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# UPSILON FAMILY DECAYS*

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## ABSTRACT

Selected topics in the investigations of decays of members of the Upsilon family are examined; the confrontation of theory with experiment is not yet adequate. The current evidence regarding the $\varsigma$(8322 MeV) is reviewed and future directions of study are indicated.

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# 1. TRADITIONAL PHYSICS OF Υ-FAMILY DECAYS

The several topics which will be considered here are not meant to comprise an exhaustive survey of Υ-family decays. Instead, the strongest results, experimentally speaking, are presented in order to see if the studies of the Υ family have progressed to the stage where useful comparisons between theory and experiment can be made. What is meant by useful is of course arbitrary, but the precedent involving charmonium can be used as a gauge. It has long been expected that it would be quite difficult to reach the precision attained in the charmonium studies, because of the smaller cross sections and higher final state multiplicities and energies of the bottomonium system. A potpourri of interesting results obtained in Υ physics has perhaps let us forget this initial skepticism; the following comparisons should serve to remind us how far we have yet to progress.

In the studies of the Υ-family, there are currently four major detectors which are contributing data; the two crystal spectrometers CUSB and CRYSTAL BALL (CB) and the two solenoidal general purpose detectors ARGUS and CLEO; the members of those collaborations are listed in (1) and (2). For other details the reader may consult the review of S. Cooper (3).

## 1.1 LEPTONIC WIDTHS

The partial width for decay into electrons, as compiled from several sources (4), is given in Table 1. The absolute value is given for the $\Upsilon(1S)$ and relative values for $\Upsilon(2S)$ and $\Upsilon(3S)$. Also given is the branching ratio for $\Upsilon(1S)$ or $\Upsilon(2S)$ decay into two muons.

Table 1. Leptonic Widths

| | 1S | 2S/1S | 3S/1S |
|---|---|---|---|
| $\Gamma_{ee}$ | 1.25±.10 KeV | 0.56±.05 | 0.40±.04 |
| | 1S | 2S | Group |
| $B_{\mu\mu} = \frac{\Gamma(\Upsilon\to\mu\mu)}{\Gamma(\Upsilon\to all)}$ | 2.7±.3±.3 | 1.86±.18±.33 | CUSB |
| | 2.84±.18±.20 | 1.8±.8±.5 | CLEO |
| | — | 1.6±.6±.5 | ARGUS |

There are no surprises here; the best data from various experiments all have precision of the order of 10%, and they agree well. The theories (not shown) are also good to about 10% and they are in substantial agreement. If the experiments were to be improved, they would find the theories, similarly pushed, somewhat ambiguous as higher order corrections are added. We conclude that improvements in both arenas are required here.

## 1.2 GAMMA SPECTROSCOPY OF P-STATES

This is the classical use of the Upsilons as model systems to test QCD and to determine the details of the color force. Figure 1 shows the structure of the $S$ and $P$ states as a function of the complexity of terms included in the potential. Data samples presently available are not expected to be sensitive to the $^1S_0$ states, but develop sensitivity to the $L \cdot S$ and relativistic terms through the effect of these terms on the $P$-state levels. These terms in the potential are interesting in their own right and because knowledge of them is useful for other calculations, such as we will encounter in questions involving the $\varsigma$ signal to be discussed below.

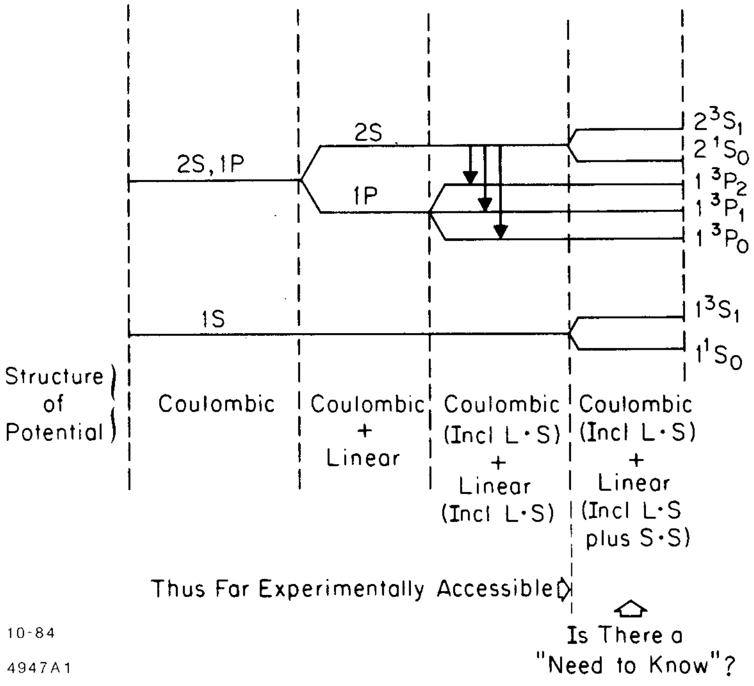

Fig. 1. The relationship of level spacings to terms in the potential.

The best data on these transitions are displayed in Figure 2; all four detectors have results on the inclusive transitions, albeit of varying statistical quality and with varying background levels caused by the intrinsic differences in technique. Qualitatively, the spectra look similar.

The differences emerge in Figure 3, where the mass of the $P$-state is plotted against the branching ration for $2S \rightarrow 1P$; the ellipses represent the extremes of the *systematic* errors quoted for each result–they tend to dominate the statistical errors. The agreement among experiments is not spectacular, but seems adequate.

How do these data agree with theoretical predictions? In the early days of charmonium physics, before various parameters had been ascertained from data and before all the important terms in the potential had been included, a theory predicting points almost anywhere on the same graph would have been appreciated; now we expect far more of a successful theory. Figure 3 also shows (with pointlike symbols or dashed lines) several theoretical predictions for these transitions. At most, one or two of the twelve predictions fall within the error ellipse of *any* experiment! Furthermore, the scatter of the predictions indicates that we are still far from a meaningful confrontation with the theory.

The problem is clearly not entirely theoretical. Careful examination of the experimental data reveals further problems. There is substantial doubt concerning the "third line" (at about 150 MeV, the 2 $^3S_1$ to triplet $^3P_0$ transition). Argus and Cleo data suffer from limited statistics in this region, the Crystal Ball has a charged particle background problem, and CUSB has both statistics and resolution problems there. For the third line, CB and CUSB are consistent at the 16% C.L. (using systematic errors) while CB and ARGUS are consistent at the 4% C. L. However, if systematic errors are assumed to be overall mass shifts and scale factors, they can be removed by using a quantity of interest to theoreticians, namely

$$r = \frac{E_2 - E_1}{E_3 - E_2} \tag{1}$$

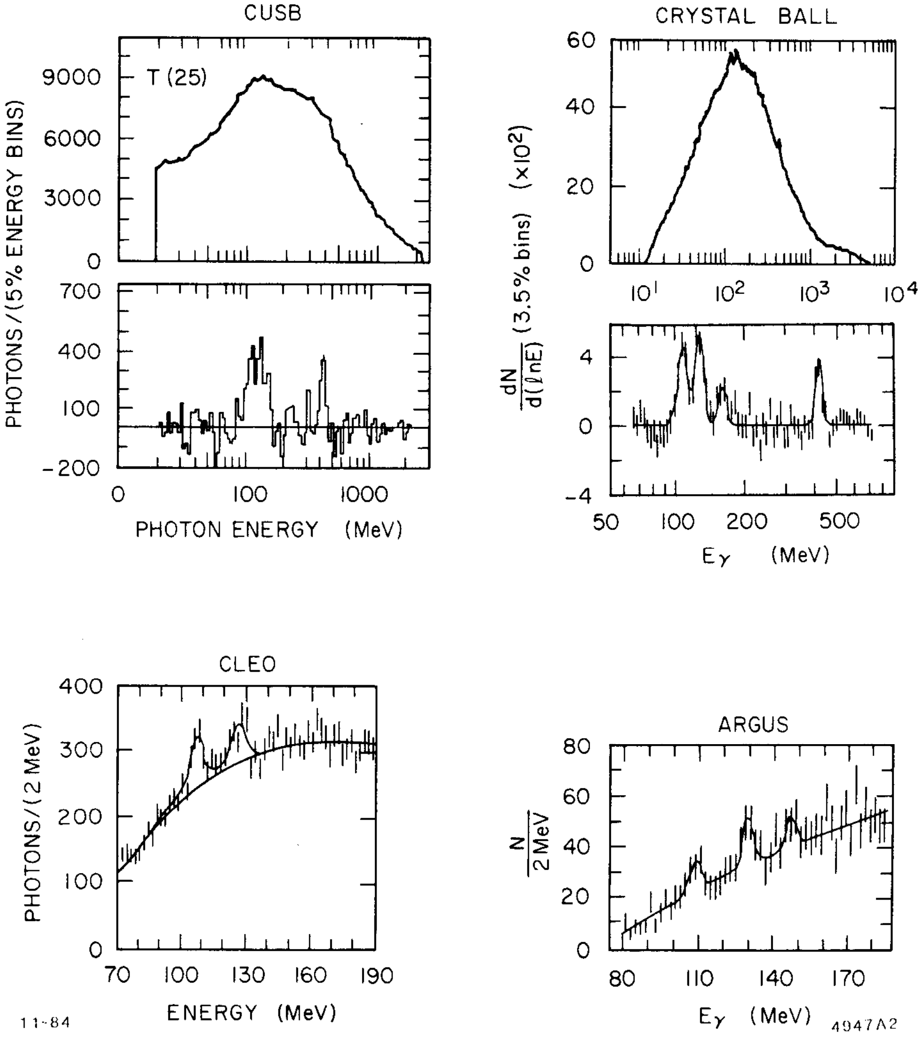

Fig. 2. Inclusive photon energy spectra (Ref. 3).

Various theories differ by $\Delta_r \approx 0.25$, so that a good experiment should attain $\sigma_r \approx 0.05$ in order to discriminate. If statistical errors are used and propagated in the above, assuming cancellation of systematics, we find:

$$\begin{aligned} r(\text{CUSB}) &= 0.952 \pm .051 \\ r(\text{CB}) &= 0.576 \pm .061 \end{aligned} \tag{2}$$

This violent disagreement implies that one experiment or another (or both!) have remnant systematics which dominate any meaningful test. There is hope for eventual checks on theory (because the statistical errors are seen above to be adequate) once these systematics are understood.

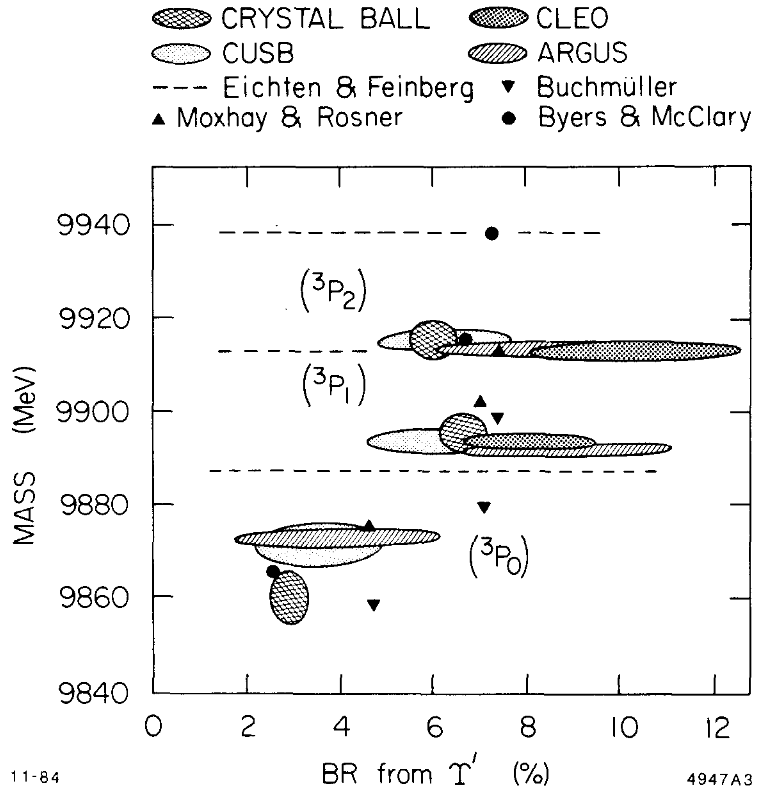

Fig. 3. Experimental and theoretical values for branching ratios of $2S \rightarrow 1P$ transitions and masses of the $1P$ states.

### 1.3 PROMPT PHOTONS FROM Υ

The prediction (5) that there should be prompt photons in quarkonia decays via the process $Q \rightarrow \gamma gg$ was augmented by the observation (6) that such a photon spectrum would be a likely place to observe gluonic mesons. Figure 4a illustrates the current state of the art for the so-called "endpoint spectrum" at the $\Upsilon(1S)$, where the data are taken from CUSB (7). Those authors conclude that the very simple zeroth-order prediction, $dN/dz \approx z$ fits the data quite well when modified to a form $z(1-z)^{0.17}$ to accommodate effects of detector resolution and photon radiative corrections. From these data and fits they then deduce a value for the color structure constant $\alpha_s = 0.226 \pm {}^{.067}_{.042}$. The data in figure 4a do not include the systematic errors incurred when $\pi^0$'s are subtracted.

This gratifying result should be placed in historical perspective by considering how the charmonium spectrum appeared at an equivalent state of art. Figure 4b shows a result (8) obtained by the Mark II detector at the $J/\psi$, wherein the statistical precision is much better than in 4a, although the energy resolution is much worse. (The solid curve shows that the simple prediction, suitably smeared for resolution, does not work well at this lower quarkonia mass). Figure 4c illustrates what signals can really be hiding in statistically meager or poor resolution data: the Crystal Ball endpoint spectrum for $J/\psi$, here *not* $\pi^0$-subtracted, shows familiar radiative decays of the $J/\psi$ plus one or two glueball candidates. The almost inevitable conclusion is that there might be interesting new information when the Υ endpoint spectrum is measured with equal precision. Because of the above-mentioned difficulties with Υ physics, it appears that none of the four detectors should be expected to do the job, and perhaps this task must await a CLEO-II class detector.

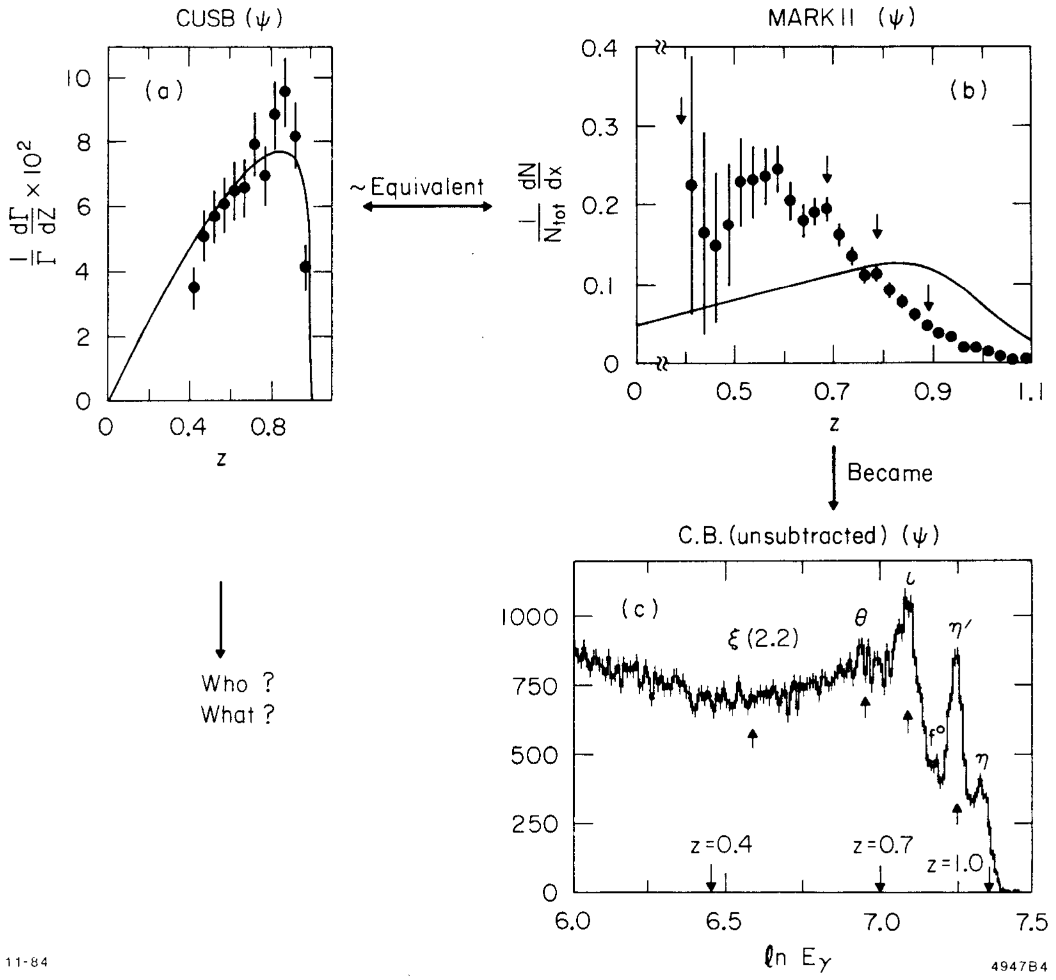

Fig. 4. a) The CUSB inclusive prompt photon spectrum from $\Upsilon$. b) The MARK II inclusive prompt photon energy spectrum from $J/\psi$. c) The Crystal Ball inclusive (unsubtracted) photon energy spectrum from $J/\psi$.

### 1.4 $\Upsilon(2S)$ HADRONIC TRANSITIONS

Here we find some of the very highest quality data yet gathered in the $\Upsilon$ system. The particular transition $\Upsilon' \rightarrow \pi\pi\Upsilon$ is the most-studied of the hadronic decays of this family, and should provide most incisive tests of QCD, by which the rates and distributions of $\pi\pi$ mass are predicted. Figure 5 shows the elements of the process, in which the gluons are radiated at a small distance scale via electric dipole matrix elements, while their fragmentation into pions is presumed to occur at a larger scale. The branching ratios measured by various detectors (9) are shown in Table 2, and agree both among themselves and with the theory.

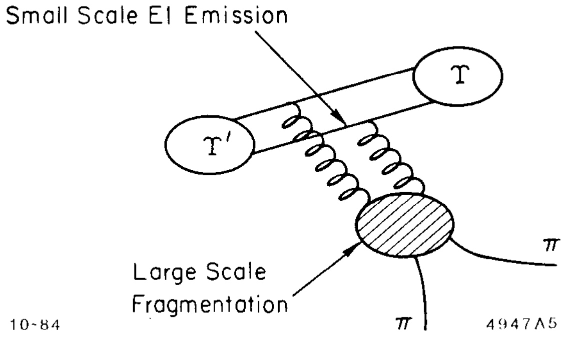

Fig. 5. Elements of the process $\Upsilon' \rightarrow \pi\pi\Upsilon$.

Table 2. Hadronic Branching Ratios for $\Upsilon' \to \pi\pi\Upsilon$

| | $B(\pi^+\pi^-)$ | $B(\pi^0\pi^0)$ |
|---|---|---|
| CUSB | $18.9 \pm 2.6\%$ | $10.3 \pm 2.3\%$ |
| CB | $18.8 \pm 4.7$ | $7.6 \pm 2.0$ |
| CLEO | $19.1 \pm 1.2 \pm .6$ | ___ |
| ARGUS | $17.9 \pm .9 \pm 2.1$ | ___ |

More interesting are the $\pi\pi$ mass distributions, which have been predicted by (among others) Novikov and Shifman and Yan, et al. (10); these distributions, respectively, are shown below.

$$\frac{d\Gamma}{dm_{\pi\pi}} = [m_{\pi\pi}^2 - 4m_\pi^2]^{\frac{1}{2}} \left[m_{\pi\pi}^2 - K(M_{\Upsilon'} - M_{\Upsilon})^2 \left(1 + \frac{2m_\pi^2}{m_{\pi\pi}^2}\right)\right]^2$$

$$\frac{d\Gamma}{dm_{\pi\pi}} = [m_{\pi\pi}^2 - 4m_\pi^2]^{\frac{1}{2}} \left\{[m_{\pi\pi}^2 - \lambda m_\pi^2]^2 + \frac{B}{A}\,[\mathrm{D-wave\ terms}]\right\} \tag{3}$$

$$(K \text{ or } \lambda \text{ is } \propto \alpha_s)$$

Let us examine the best of the data, that on the charged $\pi$ modes from the ARGUS and CLEO detectors (11), for two purposes: a) Changes evident in the $\Upsilon$-system compared to the equivalents for charmonium; b) an absolute comparison with the QCD predictions for the $\Upsilon'$. Figure 6a shows the ARGUS data, fit to the parameter $K$ of the first formulation above; it also shows the equivalent plot from MARK II for the corresponding $\psi$ transition. There is a significant drop in $K$ from $\psi'$ to $\Upsilon'$, showing that $\alpha_s$ runs, and in the proper direction. This is a very clean result, and is mirrored by the CLEO data. We use the latter to address the second concern above. Figure 6b shows that while again significant discrimination can be made on the parameter (in this case $B/A$) of a given theory, the two theoretical models predict curves which are indistinguishable from one another. Thus, even in this limiting case of very good data, the ability to resolve theoretical differences is not great.

### 1.5 A LIMITING CASE OF NON-CONFRONTATION

Finally, we note a minor result which points up (in an extreme fashion) the underlying problem in Upsilon studies. It had long been hoped (12) that an interesting limit on the hypothetical gravitino mass could be gleaned from a study of $\Upsilon' \to \pi\pi\Upsilon$, with $\Upsilon$ subsequently vanishing into two gravitinos. The CLEO group has increased the lower limit by a factor of two over that of the old MARK II result (13):

$$\begin{aligned} m &> 1.5 \cdot 10^{-8}\, eV \qquad \text{[MARK II]} \\ m &> 3.0 \cdot 10^{-8}\, eV \qquad \text{[CLEO]} \end{aligned} \tag{4}$$

This is interesting only in the context of a very limited class of theories, and if all classes are considered the theoretical uncertainty is estimated to be a factor $\approx 10^{19}$.

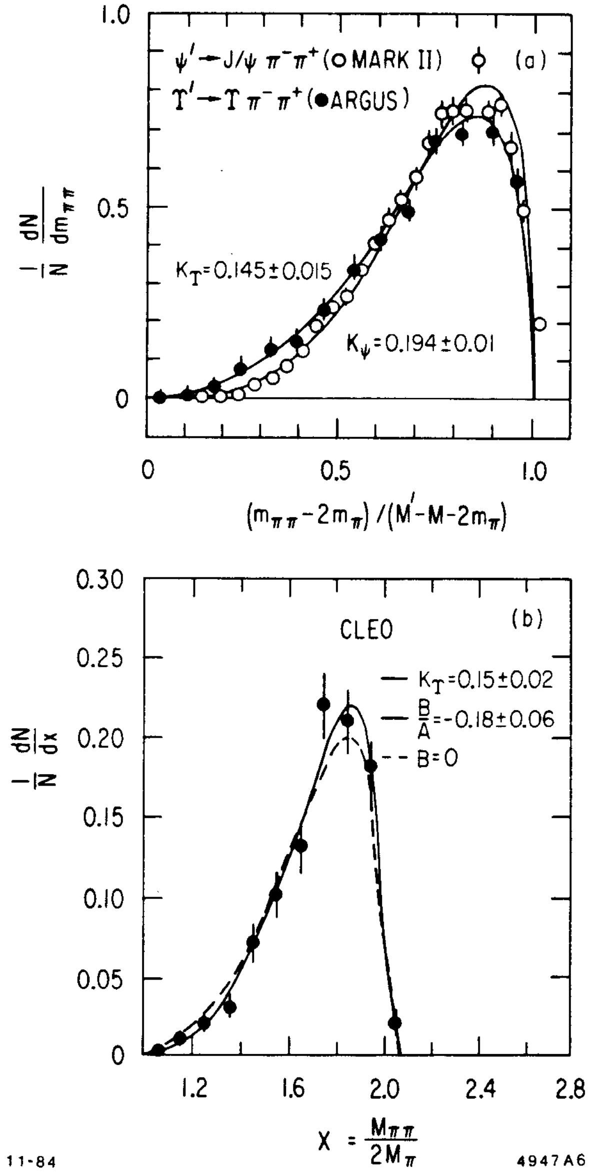

**Fig. 6. a) The Argus data for the process $\Upsilon' \to \pi\pi\Upsilon$ and the MARK II data for the process $\psi' \to \pi\pi J/\psi$. The curves show fits to each using the Shifman et al., formulation. b) The CLEO data for the same process with curve parameterized by the Yan, et al., formulation.**

## 1.6 CONCLUSIONS FOR PART 1

The traditional Υ-family decays which provide QCD tests are still in comfortable agreement with theory because of substantial uncertainties in both. There are some remnant internal problems among experiments. All of these uncertainties were anticipated, given that the limitations of the detectors were well-known and the size of the data samples is small. There should be very interesting physics tests ahead as the capabilities of detectors and the storage rings improve, and as the samples build up. In the meantime, we should distinguish among those experiments we perform for the joy of seeing *any* result (i.e., most of those quoted above) and ones in which meaningful confrontations with theory can be accomplished.

# 2. THE CURRENT EVIDENCE CONCERNING $\varsigma$(8332 MEV)

The Crystal Ball group has presented preliminary evidence for a massive narrow state at 8332 MeV, observed in the monochromatic photon transition from the $\Upsilon$ (14). It should be realized that in terms of present-day data acquisition rates at DORIS, this result is based on only about two weeks of data-taking ($10.7\ pb^{-1}$) corresponding to about $100\,K\ \Upsilon$ events, and clearly warrants a confirmation run before being considered as established. These data were accumulated over diverse short periods, mainly for purposes of counterchecking the $\Upsilon'$ data and preparing analysis for an eventual long run at $\Upsilon$.

## 2.1 NATURE OF THE SIGNAL

While the evidence is limited to a bump in the inclusive photon spectrum from $\Upsilon$-decays, it appears in two samples of data which have radically different kinematic configurations. Figure 7 shows the best signals obtained from a) a "high multiplicity" or "$c - \bar{c}$ biased" sample and from b) a "low multiplicity" or "$\tau - \bar{\tau}$ biased" sample. These two samples have no events in common, but were derived from the data in significantly different ways, and in a somewhat serial fashion. It is possible, even probable, that if these two signals correspond to physically different channels of $\varsigma$-decay, that there is significant cross-contamination between the channels. We will address this again below in more detail.

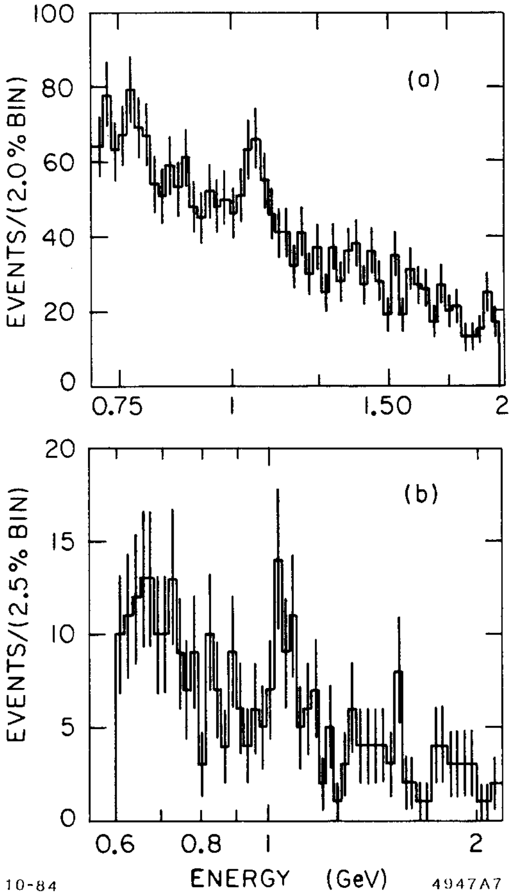

Fig. 7. a) The "high multiplicity" channel $\varsigma$-signal after all cuts. b) The "low multiplicity" channel $\varsigma$-signal after all cuts.

### 2.2 GENERAL TECHNIQUES

The explanation of the techniques used to extract these signals from raw Crystal Ball data is fairly involved; we choose a pictorial method to clarify the basic process. Figure 8 shows the projected view of the triangular prisms of $NaI(T\ell)$ of the Crystal Ball, where the $4\pi$ solid angle is projected onto a plane. [The five upward points all coincide at the North pole, as do the five downward points at the South. Crystals are removed in two regions ("tunnels") for admission of the beams]. For physical processes of little interest, such as cosmic rays, beam gas events, Bhabha scattering, etc., the energy deposition patterns are rather unique and can be readily selected and eliminated without serious loss of the interesting hadronic interactions; Figure 8 also shows a few such patterns (here unrealistically all appearing in the same event). It should be remembered that tube chambers between the interaction point and the crystals allow each clump of energy to be labeled as neutral or charged on the assumption that it came from the $e^+e^-$ annihilation.

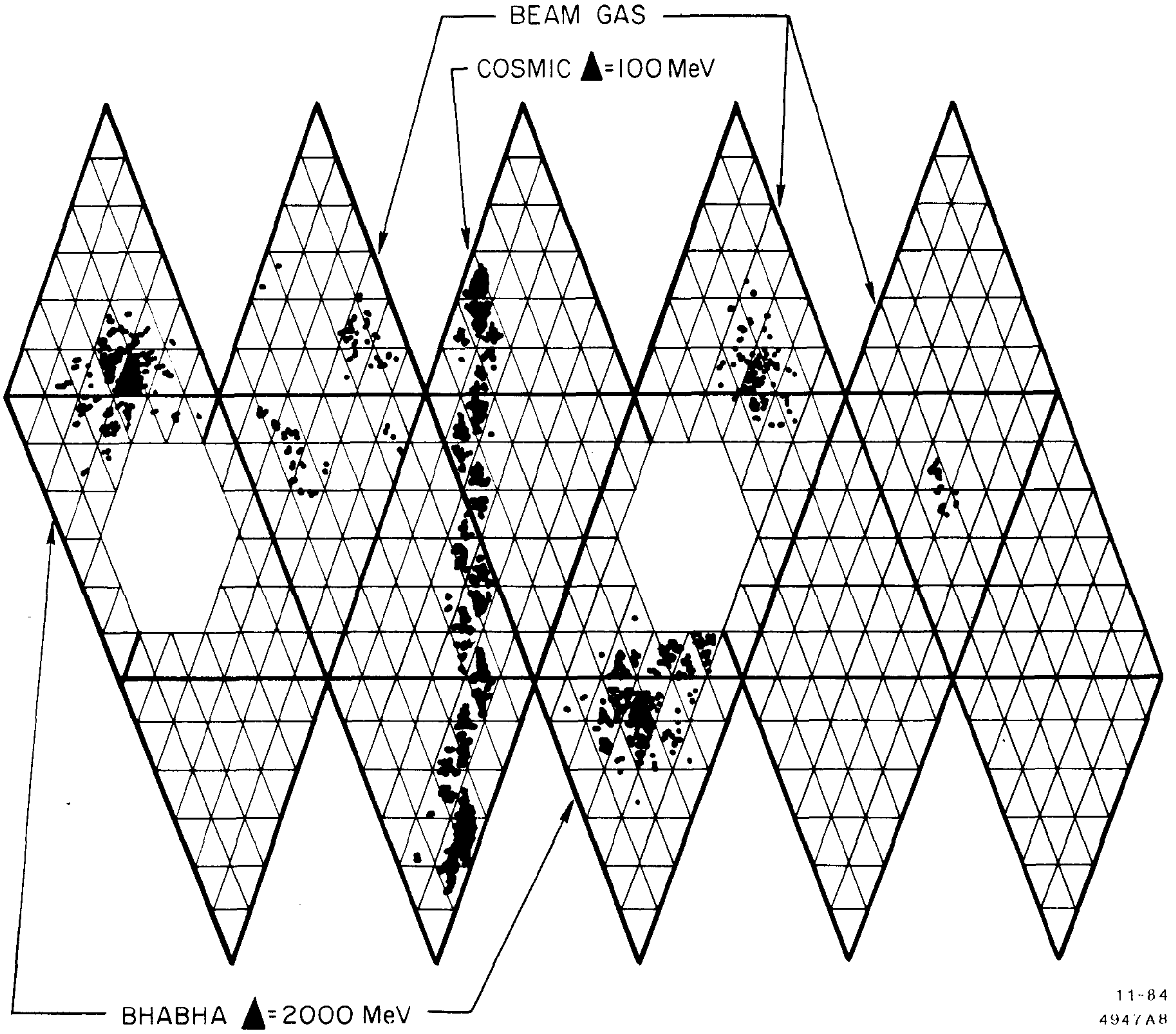

Fig. 8. The crystals of the Crystal Ball detector, in flat-projected view; energy depositions shown for a) cosmic rays, b) Bhabha scattering and c) beam-gas scattering.

If the Crystal Ball were made of an ideal material with zero radiation length and zero interaction length, then a hadronic event might appear as in Figure 9, where each crystal registers the energy of the particle which struck it, albeit with different calibration factors. The variety and number of particles appearing in Figure 9 is typical of $\Upsilon$-decays; note that $\pi^0$'s fall in several classes depending on their momentum and the consequent differing probability that they will have decay photons widely separated in space or close to the same crystal. [The dashed line between the photon pairs is to guide the eye, the Ball unfortunately has no counterpart!].

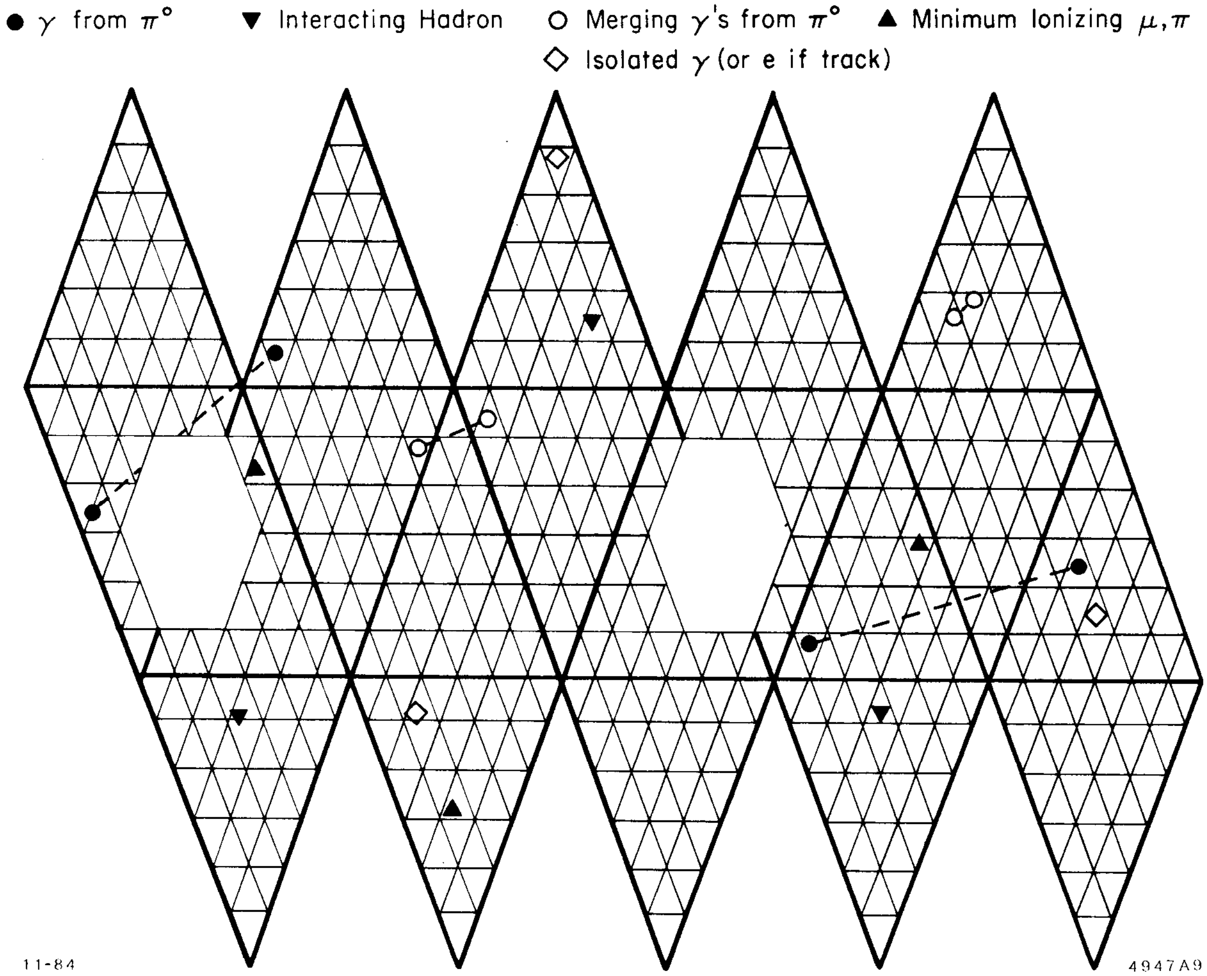

Fig. 9. Particle trajectories (in the flat-projected view) for a hypothetical hadronic event. Particle identifications are noted.

Now consider the aspect of the energy deposition pattern when the real radiation length $\approx 2.5cm$. and interaction length $\approx 40cm$ are used in Figure 10. The problem for the analyst interested in prompt photons is to use this pattern and the chamber information to eliminate all but the isolated prompt photon signals. Figure 11 shows the five basic tools available for this purpose, and their effect on this particular hypothetical event. The first two cuts follow from the observation that since the deposition patterns are broad and fluctuate, it is wise to accept only particles that are spacially well-separated from others. Thus we use a stay-away or overlap cut relative to charged tracks as well as to neutral ones. (In C. B. nomenclature, charged and neutral tracks are blobs of energy either identifiable or not, respectively, with tube chamber hits). The overlap cut for neutrals has an implication for $\pi^0$'s, of course, because for a given momentum $\pi^0$ the two decay photons will tend to cluster around the minimum opening angle, which may be antiselected by the cut. Thus, such overlap cuts are a way of getting rid of moderately fast $\pi^0$, but may eliminate one photon of a pair from a slower $\pi^0$. The order of cuts is clearly important. A third cut is simply to reconstruct pairs of photons and eliminate any forming an approximate $\pi^0$ mass; there are many variations on such algorithms. Such subtractions have considerable inefficiency and also remove single prompt photons by accident in an energy-dependent fashion. As the $\pi^0$ momentum increases (above about 1 GeV/c), this method and that of the overlap cut eventually fail because the blobs of energy merge. Then a fourth cut, based on a shape analysis to the blob, can distinguish whether a $\pi^0$ is present or not to well above 2 GeV/c. Finally, a fifth cut looks at the shower pattern of the single-photon candidate to ascertain if it is consistent with the expected fluctuations of a photon shower of that energy, or if it is more likely an untagged minimum ionizing particle or a split-off piece of energy from a secondary hadronic interaction.

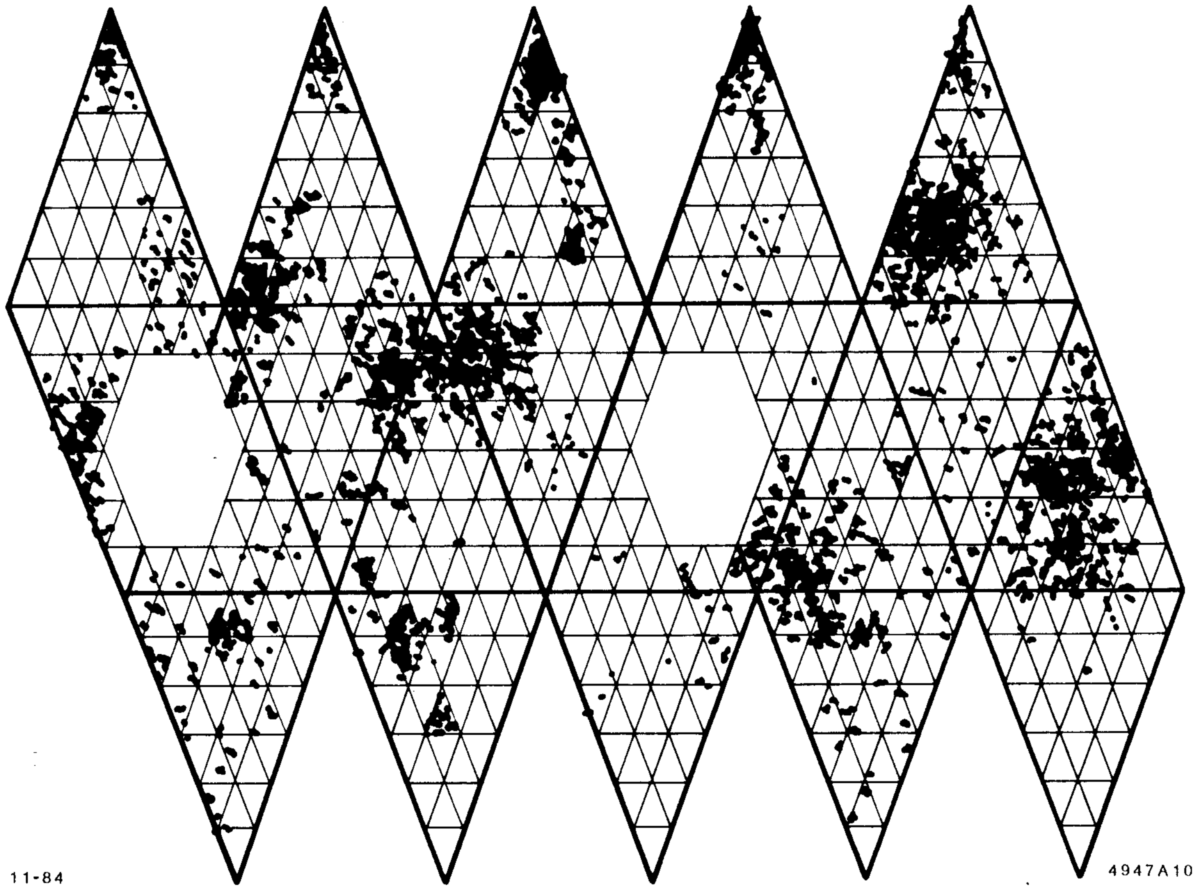

Fig. 10. The energy deposition pattern expected for the particles of Fig. 9.

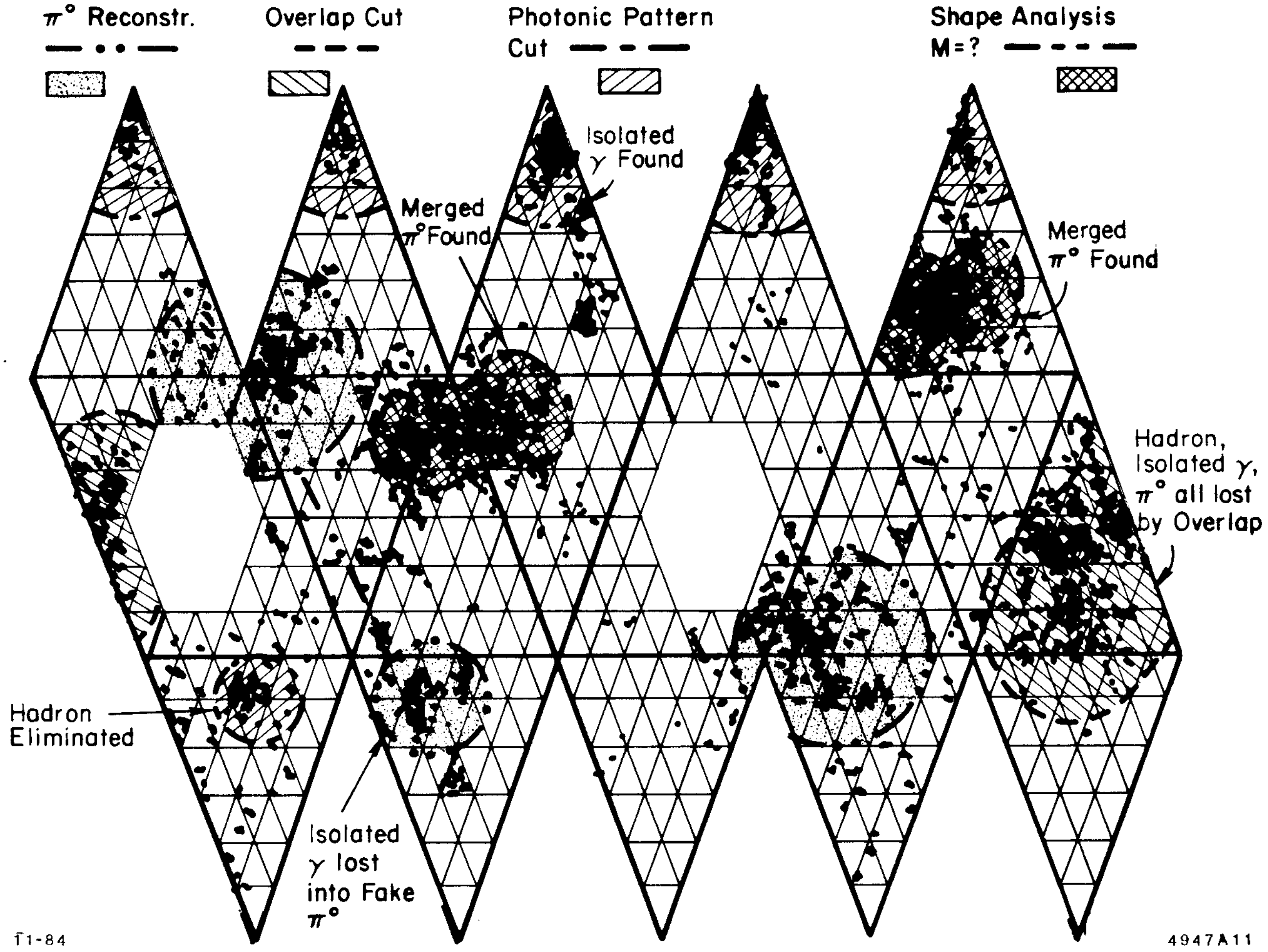

Fig. 11. Effect of the five basic topology cuts on the re-selection of the particles of Fig. 9.

In the example shown, several prompt photons are lost by improper pairing or overlap, and some photons from $\pi^0$ are left in the sample. This is also not untypical, but the Crystal Ball nontheless still provides state-of-art capabilities for photon detection (there is clearly room for improvement). For the $\zeta$ analysis, the most pertinent lesson here is that the available cuts have different efficiencies at different energies, and that the cuts interact with one another; caution is thus dictated.

### 2.3 THE $\zeta$ ANALYSIS

The $\zeta$ signal was first detected in a sample of normally-prepared hadronic events, with such events differentiated from non-interesting triggers with about 90 ± 5% efficiency, as described earlier. Then cuts similar to the five above were applied to prepare a sample of enriched prompt photons. These cuts optimized photon selection between 700 and 2000 MeV, and had decreased efficiency outside this range. Table 3 outlines these cuts (to the horizontal double line). The signal was apparent at this point with almost its full significance. Assuming that this massive state then decayed to $q\bar{q}$, further cuts were then applied, dictated by a Monte Carlo calculation simulating $c\bar{c}$ decay of a state of similar mass. These cuts are also given (below the double line) in Table 3. The resulting photon distribution is displayed in Figure 12, with the fitted parameters in Table 4. Fits with the energy resolution fixed at its expected shape and value (full width half maximum $64 \pm 5$ MeV) showed the intrinsic width of the state to be consistent with zero. The statistical significance of the effect is 4.2 standard deviations from zero in the amplitude. Using the size of the data sample and the calculated efficiency of about 20% (with a relative error of ±50%), the branching ratio for this particular decay chain is found to be of order .5%, with a large error as shown in Table 4. It was also found that none of these numbers nor their errors were sensitive to the choice of quark flavor, meaning also that there is nothing compelling about the identification of this state with $c\bar{c}$ decays.

Table 3. Selection Cuts on the
"High Multiplicity" Sample
[Optimized for $.7 < E_\gamma < 2$ GeV]

| |
|---|
| $\lvert\cos\theta_z\rvert < .766$ |
| neutral |
| transverse pattern |
| remove merged $\pi^0$ |
| overlap cut $\cos\theta_{ij} < .866$ |
| $9 \leq$ total multiplicity $\leq 20$ |
| charged multiplicity $\geq 2$ |
| neutral multiplicity $\leq 12$ |
| connected energy blobs $\geq 8$ |
| $E_{tot} < 8$ GeV |
| sphericity $> .16$ |

Table 4. Fitted Resonance Parameters for the
"High-Multiplicity" Sample.

$E_1 = (1072 \pm 8 \pm 21)\text{MeV}$

$M = (8319 \pm 10 \pm 24)\text{MeV}$

Counts $= 87.1 \pm 20.5$

$\chi^2 = 24.8$ for 32 degrees of freedom

(observed) $\Gamma = 79 \pm 28\text{MeV}$

$\text{B}\,[\Upsilon(1S) \rightarrow \gamma\varsigma] B\,[\varsigma \rightarrow \text{Hadrons}] = (0.47 \pm 0.11 \pm 0.26)\%$,

Given the massive narrow nature of the possible state, it was natural to speculate that the object might have a $\tau\bar{\tau}$ decay mode (15). It was also realized that the above analysis would have little sensitivity to such a mode, and indeed the Monte Carlo calculation predicted about a 2% efficiency for it. A new set of cuts was then applied to the original data set, with the goal to pass low multiplicity final states with good efficiency while discriminating against ubiquitous low multiplicity backgrounds such as radiative QED processes. At the end of these Monte Carlo tuned cuts (horizontal double line in Table 5), no significant signal was present in the data. Analogously to the high multiplicity sample, cuts based on the physics were then applied, in this case corresponding to $\tau\bar{\tau}$ decays explicity. A net efficiency of 24% was attained, and the distribution of Figure 13 emerged. The somewhat weaker signal (3 standard deviations) has fitted parameters (Table 6) similar to those in the different kinematic channel. The overall branching ratio to both channels is model dependent, but with this Monte Carlo would increase by about 20% over the high multiplicity channel alone.

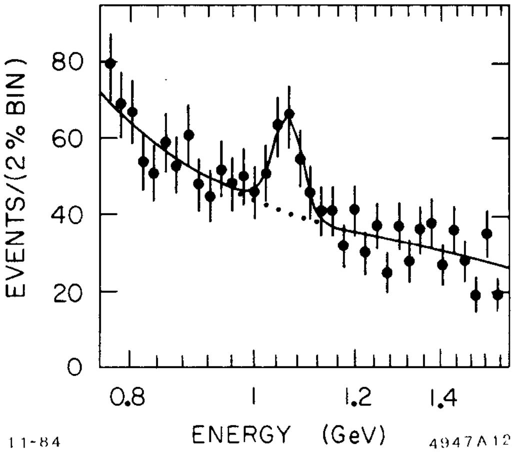

Fig. 12. The $\varsigma$-peak region of the $\Upsilon(1S) \rightarrow \gamma +$ high-multiplicity hadrons, with the fit shown as a solid line. (see text).

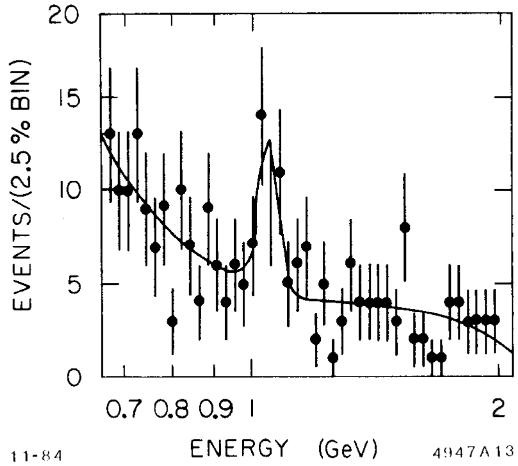

Fig. 13. The $\varsigma$-peak region of the $\Upsilon(1S) \rightarrow \gamma +$ low-multiplicity hadrons, with the fit shown as a solid line. (see text).

Table 5. Selection Cuts on the "Low – Multipliticity" Sample

$E_{tot} > 1200$ MeV
connected energy $\geq 2$
$E_{max}$ endcap $< 100$ MeV
$N_0$ $E_i > .8 E_B$
transverse pattern
$\geq 2$ charged particles
2-8 particles $w/E > 100$
$E_\gamma > 600$ MeV
$|\cos\theta_z| < .85$
transverse energy cut
neutral
merged $\pi^0$ removal
$\cos\theta_{ij} < .8$

More physics cuts
(*a ℓa* $\tau\bar{\tau}$ Monte Carlo)
total mult $< 9$

Table 6. Fitted Resonance Parameters for the "Low-Multiplicity" Sample.

$E_1 = (1062 \pm 12 \pm 21)$MeV
$M = (8330 \pm 14 \pm 24)$MeV
Counts $= 23.8^{+7.0}_{-7.3}$
$\chi^2 = 29.9$ for 41 degrees of freedom,
(observed) $\Gamma = 85 \pm 38$MeV

### 2.4 TESTS OF AUTHENTICITY OF THE $\varsigma$ SIGNAL

A large number of tests were carried out to see if there was anything suspicious in nature concerning this signal or the data sets from which it derived. Most of these are traditional and self-explanatory; a few require explanation or physics background. Most of the tests were applied to the high multiplicity channel because only there was the statistical precision adequate for the test. Table 7 shows a number of tests which were entirely satisfactory and ends with one which was not. In the original analysis, the overlap and folded-$\pi^0$ cuts seemed to be very important in reducing the background and establishing a peak; without these cuts the statistical significance was at least a full standard deviation less. There is nothing wrong with this *per se*, but such cuts should have smooth residues, to assure that no peaks are being generated by energy-dependent background removal of the type mentioned earlier (inherently present in the patchwork method of $\pi^0$ removal used here). The original cuts caused some concern in this respect, but many variants were found which retained the signal strength while maintaining smooth residues. This problem, if real, should emerge in other data samples, both concurrent and those to be gathered in the future.

Table 7. Configuration Test for Authenticity of the $\varsigma$-signal

| Test | Result |
|---|---|
| Does the signal appear: | |
| Equally in time? . . . . . . . . . . . . . . . . . . . | YES |
| Equally in $\pm x, y, z$ hemispheres? . . . . . . . . . . . . . . . . . . . | YES<br>$CL > 70\%$ |
| In random beam-crossings? . . . . . . . . . . . . . | NO |
| show: | |
| Any special trigger preference over sidebands? . . . . . . . . . . . . . | NO |
| Is the signal produced by any special cut or combination of cuts? . . . . . . . . . . . . . . . . . . | (see text) |

Continuing this line of inquiry, we examine a data set collected at the $\Upsilon'$ to see if further checks can be made. The 64.5 $pb^{-1}$ exposure resulted in about $200\,K$ $\Upsilon'$ events; the data-taking was interspersed with the $\Upsilon$ runs. The inclusive photon spectrum from $\Upsilon'$ decay, Figure 14, actually provides three tests pertinent to this investigation. The first test is to see if the sort of biases outlined above produce artificial peaks (or dips in residues) when applied to a kinematically similiar (though not identical) data sample. Arguing that such effects ~~sh~~ould simply scale with the number of photon candidates on the plot, we would predict a peak as indicated in the dashed curve in Figure 14a. The absence of such a peak is reassuring, but not conclusive because this data set is at a different machine energy; there could also be a small systematic effect which is exacerbated at $\Upsilon$ by a fluctuation. A second use of the $\Upsilon'$ data is to look for the real physics we expect to ensue if $\varsigma$ is real, namely, a slightly broadened photon transition at 1070 MeV caused by the cascade reaction $\Upsilon' \to \Upsilon\pi\pi$, followed by $\Upsilon \rightarrow \gamma\varsigma$. The former branching ratio is known and thus we calculate that $53 \pm 13$ events should appear in a peak at this energy. A fit to Figure 14b shows no evident peak, but allows an upper limit (90% C.L.) of 70 events; this result is consistent but not particularly reassuring. The third use of the $\Upsilon'$ data is to look for a direct transition to the $\varsigma$, which would appear as an narrow line in the photon spectrum at 1550 MeV. This is a softer test because it is both hypothesis-dependent, and then, for a given hypothesis, model-dependent. However, there is no hint of a peak, and the upper limit for the quantity most insensitive to uncertainties in efficiency,

$$\frac{\text{Branching Ratio}(\Upsilon' \rightarrow \gamma\varsigma)}{\text{Branching Ratio}(\Upsilon \rightarrow \gamma\varsigma)} \tag{5}$$

is < 0.22 at the 90% CL. The naïvely expected value for most physics processes is unity.

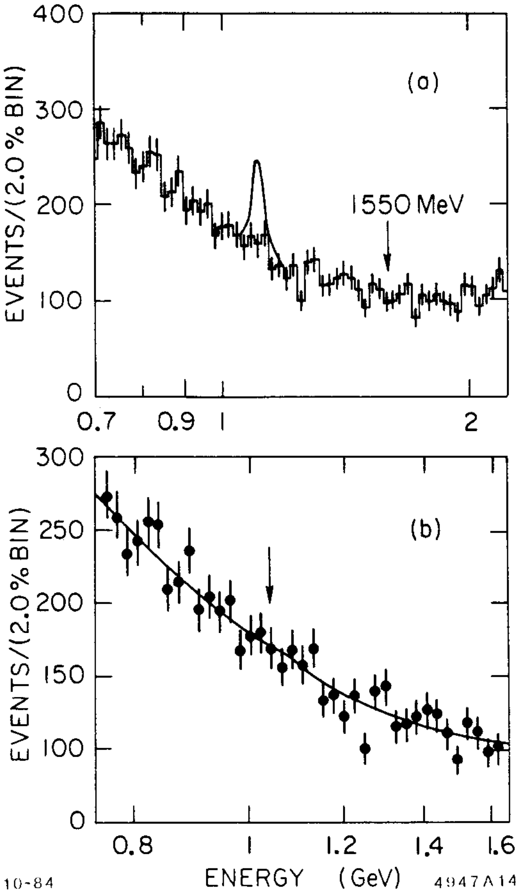

Fig. 14. The inclusive photon spectrum from the $\Upsilon'$ (high-energy portion); a) the expected peak if $\varsigma$ is cause by a common systematic in all data sets; b) a fit to determine the upper limits for $\Upsilon' \rightarrow \Upsilon +$ any, $\Upsilon \rightarrow \varsigma_\gamma$ [the limit for $\Upsilon' \rightarrow \varsigma_\gamma$ is determined similarly].

### 2.5 SOME FURTHER PHYSICS TESTS

These tests are less pertinent to the question of the existence of $\varsigma$ than to its interpretation if real. This section attempts to clarify some subtleties of the foregoing analysis. 1) Are the parameters as deduced from the fits to the two channels self-consistent? The answer is yes, and the resultant best numbers are shown in Table 8. 2) Can the signal be totally derived from $c\bar{c}$ in both high and low-multiplicity channels? We find that about half the events in the low-multiplicity channel could derive from feedthrough from the other channel, but that there is only about a 5% chance that the entire signal is so derived. A detailed analysis of the characteristics of the events in the peaks reduces this to 0.3% but this depends on nuances of the Monte Carlo. 3) Has a $\tau\bar{\tau}$ mode definitely been established? In spite of the hints and the guiding Monte Carlo, the answer is an unequivocal no. 4) Has $c\bar{c}$ mode definitely been established? Again, because of the insensitivity of the signal and cuts to different flavor hypotheses, the answer is an unequivocal no. 5) Is there a contradiction with the missing direct $\Upsilon'$ decay? This is not an answerable question for this paper, but we point to the exuberant response of the theoretical community subsequent to the Leipzig presentation as evidence that if the effect is real, they will rise to the challenge of explaining it!

Table 8. Fitted Resonance Parameters for the Combined Data Sample

$$E_\gamma = (1069 \pm 7 \pm 21)\ \mathrm{MeV}$$
$$M = (8322 \pm 8 \pm 24)\ \mathrm{MeV}$$
$$\Gamma < 80\mathrm{MeV}\ (90\%\ \mathrm{C.L.})$$
$$B[\Upsilon(1S) \to \gamma\varsigma] \sim 0.5\%.$$

Combined significance of amplitude > 5 s.d.

### 2.6 FUTURE DIRECTIONS

The experimental task is to refine the present data and to collect enough new data to eliminate unambiguously the twin threats of fluctuation or systematic error. The Crystal Ball has returned to the $\Upsilon$ and (note added in proof) has collected 21.6 $pb^{-1}$ to conclusively check the result. ARGUS has participated in the same run. At CESR, the machine has also returned to $\Upsilon$ and CLEO has installed radiator around the beam pipe to facilitate the pair-spectrometer technique of looking for photons. CUSB will be seeking to improve the limit they announced at Leipzig, namely, 0.2% for the 90% upper limit to the $\Upsilon$ decay branching ratio, which was marginally in disagreement with the CB result if the full systematic of the latter was invoked. The run is to be done using some of the BGO detector crystals in place.

### 2.7 CONCLUSIONS FOR PART 2

The totally unexpected result of an easily-detected decay product from $\Upsilon$ implies that either 1) there will be an interesting struggle with preconceived ideas trying to accommodate the newcomer, or 2) that nature isn't that easy (or unpredictable) and the new state will go away. Unlike some excruciating physics results of the past, this one should be easy to check, so the suspense should not be long.

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