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RESULTS FROM THE CRYSTAL BALL AT DORIS II*

John E. Gaiser
(REPRESENTING the Crystal Ball Collaboration)[1]
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Abstract

Results are presented from studies of the inclusive photon spectra in hadronic decays of the Υ' and Υ and the exclusive channel $\Upsilon' \to \gamma\gamma\Upsilon \to \gamma\gamma\ell^+\ell^-$, by the Crystal Ball detector at DORIS II. We measure two signals in the $\Upsilon' \to \gamma$ + anything inclusive channel at $E(\gamma) = 108.3 \pm 0.9 \pm 3.0$ MeV and at $E(\gamma) = 127.5 \pm 1.2 \pm 4.0$ MeV. Branching ratios obtained for these signals are:

$$\mathrm{BR}\,[\Upsilon' \to \gamma(108) + \text{anything}] = (6.3 \pm 1.3 \pm 1.4)\%$$

$$\mathrm{BR}\,[\Upsilon' \to \gamma(128) + \text{anything}] = (6.0 \pm 1.3 \pm 1.4)\%$$

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1. Introduction

The main focus of our investigation at DORIS is a study of the $b\bar{b}$ quarkonium system with emphasis on the radiative decays of the Υ', especially transitions to the ^3P_J states. The theoretical interest in the upsilon spectrum is encouraged by the expectation that it is a less relativistic system than charmonium.[2] From an experimental point of view, it is a new and incompletely mapped family of states associated with the relatively unknown massive b-flavoured quark.[3]

Figure 1 shows the level structure for states up to the Υ' mass as expected from non-relativistic potential models.[2] Also indicated are the predicted radiative transitions between the levels. The decays $\Upsilon' \rightarrow \gamma\, ^3P_J$ and the cascade decays $^3P_J \rightarrow \gamma\Upsilon$ are electric dipole (E1). The transitions involving the $^1S_0$ pseudoscalar states $\Upsilon' \rightarrow \gamma\eta_b'$ and $\Upsilon \rightarrow \gamma\eta_b$ are allowed magnetic dipole (M1) decays, while $\Upsilon' \rightarrow \gamma\eta_b$ and $\eta_b' \rightarrow \gamma\Upsilon$ are "hindered" M1. The M1 rates are expected to be small[4] (compared to the E1 rates) and no candidates for these states have been observed. Candidates for the ^3P_J states have been previously reported by the CUSB collaboration[5] in the inclusive photon channel $\Upsilon' \rightarrow \gamma\, ^3P_J \rightarrow \gamma$ + hadrons. Three states were seen corresponding to photon energies of 108 ± 2, 128 ± 3, 149 ± 5 MeV, where the errors reflect the dominant systematic uncertainty. The two higher mass states were also seen in the exclusive process[5] $\Upsilon' \rightarrow \gamma\, ^3P_J \rightarrow \gamma\gamma\Upsilon \rightarrow \gamma\gamma\ell^+\ell^-$. Precise identification of these states with the triplet P states of the theory awaits a measurement of their spin and parity. Finally there are hadronic transitions between Υ' and Υ. The $\Upsilon' \rightarrow \pi\pi\Upsilon \rightarrow \pi\pi\ell^+\ell^-$ decay has been observed[6] in both the $\pi^+\pi^-$ and the $\pi^o\pi^o$ channel. Neither the process $\Upsilon' \rightarrow \eta\Upsilon$ nor the isospin forbidden decay $\Upsilon' \rightarrow \pi^o\Upsilon$ have been seen.

The Crystal Ball experiment has been running at the DORIS II storage ring since the Fall 1982. We have taken data in the region of the $b\bar{b}$ resonances Υ and Υ'. The current data sets consist of 66k produced Υ' and 53k produced Υ decays, corresponding to 24.5 pb^{-1} and 7.8 pb^{-1}, respectively. The ratio of resonance to continuum hadronic decays at Υ' is about 1:1 and at Υ is about 2.5:1. We also obtained 4.8 pb^{-1} of continuum data just below the Υ', which was mainly used as a systematic check on signals observed in the Υ' resonance.

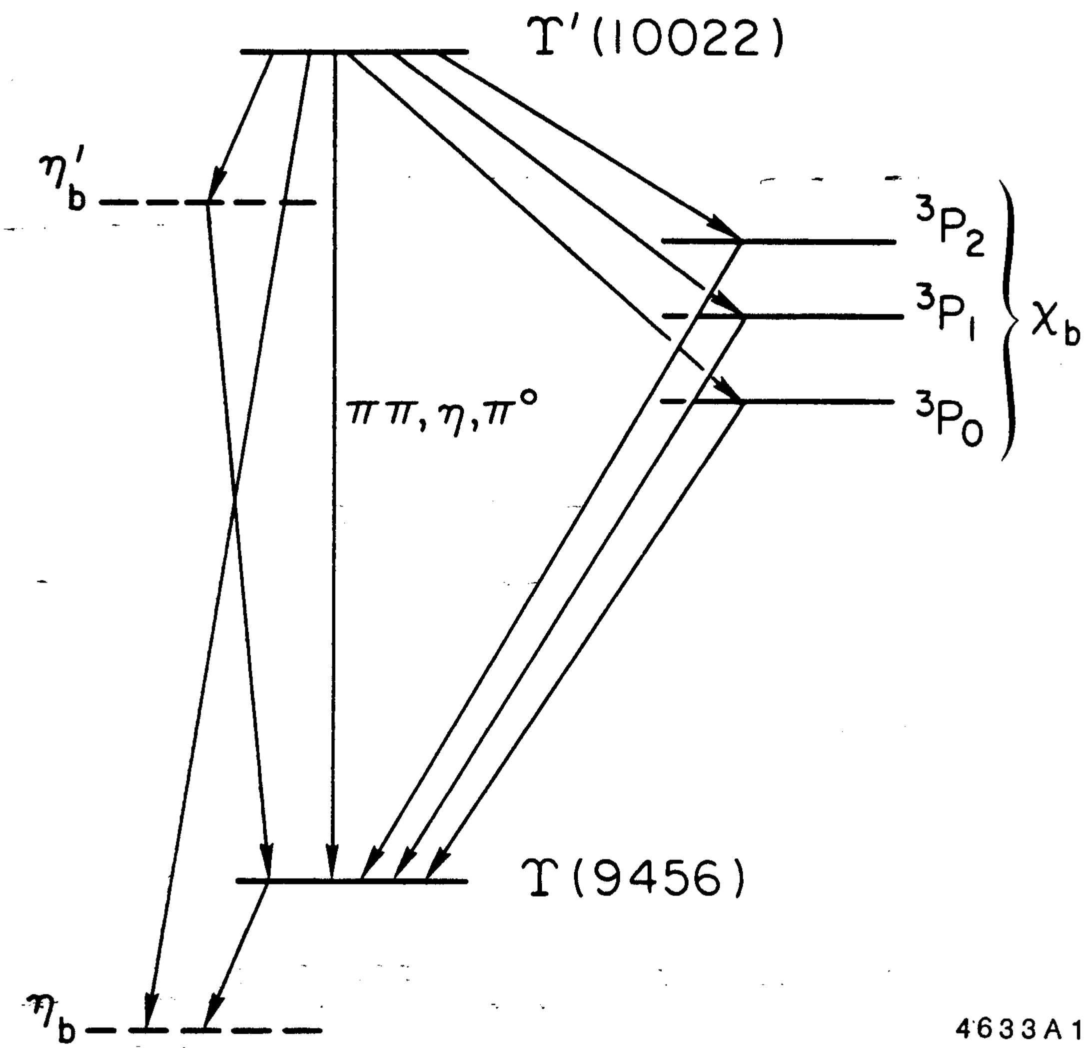

Fig. 1. The level scheme for the $b\bar{b}$ bound states below Υ'. The arrows indicate radiative transitions, except for the $\pi\pi$, η, and π^0 transitions between Υ' and Υ. The $^1P_1$ spin-singlet P-wave state, which is expected to have a mass equal to the ^3P_J center of gravity, is not shown here (it is believed to be very difficult ~~to~~ observe[4]).

We expected the analysis of the inclusive Υ' radiative decays to be more difficult than a similar analysis at the ψ', due to a combination of factors: i) smaller branching ratios; ii) large continuum contamination; iii) higher photon multiplicities; and iv) lower photon detection efficiencies. The result is a reduction in the expected signal/noise ratio of 1/10 to 1/15 compared to ψ'.

The Crystal Ball detector is well suited to study the radiative transitions between the upsilon resonances. The components of the detector in its SPEAR configuration have been described in detail elsewhere.[7,8] Only a review of the major characteristics including the modifications for DORIS will be given here (see Fig. 2). The Crystal Ball was designed to measure electromagnetically showering particles with a high resolution over a large solid angle and consists of a segmented array of 672 NaI(Tℓ) crystals (each 16 radiation lengths deep), covering 93% of the solid angle. This coverage is increased to 98% with additional crystals forming the endcaps. No particle identification is attempted in the endcaps. For inclusive hadronic decays the energy resolution achieved for photons and electrons in the main detector is $\sigma(E)/E = (2.6 \pm 0.2)\%/E^{1/4}$ (E in GeV), with an angular resolution of 1.5-2.5^o (depending slightly on energy). Charged particle tracking is provided by 3 double-layers of proportional tube chambers with charge division readout. As there is no magnetic field. The momenta of charged particles are not known while their energy is only poorly measured by the one absorption length of NaI. A minimum ionizing particle has a most probable energy loss of 205 MeV. Luminosity measurements are done by counting large angle Bhabha scattering events in the ball and independently by small angle Bhabha counters near the beam-pipe.

Several checks on the data were made to demonstrate the correct performance of the detector. In particular the $\gamma\gamma$ decay of π^o's and η's in inclusive hadronic events were studied to test the ability of the detector to measure photons (see Fig. 3). They also provided checks on the energy calibration and resolution of the crystals. Both signals have the width expected from our resolution but the fitted masses are about 2.5% below their known values[9].

In addition we checked the exclusive channel

$$\Upsilon' \rightarrow \pi^o\pi^o\Upsilon \rightarrow \gamma\gamma\gamma\gamma\ell^+\ell^-$$

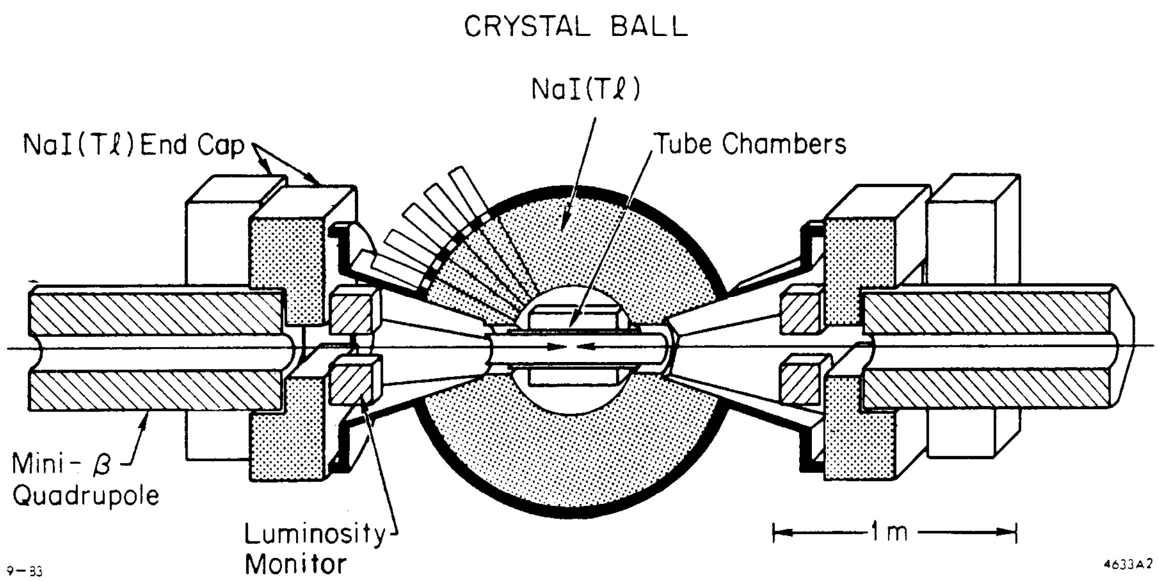

Fig. 2. The Crystal Ball detector at DORIS.

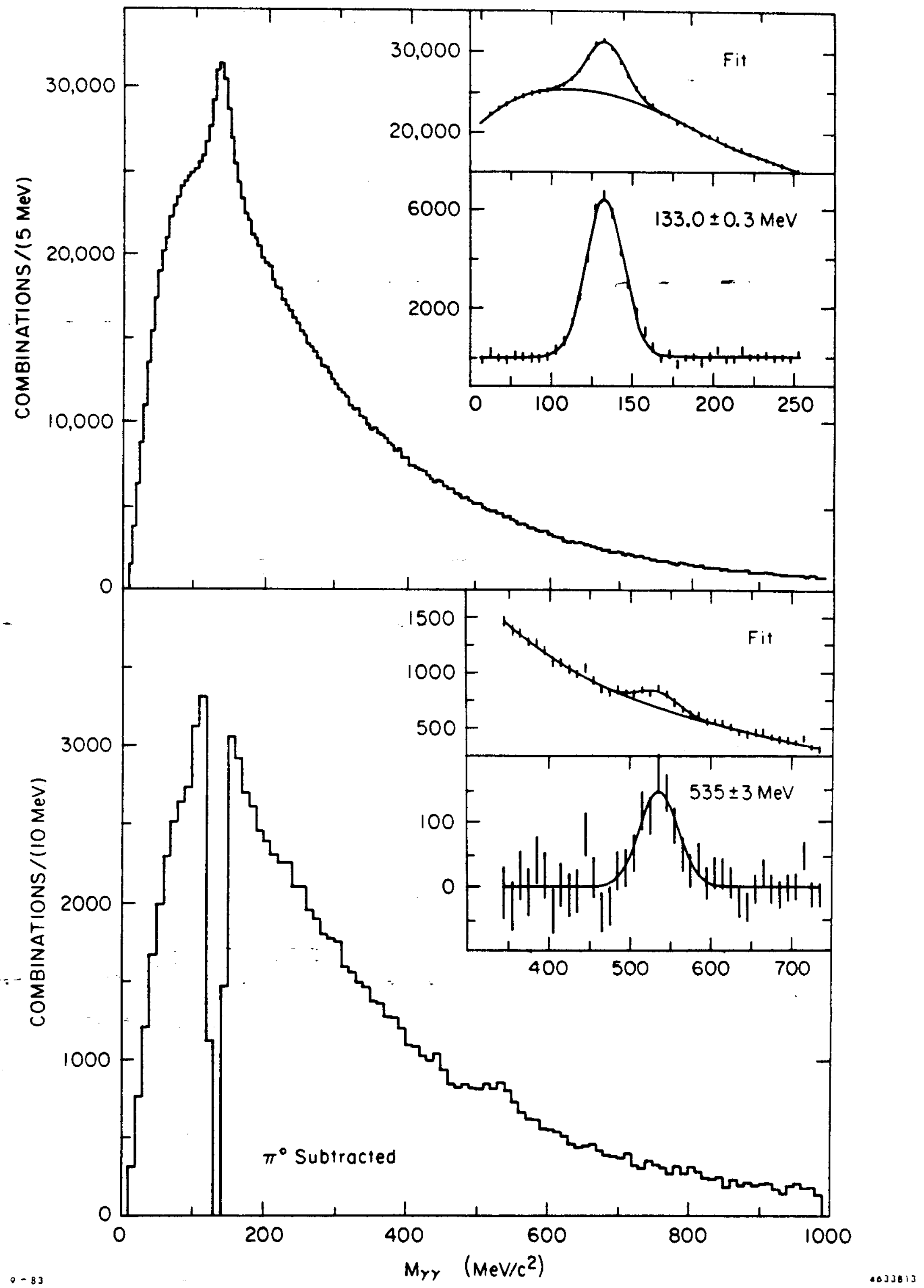

Fig. 3. The top figure shows the $\gamma\gamma$ invariant mass distribution for hadronic decays of the Υ'. The photons were required to have lateral energy deposition patterns consistent with single electromagnetic showers. The inset shows a fit to the π^0 mass signal. The bottom figure shows the spectrum after removing photons which reconstruct to a π^0 mass. The bottom inset shows a fit to the resulting enhanced η mass signal. Only statistical errors are shown.

(the Υ is detected through its decay into a lepton pair). In Fig. 4 we plot the mass-difference

$$\Delta M = M(\Upsilon') - M_{\rm recoil}$$

where $M_{\rm recoil}$ is the mass recoiling against the 4γ system. In this channel we would expect a signal at the Υ'-Υ mass difference (about 562 MeV).[10] Again we find that the width of the ΔM distribution agrees with what we expect from energy and angular resolution but that the mean of the distribution is about 3% below 562 MeV. Comparable shifts had been observed in similar analyses of SPEAR data in the charmonium system and indicate a systematic bias in our absolute energy scale.

2. Inclusive photon study

Of particular interest to the Crystal Ball experiment at DORIS is a search for the positive C-parity ^3P_J states lying below the Υ'. These states can be detected through the presence of monochromatic lines in the inclusive photon spectra. The method of selecting events and photons will be described below. Detailed descriptions of a similar study in the charmonium system may be found in the references.[8]

Hadronic decays were selected from the available triggers by criteria designed to remove backgrounds from beam-gas interactions, cosmic rays and QED events. The resulting sample of hadronic events contain not only contributions from the resonance decays, but also from the continuum process $e^+e^- \to$ hadrons. In this study no attempt was made to separate the two. The overall hadronic selection efficiency was found to be $(85 \pm 10)\%$ from Monte Carlo studies. The background contamination is about 2%.

The photon selection was designed to remove charged particles, photons from π^0 decays and photons with showers contaminated by energy deposits of near-by particles. The following criteria were used:

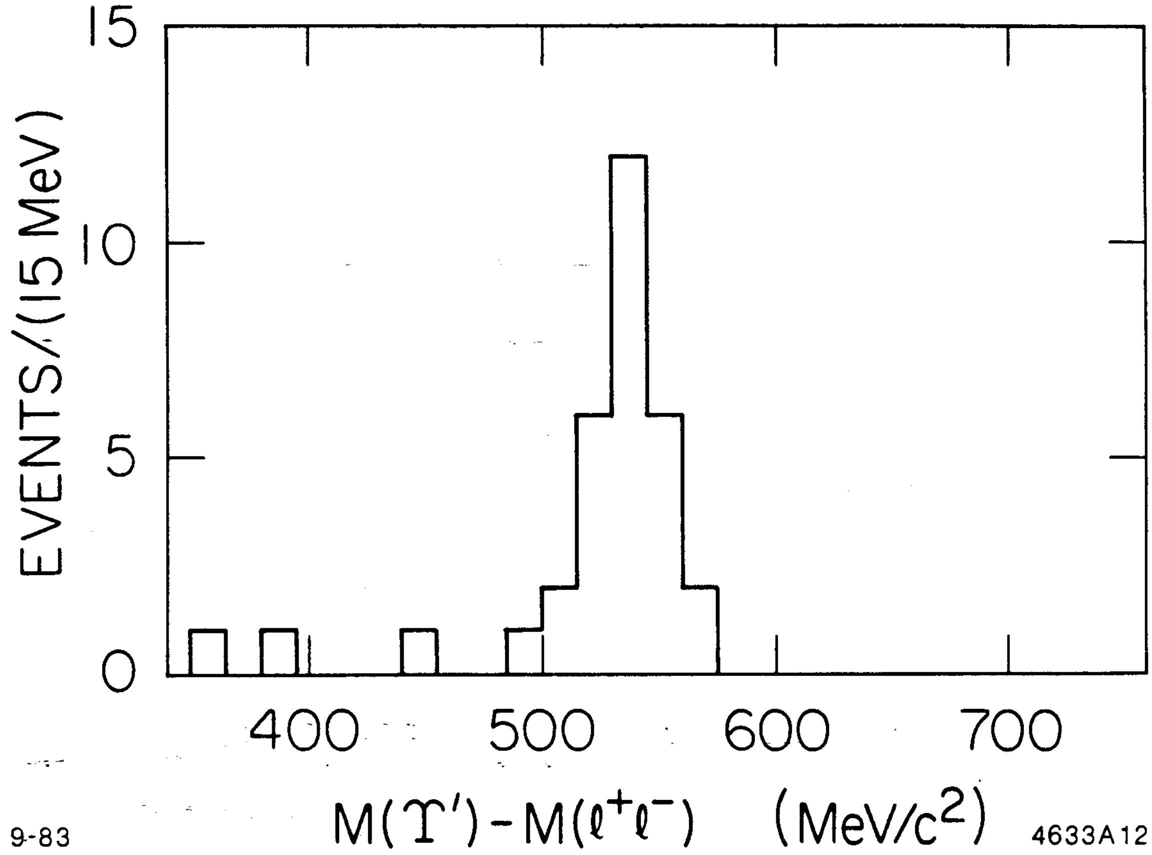

Fig. 4. For the process $\Upsilon' \to \pi^o\pi^o\ell^+\ell^- \to \gamma\gamma\gamma\gamma\ell^+\ell^-$ we plot the observed $\Delta M = M(\Upsilon') - M(\ell^+\ell^-)$ mass difference where $M(\ell^+\ell^-)$ is calculated as the mass recoiling against the 4γ system. We find that $\Delta M = (545 \pm 15)$ MeV, about 3% below the expected value of 562 MeV.[10]

1. The particle must be detected within, $|\cos\Theta_z| < 0.75$, where Θ_z is the angle between the photon and the positron beam direction. This solid angle cut ensures that the particle passes through all three proportional chambers.

2. The particle must be called neutral using information from the proportional chambers. About 7% of the charged particles were misidentified as photons, while about 15% of the photons were tagged as charged.

3. The remaining photons were searched for pairs in which both particles had lateral energy deposition patterns in the NaI consistent with a single electromagnetic shower and which reconstructed to a $\pi^0 \to \gamma\gamma$ decay. The pair could not be closer than $\cos\theta_{ij} = 0.85$. These photons were removed.

4. Finally, all remaining photons were required to have lateral energy depositon patterns consistent with a single electromagnetic shower, but the criteria imposed here were more stringent than in 3.

The resulting inclusive photon spectrum for Υ' is shown in Fig. 5(a). Several clear structures are seen in the Υ' spectrum in the regions 100-150 MeV and 430 MeV. The Υ spectrum is shown in Fig. 5(b). Fits to various regions of the Υ spectrum yielded no signal with a significance of more than 2 standard deviations. We used this as a check on the validity of the structures observed in the Υ' spectrum.

In order to calculate branching ratios the photon detection efficiency was measured between 50 MeV and 500 MeV. We employed a similar technique to that used in the ψ' inclusive photon analysis.[8] The efficiency is plotted in Fig. 6 and is seen to vary from about 20% at 100 MeV to about 38% at 500 MeV. These values are lower than we measured on charmonium due to the higher multiplicity in the upsilon final states.

To investigate the structure in the Υ' spectrum, the region between 80 and 200 MeV in Fig. 5(a) was fit with two Gaussians and a quadratic background. The resolution was fixed at $\sigma(E)/E = 2.4\%/E^{1/4}$ (the value prefered by the fit) while the means and amplitudes were allowed to vary. Two clear lines are

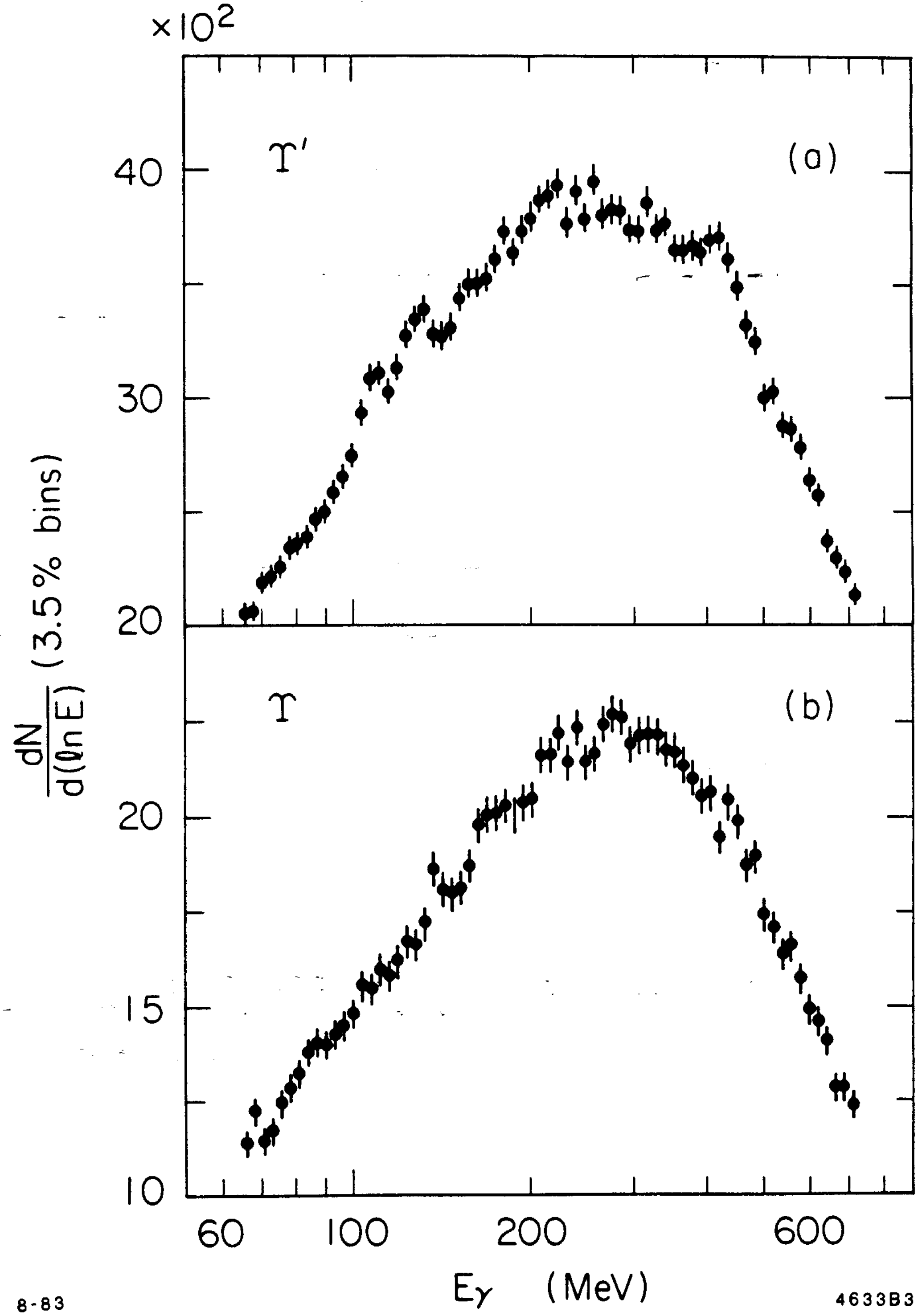

Fig. 5. Inclusive photon spectra from hadronic decays of the a) Υ' and the b) Υ resonances. The photon selection criteria are described in the text.

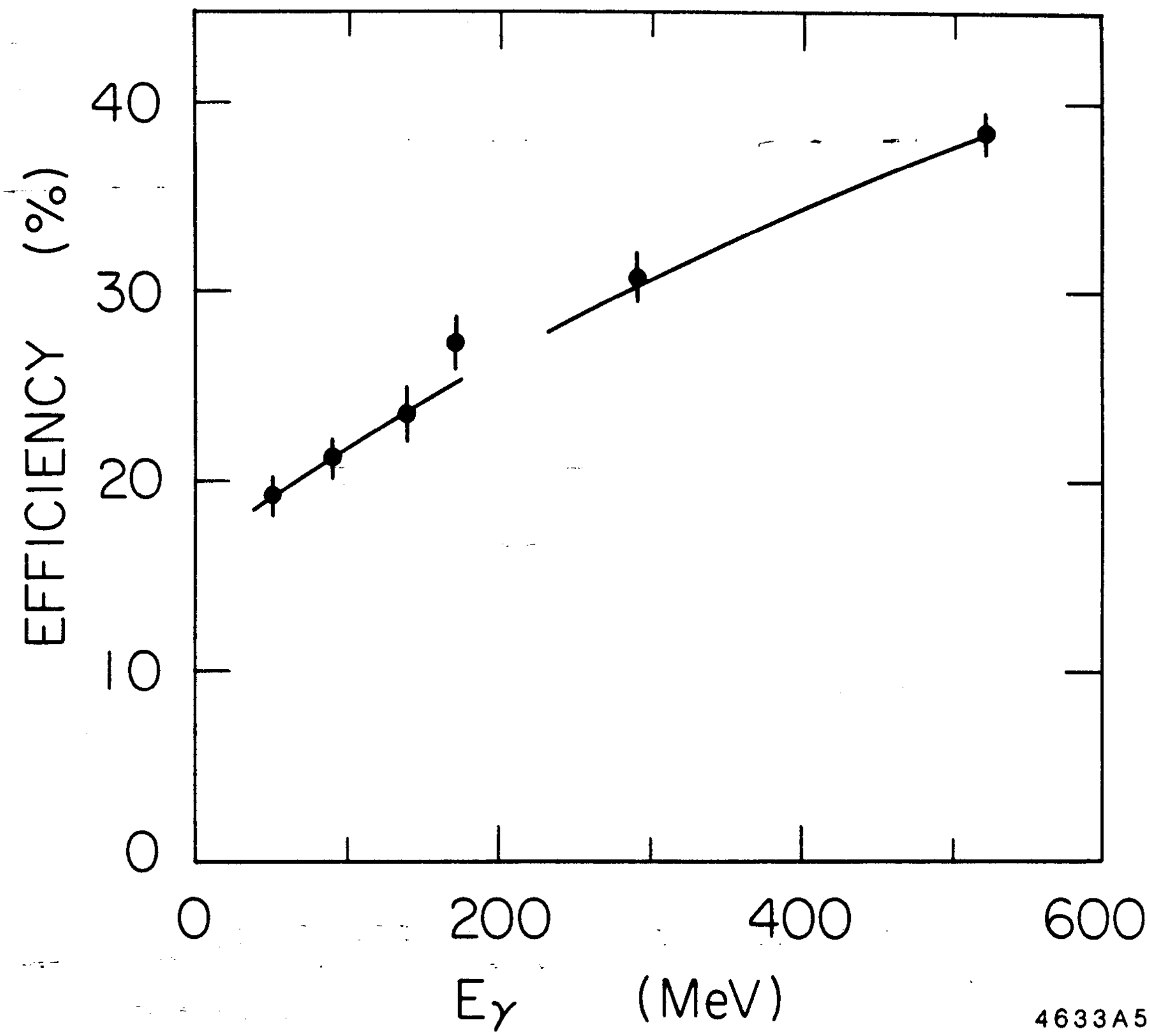

Fig. 6. Photon detection efficiency as a function of energy for the photon selection criteria used to make the spectra shown in Fig. 5. The region near 200 MeV is complicated by the contamination from minimum ionizing charged particles and so no efficiency is shown.

observed: one at about 108 MeV with a significance of 4.9σ and one at about 128 MeV with a significance of 5.0σ. The χ^2 of the fit per degrees of freedom is 7.4/19.

The results, shown in Table I, are seen to be in good agreement with the two low energy photon signals reported by the CUSB experiment,[5] both in energies and in branching ratios. In addition CUSB fitted a third line to their data at $E(\gamma) = (149.4 \pm 0.7 \pm 5.0)$ MeV. To test for the existence of this line in our data a third Gaussian folded with a Breit-Wigner line shape was included in the fit under two assumptions:

1. the natural line width of the state is negligible compared to the detector's energy resolution; and
2. the third line corresponds to a transition to a broad state with a natural line width of 10 MeV.

Table I. Results from Υ' Inclusive Photon Study.

DATUM	LINE 1	LINE 2
$E\gamma$ (MeV)		
Crystal Ball	$108.3 \pm 0.9 \pm 3.0$	$127.5 \pm 1.2 \pm 4.0$
CUSB	$108.2 \pm 0.3 \pm 2.0$	$128.1 \pm 0.4 \pm 3.0$
BR (%)		
Crystal Ball	$6.3 \pm 1.3 \pm 1.4$	$6.0 \pm 1.3 \pm 1.4$
CUSB	6.1 ± 1.4	5.9 ± 1.4

Taking into account the possible systematic uncertainty in the photon energy scale between the various experiments,[5,11] the position of the Gaussian was stepped through the region from 142 to 170 MeV. This was done to map out an upper limit for a transition in this area. Figure 7 shows an example of the fit for a third line at 155 MeV and a 10 MeV wide state. The results are given in Figure 8 along with measured branching ratios[5,11] from other experiments. Although we do not see a significant signal in the region 142-170 MeV, our upper limits are not in contradiction with these measurements.

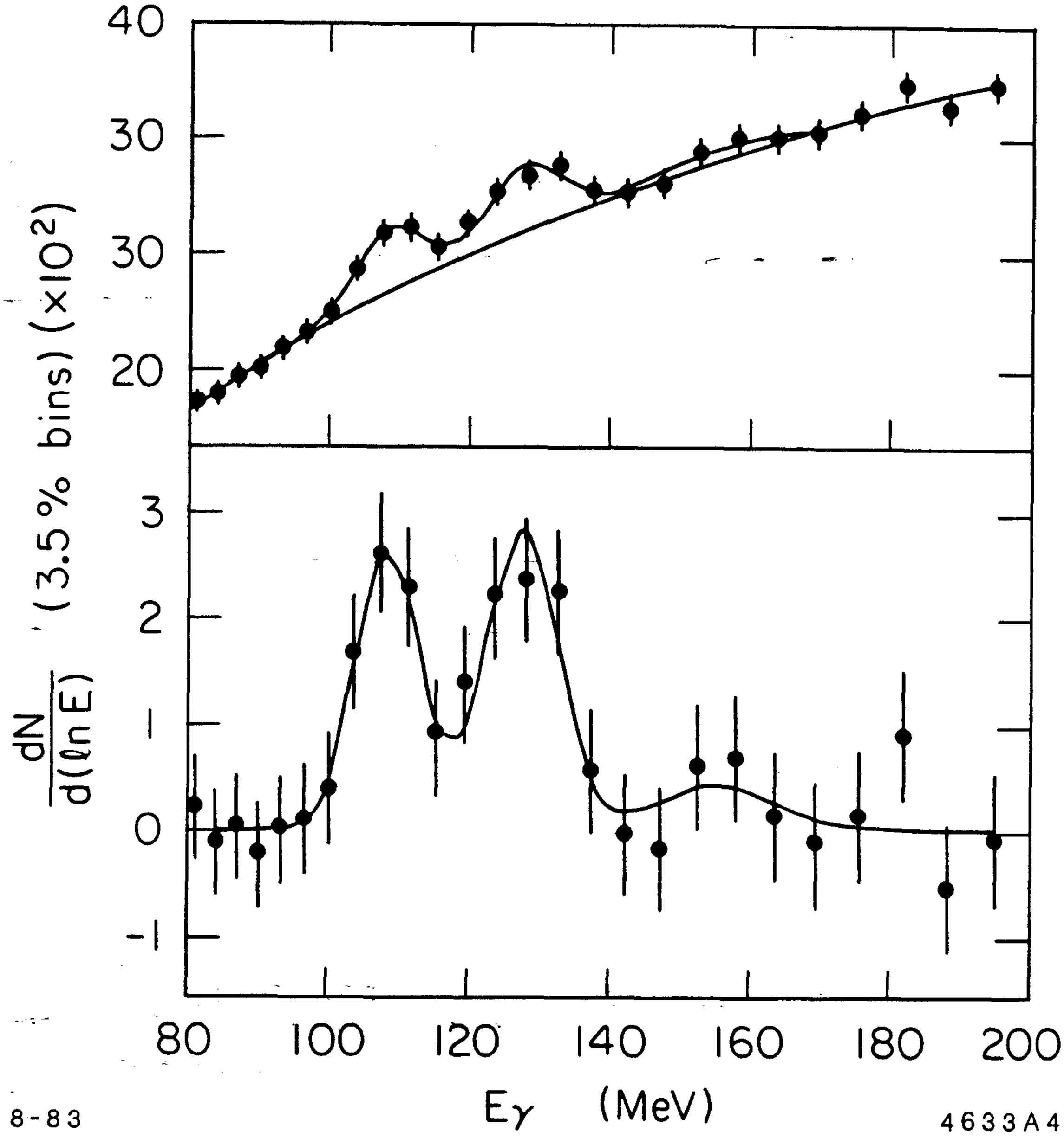

Fig. 7. An example of a fit to the Υ' spectrum in Fig. 5(a) used to map the upper limit between 142 and 170 MeV. The third line here is fixed at 155 MeV for a transition to a broad state with a natural line width of 10 MeV.

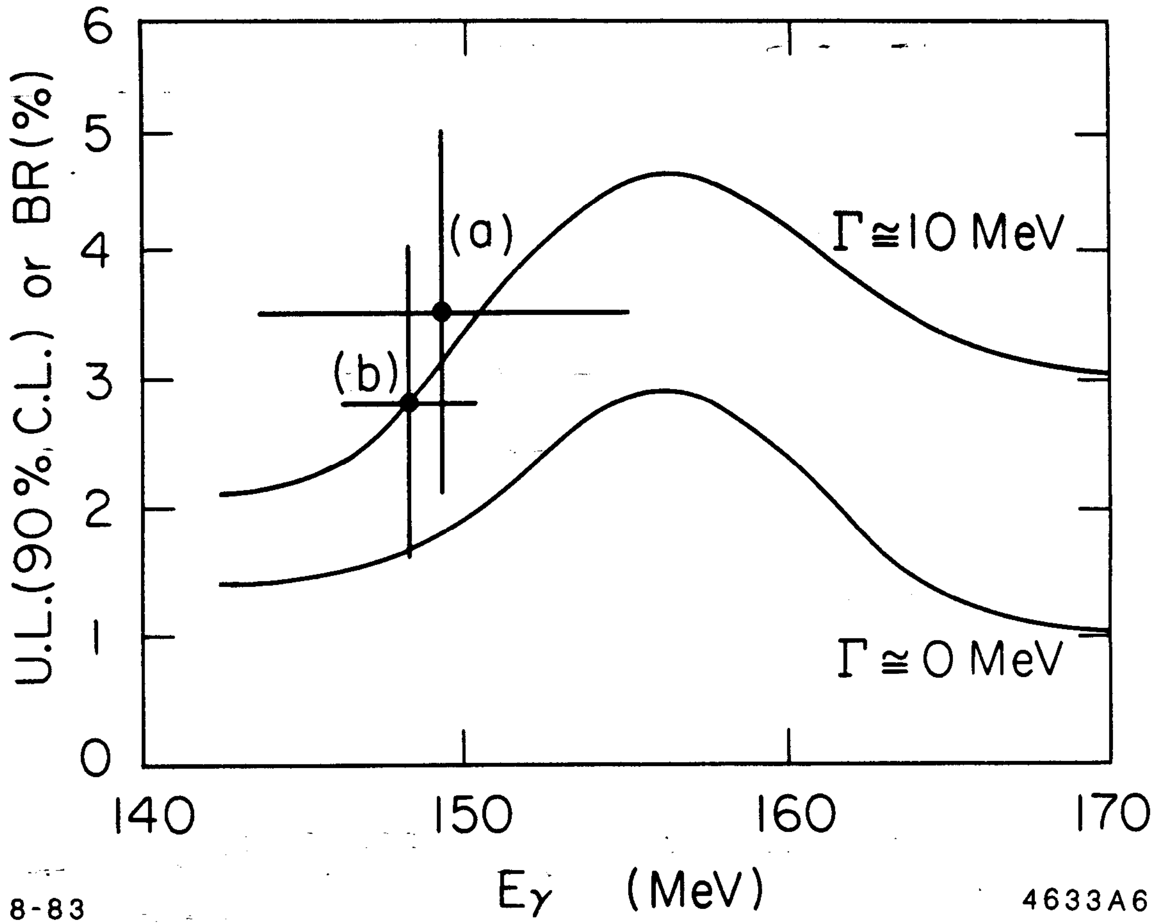

Fig. 8. The curves indicate our 90% confidence level upper limit for a radiative transition to a state with photon energy between 142 and 170 MeV, under the two indicated assumptions for the state's natural line width. The curves were obtained from fits to the Υ' inclusive photon spectrum in Fig. 5(a). A typical fit is shown in Fig. 7. The photons were assumed to have a $1 + \cos^2 \theta$ angular distribution in the U.L. calculation. The data points indicate measurements made by a) the CUSB experiment[5] and b) the ARGUS experiment.[11]

We now turn to an investigation of the other structure in the Υ' spectrum located near 430 MeV. A fit with a single Gaussian and a quadratic background yields a significance of 3.9 standard deviations. However the fitted width is wider than expected from our energy resolution. It is interesting to see if the 430 MeV structure is connected with the signals at 108 and 128 MeV under the cascade hypothesis $\Upsilon' \rightarrow \gamma X \rightarrow \gamma\gamma\Upsilon$ (see for example the ^3P_J states in Fig. 1). To test this hypothesis the region from 280 to 650 MeV was fitted with two Doppler-broadened Gaussians and a quadratic background. The means of the Gaussians were calculated from the 108 and 128 MeV lines and the Υ'-Υ mass difference, which was allowed to vary in the fit. The result is shown in Fig. 9. The measured mass difference from the fit is $\Delta M = M(\Upsilon') - M(\Upsilon) = (555.3 \pm 5.9)$ MeV, in excellent agreement with the known mass difference[10] of 562 ± 2 MeV, including our systematic error of $\simeq 3\%$. This is a very good indication for the validity of the cascade hypothesis. However, the relative strengths of the two contributing lines are poorly determined.

The resulting branching ratio for the single structure is

$E(\gamma)$ (MeV)	significance(s.d.)	BR (%)
427	3.9	$(3.6 \pm 0.9 \pm 0.8)$

This may be interpreted as the sum of product branching ratios

$$\mathrm{BR}\,(\Upsilon' \rightarrow \gamma(108) + {}^3P_2) \cdot \mathrm{BR}\,({}^3P_2 \rightarrow \gamma(427) + \Upsilon)$$

$$+\,\mathrm{BR}\,(\Upsilon' \rightarrow \gamma(128) + {}^3P_1) \cdot \mathrm{BR}\,({}^3P_1 \rightarrow \gamma(427) + \Upsilon) \quad ,$$

assuming that the two states correspond to the $^3P_2$ and $^3P_1$ states of the $b\bar{b}$ theory. The CUSB experiment[5] measures a branching ratio of BR $= (4 \pm 1)\%$ at a similar gamma energy. By simply counting the number of transition photons it is clear that the structure at 430 MeV cannot represent the primary photon line in a cascade process where the signals at 108 and 128 are the secondary lines.

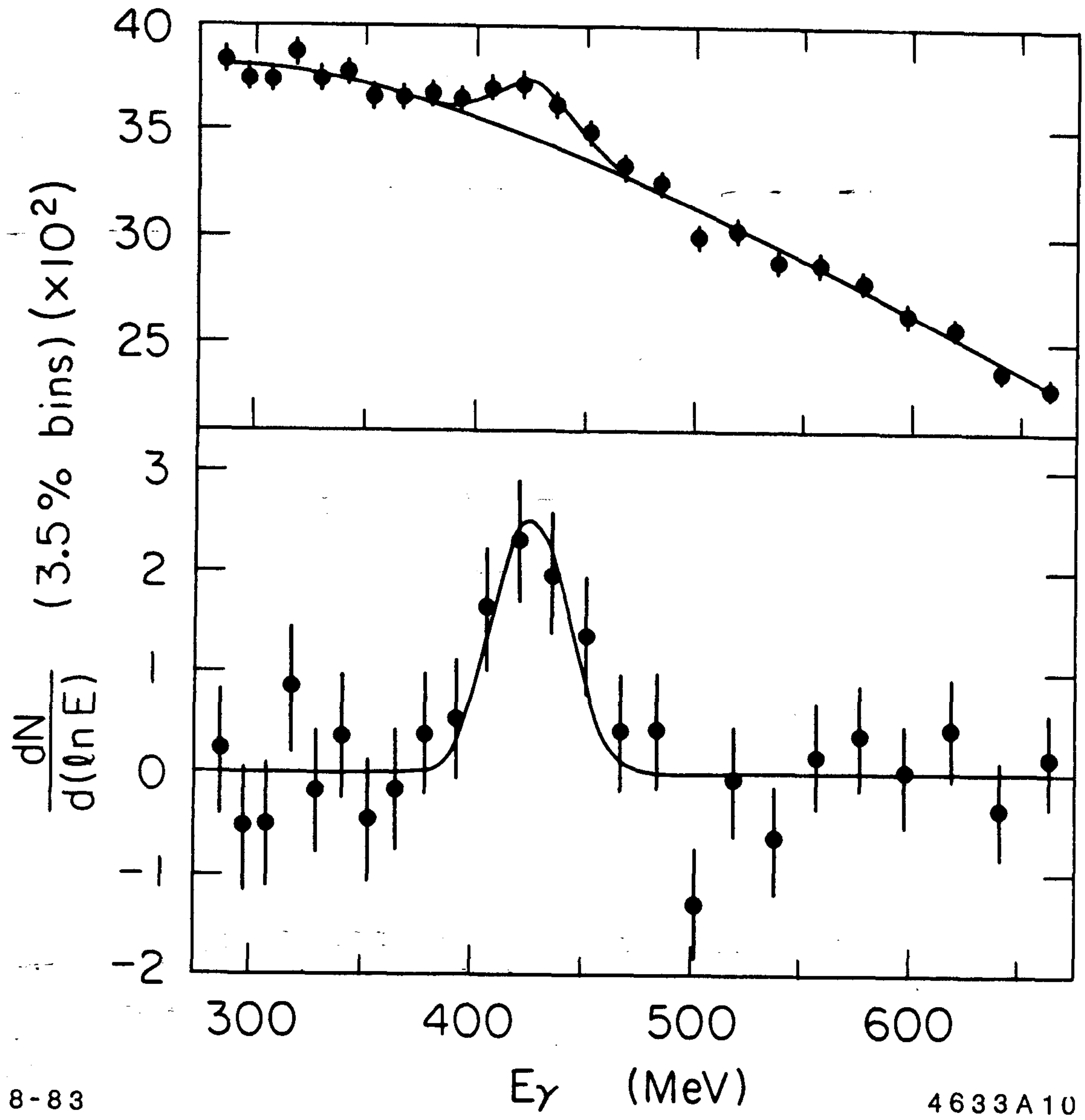

Fig. 9. The fit made to the structure near 430 MeV in the Υ' inclusive photon spectrum shown in Fig. 5(a). Two Doppler-broadened Gaussians with a quadratic background were used. The position of the signals were calculated from a cascade hypothesis assuming that the lines at 108 and 128 MeV are the primary transitions. The signals at 417 and 437 MeV are clearly not separated.

3. Exclusive Cascade Analysis

A second way to look for the ^3P_J states is to study exclusive decays in the channel

$$\Upsilon' \to \gamma\, ^3P_J \\ \quad\quad \hookrightarrow \gamma\Upsilon \\ \quad\quad\quad\quad \hookrightarrow e^+e^-\,,\ \mu^+\mu^- \ .$$

To extract candidates for these decays from the data, we imposed the following selection criteria:

1. Exactly 4 particles in the ball within a restricted angular range of $|\cos\Theta_z| < 0.90$ to ensure that detector edge effects do not degrade energy and angular resolution.
2. Two lepton candidates among the 4 particles with $\cos\theta_{ij} < -0.85$ ("back to back"). In the electron channel both electron candidates had to have an energy of $3500 < E_e < 6200$ MeV. For the muons it was required that their signature was compatible with the lateral energy deposition of a minimum ionizing particle and had an energy between 150-350 MeV.
3. The remaining two particles were considered to be the photon candidates and had to have an energy > 50 MeV and no other track closer than $\cos\theta_{ij} = 0.9$, to obtain a clean energy measurement.

The surviving events were subjected to a kinematic fit for the hypothesis $\Upsilon' \to \gamma\gamma e^+e^-$ or or $\Upsilon' \to \gamma\gamma\mu^+\mu^-$. For the electron channel this is a four constraint fit since the four momenta of all final state particles are measured. In the muon channel only the muon directions but not their energies are measured, which results in a two constraint fit. Events having a confidence level of < 10% were rejected. In Fig. 10 we plot the observed mass difference Υ'-Υ defined by

$$\Delta M = M(\Upsilon') - M_{\rm recoil}$$

where $M_{\rm recoil}$ is the mass recoiling against the $\gamma\gamma$ system. Cutting on a window around 545 ± 45 MeV, which is $\pm 3\sigma$ as determined from our study of the $\Upsilon' \to \pi^o\pi^o\ell^+\ell^-$ channel, yields our final sample of 46 events (20 $\gamma\gamma e^+e^-$ and 26 $\gamma\gamma\mu^+\mu^-$).

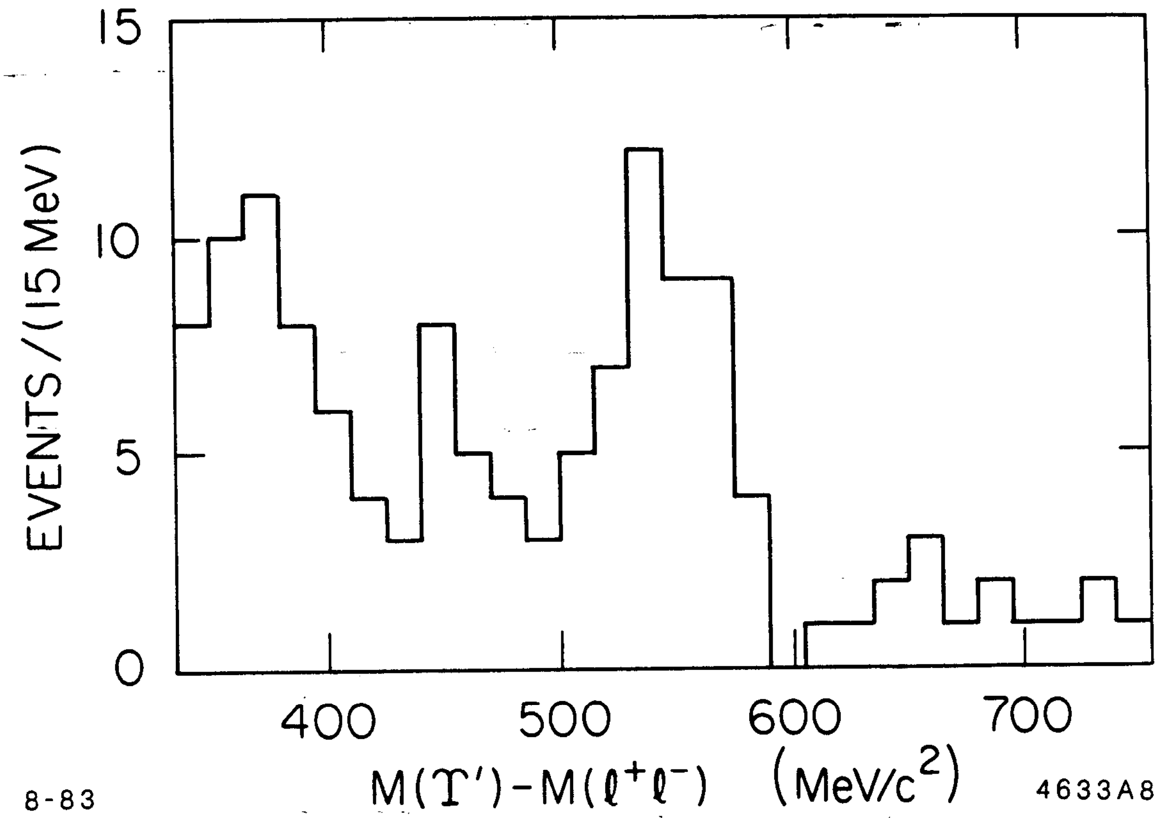

Fig. 10. A plot of the observed $M(\Upsilon')$-$M(\ell^+\ell^-)$ mass difference for events in the exclusive channel $\Upsilon' \to \gamma\gamma\ell^+\ell^-$ where $M(\ell^+\ell^-)$ is calculated as the mass recoiling against the $\gamma\gamma$ system. A cut was made at 545 ± 45 MeV to select the cascade events.

The energy distribution of the low energy photons is shown in Fig. 11. Superimposed is a fit of two Gaussians, with widths given by our detector resolution, over a flat background. The fit separates 2 lines with a confidence level of 70% and the energies are found to be $E_1 = 102 \pm 2 \pm 5$ and $E_2 = 127 \pm 2 \pm 5$ MeV. Within our errors these signals are in agreement with the transitions seen in the inclusive photon spectrum.

4. Conclusions

The Crystal Ball at DORIS has observed two monochromatic lines in the inclusive photon spectrum from decays of the Υ'; one at $E(\gamma) = (108.3 \pm 0.9 \pm 3.0)$ MeV with a branching ratio of BR $= (6.3 \pm 1.3 \pm 1.4)\%$ and one at $E(\gamma) = (127.5 \pm 1.2 \pm 4.0)$ MeV with a branching ratio of BR $= (6.0 \pm 1.3 \pm 1.4)\%$. These results are consistent with the values measured by the CUSB collaboration. We also observed a structure at $E(\gamma) \simeq 427$ MeV which has an energy and width consistent with being the second lines of the cascade process $\Upsilon' \to \gamma^3P_J$, $^3P_J \to \gamma\Upsilon$ for the two signals seen above. The summed product branching ratio for these processes is BR $= (3.6 \pm 0.9 \pm 0.8)\%$. With our present statistics we do not observe a third line between 142 to 170 MeV. We therefore set an upper limit on the branching ratio for a line in this region (see Fig. 8). We determined the mass splitting between the two observed states in the inclusive photon measurement to be

$$\Delta M = (19.2 \pm 2.0)\,\mathrm{MeV}/c^2 \quad ,$$

where we have assumed that the systematic error in our energy scale cancels in the difference. With the statistical limitations of the current data set no measure of the natural line widths of the states are possible. Presently they are consistent with our resolution. For a comparison with theory the reader is referred to the theory talk[4] in this conference.

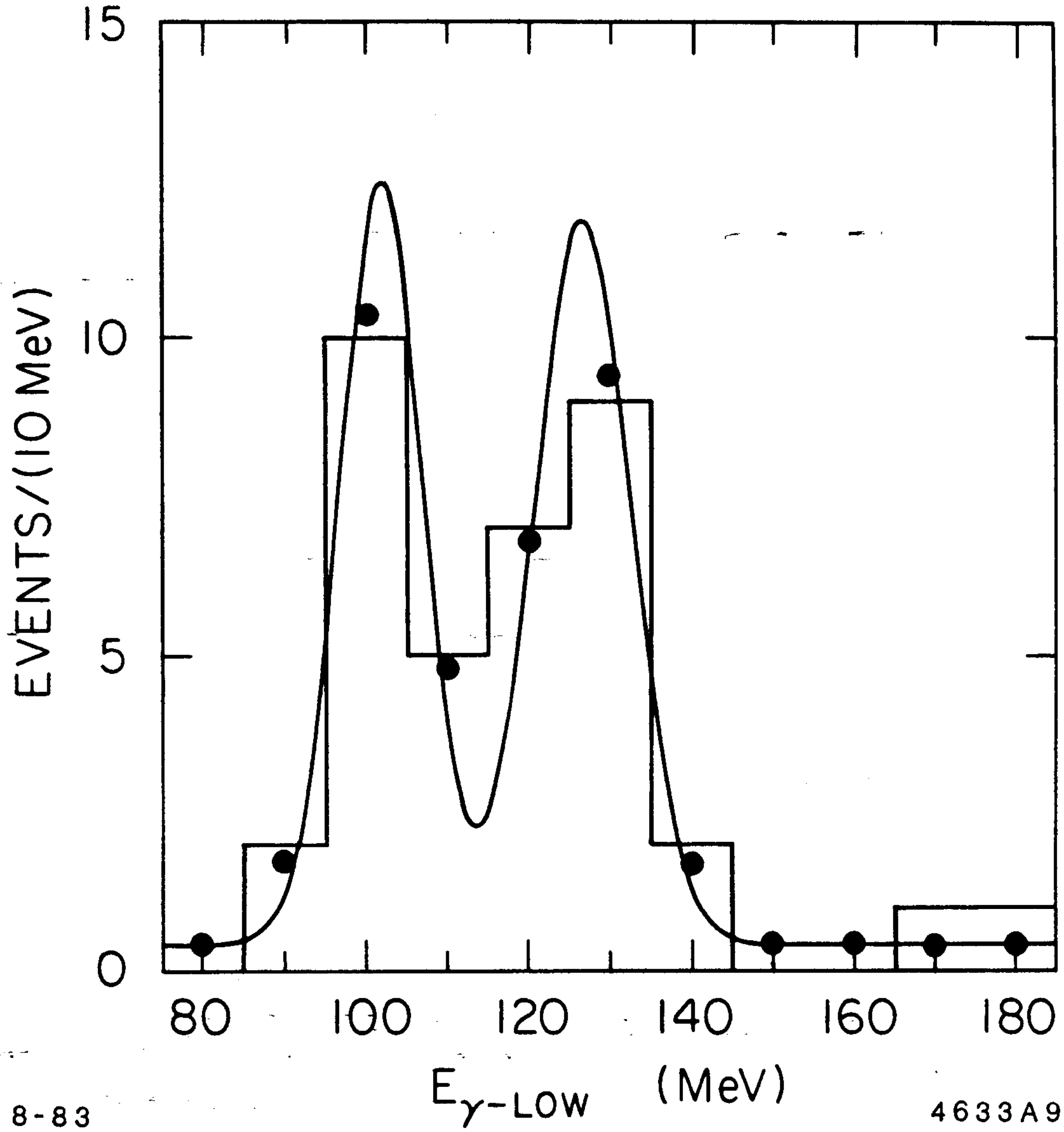

Fig. 11. The histogram shows the low energy photon distribution from the final cascade data sample ($\Upsilon' \rightarrow \gamma\gamma\ell^+\ell^-$). The curve represents a fit to the data while the dots result from integrating the fit over the data bins.

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