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 beginning 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). 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!

![Diagram of UPSILON LEVEL DIAGRAM](Image)

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

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 quadrant 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 to the Northern edge of the Cornell Alumni Athletic 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 NA1 detector, 8.3 radiation length ($X_0$) 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 Υ(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 comprises of 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 of 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 $\chi_b$ states from inclusive and exclusive E1 transitions (14). We even foretold the existence of $\chi_b$ transitions from studying event shapes(15), studied $K^0$ production at all the resonances (16), and made the first determination of $\alpha_s$ from study of $\gamma gg$ on the Υ resonances (17). From seeing high energy electrons emerging from 4S events we inferred the B-mass, plotted out the $B$ meson semileptonic decay spectra (18), and had long discussions with phenomenologists (19).
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 $\Upsilon+$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.
We searched for the $B^*$ repeatedly on the $\Upsilon(4S)$, 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 ones. We saw a rise in $\Delta R$ 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 $\Upsilon$ 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 $\Upsilon$ mass measurement (23). We also continued to establish limits for non-existent particles such as axions, short lived particles, light gluinos, $\zeta$ (8.3), light Higgs, and light squarks (24).

In Dec. 1985 we installed the complete BGO array inside the CUSB-I detector which is the heart of CUSB-II. The array is a cylinder composed of 360 trapezoid cross sectioned BGO crystals, the 5 layers's thickness was twelve radiation length.

We proved by study of $\approx 5$ GeV electrons from Bhabha scatterings that the new CUSB-II detector had achieved an improvement 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), semileptonic branching ratios from $B_u$-mesons and $B_s$-mesons semileptonic decays at the $\Upsilon(4S)$ and $\Upsilon(5S)$ (27), stringent limits on direct photon production from the $\Upsilon(4S)$ (28), precise determinations of hyperfine splittings in the $B$-meson system, and evidence for $B_s$-meson production on the $\Upsilon(5S)$ resonance (29). From April 23, 1988 to Oc-
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, Oct. 20, 1989 to Oct. 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. 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 ππ 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). The following table gives a summary of the run history and physics highlights of each run period.

| Run       | Date              | L (pb^−1) | Events | Physics |
|-----------|-------------------|-----------|--------|---------|
| 394-5513  | Oct. 18, 1979 – Jan 25, 1984 | 7.1       | 111,405 | Resonances first seen in “R-meter” 1979. |
|           |                   | 29.6      | 224,163 | (ππ, E1) transitions to 1S, discovery of χ_b. |
|           |                   | 17.7      | 89,096  | 3S ‘79, (ππ, E1) to (2S)1S, discovery of χ_b^′. |
|           |                   | 63.1      | 190,280 | 1st seen in Dec. 1979, B semileptonic decay, no B^*. |
|           | cont              | 32.7      | 72,865  | ΔR ≃ 1/3. |
|           | >4S               | 113.8     | 260,443 | Coupled channel Υ(5S, 6S, 7S), observe B^'+s. |
|           |                   | 263.7     | 948,252 | K^0 production measured, no axion seen. |
| 5515-7284 | Jul. 20, 1984 – Aug. 2, 1985 | 28.9      | 529,537 | Precision (1S) mass (10ppm), γgg |
|           |                   | 60.3      | 243,916 | Semileptonic B → μ, e, ν spectra, no b → u. |
|           | cont              | 23.9      | 70,283  | No B^+’s here (below 4S), nor on 4S. |
|           |                   | 113.3     | 844,599 | No ζ(8.3). |
| 10391-12210 | Dec. 16, 1985 – Apr. 23, 1988 | 24.4      | 458,492 | B_{µν}(1S). |
|           |                   | 144.3     | 1,001,329 | B_{µν}(3S), no η_b seen, no h_b seen. |
|           | cont              | 273.7     | 1,163,213 | Precise (4S) semileptonic decay studies. |
|           | >4S               | 122.3     | 395,013 | No B^+’s below 4S. |
|           |                   | 140.2     | 467,729  | HFS, B^+, B_s, B_s^* masses, B → e, ν at 5S. |
|           |                   | 704.9     | 3,090,763 | Limits: Higgs, squark, gluino, short τ particles. |
Table I. Continued.

| Run 20001-22542 Oct. 20 1989 – Oct. 8, 1990 CUSB-II+ | L (pb⁻¹) | Events | Physics |
|--------------------------------------------------|----------|--------|---------|
| 1S                                               | 18.5     | 332,413| $\alpha_s(1S)$, hadronic width. |
| 3S                                               | 143.6    | 969,890| $\alpha_s(3S)$, 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. |
|                                                   | 294.5    | 1,757,617| $\Lambda_{\overline{MS}}$. |

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

| L (pb⁻¹) | Events | Physics |
|----------|--------|---------|
| All      | 1376.4 | 6,641,231| Scalar nature of confining potential. |

SELECTED PHYSICS RESULTS

$\Lambda_{\overline{MS}}$ from $\Upsilon$’s → $\mu\mu$

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

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

| Resonance | $B_{\mu\mu}$ (%) | $\Gamma$ (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 $\alpha_s$ and $\Lambda_{\overline{MS}}$ obtained by us are in excellent agreement with those obtained using a number of other processes, proving that the $\Upsilon( S)$ system provides an independent probe of QCD.

Hyperfine Splitting of $B$ and $B_s$ Mesons

We have studied the inclusive photon spectrum from $2.9 \times 10^4 \Upsilon(5S)$ decays. We observe a strong signal due to $B^*\rightarrow B\gamma$ 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, $(46.7 \pm 0.4)$ MeV, ii) the photon yield per $\Upsilon(5S)$ 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 $\Upsilon(5S)$ 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 $\sim 48$ MeV is due to the decay $B^* \to B + \gamma$, 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 $\Upsilon(4S)$ and the $\Upsilon(5S)$

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

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

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

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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.

We have made a detailed study of hadronic and electric dipole (E1) transitions between the $\Upsilon$ and $\chi_b$ states, both in exclusive and inclusive channels. We have determined their branching ratios: $\text{BR}(\Upsilon'' \to \chi_b(2P_{2,1,0})\gamma) = (11.1 \pm 0.5 \pm 0.4)\%$, $(11.5 \pm 0.5 \pm 0.5)\%$, $(6.0 \pm 0.4 \pm 0.6)\%$. We have measured the center of gravity of the $\chi_b(2P)$ states to be $(10259.5 \pm 0.4 \pm 1.0)\text{ MeV}$. We have made precision measurements of the electric dipole transition rates from $\Upsilon''$ to $\chi'_b$, they are in excellent agreement with theory.

$$\bar{M} + a \text{ (spin-orbit)} + b \text{ (tensor)}$$

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

The fine structure splittings obtained using all data is $M(\chi_2) - M(\chi_1) = (13.5 \pm 0.4 \pm 0.5)\text{ MeV}$ and $M(\chi_1) - M(\chi_0) = (23.2 \pm 0.7 \pm 0.7)\text{ MeV}$, leading to a ratio
$R = 0.584 \pm 0.024 \pm 0.02$. The fine structure measures the relative contributions of the spin-orbit interaction $a = (9.5 \pm 0.2 \pm 0.1)$ MeV and tensor interaction $b = (2.3 \pm 0.1 \pm 0.1)$ MeV, that is, the spin-orbit interaction dominates over the tensor interaction. We also find that the long-range confining potential is due to the exchange of an effective Lorentz scalar. From the measured branching ratios we infer the hadronic widths of the $\chi_b(2P)$ states and find them to be consistent with QCD predictions. We use them to derive values of $\alpha_s$. We have also observed the suppressed transition $\Upsilon(3S)\rightarrow\chi_b(1P)\gamma$. The measured branching ratio suggests that relativistic effects are important.

Figure 10. Scalar contribution to the long range confining potential for $\chi_b, \chi'_b$ and their average as function of $\alpha_s$ obtained using the fine structure measurement from CUSB.

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

We have investigated the decay $\Upsilon(3S)\rightarrow\Upsilon(1S, 2S)\pi^+\pi^-$, where the final state $\Upsilon(1S, 2S)$ decays to a pair of leptons. We found $\sim 390$ events of the type $\Upsilon(3S)\rightarrow\Upsilon(1S)\pi^+\pi^-$ and $\sim 140$ events of the type $\Upsilon(3S)\rightarrow\Upsilon(2S)\pi^+\pi^-$. 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. There have been contradictions on the mass spectrum between previous experimental data and theoretical predictions. We have verified the unusual double-peak behavior on the dipion mass spectrum from $\Upsilon(3S)\rightarrow\Upsilon(2S)\pi^+\pi^-$, it is quite different from the spectra for $\pi\pi$ decays from other $\Upsilon$ and $\psi$ states as well as theories which predict 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).

![Dipion mass spectrum observed in $\Upsilon(3S) \rightarrow \Upsilon(1S) + \pi^+\pi^-$](image)

**Figure 11.** Dipion mass spectrum observed in $\Upsilon(3S) \rightarrow \Upsilon(1S) + \pi^+\pi^-$. The curve is from the model ref. 35.

**REGRETS**

While we recall our venture of CUSB at CESR with great affection and sense of accomplishments, there are regrets that we could not have stayed, ran on the $\Upsilon(3S)$ longer, on the $\Upsilon(2S)$ especially and found a few more known-to-exist states, such as the $\eta_b$ and $h_b$ (6, 7). We could have solved a few more puzzles such as the hadronic widths of the $\chi_b$ 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, Sparticles, and after we ruled out that there are neither direct photons nor excessive direct pions from the $\Upsilon(4S)$, there are still no explanations why the the $B$-semileptonic decay branching ratios do not agree with theoretical expectations (28, 9).
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