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OBSERVATION OF AN η_c' CANDIDATE STATE WITH MASS 3592 ± 5 MeV*

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ABSTRACT

An η_c' candidate state is observed at a mass M = 3592 ± 5 MeV and with a natural line width $\Gamma < 8$ MeV (95% confidence level) using the Crystal Ball NaI(Tℓ) detector at SPEAR. The evidence is found in the inclusive photon spectrum in decays of the $\psi'(3684)$, where a signal is observed corresponding to a radiative transition to this state with branching ratio between 0.2% and 1.3% (95% confidence interval, including uncertainty due to correlation with width).

Assuming that the state observed at 2980 MeV[1,2] is the hyperfine-split partner to the J/ψ, the 1^1S_0 η_c, there remain two predicted but as yet undiscovered bound states of charmonium.[3] One of these, the 2^1P_1 state with negative C-parity, expected to have a mass around 3520 MeV, is presumably very difficult to observe in decays of the ψ' resonance because the direct radiative transition from the ψ' is forbidden. The other state is the hyperfine-split partner to the ψ' resonance, the 2^1S_0 η_c', which can be reached from the ψ' via a magnetic dipole (M1) radiative transition. Predictions for the η_c' mass vary somewhat; one recent prediction[4] is $M(\eta_c') = 3604 \pm 15$ MeV. In this letter we report evidence for an η_c' candidate state in the inclusive photon spectrum for ψ' decays measured with the Crystal Ball detector at the SPEAR e^+e^- storage ring.

Various aspects of the detector have been described elsewhere.[5-6] The properties that concern us most for the inclusive photon measurement are the following: (i) large solid angle coverage with NaI(Tℓ) crystals (93% of 4π steradians with the main detector, plus 5% with crystals in the endcap regions around the beam pipe); (ii) fine segmentation of the NaI, allowing the measurement of the lateral shower distribution, and providing an angular resolution for photons between 1^o and 2^o (depending on energy); (iii) good photon energy resolution which can be empirically described by $\sigma_E/E \simeq 2.6\%/[E(\text{GeV})]^{1/4}$; and (iv) spark and proportional chambers between the beam-pipe and the NaI crystals which permit neutral particle-charged particle separation.

The ψ' data sample used in the present analysis corresponds to 1.8×10^6 produced ψ'. Events are selected for this analysis with criteria[7] designed to accept hadronic ψ' decays with high efficiency (94%) and to reject backgrounds from cosmic rays, beam gas collisions, and QED processes. In addition, very high multiplicity events are eliminated (where more than ten charged tracks or more than ten neutral tracks are observed). [Note that a "track" in our terminology, may be either neutral or charged.] The final sample of events which contain at least one neutral is 1.59×10^6.

Tracks which are called neutral by the analysis program are selected further before being added to the inclusive photon energy spectrum according to the following criteria: (a) $|\cos\theta_{\gamma\cdot\mathrm{beam}}| < 0.85$. This cut selects a region of the detector which is covered by at least two of the central charged-tracking chambers, and also eliminates photons which shower near the boundary between the NaI crystals and the beam-pipe tunnel region, where the energy resolution is poorer due to shower leakage; (b) $\cos\theta_{\gamma\cdot\mathrm{charged}} < 0.90$. This cut on the proximity of a photon to a charged track reduces the contamination from spurious "tracks" resulting from secondary interactions of charged hadrons in the NaI, and also eliminates photons which have degraded energy resolution due to shower overlap with the shower of a charged (hadronic or electromagnetic) particle; and (c) the pattern of the lateral shower energy deposition is required to be consistent with that due to an electromagnetically showering particle. This criterion is especially effective in reducing the residual contamination from misidentified charged particles.

The ψ' inclusive photon energy spectrum after the above selection is shown in Fig. 1(a). For comparison, Fig. 1(b) shows the corresponding spectrum for J/ψ decays. The most prominent features in Fig. 1(a) are the three monochromatic photon peaks from the $\psi' \to \gamma\chi_{2,1,0}$

transitions, and a peak at ~400 MeV due to the overlapping contributions from the two Doppler -- broadened transitions $\chi_{1,2} \rightarrow \gamma J/\psi$. In addition to these peaks, there are two other statistically significant, but less pronounced narrow features in the spectrum. One of these is at a photon energy of about 640 MeV, corresponding to a recoil mass of 2980 MeV, the η_c candidate.[1,2] The other structure appears at a photon energy of approximately 90 MeV, and we shall now consider this structure in more detail.

Figure 2 shows the result of a fit to the region containing the 90 MeV structure. A smooth background in the form of a sum of Legendre polynominals up to cubic order was assumed, plus a signal term corresponding to the detector's intrinsic line shape (approximately Gaussian)[7] and energy resolution width. This fit yields a signal amplitude of 5582 ± 1270 photons, with a mean energy of 90.8 ± 0.8 MeV (statistical error only). Both the signal (mean and amplitude) and the background shape were allowed to vary simultaneously. If, instead, we fix the background shape as determined by fitting to the region outside the signal, consistent results are obtained, but the statistical significance of the signal improves (to more than 6 standard deviations). Additional fits made to study the width of the state recoiling against the photon give a result which is consistent with zero width with a 95% C.L. upper limit for a Breit-Wigner full width of $\Gamma < 8$ MeV. Considering the systematic uncertainty in the photon energy (including the absolute energy calibration uncertainty and a small correlation with Γ), the mean energy is 91 ± 5 MeV, corresponding to a recoil mass of 3592 ± 5 MeV (assuming $M_{\psi'} = 3684$ MeV). The width and signal strength (and the background) are correlated, making a precise branching ratio determination difficult. Including this source of uncertainty, and correcting for the photon detection efficiency (0.44 ± 0.08), we obtain a 95% confidence interval for the ψ' radiative branching ratio to this state of (0.2 - 1.3)%.

We have considered, and ruled out, several possible sources for the signal other than the existence of a new particle:

(i) The possibility that the signal is due to misidentified charged particles is eliminated by the absence of any structure at 90 MeV in the observed-energy spectrum for identified charged particles.

(ii) Various specific channels which produce low-energy photons (such as $\psi' \to \pi^0\pi^0 \; J/\psi$ and $\psi' \to \eta \; J/\psi \to 3\pi^0 \; J/\psi$) are also eliminated as possible sources because the photon energy distributions in those reactions are much too broad.

(iii) The possibility of some not-understood effect generally appearing in the detector is ruled out by the absence of a similar structure at $\approx$90 MeV in the J/ψ spectrum. [A fit to the J/ψ spectrum of Fig. 1(b) for a signal at 91 MeV yields an amplitude of 660 ± 1280 photons.]

(iv) The possibility of a short-term or local detector malfunction is ruled out by noting that the signal exists in comparable datasets taken two years apart, and by checking that the signal is not restricted to any particular region of the detector.

We conclude that the most likely explanation for the signal is that it is a new radiative decay of the ψ', presumably the decay to the predicted 2^1S_0 $c\bar{c}$ state, the η_c'. We use the expression "η_c' candidate" in recognition of the fact that such quantum numbers as spin and parity have not been determined.

It should be noted that the DESY-Heidelberg group reported evidence[8] for a state at a mass of 3591 ± 7 MeV in the exclusive channel $\psi' \to \gamma\gamma\ J/\psi$, $J/\psi \to \mu^+\mu^-$. However, we have looked for evidence of such a state in[6] $\psi' \to \gamma\gamma\ J/\psi$, $J/\psi \to e^+e^-$ or $\mu^+\mu^-$, and find no evidence for it. We obtained a 90% C.L. upper limit of[6] $BR(\psi' \to \gamma\ 3591) \cdot BR(3591 \to \gamma\ J/\psi) < 0.04\%$, to be compared with their result[8] of $(0.18 \pm 0.06)\%$. Further, <u>if</u> we assume that the object we observe in the inclusive spectrum is the η_c', then we expect that[7] $BR(\psi' \to \gamma\eta_c') \cdot BR(\eta_c' \to \gamma\ J/\psi) < 10^{-6}$. This estimate is based on our measured branching ratio from the ψ', and on theoretical estimates[9] for the η_c' total width and radiative transition rate (estimated using the measured $\psi' \to \gamma\eta_c$ rate to reduce sensitivity to details of the wave functions[7]). Such a small product of branching ratios is not accessible in any existing experiment.

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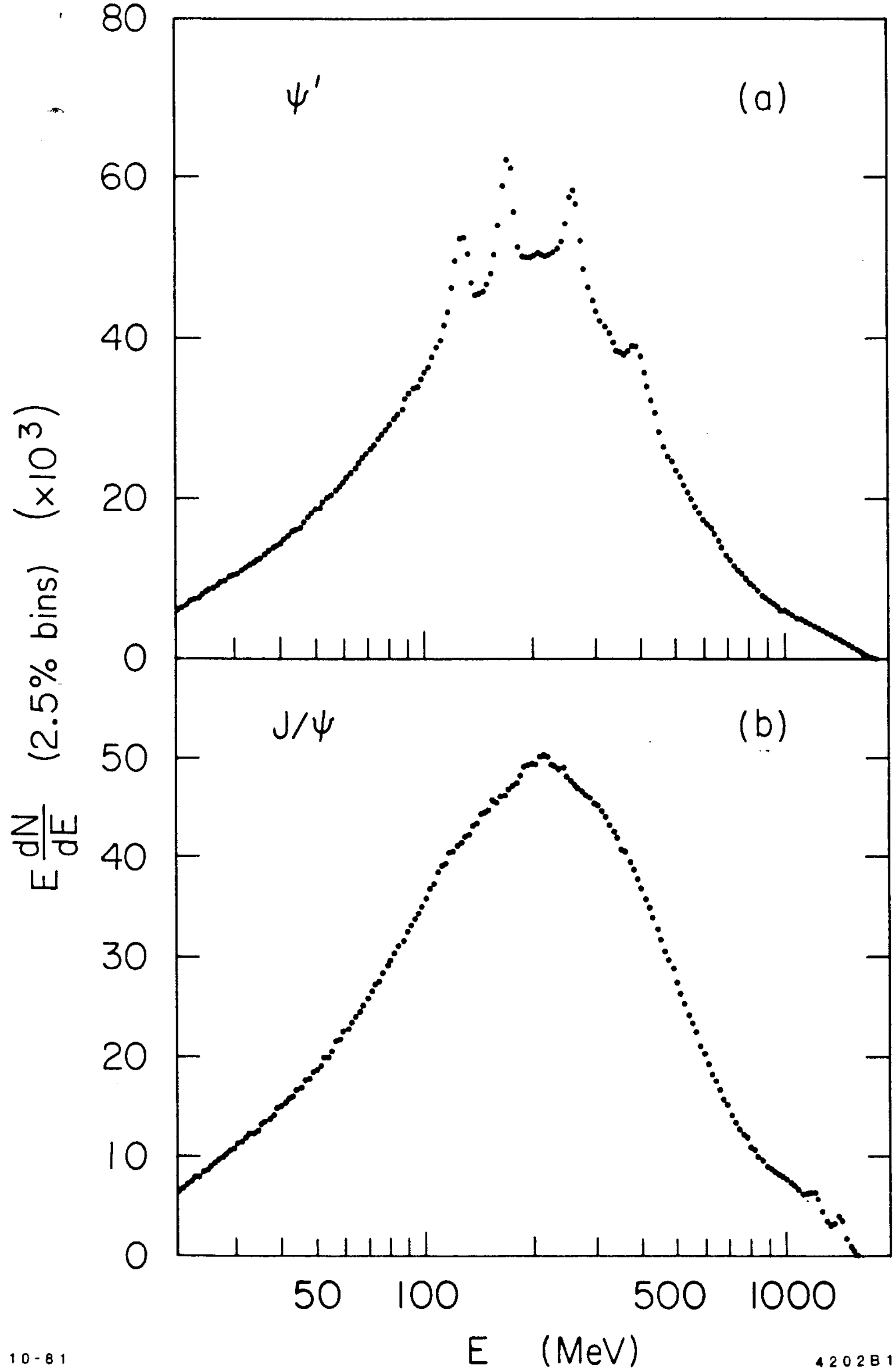
FIGURE CAPTIONS

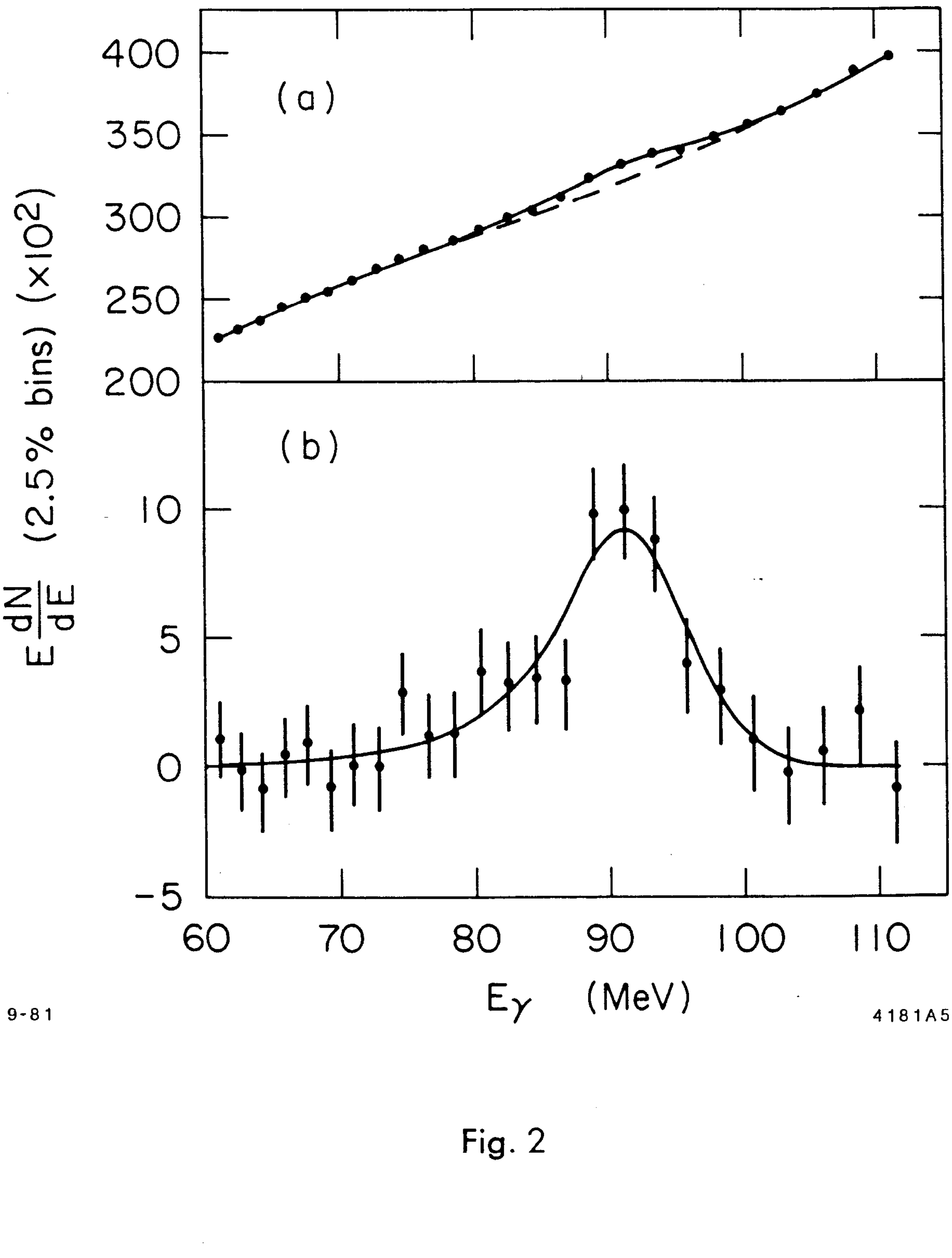
Fig. 1. Inclusive photon spectra measured with the Crystal Ball: (a) in ψ' decays; and (b) in J/ψ decays. A minimum-ionizing charged particle deposits $\sim$ 200 MeV in the NaI, which accounts for the small structure at this energy, due to a residual contamination from misidentified charged particles.

Fig. 2. Results of a fit (see text) to the ψ' inclusive photon spectrum in the region around 90 MeV: (a) Unsubtracted spectrum (dashed line is background contribution); and (b) background subtracted.



ψ′
(a)
J/ψ
(b)
80
60
40
20
0
50
40
30
20
10
0
$E\frac{dN}{dE}$ (2.5% bins) (×10³)
50
100
500
1000
E (MeV)
10-81
4202B1

Fig. 1



(a)
(b)
400
350
300
250
200
10
5
0
−5
60
70
80
90
100
110
$E\frac{dN}{dE}$ (2.5% bins) (×10^2)
E_γ (MeV)
9-81
4181A5

Fig. 2