RECENT RESULTS IN UPSILON PHYSICS FROM CUSB

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ABSTRACT

In this report, we present recent results in Υ physics from CUSB. Primary emphasis in the area of Υ spectroscopy in the last year has been in the search for the χ_b states. We review here the discovery, branching ratios and parameters of the χ_b' and report on the preliminary values for the χ_b state. We have also made significant advancement in the knowledge of the weak interactions of the b quark. Limits on exotic models, semileptonic branching ratios and constraints on the coupling of the b quark to lighter quarks are presented.

INTRODUCTION

There has been great progress in Υ physics in the past year from CESR.[1,2] The Υ system has proven to be a remarkable testing ground for our understanding of the b quark, its decays, potential models, and QCD.

Figure 1 shows $R_{visible}$ measured by CUSB as a function of total center of mass energy with the three bound and one quasi-bound states prominently featured.

The large amount of data accumulated has led to many new results: the most significant being the discovery by CUSB of the 1^3P_1 and 2^3P_1 $b\bar{b}$ states.[2a] Our knowledge of the weak interactions of the b quark is also steadily improving. In this article, we will concentrate mostly on these two subjects.

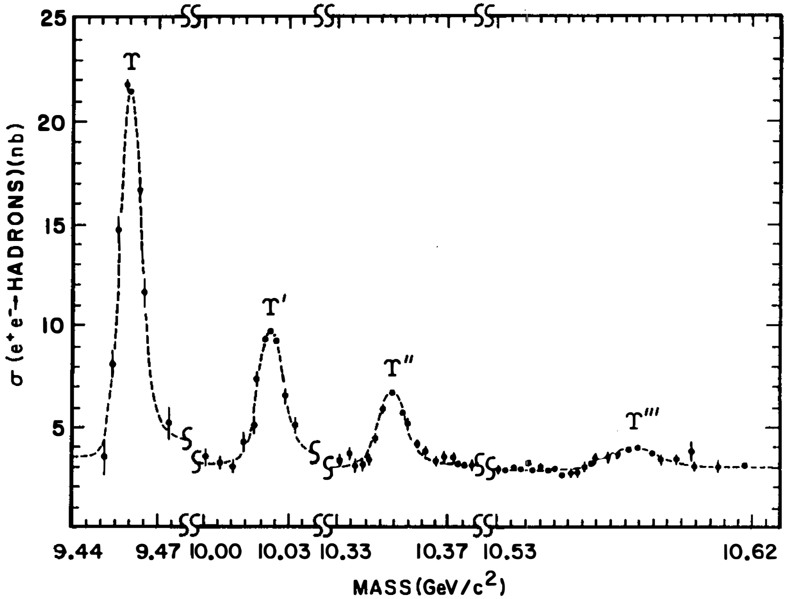


Fig. 1. The hadronic cross section measured at CESR by CUSB. Some 250,000 events were recorded.

A. Photon Transitions from the Υ''

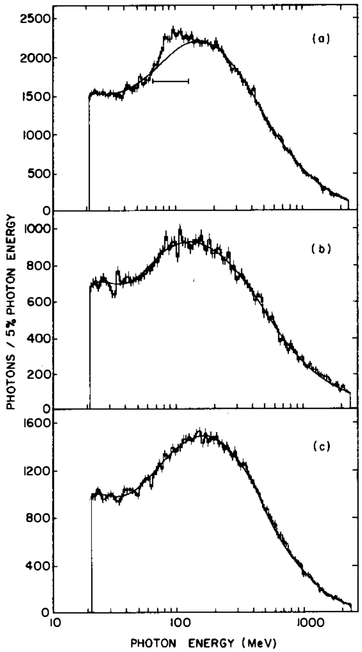
1. Inclusive spectrum.

The CUSB inclusive γ spectrum obtained at the Υ'' peak from 64,689 hadronic events is shown in Fig. 2a; some structure is visible at about 100 MeV. When the spectrum is fitted with a polynomial, a χ^2 of 148 is obtained for 86 degrees of freedom (dof) (confidence level $<$ 1/16,000). The curve shown is a fit obtained excluding 13 bins around the signal region which gave a χ^2 of 77 for 73 dof. The excess over the curve contains 2150 γ's (above $\sim$ 37,000 γ's); an 11 σ signal. The photon spectra from 31,486 continuum hadronic events and 40,491 Υ region hadronic events are shown in Figs. 2b and 2c respectively. The curves are polynomial fits to the data, they give χ^2's of 107 and 80, respectively, for 86 dof.

An alternate way to obtain the background curve is to predict it absolutely using the observed Υ and continuum γ distributions and the measured thrust values.[3] The thrust distribution at the Υ'' can be reproduced by a linear combination of that from the continuum (41.6%) and that from the Υ(58.4%). Applying these coefficients to the spectra from 2b and 2c, after they have been appropriately scaled by the number of hadronic events (64,689/31,486 for 2b; 64,689/40,491 for 2c), we obtain a background curve which is essentially indistinguishable from the one in Fig. 2a, hence which yields the same excess in the 100 MeV region.

The subtracted spectrum is shown in Fig. 3a. The measured center of gravity of the signal is 97.7 MeV. Using our efficiency for 100 MeV photons of $\sim$ 17%, we obtain a branching ratio for $\Upsilon'' \rightarrow (100\pm20\ \text{MeV})\gamma$'s + X of 34%, with 3% statistical uncertainty. Both the position and the high rate of this signal make it highly likely that X is the $2^3P_{2,1,0}$ levels (also called χ_b') and that the bump consists of three E1 transition photon lines.

The resolution function of the CUSB detector and γ search code combined is determined by Monte Carlo methods and is checked by reconstructing π^0's. Figure 3b gives the resolution function at 100 MeV, $\sigma \sim 8\%$. It is far narrower than the signal in Fig. 3a. A fit with three such lines with arbitrary intensities and locations yields a χ^2 of 16 for 14 dof. The intensities of the three lines, whose sum is shown in Fig. 3c, divided by $k^3(2J+1)$ factor (where k is the momentum of the γ and J is the presumed



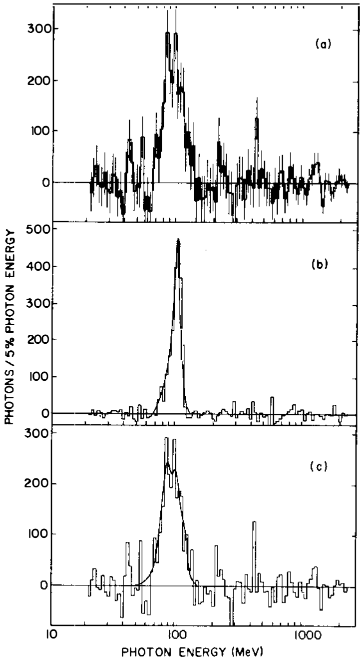


Fig. 2. CUSB inclusive photon spectrum from (a) the Υ'' region, (b) the continuum, (c) the Υ region. The bin size is 5% in $\Delta E/E$. The excluded region in the polynomial fit is indicated by the horizontal bar in (a). The solid lines are polynomial fits, see text.

Fig. 3. a) The subtracted photon signal for $\Upsilon''\rightarrow\gamma+2^3P_J$, see text. b) The experimental γ energy resolution function. The solid line is a fit to two gaussians of width 6.7 and 12.5% of the peak position, the wider one displaced down by 10% and contributing 35% of the total area. c) Fits of three lines to the subtracted photon spectrum.

angular momentum of the state) and arbitrarily normalized to 1 for the middle line, are 0.95 $\pm$ 0.3,1,1.1$\pm$0.4, consistent with the expectation that all 3 should be identical for 4π solid angle acceptance for γ's from E1 transitions. The cog for the three fitted lines, including the (2J+1) statistical factor, is 93 $\pm$ 1 ($\pm$ 4) MeV.

2. Exclusive channels.

CUSB has also searched for E1 transitions via the following double photon decay modes:

$$\text{(i)}\quad 3^3S \to 2^3P_J + \gamma_1\ ,\quad 2^3P_J \to 2^3S + \gamma_2$$
$$\text{(ii)}\quad 3^3S \to 2^3P_J + \gamma_1\ ,\quad 1^3P_J \to 1^3S + \gamma_2$$
$$\text{(iii)}\quad 3^3S \to 1^3P_J + \gamma_1\ ,\quad 1^3P_J \to 1^3S + \gamma_2$$

followed by Υ or $\Upsilon' \to \mu\mu$ or ee. Events of this kind have a characteristic signature of two almost collinear muons or electrons of about 5 GeV, plus two photons whose energies add up to the $\Upsilon''-\Upsilon'$ or $\Upsilon''-\Upsilon$ mass difference. Since we cannot distinguish γ_1 from γ_2, we shall call γ_1 the lower energy γ and γ_2 the higher energy one in each event.

Figure 4a shows the scatter plot of the two γ's for 18 $\mu\mu\gamma\gamma$ events, note that they show clean clustering corresponding to reactions (i) and (ii) and share a common photon energy of about 100 MeV. There are three candidates for reaction (iii), although two are on the 2σ boundary line. The dimuon events are virtually background free. A similar scatter plot, Fig. 4b is shown for the 50 $ee\gamma\gamma$ candidates. Assuming these double photon events come from reactions (i) through (iii), and accounting for the known branching ratio to two leptons (3.3% for the Υ and 2.0% for the Υ'), one obtains the product branching ratios listed in Table I. The last column are theoretical expectations for these product rates, summed over the three lines, obtained by using the E1 rates of Eichten et al,[4] the hadronic rates given by Barbieri et al[5] and the measured Υ'' total width.[6]

Table I: Double E1 Branching Ratios in %

Transition	CUSB	Theory
$\Sigma_{j=1}^{3}\ BR(\Upsilon''\to\gamma_j\ {}'_{bj})\times BR(\Upsilon'_{bj}\to\gamma\Upsilon')$	5.8z2.6	3.3
$\Sigma_{j=1}^{3}\ BR(\Upsilon''\to\gamma_j\ {}'_{bj})\times BR(\Upsilon'_{bj}\to\gamma\Upsilon)$	4.2±1.5	2.8
$\Sigma_{j=1}^{3}\ BR(\Upsilon''\to\gamma_j\ {}_{bj})\times BR(\Upsilon_{bj}\to\gamma\Upsilon)$	< 2.7 *	1.1

* 90% confidence level upper limit from the one event observed.

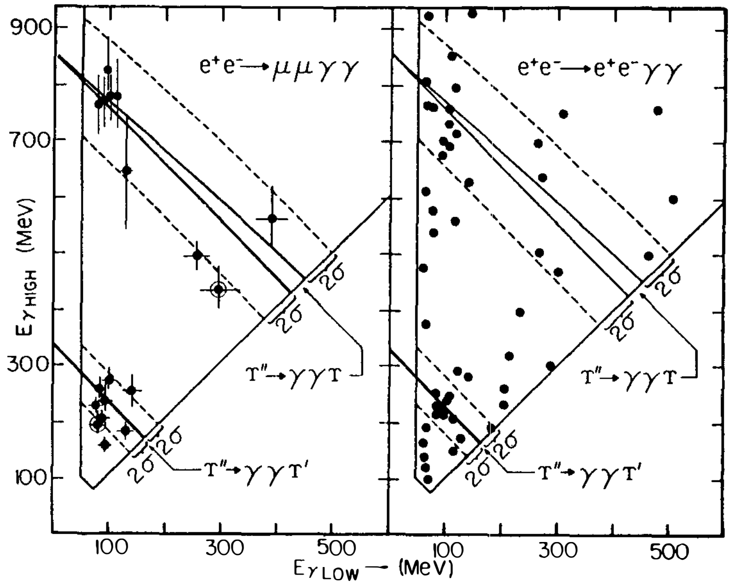


Fig. 4. CUSB scatter plot of E_{low} vs E_{high} with selection boundary (solid line) and 2σ bounds (dashed lines) indicated for (a) $e^+e^- \to \mu\mu\gamma\gamma$, and (b) $e^+e^- \to ee\gamma\gamma$ events.

3. Comparison of inclusive and exclusive photons.

Because of the large partial width of the 2^3P_o into two gluons, it is expected that its E1 branching ratio is considerably smaller than either of the other two P-states, hence most of the double γ transitions are expected to be through the $2^3P_{2,1}$ levels. Their positions can be found by making a two-line fit to the major portion of the γ_1 distribution from CUSB (see Fig. 5). Such a fit has a confidence level of 45%, whereas the probability that the observed signal is due to a single line is less than 3%. The three events with γ_1 larger than 114 MeV were used to obtain the position of the third line. The γ_1 distribution from the CUSB exclusive events is shown in Fig. 6, superimposed on the CUSB inclusive γ spectrum, with arbitrary normalization.

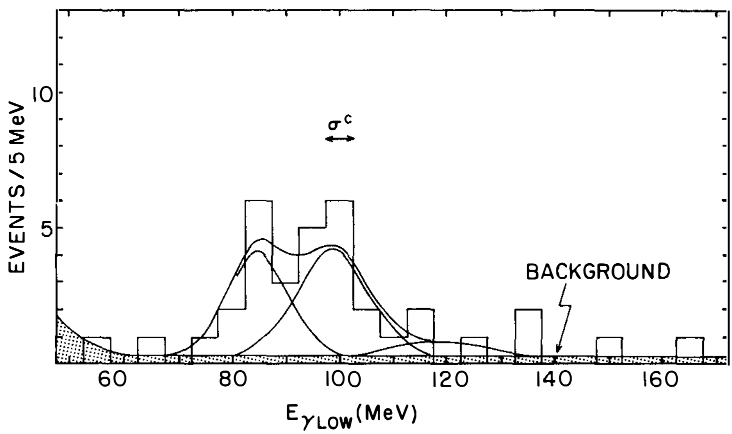


Fig. 5. Low energy γ from CUSB exclusive events, with 2 line fit and background estimate shown.

Table II: CUSB E1 Transition Photon Energies

	Inclusive Spectrum[7]	Exclusive Spectrum[8]
$3^3S_1 \rightarrow 2^3P_2 + \gamma$	$84.5 \pm 2.0 \pm 4$ MeV	$84 \pm 3 \pm [5]$ MeV
$3^3S_1 \rightarrow 2^3P_1 + \gamma$	$99.5 \pm 3.2 \pm 4$ MeV	$99 \pm 2 \pm [5]$ MeV
$3^3S_1 \rightarrow 2^3P_0 + \gamma$	$117.2 \pm 5.0 \pm 4$ MeV	$[119 \pm 5 \pm 5]$ MeV

The first error is the diagonal element of the fitted error matrix the second is a generous estimate of the systematic uncertainty.

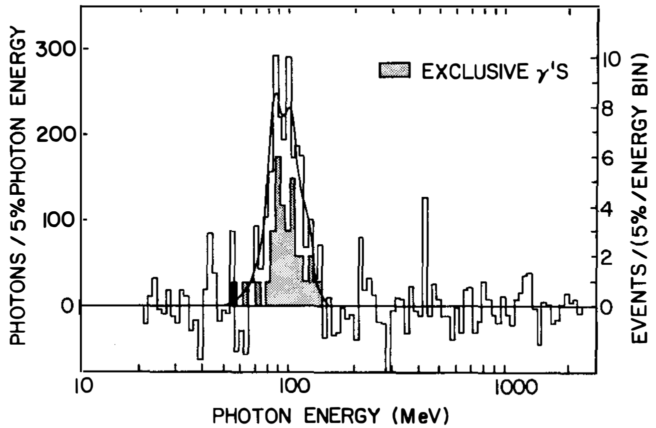


Fig. 6. Superposition of the CUSB inclusive γ spectrum (histogram) with the spectrum of the low energy photon from the exclusive decays (shaded histogram).

Table II gives the photon energies resulting from fitting the inclusive and exclusive CUSB data, as previously described. The agreement between the two completely independent methods is impressive. Using the cog of 93 MeV, subtracting the small recoil of the final state, one obtains a mass for the 2^3P states of 10.255 ± 0.004 GeV in the VEPP-4 mass scale.[9] The branching ratio of 34%, when combined with the value of $\Gamma_{ee}(\Upsilon'')$, $B_{\mu\mu}(\Upsilon'')$ and the hadronic branching ratios[2a] yields $(\Upsilon'' \rightarrow 2^3P) = 6.5 \pm 0.8 \pm 0.6$ keV, where the first error is statistical and the second is the estimated systematic uncertainty. Both the position and the width are in excellent agreement with theoretical expectations in contrast with the E1 transitions in the ψ system where the theories and experimental results differ by about a factor of two.

B. Photon Transitions from the Υ'.

Preliminary evidence has also been obtained by the CUSB group for the E1 transition $\Upsilon \rightarrow \chi_b + \gamma$ both in the inclusive photon spectrum and in exclusive channels. The cog of the 1^3P_1 state is 9908 ± 5 MeV and the E1 partial width is around 4 keV. The position of the 1^3P_1 state is in good agreement with potential model predictions, but not with QCD sum rule calculations nor bag model predictions.[9a]

C. ΔR and the b Quark Charge.

Although no narrow resonances were seen, the level of $R_{visible}$ as measured by CUSB changes from 2.29 ± 0.029 below the Υ''' to 2.54 ± 0.040 above the Υ''', see Fig. 7. Assuming that this change is due to the production of B mesons and their excited states, and using the appropriate efficiencies computed for CUSB for continuum and $B\bar{B}$ events, we obtain R below the Υ''' of 3.63 ± 0.06, above the Υ''' of 3.99 ± 0.06 and ΔR across the free flavor threshold of 0.36 ± 0.09.[10] All errors quoted are statistical only; systematic uncertainties are of the order of 10% but essentially cancel out in the evaluation of ΔR. This increase in R of 0.36 is consistent with what is expected in lowest order QCD, for having passed the threshold for production of charge 1/3 quarks.

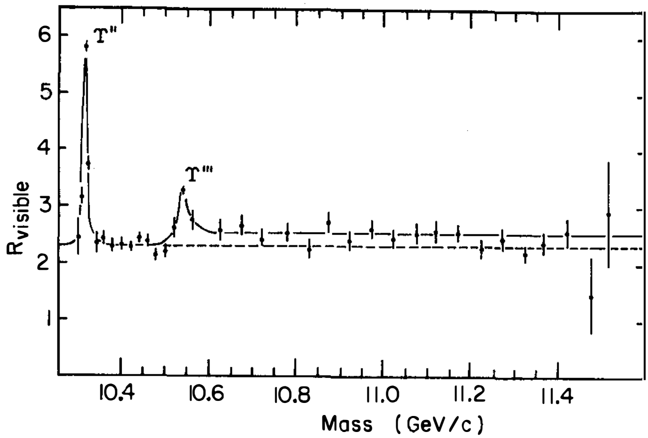


Fig. 7. $R_{visible}$ across the free flavor threshold from CUSB, showing the change in $R_{visible}$.

D. B Physics from CUSB.

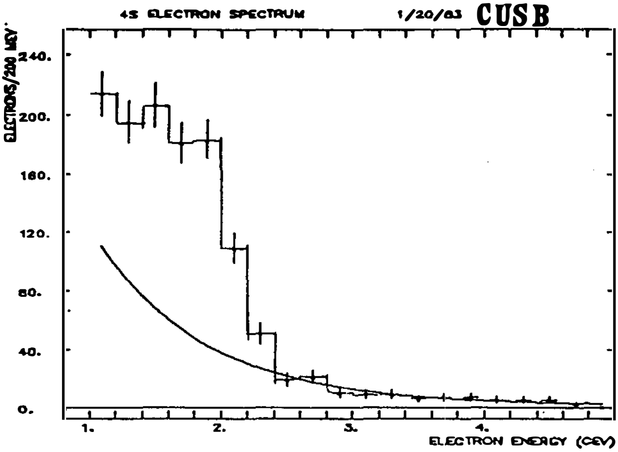
In this section, I will briefly mention some of the recent results from CUSB in the area of B physics; including limits on the B mass, limits on exotic models, semileptonic branching ratio, and constraints on the coupling of b quarks to c and u quarks.

1. The B meson mass.

CUSB has searched for the presence of B*'s in Υ''' decays.[10] We have recently improved our sensitivity and obtain a 90% c.l. upper limit of BR(Υ'''→B*B) < 7%. From these results and the measured width of the Υ''', we conclude 5263 < M_B < 5278 MeV, in the VEPP-4 mass scale.[9]

2. B decay electron spectrum.

In the CUSB detector, we obtain a very clean electron spectrum for electron energies above 1 GeV. At ~ 2.2 GeV, the end point for $B \rightarrow e\nu X_c$, our resolution is $\sigma \sim 3\%$. Our energy scale is also similarly accurate, by using 5 GeV e^+e^- bhabha scattering as calibration. Figure 8a shows the raw electron spectra obtained on the Υ''' and in the continuum nearby. There is a sharp drop in the Υ''' spectrum at about 2.2 GeV. The main complication in obtaining the electron spectrum from B decays, comes from the fact that the Υ''' is only ~ 30% of σ(hadron) and the continuum does have high energy electrons from decays of fast D's.



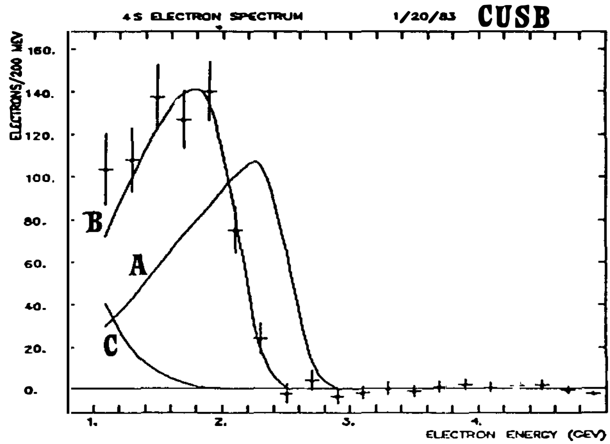


Fig. 8. a) The histogram represents the raw electron spectrum for ϒ''' events, the dashed line is a fit to the continuum electron spectrum. b) The continuum subtracted electron spectrum on the ϒ'''. For curves, see text.

3. Weak couplings of the b quark.

The subtracted electron spectrum has been compared with the calculated electron spectrum from B decays, including the fermi motion of the b quark inside the B meson and the 15 MeV kinetic energy of the B meson, using masses given by A. Martin:[14] m_b = 5.2 GeV and m_c = 1.8 GeV (see curve B in Fig. 8b). Altarelli et al[15] have recently completed a similar calculation including radiative effects and are in good agreement with our simpler calculation. Calculations including resonance effects have also been made.[16] The authors conclude that the spectrum steepens, but does not alter the end point.

If we fit our electron spectrum with m_c free, we obtain m_c = 2.0 GeV as a best fit, but are fully consistent with m_c = 1.8 GeV, and are over 10 σ away from m_q < 500 MeV. Curve A in Fig. 8b is obtained for m_q = 0 and does not vary significantly up to m_q = 700 MeV.

The experimentally measured spectrum is consistent with zero contribution from $b \to u$ with m_u < 1 GeV, and we place a 90% confidence level upper limit on $BR(B \to \nu e X_u)/(BR(B \to \nu e X_c) < 7\%$.[12] Using the factor from integrating over available phase space for $b \to u$ and $b \to c$ from Ref. 15, this limit corresponds to the following constraint on the relevant elements of the mixing matrix V: $|V_{bu}/V_{bc}| < 0.17$, which results in bounds on the Maiani angles shown in Fig. 9.

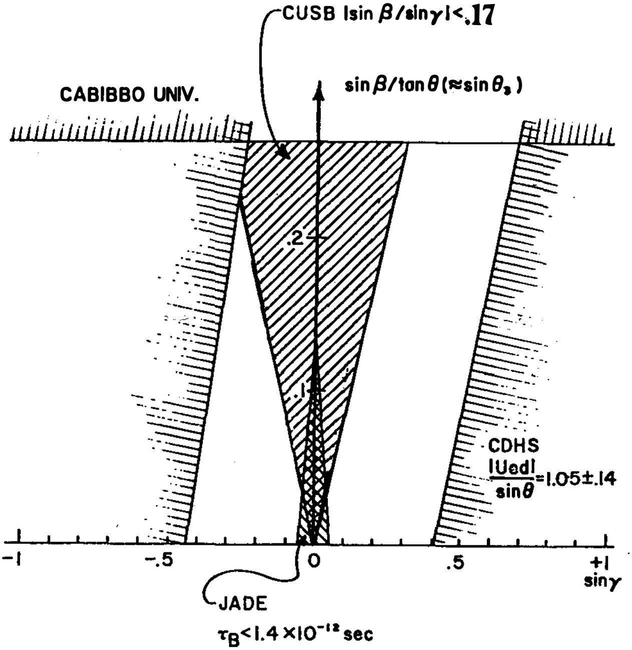


Fig. 9. Bounds on the elements of the weak mixing matrix in the Maiani notation. An update from Ref. 17.

CONCLUSIONS

The Υ system has proven to be an excellent system to study both strong and weak interactions. The various branching ratios which have been measured at CESR by CUSB and CLEO are summarized in Fig. 10. Excellent progress in filling out the spectrum in the Υ system has been made in the past year and a half. Some of the highlights are: A) Discovery of the first two P-wave $b\bar{b}$ state and their properties, confirming the flavor independent potential approach. E1 rates are in agreement with theory, unlike the ψ case. B) Hadronic transitions from the Υ'' to both the Υ and Υ' have been measured. Branching ratios are in reasonable agreement with those predicted using a multipole expansion in the color field. The unexpected difference in the pion spectra in the decay of Υ'', suggest that refinements of the theory are necessary. C) R and ΔR are consistent with lowest order QCD calculations. D) The standard axion is ruled out. E) The B meson mass if 5273±12 MeV. F) The standard model of weak interactions is confirmed and the first significant constraint on $|V_{bu}/V_{vc}|$ has been made.

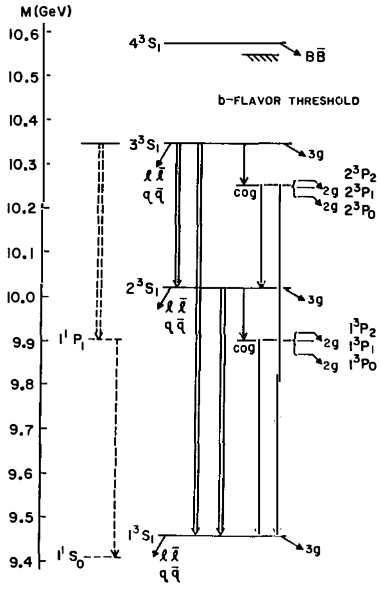


Fig. 10. Observed transitions in the Υ system with CLEO and CUSB experimental values indicated.

Acknowledgments

The author acknowledges support for his research by the U. S. National Science Foundation. Special thanks go to Juliet Lee-Franzini and R. D. Schamberger for their help in the preparation of this report.

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