PROPERTIES OF TOPONIUM

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I. Introduction

In this report, we examine the properties of the bound states $\Theta(t\bar{t})$ of t and $\bar{t}$ quarks and the possibilities of studying these bound states at different machines. Consistency of the standard electroweak model requires the presence of a top quark t. The standard model also allows (but does not require) the existence of a fourth family of quarks and leptons. Therefore, our discussion with appropriate modifications, can easily be applied to any heavy quark.

The most important properties of Toponium, $\Theta(t\bar{t})$, are

(1) its mass $M_\Theta \sim 2m_t$,

(2) its various decay widths, and

(3) its spectroscopy.

In the standard electroweak model, we expect

$$20 \text{ GeV} \lesssim m_t \lesssim 130 \text{ GeV}, \tag{1}$$

where the lower bound is provided by PETRA data and the upper bound comes from theoretical arguments based on the simplest version of the standard model[1]. As a function of the mass of Θ, the various decay widths of Θ are calculable in the standard model. They are shown[2] in Fig. 1. In the absence of the Z^o effect,

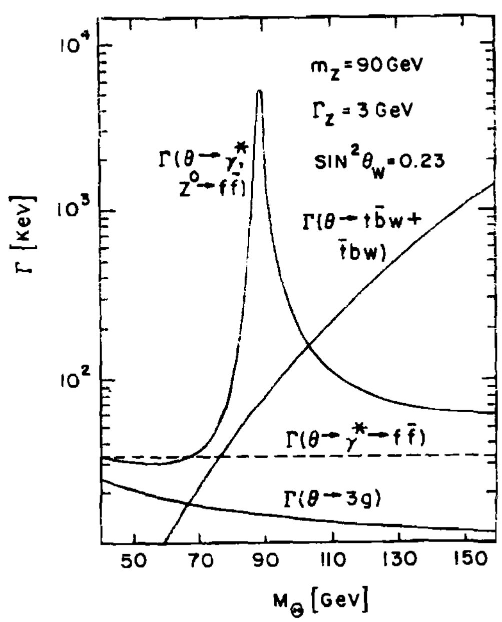

Fig. 1: The electromagnetic, the electroweak and the strong decay widths as a function of M_Θ. The sum over all fermions f in the final state has been performed and a constant decay width of $\Gamma(\Theta\to\gamma^*\to\mu\mu)$ of 5 KeV has been assumed. In $\Gamma(\Theta\to tbW)$ decay, the propagator effect of the virtual W boson is ignored (Ref. 2).

the leptonic width is roughly

$$\Gamma_{ee}(\Theta) \sim 5 \text{ KeV} . \tag{2}$$

As the mass M_Θ increases beyond 70 GeV, the weak interaction begins to dominate in the Θ decay width, followed by the electromagnetic interaction while the strong interaction provides the smallest contribution to the Θ decay width. This remarkable reversal of the strengths of the strong, electromagnetic, and weak interaction, persists for $M_\Theta > m_Z$, where the weak decays via charged currents dominate. The mass and decay widths of Θ essentially dictate its production cross section.

II. Production of $\Theta(\bar{t}t)$ and T Mesons

Here we consider the production cross section of $\Theta(t\bar{t})$. To compare the production rates of different facilities, we must assume definite luminosities and detection methods. For e^+e^- machines, the signal is rather distinct, if observed, while for hadron-hadron or ep machines, Θ's are observed via its decay to lepton pairs. To facilitate comparison, we give in Table 1 the number of μ-pairs from Θ decay per year, i.e. per 10^7 sec for various facilities.

Table 1

Numbers of μ-pairs from Toponium Decay at Different Facilities

Facilities	pp*	$\bar{p}p$	ep*	e^+e^-	e^+e^-
$\sqrt{s}$ (in GeV)	800	2000	140	100	100
Lum. ($cm^{-2}sec^{-1}$)	10^{33}	10^{30}	10^{32}	$6\cdot10^{30}$	10^{32}
$(\delta W/W)_{rms}$	1%	1%	1%	0.5%	$10^{-5}W$ (in GeV)
	(det)	(det)	(det)	(m/c)	(m/c)
Number of μ-pairs/(10^7) sec. for Different Toponium Masses					
40 GeV	50K	130	1K	860	180K
60 GeV	5K	15	200	230	32K
80 GeV	560	3	30	70	7K
100 GeV	100	1	10	80	6.6K

*The numbers for the pp facility are from F. Paige, and those for the ep facility are from J. Wiss (private communication).

(det) = detector resolution   m/c = machine resolution

A few comments are in order:

(1) It is clear that machine luminosity is very important, for both hadron-hadron and e^+e^- machines.

(2) For an e^+e^- machine, it is important to have good beam energy resolution (see discussions below).

(3) For $M_\Theta \sim 100$ GeV, the weak decay of the t quark via the charged current dominates the width so that $B_{\mu\mu}(\Theta)$ is suppressed. Hence the event rate for μ-pairs with $M_\Theta > 100$ GeV is small.

(4) For M_Θ within a few GeV of the Z^0 resonance, the dilepton signature from Θ decay may be confused with that from the Z^0 decay. For an e^+e^- machine with very good beam energy resolution, the Θ resonances may still be observed. We shall discuss this in a moment.

For the heavy bare quark t and the corresponding T meson, we must look for the associated $t\bar{t}$ production in hadron-hadron, ep and e^+e^- facilities. In this case, the relevant number is the rate of the production times the rate of detected signals. Because the capabilities of the various detectors are crucial to the estimate, and there are large uncertainties in detection efficiencies, we find it difficult to compare the capabilities of the different facilities. The most likely signature is a lepton from the semi-leptonic decay of the t quark. Since m_t is so large, it is expected that the lepton would have a transverse momentum. To differentiate the t-quark from the b- and the c-quark, the hard lepton should have no accompanying hadrons in the same direction; the signal for this should be very distinct. Another interesting possibility is to look for cascade decays to charm, e.g. $t \to b \to c$.

In hadron-hadron colliders, the $t\bar{t}$ production rates are quite substantial. The difficulty is in detection. One possible signature is provided by studying events with 3 or more leptons. This signature can be improved by also analyzing the accompanying hadron jets. Developments in microvertex detectors may, furthermore, make it possible to identify charmed mesons.

For e^+e^- machines, the question is whether there is enough phase space. In the latter case, if $m_t < m_Z/2$, many $\bar{t}t$ pairs can be produced from the Z^0 resonance. If $m_Z/2 < m_t < m_Z$, the decay mode

$$Z^0 \to t\bar{u},\ t\bar{c}$$

may be useful. In general, the branching ratio of this is calculated to be $10^{-8} \sim 10^{-10}$, which is clearly negligible. However, if there is a fourth family of quarks and leptons, then, for a sufficiently heavy b' quark

$$\mathrm{B.R.}(Z^0 \to t\bar{u},\ t\bar{c}) \propto m_{b'}^4 \ . \tag{3}$$

This may[3] give an experimentally accessible rate, i.e. B.R. $\sim 10^{-5}$; also this probes the existence of very heavy quarks. Of course, with a high-energy machine, heavy t quarks can always be produced via $e^+e^- \to \bar{t}t$.

III. $\Theta(t\bar{t})$ Studies at an e^+e^- Machine[2]

To study the spectroscopy of $\Theta(t\bar{t})$ and other related topics, we must go to an e^+e^- collider with a good beam energy resolution. Various measurements of the spectroscopy of the $(t\bar{t})$ system are found to be feasible, and some transitions among $(t\bar{t})$ states should be observable. This can be used to test QCD, and can even provide a precise determination of the QCD scale parameter $\Lambda_{\overline{MS}}$. We also note that the 1^3S toponium state, $\Theta(1S)$, is uniquely suited for definitive measurements on the Higgs sector. If charged Higgs scalar particles, $H^\pm$, exist with a mass less than the top quark mass m_t, $\Theta(1S)$ should almost always decay into $H^+ + H^-$ with experimental signatures which are quite distinct. If neutral Higgs H^0 (or a neutral hyper-pion or hyper-eta η^0) exists with a mass less than about 0.8 of $\Theta(1S)$ (i.e. up to masses of the order $1.6\ m_t$), the decay $\Theta(1S) \to qH^0$ decay should occur at the 1 to 2% level, resulting in a monochromatic high energy γ-ray which would be experimentally distinctive. Finally, for a range of t masses, weak processes of the t quark bound in $\Theta(1S)$ will be observable, enabling, for example, the determination of the semileptonic width of the t quark.

For the purpose of this study, we assume an e^+e^- collider with an average luminosity of

$$\langle \mathcal{L} \rangle = 2 \times 10^{31} \left(\frac{E_{beam}}{50\ \mathrm{GeV}} \right)^2 \mathrm{cm}^{-2}\mathrm{sec}^{-1} \tag{4}$$

(or $\langle \mathcal{L} \rangle = 2000\ (E_{beam}/50\ \mathrm{GeV})^2\ \mathrm{nb}^{-1}/\mathrm{day}$) with an rms spread in center of mass energy

$$(\Delta W)_{rms} = 100 \left(\frac{E_{beam}}{50\ \mathrm{GeV}} \right)^2 \mathrm{MeV} \ . \tag{5}$$

Defining

$$R = \frac{\sigma(e^+e^- \to \Theta)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

We have

$$\int R \cdot dW = \frac{9\pi}{2\alpha^2} \Gamma_{ee} \ . \tag{6}$$

Thus with a mean center of mass energy spread given by Eq. (5), we get a peak in R associated with the $\Theta(1S)$ of

$$R_{peak} = \frac{9\pi}{2\alpha^2} \frac{\Gamma_{ee}}{(\Delta W)_{rms}\sqrt{2\pi}} \ . \tag{7}$$

This is shown in Fig. 2, where R for $e^+e^- \to \sum_i \bar{f}_i f_i$

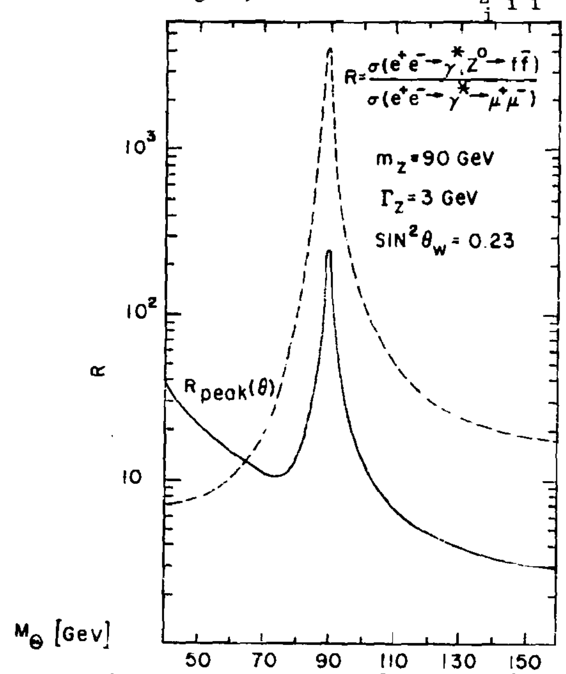

Fig. 2: R_{peak}, the contribution to R of the ground state as a function of M_Θ (solid line) as compared to the non-resonant value of R (dashed curve). The sum over all fermions f in the final state has been performed, and a constant decay width of $\Gamma(\Theta \to \gamma^* \to \mu\mu)$ of 5 KeV has been assumed. (Ref. 2)

is also shown . The reason that $R_{peak}(\Theta)$ grows dramatically when M_Θ approaches m_{Z^o} is simply because $\Gamma_{ee}(\Theta \to \gamma^*, Z^o \to e^+e^-)$ increases as Θ can decay via the virtual Z^o. For $M_\Theta = M_Z$, the Θ resonance has $R_{peak} = 400$ versus $R_{peak} \sim 5000$ for Z^o. (see Fig. 2). Since the width of Z^o is $\Gamma_{Z^o} \sim 3$ GeV, while that of Θ is given by the machine resolution, ~ 100 MeV, the Θ resonances should be clearly observable (as narrow peaks on top of a broad peak) even if $M_\Theta \sim m_{Z^o}$. For $M_\Theta << m_{Z^o}$, the situation is similar to that of Ψ and Υ resonances. In Table 2, we give the R_{max} for the toponium and the background for various M_Θ. Radiative corrections are not included in Table 2. Were we to include them, $\Delta R(\Theta)$ would be reduced by a factor of 1/2, while the Z^o signal at the peak would be reduced by 2/3. Peak R values scale inversely with ΔW_{obs}, where

$\Delta W_{obs} = 2.355\ \delta W_{rms}$ if $\delta W_{rms} >> \Gamma_{total}$ and
$\Delta W_{obs} = \Gamma_{total}$ in the opposite limit.

Table 2

Ground state Toponium signals in e^+e^- as a function of mass M_Θ compared to "background" of intermediate photon and Z^o signals for machine with beam energy resolution $(\delta W/W)_{rms} = 10^{-5} W(\text{GeV})$ in units of R.

	$e^+e^- \to$ all		$e^+e^- \to \mu^+\mu^-$	
M_Θ(GeV)	R_{Total} (Bkgrnd)	$\Delta R(\Theta)$ (Signal)	$R_{\mu\mu}(\gamma, Z^o)$ (Bkgrnd)	$\Delta R_{\mu\mu}(\Theta)$ (Signal)
40	6.9	33	1.01	3.3
50	7.4	21	1.03	2.1
60	9.0	14	1.08	1.3
70	14	11	1.3	0.81
80	43	11	2.2	0.53
90	830	69	28	2.4
93	5710	450	191	15
96	1020	84	35	2.8
100	248	24	9	0.76

Notes:

Toponium parameters are determined by $\Gamma_{ee}(\Upsilon) = 5$ KeV and $\sin^2\theta_W = 0.215$ in the standard model $M_{(Z^o)} = 93$ GeV, $\Gamma(Z^o) = 2.62$ GeV.

To illustrate the various effects, we consider in some detail the example of $M_\Theta = 75$ GeV, a mass sufficiently large so that the influence of Z^o and W^o are present, but do not dominate the Θ decay. From Table 2, we find $R_{peak} = 11$. Radiative effects will reduce this to about 6, so that the signal to noise in R at the Θ(1S) is expected to be about 1:1.

Thus, with $<\mathcal{L}>$ given by Eq.(4), we expect about the following rates in the Θ(1S) region.

Below resonance	60 events/day
On the Θ(1S)	130 events/day
Far above $t\bar{t}$ threshold	84 events/day

For E_{beam} at 5 GeV above the Θ(1S), $t\bar{t}$ production is still only half of its asymptotic value. At energies well above the $t\bar{t}$ threshold one will observe an increased R value, as well as more events with higher sphericity, and events with high momentum leptons. Scanning the energy range available to the collider in about five 10-GeV steps, taking 5 to 10 days per point, should be capable of establishing a $t\bar{t}$ threshold (if it exists), and isolating it to one 10-GeV interval. Fine scanning in 100-MeV steps would then find Θ(1S) in a maximum of 100 days. Thus about one half a year of scanning should be adequate for finding Θ(1S), determining its mass, and making a 10% measurement of $\Gamma_{ee}[\Theta(1S)]$.

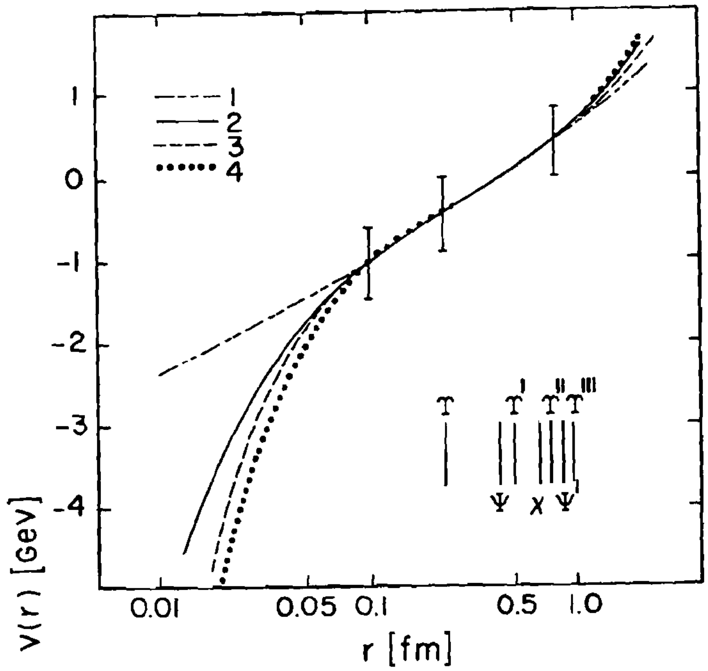

Fig. 3: Various successsful potentials are shown. The numbers refer to the following references: (1) A. Martin, Phys. Lett. 93B, 338)1980); Ref. TH 2980-TH (CERN); (2) W. Buchmuller, G. Grunberg and S.-H.H. Tye, Phys. Rev. Lett. 45, 103 (1980); 45, 587(E) (1980); (3) G. Bhanot and S. Rudaz, Phys. Lett. 78B, 119 (1978); (4) E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, and T.-M. Yan, Phys. Rev. D21, 203 (1980). (Ref. 2). For a general discussion on the potential, see C. Quigg and J. L. Rosner, Phys. Rev. D23, 2625 (1981). (Ref. 2)

A variety of potential models have predicted mass splittings and leptonic widths for Θ(2S) and higher states. In Fig. 3, various potential models are presented. We note that data-fitting of the ψ and Υ spectroscopies essentially dictates the form of the $(Q\bar{Q})$ potential at distances $0.1\ \text{fm} \lesssim r \lesssim 1$ fm. If we assume that perturbative QCD is adequate in describing the short distance part of the $(Q\bar{Q})$ potential, and that the potential is smooth as a function of r (i.e. differentiable), we can determine the $Q\bar{Q}$ potential all the way up to a distance of 1 fm, as a function of the QCD parameter $\Lambda_{\overline{MS}}$. For $\Lambda_{\overline{MS}} = 0.5$ GeV, the predictions are shown in Table 3.

Table 3

Θ Spectroscopy (Weak Interaction Effects Neglected)

m_t (GeV)	20	30	40	50	60
Binding Energy $-E_B$(GeV)	0.93	1.18	1.39	1.57	1.74
$E_2 - E_1$ (GeV)	0.67	0.76	0.85	0.93	1.01
$E_3 - E_1$ (GeV)	0.99	1.09	1.19	1.29	1.38
$E_4 - E_1$ (GeV)	1.21	1.31	1.41	1.51	1.61
$E_{1P} - E_{1S}$ (GeV)	0.58	0.67	0.75	0.84	0.91
Γ_{ee}(1S). (KeV)	5.10	5.68	6.26	6.69	7.14
$\Gamma_{ee}(2S)/\Gamma_{ee}(1S)$	0.33	0.30	0.28	0.26	0.25
$<r^2>^{1/2}$(1S) (fm)	0.09	0.07	0.06	0.05	0.04

Different potential models agree on the position of the $\Theta(2S)$ to within about 60 MeV, and $\Gamma_{ee}[\Theta(2S)] \simeq 1/3\ \Gamma_{ee}[\Theta(1S)]$. Thus a month of scanning in the predicted region should suffice to find $\Theta(1S)$ and measure the 2S - 1S mass splitting well enough to distinguish between the various models. In that time, $\Gamma_{ee}(2S)$ could be determined to 10 to 15%. Higher excitation ($\sim$10 narrow excitations are expected to exist below $T\bar{T}$ threshold) are expected to have lower peak cross sections and will require correspondingly more time to accumulate events. Typical values of the various widths are listed in Table 4. (In Table 3 and 4, the weak interaction effects are neglected. The weak interaction effects are sensitive to the mass difference between Θ and Z^0. They can easily be incorporated using Fig. 1, once the precise value of $M_\Theta - m_Z$ is known.

Table 4

Typical Widths of Toponium
(Weak Interaction Effects Neglected)

	$\Theta(1S)$ Γ(keV)	$\Theta(1S)$ BR	$\Theta(2S)$ Γ(keV)	$\Theta(2S)$ BR
$\Gamma_{\mu^+\mu^-}$	5	0.08	1.7	0.07
Γ_{γ^*}	26	0.44	9	0.36
Γ_{3g}	24	0.41	8	0.32
$\Gamma_{\gamma gg}$	4	0.07	1.4	0.06
$\Gamma_{\pi\pi}\ \Theta(1S)$			0.7	0.03
$\Gamma_{\gamma\ ^3P_J}$			4	0.16

According to this model, $BR(\Theta(1S) \to \mu\mu) = 0.08$, or about 5 $\Theta(1S) \to \mu^+\mu^-$ events/day. This occurs against a background of 17 e^+e^- events from the continuum. Assuming a dimuon acceptance of 75%, we expect, after 100 days of running on the peak of the resonance and 100 days of running off resonance,

$\mu^+\mu^-$ "expected" = 1650±40 on the resonance

$\mu^+\mu^-$ "expected" = 1280±35 in the nearby continuum

yielding a $\mu^+\mu^-$ branching ratio with 14% precision. This, in turn, can be used in conjunction with the measurement of Γ_{ee} to determine the $\Theta(1S)$ total width with a similar precision.

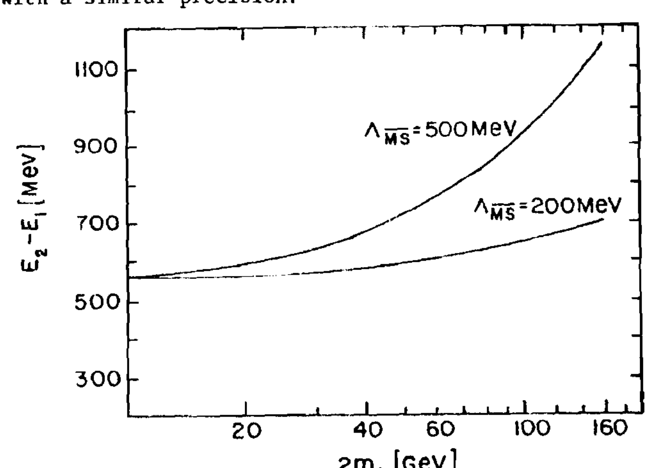

Fig. 4: The mass splitting of $\Theta(2S)$-$\Theta(1S)$ as a function of $2m_t$, for two typical values of $\Lambda_{\overline{MS}}$ (Ref. 2).

For values of QCD scale parameters other than $\Lambda_{\overline{MS}} = 0.5$ GeV, the short distance part of the $Q\bar{Q}$ potential differs accordingly. In Fig. 4, the $\Theta(2S)$ - $\Theta(1S)$ splitting is shown for $\Lambda_{\overline{MS}} = 0.5$ GeV and $\Lambda_{\overline{MS}} = 0.2$ GeV as a function of $2m_t$. The 2S state is sensitive to the potential at distances between 0.1 fm and 1 fm (where the potential is well determined from phenomenology (see Fig. 3)) and is relatively insensitive to the short distance part of the potential (which is determined by perturbative QCD). On the other hand, the 1S state is sensitive to the short distance part of the potential, and hence to the QCD scale parameter $\Lambda_{\overline{MS}}$. The wavefunction at the origin of $\Theta(1S)$ is also a function of $\Lambda_{\overline{MS}}$. In Fig. 5, the leptonic width of $\Theta(1S)$, $\Gamma_{ee}(\Theta \to \gamma^* \to e^+e^-)$ is also

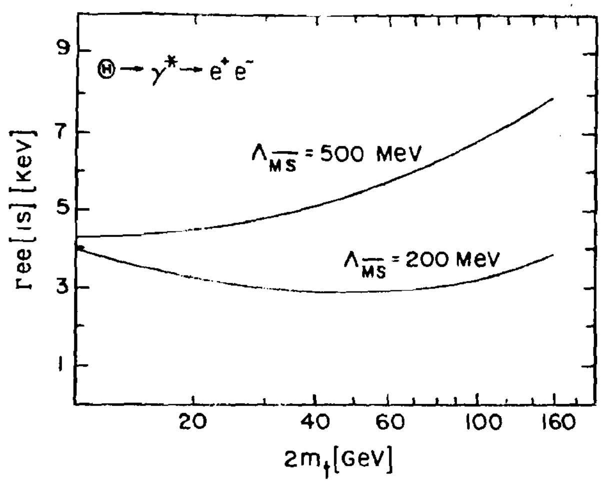

Fig. 5: The leptonic width of Θ in the absence of the Z^0-boson effect, as a function of $2m_t$ for two typical values of $\Lambda_{\overline{MS}}$. (Ref. 2).

shown as a function of $2m_t$ for two values of $\Lambda_{\overline{MS}}$. Of course, once the $M_\Theta - m_{Z^0}$ difference is determined, the weak interaction contribution to the leptonic width should be included in the comparison of theory and experiment. Hence the $\Theta(1S)$ - $\Theta(2S)$ splitting, together with the $\Gamma_{\mu\mu}(\Theta)$ value, can give an accurate determination of $\Lambda_{\overline{MS}}$.

The $W^\pm$ boson effects on toponium are extremely interesting. These cause the weak decays of the t quarks in Θ to compete with its "normal" strong and e.m. decays, as illustrated in Fig. 1, where the estimated width for this decay mode is shown as a function of M_Θ. We expect $W^\pm$ induced decays with BR's which are of order 2% for $M_\Theta \sim 40$ GeV and $\sim$20% for $M_\Theta = 75$ GeV. Since W is expected to have a BR into $e\nu$ or $\mu\nu$ of about 11% each, this should give rise to measurable yields of direct leptons at the Θ (ranging from $\sim$0.4% at $M_\Theta = 40$ GeV, to 4% at M_Θ - 75 GeV) having a momentum spectrum significantly harder than that expected from B and D meson decays.

A 100-day run on $\Theta(1S)$ would provide a total 240 inclusive electron events for $M_\Theta = 75$ GeV, which would provide about a 10% determination of the width for t quark semileptonic decays without the requirement of a direct t quark lifetime measurement. For $M_\Theta \sim 100$ GeV, the dominant decay mode of $\Theta(t\bar{t})$ is

$$\Theta(t\bar{t}) \to Wq\bar{t}$$
$$\hookrightarrow W\bar{q}\ .$$

with width given by

$$\Gamma(t \to Wq) = \frac{G_F\, m_t^3}{8\pi\sqrt{2}} \; |V_{tq}|^2 \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + \frac{2\, m_W^2}{m_t^2}\right)$$

where m_q is neglected and V_{tq} is the appropriate matrix element of the Kobayashi-Maskawa matrix. This may be a good source of $W^{\pm}$ bosons if $m_{\Theta} > m_W$.

On the $\Theta(2S)$, we expect about 20 resonant events/day. In a 150 day run, about 3000 $\Theta(2S)$ decays should be accumulated. Decays of the type

$$\Theta(2S) \to \pi\pi\, \Theta(1S)$$
$$\hookrightarrow \mu^+\mu^-$$

are expected[4] to have a net BR of 0.2%, as can be obtained from Fig. 6.

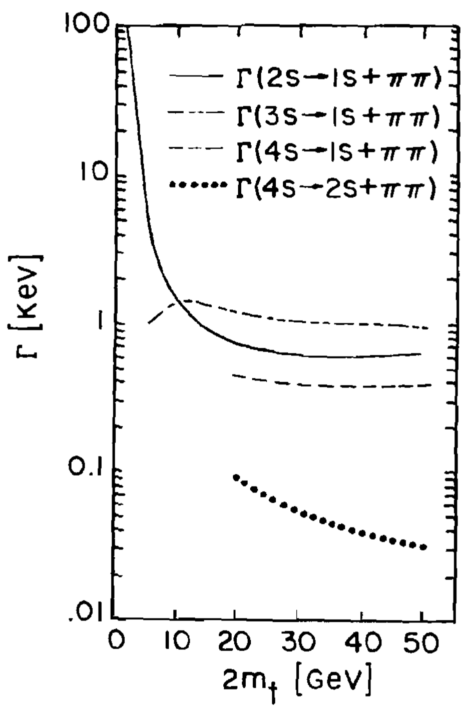

Fig. 6: $\Theta(2S) \to \pi\pi\Theta(1S)$ transition rate as a function of m_t (Ref. 4).

Theoretical estimates for the branching ratio for the decays

$$\Theta(2S) \to \gamma\Theta(13P_J), \qquad J = 0,1,2$$

are 10 to 15%. This BR is comparable to those observed in the T system. During a six-month run at CESR, in a sample of about 35 observed T(3S) decays, evidence for monochromatic inclusive photons from the decays $T(3S) \to \gamma\ 2^3P_J$ has been isolated in the CUSB detector. A run of similar duration at the $\Theta(2S)$ would produce one-tenth as many resonance decays with a signal to background (i.e. resonance-to-continuum) ratio which is about 3 times worse. Since π^0 multiplicities are likely to be twice as high the background level in an inclusive photon spectrum will be twice as high as in the T(3S) case. Thus an experiment like CUSB, working at the $\Theta(2S)$, will be nominally 60 times harder than similar experiments in the T region. An inclusive photon experiment of the CUSB/Crystal Ball type will be futile.

On the other hand, some potential models predict that the BR for the decay

$$^3P_{0,1,2} \to \gamma\ \Theta(1S)$$

may be 50% or even larger. In that case, one might expect that the cascade decay process

$$\Theta(2S) \to \gamma\ \Theta(1^3P_{2,1,0})$$
$$\hookrightarrow \gamma\ \Theta(1S)$$
$$\hookrightarrow \mu^+\mu^-$$

will have combined BR of $\sim 0.15 \times 0.5 \times 0.08 \sim 0.6\%$. Thus in a sample of 3000 $\Theta(2S)$ decays, we might see 18 cascade events with a distinctive $\mu\mu\gamma\gamma$ signal. A detector that has good acceptance and sufficient resolution, particularly in the determination of muon directions, should have a good chance of finding and studying the ^3P states via this process in an extended run.

A few comments on the toponium properties are in order:

(1) The hadronic decay of Θ may be used to obtain a precise determination[5] of the QCD parameter $\Lambda_{\overline{MS}}$. We expect that this measurement together with the level spacings and the leptonic widths, should give an accurate and reliable determination of $\Lambda_{\overline{MS}}$ to 10-20%.

(2) Since $m_T^* - m_T \sim 50$ MeV $\left(\frac{m_B}{m_T}\right)$, we might expect that mostly T*, $\overline{T}$* are produced once we pass the $T\overline{T}$ threshold.

(3) Toponium is a good source of gluon jets and is an ideal place to study the properties of gluon jets, such as multiplicity and jet broadening.

IV. Toponium as a Higgs Source

The Higgs mechanism is an important feature of the standard model. Experimental investigations into the Higgs sector are of the highest importance today.

In the Weinberg-Salam model, the Higgs mechanism is responsible for generating the $W^{\pm}$ and Z^0 masses, but the actual mass m_H of the Higgs particles are only loosely constrained. If $m_H < M_{\Theta(1S)}$, the decay[6]

$$\Gamma(\Theta(1S) \to H^0\gamma) \simeq \frac{G_F\, m_t^2}{\sqrt{2}\,\alpha\pi}\left[1 - \frac{m_H^2}{M_\Theta^2}\right]\Gamma(\Theta(1S) \to \gamma^* \to \mu^+\mu^-)$$

should be substantial. The expected BR for this decay is shown in Fig. 7 as a function of m_H when $\Theta(1S)$ has the mass 75 GeV. Note that for m_H as high as 65 GeV, this branching ratio is greater than 1%. Thus with 60 $\Theta(1S)$ decays/day, we could expect an event every few days. These yield a monochromatic high energy γ and would be quite distinct. Not only would this establish the existence of a Higgs particle, but it would also provide a clean sample of Higgs decays for more detailed studies.

A number of theoretical models have been proposed to replace the Higgs mechanism by dynamical symmetry breaking. "Technicolor" or "Hypercolor" models typically have two charged and two neutral Higgs-like scalars, with masses[7] expected to be in the range 8 to 40 GeV. A dramatic prediction of these models is that if the charged Higgs are lighter than

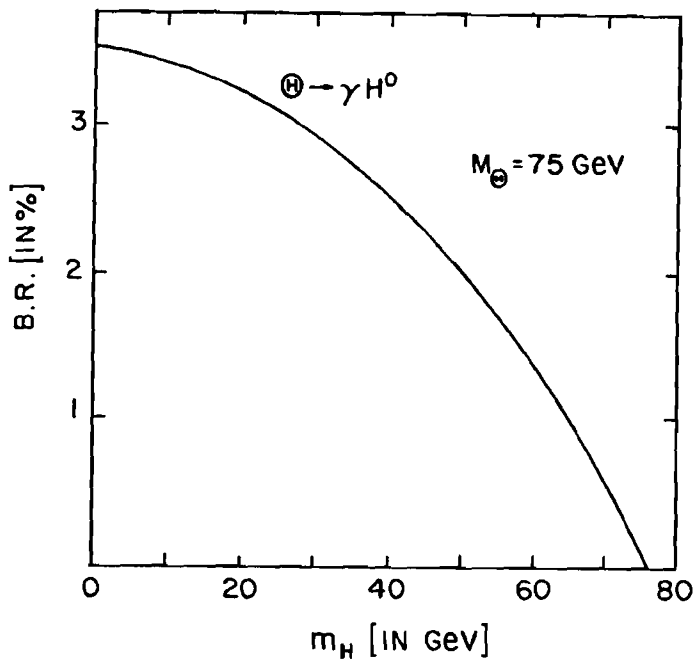

Fig. 7: The branching ratio of $\Theta \to \gamma H$ as a function of m_H; here $M_\Theta = 75$ GeV.

$M_{\Theta(1S)}/2$, then each t quark in $\Theta(1S)$ will decay almost 100% of the time into charged Higgs and a quark. If it is energetically possible, the accompanying light quark can be a b quark, and the charged Higgs will decay into $q\bar{b}$. Thus, for a charged Higgs with $m_{H^\pm} < M_\Theta/2$, we will have 4 or more kaons for every $\Theta(1S)$ decay. This should be a very dramatic signature. It has been calculated that this decay mode would increase the total decay width of the Θ to as much as 40 to 50 MeV. While this will make the more conventional decay modes (such as $\Theta \to \mu\mu$ discussed in the previous section) very difficult to observe, it will still be narrow compared to the E_{cm} energy spread, and will thus not diminish the observability of the $\Theta(1S)$ as a "narrow" s-channel resonance.

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