RESULTS FROM CUSB-II

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ABSTRACT

During 1986 we installed the complete BGO array inside the CUSB-I detector and proved by studying ≈5 GeV electrons from Bhabha scatterings that the new CUSB-II detector had achieved an improvement of two in resolution. In this configuration we took some 660 pb^{-1} of integrated luminosity at the various resonances and on the continuum. Results from this run include accurate measurements of the branching ratios $B_{\mu\mu}$(3S) and $B_{\mu\mu}$(1S), of the fine splitting of the χ_b' states, and of the hadronic widths of the χ_b' states. Above the flavor threshold, we determined the hyperfine splittings in the B-meson system, measured semileptonic branching ratios from B_u and B_s semileptonic decays at the Υ(4S) and Υ(5S), and found evidence of B_s production on the Υ(5S) resonance. We also obtained limits on direct photon production from the Υ(4S).

1. BRANCHING RATIOS FOR $\Upsilon(n^3\text{S}_1) \rightarrow \mu\mu$

We have measured $B_{\mu\mu}$[1] from the increase of the muon yield at the Υ's peak. The measured $B_{\mu\mu}$ values can be combined with the measured leptonic widths to determine the total widths (see the table below). Using $B_{\mu\mu}$ and measured branching ratios for $\Upsilon(n\text{S})$ transitions we extract $\Gamma_{ggg}/\Gamma_{\mu\mu}$, where Γ_{ggg} is the 3 gluon decay width. This ratio is proportional to $\alpha_s^3(q) \times (1 + c(q) \times \alpha_s(q)/\pi)$ where the scale q is not uniquely defined by theory. Following Kwong and colleagues,[2] we use $q = m_b$ and obtain α_s and $\Lambda_{\overline{MS}}$ as displayed in the following table.

Table 1. $B_{\mu\mu}(nS)$ Summary.

State	$B_{\mu\mu}$ %	Γ keV	$\alpha_s(m_b)$	$\Lambda_{\overline{MS}}$ MeV
Υ(1S)	$2.61 \pm .09$	51.1 ± 3.2	$.174 \pm .004$	150 ± 13
Υ(2S)	$1.38 \pm .25$	42.3 ± 9.2	$.176 \pm .016$	167 ± 58
Υ(3S)	$1.73 \pm .15$	27.7 ± 3.7	$.173 \pm .008$	154 ± 29
$\langle\Upsilon(nS)\rangle$	—	—	$.174 \pm .003$	157 ± 12

The above values are to be compared with our previous measurement of $B_{\mu\mu}$(3S)= $(1.53\pm0.33\pm0.21)$% from an analysis of a smaller Υ(3S) sample,[3] and with the world average value of $B_{\mu\mu}(1\text{S}) = (2.8 \pm 0.2)$%. For the average values of $\alpha_s(m_b)$ and $\Lambda_{\overline{MS}}$ we have to include a reasonable guess of the theoretical uncertainty in fixing the energy scale in the systematical error, this is the second error shown: $\alpha_s(m_b) = .1736 \pm .0033 \pm .0173$ and $\Lambda_{\overline{MS}} = 157 \pm 12 \pm 60$ MeV. These α_s and $\Lambda_{\overline{MS}}$ values are in excellent agreement with those obtained using a number of other processes, proving that the Υ system provides an independent probe of QCD.

2. FINE SPLITTING OF THE χ_b' AND χ_b STATES

Using the CUSB-II detector at CESR, we have made a precision determination of the fine splitting of the χ_b' states.[4] The measurement of the fine structure is obtained from an analysis of the inclusive photon spectrum from $\Upsilon'' \rightarrow \gamma + X$ obtained with an integrated luminosity of ~180 pb^{-1}. The fine structure splitting is found to be $M(\chi_{b2}') - M(\chi_{b1}') = (13.2 \pm 1.0)$ MeV, $M(\chi_{b1}') - M(\chi_{b0}') = (21.8\pm1.2)$ MeV and $M(\chi_{b2}') - M(\chi_{b0}') = (34.9 \pm 1.25)$ MeV, leading to a ratio r of the mass splittings of $r = 0.61 \pm 0.03$. The measured values are used to derive the contributions of the spin-orbit and tensor interactions to the splittings. They are $a = (9.1 \pm 0.4)$ MeV and $b = (2.1 \pm 0.2)$ MeV respectively. The results also support the postulate that the confining potential is long ranged.

3. HADRONIC WIDTHS OF THE χ_b' STATES

We have studied the decay chain $\Upsilon'' \rightarrow \chi_b'\gamma \rightarrow \Upsilon'(\Upsilon)\gamma\gamma \rightarrow \mu\mu(ee)\ \gamma\gamma$ with the CUSB-II detector at the CESR e^+e^- collider.[5] From a sample of 1.3×10^6 produced Υ'''s obtained in two running periods with a combined integrated luminosity of 284 pb^{-1}, we collected ~400 such events. We obtain the branching ratios for $\chi'_{bJ} \rightarrow \Upsilon'(\Upsilon)\gamma$ and derive the hadronic widths of the χ'_b states from the measured branching ratios and calculated E1 rates. We obtain $\Gamma_{had}(\chi'_{b2}) = (82 \pm 10 \pm 11\ )keV$, $\Gamma_{had}(\chi'_{b1}) = (58 \pm 7 \pm 8\ )keV$ and $\Gamma_{had}(\chi'_{b0}) = (688 \pm 373 \pm 57\ )keV$. The first error is statistical, the second one systematical. Except for the $\Gamma_{had}(\chi'_{b2})$ width, which is narrower by a factor of two, the other two widths are in agreement with QCD predictions.

4. HYPERFINE SPLITTING OF B AND B_s-MESONS

Using the CUSB–II detector we have studied the inclusive photon spectrum from 2.9×10^4 $\Upsilon(5S)$ decays. We observe a strong signal due to $B^* \rightarrow B\gamma$ decays.[6] From fitting the subtracted photon spectrum using a Doppler smeared spectrum folded with our resolution, we obtain: i) the average B^*–B mass difference, (46.7±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. We confirm that these photons are associated with B mesons by tagging them with high energy electrons from their semileptonic decays.

The width of this peak, with a full width at half max (FWHM) of 15.7 ± 0.77 MeV, is wider than that expected from the intrinsic resolution of CUSB-II (~5.2 MeV, FWHM) and is narrower than that resulting from the decay of B^* mesons moving with velocity $\beta = 0.21$, the average velocity of B^* mesons from $\Upsilon(5S) \rightarrow B^*\overline{B}^*$, $B\overline{B}^* + cc$ in our sample. From a study of the shape of the photon signal from $B^* \rightarrow B+\gamma$ and $B_s^* \rightarrow B_s+\gamma$ transitions from $\Upsilon(5S)$ decays we determine the hyperfine splitting of non strange and strange B–mesons to be: ΔM_{ns}=(45.4±1.0) MeV, ΔM_s=(47.0±2.6) MeV. Using coupled-channel calculations which accurately reproduce the shape of the cross section above the b–flavor threshold[7] to determine the relative abundance of the six B pair channels and the yield of photons per resonance decay, we also obtain $M(B_s) - M(B) = 80$ to 120 MeV corresponding, respectively, to the fraction f of strange B meson produced being f=0.4 to 0.25, making the $\Upsilon(5S)$ a promising B_s factory.

5. B SEMILEPTONIC DECAYS AT THE $\Upsilon(4S)$ AND THE $\Upsilon(5S)$

B meson semileptonic decay spectra have been obtained from data taken at the $\Upsilon(4S)$ and at the $\Upsilon(5S)$ with the CUSB-II detector.[8] The branching ratio for $B \rightarrow e\nu X$ at the $\Upsilon(4S)$ is found to be $(11.1 \pm 0.6)\%$. The semileptonic electron spectrum of B–mesons from $\Upsilon(5S)$ decays 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 the $\Upsilon(4S)$ decays.

For pure $B\overline{B}$ production one expects the end point of the electron spectrum to move to higher energy and to exhibit considerable Doppler smearing because $B_{u,d}$ are the lightest B mesons and receive the largest boost. Results of fits to the electron spectrum assuming that only one particular channel contributes are shown in the following table. The momentum p and velocity β for each channel are shown in the first two columns.

Table 2. Fits to the electron spectrum at the $\Upsilon(5S)$.

Final state	p GeV/c	β	BR($B \rightarrow e$) %	χ^2 /dof
$B\overline{B}$	1.307	0.241	$9.0 \pm 0.5^{(*)}$	23.8/11
$B\overline{B^*}$ + c.c.	1.184	0.228	9.2 ± 0.5	18.9/11
$B^*\overline{B^*}$	1.045	0.192	9.2 ± 0.5	15.2/11
$B_s\overline{B}_s$	0.788	0.145	11.2 ± 0.6	12.5/11
$B_s\overline{B}_s^*$ + c.c.	0.593	0.110	11.2 ± 0.6	11.2/11
$B_s^*\overline{B}_s^*$	0.285	0.053	11.0 ± 0.6	13.0/11

(*) Statistical errors only.

From the values of χ^2 shown in the fifth column, computed from the spectrum for electron energy greater than 1.6 GeV, a relatively small Doppler smearing is favored, corresponding to production of slow B–mesons, i.e. production of B mesons which are heavier than normal B's, presumably strange B's, at the $\Upsilon(5S)$.

6. SEARCH FOR DIRECT PHOTONS IN $\Upsilon(4S)$ DECAYS

Suggestions have been put forth to explain a reported observation of direct J/ψ production in $\Upsilon(4S)$ decays of 0.22%,[9] devising mechanisms whereby a large annihilation rate of the $b\bar{b}$ pair in the $\Upsilon(4S)$ to two gluons becomes possible, since the allowed three gluon rate is expected to be ~1/1000 of the measured total rate. In a recent paper,[10] Khodjamirian *et al.* suggest that the $\Upsilon(4S)$ contains, in addition to the $b\bar{b}$ pair, some *piece of light quark and/or gluonic matter.* The $b\bar{b}$ pair, mostly in a color octet, can annihilate into 2 gluons, giving J/ψ's and a gluon plus photon resulting, according to the authors of reference 10, in the emission of a quasi monochromatic photon in the energy range from 4 to 5 GeV, with a branching ratio for $\Upsilon(4S)\to\gamma+X$ of at least 0.5%.

We have searched for such signal in a sample of ~300,000 $\Upsilon(4S)$ mesons produced at the CESR e^+e^- collider at the $\Upsilon(4S)$ peak.[11] Photons in hadronic events at the $\Upsilon(4S)$ peak are detected in the CUSB-II detector, which has an *rms* energy resolution of ~1% at 5 GeV. The photon spectrum observed at the $\Upsilon(4S)$ resonance has an almost flat tail when plotted in constant energy fraction bins (1%), extending from 2.9 GeV to the kinematic limit, where a peak with a full width of ~2% is observed. The whole spectrum above 2.9 GeV, containing ~13600 photons, is entirely due to the large continuum contribution. This is directly checked by subtracting the yield measured in the continuum just below the $\Upsilon(4S)$ peak properly accounting for the luminosities of the two samples. The subtraction gives a *negative* excess of -71 ± 171 photons from $\Upsilon(4S)$ decays in the entire energy interval of 2.9 to 5.1 GeV.

From a maximum likelihood calculation, using our energy resolution of $1\%/\sqrt[4]{E_\gamma/5\text{ GeV}}$, folded with the Doppler smearing due to the motion of the $b\bar{b}$ pair, we find 90% confidence level (c. l.) upper limit for the branching ratios (BR), BR< 0.07% for photon energies between 4 and 5 GeV, which is seven times less than the minimum prediction in reference 10.

Above 5.1 GeV, the presence of the peak due to $e^+e^-\to\gamma+\rho$ requires subtraction. The upper limit that we can place on an additional signal is about 1.5 times larger for $5100 < E_\gamma < 5290$ MeV than for $E_\gamma < 5100$ MeV. It is difficult however to see how photons at the kinematic limit could be produced in the framework of the mechanism proposed in reference 10.

A different suggestion by Atwood *et al.*[12] is that the $\Upsilon(4S)$ decays into the as yet unobserved h_b (1^1P_1 $b\bar{b}$) state by emission of an η meson with ~20% BR. The h_b decays to $\eta_b+\gamma$ with a 50% BR according to Kuang & Yan[13] (at least 10% according to reference 12, although this is clearly an underestimate[14]) and the η_b decays into two gluons, resulting in a width for non-B-meson pair decays which is a sizeable fraction of the total $\Upsilon(4S)$ width. The decay $h_b\to\eta_b+\gamma$ gives a monochromatic photon of about 500 MeV, Doppler smeared by the motion of the h_b ($\beta = 0.039$) with a BR for $\Upsilon(4S)\to\gamma+X$ of ~10% (at least 2% according to reference 12). In the above we have assumed that the mass of the h_b is given by the center of gravity of the χ_b states, or $M(h_b) = 9900$ MeV and that the $\Upsilon(1S)$–η_b splitting is 60 MeV.[4] The uncertainty in the predicted photon energy is of the order of -30 to $+57$ MeV.[15]

Again we do not observe any signal. From a fit of the inclusive photon spectrum with the assumption of a line anywhere in the interval $400 < E_\gamma < 600$ MeV, smeared by our resolution and Doppler broadening, we derive an upper limit for the branching ratio of < 0.7% at 90% c. l., for $E_\gamma = 500$ MeV. This limit is ~14 (~3, following ref. 12) times smaller than the prediction. The upper limit for E_γ in the 400–600 MeV interval is < 0.72%–< 0.55% .

Finally we note that we do not observe any high energy photons coming from $\Upsilon(4S)$ decays while in an equivalent continuum sample we find ~13600 "photons". In our detector high energy π^0's are not distinguishable from photons. The high energy signal observed in the continuum is due to either high energy π^0's or photons from asymmetric high energy π^0 decays. The neutral pions are from the hadronization following the standard continuum process $e^+e^- \to q\bar{q}$. The observed continuum spectrum is in good agreement with Monte Carlo simulation. At our energies, the hadronization of two gluon final states is very similar to that of light quarks.[16] The absence of signal in $\Upsilon(4S)$ decays, can therefore be directly translated into an upper limit for 2 gluon decays for the $\Upsilon(4S)$. From our data we obtain, at 90% c. l., BR($\Upsilon(4S)\rightarrow gg+X$)<4.5–6.0%, depending on the mass of X, the lower value corresponding to $M(X)$=0 and the higher to $M(X)$=1.2 GeV.

7. CONCLUSIONS

1. $\alpha_s(m_b)$ =(0.1736 ± 0.0033 ± 0.0173),
   $\Lambda_{\overline{MS}}$ =(157 ± 12 ± 60 MeV).

2. $M(\chi'_{b2}) - M(\chi'_{b1})$ =(13.2 ± 1.0) MeV,
   $M(\chi'_{b1}) - M(\chi'_{b0})$ =(21.8 ± 1.2) MeV,
   $M(\chi'_{b2}) - M(\chi'_{b0})$ =(34.9 ± 1.25) MeV.

3. $\Gamma_{had}(\chi'_{b2})$ =(82 ± 10 ± 11)keV,
   $\Gamma_{had}(\chi'_{b1})$ =(58 ± 7 ± 8)keV,
   $\Gamma_{had}(\chi'_{b0})$ =(688 ± 373 ± 57)keV.

4. ΔM_{ns} =(45.4 ± 1.0) MeV,
   ΔM_s =(47.0 ± 2.6) MeV.

$M(B_s) - M(B)$ = 80 to 120 MeV corresponding, respectively, to the fraction f of strange B meson produced on the $\Upsilon(5S)$ being f=0.4 to 0.25.

5. $B \rightarrow e\nu X$ at the
   $\Upsilon(4S)$ is (11.1 ± 0.6)%,
   $\Upsilon(5S)$ is (11.2 ± 0.6)%.

6. We have not observed any signal which might be interpreted as due to direct (or cascade) photons in $\Upsilon(4S)$ decays to non-B-meson pairs as expected in models constructed to explain possible direct J/ψ production in $\Upsilon(4S)$ decays. In addition we exclude, in a model independent way, $\Upsilon(4S)$ decays via two gluons, with BR>4.5–6.0% at 90% c. l. .

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14. The authors of ref. 12 estimate the radiative transition width of the h_b by scaling from $\Upsilon(2S)\rightarrow\chi_b+\gamma$ as the photon momentum k. E1 radiative transition rates however scale as k^3, making the estimate of reference 13 more correct.
15. The mass of the η_b is between 30 and 117 MeV lower than that of the $\Upsilon(1S)$ from potential models and scaling from the J/ψ–η_c case; see for instance J. Pantaleone, S.-H. H. Tye and Y. J. Ng, Phys. Rev. D **33**, 777 (1986); the value of 117 MeV is the measured J/ψ–η_c splitting suggested by N. Byers (private communication) to hold for the b case as well.
16. This is experimentally verified by studying the thrust distribution of χ_b, see for instance: D. Peterson *et al.* (CUSB), Phys. Lett. B **114**, 277 (1982). Lund Monte Carlo simulations confirm this. It can also be noted that the large cross section to $c\bar{c}$ pairs lowers the hard component in $e^+e^-\rightarrow q\bar{q}$ with respect to two gluon states.

DISCUSSION

Q. **Karl Berkelman** *(Cornell Univ.)*: Were the $\Upsilon(3S)$ data you showed from the most recent running?

A. **J. Lee-Franzini**: The exclusive data are from the lastest run. The inclusive data were from the earlier run.