B Decays and

the Upsilon Family Above B Threshold

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Introduction

The primary focus of this report will be new results on B decays. In the past year, the CLEO and CUSB collaborations at CESR have taken no new data at the $\Upsilon(4S)$ B factory. However, CLEO has done a fair amount of new data analysis. At DORIS, the situation is reversed: ARGUS has obtained substantial amounts of new data, but so recently that they have not had time to digest them yet.

CESR has taken a great deal of data in the past year at energies above the $\Upsilon(4S)$. As an update on this activity, this report will also describe the search for the $\Upsilon(5S)$ and $\Upsilon(6S)$ and CUSB's evidence for the existence of the B^*.

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In the past year CLEO has succeeded in observing three new B decays using the decay chain sequence $B^- \to D^{*+} \pi^-$, where the D^* decayed to $D^0 \pi^-$ and the D^0 decayed to a kaon and three pions.[2] These new events permit an improved measurement of the B mass, which is listed in Table I.

As of July 1984 ARGUS had also fully reconstructed three new B mesons in 12 pb^{-1} of $\Upsilon(4S)$ data.[3] Once their data analysis is going smoothly, they should be able to reconstruct more B's than CLEO, since, in addition to being able to see all of the decays CLEO can, they have good enough photon detection to observe modes with π^0's in the final state. Better identification of low momentum kaons should also help reduce combinatorial confusion. ARGUS's only instrumental disadvantage is that the wider beam energy spread at DORIS makes the mass calculated using Equation 1 less precise.

Once a substantial number of reconstructed B's is accumulated, this can also be used to tag the second B produced in the $\Upsilon(4S)$ decay, thus giving information on semileptonic branching rates of neutral as opposed to charged B's, B^0-$\bar{B}^0$ mixing, etc.

The reasonably accurate value of the B mass obtained in Table 1 permits a guess of the production ratio of neutral to charged B's in $\Upsilon(4S)$ decay. Using the mass difference between the $\Upsilon(4S)$ and two B's to give the available phase space, taking Eichten's estimate[4] of the $\bar{B}^0$ - B^- mass difference, and assuming a p^3 onset of phase space, one calculates that 60% of the time $\Upsilon(4S)$ decays to charged B's and 40% to neutral. Thus CLEO has produced about 17000 neutral B's and 25000 charged B's in their data. These numbers are in the denominator of any calculation of branching ratios. They have been assumed in compiling Table 1.

A New Search for $b \to u$

Studies of the endpoint of the lepton momentum spectrum have shown that non-charm b quark decays are less than 4% as common as charm decays.[5] If $\bar{B}^0 \to \pi^+ \pi^-$ and $B^- \to \rho^0 \pi^-$ were about 2% of all non-charm B decays (as is $B \to D \pi$ compared to all charm B decays, or as $D \to K \pi$ is compared to all strange D decays), then you might hope to see some non-charm two body B decays at the 0.08% level if $b \to u$ was at the 4% limit.

The topology of $B \to \pi \pi$ events allows a level of background rejection to be attained which makes a measurement possible.[2] In B decay, if one B decays to two pions, the other, which decays independently, shows no spatial correlation to the direction of the pions. For the principle background, two jet production, the sphericity axis of the nonleading particles is highly correlated with the direction of the two most energetic particles. Thus a simple cut on the angle of the sphericity axis of the remaining particles of an event gives good rejection of background.

The data can be seen in Fig. 1. An upper limit of 0.05% is set for the branching ratio (for neutral B's) of $\bar{B}^0 \to \pi^+ \pi^-$, and a limit of 0.06% for $B^- \to \rho^0 \pi^-$ (for charged B's).

and the beam energy. Figure 2 shows the mass spectrum obtained in a Monte Carlo simulation of this technique.

The experimental procedure[2] was to search for events containing two particles of opposite sign, one with momentum above 2.0 GeV/c and the other with momentum below 0.25 GeV/c. The B mass was calculated as above. To estimate backgrounds, this procedure was repeated both on the $\Upsilon(4S)$ and in the continuum, and for both the real events and events with the spatial direction of the soft pion inverted to simulate combinatorial background. In Fig. 3, with data taken in the continuum, you can see that inverting the direction of the soft pion gives a good representation of the background. Figure 4, showing the data taken on the $\Upsilon(4S)$ resonance, has an excess of 205 ± 32 events in the region which should be populated by $\bar{B}^0 \rightarrow D^{*+} \pi^-$.

Unfortunately, about 40 of these events are $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}$ where the neutrino happens to have very low energy. Rather than trying to estimate this contamination accurately, CLEO eliminates these events completely by additionally requiring that the fast pion have momentum above 2.3 GeV/c. This leaves 41 ± 12 events, corresponding to a branching ratio (assuming a 60/40 charged to neutral B production ratio) of $BR(\bar{B}^0 \rightarrow D^{*+} \pi^-) = (2.1 \pm 0.6 \pm 0.5)\%$.

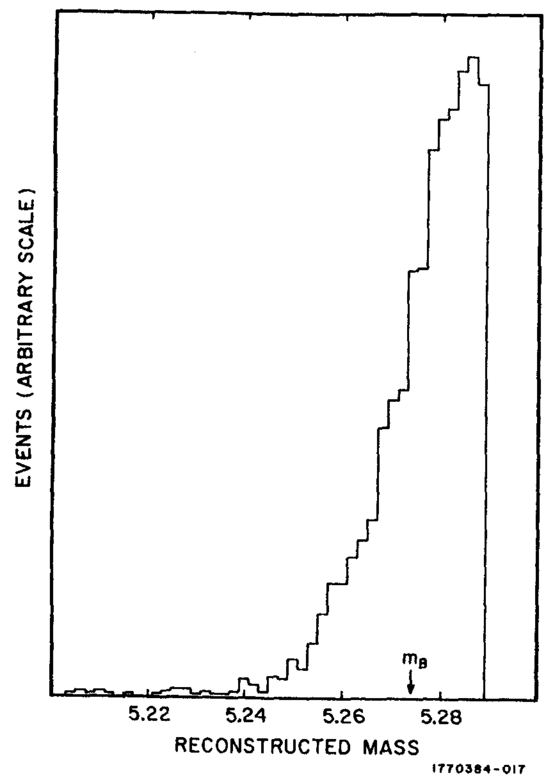

Fig. 2: A Monte Carlo simulation of the technique of partial reconstruction for $\bar{B}^0 \rightarrow D^{*+} \pi^-$. The number of events reconstructed is plotted as a function of the B mass obtained using fast and slow pions as described in the text.

$\bar{B}^0 \to D^{*+} \rho^-$

The same partial reconstruction technique can be used to observe $\bar{B}^0 \to D^{*+} \rho^-$. It is necessary here to observe the π^0 produced in the rho decay. Figure 5 shows how well CLEO can do this at high pion momentum.

Because background levels are higher, a cut on event shape[6] $R_2 = H_2/H_0 < 0.3$ is made, which preferentially rejects two-jet continuum events. Four different background estimation techniques are used. Inverting the spatial direction of the soft pion as in the $\bar{B}^0 \to D^* \pi$ analysis yields an estimate of 6 background events. Seeking the decay $\bar{B}^{++} \to D^{*+} \pi^+ \pi^0$, which contains a doubly charged "B", yields 7 background events. By interpolating into the ρ mass region from above and below, we estimate 9 background events. The technique with the most precision is to seek the decay $\bar{B}^0 \to D^{*+} \pi^+ \pi^-$, which is forbidden since it requires a b quark to decay to a $\bar{c}$ quark. The momentum resolution of the π^- is smeared to simulate the energy resolution for a π^0. This technique estimates 6.7 background events. A Monte Carlo calculation verifies that the analysis can find real $B \to D^* \rho$ decays, but does not pick up a significant number of events in any of these background channels. Data taken at energies below B threshold show no signal.

Figure 6 shows the signal and various background estimates for different $\pi^- - \pi^0$ mass regions. Evidence of the decay $\bar{B}^0 \to D^{*+} \rho^-$ is visible as an excess of 20 ± 4.6 events at the high mass end of the upper right-hand plot. Subtracting the estimated background and correcting for efficiency, CLEO finds a branching ratio

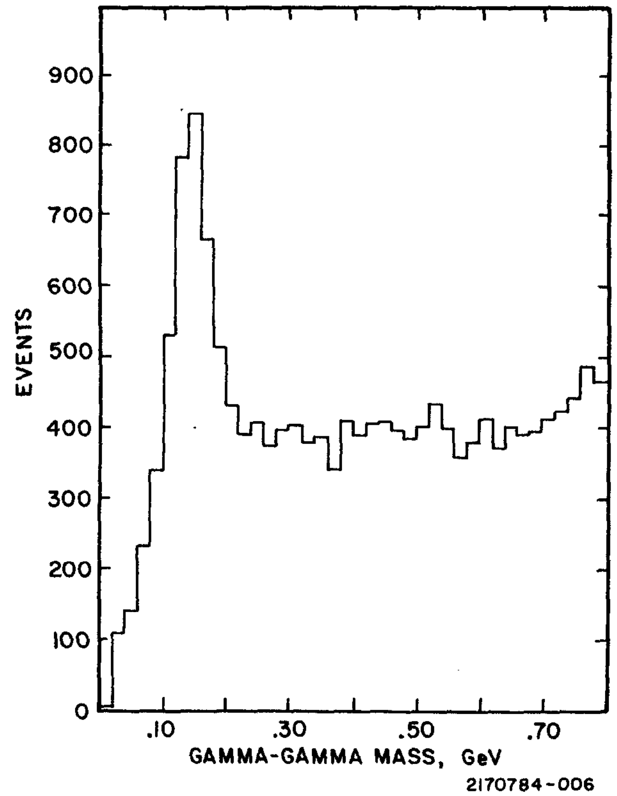

Fig. 5: Photon-photon invariant mass for combinations having over 1.0 GeV/c momentum.

Neutral/Charged B Lifetimes

The "spectator" decay of a B meson, where the normal quark just sits while the b quark decays to a virtual W and a charmed quark, should occur with roughly equal partial rates for both charged and neutral B's. However, there are other diagrams which are available to charged B's (e.g. when b and $\bar{u}$ quarks annihilate to a virtual W) or to neutral $\bar{B}^0$ (e.g. W exchange) and not to the other, which in principle could make the charged and neutral lifetimes differ. Since only the spectator diagram is involved in semileptonic decays, the partial widths are the same for charged and neutral B's. Thus the lifetime difference would be reflected in differing branching ratios for semileptonic decays.

CLEO can study the semileptonic decay rates by comparing the number of leptons produced

$$N_\ell = N_{B^\circ} b_0 + N_{B^-} b_-$$

to the number of dileptons produced

$$N_{\ell\ell} = N_{B^\circ} b_0^2 + N_{B^-} b_-^2$$

where N_{B°, N_{B^-} are the number of neutral or charged B's produced and b_0, b_- are the neutral and charged B semileptonic branching ratios. For example, if $b_0 = b_-$, the ratio $N_\ell^2 / 4N_{\ell\ell}$ would be just the number of B's produced, $N_{B^\circ} + N_{B^-}$, but if $b_0 = 0$ the ratio is N_{B^-}. If $b_0 = b_-$, CLEO expects 86 dileptons [7]; 85 ± 16 are actually seen, which puts 90% confidence level bounds on the ratio of branching ratios:

$$0.25 < \frac{BR(B^0 \to \ell \nu X)}{BR(B^- \to \ell \nu X)} < 2.9$$

assuming 60% of the B's produced are charged.

A Limit on B^0-$\bar{B}^0$ Mixing

The mixing parameter y can be defined as the number of observed $\bar{B}^0$-$\bar{B}^0$ and B^0-B^0 pairs compared to the number of B^0-$\bar{B}^0$ pairs:

$$y = \frac{N_{\bar{B}^\circ\bar{B}^\circ} + N_{B^\circ B^\circ}}{N_{B^\circ\bar{B}^\circ}} = \frac{N_{\ell^+\ell^+} + N_{\ell^-\ell^-}}{N_{\ell^+\ell^-}},$$

where the first equality is definition and the second holds for the background-corrected number of same sign and opposite sign dilepton events. This mixing parameter is such a sensitive function of the ratio of charged/neutral semileptonic branching ratios that the limit must be plotted as a function of that ratio as in Fig. 7. In this figure, X axis values below .25 or above 2.9 are excluded by the analysis of the previous section. The observed number of like and unlike sign dileptons excludes the shaded region in the upper right corner of Fig. 7. If the neutral B's semileptonic branching ratio is less than half of the charged B's, there is no limit on mixing. If, however, the branching rates are assumed equal, y cannot be larger than 25%, again assuming 40% of the B's produced are neutral.

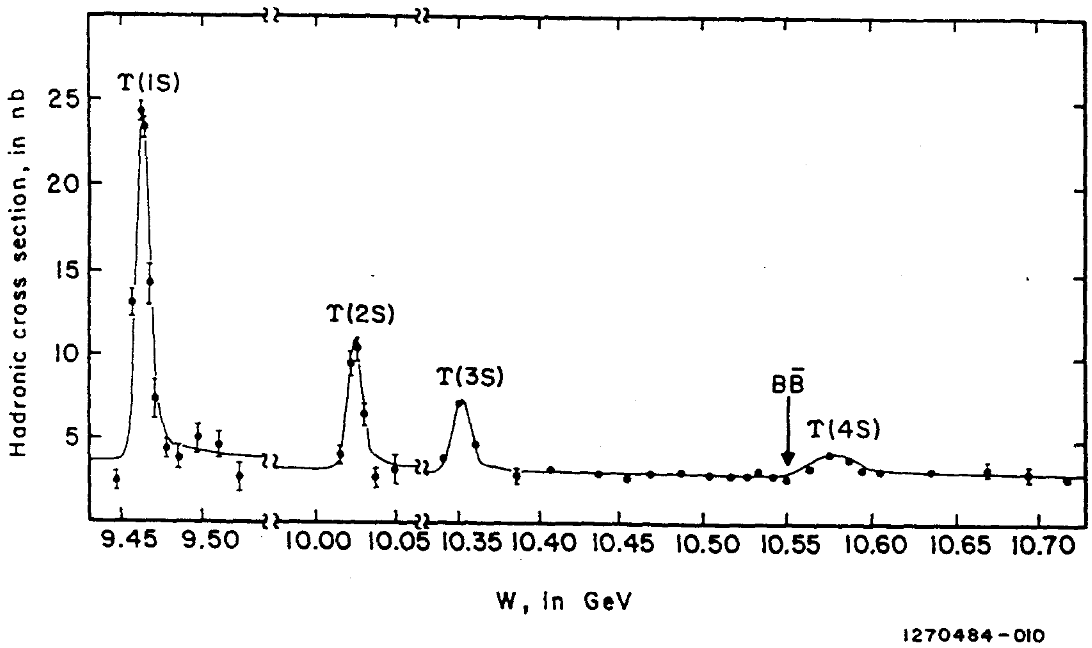

Fig. 8: The cross section for $e^+ e^- \to$ hadrons as a function of CM energy.

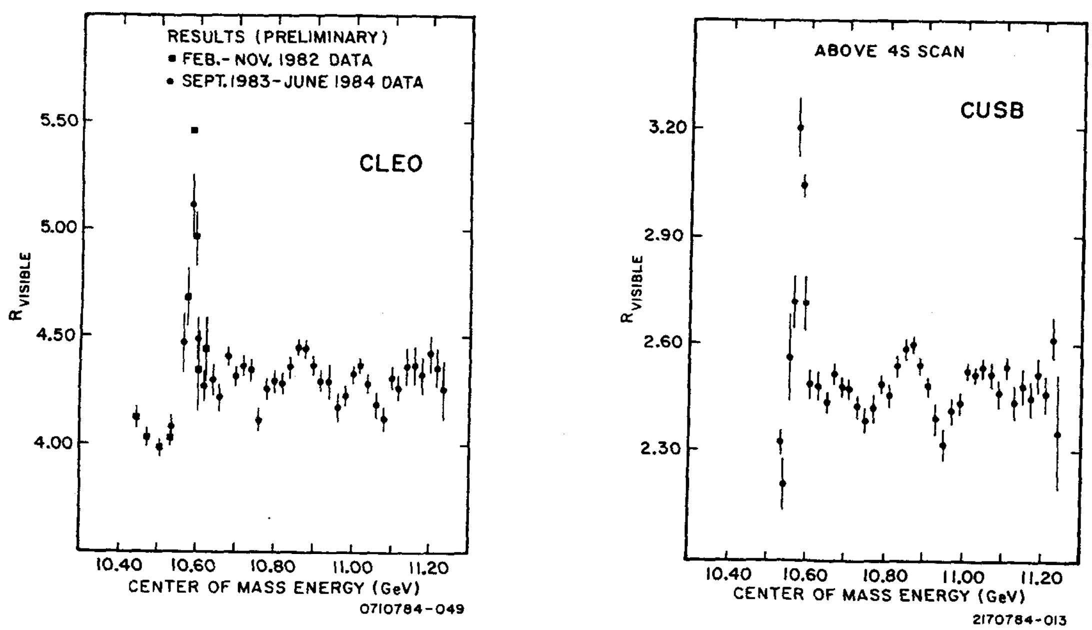

Fig. 9: The visible cross section for e^+e^- annihilation to hadrons divided by the QED muon pair cross section, $R_{visible}$, as a function of CM energy near and above open b threshold measured by a) CLEO and b) CUSB.

All the plots show very similar structure. Just above the Υ(4S) there appears to be a shoulder. A well defined peak is visible near E_{CM} = 10.86 GeV and perhaps a less definite peak is visible near E_{CM} = 11.02 GeV.

If this structure in the total cross section is really associated with b quarks, it should also be visible in other variables sensitive to the presence of b quarks. Figure 11a shows the R visible for muons and electrons as a function of CM energy. The structure is very similar, although the shoulder and higher energy peak may be less prominent. You might expect that kaons, produced when b quarks decay to c quarks, would show the same structure or even an enhancement once the threshold for producing a B_s (the $b\bar{s}$ quark combination) was crossed. Figure 11b shows that the statistical precision of the data is not good enough to permit that conclusion.

So it appears that there is significant structure above the Υ(4S) associated with b quarks. What does it mean? This energy region is expected to show complex behavior. In addition to possible Υ(5S) and Υ(6S) resonances, thresholds for $B^*\bar{B}$, $B^*\bar{B}^*$, $B_s\bar{B}_s$, etc. are probably being crossed.[9] There could even be a $b\bar{b}g$ state in this region.[10] Interference leads to a very complex structure, as illustrated by the prediction of Törnqvist[11] using a coupled channel model shown in Fig. 12.

Faced with this complexity CLEO and CUSB have chosen different and complementary ways to present the data. CLEO shows a simple phenomenological fit with three radiative Gaussians, which gives a qualitative idea where the structure is and how big it is. The results of this fit are shown in Fig. 13. CUSB chooses to fit

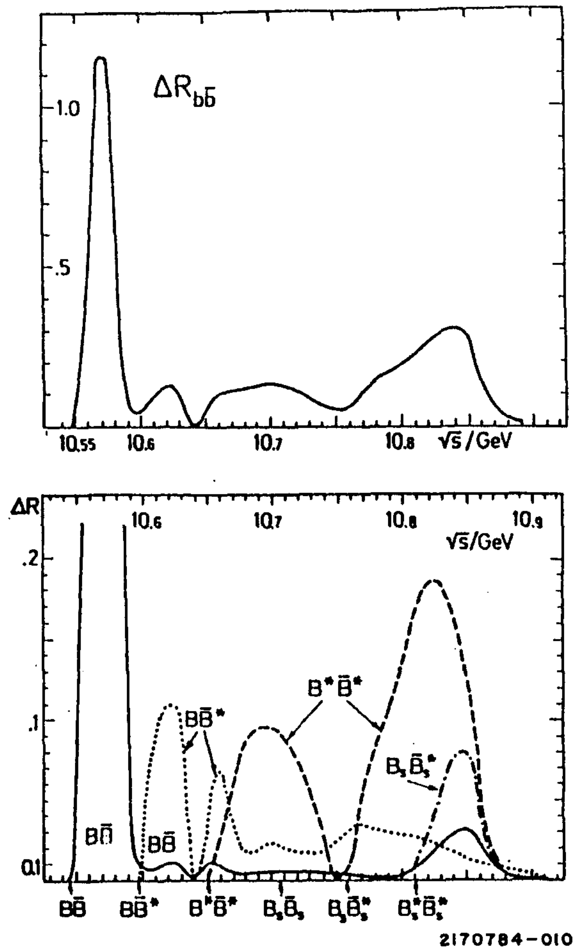

Fig. 12: The shape of R as a function of CM energy predicted by a coupled channel model.[11] The lower portion of the plot shows thresholds and the contribution of individual channels. Note the energy scale includes only about half the range shown in Figs. 9-11.

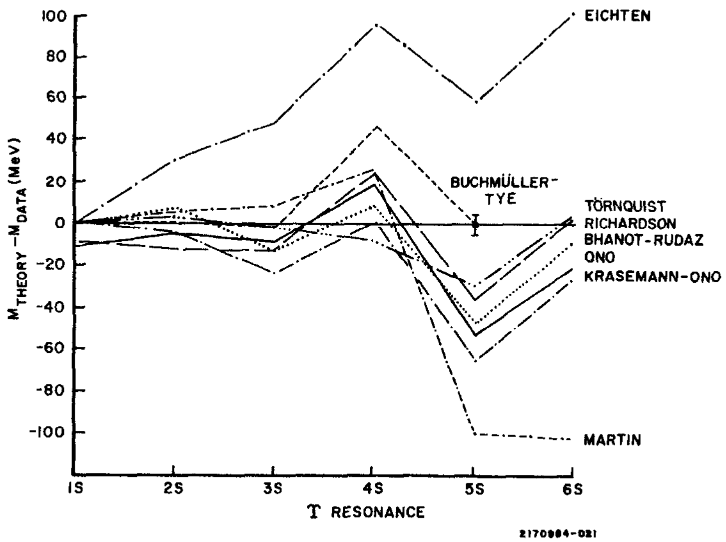

Fig. 14: A comparison of various predictions of the masses of the S-wave Υ resonances with the measured values.

Υ resonances. All but one of them predict a Υ(5S) mass much lower than what is measured.

III. Evidence for the Existence of the B^*

If the shoulder in the total cross section near 10.69 GeV is due to the crossing of the thresholds for producing B^*B and B^*B^*, it should be possible to observe nearly monoenergetic photons from the decay $B^* \to B\,\gamma$. Extrapolations from the $D - D^*$ mass difference lead to the expectation that the $B - B^*$ mass difference should be about 50 MeV. Last year, CUSB[13] had already sought in vain for evidence of this low energy photon at the Υ(4S). Now they have searched in the CM energy region 10.62 - 10.94 GeV, where the photon, if emitted, will not be Doppler-shifted too badly by the motion of the B^*.

Figure 15 shows the results of that search. The top plot shows the photon spectrum at the Υ(4S). The photon energy on the abscissa is shown on a logarithmic scale so that the bins are roughly constant in photon resolution. These data have been subjected to a severe cut on pseudothrust which favors spherical events. This cut, which discards about 90% of continuum events at the cost of 2/3 of the $B\bar{B}$ events, enhances the signal to noise ratio enough to make the signal (in part b of the figure) visible to the naked eye. No enhancement is visible in the Υ(4S) data near 50 MeV.

Figure 15b shows the same plot for data taken at energies corresponding to the shoulder above the Υ(4S) resonance. Although the general shape of the spectrum is the same as on the Υ(4S), a

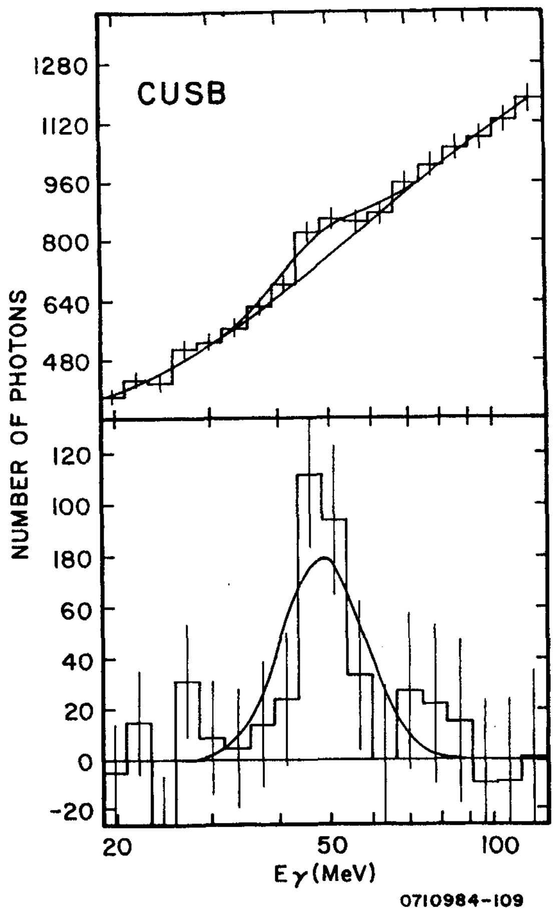

Fig. 16: CUSB's fit to the photon spectrum. The data have a less severe thrust cut of $T < 0.8$. The Gaussian fit has a width corresponding to the expected resolution.

B^* exists with a mass 50 ± 6 MeV above the B and that an average of one or more B^*'s are produced per $b\bar{b}$ quark pair.

V. Acknowledgements

I would like to thank my CLEO colleagues and members of the CUSB collaboration for discussions about the results presented here. Tom Ferguson also helped in the preparation and proofreading of this paper.

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