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Evidence for a Narrow Massive State in the Radiative Decays of the Upsilon*

Crystal Ball Collaboration

ABSTRACT

Evidence is presented for a state, which we call ς, with a mass $M = (8322 \pm 8 \pm 24)$ MeV and a line width $\Gamma < 80$ MeV (90% confidence level) obtained using the Crystal Ball NaI(Tl) detector at DORIS II. Radiative transitions to this state are observed from about 100,000 $\Upsilon(1S)$ decays in two independent sets of data: One in which $\varsigma \rightarrow$ multiple hadrons, and one which is strongly biased towards $\varsigma \rightarrow 2$ low multiplicity jets. The branching ratio to this state from the $\Upsilon(1S)$ is of order 0.5%.

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THE CRYSTAL BALL COLLABORATION:

C. Peck, F. C. Porter, P. Ratoff
California Institute of Technology, Pasadena, USA

D. Aschman
University of Cape Town, South Africa

I. Brock, A. Engler, R. W. Kraemer, D. Marlow,[a] F. Messing,[b] D. Prindle, B. Renger, C. Rippich, H. Vogel
Carnegie-Mellon University, Pittsburgh, USA

Z. Jakubowski, G. Nowak
Cracow Institute of Nuclear Physics, Cracow, Poland

J. K. Bienlein, T. Kloiber, W. Koch, M. Schmitz
M. Schneider, T. Skwarnicki,[c] H.-J. Trost, K. Wachs, P. Zschorsch
Deutsches Elektronen Synchrotron DESY, Hamburg, Germany

G. Folger, B. Lurz, U. Volland, H. Wegener
Universität Erlangen-Nürnberg, Erlangen, Germany

A. Cartacci, G. Conforto, B. Monteleoni, P. G. Pelfer
INFN and University of Firenze, Italy

A. Fridman,[d] F. Heimlich, R. Lekebusch, P. Lezoch, W. Maschmann, R. Nernst, D. Sievers, U. Strohbusch
Universität Hamburg, I. Institut für Experimentalphysik, Hamburg, Germany

D. Antreasyan, J. Irion, K. Strauch, D. Williams
Harvard University, Cambridge, USA

A. König, W. Metzger, J. Schotanus, R. T. Van de Walle, W. Walk
University of Nijmegen and NIKHEF-Nijmegen, The Netherlands

D. Besset, R. Cabenda, M. Cavalli-Sforza, R. Cowan, D. Coyne, C. Newman-Holmes[e]
Princeton University, Princeton, USA

E. D. Bloom, R. Clare, S. Cooper, J. Gaiser,[f] G. Godfrey, S. Leffler, W. Lockman,[g]
S. Lowe, B. Niczyporuk,[c] A. Schwarz, K. Wacker, J. Yeager[h]
Stanford Linear Accelerator Center, Stanford University, Stanford, USA

D. Gelphman, R. Hofstadter, I. Kirkbride, R. Lee, A. M. Litke,[g] B. Pollock, J. Tompkins
Stanford University, Department of Physics and HEPL, Stanford, USA

S. Keh, H. Kilian, K. Königsmann, M. Scheer, P. Schmitt
Universität Würzburg, Germany

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[a] Present Address: *Physics Department, Princeton University, Princeton, New Jersey 08544, USA*

[b] Present Address: *Computer Sciences Corporation, 4600 Powder Mill Rd., Beltsville, MD 20705, USA*

[c] Permanent Address: *Cracow Institute of Nuclear Physics, Cracow, Poland*

[d] Permanent Address: *DPHPE, Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France*

[e] Present Address: *Fermilab, MS-223, P.O. Box 500, Batavia, Illinois, 60510, USA*

[f] Present Address: *Space Applications, Inc., 440 Persian Dr., Sunnyvale, California 94086, USA*

[g] Present Address: *Institute for Particle Physics, University of California, Santa Cruz, USA*

[h] Present Address: *IBM Corp., 5600 Cottle Rd., San Jose, California 95193, USA*

It has been realized for some time that precision measurements of the radiative decay of the various quarkonium states provide a powerful tool with which to search for hypothetical particles, such as gluonic mesons,(1) Higgs bosons,(2) or supersymmetric-particles.(3) We report here such an investigation using $\Upsilon(1S)$ and $\Upsilon(2S)$ data. Compared to similar searches at the J/ψ,(4) our investigation suffers from a sparser data sample. Most theoretical estimates for radiative $\Upsilon(1S)$ decay to these objects suggest rates below the level of sensitivity for detection in the experiment described below, but there is substantial uncertainty in some of these calculations. Thus, a careful search is warranted both because of the increase in final state mass range made available by the $\Upsilon(1S)$ as compared to the J/ψ, and because of the fundamental importance of the questions involved.

The data were obtained using the Crystal Ball NaI(Tl) detector(5,6) installed in the DORIS II storage ring at DESY. The data sets used in the analyses described below were accumulated over a period extending from the middle of 1982 until early 1984. The $\Upsilon(1S)$ sample consists of about 100K produced upsilons corresponding to an integrated luminosity of 10.7 pb^{-1}. These data were gathered during three (relatively short) runs interspersed with the collection of about 200K $\Upsilon(2S)$-events corresponding to an integrated luminosity of 64.5 pb^{-1}. In addition some 4.5 pb^{-1} off-resonance hadronic events were accumulated for background comparisons at $\sqrt{s} = 10$ GeV, *i.e.* just below the $\Upsilon(2S)$. The $\Upsilon(2S)$ sample is of relevance for our discussion because it is used for checks of the $\Upsilon(1S)$ results.

The ability of the Crystal Ball detector to resolve and measure monochromatic γ's in the DORIS II-environment has been demonstrated.(7,8,9,10) The detector has been shown to have the resolution and absolute energy measurement capabilities projected from previous SPEAR performance. In these earlier studies a key role was played by the ability of the detector to reduce background caused by π^0-decay γ's and from other particles faking single γ's. Our ability to identify photons and to eliminate background is energy dependent. The results reported here were obtained using algorithms and subtraction techniques optimized for the region of E_γ from ~700 to ~2000 MeV. Other energy regions are still under investigation.

Below we describe two analyses of our data searching for particles X in the reaction $\Upsilon \rightarrow \gamma X$. The first involves isolation of events in which X decays into many particles (including photons). Additional cuts based on an $X \rightarrow c\bar{c}$ decay model are subsequently applied. The second analysis isolates events in which X typically decays into a few particles (including photons); it uses cuts developed from an $X \rightarrow \tau\bar{\tau}$ decay model. As described below, the two analyses select two independent $\Upsilon(1S)$ decay samples. Both show evidence for the new particle which hereafter we call ς. However, no definite conclusion on any specific decay mode can be drawn using the existing limited data sample. In both analyses the good energy resolution and the fine spatial segmentation of the Crystal Ball detector are of prime importance, not only to define small monochromatic γ signals and their widths, but also to separate out the $\pi^0 \rightarrow \gamma\gamma$ decays in which the two photons are overlapping.

The first analysis uses a sample of events at the $\Upsilon(1S)$ energy which has been selected for multihadron decays. From all the recorded triggers at the $\Upsilon(1S)$ energy, multihadron events are selected$^{(11)}$ by efficiently removing beam gas, cosmic rays, $e^+e^- \rightarrow e^+e^-X$ and QED events (including radiative $\gamma\tau\bar{\tau}$ events). The efficiency for selecting multihadron events is found to be $\epsilon_h = (0.90 \pm 0.05)$. The resulting sample of multihadron events contains contributions from $\Upsilon(1S)$ and continuum decays approximately in the ratio of 2.5 to 1.

The next set of cuts applied to the multihadron events was designed to obtain a good acceptance, a minimal background, and to optimize the energy resolution for photons from about 700 MeV to 2000 MeV. These cuts remove charged particles, photons with showers contaminated by energy depositions from nearby particles, and photons resulting from π^0 decay. The π^0's were identified as either a pair of clearly separated photons or as a single cluster formed by the two merged photon showers. The general character of these cuts has been discussed in detail previously (6,10,12); however, the region of E_γ studied here poses specific additional problems due to the presence of a larger fraction of partially merged π^0-decays; thus, many of these previously used cuts needed considerable refinement.

Fig. 1a shows the resulting inclusive photon spectrum from the $\Upsilon(1S)$. The spectrum of Fig. 1a was fitted in the region of E_γ between 750 MeV and 1604 MeV using a line shape of the Crystal Ball measured at 1.5 GeV(6). This line shape had variable amplitude and mean, a fixed $\sigma_E/E = 0.027/E^{1/4}(\mathrm{GeV})$ (our expected resolution for photons in a multihadron environment), and was superposed on a background polynomial of order 3. The fit yielded a 4.0 standard deviation signal of (89.5 ± 22.5) counts at $E_\gamma = (1074 \pm 9)$ MeV, where only the statistical error is given (an overall scale error of ±2% on the energy is yet to be applied). When allowed to vary in the fit, $\sigma_E/E = 0.028^{+0.013}_{-0.009}/E^{1/4}(\mathrm{GeV})$ which is consistent with our expected resolution. No other potential line in the spectrum of Fig. 1a can be fitted, consistent with our resolution, with a statistical significance of more than 2.2 standard deviations.

Additional cuts designed to enhance multihadronic decays of the ς were then applied to the data to further investigate the signal. These cuts were developed by the use of Monte Carlo(13) calculations which simulated the process $\Upsilon(1S) \to \gamma\varsigma$, $\varsigma \to 2$ hadron jets. While charm quark jets were used as a model, jets due to lighter quarks or gluons lead to very similar results. This led to the following cuts (in the following particles are defined as energy clusters with energy deposition in the NaI(Tl) greater than 50 MeV): total multiplicity between 9 and 20; charged multiplicity ≥ 2; neutral multiplicity ≤ 12; total energy deposited in the NaI(Tl) ≤ 8000 MeV; sphericity of the event ≥ 0.16.

Figure 2a shows the inclusive photon spectrum for the $\Upsilon(1S)$ after the application of the above cuts. A fit to the spectrum of the same type as described above (see Fig. 2b) now yields a significance of 4.2 standard deviations for the signal. The signal-parameters become

$$\begin{aligned} E_\gamma &= (1072 \pm 8 \pm 21)\ \mathrm{MeV} \\ M &= (8319 \pm 10 \pm 24)\ \mathrm{MeV} \\ \mathrm{Counts} &= 87.1 \pm 20.5 \\ \chi^2 &= 24.8 \text{ for 32 degrees of freedom,} \end{aligned} \tag{1}$$

where the first error in E_γ or M is statistical and the second is systematic.(6)

The possibility exists that the signal, while statistically significant, results from some trigger bias, background effect and/or software procedural bias. Several tests were performed to increase confidence that this is not the case.

First, all of the cuts used to arrive at the inclusive photon spectrum of Fig. 1 were removed one at a time; the signal never became less significant than 3.6 standard deviations (as compared to the 4.0 σ effect seen with all cuts included), except for one cut where the significance dropped to 2.8 standard deviations. This cut is an overlap cut between the photon candidate and other particles, and is taken in the inclusive analysis as $\cos\theta_{ij} \leq 0.866$ (where θ_{ij} is the angle between the two particles, 30° at the limit). A geometric cut of this type was frequently used in Crystal Ball inclusive and exclusive analyses in the past, and has been studied in those contexts.(5,6) However, given the complexity of the 1 GeV energy region in the present experiment, additional studies using both data and Monte Carlo simulations have been carried out. These show that the overlap cut is not only effective at removing hadronic debris, but is also most important for removing photons which come from π^0's, and which are missed by the other cuts.

Second, the $\Upsilon(2S)$ data set, analysed similarly to the $\Upsilon(1S)$ sample, offers the possibility for additional checks on the systematics at a nearby C.M. energy with six times the integrated luminosity, two times the number of resonance events, and four times the number of hadronic events. Fig. 3a shows the inclusive γ spectrum from the Υ(2S) using the same sets of cuts employed for the Υ(1S) in Fig. 1a. Fig. 3b,c show the spectrum fitted with the same functional forms as used in Fig. 1. The fit shows a smooth dependence in the region of $E_\gamma \approx 1$ GeV; no line with a statistical significance of more than 0.3 standard deviations (15 events) appears. If the signal at the Υ(1S) were just instrumental, or induced by the analysis procedure we would expect a narrow peak at the same E_γ. This peak would contain about 150 events if induced by 3 gluon decays, and about 275 events if induced by all hadronic decays.

However, a slightly Doppler-broadened signal for the ς arising from the cascade $\Upsilon(2S) \rightarrow \pi\pi\Upsilon(1S)$, or $\gamma\gamma\Upsilon(1S)$ is expected. In the fit of Fig. 3b,c, σ_E/E is fixed at 0.033 to take account of the Doppler broadening, and the upper limit obtained from the fit is 70 counts (90% C.L.) at $E_\gamma = 1072$ MeV. This is to be compared to the expected Υ(2S) cascade signal. After correcting for a 10% decrease in efficiency compared to the Υ(1S), caused by the presense of additional pions or photons, one expects a signal of 53 ± 13 events. Thus there is consistency in this respect between the Υ(1S) and Υ(2S) results, but disagreement with the peak expected from an instrumental or analysis induced effect in the Υ(2S) data.

Third, to check further for possible systematic effects, the data were divided in two roughly equal luminosity samples coming from different running periods; the signal appeared with equal strength in both samples. The data were also spatially divided to detect preferences for specific Crystal Ball hemispheres; no significant preference could be detected. Correlations between γ-energy and the triggers generated by the events containing the candidate γ's were examined but found to be essentially constant moving from below to beyond the region of E_γ = 1 GeV. Off-resonance data, Monte Carlo three-gluon and $q\bar{q}$ events, and random beam cross events were subjected to the same analysis procedure and showed no significant fluctuations near 1 GeV.

Fourth, an old sample of J/ψ data taken at SPEAR was analyzed by the same program to see if any artifacts of the cuts would be produced. No narrow photon line was seen at about 1 GeV.

Including all the cuts leading to result (1), we estimate a photon efficiency varying from $(15 \pm 10)\%$ at 700 MeV to $(28 \pm 10)\%$ at 2000 MeV. Near 1 GeV the efficiency is $(18 \pm 10)\%$; using this value and the number of produced $\Upsilon(1S)$ events one finds a branching ratio for this process:

$$B\left[\Upsilon(1S) \to \gamma\varsigma\right] B\left[\varsigma \to \text{Hadrons}\right] = (0.47 \pm 0.11 \pm 0.26)\%, \tag{2}$$

where the first error is statistical and the second error is systematic.

In addition, one might expect to see at some level the direct process $\Upsilon(2S) \to \gamma + \varsigma$ which for a ς-mass of 8.32 GeV would correspond to a peak of $\bar{E_\gamma} = 1556$ MeV. Fig. 3 does not show a distinct signal at this energy. Studies of the photon selection efficiencies E_γ under different model assumptions and over a wide range of photon energies (from 700 to 2000 MeV) showed that the systematic uncertainty on the absolute value of ϵ_γ (the photon efficiency) is rather large. The ratio $\epsilon(E_\gamma = 1070 \text{ GeV })/\epsilon'(E_\gamma = 1560 \text{ MeV})$ however, depends only weakly on the model assumed. Therefore, the ratio of direct branching ratios $\frac{B[\Upsilon(2S)\to\gamma+\varsigma]}{B[\Upsilon(1S)\to\gamma+\varsigma]}$ is affected by systematic uncertainties on only the 10% level. The results of the fits to the $\Upsilon(1S)$ and $\Upsilon(2S)$ spectrum gives an upper limit $\frac{B[\Upsilon(2S)\to\gamma+\varsigma]}{B[\Upsilon(1S)\to\gamma+\varsigma]} < 0.22$ (90% C.L.).

The second analysis consisted of looking for low multiplicity decays, motivated by a possible Higgs interpretation of the signal described above for which the decay into $\tau^+\tau^{-(2)}$ might be substantial. The data selection used previously tends to anti-select the $\gamma\tau^+\tau^-$ sample, in particular because of the bias towards multihadron states of high multiplicity. To obtain a data set biased in favor of $\gamma\tau^+\tau^-$ decay, a different set of cuts was employed. Disregarding the motivational bias, this data set can be viewed as an orthogonal set of events of low multiplicity.

A new pre-selection was performed on all the recorded $\Upsilon(1S)$-region triggers by requiring a total energy of at least 1200 MeV and at least 2 particles in the detector. As in the first analysis, an initial set of cuts was applied to arrive at an inclusive photon spectrum in the E_γ-region of 700 to 2000 MeV. Although similar to the cuts leading to Fig. 1, the details of these cuts are different. Care was taken not to exclude low multiplicity events, using a Monte Carlo calculation(14) as a guide. QED-background was substantially reduced by exploiting the correlation of the γ with the beam direction (strong in the case of radiative QED and weak for a possible ς related $\gamma\tau^+\tau^-$ final state). In addition cuts were applied to eliminate unwanted $e^+e^- \rightarrow e^+e^-X$ events, beam-gas interactions, and cosmic ray events.

The remaining series of cuts was derived from the Monte Carlo simulation of $\Upsilon(1S) \rightarrow \gamma\varsigma \rightarrow \gamma\tau^+\tau^-$.(14) In essence these cuts were just boundary tunings (both in one and two dimensional distributions) of such variables as thrust, multiplicity, event track-alignment, transverse momentum to the beam, etc. Some of these cuts were not new; they just strengthened earlier ones up to the more restrictive boundaries now allowed by the limitation to a $\gamma\tau^+\tau^-$ type configuration. In particular, a total multiplicity requirement of less than 9 guarantees no overlap with the results of (1). A check that no important bias towards $E_\gamma \sim 1070$ MeV was introduced by the cuts derived from the Monte Carlo was made by evaluating the efficiency of the sum of all these cuts for Monte Carlo $\gamma\tau^+\tau^-$ events with E_γ between 700 and 2000 MeV (9 discrete values of E_γ in this range were taken). The efficiency distribution obtained is approximately constant (at 24%) from 700 to 1500 MeV, and then drops off to ~18% at 2000 MeV; no peaking in the 1000 MeV region is seen.

Fig. 4 shows the final signal obtained. The fit of 4b (similar to that in Fig. 1), with σ_E/E fixed at $2.7\%/E^{1/4}$(GeV), yields a 3.3 standard deviation signal with the following parameters:

$$\begin{aligned} E_\gamma &= (1062 \pm 12 \pm 21)\ \text{MeV} \\ M &= (8330 \pm 14 \pm 24)\ \text{MeV} \\ \text{Counts } &= 23.8^{+7.9}_{-7.2} \\ \chi^2 &= 29.9 \text{ for 41 degrees of freedom,} \end{aligned} \qquad (3)$$

in excellent agreement with the values recorded in (1). Fitting 4a with a variable width yields a $\sigma_E = 0.034^{+0.027}_{-0.012}/E^{1/4}(\text{GeV})$, consistent with the expected resolution.

These results are statistically independent of those shown in (1). The combined significance of both peaks is thus greater than 5 standard deviations. They also provide evidence that these signals do not derive from (either real Υ(1S) or background) events of a particular kinematic configuration. Of course this fact would not exclude a common experimental systematic error, producing a sharp anomaly at $E_\gamma \sim 1070$ MeV independent of the final state kinematics. However, such an error is unlikely because in the first analysis no such effect is seen in the closely-related Υ(2S)-sample.

The two independent signals have been used to make an estimate for an upper limit to the intrinsic width of the ς. The observed peaks are consistent with the known Crystal Ball resolution function at $E_\gamma \sim 1$ GeV, which is an asymmetric Gaussian of FWHM (64 ± 5) MeV$^{(6)}$. Unfolding this resolution from the combined observed FWHM (82 ± 23) MeV yields a 90% C.L. upper limit on the intrinsic ς width of 80 MeV. This result is dominated by statistical precision in the observed width, not by the systematic error in the resolution function; if the resolution error is increased by a factor three, the upper limit increases by only 10 MeV.

To obtain a value for B[$\Upsilon(1S) \rightarrow \gamma\varsigma$] which includes final states contributing to the second signal and not to the first it is necessary to use a model. We thus assume that the ς has two kinds of decay, represented by the $c\bar{c}$ and $\tau\bar{\tau}$ Monte Carlo models. The data is found to be consistent with these models and indicates that inclusion of low multiplicity $\tau\bar{\tau}$ like final states will increase the branching ratio (2) by about 20%. We have tried to model both signals by using the $\gamma c\bar{c}$ Monte Carlo alone, and this results in a poor fit to the data (2–3 standard deviation disagreement). However, this may be due to an inadequate $c\bar{c}$ Monte Carlo. **It must be emphasized that we do not prove that the ς decays into $c\bar{c}$ and $\tau\bar{\tau}$, we only show consistency with the model used as an aid in extracting the signal of (3).**

We have also looked for the possible contributions from $\Upsilon(1S) \rightarrow \gamma\varsigma \rightarrow \gamma\tau^+\tau^-$ followed by the decays $\tau^\pm \rightarrow e^\pm\nu\bar{\nu}$, $\tau^\pm \rightarrow \mu^\pm\nu\bar{\nu}$. An upper limit of 0.2% (90% C.L.) for $B\left[\Upsilon(1S) \rightarrow \gamma\varsigma\right] B\left[\varsigma \rightarrow \tau^+\tau^-\right]$ has been found, compatible with the signal from the second analysis – even if we assume that this signal is entirely caused by a $\tau\bar{\tau}$-decay of the ς. Additionally, an upper limit of 3×10^{-4} (90% C.L.) for the branching ratio $B\left[\Upsilon(1S) \rightarrow \gamma\varsigma\right] B\left[\varsigma \rightarrow e^+e^-\right]$ has been determined.

In conclusion we have observed two statistically independent signals at the same mass; one of 4.2 and the other 3.3 standard deviations. The fact that both peaks appear at the same position with a compatible width supports the hypothesis that we are seeing the same state in two different channels. We can thus combine the significance of both peaks; this yields a greater than 5 standard deviation effect. Both our signals have widths consistent with the detector energy resolution. Taking the weighted average of the radiated photon's fitted peak value and width in the two cases gives the best estimate of the mass and width of this new state, herein named ς,

$$\begin{aligned} E_\gamma &= (1069 \pm 7 \pm 21)\ \text{MeV} \\ M &= (8322 \pm 8 \pm 24)\ \text{MeV} \qquad (5) \\ \Gamma &< 80\ \text{MeV}\ \ (90\%\ \text{C.L.}) \\ B\left[\Upsilon(1S) \rightarrow \gamma\varsigma\right] &\sim 0.5\%. \end{aligned}$$

The interpretation of this new state as the neutral Higgs boson expected in the standard model gives a disagreement of approximately two orders of magnitude between this observed branching ratio and that predicted. This branching ratio can be accomodated in some extensions of the standard model, *e. g.* two-Higgs-doublet models. A less model-dependent quantity is the ratio $\frac{B[\Upsilon(2S)\rightarrow\gamma\varsigma]}{B[\Upsilon(1S)\rightarrow\gamma\varsigma]}$, in which the strength of the Higgs' coupling to b-quarks cancels out; in either model this ratio is predicted to be ~ 1.0,(2) while our upper limit is 0.22, in apparent disagreement. Further, given the limited statistics of the present experiment, it cannot be proven that the mode $\varsigma \rightarrow \tau\bar{\tau}$ exists, although our analysis is consistent with it. It has been suggested within the framework of supersymmetry that quarkonium states may radiatively decay to gluino-gluino bound states. For this mass range one expects branching ratios from the $\Upsilon(1S)$ of order 0.05%. This is an order of magnitude smaller than observed for $\Upsilon(1S) \rightarrow \gamma\varsigma$, although the uncertainties in this case, which arise from the use of the non-relativistic approximation, are even larger than in the Higgs case.

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(14) The events $\Upsilon(1S) \rightarrow \gamma\varsigma(8.3\ \text{GeV}), \varsigma \rightarrow \tau^+\tau^-$ were generated. The ς decayed isotropically into $\tau^+\tau^-$ in its center-of-mass system, and the τ decays were modeled as described in C.A. Blocker *et al.*, Phys. Rev. Lett. 49 1369 (1982).

Figure 1

(*a*) The inclusive spectrum for $\Upsilon(1S) \rightarrow \gamma +$ multiple hadrons before physics-oriented cuts.

(*b*) The ς-peak region of (a), with fit (see text) shown as a solid line.

(*c*) Same as (b) with the fitted background subtracted.

Figure 2

(*a*) The inclusive spectrum for $\Upsilon(1S) \rightarrow \gamma +$ multiple hadrons after all cuts including physics-oriented cuts.

(*b*) The ς-peak region of (a), with fit (see text) shown as a solid line.

(*c*) Same as (b) with the fitted background subtracted.

Figure 3

(*a*) The inclusive spectrum for $\Upsilon(2S) \rightarrow \gamma +$ multiple hadrons after the same cuts as used for Figure 1.

(*b*) The ς-peak region of (a), with fit (see text) shown as a solid line.

(*c*) Same as (b) with the fitted background subtracted.

Figure 4

(*a*) The inclusive spectrum for $\Upsilon(1S) \rightarrow \gamma + (\tau^+\tau^-)$-biased sample including all cuts.

(*b*) The ς-peak region of (a), with fit (see text) shown as a solid line.

(*c*) Same as (b) with the fitted background subtracted.

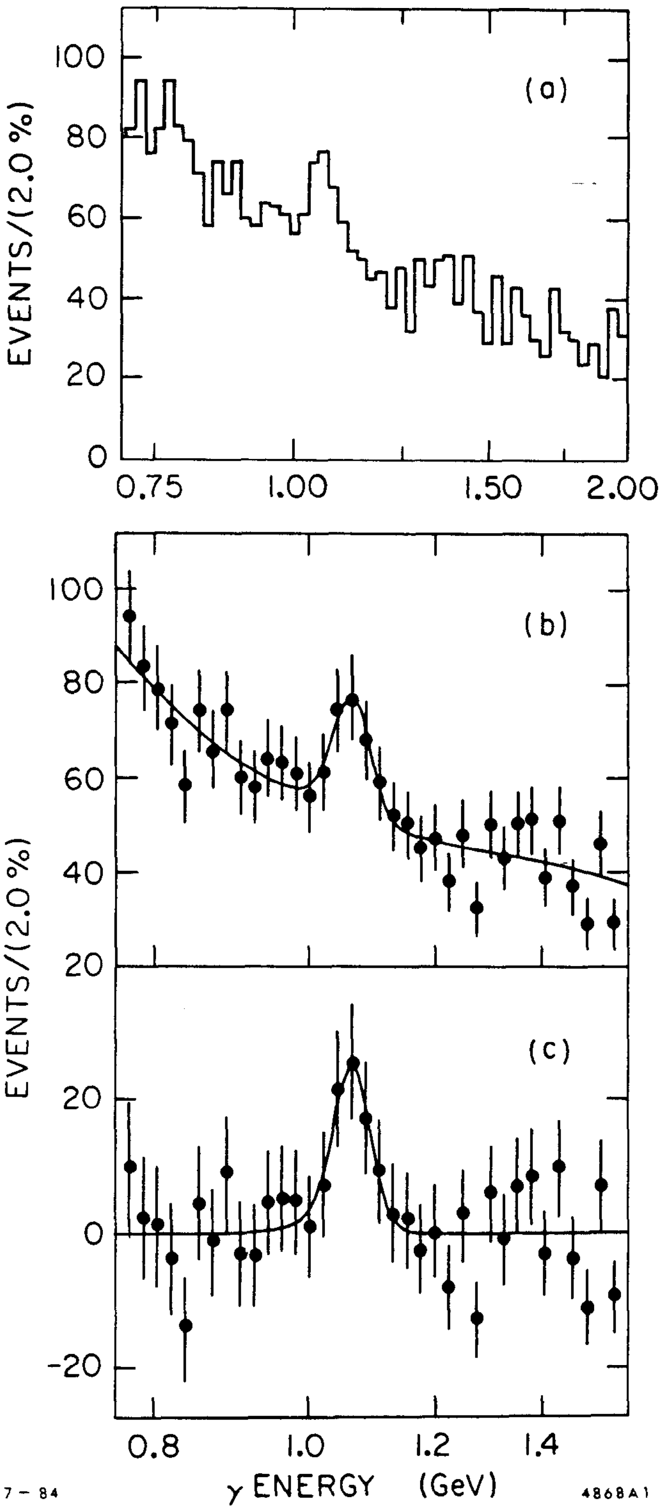
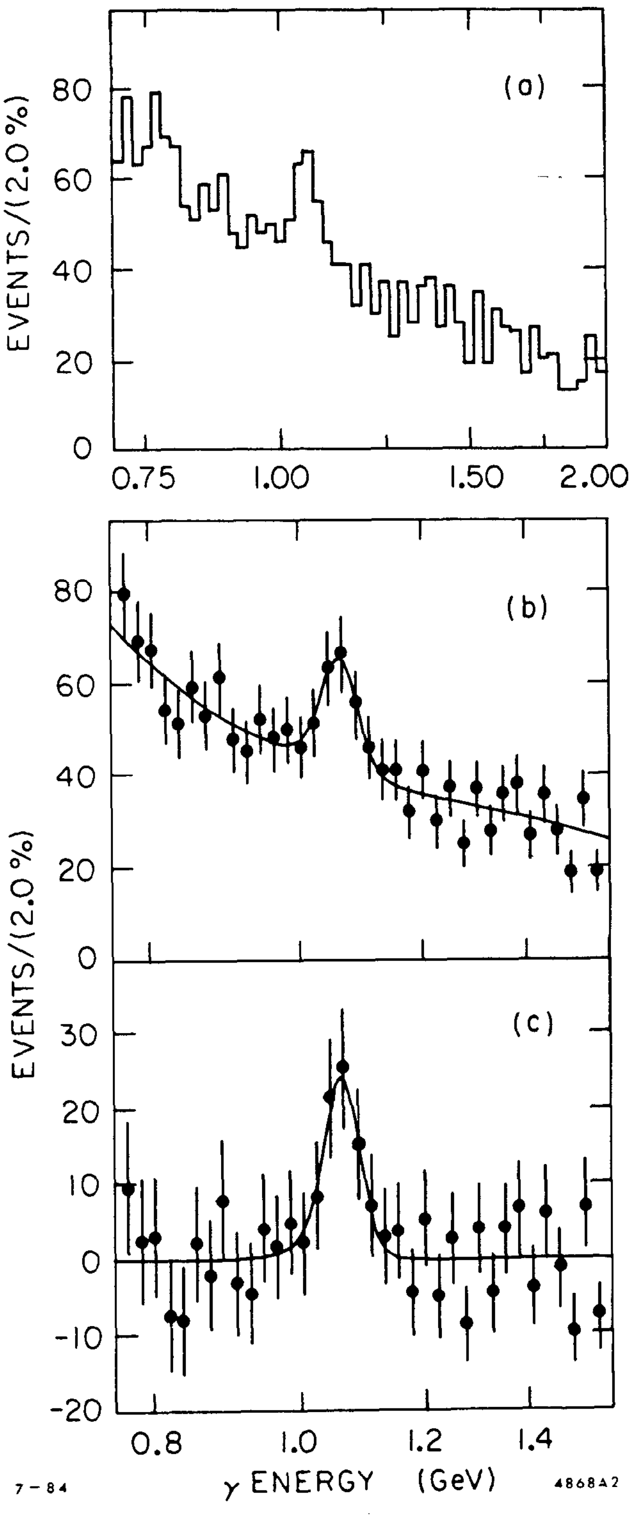

(a)
(b)
(c)
EVENTS/(2.0 %)
EVENTS/(2.0 %)
100
80
60
40
20
0
0.75
1.00
1.50
2.00
100
80
60
40
20
20
0
-20
0.8
1.0
1.2
1.4
γ ENERGY (GeV)
7 - 84
4868A1

Fig. 1



EVENTS/(2.0 %)
80
60
40
20
0
(a)
0.75
1.00
1.50
2.00
(b)
EVENTS/(2.0 %)
30
20
10
0
-10
-20
(c)
0.8
1.0
1.2
1.4
γ ENERGY (GeV)
7-84
4868A2

Fig. 2

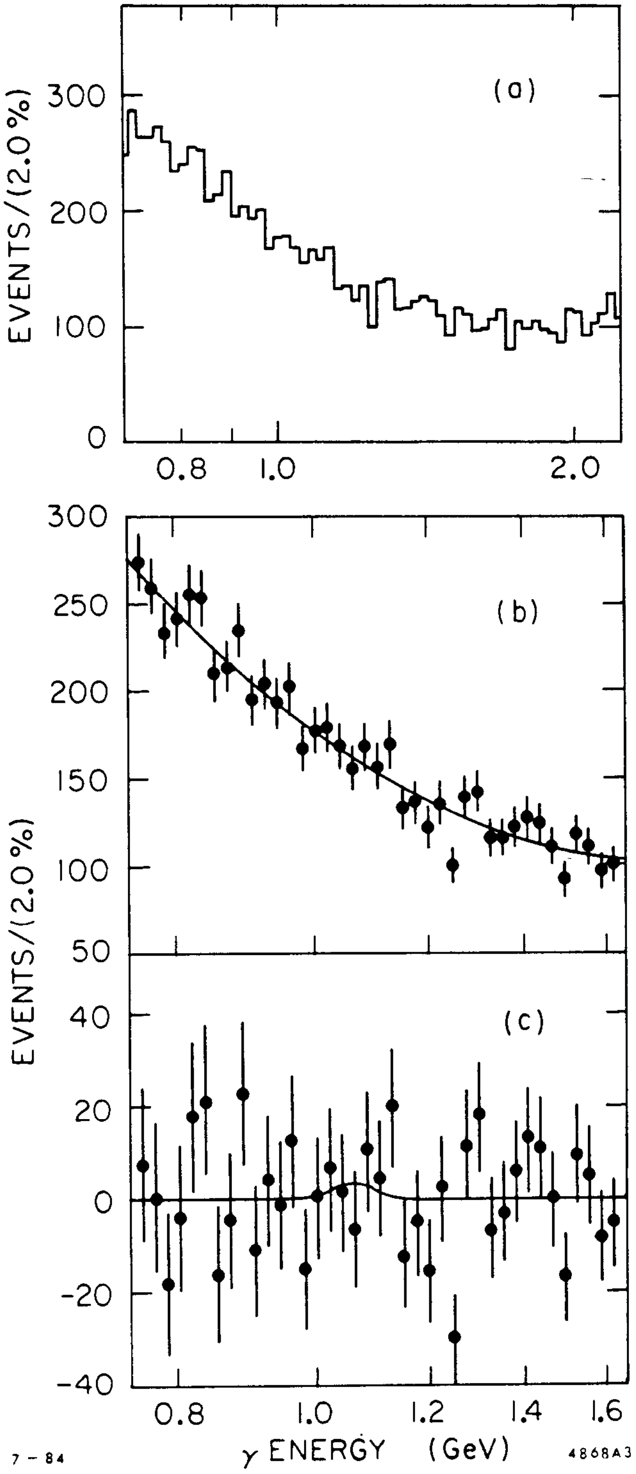

(a)
EVENTS/(2.0%)
0
100
200
300
0.8
1.0
2.0
(b)
300
250
200
150
100
50
(c)
40
20
0
-20
-40
EVENTS/(2.0%)
0.8
1.0
1.2
1.4
1.6
γ ENERGY (GeV)
7-84
4868A3

Fig. 3

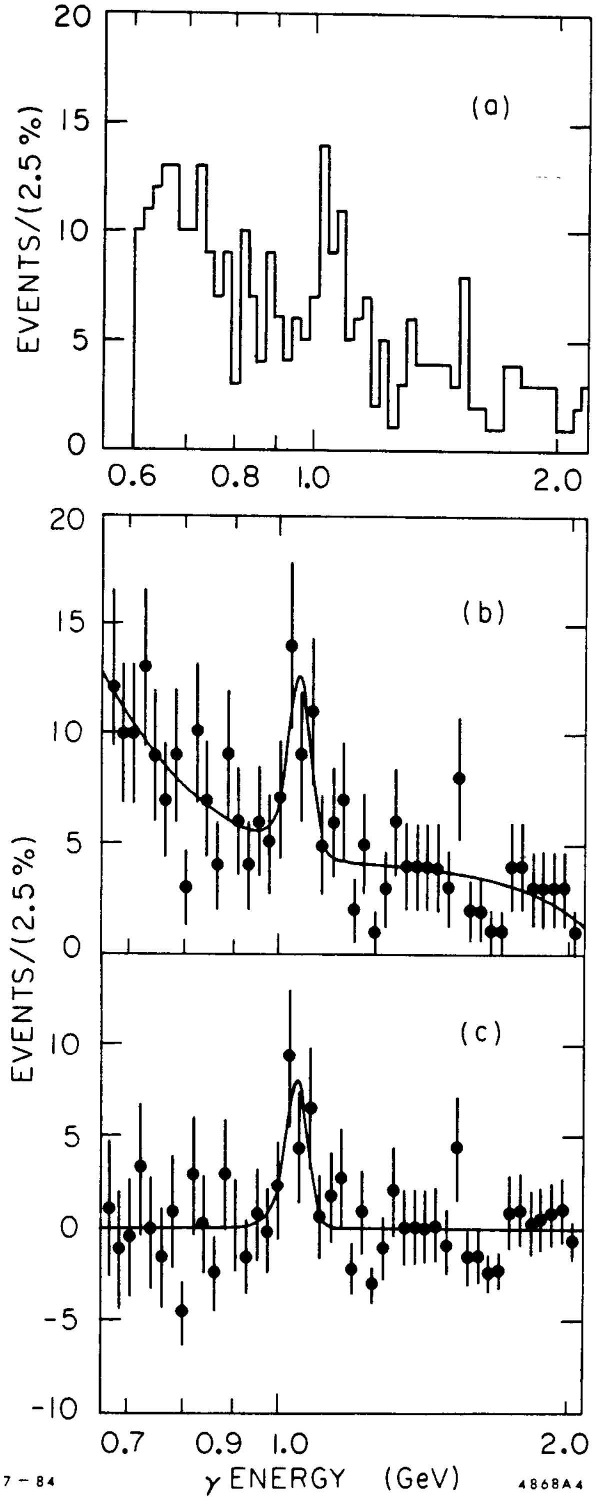

(a)
(b)
(c)
EVENTS/(2.5 %)
EVENTS/(2.5 %)
20
15
10
5
0
-5
-10
0.6
0.8
1.0
2.0
0.7
0.9
1.0
2.0
γ ENERGY (GeV)
7 – 84
4868A4

Fig. 4