EVIDENCE FOR A NARROW MASSIVE STATE IN THE RADIATIVE DECAYS OF THE UPSILON*

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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 $<$ 80 MeV (90% confidence level) using the Crystal Ball NaI(Tl) detector at DORIS II. Radiative transitions to this state are observed from about 100,000 Υ(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 Υ(1S) is on the order of 0.5% .

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1. Introduction

It has been realized for some time that precision measurement of the radiative decay of the various quarkonium states provides a powerful tool with which to search for hypothetical particles, such as gluonic mesons,[2] Higgs bosons,[3] or supersymmetric particles.[4] We report here such an investigation using Υ(1S) and Υ(2S) data. The data were obtained using the Crystal Ball NaI(Tl) detector[5,6] installed in the DORIS II storage ring at DESY. The data samples consist of about 100K produced Υ(1S) (integrated luminosity of 10.7/pb) and of about 200K produced Υ(2S) (integrated luminosity of 64.5/pb). 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 studies a key role was played by the ability of the detector to reduce background caused by π decay γ's and from other particles faking single γ's. 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 $Y \rightarrow \gamma X$. 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 few particles (including photons); the analysis uses cuts developed from an $X \rightarrow \tau\bar{\tau}$ decay model. As described below, the two analyses select two independent Υ(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 width, but also to separate out the $\pi^0 \rightarrow \gamma\gamma$ decays in which the two photons are overlapping.

2. High Multiplicity Analysis

The first analysis uses a sample of events at the Υ(1S) energy which has been selected for multihadron decays. From all the recorded triggers at Υ(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 $\epsilon_h = (0.90 \pm 0.05)$ using Monte Carlo calculations. The resulting sample of multihadron events contains contributions from Υ(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 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 a single cluster formed by the two, merged-photon showers.

To illustrate our methods, a single photon and a, generated by Monte Carlo with 1.0 GeV energy and tracked through the detector using the EGS shower program, are displayed in Fig.1. For each crystal the measured deposited energy is indicated. To reconstruct a particle, we first set a threshold (10 MeV is chosen)

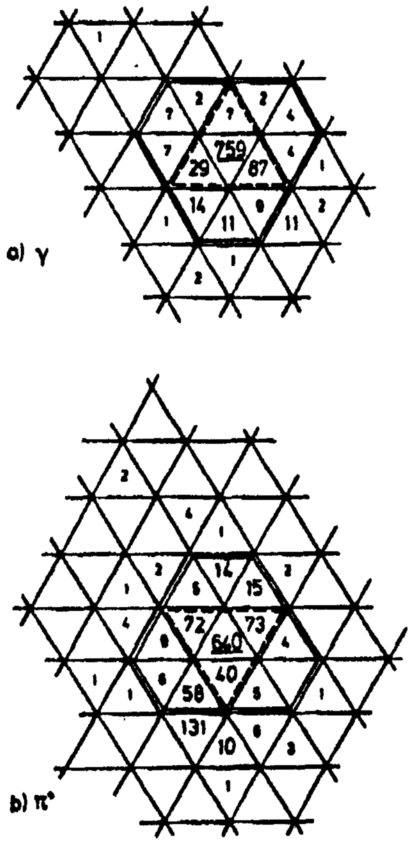

Fig. 1. Energy distributions of showers for a photon (a) and a π^0 (b), each generated with 1 GeV energy by Monte Carlo.

for energies in single crystals and draw a contour line around all crystals showing an energy above this threshold. Each connected contour line thus defines a "connected region"; in Fig.1 the module energies inside these regions are shown with larger type. Next we look for local maxima of the energy distribution inside the connected regions; the corresponding crystals are called "bump modules" (underlined numbers in Fig.1). Their orientation already gives a crude measurement of the direction of the particle that caused the observed energy deposition. This figure nicely illustrates the problem of overlapping showers, because the two decay photons from the π^0 generates the structure observed. The quantities used to detect and distinguish showers are:

- The energy in the bump module "E1," underlined in Fig. 1;
- The sum over the energies of the bump module and three crystals sharing a whole face with the bump module, "E4," enclosed by dashed lines in Fig.1;
- The sum over the energies of the bump module and the twelve crystals sharing a face or an edge with the bump module, "E13," enclosed by solid lines in Fig.1;
- The energy sum over all crystals belonging to the connected region, "ECR," indicated by larger size of the energy numbers in Fig.1;
- The invariant mass "$m_{\gamma\gamma}$" resulting from an attempt to fit two shower distributions to the energy distribution inside the connected region; and
- The difference of the logarithm of likelihoods for the fit with two shower functions just mentioned and a fit with only one shower function, "DLL" $= \ell n(L_{2\gamma}) - \ell n(L_{1\gamma})$. This quantity is near zero if the two hypotheses cannot be distinguished.

The method and algorithms used for the last two quantities will be referred to as "PIFIT." The high lateral segmentation of our detector is an essential prerequisite for this type of analysis. The separation power between γ's and π^0's reaches up to around 2 GeV particle energy.

The set of our cuts applied to the multihadron events to identify photons are listed below:

1. A photon track must be within a solid angle of $|\cos\vartheta_z| < 0.766$ (ϑ_z is the angle of the photon direction with respect to the beam). This is the acceptance covered by all three tube chambers.
2. The track must be neutral.
3. The lateral energy distribution in the crystals has to be consistent with the typical pattern of a single electromagnetic shower:
   (a) $E13 > 0.98 \times ECR$,
   (b) $0.44 < E1/E4 < 0.96$,
   (c) $0.78 < E4/E13 < 0.98$,
   (d) $DLL < 2.0$, and
   (e) $m_{\gamma\gamma}(PIFIT) < 17.175 + 0.0571 \times E_\gamma$.
4. An overlap cut between the photon candidate and other particle is taken as $|\cos\theta_{ij}| < 0.866$ (30° at the limit). The studies using both data and Monte Carlo simulations show that the overlap cut is not only effective at removing hadronic debris, but is also most effective for removing photons which come from π^0's, and which are missed by the other cuts.
5. Photon pairs which reconstruct to the π^0 mass are removed.

Figure 2a shows the resulting inclusive photon spectrum from the $\Upsilon(1S)$. The spectrum of Fig. 2a 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 $\sigma_E/E = 0.027/E^{1/4}$ (GeV) (our expected resolution for photons in a multihadron environment), and was superimposed 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 $\pm 2\%$ on the energy is yet to be applied). When allowed to vary in the fit, $\sigma_E/E = 0.028^{+0.013}_{-0.009}/E^{1/4}$ (GeV) which is consistent with our expected resolution. No other potential line in the spectrum of Fig. 2a 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[12] 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) ≤ 800 MeV; and sphericity of the event ≥ 0.16.

Figure 3a 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. 3b) now yields a significance of 4.2 standard deviations for the

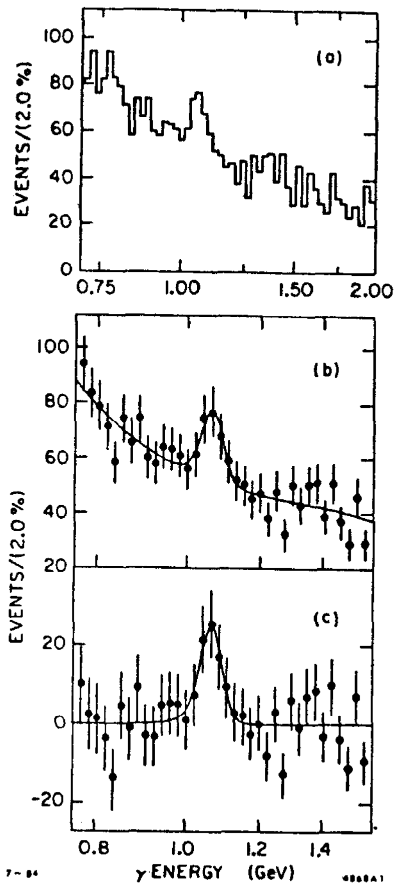

Fig. 2. (a) The inclusive spectrum for $\Upsilon(1S) \to \gamma +$ multiple hadrons before physics-oriented cuts. (b) The ς-peak region of (a), with fit (see text) shown as a solid line. (c) Same as (b) with the fitted background subtracted.

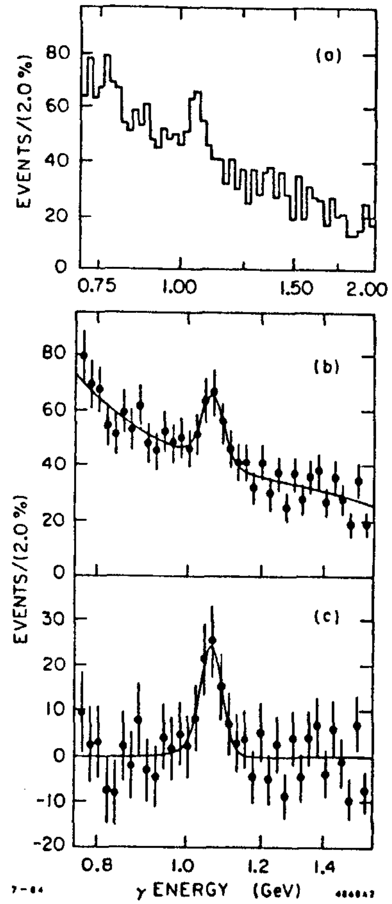

Fig. 3. (a) The inclusive spectrum for $\Upsilon(1S) \to \gamma +$ multiple hadrons after all cuts including physics-oriented cuts. (b) The ς-peak region of (a), with fit (see text) shown as a solid line. (c) Same as (b) with the fitted background subtracted.

signal. The signal–parameters become

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

where the first error in E_γ or M is statistical and the second is systematic.[6]

The efficiency for this selection was investigated in various ways. First we used a γ–jet–jet Monte Carlo simulation for various fixed photon energies and jet-jet models ($u\bar{u}$, $c\bar{c}$, gg). Second we superimposed Monte Carlo generated photons onto real hadronic events at the c.m. energy of interest ($\Upsilon(1S)$ or $\Upsilon(2S)$). The methods show a systematic difference, causing a large contribution to the systematic error of the efficiency.

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:

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

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

A number of checks were made to ensure that the signal was not instrumental or an artifact of the analysis. First, all the cuts used to obtain the spectrum of Fig. 2 were removed one at a time; this procedure indicated that none of the cuts used had anomalous effects. Second, by dividing the data appropriately, no preference for a particular period or geometrical region could be detected. Correlations between γ-energy and the triggers generated by the events containing the candidate γ's were found to be essentially constant moving from below to beyond the region of $E_\gamma = 1$ GeV. Off-resonance data, Monte Carlo $3g$ and $g\bar{g}$ events, and random beam cross events were subjected to the same analysis procedure and showed no significant fluctuations near 1 GeV. Finally, J/Ψ data taken at SPEAR and analyzed by the same program showed no narrow line at about 1 GeV.

The $\Upsilon(2S)$ data set, analyzed similarly to the $T(15)$ sample, does not show any narrow line (Fig. 4). This is strong evidence that the signal from the $1S$ is not artificially induced. However, a signal for the ς from the cascade $\Upsilon(2S) + \pi\pi\Upsilon(1S)$, or $\gamma\gamma\Upsilon(1S)$ is expected. A fit using a fixed width $\sigma_E/E = 0.033$ (taking account of the Doppler broadening) leads to an upper limit of 70 events (90% C.L.) at $E_\gamma = 1072$ MeV. This is consistent with an expectation of 53 ± 13 events based on the observed signal on the $\Upsilon(1S)$.

In addition, one might expect to see at some level the direct process $\Upsilon(2S) \to +\varsigma$ which for a ς-mass of 8.32 GeV would correspond to a peak of $E_\gamma = 1556$ MeV. Figure 4 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 $\epsilon(E_\gamma = 1070\ \mathrm{GeV})/\epsilon'(E_\gamma = 1560\ \mathrm{MeV})$ 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

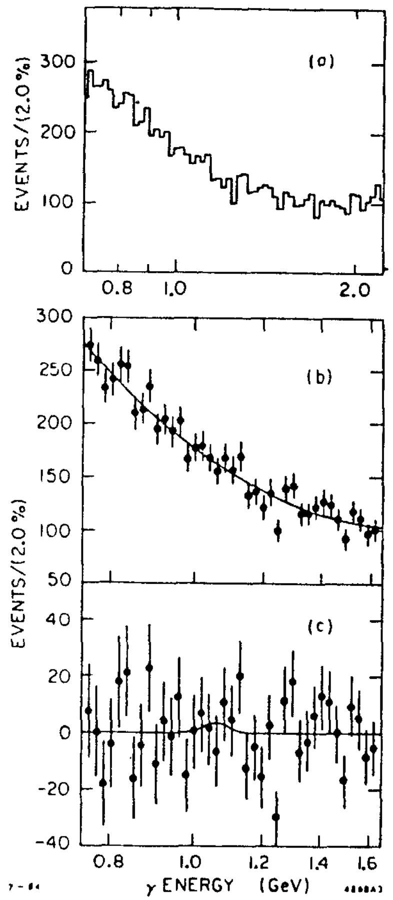

Fig. 4. (a) The inclusive spectrum for $\Upsilon(2S) \to \gamma +$ multiple hadrons after the same cuts as used for Fig. 2. (b) The ς-peak region of (a), with fit (see text) shown as a solid line. (c) Same as (b) with the fitted background subtracted.

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.).

3. Low Multiplicity Analysis

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 $\tau^+\tau^-$ [3] 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. 2, the details of these cuts are different. Care was taken not to exclude low multiplicity events, using a Monte Carlo calculation[13] as a guide. 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) QED–background was substantially reduced. In addition cuts were applied to eliminate unwanted $e^+e^- \to e^+e^-X$ events, beam-gas interactions, and cosmic ray events.

The remaining series of cuts was derived from the Monte Carlo simulation of $\Upsilon(1S) \to \gamma\varsigma \to \gamma\tau^+\tau^-$.[13] 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 $\sim$ 18% at 200 MeV; no peaking in the 1000 MeV region is seen.

Figure 5 shows the final signal obtained. The fit of 5b (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.

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

in excellent agreement with the values recorded in (1). Fitting 5a with a variable width yields a $\sigma_E = 0.034^{+0.027}_{-0.012}/E^{1/4}$ (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

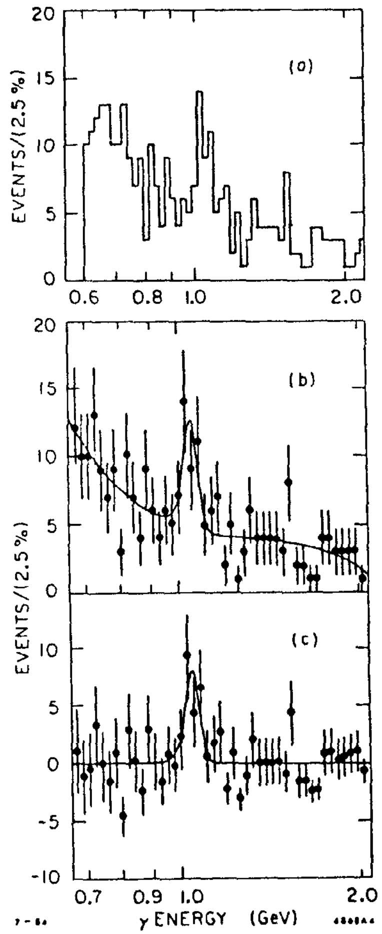

Fig. 5. (a) The inclusive spectrum $\Upsilon(1S) \to \gamma + (\tau^+\tau^-)$-biased sample including all cuts. (b) The ζ-peak region of (a), with fit (see text) shown as a solid line. (c) Same as (b) with the fitted background subtracted.

also provide evidence that these signals do not derive from (either real $\Upsilon(1S)$ 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 $\Upsilon(2S)$-sample.

4. Further Investigations

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 at 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 $B[\Upsilon(1S) \to \gamma\varsigma]$, 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 $\Upsilon(1S) \to \gamma\varsigma \to \gamma\tau^+\tau^-$ followed by the decays $\tau^\pm \to e^\pm\nu\bar{\nu}$, $\tau^\pm \to \mu^\pm\nu\bar{\nu}$. An upper limit of 0.2% (90% C.L.) for $B[\Upsilon(1S) \to \gamma\varsigma]B[\varsigma \to \tau^+\tau^-]$ 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 $B[\Upsilon(1S) \to \gamma\varsigma]B[\varsigma \to e^+e^-]$ has been determined.

5. Conclusions and Outlook

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 data samples. 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,

$$\begin{aligned} E_\gamma &= (1069 \pm 7 \pm 21)\text{MeV}, \\ M_\varsigma &= (8322 \pm 8 \pm 24)\text{MeV}, \\ \Gamma &< 80 \text{ MeV } (90\%\ C.L.), \quad \text{and} \\ B[\Upsilon(1S) &\to \gamma\varsigma] \sim 0.5\% \ . \end{aligned} \tag{4}$$

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 accommodated 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,[3] 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.

Given the potential importance of ς, more data on the $\Upsilon(1S)$ are likely to be taken in the near future, both at DORIS and at CESR; they should allow confirmation of the ς, if it is real.

References

1. THE CRYSTAL BALL COLLABORATION: C. Peck, F. C. Porter and 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,[‡1] F. Messing,[‡2] D. Prindle, B. Renger, C. Rippich and H. Vogel, *Carnegie-Mellon University, Pittsburg, USA*; Z. Zakubowski and G. Nowak, *Cracow Institute of Nuclear Physics, Cracow, Poland*; J. K. Bienlein, T. Kloiber, W. Koch, M. Schmitz, M. Schneider, T. Skwarnicki,[‡3] H. -J. Trost, K. Wachs and P. Zschorasch, *Deutsches Elektronen Synchrotron DESY, Hamburg, Germany*; G. Folger, B. Lurz, U. Volland and H. Wegener, *Universität Erlangen-Nürnberg, Erlangen, Germany*; A. Cartacci, G. Conforto, B. Monteleoni and P. G. Pelfer, *INFN and University of Firenze, Italy*; A. Fridman,[‡4] F. Heimlich, R. Lekebusch, P. Lezoch, W. Maschmann, R. Nernst, D. Sievers and U. Strohbusch, *Universität Hamburg, I. Institut für Experimentalphysik, Hamburg, Germany*; D. Antreasyan, J. Irion, K. Strauch and D. Williams *Harvard University, Cambridge, USA*; A. König, W. Metzger, J. Schtanus, R. T. Van de Walle and W. Walk, *University of Nijmegen and NIKHEF-Nijmegen, The Netherlands*; D. Besset, R. Cabenda, M. Cavalli-Sforza, R. Cowan, D. Coyne and C. Newman-Holmes[‡5] *Princeton University, Princeton, USA*; E. D. Bloom, R. Clare, S. Cooper, J. Gaiser,[‡6] G. Godfrey, S. Leffler, W. Lockman,[‡7] S. Lowe, B. Niczyporuk,[‡3] A. Schwarz, K. Wacker and J. Yeager,[‡8] *Stanford Linear Accelerator Center, Stanford University, Stanford, USA*; S. Keh, H. Kilian, K. Königsmann, M. Scheer and P. Schmitt, *Universität Würzburg, Germany.*
2. S. Brodsky, et al., Phys. Lett. B73, 203 (1978); K. Koller, T. Walsh, Nucl. Phys. B140, 449 (1978); J. D. Bjorken, in Proc. 1980 Summer Inst. on Particle Physics, SLAC-244, Stanford, CA, 1980.

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3. F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977); J. Ellis, et al., Phys. Lett. 83B, 339 (1979); S. Weinberg, Phys. Rev. Lett. 36, 294 (1976); H. E. Haber, G. L. Kane, Phys. Lett. 135B, 196 (1984).
4. J. H. Kühn and S. Ono, Aachen preprint PITHA 83/25 (Dec. 1983); T. Goldman and H. Haber, Los Alamos preprint LA-UR-84-634 (1984); W. -Y. Keung, A. Khare, Phys. Rev. D29, 2657 (1984) and Phys. Rev. D28, 1129 (1983).
5. M. Oreglia, et al., Phys. Rev. D25, 2259 (1982); M. Oreglia, PhD thesis, Stanford Univ. SLAC-236 (1980), unpublished.
6. J. Gaiser, PhD thesis, Stanford Univ. SLAC-255 (1982), unpublished.
7. J. Gaiser, et al., Results of the Crystal Ball at DORIS II, in Proceedings of Summer Institute on Particle Physics, SLAC-PUB-3232, 1983, Stanford, CA.
8. A. Schwarz, et al., DESY-report 83-108 (1983), unpublished; A. Schwarz, et al., Proceedings of the International EPS Conference on High Energy Physics, 20-27 July, 1983; p. 376.
9. C. Conforto, et al., Physics in Collision III and Search for Heavy Flavors, G. Bellini, A. Bettini and L. Perasso, Editors, Editions Frontieres, Gif-sur-Yvette 1984, p. 379.
10. J. Irion, et al., Rencontre de Moriond, New Particle Production, La Plagne, France, March 4-10, 1984; also SLAC-PUB-3325 (1984).
11. The general method for selecting hadrons is described in C. Edwards, et al., SLAC-PUB-3030 (1984). A more restrictive set of cuts of a similar type were used in this analysis.
12. The events $\Upsilon(1S) \to \gamma\varsigma$ (8.3 GeV), $\varsigma \to c\bar{c}$ were generated. The ς decayed isotropically into $c\bar{c}$ in its center of mass system, and the $c\bar{c}$ pair was then hadronized using the symmetric Lund model (Monte Carlo version 5.2). Ref: B. Andersson et al., Physics Reports 97, 33 (1983).
13. The events $\Upsilon(1S) \to \gamma\varsigma$ (8.3 GeV), $\varsigma \to \tau^+\tau^-$ 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).