Hidden and Open Beauty in CUSB

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Abstract. We present a brief history and a summary of the physics results of CUSB at CESR.

HISTORY

Since the discovery of the Υ system at FNAL, as told at the begining of this volume, the CUSB (Columbia University-Stony Brook) collaboration at CESR (Cornell Electron Storage Ring) has played a pivotal role in the study of the upsilon system, potential models, QCD, and weak interactions of the b quark [1-9].

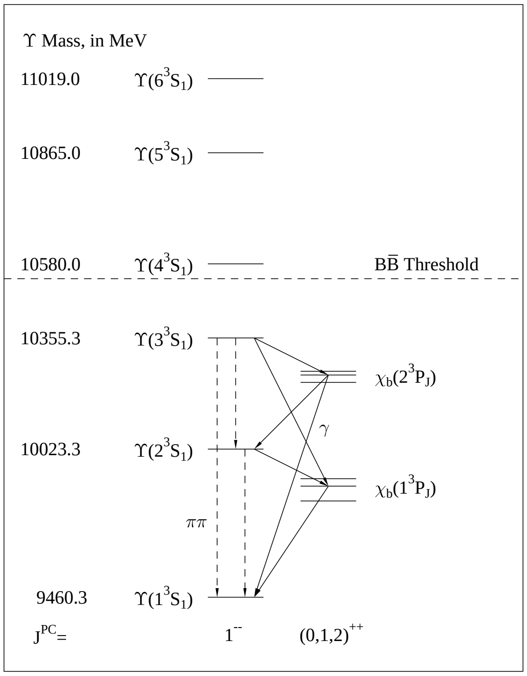

Figure 1. Υ's Level Diagram, CUSB observed and studied all levels and transitions between levels indicated above. Open beauty was discovered in the decay $\Upsilon(4S)\to$high energy electrons. The B^*'s were found in the continuum above the $\Upsilon(4S)$.

In retrospect, things happened very fast. CUSB's formal proposal was submitted to Cornell on December 2nd, 1977 and was approved by February 15th, 1978! On August 16th, 1979 we paid our first visit to the North Area (NA) underground *cul de sac* which became the home for our electronics. In May 1979 we installed the first NaI qradrant at the NA interaction region. In September of 1979 a caravan of two trailers containing electronics, escorted by a truck and passenger cars driven by and containing a dozen physicists, arrived at the Northern edge of the Cornell Alumni Atheletic Fields. The trailers functioned as the CUSB data acquisition center, until May 1991 when they were honorably retired, their outer skins showing various indentations resulting from seasonal sport projectiles. On October 18th, 1979, with half of the sodium iodide, NAI, detector, 8.3 radiation lengths (X_0) deep, centered upon the NA interaction area, we observed the first Bhabha ever seen at CESR.

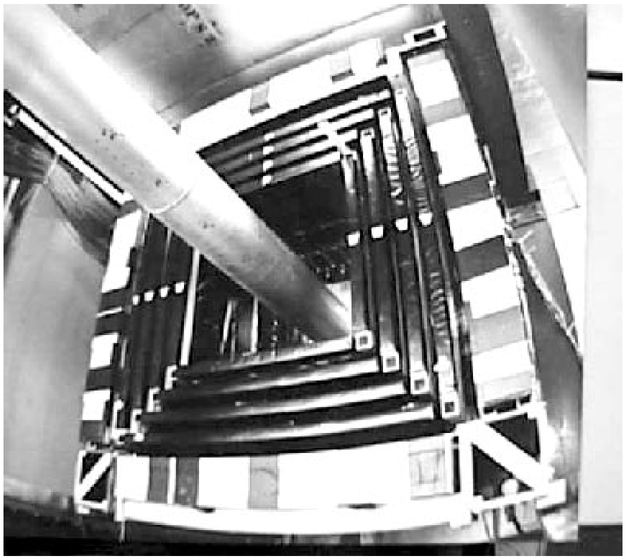

Figure 2. In this form, *i.e.* just one half of the NaI crystal array, CUSB observed the three Υ's below threshold and on December 1979 had evidence for the $\Upsilon(4S)$, the first level above threshold.

From then until January 1984, in between collecting 950,000 events, we completed CUSB-I. The CUSB-I detector comprised 320 rectangular NaI crystals in a square geometry, surrounded by an array of lead glass cubes ($15 \times 15 \times 17.5$ cm^3, 7.7 X_0) for shower leakage containment. These in turn are surrounded by scintillator muon counters [10]. In this period we did a whole series of exploratory experiments, and one of us (J. L-F) also had a wonderful time re-learning quantum mechanics from "guru" K. Gottfried. We resolved the first three Υ resonances to the chime of the CUSB "R" meter (a scalar counting a restrictive trigger) [11]. We saw the first Υ(4S) signal in December 1979 [12]. We observed the $\pi\pi$ transitions between the Υ bound states [13]. We discovered the χ_b states from inclusive and exclusive E1 transitions [14]. We even foretold the existence of χ_b transitions from studying event shapes [15], studied K^0 production at all the resonances [16], and made the first determination of α_s from study of γgg on the Υ resonances [17].

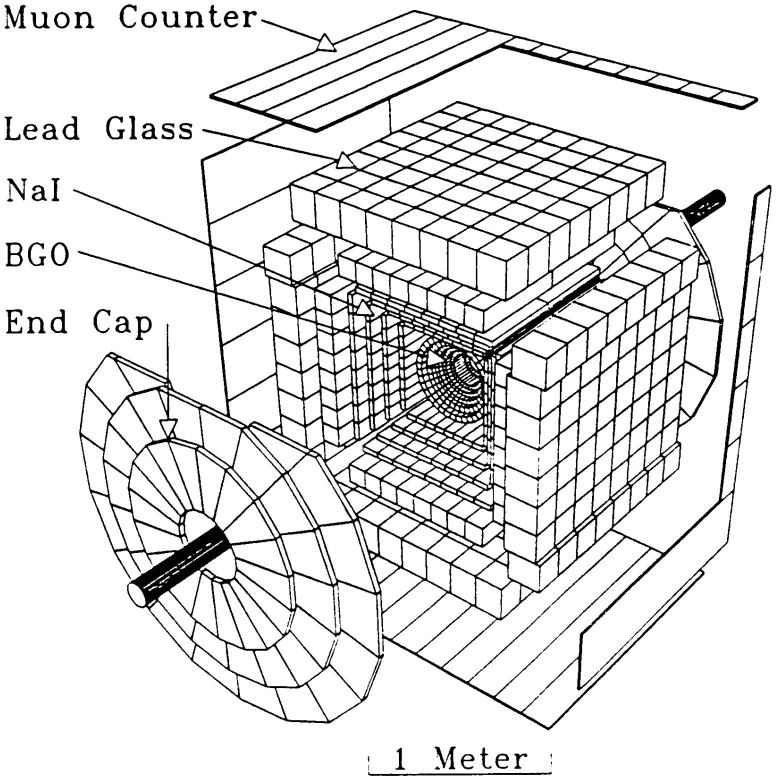

Figure 3. The complete CUSB detector. This configuration was only reached in 1989. The BGO calorimeter and the endcap trigger counters were not present at the beginning. Because of the high cost of NaI, lead glass was used as a catcher for the electromagnetic showers. The lead glass was used later for muon identification.

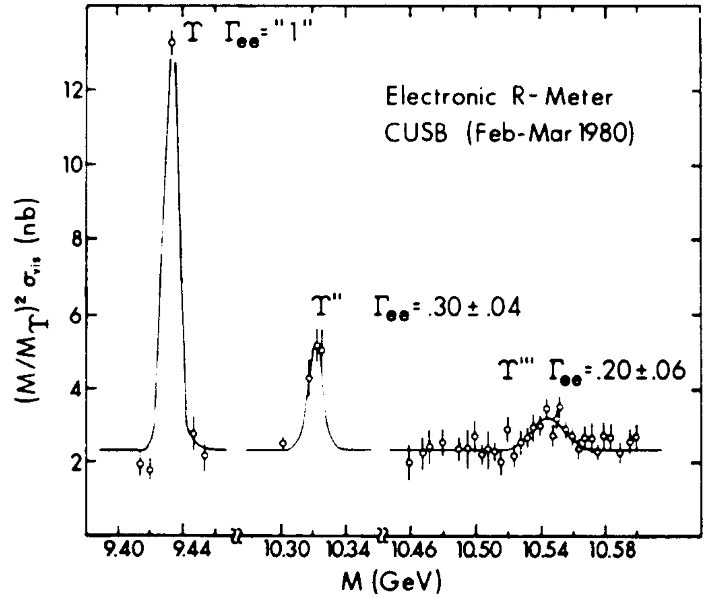

Figure 4. The $\Upsilon(4S)$ was observed by CUSB by counting on scalers small angle Bhabha and hadronic Υ+continuum events. Thus the fourth upsilon was discovered without analysis of the collected events. The latter confirmed the former and gave information on event shape and on the production of B mesons.

From the observation of high energy electron production in $4S$ events we inferred the B-mass, plotted out the B meson semileptonic decay spectra [18], and had long discussions with phenomenologists [19]. We searched for the B^* repeatedly on the Υ(4S), in vain, finally observing it as a broadish bump in the continuum above (due to the Doppler shift of the parent B's) [20]. This last signal inspired us to improve our photon resolution by using BGO crystals in addition to NaI. We saw a rise in ΔR of $\simeq 1/3$ due to the production of $b\bar{b}$-quarks [21], and did a complete coupled channel analysis to obtain the parameters of the higher Υ resonances [22]. In July 20, 1984 we inserted a BGO quadrant inside the CUSB-I NaI array. With this set up, together with the Cornell Polarization group, we made a precision Υ mass measurement [23]. We also continued to establish limits for non existent particles such as axions, short lived particles, light gluinos, ζ (8.3), light Higgs, and light squarks [24].

In December 1985 we installed the complete BGO array, the heart of CUSB-II, inside CUSB-I. The array is a cylinder composed of 360 trapezoidal-cross-sectioned BGO crystals. The 5 layers's thickness is twelve radiation lengths.

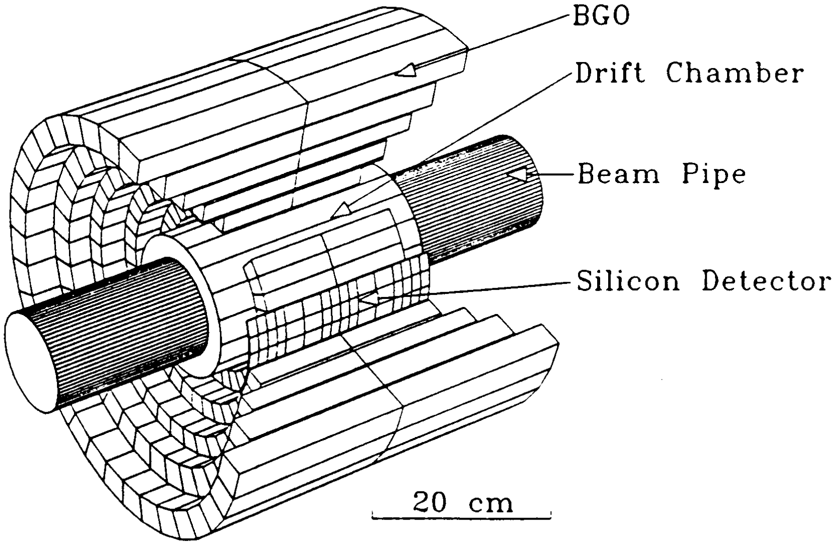

Figure 5. The "BGO cylinder" improved the CUSB energy resolution for low energy photons by a factor of two. In its final configuration, silicon pads were between BGO crystals to obtain better angular resolution for photons. A small drift chamber inside the BGO array detected charged particles.

We proved by study of $\approx$5 GeV electrons from Bhabha scatterings that the new CUSB-II detector had achieved an improvement of a factor of two in resolution [25]. The CUSB-II physics results obtained in this configuration include accurate measurements of the branching ratios $B_{\mu\mu}$(3S) and $B_{\mu\mu}$(1S) [26], stringent limits on direct photon production from the Υ(4S) [27], precise determinations of hyperfine splittings in the B-meson system, evidence for B_s-meson production on the Υ(5S) resonance [28] and semileptonic branching ratios from B_u-mesons and B_s-mesons semileptonic decays at the Υ(4S) and Υ(5S) [29].

Table I. The data taking history of CUSB is presented. For each sample the integrated luminosity and the number of collected events is listed. Some major physics topic studied are also listed.

Run 394-5513 Oct. 18, 1979 – Jan 25, 1984 CUSB

	$\mathcal{L}$ (pb^{-1})	Events	Physics
1S	7.1	111,405	Resonances first seen in "R-meter" (1979).
2S	29.6	224,163	($\pi\pi$, E1) transitions to 1S, discovery of χ_b.
3S	17.7	89,096	3S (1979), ($\pi\pi$, E1) to 2S,1S, discovery of χ'_b.
4S	63.1	190,280	1st seen in Dec. 1979, B semileptonic decay, no B^*.
cont	32.7	72,865	$\Delta R \simeq 1/3$.
>4S	113.8	260,443	Coupled channel $\Upsilon(5S, 6S, 7S)$, observe B^*'s.
Total	263.7	948,252	K^0 production measured, no axion seen.

Run 5515-7284 Jul. 20, 1984 – Aug. 2, 1985 CUSB-1.5

	$\mathcal{L}$ (pb^{-1})	Events	Physics
1S	28.9	529,537	Precision (1S) mass (10ppm), γgg
4S	60.3	243,916	Semileptonic $B \to \mu, e, \nu$ spectra, no $b \to u$.
cont.	23.9	70,283	No B^*'s here (below 4S), nor on 4S.
Total	113.3	844,599	No $\zeta(8.3)$.

Run 10391-12210 Dec. 16, 1985 – Apr. 23, 1988 CUSB-II

	$\mathcal{L}$ (pb^{-1})	Events	Physics
1S	24.4	458,492	$B_{\mu\mu}(1S)$.
3S	144.3	1,001,329	$B_{\mu\mu}(3S)$, no η_b seen, no h_b seen.
4S	273.7	1,163,213	Precise (4S) semileptonic decay studies.
cont	122.3	395,013	No B^*'s below 4S.
$> 4S$	140.2	467,729	HFS, B^*, B_s, B_s^* masses, $B \to e, \nu$ at 5S.
Total	704.9	3,090,763	Limits: Higgs, squark, gluino, short τ particles.

Run 20001-22542 Oct. 20 1989 – Oct. 8, 1990 CUSB-II+

	$\mathcal{L}$ (pb^{-1})	Events	Physics
1S	18.5	332,413	$\alpha_s(1S)$, hadronic width.
3S	143.6	969,8903	$\alpha_s(3S)$, hadronic width, precision FS, $\pi\pi$ spectra.
4S	36.9	150,750	No direct photons from 4S, no $\pi\pi$ to (2S), (1S).
cont	32.4	99,608	
BB^*	63.1	204,356	Precision B^* mass.
Total	294.5	1,757,617	$\Lambda_{\overline{MS}}$.

Run 394-22542 Oct. 18 1979 – Oct. 8, 1990 CUSB to CUSB-II+

	$\mathcal{L}$ (pb^{-1})	Events	Physics
All	1376.4	6,641,231	Scalar nature of confining potential.

From April 23, 1988 to October, 1989, during CESR's shutdown for completing CLEO-II, we constructed and installed the remaining portions of CUSB-II, including new BGO read-out electronics, a shower centroid detector, and a forward-backward lepton end-cap trigger. Data obtained from the last CUSB run, October 20, 1989 to October 8, 1990, resulted in precision measurements of the relative contributions of the spin-orbit and tensor interactions to the fine structure of the 2P state and we determined that the long-range confining potential transforms as a Lorentz scalar [30]. We made precise studies of the sequential decays of the Υ(3S), measured the hadronic widths of the χ_b states and observed the rare decay transition from the Υ(3S) to the χ_b [31]. We measured the $\pi\pi$ mass spectra of the dipions from Υ(3S) hadronic transitions to (2S) and (1S) and determined the beam energy window where single B^*B production is dominant [32].

The total running period for CUSB-I, CUSB I.5, and CUSB-II span from October 1979 to October 8, 1990. The CUSB collaboration had always been a small one, with at most two dozen members at any one time during the CUSB-I stage [33] and no more than one dozen at any one time, including students, technicians and senior physicists, for CUSB-II [34]. Table I gives a summary of the run history and physics highlights of each run period.

SELECTED PHYSICS RESULTS

$\Lambda_{\overline{MS}}$ from Υ's $\to \mu\mu$

From our measurements of the branching ratio for $\Upsilon \to \mu^+\mu^-$, $B_{\mu\mu}$, and the other measured parameters of the Υ's we obtain the branching ratio for $\Upsilon \to gg$ and thus we determine $\alpha_s(m_b)$ and $\Lambda_{\overline{MS}}$, Table II.

Table II. Measurements of $B_{\mu\mu}$ and the derived $\alpha_s(m_b)$ values.

Resonance	$B_{\mu\mu}$ (%)	Γ (keV)	$\alpha_s(m_b)$	$\Lambda_{\overline{MS}}$
$\Upsilon(1S)$	2.61±0.09	51.1±3.2	0.174±0.004	150±13
$\Upsilon(2S)$	1.38±0.25	42.3±9.2	0.176±0.016	167±58
$\Upsilon(3S)$	1.73±0.15	27.7±3.7	0.173±0.008	154±29
Average	—	—	0.1736±0.0033±0.017	157±12±60

For the average values of $\alpha_s(m_b)$ and $\Lambda_{\overline{MS}}$ we have included a reasonable guess of the theoretical uncertainty in fixing the energy scale in the systematical error. The α_s and $\Lambda_{\overline{MS}}$ obtained by us are in excellent agreement with those obtained using a number of other processes, proving that the Upsilon system provides an independent probe of QCD.

Hyperfine Splitting of B and B_s Mesons

We have studied the inclusive photon spectrum from 2.9×10^4 Υ(5S) decays. We observe a strong signal due to $B^* \to B\gamma$ decays, both from inclusive hadronic events a) and from electron tagged events b). From a detailed analysis we obtain: i) the average B^*–B mass difference, (46.7 ± 0.4) MeV, ii) the photon yield per Υ(5S) decay, $\langle\gamma/\Upsilon(5S)\rangle = 1.09 \pm 0.06$ and iii) the average velocity of the B^*'s, $\langle\beta\rangle = 0.156 \pm 0.010$, for a mix of non-strange (B) and strange (B_s) B^*–mesons from Υ(5S) decays. From the shape of the photon line, we find that significant production of B_s is required implying nearly equal values for the hyperfine splitting of the B and B_s meson systems.

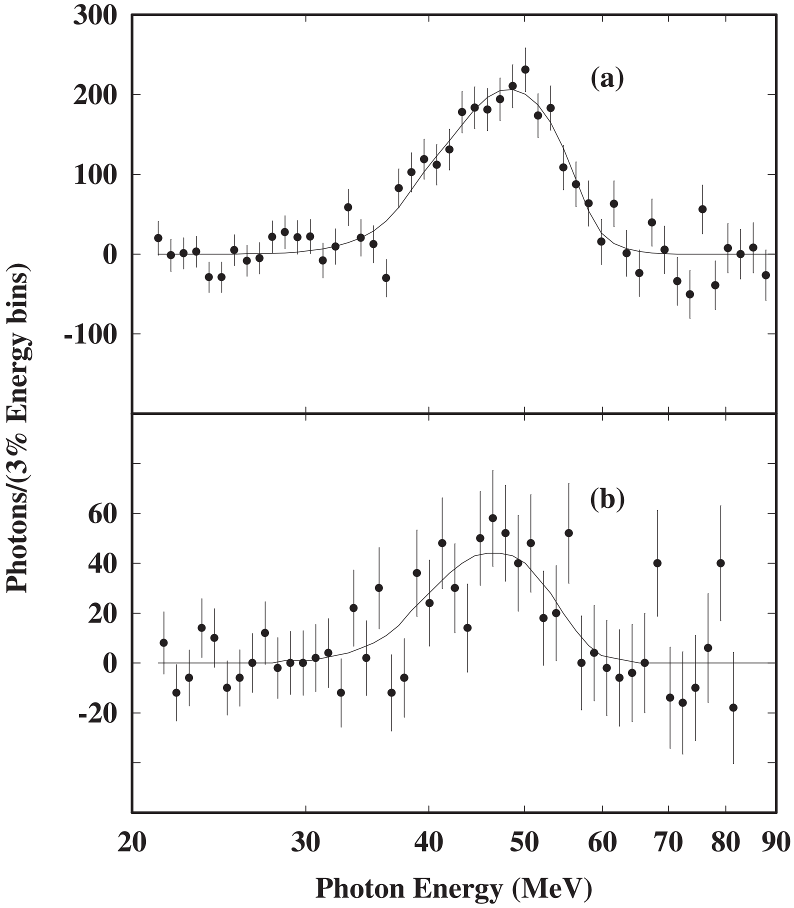

Figure 6. Photon spectrum in inclusive hadronic events above the flavor threshold. (a) The line at ~48 MeV is due to the decay $B^* \rightarrow B + \gamma$, proving the existence of the B^* meson and measuring its mass. (b) The line is present also selecting events with a high energy electron, confirming the presence of a B meson decaying semileptonically.

B Semileptonic Decays at the Υ(4S) and the Υ(5S)

B meson semileptonic decay spectra have been obtained at the Υ(4S) and at the Υ(5S). The branching ratio for $B \rightarrow e\nu X$ at the Υ(4S) is found to be $(10.0 \pm 0.5)\%$. The electron spectrum of $B \rightarrow e\nu X$ at the Υ(5S) is observed for the first time and the average branching ratio for $B, B_s \rightarrow e\nu X$ is consistent with that for B's from Υ(4S) decays. The shape of the electron spectrum at the Υ(5S) indicates production of B mesons which are heavier than non-strange B's, presumably B_s's.

$b\bar{b}$ Spectroscopy from the Υ(3S) State

We have made a detailed study of electric dipole (E1) and hadronic transitions between the Υ and χ_b states. The amplitude for these transitions are depicted in figure 7.

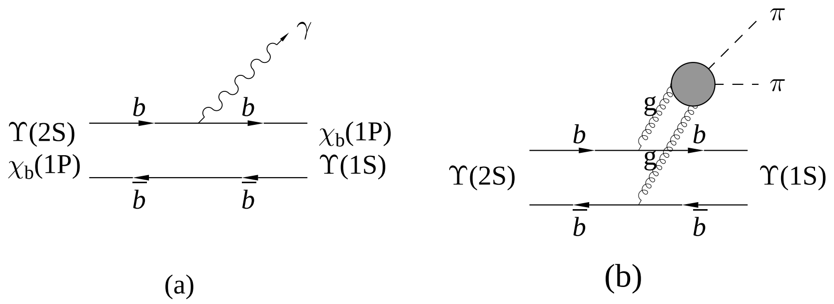

Figure 7. Amplitudes for: (a) electric dipole transitions (E1) $^3S(^3P)\to{}^3P(^3S)+\gamma$ and (b) double *color-electric* dipole transitions $n\,^3S\to(n-1)\,^3S+gg(2\pi)$.

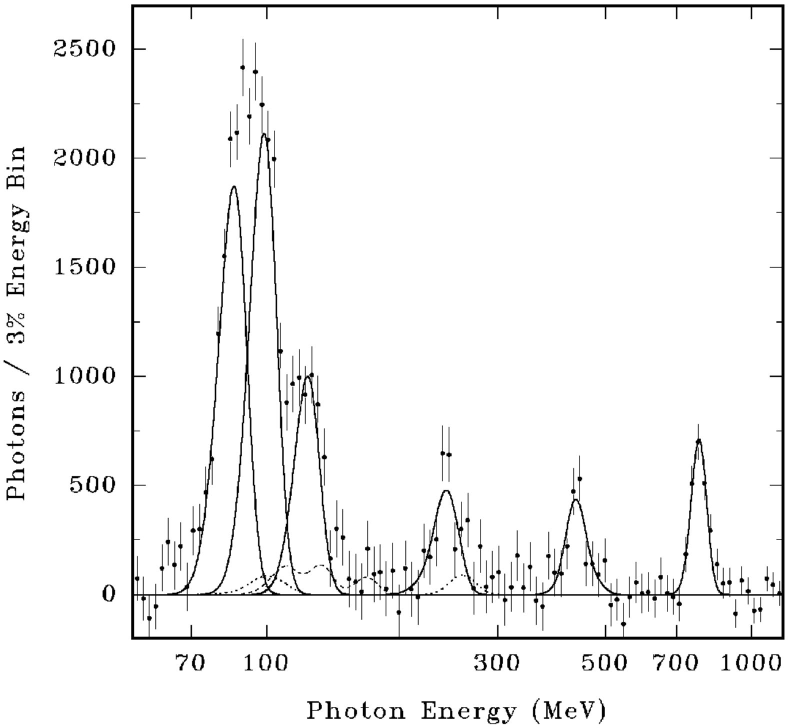

Figure 8. The inclusive photon spectrum at the $\Upsilon(3S)$, after background subtraction. Both lines from direct $\Upsilon(3S)$ decays as well as from decays of daughter $b\bar{b}$ states, see figure 1, are observed.

The data were collected both from exclusive and inclusive channels. An inclusive photon spectrum at the 3S is shown in figure 8. We have determined their branching ratios: BR($\Upsilon'' \to \chi_b(2P_{2,1,0})\gamma$)=(11.1±0.5±0.4)%, (11.5±0.5 ±0.5)%, (6.0±0.4±0.6)%; BR($\Upsilon'' \to \chi_b(2P_{2,1,0})\gamma \to \Upsilon'\gamma\gamma$)=(4.2±0.6±0.5)%; BR($\Upsilon'' \to \chi_b(2P_{2,1,0})\gamma \to \Upsilon\gamma\gamma$)=(2.0±0.2±0.2)%. We have measured the center of gravity of the $\chi_b(2P)$ states to be (10259.5±0.4±1.0) MeV. We have made precision measurements of the electric dipole transition rates from Υ'' to χ'_b, which are in excellent agreement with theory.

The fine structure splittings obtained using all data are $M(\chi'_2)-M(\chi'_1)=$ 13.5±0.5 MeV and $M(\chi'_1)-M(\chi'_0)$=23.2±1.0 MeV which determines the spin orbit contribution as a=9.5±0.22 MeV and that of the tensor interaction as

b=2.3±0.14 MeV. The resolution of the fine strucure in terms of spin orbit and tensor interactions is illustrated in figure 9.

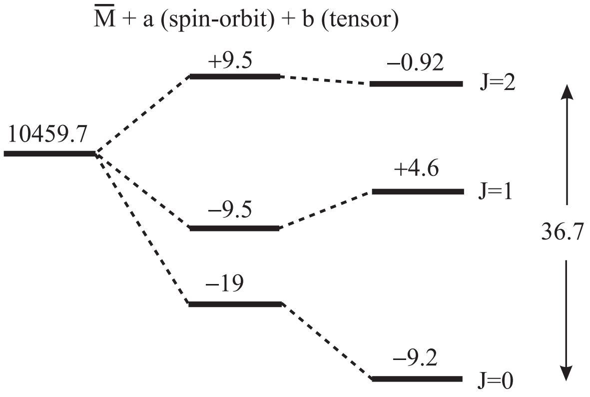

Figure 9. Fine structure of the χ_b' state, resolved in their spin-orbit and tensor contributions as determined by CUSB. Energies are in MeV.

This is an important results which confirms expectactions that the long range, confining part of the quark anti-quark potential is due to the exchange of an effective (multi-gluon) scalar state, while the short range, coulombic part is due to single gluon (vector) exchange. The long range potential has the form kr, with k the so called string tension. We define the scalar fraction f as the part of the kr contribution due to exchange of a Lorentz scalar. Then the 'vector' and 'scalar' potentials are respectively $V_v = -(4/3)(\alpha_s/r) + (1-f)kr$ and $V_s = fkr$. The fine structure of the χ_b states or, equivalently, the values of the spin orbit and tensor contributions to the splitting, are sensitive to f

The value of k is presently known to be between 0.14 and 0.18 GeV^2. Combining this with our measurements of the fine structure of the $\chi_b(2P)$ states results in f∼1 with an error of about 5% from our measurement and another similar uncertainty due to the abovementioned uncertainty in the value of k. The value of f determined from the fine structure of the $\chi_b(1P)$ states is consistent with the same value, however no precise measurments have been performed for this case.

Unlike in the charmonium system, the hadronic width of the $b\bar{b}$ P-wave states, which are expected to be of the order of tens to hundreds of keV, are too narrow to be measured directly. We have pioneered the method of deriving them from our measured branching ratios of $\chi_b \to \Upsilon\gamma$ and calculated widths of electric dipole transitions, the latter had been well verified from our measurements. The resultant hadronic widths are in excellent agreement with QCD predictions, and can be used to extract α_s. For example, the values obtained from the $\chi_b(2P)$ states are 0.16±0.01, 0.21±0.02, and 0.14±0.03 from the J=2,1,0 states respectively. These values and those from the $\chi_b(1P)$ states are in good agreement with the results of measuring α_s in the $b\bar{b}$ system. We have also observed the suppressed transition $\Upsilon(3S)\to\chi_b(1\mathrm{P})\gamma$. The measured branching ratio suggests that potential models which include relativistic effects are correct.

Study of $\pi^+\pi^-$ Transitions from the $\Upsilon(3S)$ State

We have investigated the decay $\Upsilon(3S) \to \Upsilon(1S,\ 2S)\pi^+\pi^-(\pi^0\pi^0)$, where the final state $\Upsilon(1S, 2S)$ decays to a pair of leptons. We found $\sim$ 390 events of the type Υ(3S)$\to\Upsilon$(1S)$\pi^+\pi^-$ and $\sim$ 140 events of the type Υ(3S)$\to\Upsilon$(2S)$\pi^+\pi^-$. The corresponding branching ratios are $(3.27 \pm 0.30)\%$ and $(3.59 \pm 0.49)\%$ respectively. We have also studied the $\pi\pi$ invariant mass spectrum where earlier data already indicated a deviant behavior from theoretical expectations. Both $\pi^+\pi^-$ and $\pi^0\pi^0$ invariant mass spectra, albeit the latter has less statistics, exhibits the same behavior. In short, we see an unusual double-peak behavior on the dipion mass spectrum from Υ(3S)$\to\Upsilon$(1S)$\pi^+\pi^-(\pi^0\pi^0)$, figure 10 is the one from the $\pi^+\pi^-$ transitions. It is quite different from the spectra for $\pi\pi$ decays from other Υ and ψ states and disagrees with theoretical predictions of a single peak in the high mass region of the distribution. We have compared our spectrum with several current theoretical modifications to various models and found that none of them could successfully explain the observed shape of the double-hump spectrum[35].

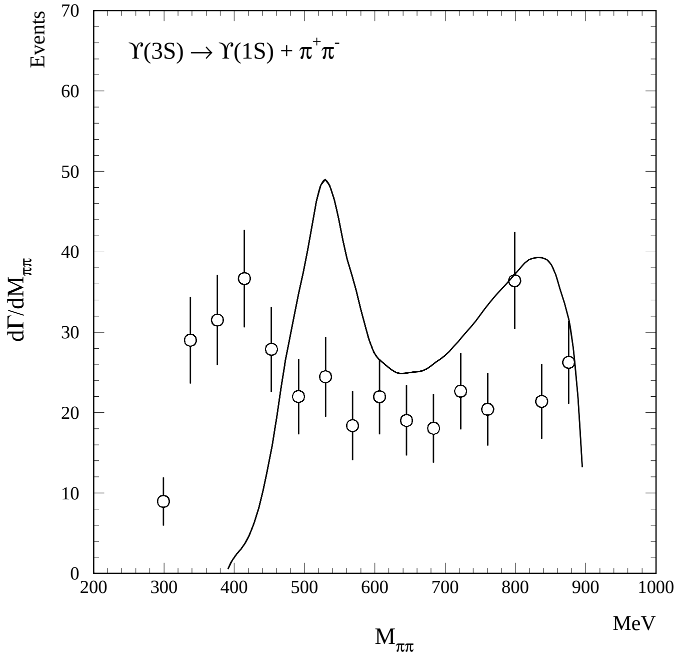

Figure 10. Dipion mass spectrum observed in $\Upsilon(3S)\to\Upsilon(+S)\pi^+\pi^-$. The curve is from the model ref. 35.

REGRETS

While we recall our venture of CUSB at CESR with great affection and sense of accomplishment, there are regrets that we could not have stayed, run on the Υ(3S) longer, on the Υ(2S) especially and found a few more known-toexist states, such as the η_b and h_b [6, 7]. We could have solved a few more puzzles such as the hadronic widths of the χ_b states [8] and whether there is a pseudoscalar field in the $Q\bar{Q}$ potential [7]. There are, however, other problems which no amount of additional CUSB running would have helped. For example, there are no light Higgs particles nor sparticles, and after we established that there are neither direct photons nor excessive direct pions from the Υ(4S), there is still no explanations why the the B-semileptonic decay branching ratios do not agree with theoretical expectations [27,9].

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33. CUSB-I began with members from Columbia University which in total included: T. Böhringer, F. Costantini, J. Dobbins, P. Franzini (spokesperson), K. Han, S. W. Herb, D. M. Kaplan, L. M. Lederman, G. Mageras, D. Peterson, E. Rice, D. Son, J. K. Yoh, S. Youssef, and T. Zhao, and similarly, from SUNY at Stony Brook: G. Finocchiaro, G. Gianinni, J. E. Horstkotte, D. M. J. Lovelock, C. Klopfenstein, J. Lee-Franzini, R. D. Schamberger, M. Sivertz, L. J. Spencer, and P. M. Tuts. We were joined in 1981 by R. Imlay, G. Levman, W. Metcalf and V. Sreedhar of Louisiana State Univesity and G. Blanar, H. Dietl, G. Eigen, V. Fonseca, E. Lorenz, F. Pauss, L. Romero and H. Vogel of MPI Munich. Louisiana State and MPI Munich left in 1984.
34. CUSB-I.5, CUSB-II: P. Franzini (co-spokesperson), U. Heintz, J. Horskotte, T. Kaarsberg, S. Kanekal, J. Lee-Franzini (co-spokesperson), D. M. J. Lovelock, M. Narain, R. D. Schamberger, S. Sontz, P. M. Tuts, J. Willins, Q.W. Wu, C. Yanagisawa, S. Youssef, and T. Zhao.
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