SPECTROSCOPY OF HEAVY QUARK-ANTIQUARK STATES

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Abstract

In the following, I review the recent experimental developments in heavy quark spectroscopy. Emphasis is placed predominately on the Υ system where numerous new results help establish the main features of the $^3S_1$ states, energy levels, and hadronic transition rates and place limits on the presence of other narrow resonances. Preliminary estimates of Υ E1 transition rates from $^3S_1$ to χ_b states are compared with the corresponding ones of the J/ψ system where new measurements of better accuracy have been reported.

Introduction:

In 1975 it had been pointed out that heavy quark-antiquark pairs form positronium like systems, thereafter dubbed "quarkonium"[1]. Their bound states, especially the radial excitation levels can be described by means of flavor independent, non-relativistic potential models. In the past years, the two bound triplet S levels of charmonium (the J/ψ system) were used to fix parameters in many potentials[2,3,4,5,6], which are then used to predict other experimentally accessible quantities such as the E1 transition rates. By scaling in mass, the potentials also predict level spacing and transition rates in heavier quarkonia systems, for example the Υ system (bottomonium). These predictions can be confronted with experimental measurements to test the validity of both the premises and applications of the models.

For this report, I adopt the standard spectroscopic notation where the low lying states are:

S-WAVE	^3S with $J^{PC} = 1^{--}$ (same as the photon) ^1S with $J^{PC} = 0^{-+}$
P-WAVE	^3P with $J^{PC} = 0^{++}, 1^{++}, 2^{++}$ ^1P with $J^{PC} = 1^{-+}$
D-WAVE	^3D with $J^{PC} = 1^{--}, 2^{--}, 3^{--}$ ^1D with $J^{PC} = 2^{-+}$

Most of the information on heavy quark bound states are obtained at electron-positron colliders from studing the reaction $e^+e^- \to \gamma \to Q\bar{Q}$, thus the directly experimentally accessible states are those having the same J^{PC} as the photon (i.e. ^3S states). Other states are studied via radiative and hadronic transitions from the triplet S states.

In figure 1a, we see the J/ψ spectrum with some of the observed photonic and hadronic transitions indicated. Only two triplet S states exist below the free flavor threshold of charmed meson $\begin{pmatrix} & u \\ c, & d \\ & s \end{pmatrix}$ production. The Τ system, due to the massiveness of the b quark, has a richer spectrum below threshold (see figure 1b). To date three triplet S states below threshold and one just above threshold have been observed. The hadronic transition rates between the bound triplet S states have also been measured.

In the past a great deal of experimental effort has been concentrated on the J/ψ system, which is therefore relatively well understood. In fact, the Crystal Ball Group, which has doubled its statistics since last year, spent most of their effort not on spectroscopy but on searches for axions and glueballs, which D. Scharre has presented and to whose report I refer you.[7] They also refined their measurements on photon transitions which I will comment on briefly.

Instead, the Τ spectroscopy study has made great strides just this past year and most of my report will deal with that system.

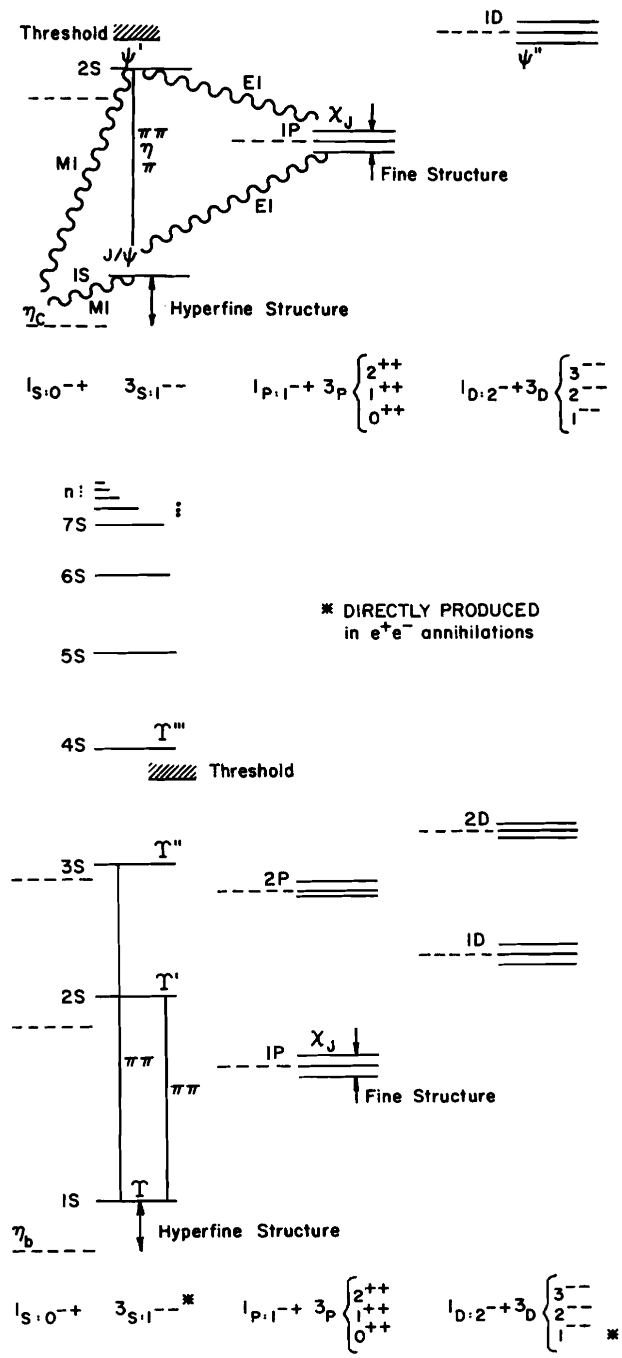

Fig 1 a(top) J/ψ system with some of the observed transitions.
b(bottom) Τ system with the two hadronic cascades indicated.

J/ψ System

The two new developments in charmonium are a) more precise determinations of E1 photon transition rates, and b) a better determination of η_c parameters and the discovery of an η_c' candidate. The following table shows our present knowledge on the transition rates for $\psi' \to \gamma + {}^3P_n$ and a comparison with the coupled channel model predictions.

TABLE 1

		1^3P_0	1^3P_1	1^3P_2
Exp.[7]	BR($\psi' \to \gamma + \chi$) [in %]	10.1±0.6	8.4±0.6	7.6±0.5
	Ratio to 1^3P_0	≡ 1	0.83±0.08	0.75±0.07
theory [8]	BR($\psi' \to \gamma + \chi$) [in %]	20±4	16±3	11±2
	Ratio to 1^3P_0	≡ 1	0.8±0.2	0.55±0.15

The rates have now been measured accurately enough to see the expected $(2J+1)k^3$ dependence predicted by theory, however the absolute rates are still low by a factor of two.

The level splitting and transition rates from triplet S to singlet S states are listed below for both the η_c and the η_c' candidate, as well as some theoretical expectations for these values.

		Exp.[7]	theory
$\Delta M(\psi-\eta_c)$	[in MeV]	117±5	99[9] 90[10]
$\Delta M(\psi'-\eta_c')$	[in MeV]	92±5	80±15[11] 80 10[12]
BR($\psi \to \gamma+\eta_c$)	[in %]	0.7 to 1.5	2.8[13]
BR($\psi' \to \gamma+\eta_c$)	[in %]	0.32±0.05	0.47[13]
BR($\psi' \to \gamma+\eta_c'$)	[in %]	0.3 to 1.2	0.45[13]

Obviously within statistics data and theory are in good agreement. The η_c' candidate ranges in significance from 4σ to 6σ depending on the method of data extraction (see D. Scharre in these proceedings[7]), and no exclusive decay channels for the η_c' candidate have been seen yet.

The T System

A large body of new experimental results have been accumulated at CESR which devoted all its running time to T physics. Meanwhile analysis of data taken on the first two T's at DORIS were refined.[14] The discovery of a broad fourth T and the observation of the weak decay of a stable meson of ∿5 GeV mass give conclusive proof of the existence of a new flavor of heavy quark: the b quark. Figure 2 shows the hadronic cross section observed at CESR in CUSB in the past eighteen months and the number of hadronic events accumulated at the four resonances and in the continuum.

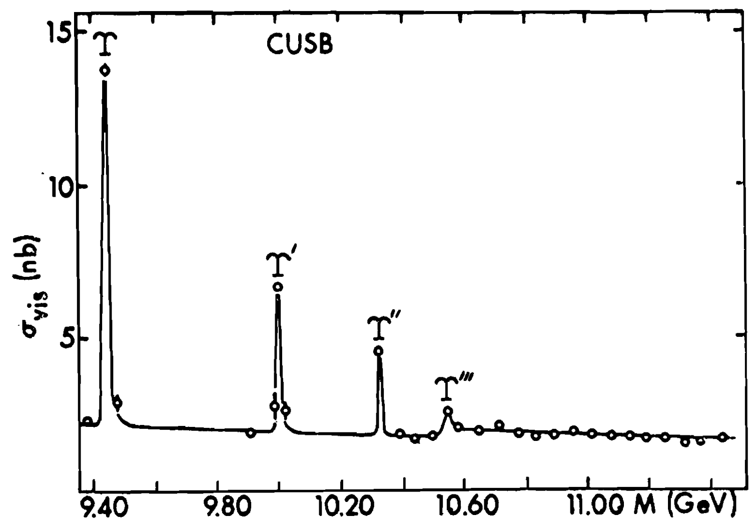

Fig. 2 A summary of all the data collected at CESR with the CUSB detector. 55,000 e^+e^- annihilations into hadrons were collected distributed as: 6,000 events at the T, 14,000 at the T', 9,000 at the T", 16,000 at the T"', 6,000 between the T" and T"' and 4,000 above the T"'.

Masses and Leptonic Widths:

The mass value and leptonic width of the T ground state is presented in Table 2, together with some potential model predictions for their value. For the excited states, their mass differences and leptonic width ratios to the ground state are presented and again can be directly compared to the potential model predictions.

TABLE 2

		Exp.†	Model M[2]	BGT[3]	R[4]	QR[5]	KO[6]
M (GeV)	T	9.4332±0.0002					
M-M(T)	T'	560.0±0.3	---	555	555	---	552
(MeV)	T"	890.3±0.4	---	890	886	898	862
	T'''	1113±1	1116	1180	1170	1170	1108
Γ_{ee}(KeV)	T	1.17±0.04††	---	1.07	---	---	1.05
Γ_{ee}/Γ_{ee}(T)	T'	0.46±0.03	0.43	0.46	0.42	0.48	0.45
	T"	0.33±0.03	0.28	0.32	0.30	0.34	0.31
	T'''	0.23±0.02†††	0.20	0.26	0.27	0.28	0.25

† All errors are statistical only

†† QCD sum rules predict 1.15±0.2 KeV[10]

††† Assuming a gaussian shape, with radiative corrections and no threshold step under the resonance.

The data in table 2 has been averaged over the DORIS and CESR results except for the mass of the T which is in the CESR energy scale. The 0.3% mass scale difference between CESR and DORIS is still there. This difference is due to uncertainties in measuring $\oint B d\ell$ for the machine guide fields, and one should not be surprised. CESR this fall will try to find the g-2 depolarizing resonances to establish an absolute energy scale.

All measured quantities are in excellent agreement with the potential model predictions for the first four radial states of a ($b\bar{b}$) quarkonium system, the $1^3S_1, 2^3S_1, 3^3S_1$, and 4^3S_1 states (often referred to as 1S,2S,3S, and 4S) and hence are identified with them. The fact that these models were originally constructed for the $c\bar{c}$ system and work so well for the $b\bar{b}$ system argues well for the flavor independence of the interquark (heavy) forces. It is also apparent that these radial states' properties do not differentiate amongst the various models, partly because all of them overlap in the region probed by the J/ψ and T radii of 0.1 to 1.0 fermi (see figure 3).

In addition the value of Γ_{ee}(T) and Γ_{ee}(T') are still in good agreement with the assignment of $q_b = 1/3$ (see figure 4).

Total and Partial decay rates of the T:

The classical resonance formula, integrated over the observed resonance cross section gives for spin 1 resonances the relation:

$$\Gamma_{ee}(T) = \frac{M^2}{6\pi^2} \int_{\text{resonance}} \sigma_{tot}(e^+e^- \to T)\, dW$$

where Γ_{ee} is the partial width for T decay into e^+e^- and W is the c.m. energy.

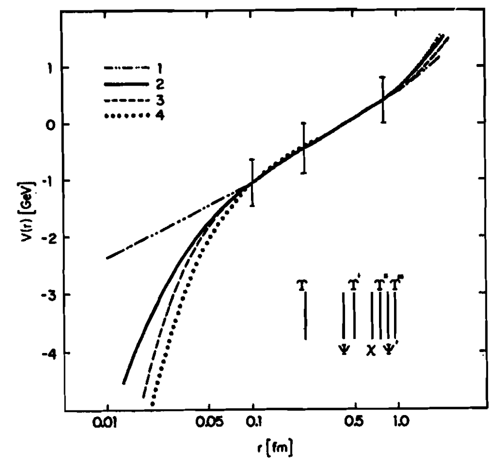

Fig 3. Potentials used by various potential models.
#1 see ref. [3]
#2 see ref. [2]
#3 see ref. [15]
#4 see ref. [6]

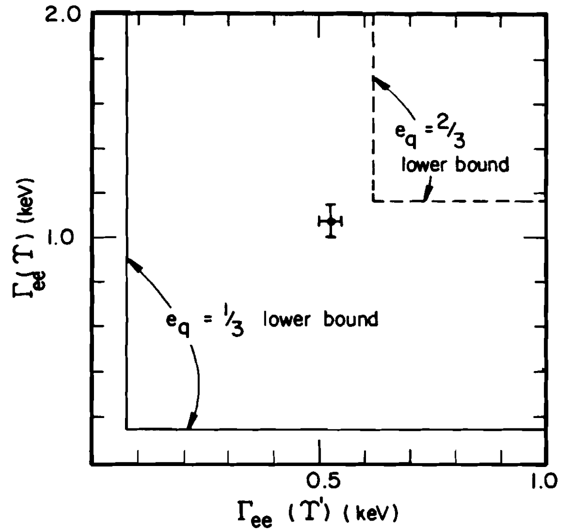

Fig. 4 Update of the 1979 figure by C. Quigg (ref. [16]) proving that the b-quark charge is still 1/3.

The following values have been reported:

$\Gamma_{ee}(\Upsilon)$ =	1.23±0.08±0.22 keV	DASP II, ref. [17]
	1.33±0.14	PLUTO, ref. [17]
	1.23±0.1 ±0.14	LENA, ref. [17]
	1.07±0.07±0.15	CUSB, ref. [18]
	1.19±0.02±0.10	CLEO, ref. [19]

We shall use in the following the average value $\Gamma_{ee}(\Upsilon)=1.17\pm0.05$ keV. The total width of the Υ, $\Gamma_{tot}(\Upsilon)$, can be obtained from measurements of the branching ratio $B_{ee}=\Gamma_{ee}/\Gamma_{tot}$ or, assuming lepton universality, $B_{\mu\mu}=\Gamma_{ee}/\Gamma_{tot}$. Direct measurements at DORIS[17] give a value $B_{\mu\mu}= 3.2\pm0.8\%$. Combining this result with data from CLEO, CUSB, and LENA on Υ' cascades (which will be discussed later), one obtains $B_{\mu\mu}= 3.3\pm0.5\%$, and therefore $\Gamma_{tot}(\Upsilon)= \Gamma_{ee}/B_{\mu\mu} = 35.5\ {+6.3}\ {-4.7}$ keV.

What gives rise to this total width? The dominant decay modes of the ground state are, annihilation into a virtual photon, into three gluons ($b\bar{b}$ annihilation into a single gluon is forbidden by color conservation), or into two gluons and a photon. Defining:

$$R = \frac{\sigma(e^+e^-\to\text{hadrons})}{\sigma(e^+e^-\to\mu^+\mu^-)_{\text{lowest order in QED}}}$$

and assuming μ-e-τ universality, the decay rate of $b\bar{b}$ annihilation into a virtual photon which subsequently creates pairs of leptons or quarks (which hadronize with unit amplitude) is given by:

$\Gamma_{"\gamma"} = (3+R)\Gamma_{ee} = 7.9$ keV (using the value R=3.75)

In lowest order QCD the ratio $\Gamma_{\gamma gg}/\Gamma_{ggg}$ for the Υ system is given by[20] $(36/5)\times(\alpha q_b^2/\alpha_s) \sim 0.04$. Since $\Gamma_{\gamma gg}$ is so small I will neglect it in all subsequent calculations. (Equivalently since $\Gamma_{\gamma gg}$ scales with Γ_{ggg} the "Γ_{ggg}" that I quote is a shorthand notation for $\{1+(36/5)\times(\alpha q_b^2/\alpha_s)\}\Gamma_{ggg}$.)

In addition small exculsive channels exist such as $\Upsilon \to {}^1S_0 + \gamma$ or $\Upsilon \to \rho^0 + \pi^0$. The first rate is expected to be small[8] and the second has been searched for by LENA and CUSB without success. The 90% confidence level upper limit on $BR(\Upsilon\to\rho^0\pi^0)$ is < 0.2% from LENA[14] and < 0.15% from CUSB (preliminary)[21]. Therefore, ignoring these modes one obtains:

$$\Gamma_{tot}(\Upsilon) = \Gamma_{ee}/B_{\mu\mu} \simeq \Gamma_{ggg} + (3+R)\Gamma_{ee}$$

$$\text{or} \quad \Gamma_{ggg}(\Upsilon) = \{1/B_{\mu\mu} - (3+R)\}\Gamma_{ee} = 27.5\ {+6.3}\ {-4.7}\ \text{keV}$$

The three gluon annihilation of triplet $q\bar{q}$ states is formally identical to the triplet positronium annihilation into 3γ's and requires knowledge of $|\Psi(0)|^2$. The decay into two electrons can also be expressed in terms of $|\Psi(0)|^2$ and the quark charge. This was computed a long time ago by Weisskopf and Van Royen[22]. Thus the ratio $\Gamma_{ggg}/\Gamma_{ee} = 1/B_{\mu\mu}-(3+R)$ is independent of the wave function at zero quark separation and the experimental value of the leptonic width. The first order QCD corrections to the W.-V.R. formula have been known for some time. Recently, LePage and McKenzie at Cornell[23] have computed the next order QCD correction to Γ_{ggg}. The relevant formulae are:[23,24]

$$\Gamma_{ee} = 16\pi\alpha^2 q_b^2 \frac{|\Psi(0)|^2}{M^2}\left(1 - \frac{16}{3}\frac{\alpha_s}{\pi}\right)$$

$$\Gamma_{ggg} = \frac{160}{81}\alpha_s^3(q^2)\ (\pi^2-9)\ \frac{|\Psi(0)|^2}{M^2}\ \left(1 + 3.8\ \frac{\alpha_s}{\pi}\right)$$

from which $\alpha_s(q^2=100\ \text{GeV}^2) = 0.140\pm0.008$. Note that $\Gamma_{ggg}/\Gamma_{ee} \propto \alpha_s^3$ and therefore the percentage error of α_s is 1/3 that of $B_{\mu\mu}$. Finally from this value of α_s one can estimate the scale parameter of QCD: $\Lambda_{\overline{MS}} = 115\pm40$ MeV[23]. Buchmüller and Tye have used the ψ to η_c mass splitting to calculate $\Lambda_{\overline{MS}} = 160\pm20\pm70$ MeV[12] and the known shape of the potential above 0.1 fermi to obtain a lower limit of $\Lambda_{\overline{MS}} > 0.1$ GeV[9]. For a complete discussion of Λ under different renormalization schemes see the report of A. Buras in these proceedings.

Note that the muon pair yield at CESR increases by 60-70% at the Υ peak and one might look forward to measurements of $B_{\mu\mu}$ with < 5% errors, vs.15%

at present. As well as being the dominant experimental uncertainty in the determination of α_s, it dominates many of the decay width determinations that I am reporting.

The whole preceeding analysis using QCD assumes vector colored gluons. The narrowness of the Υ width can be taken as evidence that color conservation is in operation, i.e. the $b\bar{b}$ pair does not annihilate into a single gluon which would result in a much larger rate, hence the gluon is colored. Since gluons are not directly observable and are only inferred through their fragmentation products(the hadrons), the spin and number of gluons is determined via indirect measurements of hadron distributions.

QCD predicts the orientation of the three gluon configuration in space and their Dalitz plot density configuration, both depending on the spin of the gluon assumed. If we define θ as the angle between the most energetic gluon and the beam direction, then explicitly for the angular distribution one gets:

$$f(\cos\theta) = 1 + \langle\alpha_T\rangle \cos^2\theta$$

with $\langle\alpha_T\rangle = 0.39$[25] for vector gluons and $\langle\alpha_T\rangle = -0.995$[26] for scalar gluons. Experimentally, the direction of the most energetic gluon is identified with the thrust axis and $\langle\alpha_T\rangle$ has been measured by many groups. Combining the CLEO value of 0.35 ± 0.11[27] and the DORIS value of 0.33 ± 0.16[14] one obtains 0.34 ± 0.09, consistent with the spin 1 value and 15σ away from the spin 0 value.

The energy flow pattern of an event reflects the Dalitz plot density distributions of the three gluons or two jets. Various groups use different parameterizations of the energy flow patterns. I briefly describe the thrust-like variable used by CUSB since it pertains to an analysis of higher Υ states as well as determining the gluon spin via energy flow patterns.

For a non-magnetic calorimeteric detector like CUSB, the energy deposition can be used to define a variable: planar thrust (T'), a thrust variable which is projected onto the plane perpendicular to the beam axis. In particular, we define T' to be:

$$T' = \mathrm{Max}_{\phi_n}\{(\Sigma_i E_i \times |\cos(\phi_i - \phi_n)| / (\Sigma_i E_i)\}$$

where E_i is the energy in sector i of azimuth ϕ_i, ϕ_n runs over the 32 ϕ[28] sectors. This variable ranges over $2/\pi < T' < 1.0$ with large values corresponding to events with particles collimated into two back to back jets. We have measured T' distributions for the Υ bound states and the continuum, and find that this variable is highly efficient in separating two jet and spherical events. For example, figure 5 shows the experimental T' distributions in our detector for the continuum events (labeled $q\bar{q}$ in the figure) and for the Υ ground state after continuum and virtual photon contribution removal (labeled ggg in the figure). The two mean values: $\langle T'\rangle_{ggg} = 0.788 \pm 0.0009$ and $\langle T'\rangle_{q\bar{q}} = 0.848\pm0.0008$ are 48σ apart!

Krasemann[26] has computed both the matrix element involving three vector gluons and three scalar gluons, which after hadronization, yields a thrust distribution whose average value in CUSB for the former is 0.80±0.01 and for the latter yields a thrust distribution very close to the $q\bar{q}$ one with an average value in CUSB of 0.85±0.01. This method also leads to the conclusion that the three gluons resulting from Υ decay are colored vector gluons.

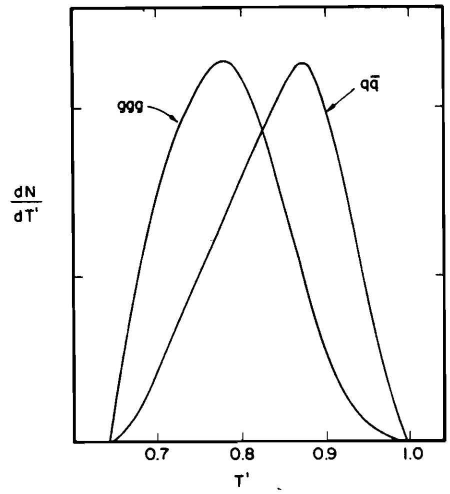

Fig. 5 Experimental planar thrust distribution for three jets (three gluons from Υ) and for two jets ($q\bar{q}$ from continuum) as observed in the CUSB detector.

Υ' Decay Rates:

For the excited radial states, new channels not requiring $b\bar{b}$ annihilation into photons and gluons can compete, these are hadronic and photonic transitions to lower levels. Such transitions have already been seen in the $c\bar{c}$ system where the $\psi' \to \psi\pi\pi$ has a 50% branching ratio and $\psi' \to \chi_c\gamma$ where χ_c is a P-wave, triplet $c\bar{c}$ state, has a 25% branching ratio. Therefore the total width of the ψ' is approximately three times that of the ground ψ state. For the $b\bar{b}$ system however, the E1 transitions are suppressed by the ratio of the quark charge squared $(q_b/q_c)^2 = 1/4$ and by the average radii squared $\langle r_\Upsilon^2\rangle/\langle r_\psi^2\rangle \simeq 1/3$, a total suppression of about 1/12. The hadronic transitions have recently been understood in a multipole expansion of the QCD gluon field[29], with the $\pi\pi$ transitions being analogous to two E1 transitions, hence would be suppressed by the above radii factor squared, i.e. by $\sim 1/10$. Incidentally, such a suppression only exists for vector gluons, not for scalar gluons, thus a measurement of this partial rate provides another check on the spin of the gluon.

The search for $\Upsilon' \to \Upsilon\pi\pi$ has been performed at DORIS by LENA and at CESR by CLEO and CUSB, via the observation of $\Upsilon' \to \pi^+\pi^-\Upsilon \to \pi^+\pi^-\ell^+\ell^-$. The following number of events were found:

LENA	5 e^+e^- + 2 $\mu^+\mu^-$	see ref. [30]
CLEO	17 e^+e^- + 8 $\mu^+\mu^-$	see ref. [31]
CUSB	23 e^+e^-	see ref. [18]

The dielectron mass for the 23 events seen by CUSB is shown in figure 6. CLEO also observed $\Upsilon' \to \Upsilon\pi\pi$ by computing the missing mass of all oppositely charged pion pairs (see figure 7). Combining all results, one obtains:

$$BR(T' \to T\pi^+\pi^-) = 0.191 \pm 0.031$$ [31]

and for all pion charges,

$$B_{\pi\pi}(T') = 0.287 \pm 0.046$$

The measured values for the product $BR(T' \to T\pi^+\pi^-) \times B_{ee}(T)$ are:

CUSB	0.0063±0.0013
CLEO	0.0068±0.0014
LENA	0.0061±0.0026

which combined with the above CLEO measurement of $BR(T' \to T\pi^+\pi^-)$ gives:

$$B_{ee}(T) = 0.034 \pm 0.007$$

Together with the direct DORIS results, one obtains the new best value:

$$B_{\mu\mu}(T) = 0.033 \pm 0.005$$

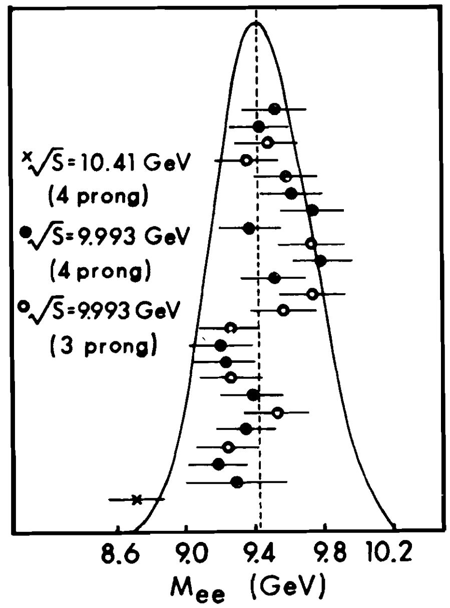

Fig. 6 Dielectron mass observed from eeππ events in CUSB.

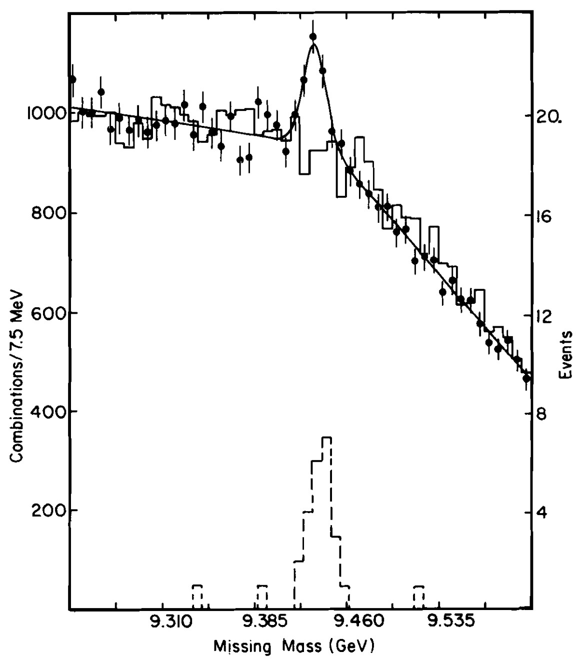

Fig. 7 Spectrum of the mass recoiling against two pions in the reaction $T' \to \pi^+\pi^- X$. A clear peak is visible at M_T.

In order to obtain the total and partial decay rates of the Υ', we write $\Gamma'_{tot} = \Gamma'_{ggg} + \Gamma'_{"\gamma"} + \Gamma'_{\pi\pi} + \Gamma'_{radiative\ (E1)}$, all for the Υ'. The first two terms scale as Γ'_{ee}, and can be written in terms of $B_{\mu\mu}(\Upsilon)$. Therefore:

$$\Gamma'_{"\gamma"} + \Gamma'_{ggg} = \Gamma_{ee}(\Upsilon')/B_{\mu\mu}(\Upsilon)$$
$$\Gamma'_{\pi\pi} = \Gamma'_{tot} \times B_{\pi\pi}(\Upsilon')$$
$$\Gamma_{ee}(\Upsilon') = 0.54 \pm 0.03 \text{ keV}$$

We take the radiative E1 transition rate from potential model calculations[32] to be 3 keV. Finally we obtain:

$\Gamma_{tot}(\Upsilon') = 27.3 \pm 4.7$ keV	$B_{\mu\mu}(\Upsilon') = 2.0 \pm 0.4$ %
$\Gamma_{\pi\pi}(\Upsilon') = 7.8 \pm 1.5$ keV	
$\Gamma_{"\gamma"}(\Upsilon') = 3.6 \pm 0.3$ keV	$B_{rad}(\Upsilon') = 11\%$
$\Gamma_{ggg}(\Upsilon') = 13.0 \pm 3.4$ keV	$(2/3)B'_{rad} = 7.3\%$

This indirect determination of $B_{\mu\mu}(\Upsilon')$ is in good agreement with the only direct measurement of it by CLEO of 1.6±1.0 %[33].

We note that the $\Gamma'_{\pi\pi}$ of 7.8 keV is indeed suppressed by over a factor of ten from the $\Gamma_{\pi\pi}(\psi')$ of 107 keV, and this fact can be taken as another confirmation that the spin of the gluon is 1. The same theory which predicts the suppression factor of $\sim$ 16, also predicts a dipion mass spectrum which is peaked at high mass, in good agreement with the data. LENA has searched for triple cascade events of the type $\Upsilon' \to {}^3P_n + \gamma \to \gamma + \gamma + \Upsilon \to \gamma + \gamma + \ell^+ + \ell^-$. They have one candidate in the muon channel and none in the electron channel from which they arrive at a 90% confidence level upper limit for the double cascade (using the known $B_{\mu\mu}(\Upsilon)$) of <7%[14]. CUSB has also searched for triple cascades and seen none from which we obtain a 90% confidence level upper limit on $BR(\Upsilon' \to \gamma\gamma\Upsilon)$ of <6%(preliminary)[21].

Υ'' Decay Rates:

The Υ family has three bound s-wave states below threshold as compared to two for the ψ family. This had been predicted. The Υ'' again has decay channels which do not involve $b\bar{b}$ annihilations.

The $\Upsilon''(3S)$ decay pattern is greatly more complicated relative to that of the lower excited state. In figure 8 some of the more outstanding hadronic and electromagnetic transitions are indicated. The hadronic transition to the Υ' is suppressed by phase space (Q value of 50 MeV), to the ground state is suppressed because the overlap integral is small. Radiative transitions are expected to be relatively large because of the larger radius of the Υ'' and the 2^3P states. In a search similar to that performed on the Υ' data, both CLEO and CUSB have looked for $ee\pi\pi$ events of the type $\Upsilon'' \to \Upsilon(\text{or } \Upsilon')\pi\pi$. Neither group has seen any events consistent with the mass of the T'. CUSB has seen 6 $ee\pi\pi$ events[34] and CLEO has seen 4 $ee\pi\pi$ and 1 $\mu\mu\pi\pi$ event[35] with a dilepton mass of the T. The average $BR(T''\to T\pi^+\pi^-) = 4.8\pm1.7\%$.

In order to get the total and partial decay rates of the T", we write a similar formula as the one for the T', ignoring small terms:

$$\Gamma''_{tot}=\Gamma''_{ggg}+\Gamma''_{"\gamma"}+\Gamma''_{\pi\pi}+\Gamma''_{radiative(E1)}$$

taking

$$\Gamma_{ee}(T'') = 0.37\pm0.03 \text{ keV}$$

again scaling Γ''_{ggg} and $\Gamma''_{"\gamma"}$, using the measured

$$B_{\pi\pi}(T'') = 7.2\pm2.6\%$$

and again taking potential model prediction $\Gamma''_{E1} = 5$ keV,

we obtain:

$$\Gamma_{tot}(T'') = 17.5\pm3.5 \text{ keV}$$
$$\Gamma_{\pi\pi}(T'') = 1.3\pm0.6 \text{ keV}$$
$$\Gamma_{"\gamma"}(T'') = 2.5\pm0.2 \text{ keV}$$
$$\Gamma_{ggg}(T'') = 8.7\pm2.6 \text{ keV}$$

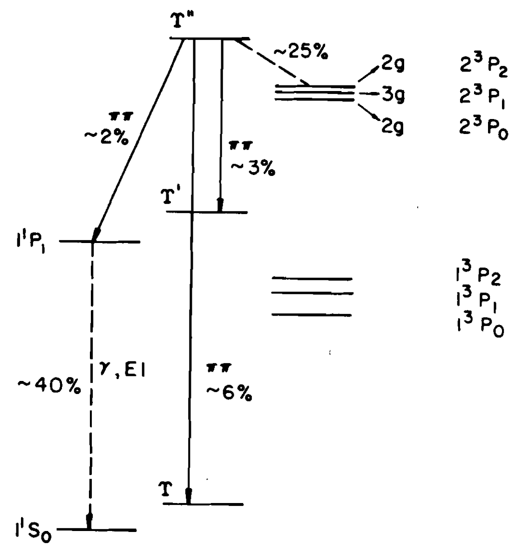

Fig. 8 T" decay scheme, with some of the more outstanding hadronic and electromagnetic transitions indicated.

$$B_{\mu\mu}(T'') = 2.1\pm0.5\%$$

$$B_{rad}(T'') = 29\%$$
$$(2/3)B_{rad}(T'') = 19\%$$

Note the relatively large $B_{rad}(T'')$ obtained relative to $B_{rad}(T')$, which is due both to the relatively larger radius of the T" and the suppressed hadronic transition modes. No direct measurement of $B_{\mu\mu}(T'')$ is available for comparison.

Search for the E1 Transitions:

CUSB has made a search for the photons emitted in the E1 transitions both from the 9404 T' and the 5503 T" events. No distinct monochromatic photon lines are apparent[36], nor are they expected given the high photon multiplicity ($\sim$7 to 8 in CUSB) at these resonances and the limited data samples. However, the presence of these transitions have been indirectly inferred by studing the thrust distributions. We recall that the P waves reached by E1 transitions have $J^{PC} = 0^{++}, 1^{++}$, and 2^{++}. The spin 0 and 2 states therefore decay via two gluons, resulting in two jet final states similar to two quark events in the continuum. The decay of the spin 1 state into two gluons is forbidden by angular momentum conservation. It can however decay into three gluons because the totally color antisymmetric state $\underline{1}$ contained in the $\underline{8}\otimes\underline{8}\otimes\underline{8}$ product has positive C (see figure 8). The presence of two jet E1 transitions at the T's can be detected in CUSB because of our thrust parameter's(T') high sensitivity to 2 jet and 3 jet admixtures. For each of the resonances, the normal amount of 2 jet content is known since they come from the continuum and virtual photon contributions at the resonance. In particular, if there were no radiative transitions, it is expected at the T' the 2-jet fraction is 0.338±0.005, and at the T" it is 0.430±0.006. In figure 9, we show the experimental thrust distribution, and the predicted curve using the above predicted fraction of 2 jet/3 jet admixture, and the experimentally determined 2 jet and 3 jet thrust distributions shown earlier. The data is grossly different from the predicted curve.

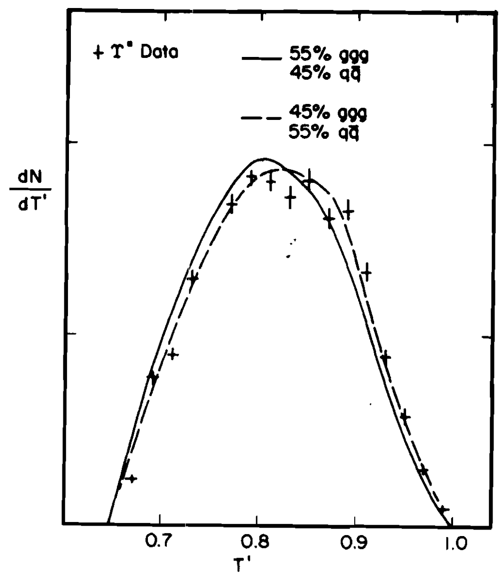

Fig. 9 Planar thrust distribution for T" decay. The solid line is the expected distribution for no T" → χ_b' + γ. The dashed line is a best fit, proving the presence in T" decays of an excess of two jet final states. CUSB

These excesses of two jet events can be quantitatively found by fitting the data with a variable amount of 2 jet/3 jet admixture, using the measured T' distributions. The fitted 2 jet fractions are 0.400±0.015 and 0.552±0.017 for the T' and T" respectively (shown as dashed curve in figure 9), which amounts to 0.062±0.016 and 0.122±0.018 excess 2 jet fraction in the two cases[37]. The branching ratio of these excess two jet events are given by:

Υ') $(0.062\pm0.016)/(0.706\pm0.009) = 0.09\pm0.02$; $(2/3)B'_{rad} = 7.3\%$

Υ'') $(0.122\pm0.018)/(0.608\pm0.008) = 0.20\pm0.03$; $(2/3)B''_{rad} = 19\%$

where the denominators are the total resonance event fraction (including virtual photon transitions) of the total hadronic events. One notes that the E1 branching ratios derived previously, when multiplied by 2/3 (for two P states out of three), are in extremely good agreement with the observed 2 jet excess.

A further check that the 2 jet excesses come from E1 radiative transitions to P states can be obtained by **studying inclusive photon spectra.** For a detailed description of that analysis, see reference [36]. The results are again consistent with the predicted transition rates. This however is in contrast with the ψ system where the predictions are off by about a factor of two.

Search for Other Narrow Resonances:

In addition to the four triplet S resonances which have been observed so far, other resonant states are expected to exist in the Υ system which are accessible via e^+e^- annihilations. Between the Υ''(3S) and the Υ''' (4S), for example, states which carry a "vibrational" quantum number[38] and D states might appear (the latter via S-D mixing). Above the Υ''' (4S), higher nS states exist, which some theorists[39] expect to have narrow widths. None were found and therefore the 90% confidence level upper limit on Γ_{ee} for a narrow resonance are summarised in Table 3.

TABLE 3

Mass interval studied	Exp.	Γ_{ee} upper limit
$7.4 < M < 7.6$ GeV $8.7 < M < 9.4$ GeV	LENA	< 0.27 keV
$10.38 < M < 10.51$ GeV	CUSB	< 0.035 keV
	CLEO	< 0.08 keV
$10.6 < M < 11.6$ GeV	CUSB	< 0.3 keV (using a width $\sim$40 MeV)

These limits are the highest value of the 90% confidence level upper limit in the mass region studied. Typically a tighter limit can be obtained for certain mass intervals where more running has occurred. In figure 10, we show $R_{visible}$ in CUSB, in the scan binning for the region between the Υ'' and the Υ'''. A maximum likelihood analysis was carried out to determine

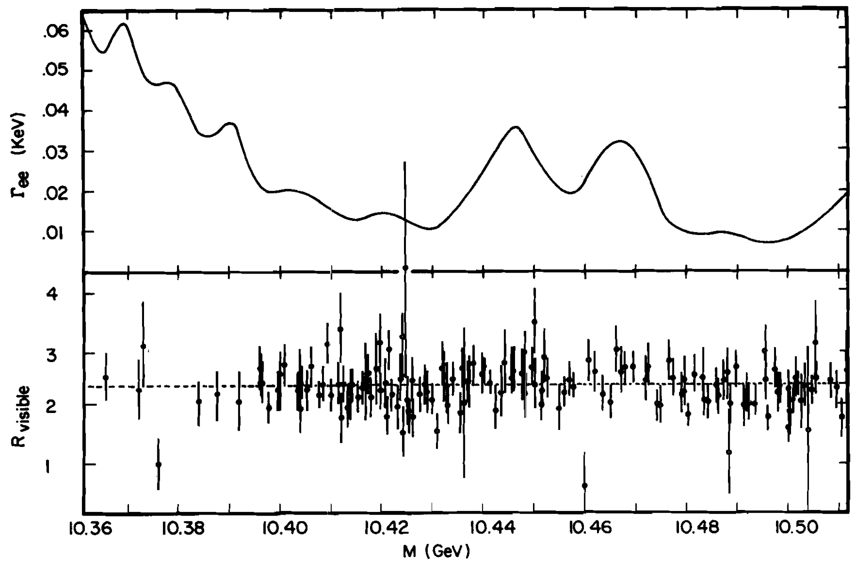

Fig. 10 (bottom) R visible in CUSB detector in the scan bins for the region between the Υ'' and Υ'''.
(top) 90% confidence level upper limit on Γ_{ee} for a narrow resonance as a function of mass.

an upper limit on Γ_{ee} for a narrow resonance. We calculate the likelihood for a fixed continuum level of $R_{vis} = 2.33$ plus a single Gaussian of width equal to the machine resolution at that energy ($\sigma_{machine} \sim 4$ MeV) and variable height, at a given mass. The value of $R_{vis} = 2.33 \pm 0.027$ for the continuum level between the Υ'' and Υ''' was obtained by averaging all the data in that energy range. The resulting 90% confidence level upper limit for the area of a narrow resonance, related to the leptonic width in the usual way, is also shown in figure 10 as a function of mass. We conclude that the $\Upsilon_{v=1}$ does not exist at the level predicted by reference [38] in this energy range, and that there is not sufficient S-D mixing to have made the 2D state visible.

For the region above the Υ'''(4S) where the CUSB data is shown in figure 11, again no narrow resonance is seen, but at the present level of statistics we are not able to solve for a series of broad overlapping resonances which would be the expected contribution from the nS states whose leptonic widths are expected to scale as 1/n. A maximum likelihood search similar to the one described before was done but for a resonance twice the width of the Υ''' and a fixed continuum level of $R_{vis} = 2.56$ (which is the average of the continuum level above the Υ'''). The 90% confidence level upper limit for Γ_{ee} as a function of mass is shown in figure 11.

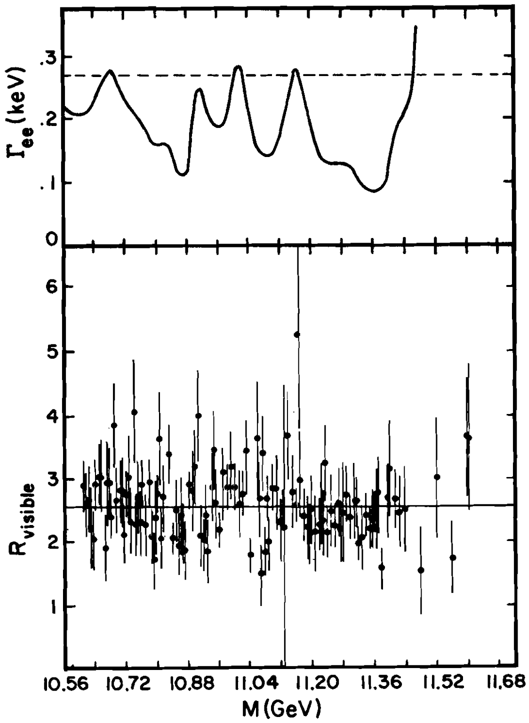

Fig. 11 (bottom) R visible in CUSB detector in the scan bins for the region above the T'''. Solid line is the average value of the data.

(top) 90% confidence level upper limit for a resonance above the average level with a width ≃ 40 MeV as a function of mass. Dashed line is the measured value of Γ_{ee}(T''').

Continuum:

Both CESR and DORIS have also devoted time to measure the continuum cross section; at DORIS this was measured just below the T. At CESR measurements were made in the region between the T'' and T''' , and above the T'''. Results of these measurements are given below as values of R.

TABLE 4

Machine	R†	Exp	Mass	Reference
DORIS	3.8 ±0.7	DHHM	∿ 9.4 GeV	[14]
DORIS	3.73±0.16	DASP II	∿ 9.4 GeV	[14]
DORIS	3.63±0.15	PLUTO	∿ 9.4 GeV	[14]
CESR	3.46±0.07	CUSB	∿10.4 GeV	[41]
CESR	4.06±0.05	CLEO	∿10.4 GeV	[19]
CESR	3.75±0.06	CUSB	10.6 to 11.5 GeV	[41]
CESR	4.26±0.07	CLEO	10.6 to 11.5 GeV	[19]

† The errors quoted are statistical only, all measurements carry an additional systematic uncertainty of ∿10%.

Because of the large systematic uncertainty, it is difficult to compare results from different experiments at different energies. However in a single experiment most of the uncertainties cancel out and a meaningful measurement at different energies can be made. The LENA group at DORIS has contributed[14] the result R(W=7.45 GeV)/R(W=8.6 to 9.4 GeV)=1.05±0.05, while both groups at CESR have reported a change in R across the B meson threshold. CUSB obtained R(W=10.6 to 11.5)-R(W=10.4) = 0.29±0.06[41] while CLEO obtained ΔR = 0.20±0.08[19] (see figure 12).

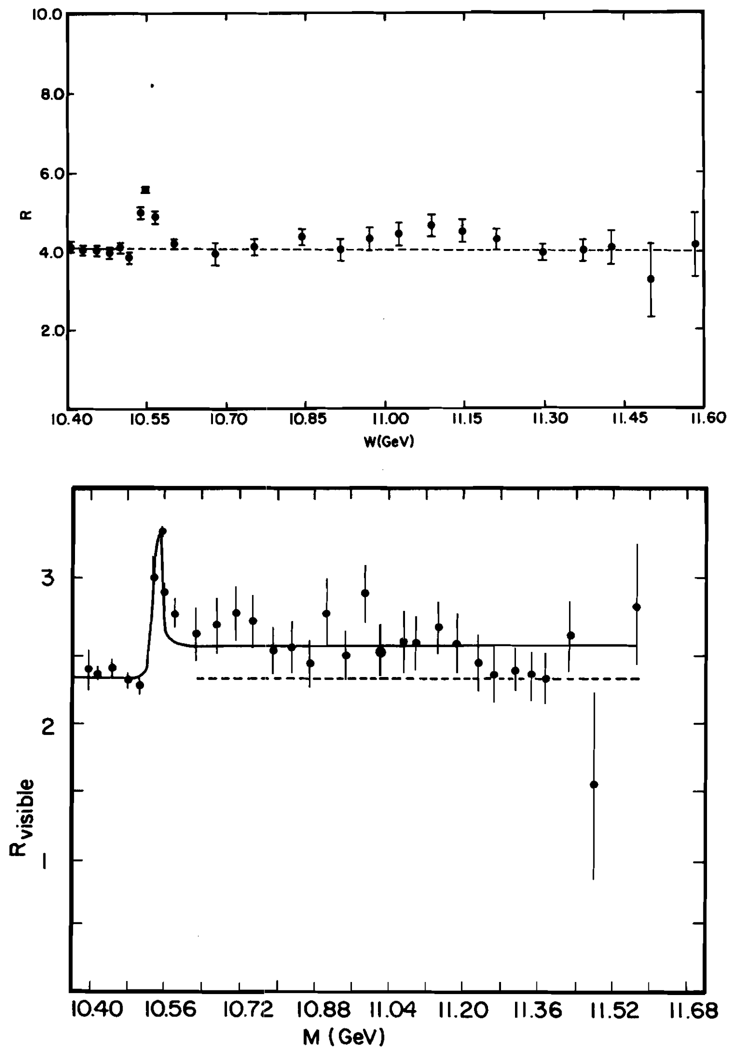

Fig. 12 (top) R (corrected for detector efficiency) just below and above the b flavor threshold as measured by CLEO. Dashed line is extrapolation of the continuum below the Υ'''.
(bottom) R visible in the same region as measured by CUSB. Dashed line is extrapolation of continuum below the Υ'''.

This last measurement, across a new flavor threshold constitutes a new proof that the b quark carries charge 1/3 for which one expects R=1/3.

Mass and Γ_{ee} of the Υ''':

The values quoted earlier were obtained by fitting the data to a continuum value (obtained by averaging the data below the Υ''') plus a single gaussian of variable height and width. However, the determination of the mass value and the leptonic width for the Υ''' is complicated by the fact that its total width, unlike those of the first three resonances, is wider than the beam energy spread. Furthermore the free flavor threshold is crossed at the Υ'''. Thus both the resonance shape, which is composed of several components, and how the continuum level underneath changes, are at present unknown. Any description of its resonance shape must include decay channel information not included in the normal potential models. One illustration of the shape dependence on decay channels is shown in figure 13, where Eichten used the very successful coupled channel model[15], which had described the above threshold behavior of the charm system, on the $b\bar{b}$ system[42]. While the experimentally measured width clearly excludes the

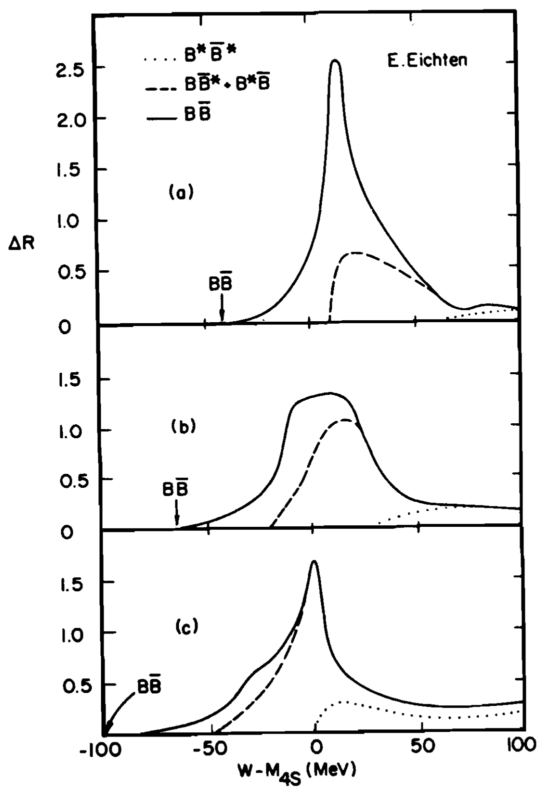

Fig. 13 Coupled channel prediction for the Υ''' shape as a function of position above $B\bar{B}$ threshold. See ref. [42].

(top) shape and mixture of B's and B^*'s assuming 40 MeV above threshold.
(middle) Assuming 70 MeV above threshold. Ruled out by measured width. (see text)
(bottom) Assuming 100 MeV above threshold. Also ruled out by measured fraction of B^*'s. (see section on B meson mass)

middle bump of ∿ 50 MeV width, both the top and bottom narrow bumps exhibit neither a Breit-Wigner nor a Gaussian shape. The shape of the resonance and how the free flavor threshold sets in, lead to an uncertainty in the value of the leptonic width of about ±8% each. Differences in how the threshold sets in can also shift the apparent mass of the ϒ''' by ±1 MeV.

Baryon and Strange Particle Production:

The following table summarizes the present knowledge[43].

TABLE 5†

W(GeV)	Exp.	K^0/Event	All Kaons/Event	$2\times\bar{p}$/Event	Λ or $\bar{\Lambda}$/Event
9.4	PLUTO	0.73±0.16			
	DASP II			0.05±0.03	
ϒ	PLUTO	0.97±0.22			
	DASP II			0.32±0.08	
	CLEO		1.7±0.2	0.32±0.07	0.23±0.04
	CUSB	0.82±0.08			
ϒ'	CLEO		1.7±0.2	0.41±0.08	0.13±0.03
	CUSB	0.82±0.08			
ϒ''	CLEO		2.0±0.2	0.38±0.10	0.17±0.05
	CUSB	0.82±0.08			
10.4	CLEO	0.75±0.05	1.8±0.2	0.22±0.04	0.14±0.05
	CUSB	0.82±0.08			
ϒ'''	CLEO	1.43±0.25	3.5±0.4	0.29±0.19	-0.07±0.10
	CUSB	1.52±0.20			

† The resonance results are all corrected for continuum yield; systematic uncertainties are not included.

Results for particle ratios and multiplicities discussed in other talks are important for a better understanding of gluon and quark "hadronization". The values presented tend to indicate that quarks and gluons jets are very similiar. There still appears to be an enhancement in the baryon production from gluons, but only a factor of two or less[44]. The LENA group has presented additional evidence that gluons and quarks fragment similarly.[14]

New Flavor Production at the ϒ''':

It has already been stated that the ϒ''' width indicates that it is

above the free flavor threshold, that the quasibound $b\bar{b}$ state decays predominately into $B\bar{B}$ pairs which are bound stable states of a b quark and a light quark (u,d,s) and are stable except for the weak decay. The evidence for this is by now overwhelming[45] and has been discussed in great detail by A. Silverman in these proceedings.

Bounds on the B Meson Mass:

The direct observation of B mesons through structures in the multiparticle mass spectra is difficult due to the combinatorial background arising from the high particle multiplicity in $B\bar{B}$ events, and has not yet been successful. However, since the $\Upsilon''(3S)$ is narrow, it lies below the flavor threshold. We have then:

$M(\Upsilon''') > 2M_b + 2M_{u,d}$ - Binding Energy of a $b\bar{u}$,... pair.

$M(\Upsilon''') > 2M_B > M(\Upsilon'')$

To get a tighter bound,short of reconstructing a B meson, is to search for the presence of the next excited B-meson, the B^*, which from scaling from K^*-K, D^*-D system, is expected to be $\sim$ 50 MeV heavier than the B meson. Recently Martin[46] placed limits on $\Delta M = M_{B^*} - M_B$ to be between 52 and 57 MeV. Given this mass difference the only kinematically allowed decay mode for the B^* is $B^* \to B + \gamma$. The copiousness with which the B^* is produced at the $\Upsilon'''(4S)$ clearly depends on how far above the threshold it is located and the specific mechanisms responsible for the decay channels. Ono[39], for example expects no B^* production since the Υ''' is situated $\sim$9 MeV above $B\bar{B}$ threshold. Eichten (see figure 13) expects 1 B^*/Υ''' event if the Υ''' is 100 MeV above threshold and less than 1/4 per Υ''' if the Υ''' is $\sim$ 40 MeV above threshold. Note that by this model we have already excluded the inbetween case of 70 MeV above threshold by virtue of the measured width of the Υ''' being $\simeq$20 MeV, and not 50 MeV. CUSB has searched for such $\sim$ 50 MeV photons. Our efficiency for such photons, assuming isotropic distribution, is $0.63(\Delta\Omega/4\pi)\times 0.26(\gamma$ finding efficiency$) = 0.165$. For our sample of hadronic events this results in a signal of 836 50 MeV photons in approximately four 5 MeV bins, for the case $BR(\Upsilon'''\to BB^*)=1$. The inclusive photon spectrum for the Υ''' events after continuum subtraction is shown in figure 14, together with the photon spectrum expected for one $B^*\to B+\gamma$ decay per Υ''' . No obvious signal is observed. A maximum likelihood calculation yields less than 0.2 γ/Υ''' event at the 90% confidence level upper limit[47], for photon energies between 45 and 60 MeV. Thus we conclude that $M_B \simeq 5255\pm 10$ MeV (in the CESR energy scale).

Conclusions:

In the past year charmonium spectroscopy has been solidified by the

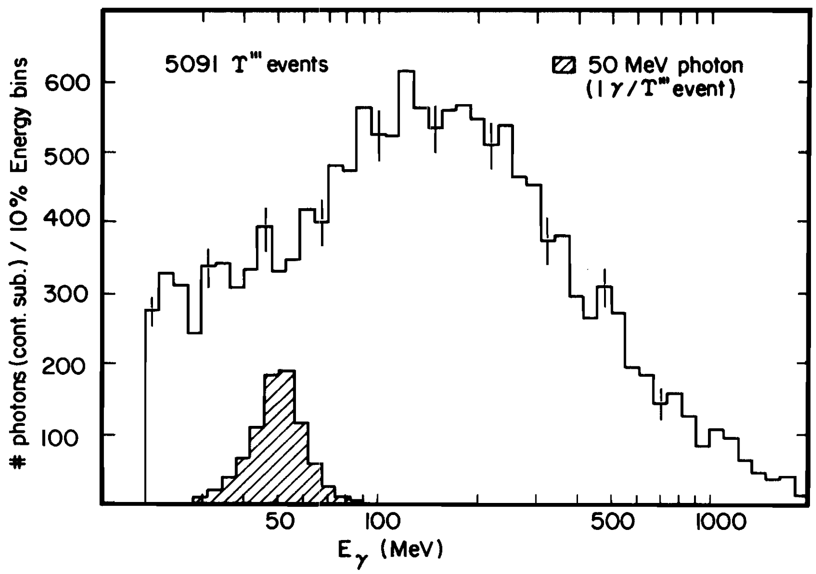

Fig. 14 Inclusive photon spectrum for Υ''' events (continuum subtracted). Hashed area is the expected number of 50 MeV photons if there were one B*/Υ''' event.

discovery of one and possibly two singlet S (η_c and η_c') states. Better values for BR($\psi' \to \gamma + {}^3P_n$) are now available, such that the relative E1 transition rates agree with the $(2J+1)k^3$ theoretically expected weights; however the absolute rates are still a factor of two lower then potential model expectations.

In bottomonium, the large body of new data from CESR and continued analysis from DORIS have yielded the following information:

(1) The Υ does decay predominantly via three colored vector gluons. It is the massiveness of the Υ system which allowed for experimental verification of this mode of OZI rule violation.

(2) The level splitting and leptonic widths of the bound and quasibound ${}^3S_1(b\bar{b})$ states apparently are well described by the same potential models which describe the J/ψ system, arguing in favor of flavor independence of interheavy quark forces.

(3) The fourth radial excitation in bottomonium lies just above free b flavor threshold (as expected from potential model considerations), its position, total width, and lack of 50 MeV photon emission lead to a determination of the B meson mass of 5255±10.

(4) No narrow states with Γ_{ee}>0.03 keV exists between the Υ'' and Υ''', where vibrational states and D states (via S,D mixing) might be expected

to appear.

(5) Indirect measurements of E1 transition rates agree with potential model expectations, unlike the J/ψ system. Could the difference be simply due to the smaller $\langle v^2/c^2\rangle \sim 0.07$ of the Υ system versus $\langle v^2/c^2\rangle \sim 0.23$ for the J/ψ system?

(6) The multipole expansion in QCD of the gluon field describe well the hadronic transitions between the radial excitations of the J/ψ system and in the Υ system which have now been measured. Comparison of the rates between the two systems give another confirmation that the gluon spin is 1.

(7) The major impetus in quarkonium spectroscopy in the near future will be concentrated on the Υ system, from CESR which expects to upgrade its luminosity and DORIS which will upgrade its energy to include the whole Υ system.

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Discussion

Le Yaouanc, LPTHE Orsay: On the behavior above $B\bar{B}$ threshold and the description of the Υ''', it is necessary to mention the very extensive study by S. Ono from Aachen.

F.H. Heimlich, Univ. of Hamburg: You determined the γ branching ratio for Υ' and Υ'' to the P states from the measured branching ratio to 2 jet-like states. Apparently you assume that the P_1 decays 3 jet-like as the Υ itself. Now it is claimed that the P_1 decays predominantly associated with a soft gluon, i.e. rather 2 jet-like. This would mean that you have no factor 1.5 between 1-jet and γP branching ratios.

R. D. Schamberger: If the P_1 state decayed like the P_0 or P_2 you would indeed not get the factor of 1.5. However I would like to know how soft is soft? In particular how much different the thrust distributions would be?

B. Kayser, SLAC and US-NSF: We have heard that the ratio of the 2π decay rates of Υ' and Ψ' is very different for vector gluons and scalar gluons. Is this big difference real, or is the theory approximate enough that the difference can be made small?

R. D. Schamberger: That is really a question for a theorist.

M. Krammer, DESY: I would like to add a remark on excluding experimentally scalar gluons: Based on the elementary spin-parity selection rules: $0^- \leftarrow\rightarrow 0^+ + 0^+$ and $0^- \leftarrow\rightarrow 0^+ + 0^+ + 0^+$, scalar gluons are excluded already by the observation $\Psi' \rightarrow \eta + J/\Psi$ and $J/\Psi \rightarrow \eta + \gamma$, $J/\Psi \rightarrow \eta' + \gamma$.

D. Coyne, Princeton Univ.: It would be most interesting to look for the reoccurrence of the iota (ι) and theta (θ) glueball candidates in the hard photon spectrum ($x \gtrsim .9$) from the Υ. Is there any chance that you will have data sufficient to investigate this subject?

D. Schamberger: We will certainly not ever see 2 million Υ's. If it is at large x ($x \gtrsim .9$), it should be easier to see, but how much I am not sure.