Observation of an η_c Candidate State with Mass 2978 ± 9 MeV

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An η_c candidate state has been observed with a mass $M = 2978 \pm 9$ MeV and a natural line width $\Gamma < 20$ MeV (90% confidence level) using the Crystal Ball NaI(Tl) detector at SPEAR. Radiative transitions to this state are observed from $\psi'(3684)$ and $J/\psi(3095)$ in the inclusive photon spectra. The branching fraction to this state from the ψ' is $(0.43 \pm 0.08 \pm 0.18)\%$, where the errors are statistical and systematic, respectively. In addition, evidence is presented for the decay of this new state into $\eta\pi^+\pi^-$ and an upper limit is presented on the decay into $\pi^0 K^+ K^-$.

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The properties of charmonium have been the subject of intense experimental and theoretical work since the J/ψ and ψ' were discovered more than five years ago. Of particular interest has been the question of the existence, mass, and width of the η_c, the 1^1S_0 partner of the 1^3S_1 charmonium state, the J/ψ. Potential models[1] and dispersion relation models[2] indicate that the η_c lies between 20 MeV above and 100 MeV below the J/ψ. In addition, a number of detailed calculations[3] have been made of the expected radiative rates to the η_c from J/ψ and ψ'.

From their first publication, these theoretical predictions have stimulated experimental searches for the η_c. An initial candidate for the η_c state, called $X(2830)$,[4] had a mass lower than theoretically expected. This state was not observed in inclusive photon spectra from the J/ψ; an upper limit[5] was set much below the expected branching fraction.[3] The $X(2830)$ was not confirmed by the Crystal Ball collaboration in a more sensitive experiment[6]; thus the question of the existence of the η_c has remained open.

We have observed a new state with mass $M = 2978 \pm 9$ MeV in radiative decays of the J/ψ and ψ', as well as the decay of this new state into $\eta\pi^+\pi^-$. For the present we call this state the η_c candidate.

The data were obtained using the Crystal Ball NaI(Tl) detector[6,7] at the SPEAR e^+e^- storage ring of the Stanford Linear Accelerator Center (SLAC). The trigger efficiency for hadronic events is greater than 98%. Of the initial triggers at the J/ψ and ψ', roughly 30% and 20%, respectively, are hadronic events, the rest being cosmic rays, beam-gas interactions, and QED events. After removal of these three background sources by a series of software cuts, the efficiency of selection of hadronic decays is $(93 \pm 5)\%$ with a residual background of less than 2%. The resulting final samples of 752×10^3 J/ψ and 775×10^3 ψ' hadronic decays, corresponding to integrated luminosities of 323 and 1630 nb^{-1}, respectively, were used in the present analysis.

A number of cuts were applied to obtain inclusive photon spectra[8,9]. Photon showers were required to be entirely contained in the detector and to be well separated from charged particles. Photon pairs that could be reconstructed to a π^0 were removed. Figure 1 shows the inclusive photon spectrum obtained from hadronic decays of the ψ'. The transitions[5,10] to the well-established χ states are indicated in the figure as are the cascade transitions.[10-12] Also clearly seen is a signal of greater than 5 standard deviations at $E_\gamma = 634 \pm 13$ MeV. The error in the photon energy is primarily systematic, resulting from a $\pm 2\%$ uncertainty in the absolute NaI(Tl) energy calibration. This signal corresponds to a transition to a state of mass $M = 2983 \pm 16$ MeV. Several systematic checks[9] were made to verify that the signal appears uniformly over the solid angle of the apparatus and in the data obtained in the earlier and later parts of the data collection period. To check the sensitivity of the detector to a small signal in the 630-MeV region,[9] we looked for the 617-MeV photon radiated in the reaction $e^+e^- \to \gamma J/\psi$ at the $\psi''(3770)$ resonance; this photon was seen at the expected level. In addition, to check that the signal is not an instrumental effect, the inclusive photon spectrum from hadronic decays of the J/ψ, shown in Fig. 2, was analyzed and no signal was found in the 630-MeV region.

If the signal from the ψ' corresponds to the hindered $M1$ transition[3] $\psi' \to \gamma\eta_c$, then we expect to observe the transition $J/\psi \to \gamma\eta_c$ at a photon energy of about 110 MeV. In the J/ψ inclusive photon spectrum, shown in Fig. 2, there appears to be an enhancement about a photon energy of 112 MeV, corresponding to a state of mass $M \sim 2981$ MeV. A simultaneous fit was therefore performed to the mass, M, and natural linewidth, Γ, of the η_c candidate for both the ψ' and J/ψ signal regions. The two observed signals were fit by a Breit-Wigner line shape convoluted with a Gaussian energy resolution; independent quadratic forms were used for the backgrounds. The Gaussian resolutions ($\sigma = 4.7$ MeV at $E_\gamma = 112$ MeV and $\sigma = 18.3$ MeV at $E_\gamma = 634$ MeV) were derived from other Crystal Ball measurements.[7]

Figures 3(a) and 3(b) show the best fit obtained, together with the data for the ψ' and J/ψ inclusive spectra, respectively, before and after background subtraction. The parameters from the best fit, excepting the primarily systematic error in M, are

$$M = 2981 \pm 15 \text{ MeV}, \quad \Gamma = 20^{+16}_{-11} \text{ MeV}, \quad \chi^2 = 53 \text{ for 66 degrees of freedom.} \tag{1}$$

The signal obtained from the fit has a statistical significance of over 5 standard deviations. The systematic error in M arises mainly from the energy calibration uncertainty in the ψ' contribution to the fit, and uncertainty in the background shape in the J/ψ contribution; it dominates the ± 2 MeV statistical error. The dependence of χ^2 on Γ exhibits a broad minimum in χ^2 centered at[13] $\Gamma = 20$ MeV, where the value of Γ is primarily determined from the J/ψ inclusive spectrum. The error in Γ, shown in (1), is essentially statistical; an additional uncertainty due to the choice of the functional form for the background to the J/ψ signal has not yet been evaluated.

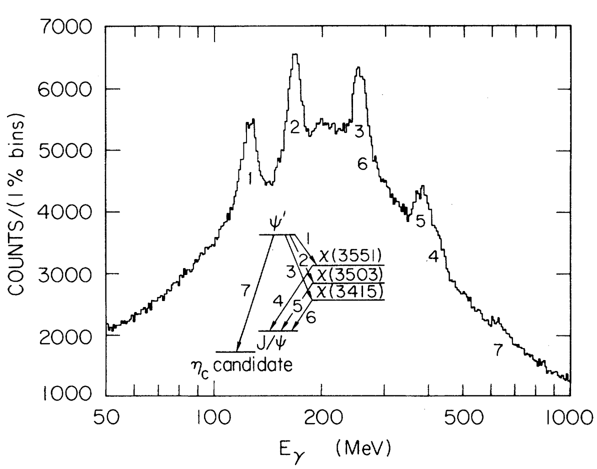

FIG. 1. The inclusive photon spectrum from ψ' hadronic decays. Counts are plotted in logarithmic bins since the resolution, $\Delta E/E$, is nearly constant in E for NaI(Tl).

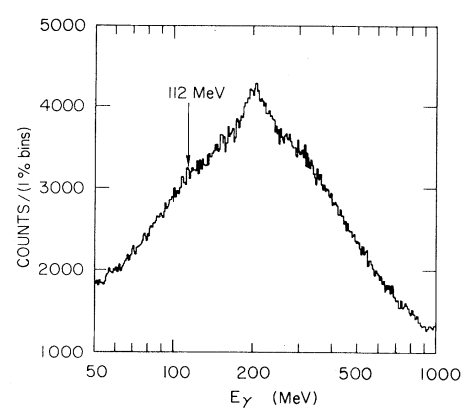

FIG. 2. The inclusive photon spectrum from J/ψ hadronic decays. The structure at $E_\gamma \sim 200$ MeV results from minimum ionizing charged particles which have been misidentified as photons (Refs. 8 and 9).

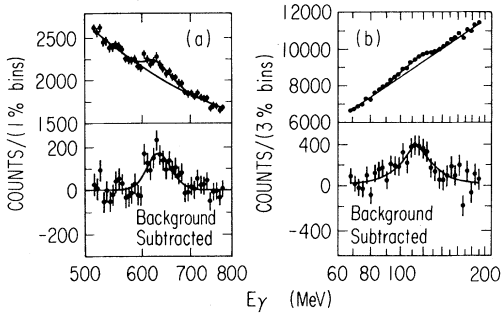

FIG. 3. Inclusive photon spectra from (a) ψ' and (b) J/ψ decays in the region of the η_c candidate signal, with fit results overplotted (Γ = 20 MeV). Unsubtracted and background subtracted spectra are shown; the background is determined from the fit described in the text.

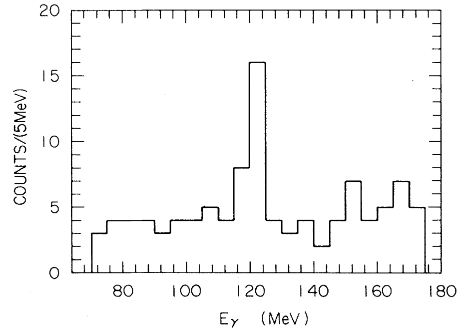

FIG. 4. Fitted energy of the photon for events fitted to the hypothesis $J/\psi \rightarrow \gamma\eta\pi^+\pi^-$.

The reconstruction efficiency for a single photon in an inclusive hadronic final state can at present be reliably estimated only for the ψ' decays, where the photon energy is 634 MeV. For the low-energy photons from the J/ψ, background sources are much more severe. Using a Monte Carlo estimate of the efficiency, assuming $J^P = 0^-$ for the η_c candidate, we obtain the inclusive branching ratio $R(\psi' \rightarrow \gamma\eta_c$ candidate$) = (0.43 \pm 0.08 \pm 0.18)\%$. The errors shown are statistical and systematic, respectively, with the latter dominated by the uncertainty in the photon reconstruction efficiency. The value for the branching ratio compares well with theoretical estimates[3] of (0.2–0.4)%.

We have also looked for exclusive decays of the η_c candidate into hadrons by performing kinematic fits to exclusive final states with multiple photons and two charged hadrons.[14] The Crystal Ball measures both the energy and angle of electromagnetically showering particles; for charged hadrons (π, K) only the angles are measured well. Secondary interactions of the charged hadrons in the sodium iodide complicate the fitting of some events, but special pattern recognition algorithms have been developed to deal with this effect.

Events with a three-photon, two–charged-particle topology were selected from the sample of J/ψ hadronic decays and subjected to a three-constraint kinematic fit to the hypotheses

$$J/\psi \rightarrow \gamma\eta\pi^+\pi^- \text{ and } \gamma\eta K^+K^-, \quad \eta \rightarrow \gamma\gamma. \tag{2}$$

The energy spectrum for the low-energy radiated photon is shown in Fig. 4 for events which pass the fit with a probability of χ^2 greater than 0.10 for the $\eta\pi^+\pi^-$ hypothesis. A clear signal is seen above background. No comparable signal is seen for the ηK^+K^- hypothesis. A maximum likelihood fit gives the $\eta\pi^+\pi^-$ mass corresponding to this signal as $2974 \pm 2 \pm 9$ MeV, where the first error is statistical and the second is an estimate of the systematic uncertainty. The mass agrees within errors with the value determined from the inclusive spectra.

The $\gamma\eta\pi^+\pi^-$ data contain additional information on the width of the η_c candidate. Given the limited statistics of this measurement, we choose to combine the $\chi^2(\Gamma)$ function obtained from the likelihood fit to these data with the function obtained from the fit to the inclusive[13] data. The resulting function provides an upper limit on the natural line width of $\Gamma < 20$ MeV (90% C.L.).

The detection efficiency for the exclusive reaction $\gamma\eta\pi^+\pi^-$ has been estimated by a Monte Carlo calculation where the η_c was assumed to have $J^P = 0^-$, and to decay with a phase-space distribution. The signal of 18 ± 6 events corresponds to a product branching ratio $R(J/\psi \rightarrow \gamma\eta_c$ candidate$) \cdot R(\eta_c$ candidate $\rightarrow \eta\pi^+\pi^-) = (3.1 \pm 1.1 \pm 1.5) \times 10^{-4}$, where the errors are statistical and systematic, respectively.

The Mark II collaboration at SPEAR has observed an enhancement in $\psi' \rightarrow \gamma\pi^{\pm}K^{\mp}K_s{}^0$ at $M(\pi KK) = 2980 \pm 8$ MeV.[15] We do not observe a signal in $J/\psi \rightarrow \gamma\pi^0K^+K^-$ in this mass range, with an upper limit of 1.5×10^{-4} (90% C.L.). Comparison of these two results awaits a reliable determination of $R(J/\psi \rightarrow \gamma\eta_c$ candidate).

In summary, an η_c candidate state is observed with mass 2978 ± 9 MeV. This estimate of the mass is obtained by averaging the masses determined from the inclusive and exclusive decays. The error shown is primarily systematic. The upper limit on the width of the state of $\Gamma < 20$ MeV

(90% C.L.) is consistent with the value of 5 MeV preferred by lowest-order quantum chromodynamics theory.[3] Final identification of this state as the pseudoscalar hyperfine partner of the J/ψ will depend on the determination of J^P and 0^-, and approximate agreement between the experimentally measured transition rate from the J/ψ and the value predicted by the charmonium model.[1]

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[1]T. Appelquist and H. D. Politzer, Phys. Rev. Lett. 34, 43 (1975); T. Appelquist, A. De Rújula, H. D. Politzer, and S. L. Glashow, Phys. Rev. Lett. 34, 365 (1975); H. J. Schnitzer, Phys. Rev. D 13, 74 (1976); R. Barbieri, R. Kögerler, Z. Kunszt, and R. Gatto, Nucl. Phys. B105, 125 (1976); H. J. Lipkin, H. R. Rubinstein, and N. Isgur, Phys. Lett. 78B, 295 (1978); P. Minkowski, Phys. Lett. 85B, 231 (1979); E. Eichten and F. L. Feinberg, Phys. Rev. Lett 43, 1205 (1979); C. Quigg, in *Proceedings of the Ninth International Symposium on Lepton and Photon Interactions at High Energies, Batavia, Illinois, 1979,* edited by T. B. W. Kirk and H. D. I. Abarbanel (Fermilab, Batavia, Ill., 1979), p. 247.

[2]V. A. Novikov, L. B. Okun, M. A. Shifman, A. I. Vainshtein, M. B. Voloshin, and V. I. Zakharov, Phys. Lett. 67B, 409 (1977); M. Shifman, A. Vainshtein, and V. Zakharov, Nucl. Phys. B147, 448 (1979).

[3]Two extensive reviews of the charmonium model and its comparison to experiment are T. Appelquist, R. M. Barnett, and K. D. Lane, Ann. Rev. Nucl. Part. Sci. 28, 387 (1978); E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, and T.-M. Yan, Phys. Rev. D 21, 203 (1980).

[4]W. Braunschweig *et al.*, Phys. Lett. 67B, 243 (1977); S. Yamada, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, 1977,* edited by F. Gutbro (DESY, Hamburg, Germany, 1977), p. 69; W. D. Apel *et al.*, Phys. Lett. 72B, 500 (1978).

[5]C. Biddick *et al.*, Phys. Rev. Lett. 38, 1324 (1977).

[6]R. Partridge *et al.*, Phys. Rev. Lett. 44, 712 (1980).

[7]E. D. Bloom, in *Proceedings of the Fourteenth Rencontre de Moriond, Les Arcs, France, 1979,* edited by J. Tran Than Van (Editions Frontieres, France, 1979); Y. Chan *et al.*, IEEE Trans. Nucl. Sci. 25, 333 (1978); I. Kirkbride *et al.*, IEEE Trans. Nucl. Sci. 26, 1535 (1979).

[8]E. D. Bloom, in *Proceedings of the Ninth International Symposium on Lepton and Photon Interactions at High Energies, Batavia, Illinois, 1979,* edited by T. B. W. Kirk and H. D. I. Abarbanel (Fermilab, Batavia, Ill., 1979), p. 92, and SLAC Report No. SLAC-PUB-2425, 1979 (to be published).

[9]C. W. Peck, in *Particles and Fields—1979,* edited by B. Margolis and D. G. Stairs, AIP Conference Proceedings No. 59 (American Institute of Physics, New York, 1980), and California Institute of Technology Report No. CALT 68-753, 1979 (unpublished).

[10]J. S. Whitaker *et al.*, Phys. Rev. Lett. 37, 1596 (1976).

[11]W. Bartel *et al.*, Phys. Lett. 79B, 492 (1978); W. Tanenbaum *et al.*, Phys. Rev. D 17, 1731 (1978).

[12]M. Oreglia, in Proceedings of the Fifteenth Rencontre de Moriond, Les Arcs, France, 15–21 March 1980 (to be published), and SLAC Report No. SLAC-PUB-2529, 1980 (to be published).

[13]E. D. Bloom, in Proceedings of the Sixth International Conference on Experimental Meson Spectroscopy, Brookhaven National Laboratory, Upton, New York, 25–26 April, 1980 (to be published), and SLAC Report No. SLAC-PUB-2530, 1980 (to be published).

[14]D. G. Aschman, in Proceedings of the Fifteenth Rencontre de Moriond, Les Arcs, France, 15–21 March 1980 (to be published), and SLAC Report No. SLAC-PUB-2550, 1980 (to be published).

[15]T. M. Himel, Ph.D. thesis, 1979, SLAC Report No. SLAC-223 (unpublished); T. M. Himel *et al.*, preceding Letter [Phys. Rev. Lett. 45, 1146 (1980)], and to be published.