SPECTROSCOPY ABOVE THE b-FLAVOR THRESHOLD FROM CUSB

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ABSTRACT

Evidence for new triplet S-wave states of the $b\bar{b}$- system, above the b-flavor threshold, and for an excited B meson, B^*, is presented. The masses, total widths and leptonic widths of the $\Upsilon(4S)$, $\Upsilon(5S)$ and $\Upsilon(6S)$ are determined from measurements of the cross section for e^+e^- annihilation into hadrons for $10.55<W<11.25$ GeV. B^* production is signalled by observation of monochromatic, low energy photons ($E_\gamma \sim 50$ MeV) from the decay $B^* \to B + \gamma$. This is the first experimental evidence for the existence of vector $b\bar{u}$ or $b\bar{d}$ states.

Four spin-triplet S-wave $b\bar{b}$ bound states, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(4S)$ are known to exist, their identification being mostly based on the agreement between level spacings computed in potential models and experimental observation. The first three Υ

states are observed as narrow peaks in the e^+e^- annihilation cross-section, with widths much less than the machine energy resolution. The first evidence of b-flavored mesons was provided by the discovery at CESR of the $\Upsilon(4S)$, with a mass of 10.577 GeV and a natural width of ~20 MeV, [1] and the observation [2] of a large yield of high energy leptons at the $\Upsilon(4S)$ peak due to the semileptonic decay of a meson of mass ~$M(\Upsilon(4S))/2$. The mass of the B meson was recently determined to be 5.272±2.5 MeV from reconstruction of exclusive final states resulting from hadronic decays. [3]

At center of mass energies above the $\Upsilon(4S)$ one expects several additional triplet S-wave $b\bar{b}$ states, with mass spacings of the order of 200 MeV. [4] In addition excited B mesons should be produced. Both spin singlet (pseudoscalar) and spin triplet (vector) $b\bar{u}$ and $b\bar{d}$ states are expected to exist and, as for lighter mesons, the vector state, B^*, is expected to be heavier than the pseudoscalar B. Scaling arguments and potential model fits, [5,6] as well as the empirical observation that the difference of the square of the masses for the known vector-pseudoscalar meson pairs (ρ-π, K^*-K, D^*-D) is constant suggest that $\Delta M = M(B^*)-M(B) \sim 50-55$ MeV. If this is the case then the dominant decay mode of the B^* is $B^* \rightarrow \gamma + B$, resulting in the emission of a photon of energy equal to ΔM in the B^* center of mass.

During the period July 1983 to June 1984, CESR delivered 123 pb^{-1} of integrated luminosity in the energy region $10.60<W<11.25$ GeV. In this energy region two or three triplet S states $\Upsilon(nS)$ (n=5, 6, 7) are expected to exist. Some data was also collected in the continuum below the $\Upsilon(4S)$ and at the $\Upsilon(4S)$ peak, showing very good consistency with larger previous data sets. Figure 1a shows R_{vis} versus W, where vis stands for visible, i.e. uncorrected for detector efficiency, as observed with the CUSB detector, where R is defined as $\sigma(e^+e^- \rightarrow hadrons)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$. CUSB is a purely calorimetric detector, composed of NaI crystals and lead glass blocks, with excellent identification of hadronic final states and electromagnetic energy resolution. A detailed description of the detector is given in Reference 7. Hadronic final states from $b\bar{b}$ resonance decays have lower thrust than continuum events, especially for resonances above threshold which decay into pairs of B mesons. Figure 1b shows R_{vis} for the same data after applying a thrust cut [8] which retains 70% of the resonance decays and 34% of the continuum events. Both figures show complex and very similar structure of approximately the same magnitude, proving that the excess hadronic yield above the $\Upsilon(4S)$ is due to resonance decays. Table I gives a summary of the data. The features in R are reflected in the fractional yields of resonance events versus W. These yields are obtained by subtracting the value of R_{vis} below the flavor threshold.

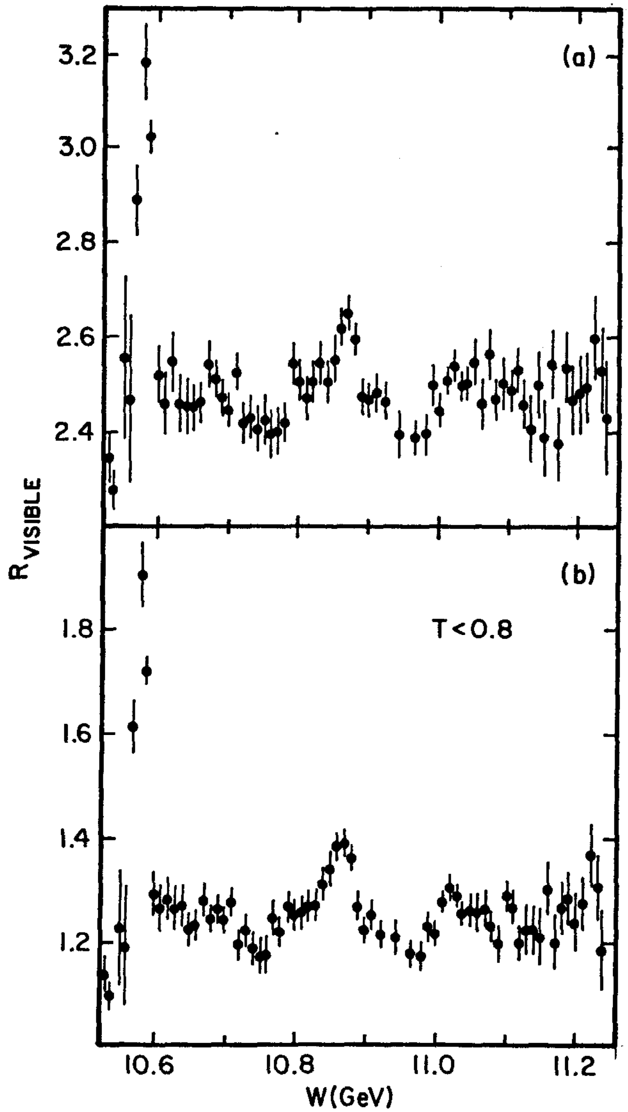

Figure 1

Table I. Summary of data.

Region (GeV)	∫ Ldt (nb^{-1})	Continuum Events	Resonant Events	Resonant Fraction
10.44-10.54	3141	5699	0	0.000
10.54-10.60	6057	14062	3169	0.225
10.60-10.67	8828	16844	1127	0.067
10.67-10.73	15154	28803	2122	0.074
10.73-10.77	6909	12610	561	0.045
10.77-10.83	12896	24104	1833	0.076
10.83-10.93	25374	47785	4600	0.096
10.93-10.99	7616	13267	502	0.038
10.99-11.06	25284	45700	3761	0.082
11.06-11.25	21073	37223	2940	0.079

Table II. Seven Gaussian fit results.

Gaussian	Mass* (GeV)	Γ* (MeV)	Γ_{ee} (keV)
1	10.579±0.001	25±2.6	0.185±0.024
2	10.63	82	0.114±0.016
3	10.70	61	0.083±0.009
(2+3)			(0.197±0.018)
4	10.79	61	0.102±0.010
5	10.86	47	0.115±0.009
6	10.91	59	0.076±0.010
(4+5+6)			(0.293±0.018)
7	11.02	66	0.113±0.008

*The central positions and widths were fixed for Gaussians 2-7.

Table III. Summary of resonance properties.

Resonance	Mass (GeV)	Γ (MeV)	Γ_{ee} (keV)
ϒ(4S)	10.5774±0.001	25± 2.5	0.283±0.20
ϒ(5S)	10.845 ±0.020	110±15	0.365±0.070
ϒ(6S)	11.02 ±0.03	90±20	0.156±0.040

The R(W) above threshold has a rather complicated behavior. Just above the $\Upsilon(4S)$ peak the cross section remains higher than below threshold, by about 0.2 units in R. A relatively large peak is observed at ~10.9 GeV, preceded and followed by dips. Just above 11.0 GeV a second peak is possibly present and finally R appears to level out at a value of R_{vis}~2.5. This behavior of R from below the $\Upsilon(4S)$ to 11.25 GeV, cannot be fit with three Gaussian (or Breit-Wigner) functions. A good fit to the data is obtained with seven Gaussians plus a smooth step in R. The parameters of the Gaussians are given in Table II. When the appropriate Gaussians are added as indicated in the table, the effective leptonic widths obtained are in good agreement with the results of the CLEO collaboration.[9] There is however no obvious correspondence between the seven fitted Gaussians and potential model expectations.

Eichten et al. in a series of papers have constructed a coupled channel model which explains qualitatively the features of R above the charm threshold.[5] Eichten has applied the same model to the $b\bar{b}$ system showing that if the $\Upsilon(4S)$ were close to the flavor threshold, the $\Upsilon(4S)$ resonance shape would be altered from a Breit-Wigner form.[10] We have used a simplified version of the coupled channel model of Eichten et al., to identify the origin of the various components in the cross section observed in the region from W=10.55 to W=11.05 GeV. We assume that four triplet S-wave states (4S, 5S, 6S, 7S) decay mostly into the six two body channels : $B\bar{B}$, $B\bar{B}^*+B^*\bar{B}$, $B^*\bar{B}^*$, $B_s\bar{B}_s$, $B_s\bar{B}_s^*+B_s^*\bar{B}_s$ and $B_s^*\bar{B}_s^*$, where B^*'s are excited B mesons and B_s's are bound $(b\bar{s})$ states. This assumption becomes inadequate at energies where many body decay channels such as $B\bar{B}+n\pi$ become important. We account for them by a smooth step in R as in the empirical fit described above. The decay amplitudes of the resonances in momentum space and the wave function at the origin are extrapolated from References 10 and 5 respectively. No S-D mixing is included and the relative contribution of $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ are weighted by statistical factors.[11] The masses of B^*'s and B_s's are taken as $M(B^*)-M(B)$=55 MeV, $M(B_s)-M(B)$=103 MeV and $M(B_s^*)-M(B_s)$=50 MeV.[12] These values are in agreement with simple scaling arguments. Masses and total widths of the resonances were varied as allowed by the data and within the range suggested by potential models. The following values were used : $M(\Upsilon(4S))$=10.5774 GeV, $\Gamma(\Upsilon(4S))$=25 MeV, $M(\Upsilon(5S))$=10.845 GeV, $\Gamma(\Upsilon(5S))$=110 MeV, $M(\Upsilon(6S))$=11.02 GeV, $\Gamma(\Upsilon(6S))$=90 MeV, $M(\Upsilon(7S))$=11.20 GeV, $\Gamma(\Upsilon(7S))$=100 MeV. In addition a smooth step in R, ΔR=0.18, turning on at 11.075 GeV, was included. The computed contribution to R is corrected for finite machine energy spread, radiative effects [13] and our detection efficiency of 0.69 for resonance events.

The results of the calculation, shown superimposed on the data in Figure 2, reproduce the main features remarkably well (the excess cross section at W=10.7 GeV may be due to D-wave states). The thrust cut data of Figure 1b is equally well described by this calculation. Table III gives the properties of the ϒ(4S), ϒ(5S) and ϒ(6S). The quoted error on each parameter reflects the freedom in changes which can be tolerated by the comparison with the data. Figure 3a shows the contributions of the four resonances to the cross section for two body final states. Most of the cross section in the energy region 10.7 to 10.95 GeV is due to the presence of the ϒ(5S), while the ϒ(7S) contributes practically nil. The complex structure seen is due to the radial nodes of the ϒ's wave functions and the six two body thresholds in an energy interval of ~300 MeV. Similar complexity is obtained by Tornqvist, using a pair creation model. [14] The contributions from B mesons (solid curve) and strange B mesons (dashed curve) are shown in Figure 3b. The narrow peak at 10.7 GeV is mostly due to $B_s^*\bar{B}_s^*$ production. This could be verified experimentally, given enough statistics, by looking for increased strange particle yield.

The relative population of ground state B mesons to states containing one excited B, and to states containing two excited B's, in the energy region 10.73-10.93 GeV, is calculated to be 0.19:0.32:0.49. One therefore expects on the order of one B^* per

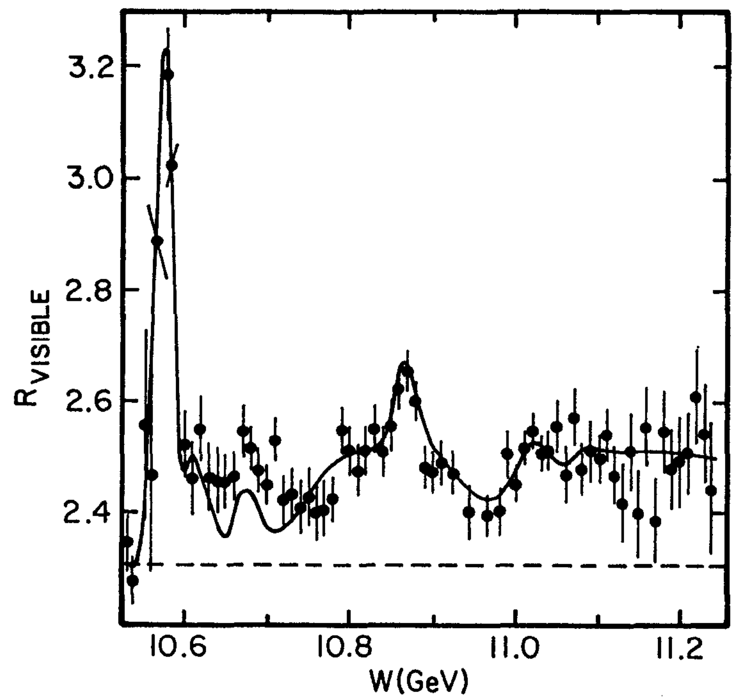

Figure 2

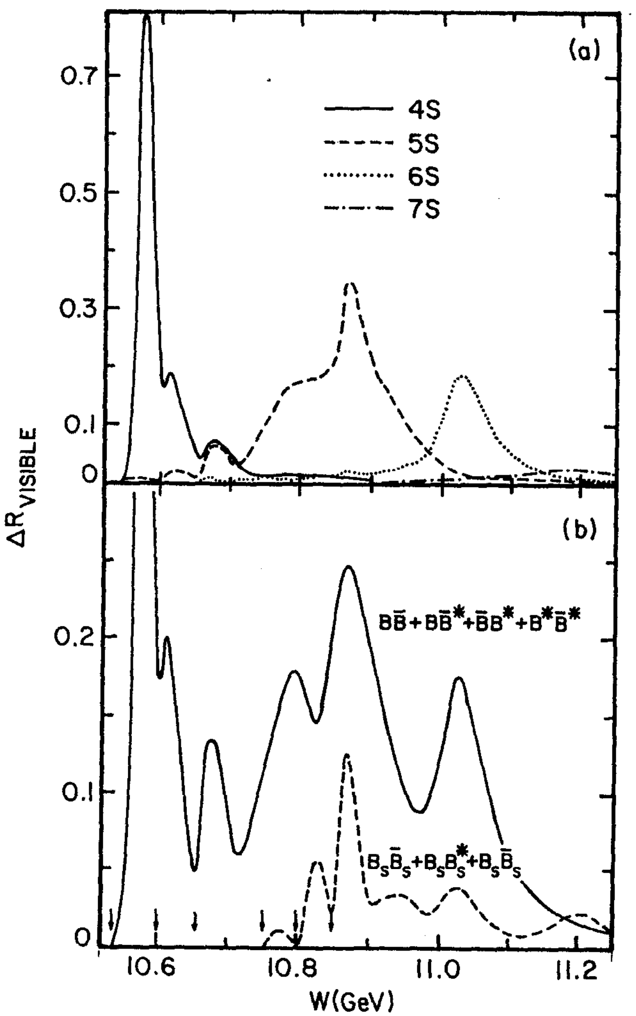

Figure 3

resonance, or approximately one B^* per 14 hadronic annihilations, with the best signal to background near the $\Upsilon(5S)$ peak where the cross section is largest.

We have searched for a monochromatic photon signal from the decay $B^* \rightarrow B+\gamma$. Only photons detected in the central calorimeter are used in the analysis. The segmentation of the detector allows construction of transverse and longitudinal shape criteria, which, along with a charged particle veto, are used to identify photons and reduce overlaps with other photons and charged particles. Fiducial cuts in azimuth are made to ensure containment of the photon shower. The NaI array is calibrated with 0.67, 1.33 and 1.37 MeV photons from ^{137}Cs and ^{60}Co sources in real time, while taking data. The overall energy scale has been checked using events from the decay $\Upsilon' \rightarrow \Upsilon\pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma(e^+e^-$ or $\mu^+\mu^-)$ for which the π^0 mass and $M(\Upsilon')-M(\Upsilon)$ are computed using the measured photon energies.[15]

The photon detection efficiency and energy resolution are determined by Monte Carlo calculations. Photon showers generated using the EGS shower code [16] are randomly superimposed on hadronic events which are then processed through the same photon finding code as real data. The expected Doppler broadening of a B^* signal is included in the calculation. We find a photon finding efficiency of $(9.2\pm3.8)\%$ for resonance events, and an rms resolution $\Delta E/E=17\%$, including Doppler broadening.

While the fraction of resonance events at the $\Upsilon(4S)$ is approximately 30%, at higher energies it is only about 7% in average, making the search for photons from B^* decay extremely difficult. Since resonance decays have lower thrust on average than continuum events, a thrust cut can enhance signals due to B^* decays. It should be noted that there is a strong correlation between low thrust and high multiplicity. In the energy region $10.62<W<10.94$ GeV, where we collected 68 pb^{-1} of data, copious production of $B^*\bar{B}$ and $B^*\bar{B}^*$ meson pairs is expected while Doppler broadening of the photons from B^* decay is smaller than, or comparable to, the energy resolution. The observed photon spectrum for the data in this energy region is shown in Figures 4a, 4b and 4c for thrust values of $T<1.0$, $T<0.80$ and $T<0.75$ respectively. An enhancement can be seen around 50 MeV whose visual significance appears to increase with increasingly stronger thrust cuts, which result in data samples which are richer in resonance events. We conclude that the enhancement seen in Figure 4 is associated with resonance events. No such enhancement is observed in the corresponding $\Upsilon(4S)$ samples.

In order to determine the position of the enhancement we fit the photon spectrum in the interval $20<E_\gamma<120$ MeV to a Gaussian plus cubic function, where the Gaussian represents our computed resolution. The results of these fits are shown as continuous lines in Figure 4. Figure 5 shows the same data after

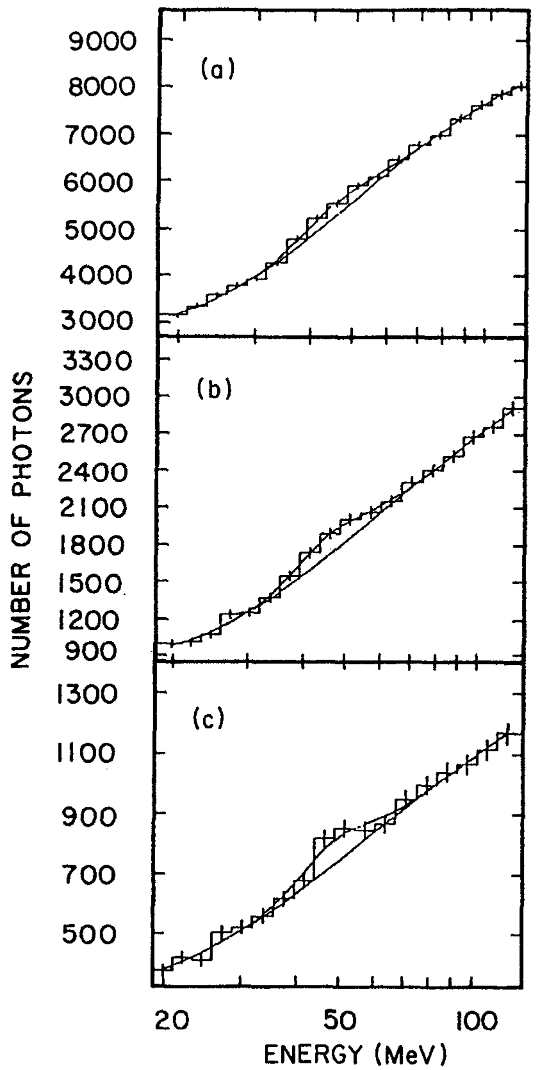

Figure 4

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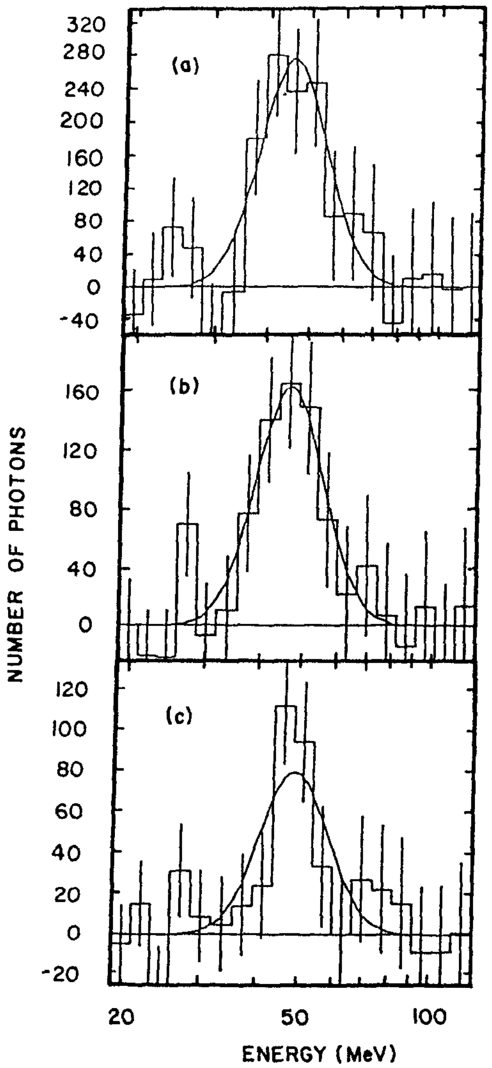

Figure 5

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subtraction of the cubic background for the three thrust cuts. Table IV gives the observed number of counts, together with the number of resonance events, the fraction of resonance events, and the observed yield of photons per resonance event.

TABLE IV

	T<1.0	T<0.8	T<0.75
N_γ	1374±365	787±210	396±141
N_{res}	12800	9000	5900
N_{res}/N_{tot}	0.07	0.16	0.22
N_γ/N_{res}	0.107	0.087	0.067

For all three samples we observe good agreement with the computed resolution and approximately constant photon yield, except for the most stringent thrust cut, where the high event multiplicity results in a much lower efficiency and the very poor statistics makes comparison of observed and computed widths uncertain. From the fits shown in Figure 5 we obtain a photon peak position of 51±6 MeV, where most of the error is due to uncertainties in the determination of the energy scale. While uncertainties in the photon finding efficiency as a function of thrust prevent a precise evaluation of the B^* production rate, we estimate that ~1.0-1.5 B^* are produced per resonance event.

In summary, we have measured the hadronic cross section and inclusive photon spectrum in the region above the b-flavor threshold, revealing evidence for several new states. Most of the structure in R in the energy interval 10.75 and 10.95 GeV is due to the fifth Υ $^3S_1$ state, $\Upsilon(5S)$. Its mass value is within 50 MeV of most predictions, for example Reference 9, and is within 5 MeV of the latest potential model calculation.[14] Its large leptonic width (0.365 keV) indicates that it is coupled to many decay channels and that the simple relation between Γ_{ee} and $|\psi(0)|^2$ is considerably modified.[5]

The identification of the next resonance as the sixth Υ state is more tenuous. From a theoretical standpoint one expects the next higher triplet state to be about 200 MeV above the $\Upsilon(5S)$. Experimentally, there is a relatively sharp rise in the cross section around 11 GeV. Both the empirical fit and the model calculation can accomodate its presence nicely. However, since it is located at an energy where multiparticle (rather than two body) final states are expected to give sizeable contributions, this interpretation is not unique. Perhaps the best way to state the situation is: if the peak at 11.02 GeV is the $\Upsilon(6S)$, then its parameters are those given in Table III. Our findings for the higher upsilon resonances are in substantial agreement with those of the CLEO collaboration.[9]

We have observed a monochromatic photon signal which is associated with the presence of B meson pairs in the final state, as verified by the dependence of the signal on thrust cuts. We take this as evidence that this signal is due to the decay $B^* \to B+\gamma$. The B^*-B mass difference is 51±6 MeV, for an unknown mixture of neutral and charged mesons. This value of ΔM is in agreement with most theoretical estimates.[10,17]

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