UPSILON SPECTROSCOPY AT HIGH LUMINOSITIES

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Summary

This report discusses the advantages of high luminosity running on the $b\bar{b}$ system as a test of QCD and the quark-antiquark forces. We limit ourselves to the cases of 1,000 pb^{-1}/year and 10,000 pb^{-1}/year, and what physics goals can be achieved at these integrated luminosity levels. A summary of theoretical spectroscopic predictions is presented, together with a detailed evaluation of the decays $3^3S \rightarrow \pi\pi 1^1P_1 \rightarrow \pi\pi\gamma 1^1S_0$ and $1^3S_1 \rightarrow \gamma 1^1S_0$. A brief discussion of other possible 'exotic' spectroscopy follows.

Introduction

Over the past few years the spectroscopy of heavy quark-antiquark bound states (quarkonia) has lead to an exciting new field in high energy physics. Besides the very early discoveries at fixed target machines[1] most of the results come from experiments at e+e- storage rings. Data from SPEAR[2], DORIS[3] and CESR[3] have provided first tests of flavor independent theories describing heavy quark-antiquark bound states. Our present knowlede of the theory of quarkonia is far from being complete. Precision measurements of the production and decay properties of heavy bound states in the near future will help to clarify the situation.

The $c\bar{c}$ bound states (ψ family) with masses around 3.5 GeV have been described successfully by nonrelativistic potential models, although some predictions disagree with experiments. The Υ family ($b\bar{b}$ bound states) with masses around 10 GeV has recently enriched the field of heavy quark spectroscopy, by the addition of a fifth quark, with a mass ~5 GeV. The partner of the b quark in the third quark doublet, the t quark, has not yet been discovered. The lower experimental limit[4] for the mass of the t is presently $m_t \geq 18$ GeV.

In Table I a comparison between $c\bar{c}$,$b\bar{b}$ and $t\bar{t}$ bound states is given. The $c\bar{c}$ system is not heavy enough to justify a pure nonrelativistic treatment although the predictions for the spectrum have been quite successful. The rates for E1 transitions disagree by a factor of 2 to 3 with current models. In the $b\bar{b}$ case, however, due to the heavier b quark, theoretical predictions using a nonrelativistic potential model agree very well with experimental results obtained so far, as will be discussed below.

The bound states are expected to decay dominantly via gluons, which then fragment into hadrons. No jet structure is observed from decays of the $c\bar{c}$ bound states because of their relativly low mass. Similarly in the decay of the Υ's, with an average gluon jet energy of about 3 GeV, no pronounced 3-jet structure has been observed. However, the decay of the χ_b states (n^3P_0 , n^3P_2) or η_b's (1^1S_0) into 2 gluon jets (average gluon jet energy about 5 GeV) provide the only source of gluon jets allowing a direct comparison of quark and gluon decay properties (as long as the $t\bar{t}$ states are not found). To obtain a highly enriched 2 gluon event sample one can tag on the monochromatic γ's from the decay of the ^3S states to the χ_b states or on the $\Upsilon'' \rightarrow \pi\pi^1P_1 \rightarrow \gamma\eta_b$ and $\eta_b \rightarrow gg$ decay. One can then make an excellent comparison of quark and gluon jets at the same energy.

Table I. Comparision of $c\bar{c}$, $b\bar{b}$, and $t\bar{t}$ bound states

item	$c\bar{c}$	$b\bar{b}$	$t\bar{t}$
quark mass	~ 1.5	~5	$\geq$18 Gev
#of narrow ^3S states	2	3	$\geq$6
#of narrow S,P,D states	12	18	$\geq$52
decay multiplicity	~10	~20	>30
$B_{\mu\mu}(1^3S_1)$	7%	3.3%	$\leq$3%
dominant BR	20-50%	5-30%	$\leq$5%
fine splitting	140MeV	30-60MeV	10-20MeV
hyperfine splittting	120MeV	20-100MeV	$\leq$30MeV
gluon jets	no separation	3jet not separated, 2jet very likely separated	clear jet separation expected
glue ball production	0^+,2^+ via γG	all G^{JP} states accessible, < 5GeV mass~1-2GeV prefered	all G^{JP} states accessible high mass, complex decay modes
signal over continuum (for 1^3S_1)	>1000:1[a]	>6:1[b]	>2:1[d]
radiative corrections	small	medium	large
machine resolution	< 1MeV	3.7MeV[b] 10 MeV[c]	>30 MeV[d]
typical event rate per year (present)	10^6,[a]	10^5 ,[b],[c]	10^4,[d]

[a] SPEAR
[b] CESR
[c] DORIS
[d] PETRA (40 GeV)

Production of $t\bar{t}$ bound states may permit the observation of cleanly separated gluon jets at much higher energy and in the 3-jet configuration (see report by Jackson, Olsen, and Tye).

Three narrow ^3S states are observed in the Υ family (Υ, Υ', Υ'' or in the standard spectroscopic notation 1^3S_1,2^3S_1,3^3S_1), compared with two in the ψ system. This results in a much larger number of transitions imposing more constraints on theoretical predictions. Hadronic transitions are an excellent tool for obtaining more information about soft gluon processes which are not yet well understood. In the $t\bar{t}$ case one has to face the problem of small branching ratios. Fine splitting (<10MeV) is nearly impossible to measure with the present detectors. The situation is similar for the hyperfine splitting. Also, the present storage ring energy resolution of $\sigma \geq 30$ MeV (PETRA) will reduce the signal of resonance $t\bar{t}$ states with respect to the continuum much more than in the $b\bar{b}$ energy range, even after the benefit of the 2/3 quark charge. The higher $t\bar{t}$ bound states are expected to be so closely spaced that they can hardly be resolved. Obviously the production rates for the $t\bar{t}$ states are much lower than for the $b\bar{b}$ states because of the 1/s factor. The situation in the $t\bar{t}$ spectroscopy might be very complicated if the $t\bar{t}$ mass is very high where contributions from the weak interaction become important.

Therefore the $b\bar{b}$ states will be very likely the only quarkonia states where precise predictions can be made and tested thoroughly with high statistics. We would like to point out that the Υ system (QCD bound state bottomium) is fundamental (the analog of the QED positronium bound state) and should therefore be exploited by precise measurements of level structure, transition rates and various (i.e.exotic) decay modes.

We are going to elaborate a working schema using 10 and 100 times more luminosity compared to the present situation (1982: CESR $\sim 10^{31} cm^{-2} sec^{-1}$). Rates for interesting decay modes are given together with assumed detector improvements. The present peak luminosity of $\sim 10^{31}$ leads to $\sim 100 pb^{-1}$ per year. In Table II the number of events are listed for present, upgraded and super luminosity (i.e.for 10^2, 10^3 and 10^4 pb^{-1} respectively).

Table II. Number of events for present, upgraded and super luminosity. For evaluation of numbers of events a machine resolution of $\sigma \sim$ 4 MeV (CESR) as been used.

	now	upgrade	superluminosity
Υ	2×10^6	20×10^6	20×10^7
Υ'	7×10^5	7×10^6	7×10^7
Υ''	4×10^5	4×10^6	4×10^7

$b\bar{b}$ Spectroscopy

As has been pointed out, the Υ system may prove to be one of the best testing grounds for QCD[5] and the understanding of the interquark potential, due to the rich spectrum of states accessible to the experimental spectroscopist (Figs. 1 and 2 in the summary report by Tuts et al. demonstrate this well). Thus the task of the Υ spectroscopist is to precisely determine the positions of all these levels. This will put constraints on theoretical models, in particular, there is a large discrepancy between potential model and QCD sum rule predictions for the position of the 1^3P center of gravity (as shown in Table VI). We have tried to summarise some of those level predictions (with apologies to those we have omitted) for S,P, and D states in the following Tables III-VI and VIII-IX. Although this is far from a comprehensive list, it does cover the range of predictions from phenomenological potentials[7-11], QCD inspired potentials[12-17], to the predictions of the QCD sum rules[18-20]. Predictions including the next order QCD corrections[32] give $\Upsilon - \eta_b$= 25-50 MeV, depending on $\Lambda_{\overline{MS}}$. Note that in accordance with the latest VEPP-4 findings[22] we have adjusted all masses such that $M(\Upsilon)$=9.46 GeV/c^2.

The easiest part of the spectroscopy program has already been completed (i.e. Table III) in the observation of four of the triplet S-states of the $b\bar{b}$ system[6]. These states are readily accessible because they are directly produced in e^+e^- annihilations (since their quantum numbers $J^{PC}=1^{--}$ are those of the photon).

The next step, the observation of the triplet P-states (n^3P_J), has begun with the discovery of the 2^3P states[26]. All of this spectroscopy can be carried out with the existing luminosity (although improved detector capabilities would be desirable). An experimental determination of the P-states will greatly aid our understanding of the spin forces that determine the P-state fine structure. A convenient comparison of the fine structure is provided by the ratio $r = \Delta M(n^3P_2 - n^3P_1)/\Delta M(n^3P_1 - n^3P_0)$. We have listed in Table VII the value r, for some of the theoretical models in Table VI.

Table III. Some theoretical predictions for the n^3S_1 states of the $b\bar{b}$ system. Note that masses are in GeV/c^2 and $M(\Upsilon)$=9.46 GeV/c^2. Asterisk denotes input.

Model	1^3S_1	2^3S_1	3^3S_1	4^3S_1
Experiment [6](1982)	9.46	10.02	10.349	10.545
Eichten et al [7](1980)	9.46*	10.05	10.40	10.67
Eichten,Feinberg [8](1981)	9.46*	10.02*	10.358	—
Martin [9](1981)	9.46*	10.025	10.36	10.60
Gupta et al [12](1982)	9.46*	10.011	10.353	—
Krasemann [13](1981)	9.46*	10.019	10.345	10.605
Buchmuller,Tye [14](1981)	9.46*	10.02	10.35	10.62
Baacke et al A [15](1981)	9.46*	10.02*	10.365	10.678
B	9.46*	10.02*	10.365	10.682
McClary,Byers [17](1982)	9.46*	10.02	10.355	10.574

Table IV. Some predicted n^1S_o states. Masses in GeV/c^2 and $M(\Upsilon)$=9.46 GeV/c^2. The $\Upsilon - \eta_b$ splitting is given in MeV.

Model	$\Upsilon - \eta_b$	$1^1S_0(\eta_b)$	2^1S_o	3^1S_o	4^1S_o
Eichten,Feinberg [8](1981)	94	9.366	9.979	10.327	—
Martin [9](1981)	61	9.399	9.899	10.174	—
Khare [11](1981)	29	9.431	—	—	—
Gupta et al [12](1982)	35	9.425	9.992	10.337	—
Krasemann [13](1981)	60	9.400	—	—	—
Buchmuller,Tye [14](1981)	46	9.414	9.997	10.332	—
Baacke et al A [15](1981)	86	9.374	9.984	10.335	—
B	81	9.379	9.985	10.334	—
McClary,Byers [17](1982)	101	9.359	9.980	10.324	—
Voloshin et al [18](1980)	30	9.43	—	—	—
Leutwyler [19](1980)	90	9.370	—	—	—
Reinders et al [20](1980)	60	9.40	—	—	—
Iwao,Yamawaki [23](1980)	100	9.36	—	—	—
Barbieri et al [24](1981)	32	9.428	—	—	—

Table V. Some predicted n^1P_1 states. Masses in GeV/c^2 and $M(\Upsilon)$=9.46 GeV/c^2.

Model	1^1P_1	2^1P_1	3^1P_1
Kuang,Yan [25](1981)	9.92	--	--
Eichten,Feinberg [8](1981)	9.924	10.271	--
Khare [11](1981)	9.958	--	--
Gupta et al [12](1982)	9.898	10.256	--
Buchmuller A	9.887	10.250	--
[16](1982) B	9.889	10.249	10.527
McClary,Byers [17](1982)	9.925	10.269	10.541

Table VI. Some predicted n^3P_J states. Masses are in GeV/c^2 with $M(\Upsilon)$=9.46 GeV/c^2. The numbers in parentheses are the (2J+1) weighted centers of gravity.

Model	1^3P_o	1^3P_1	1^3P_2	2^3P_o	2^3P_1	2^3P_2
Eichten et al	--	--	--	--	--	--
[7](1980)		(9.958)			(10.312)	
Kuang,Yan	--	--	--	--	--	--
[25](1981)		(9.92)			(10.27)	
Eichten,Feinb.	9.888	9.913	9.939	10.245	10.263	10.281
[8](1981)		(9.924)			(10.271)	
Martin	--	--	--	--	--	--
[9](1981)		(9.861)			(10.242)	
Quigg,Rosner	--	--	--	--	--	--
[10](1981)		(9.888)			(10.245)	
Khare	9.843	9.867	9.879	--	--	--
[11](1981)		(9.871)			(--)	
Gupta et al	9.866	9.891	9.908	10.230	10.250	10.264
[12](1982)		(9.898)			(10.256)	
Krasemann	9.896	9.926	9.950	10.232	10.262	10.282
[13](1981)		(9.936)			(10.271)	
Buchmuller,Tye	--	--	--	--	--	--
[14](1981)		(9.89)			(10.25)	
Baacke et al A	9.932	9.962	9.984	10.278	10.304	10.324
[15](1981)		(9.971)			(10.312)	
B	9.957	9.988	10.012	10.291	10.321	10.344
		(9.887)			(10.330)	
Buchmuller A	9.859	9.881	9.897	10.226	10.244	10.258
[16](1982)		(9.887)			(10.250)	
B	9.835	9.876	9.907	10.207	10.239	10.263
		(9.889)			(10.249)	
McClary,Byers	9.867	9.916	9.938	10.221	10.261	10.280
[17](1981)		(9.923)			(10.267)	
Voloshin et al	--	--	--	--	--	--
[18](1980)		(9.835)			(--)	
Bartlmann	--	--	--	--	--	--
[21](1981)		(9.803)			(--)	

Table VII. Some predictions for the ratio $r=\Delta M(n^3P_2 - n^3P_1)/ \Delta M(n^3P_1 - n^3P_o)$, using Table VI. The quotient repesents the actual predicted splitting in MeV.

Model	n=1	n=2
Eichten,Feinberg [8](1980)	26/25=1.04	18/18=1.00
Khare [11](1981)	12/24=0.50	0.50
Gupta et al [12](1982)	17/25=0.68	14/20=0.70
Krasemann [13](1981)	24/30=0.80	20/30=0.67
Baacke et al A	22/30=0.73	20/26=0.77
[15](1981) B	24/31=0.79	23/30=0.77
Buchmuller A	16/22=0.73	14/18=0.78
[16](1982) B	31/41=0.76	24/32=0.75
McClary,Byers [17](1982)	22/49=0.45	19/40=0.48

Table VIII. Some n^1D_2 predictions. Masses are in GeV/c^2 and $M(\Upsilon)$=9.46 GeV/c^2.

Model	1^1D_2	2^1D_2
Eichten et al [7](1980)	10.207	10.500
Eichten,Feinberg [8](1981)	10.166	10.455
Krasemann [13](1981)	10.174	10.449
Buchmuller,Tye [14](1981)	10.14	10.43

Table IX. Some predictions for n^3D_J states. Masses are in GeV/c^2 and $M(\Upsilon)$=9.46 GeV/c^2.

Model	1^3D_1	1^3D_2	1^3D_3	2^3D_1	2^3D_2	2^3D_3
Eichten,Fein [8](1981)	10.153	10.163	10.174	10.444	10.453	10.462
Gupta et al [12](1982)	10.153	10.160	10.165	10.445	10.452	10.457
Krasemann [13](1981)	10.162	10.172	10.180	--	--	--
Baacke et al [15](1981)	10.187	10.195	10.202	10.496	10.504	10.511
McClary,Byers [17](1982)	10.17	--	--	10.451	--	--

The final step in unraveling the $b\bar{b}$ spectrum will have to wait for improved luminosities and improved detectors. The observation of some decays such as $3^3S_1 \to \pi\pi 1^1P_1 \to \pi\pi\gamma 1^1S_o$ should be possible with the proposed 'upgrades' of present accelerators and detectors, providing information on the positions of interesting states such as the 1^1P_1 and 1^1S_o (η_b). More detailed studies of the rare M1 decays or precise measurements of the η_b width (which can provide theoretically reliable values of the strong coupling constant α_s) will have to wait for the 'super high' luminosity accelerators and much improved detectors. In Table X we have listed some of the rare decay modes that might be observed.

Table X. Some rare hadronic and photonic decays of $b\bar{b}$ bound states (assuming $\Gamma_{tot}(\Upsilon')\sim19$ KeV).

Reaction	BR	upgrade (1,000 pb^{-1})	Ref.
$\Upsilon''\rightarrow 1^3P$	.0005-.05	$2\times10^{3-5}$	8,14
$\Upsilon''\rightarrow\gamma 2^3P\rightarrow\gamma\gamma 1^3D$	.002-.003	$(8-12)\times10^3$	8,14
$\Upsilon''\rightarrow\pi\pi 1^1P\rightarrow\pi\pi\gamma\eta_b$	.002-.005	$(8-20)\times10^3$	25
$\Upsilon''\rightarrow\gamma 2^3P\rightarrow\gamma\eta_b\pi\pi$	.01-.05	$(4-20)\times10^4$	25
$\Upsilon''\rightarrow\gamma\eta_b$	<.0005	$<2\times10^3$	8
$\Upsilon\rightarrow\gamma\eta_b$	$2\times(10^{-3}-10^{-5})$	400-40,000	8,13
$\Upsilon\rightarrow\gamma$+Higgs,etc.	$10^{-4}-10^{-5}$	200-2,000	27

In addition to this conventional spectroscopy, there is a whole field of what might be termed 'exotic' spectroscopy, including gluonium spectroscopy (for which the reader is refered to the article by Tye), searches for exotic particles such as axions, light neutral Higgs, etc. in the radiative decays of the Υ resonances, or even searches for the elusive gluinos as observed through total energy measurements. In what follows, we have chosen some of these topics to discuss in more detail, under the above assumptions of integrated luminosities. Also, from our experience with CUSB and detailed Monte Carlo studies of new electromagnetic calorimeters, we will assume that resolutions of $\sigma\sim3\%$, π^0 rejection of a factor of two, and energy dependent efficiencies for photon finding of 25% to 50% are achievable. We believe that these numbers can be achieved using recent developments in detector technology, outlined in the report by Ruchti et al[28].

Conventional Spectroscopy

We will limit ourselves to the study of two specific reactions listed in Table X, however the results for other reactions can be calculated similarly.

A) $3^3S_1\rightarrow\pi\pi 1^1P_1\rightarrow\pi\pi\gamma 1^1S_0$.

This reaction is particularly interesting because not only does one observe the singlet P (not yet observed in the $c\bar{c}$ system) and singlet S states, but also it can be done with only slightly upgraded luminosities and detectors from the existing ones. A measurement of the 1^1P_1 state relative to the triplet 1^3P_J states will provide information on the spin forces - a large splitting would indicate an unexpected long range component to the spin forces. A measurement of the 1^1S_0 (η_b) state would settle the large range (29 to 101 MeV as shown in Table IV) of theoretical predictions on the Υ-η_b splitting, which should provide a theoretically sound value for α_s. Due to Doppler broadening, a measurement of the width, $\Gamma_{tot}(\eta_b\rightarrow2g)$, would be difficult to achieve with this particular reaction. The range of theoretical branching ratios for this transition is listed in Table X.

The principal 'background' to the photons from $1^1P_1\rightarrow\gamma 1^1S_0$ decay are those from the double cascade decays via the 1^3P_J states to the Υ (i.e. $3^3S_1\rightarrow\gamma 1^3P_J\rightarrow\gamma\gamma 1^3S_1$) . We have studied the production of the $1^1P_1\rightarrow\gamma 1^1S_0$ line among the numerous background lines. There are four possible ways to reach the 1^3P_J states:

1) $3^3S_1\rightarrow\gamma 1^3P_1$
2) $3^3S_1\rightarrow\gamma 2^3P_1\rightarrow\gamma\gamma 2^3S_1\rightarrow\gamma\gamma\gamma 1^3P_1$
3) $3^3S_1\rightarrow\pi\pi 2^3S_1\rightarrow\pi\pi\gamma 1^3P_1$
4) $3^3S_1\rightarrow\gamma 2^3P_1\rightarrow\gamma\pi\pi 1^3P_1$

and we have estimated the approximate branching ratios for these decays from Kuang and Yan[25]. The last three are expected to have branching ratios of $\sim2\times10^{-3}$, 10^{-3}, and 3×10^{-4} respectively. The decay $3^3S_1\rightarrow\gamma 1^3P_1$ is very sensitive to the nodes in the wave function, and estimates of the branching ratio range from $\sim10^{-2}$ to $\sim10^{-4}$ (see Table X). We have assumed a branching ratio of $\sim3\times10^{-3}$ as the background from the above transition (1), the 1^3P_J positions are from Ref. 9, and the rates for 1^3P decay are from Ref 25. With these assumptions we have listed in Table XI the contributions to the photon spectrum in the 400 MeV region for a sample of 4×10^6 Υ'' decays (i.e. 1,000 pb^{-1}).

Table XI. The expected 'background' photons to the reaction $1^1P_1\rightarrow\gamma\eta_b$ for 4×10^6 Υ'' decays.

Reaction	k_γ(Mev)	γ produced
$\Upsilon''\rightarrow\gamma 1^3P_0$	402	10,000
$\Upsilon''\rightarrow\gamma 1^3P_1$	427	7,200
$\Upsilon''\rightarrow\gamma 1^3P_2$	451	2,800
$1^3P_0\rightarrow\gamma\Upsilon$	487	1,300
$1^3P_1\rightarrow\gamma\Upsilon$	462	2,400
$1^3P_2\rightarrow\gamma\Upsilon$	438	106

The expected number of 'signal' photons produced is 8,000-20,000 (from Table X) at k_γ=416 MeV. This photon can be disentangled from the 402 MeV and 427 MeV photons from the inclusive decays $\Upsilon''\rightarrow\gamma 1^3P$, by a precise measurement of the expected number of photons obtained from inclusive ($\Upsilon'\rightarrow\gamma 1^3P$) and exclusive ($\Upsilon'\rightarrow\gamma 1^3P\rightarrow\gamma\gamma\Upsilon\rightarrow\gamma\gamma e^+e^-$ (or $\mu^+\mu^-$)) decays of the Υ', and exclusive ($\Upsilon''\rightarrow\gamma 1^3P\rightarrow\gamma\gamma\Upsilon\rightarrow\gamma\gamma e^+e^-$ (or $\mu^+\mu^-$)) decays of the Υ''. The final sample of events would be ~4,000-10,000 events (assuming a photon efficiency of ~50%). The π^0 background would be ~4,000 γ/MeV in the 400 MeV region (where we have assumed a 2:1 π^0 rejection). An example of what such a signal might look like is shown in Fig. 1 assuming 10,000 photons (efficiency ~50%) of 416 MeV.

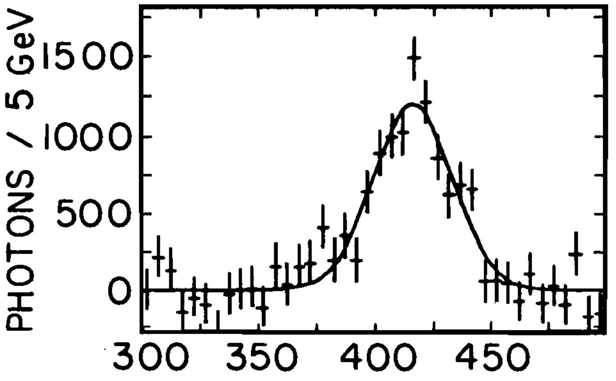

Figure 1. 10,000 photons from the decay $\Upsilon''\rightarrow\pi\pi 1^1P_1\rightarrow\pi\pi\gamma\eta_b$ for 4×10^6 Υ'' decays after background subtraction.

We conclude that a 1,000 pb^{-1} sample of integrated luminosity on the Υ' and Υ'' (together with detector upgrades) is more than sufficient to measure this decay mode and determine the Υ-η_b splitting.

B) $3^3S_1\rightarrow\gamma 1^1S_0$ (η_b).

The observation and detailed measurement of the η_b is of importance for testing QCD. Unfortunately the rates for M1 transitions in the $b\bar{b}$ system are significantly smaller than in the $c\bar{c}$ system where the η_c has already been observed. We have summarised some of the expected characteristics of the 1^1S_0 (η_b) in Table XII.

Table XII. Some of the theoretical predictions for the η_b state, where we have assumed $\Gamma_{tot}(\Upsilon)$=35 KeV, and $\Gamma_{ee}(\Upsilon)$=1.17 KeV (from Ref. 29).

Υ-η_b	30-120 (MeV)	see Table IV
$\Gamma(\Upsilon\text{->}\gamma\eta_b)$	16 eV (k/70 MeV)^3 13 eV (k/70 MeV)^3	[13]Krasemann [8]Eichten et al
BR(Υ->$\gamma\eta_b$)	$3\text{x}10^{-5}$-$2.5\text{x}10^{-3}$	
$\Gamma(\Upsilon\text{->}2g)$	4-11 MeV 6.4 MeV	[23]Iwao,Yamawaki [24]Barbieri et al
$\Gamma(\Upsilon\text{->}2\gamma)$	.2-.6 KeV .4 KeV	[23]Iwao,Yamawaki [24]Barbieri et al

In the calculation that follows we have assumed k_γ~70 MeV, and therefore BR(Υ->$\gamma\eta_b$) ~$5\text{x}10^{-4}$. The number of γ's and η_b's produced are ($5\text{x}10^{-4}$)x($20\text{x}10^7$) ~10^5 for a 10,000 pb^{-1} sample of Υ decays. Since these are low energy photons, we assume a photon finding efficiency of ~25%, together with a background π^0 spectrum of ~10^6 γ/MeV. If we assume a total width of $\Gamma_{tot}(\eta_b\text{->}2g)$~6 MeV, and σ~3% for the detector resolution, then the effective resolution is σ~$((2.6)^2+3^2)^{1/2}$ ~4%. In a 2σ region around the photon peak (in the inclusive photon spectrum) there would be an excess of $0.25\text{x}10^6$=25,000$\pm$2,200 photons, a very respectable 11 standard deviation effect. The error is calculated from an expected $5\text{x}10^6$ background photons in that region. Assuming that the detector resolution is well measured from other decays, then the width can be determined to ~25%. A typical subtracted photon spectrum is shown in Fig. 2 under the above assumptions. We conclude that a 10,000 pb^{-1} integrated luminosity sample of Υ events will allow a reasonably detailed study of the η_b, including its total width.

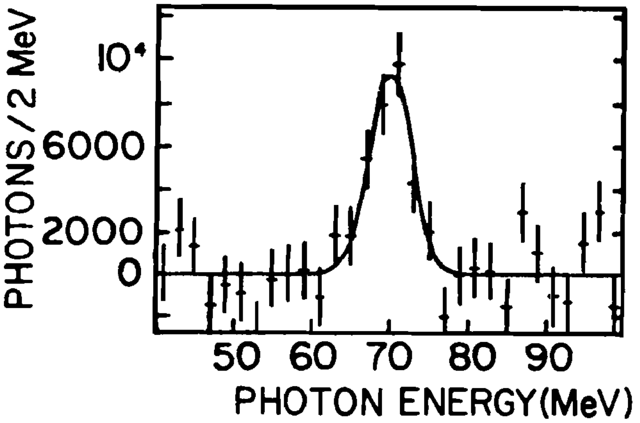

Figure 2. 25,000 photons from Υ->$\gamma\eta_b$ decay from a sample of $200\text{x}10^6$ Υ, after background subtraction. For details see text.

Exotic Spectroscopy

A) Radiative Υ Decays

The large number of Υ decays possible with the super luminosity will allow the determination of precise bounds on radiative decays Υ->γX where X might be a light neutral H^0, axions, etc. A super integrated luminosity sample (10,000 pb^{1}) of $200\text{x}10^6$ Υ decays, assuming photon efficiencies of ~50% for photons of energies from 400 to 3 GeV, would allow determinations of upper limits on branching ratios of $(5\text{-}10)\text{x}10^{-6}$. We have as usual assumed a π^0 rejection of a factor of ~2 in calculating the background photon spectrum. The contribution is 800-9,000 γ/MeV for E_γ from 2.8 GeV to 450 MeV respectively. A plot of the 90% CL upper limit branching ratio for Υ->γX as a function of M_X is shown in Fig. 3.

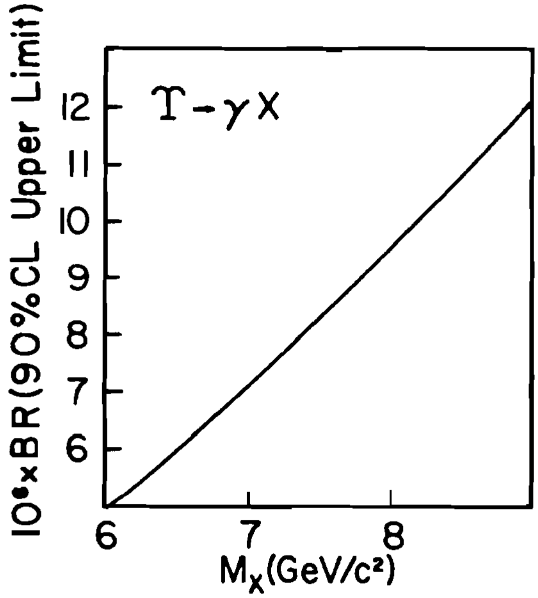

Figure 3. The 90% CL upper limit on BR(Υ->γX) with $200\text{x}10^6$ Υ decays.

As a concrete example we plot in Fig. 4 the expected branching ratio for Υ->γH^0 and Υ'->γH^0 vs the neutral Higgs mass. The graph is calculated from $\Gamma(V\text{->}\gamma H^0)/\Gamma(V\text{->}\mu\mu)=(G_F m_V^2/4\sqrt{2}\pi\alpha)(1-(m_H/m_V)^2)$ in Ref. 27.

B) Missing Energy

One can search for rare particles such as gluinos (λ) by looking for missing visible energy. If indeed the branching ratios for 1^3P->$\lambda\lambda$ are as high as predicted[30] (~5-10% for $1^3P_{0,2}$ and ~50% for 1^3P_1) and ~1-2 GeV of the energy is invisible, then by tagging 1^3P_1 events with the ~100 MeV photon in the inclusive photon spectrum it is possible to detect the change in the average observed energy between tagged and untagged events. With signal to backgrounds of 1:2, which we believe to be achievable, a statistically significant measurement can be made.

Conclusion

The rich spectrum of the $b\bar{b}$ system is yet to be fully exploited. The study of the E1 photon transitions, and the $\pi\pi$ hadronic cascades can be completed with only modest improvements in luminosity and detectors. The more difficult M1 transitions, and other subpercent level photonic and hadronic transitions will only be accessible at the highest luminosities together with significantly improved detectors.

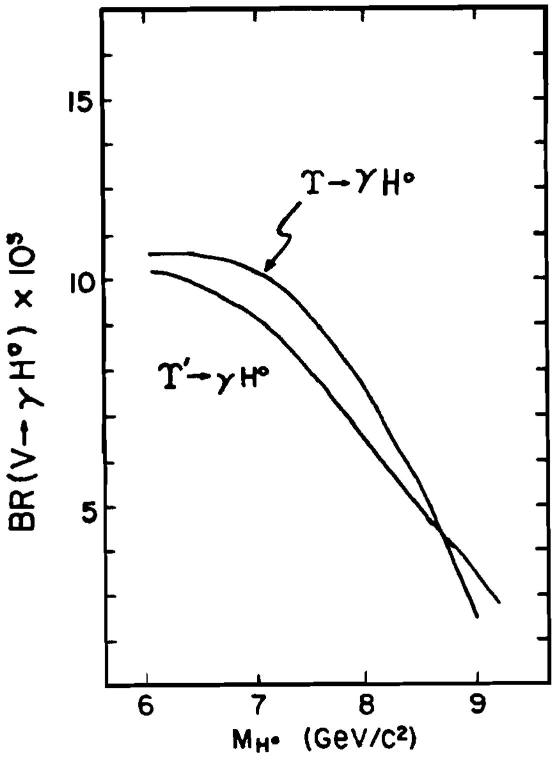

Figure 4. The expected BR(V->γH^0) for V= Υ and Υ' (from Ref. 27).

It is the study of the η_b that can be completed with these large improvements, providing stringent tests of QCD (i.e. measuring α_s), and thus very important. These high luminosities may also allow the observation of the gluonium states (see the article by Tye[31] on gluonium spectroscopy on the Υ) and put stringent bounds on other radiative Υ decays.

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