^{-6}$
	$q\bar{q} \to \chi_1$	10^{-7}

to the charm mass itself. For superheavy onia with a mass of a couple of hundred GeV, on the other hand, the typical mass scale is orders-of-magnitude larger than that for charm, but the extent of the resonance region does not change much (at most a few GeV). Thus the importance of the resonance region in the cross section is much diminished.

There are various mechanisms for onia production in proton interactions. These are summarized in Table III.

The most important is two-gluon fusion into the pseudoscalar η. The cross section is proportional to the decay width $\Gamma(\eta \to gg)$, which gives the inverse reaction rate. The η cross section decreases by many orders of magnitude when the onium mass changes from 100 to 1000 GeV. Fig. 4 shows the η cross section in pp interaction at $\sqrt{s} = 40$ TeV. At this energy the cross section is ~ 100 pb for $M = 250$ GeV, and ~ 1 pb for $M = 750$ GeV. Note, however, that the expected number of η per year at the SSC is quite large; For the nominal luminosity of 10^{33} cm^{-2} sec^{-1}, a cross section of 1 pb corresponds to 10^4 events per year.

The vector (ψ) cross section is $\sim 1/100$ of the η cross section for the mass range under consideration. The suppression is because there is no gg coupling to the ψ, so that the higher-order process $gg \to \psi g$ must be invoked.* The cross section of χ_0 production is further suppressed and is only $\sim 1/1000$ of the η production. This is due to the previously stressed relation $F_P \ll F_S$, in spite of the fact that the two-gluon fusion channel is possible. The χ_2 cross section is similar ($\frac{4}{3}$ times that for χ_0). Other states h and χ_1 have even smaller cross sections.

These production properties are the same for heteronia and homonia, since they have identical color interactions. The production cross section of gluinonium is larger since the larger color charge of the gluino leads to a larger annihilation strength.

DECAYS OF SUPERHEAVY ONIA

I now turn to the decay of superheavy quarkonia. According to their decay properties one

* The feeddown from $\chi \to \psi\gamma$, which is important for charmonium, is here much smaller than the direct production due to the smaller χ production cross section.

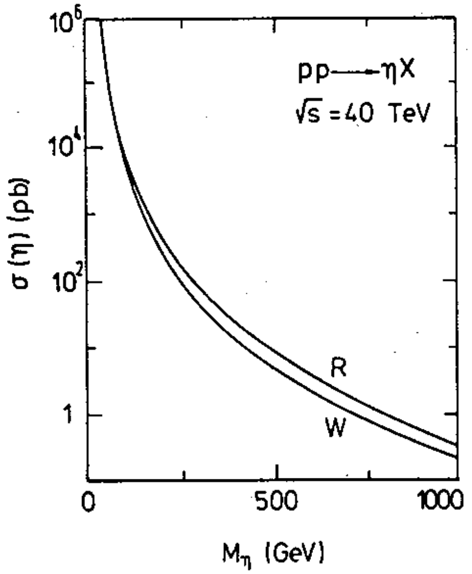

Fig. 4. η cross section at the SSC. Potential dependence enters here because the ηgg coupling is proportional to the quarkonium wave function.

can classify three types of superheavy onia.

(1) *Nonexistent quarkonium*
(2) *Heteronium*
(3) *Homonium*

The first one, although sounding nonsensical, is an important class, because a superheavy toponium would belong to this category. An example of the second class (heteronia) is the lighter of the fourth-generation quarkonia (probably $(b'\bar{b}')$), if the Kobayashi-Maskawa (KM) mixing to lighter quarks is sufficiently small. The heavier of the fourth-generation quarkonia $(t'\bar{t}')$ is in either (1) or (2) depending on the mass splitting. The last class (homonia) includes the E_6 exotic onia.

Nonexistent quarkonia

If the decay width of a bound state exceeds the binding energy, it follows from the uncertainty principle that it is not possible to distinguish the bound state from the continuum (see Fig. 5).

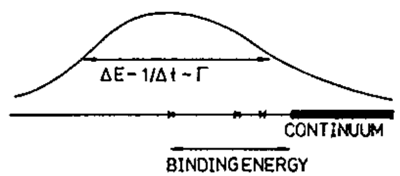

Fig. 5. Bound states with large widths are indistinguishable from the continuum.

This situation actually occurs for a heavy toponium[11] when $m_t \gtrsim 150\,\mathrm{GeV}$, as the decay rate $\Gamma((t\bar{t}) \to t\bar{b}W)$ is proportional to m_t^3 while the binding energy $2m_t - M$ is roughly proportional to m_t:

$$\Gamma \sim \frac{\alpha m_t^3}{m_W^2}\,, \qquad \text{binding energy} \sim \alpha_s m_t\,.$$

Existent quarkonia: three classes of onium decay

Just as there are three classes of onia, one also finds three types of decay modes.

1. *Annihilation decay:* Here constituent quark and antiquark annihilate to produce the final state (Examples: $\eta \to gg$, $\gamma\gamma$, $\psi \to ggg$, $\ell^+\ell^-$).

2. *Transition:* Transition inside the onium family can occur by emitting light particles. There are two subtypes: hadronic transitions (Example: $\psi' \to \psi\pi\pi$) and radiative transitions (Examples: $J/\psi \to \eta_c\gamma$, $\chi_J \to \psi\gamma$).

3. *Constituent decay:* The constituent quark or antiquark decays singly, while the other remaining as a spectator. No known example exist yet, but it will be important for heavier onia (Example: $\psi_t \to t\bar{b}\ell\bar{\nu}$ or $t\bar{b}W$).

Constituent decay

The weak decay rate of a (hetero) quark is proportional to m_Q^5 if $m_Q < m_W$ or m_Q^3 if $m_Q > m_W$. As the quark mass increases, the weak decay starts competing with the strong and electromagnetic decays. The decay of a superheavy quarkonium can be dominated by the weak decay (constituent decay). The decay rate is shown in Fig. 6. If there is no mixing suppression, the large width $\Gamma((Q\bar{Q}) \to Q\bar{q}W \text{ or } \bar{Q}qW)$ totally masks other (interesting!) decay modes. However, if the mixing is less than a few percent, the constituent decay is much suppressed and the S-wave states (η, ψ) mainly decay by annihilation. (To get a feeling, the annihilation rate for $\eta \to gg$ is between 5 and 10 MeV for the relevant mass range.) For the P-wave states a smaller mixing ($\lesssim 10^{-3}$) is required for this to occur. The constituent decay is also suppressed by the available phase space, if the quark mass difference $m_Q - m_q$ is not so large ($\lesssim 50\,\mathrm{GeV}$), which could happen for $t' \to b'$. In this case a real W cannot be produced and the decay rate $\Gamma((t'\bar{t}') \to t'\bar{b}'\ell\bar{\nu})$ *etc.* receives a suppression factor of $(m_{t'} - m_{b'})^5$. The constituent decay of a superheavy toponium is never suppressed, since we know that the mixing U_{tb} should be essentially unity. On the other hand, there are models which predicts a small mixing for the fourth generation quarks.

For a homoquark, the constituent decay is not important since it usually occurs only via a small mixing with a heteroquark.

Transition to lower-lying states

The M1 transition $\psi \to \eta\gamma$ is completely negligible ($\Gamma \ll 1\,\mathrm{eV}$). The E1 transitions $\chi_J \to \psi\gamma$ and $h \to \eta\gamma$ have comparable rates to annihilation decays, typically $\Gamma \sim 5\,\mathrm{keV}$. The hadronic transitions such as $\chi_J \to \eta\pi\pi$, $\psi\omega$, and $h \to \psi\pi\pi$ may be estimated by a QCD multipole expansion and are expected to be negligible. Thus the only important transitions are the E1 radiative decays from the P states to the S states.

Annihilation decays

The annihilation decay rate is related to the annihilation strength discussed earlier. For the strong decay to two gluons, we have $\Gamma \sim \alpha_s^2 F$ and for the electromagnetic decay modes to $\gamma\gamma$, e^+e^- the rate is $\Gamma \sim \alpha^2 F$, which is smaller than the strong decay by a factor of $(\alpha/\alpha_s)^2$. For these two kinds of decay there is no difference between heteronia and homonia.

The weak (annihilation) decay modes to ZZ, W^+W^-, ZH, ... are more involved. Here heteronia show totally different behavior than homonia. The decay rates of homonia are of the normal order $\Gamma \sim \alpha^2 F$. However, the rates for heteronia are sometimes enhanced, depending on the final state and on the quantum number of the initial state. In some cases the rate is doubly enhanced ($\Gamma \sim (M^4/m_W^4)\alpha^2 F$), rather than singly enhanced ($\Gamma \sim (M^2/m_W^2)\alpha^2 F$). It can also happen however that there is no enhancement at all ($\Gamma \sim \alpha^2 F$).

The annihilation decay rates of the six states are summarized in Table IV for heteronia (explicit formulas for these rates can be found in Ref. 1). This table should be compared to the corresponding table (Table V) or homonia.

The dominant decay mode of heteronia differs for each onium state; They are

$$\eta \to ZH\,,$$
$$\psi \to W^+W^-\,,$$
$$h \to \eta\gamma\,,$$
$$\chi_0 \to HH\,,$$
$$\chi_1 \to ZH\,,$$
$$\chi_2 \to W^+W^-,\ ZZ\,.$$

The branching fraction for these decays can reach nearly 100% provided that the mode is not kinematically suppressed.

The dominant decay of homonia, on the other hand, is always the strong decay mode to gg, ggg, or $gq\bar{q}$ (and possibly the radiative transition for the P states).

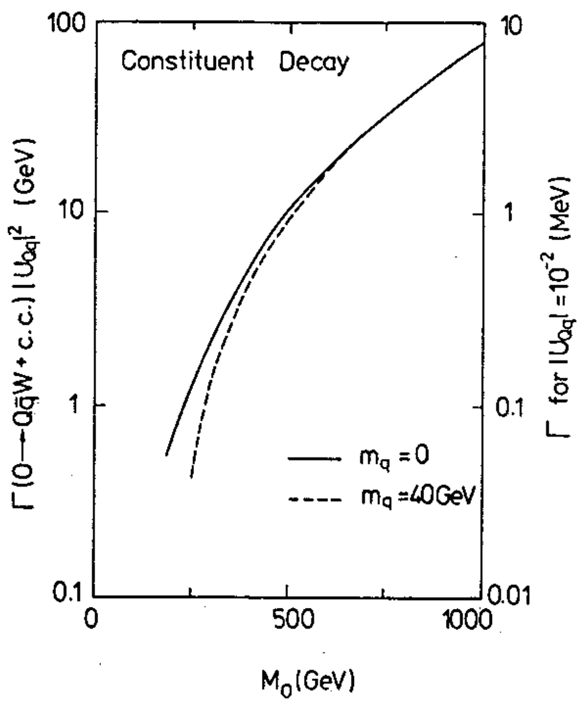

Fig. 6. Single quark decay rate of a heteronium.

Table IV. Heteronia annihilation decay. The symbols are: — : the decay does not occur (at least in lowest order); o: the decay is of normal strength; ↑: singly enhanced; ↑↑: doubly enhanced; ↓: singly suppressed; ↑↿ shows that the decay is doubly enhanced but there is an additional helicity suppression factor, resulting in the net factor of $M^2 m_L^2/m_W^4$.

Mode	η	ψ	h	χ_0	χ_1	χ_2
gg	o	—	—	o	—	o
$ggg/gq\bar{q}$	o	o	o	o	o	o
$\gamma\gamma$	o	—	—	o	—	o
$\ell^+\ell^-$, $q\bar{q}$	—	o	—	—	o	—
L^+L^-, $t\bar{t}$	↑↿	o	—	↑↿	o	—
$Z\gamma$	o	↑	↑	o	↓	o
ZZ	o	↑	↑	↑↑	↑	↑↑
W^+W^-	o	↑↑	↑	↑↑	↑	↑↑
γH	—	↑	↑	—	—	—
ZH	↑↑	↑	↑	—	↑↑	↑
HH	—	—	—	↑↑	—	↑↑

Table V. Annihilation decays of a homonium. Symbols are the same as in Table IV. The parenthesis means that the decay occurs only if the constituent quark is a weak non-singlet.

Mode	η	ψ	h	χ_0	χ_1	χ_2
gg	o	—	—	o	—	o
$ggg/gq\bar{q}$	o	o	o	o	o	o
$\gamma\gamma$	o	—	—	o	—	o
$\ell^+\ell^-$, $q\bar{q}$	—	o	—	—	o	—
L^+L^-, $t\bar{t}$	—	o	—	—	o	—
$Z\gamma$	o	—	—	o	↓	o
ZZ	o	—	—	o	↓	o
W^+W^-	(o)	o	(o)	(o)	(↓)	(o)
γH	—	—	—	—	—	—
ZH	—	o	—	—	—	—
HH	—	—	—	—	—	—

The mechanism causing the enhancement of the weak-boson modes for heteronia is the following: The spin vector of a longitudinally polarized massive spin-1 particle (say W) is proportional to E_W/m_W at high energies (where $E_W \sim \frac{1}{2}M$ for onium decay), giving the possibility of a single enhancement factor per W. Actually, the spin vector is approximately proportional to the momentum ϵ^μ(longitudinal) $= (1/m_W)\,k^\mu + O(m_W/E_W)$. If the current which couples to the W is conserved, this possible enhancement does not appear in the physical amplitude, since the remaining part of the spin vector is suppressed as the energy increases. For an axial vector coupling of a heavy quark, the current is not conserved and the divergence will be proportional to the quark mass, resulting in an enhancement factor of M/m_W in the amplitude. When there are two longitudinally polarized W's in the final state, one can thus get a double enhancement of M^2/m_W^2 in the amplitude.

In addition, if there is a Higgs boson in the decay product, the Yukawa coupling (proportional to the quark mass) enhances the amplitude, giving a factor of M/m_W relative to the gauge coupling.

On the contrary, there is no enhancement at all for homonia. This is because a homoquark couples to the weak bosons only through a vector coupling. For instance, the vector and axial couplings of a fermion to the Z^0 are

$$v = I_{3L} + I_{3R} - 2Q\sin^2\theta_W \ ,$$
$$a = I_{3L} - I_{3R} \ .$$

For a vectorlike (homo) fermion the axial coupling vanishes. If there is only a vector coupling, the possible enhancement for longitudinal W's is killed by current conservation. To complete the argument one should note that there is no (enhanced) Yukawa coupling to the Higgs boson.

The total width of the heteronium ($b'\bar{b}'$) is shown in Fig. 7. The Higgs boson is assumed here to be very massive. The η width is dominated by the two-gluon mode and increases only moderately with the mass. On the contrary, the ψ width at higher masses is controlled by the WW mode and rapidly increases with the mass. These two annihilation widths are larger than the constituent decay (SQD) with a 1% mixing.

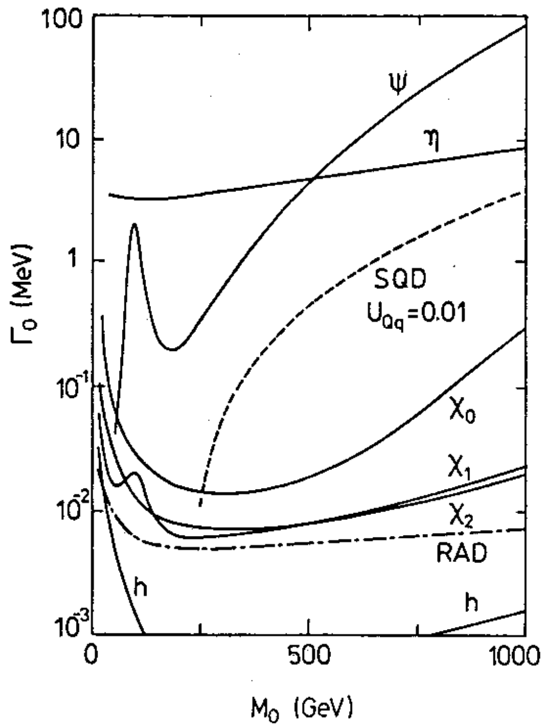

Fig. 7. Heteronium total annihilation width (for a charge-$\frac{1}{3}$ quark) compared to the constituent decay and radiative (E1) transition widths. Wisconsin potential is used.

For the modes with the Higgs boson, the $\psi_{b'} \to H\gamma$ branching ratio can reach more than 10% for some mass range (even four times bigger for the $\psi_{t'}$), the $\eta \to ZH$ and $\chi_1 \to ZH$ can be almost 100% for higher masses, and the $\chi_0 \to HH$ mode can be close to 100%.

DETECTION OF ONIA AT SUPERCOLLIDERS

At proton-proton colliders the most important backgrounds for quarkonium signals come from the generalized "Drell-Yan" processes, which produce ($q\bar{q}$-originated) electroweak final states such as e^+e^-, $\gamma\gamma$, ZZ, W^+W^-, *etc.* These backgrounds are more important (relative to the signal) for higher onium mass, because the gluon-gluon luminosity responsible for onia production is steeper than the quark-antiquark luminosity. For a fixed mass, the background is less important at higher pp c.m. energies, because of the same reason.

At SSC energies, the backgrounds are in general severe and the expected onia signal tends to be buried in the background, especially when one takes into account the fact that one cannot observe the W and Z directly and that only the leptonic decays are likely to be observable. The best prospects lie in the decays $\psi \to e^+e^-, \mu^+\mu^-$, for masses under the W pair threshold ($M \lesssim 200$ GeV), and $\eta_{t'} \to \gamma\gamma$[12] ($\eta_{b'} \to \gamma\gamma$ is sixteen times smaller).

The most intriguing signal is the decay $\eta \to ZH$ which can have almost 100% branching ratio. The η is the state with the largest production cross section. Furthermore, the signature is rather clean. One can tag the event by the Z^0, which has a Jacobian peak in p_T, and the whole system is highly constrained by the kinematics, $M(ZH) = M_\eta$, *etc.*

For $m_H > 2m_W$, one has three-boson events with $M(ZZ, WW) = m_H$ and $M(ZZZ, WWZ) = M_\eta$. For $m_H < 2m_t$, one can look for the decay $h \to \tau^+\tau^-$ with $\sim 4\%$ branching ratio. (One can reconstruct two τ four-momenta from the observed directions of the τ decay products and the missing transverse momentum, provided that the two taus are not parallel.)

For the notorious intermediate mass range[13] $2m_t < m_H < 2m_W$,* the dominant Higgs decay mode is $H \to t\bar{t}$. The most serious background comes from the process $gg \to Zt\bar{t}$, if the top quark can be identified through its decay. This background has been examined and it is concluded that one can achieve a signal-to-background ratio of better than 1:1 under generous cuts on the $t\bar{t}$ and $Zt\bar{t}$ masses.[14] Thus one may have the possibility of finding the fourth generation quarkonium and the Higgs boson at the same time!

MORE EXOTIC STATES

Gluinonium

Due to Fermi statistics, we have only the η and χ_J states of gluinonium. The production cross section at pp colliders is $\sim$77 times that for a quarkonium, due to the larger color factor. There are no electroweak decay modes. The main decay mode is to two gluons, and possibly to $q\bar{q}$ via squark exchange. It is very difficult to detect these states, because one has to look for a peak in the jet-jet invariant mass where there is a huge QCD background. Constituent decay is also possible via $\tilde{g} \to \tilde{q}\bar{q}$ or $\tilde{g} \to q\bar{q}\tilde{\gamma}$. These would give a missing momentum signal, but the continuum $\tilde{g}\tilde{g}$ production is much larger and essentially indistinguishable from the onium signal.

Technipionium

In extended technicolor models many pseudo-Goldstone bosons (called technipions in this section) are predicted. Among these there are color-octet technipions, which are also weak

* If $m_t > m_W$ (in which case no "intermediate" region), look for τ pair for $m_H < 2m_W$, W^+W^-/ZZ for $m_H > 2m_W$. The branching ratio for $H \to W^+W^-/ZZ$ is large unless $m_W \ll m_t \lesssim \frac{1}{2}m_H$.

triplets ($\pi_8^+, \pi_8^0, \pi_8^-$). These states can form color-singlet bound states below threshold. Assuming that their gauge couplings are not suppressed by form factors, one can predict the properties of these states.[15] Because the constituents are color octet, the production cross section is similar to gluinonium production. Unlike the gluino case, the constituents have electroweak charges, leading to distinctive electroweak decay modes such as W^+W^-, $\gamma\gamma$, and $Z\gamma$. The branching ratios are in the range of 0.1–0.3% for these modes. There are no enhancement factors. However due to the large cross section the signal should stand out over the background.

Extra Z

Although it is not a bound state but an elementary gauge boson, I will touch upon this subject, since some of the overall characteristics resemble that of the onia. In particular, the extra U(1) gauge boson in the superstring-inspired E_6 model may have a substantial branching fraction to W^+W^- and to ZH at the few percent level.[16] There is no enhancement in these decays: For the WW mode, the double enhancement coming from the two longitudinal W's is cancelled by the small Z'–Z mixing. In fact, the $Z'WW$ vertex can come only from the SU(2) non-Abelian vertex and the SU(2) impurity in the extra U(1) boson is suppressed by $(m_Z/m_{Z'})^2$. The ZH mode is singly enhanced by the longitudinal Z, but counter-suppressed by the dimensional $Z'ZH$ coupling proportional to m_Z. The interesting fact that there is a nonvanishing off-diagonal $Z'ZH$ coupling arises because there is more than one Higgs field in the theory.

Though the branching ratios are not terribly large, the production rate is much larger, because the Z' has an elementary gauge coupling strength to the initial quarks.

ONIA PRODUCTION AT HIGHER ENERGIES

Since this Workshop is aimed at the ELOISATRON, it is appropriate to ask what the gain would be if one goes from 40 TeV to 200 TeV. The production rate of onia from gluon fusion increases by an order of magnitude (although there are more forward events). The $q\bar{q}$-induced background increases more slowly. One can achieve an improvement in the signal-to-background ratio of up to a factor 2–3. For the elementary gauge bosons produced by $q\bar{q}$, one has an increase of the cross section, but there is no change in the S/B ratio.

CONCLUSION

To summarize:

(1) At super proton-proton colliders the pseudoscalar onium (η) is substantially produced for a wide mass range. The vector (ψ) production cross section is 10^{-2} times that of the η, and the scalar and tensor ($\chi_{0,2}$) are another order of magnitude smaller.
(2) Superheavy toponium does not exist.
(3) The decay of homonium (*e.g.* E_6 exotic onium) is mostly strong (to gluons) and only a small fraction goes to electroweak final states.
(4) Heteronia (*e.g.* the fourth-generation onium with small KM mixing) have enhanced electroweak decay modes. $\eta \to ZH$ and $\psi \to W^+W^-$ are dominant.
(5) The decay η(hetero) $\to ZH$ provides a good opportunity for Higgs detection, with manageable background.
(6) An extra U(1) gauge boson, with the decay $Z' \to ZH$, is an alternative to a heteronium for a Higgs search.

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