Observation of the $\eta_c(2980)$ Produced in the Radiative Decay of the $\psi'(3684)$

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In a study of $\psi'(3684)$ radiative decays with the Mark II detector at SPEAR, the decay sequence $\psi' \to \gamma\eta_c(2980)$ is observed, with the $\eta_c(2980)$ decaying into several completely reconstructed hadronic modes. A mass $M = 2980 \pm 8$ MeV/c^2 and a width $\Gamma < 40$ MeV/c^2 (90% confidence level) are obtained, and estimates of some of the decay branching ratios are presented.

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The lowest-lying pseudoscalar bound state of the charmed quark and antiquark, the η_c, has been the object of considerable search ever since the discovery of the corresponding vector state, the $\psi(3095)$. If one assumes the η_c to be lighter than the ψ, the processes in which one might expect to observe it are

$$\psi \to \gamma\eta_c, \tag{1a}$$

$$\psi' \to \gamma\eta_c, \tag{1b}$$

where ψ' denotes the $\psi(3684)$.

Early observations[1] by the DASP group of a 2γ peak at a mass of 2.83 GeV/c^2 in the decay mode $\psi \to 3\gamma$ have not been confirmed in the more recent work of the Crystal Ball Collaboration.[2] The latter group has however reported the observation of peaks in the study of the ψ' and ψ inclusive photon spectra,[3] which they ascribe to the production via Reaction (1) of a possible η_c of mass 2978 ± 9 MeV/c^2.

In this paper, we present evidence, based on a high-statistics study of ψ' decays with the Mark II detector at SPEAR, for the production through (1b) of a state of mass 2980 MeV/c^2 which decays into several identified hadronic final states. This work provides confirmation by an independent technique of the existence of the 2980 MeV/c^2 state.

The Mark II detector has been described in detail in earlier publications,[4] and we confine ourselves here to a brief discussion of those features crucial to the present analysis. A cylindrical drift chamber system[5] in a magnetic field is used to measure the momenta of charged particles. Photons are detected by a liquid-argon calorimeter[6] which provides precise direction information and a somewhat less accurate energy measurement. Charged-particle identification is obtained with a system of 48 time-of-flight (TOF) counters which provide 0.3 ns timing resolution over a flight path of average length 1.7 m. The solid angle subtended by these devices is about 70% of 4π sr except for the drift chamber which has a somewhat larger acceptance.

Our photon energy resolution is not sufficiently good to search for monoenergetic photons inclusively, and we have therefore studied specific final states in which all outgoing particles are detected. The actual states chosen for study are the following:

$$\psi' \to \gamma p\bar{p}, \tag{2a}$$

$$\psi' \to \gamma\pi^+\pi^-\pi^+\pi^-, \tag{2b}$$

$$\psi' \to \gamma\pi^+\pi^-K^+K^-, \tag{2c}$$

$$\psi' \to \gamma\pi^+\pi^-p\bar{p}, \tag{2d}$$

$$\psi' \to \gamma K^\pm\pi^\mp K_S, \quad K_S \to \pi^+\pi^-. \tag{2e}$$

These choices are the simplest ones which can arise from the decay of a pseudoscalar particle into charged hadrons and K_S. Candidate events are required to have two [Reaction (2a)] or four reconstructed tracks plus at least one photon detected in the calorimeter. Events with more than one detected photon are retained because noise in the liquid-argon preamplifiers occasionally causes the tracking program to find false photons. For Reaction (2e) the decay products of the K_S are required to have a measured invariant mass between 476 and 520 MeV/c^2. The mass assignments for the charged particles are based on rather loose TOF cuts coupled with the kinematic fits to Reactions (2a)–(2e) which are discussed below.

We now consider the problem of establishing the presence of a single photon as required by Reactions (2), for which we set up criteria which are as independent as possible of the energy carried off by the photon. First we require a small missing mass recoiling against the charged particles and K_S in (2) by cutting on the quantity U defined by

$$U \equiv E - P,$$

where E and P are the missing energy and momentum, respectively. The virtue of the quantity U is that its measurement uncertainty is insensitive to the value of the missing momentum P whereas the missing mass squared, roughly equal to $2PU$, has an error which is proportional to P. For our sample, we use the cut $|U| \leq 0.1$ GeV, which removes almost all events with more than one π^0 but does not distinguish between single-π^0 and single-photon events for $P > 0.3$ GeV/c. To make this latter distinction we use the measured direction of the observed photon candidate by forming the quantity

$$q^2 \equiv (2P \sin\tfrac{1}{2}\alpha)^2 \approx (P\alpha)^2,$$

where α is the angle between the direction of the missing momentum $\vec{P}$ and the measured direction of the photon. Again the choice of the quantity q^2 is motivated by the fact that, to a good approximation, its distribution is independent of the momentum of the outgoing neutral be it a π^0 or a photon. For direct photon emission, the expected distribution of q^2 is highly peaked near $q = 0$ with about 80% of the events in the signal interval $q^2 < 0.001$ GeV$^2/c^2$.

The q^2 distribution for photons from events with single π^0 is much broader. We have calculated that only 10% of such events lead to photons within the above q^2 signal interval. To evaluate the actual number of such background photons, we use a control interval $0.002 \leq q^2 \leq 0.01$ GeV$^2/c^2$, and determine that 51% of single-π^0 events give rise to a photon within that control interval. Thus about 20% as many events as are in the control interval will be a background in the signal interval.

The data discussed in this analysis come from a study of 10^6 ψ' decays. Events satisfying the topological and TOF criteria already mentioned and satisfying the cut $|U| < 0.1$ GeV are selected for further study. We determine the hadronic effective mass M for these events by a one-constraint (1-C) kinematic fit which constrains the neutral to be massless. Figure 1 shows the distribution of q^2 for two intervals of M: $3.35 \leq M \leq 3.45$ GeV/c^2 in Fig. 1(a) and $M \leq 3.35$ GeV/c^2 in Fig. 1(b). The distribution in Fig. 1(a) is dominated by the well-known χ state at 3.41 GeV/c^2 and shows the expected large direct photon peak at low q^2. The sample plotted in Fig. 1(b) which corresponds to M values below all known χ states has a very sizable direct-photon peak plus a substantial single-π^0 background. Figure 2(a) shows the mass spectrum for events in the direct-photon signal interval $q^2 < 0.001$ GeV$^2/c^2$, and Fig. 2(b) the corresponding spectrum for the π^0 control interval $0.002 < q^2 < 0.01$ GeV$^2/c^2$. Figure

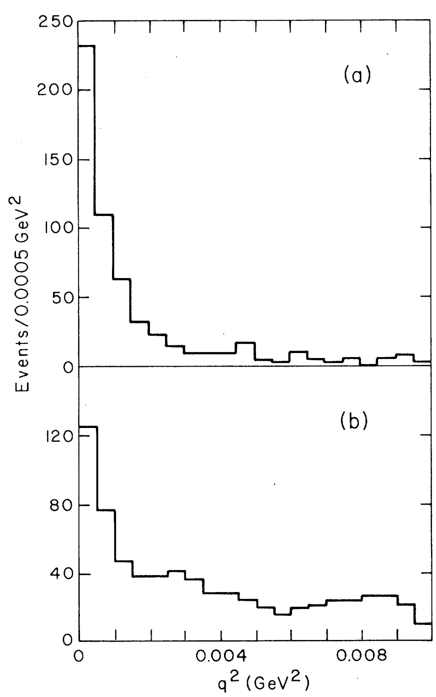

FIG. 1. Distribution of the quantity q^2 for low-missing-mass events. (a) Hadronic mass M in the range 3.35–3.45 GeV/c^2; (b) $M < 3.35$ GeV/c^2.

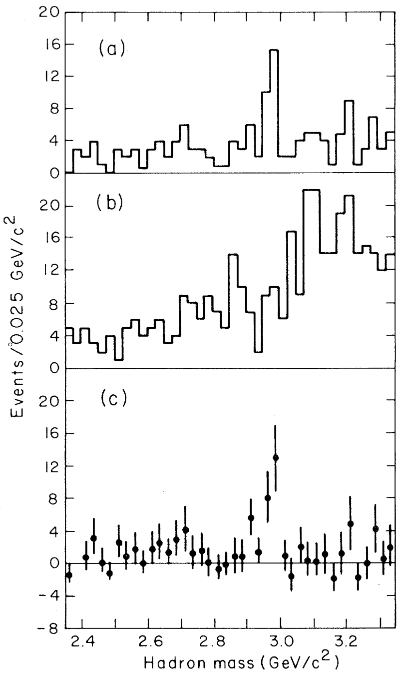

FIG. 2. Hadronic mass spectrum for (a) $q^2 < 0.001$ GeV^2/c^2, (b) $0.002 < q^2 < 0.01$ GeV^2/c^2, and (c) background-subtracted direct-photon event sample.

TABLE I. Branching ratios for the decay $\psi' \to \gamma + \eta_c \to \gamma +$ hadrons.

Hadronic mode	$B(\psi' \to \gamma\eta_c) B(\eta_c \to \text{hadrons})$
$K^{\pm} K_s \pi^{\mp}$	$(1.5^{+0.8}_{-0.6}) \times 10^{-4}$
$2\pi^+ 2\pi^-$	$(5.7^{+3.9}_{-2.4}) \times 10^{-5}$
$\pi^+\pi^- K^+ K^-$	$(4.0^{+6.0}_{-2.5}) \times 10^{-5}$
$p\bar{p}$	$(8^{+8}_{-4}) \times 10^{-6}$
$\pi^+\pi^- p\bar{p}$	$< 5 \times 10^{-5}$ (90% confidence level)

2(c) shows the background-corrected direct-photon mass spectrum obtained by subtraction of the suitably renormalized spectrum in Fig. 2(b) from that in Fig. 2(a). From Fig. 2 one can make the following observations concerning the mass spectrum below 3.35 GeV/c^2: (i) The hadronic mass spectrum of the direct-photon events is quite different from the spectrum for those corresponding reactions in which the photon is replaced by a π^0; (ii) there is evidence for a narrow bump in the mass interval between 2.95 and 3.00 GeV/c^2 produced only in the direct photon decays; and (iii) the bump contains about 20% of the total number of direct photon events present in Fig. 1(b), the remainder being associated principally with hadronic masses below 2.8 GeV/c^2. The statistical significance of the bump can be assessed from Fig. 2(a) by noting that the population in the interval from 2.95 to 3.00 GeV/c^2 expected from sidebands is 6.8 events whereas 25 events are actually observed. The probability of a fluctuation as large or larger than this, due account being taken of the uncertainty of the background estimate, is 7×10^{-7}. If we allow that our histogram in Fig. 2(a) contains 40 adjacent bin pairs, the probability that anyone of these pairs provides such a large fluctuation is then only 3×10^{-5}. Thus, independent of other observations the present data taken on its own provide strong evidence of a narrow structure between 2.95 and 3.00 GeV/c^2. The fact that this structure falls at just the same mass as that of the report by the Crystal Ball Collaboration[3] makes the case for the existence of a particle near 2.98 GeV/c^2 produced in radiative ψ' decay compelling.

We now consider further what properties of this particle, which we denote as the $\eta_c(2980)$, can be deduced from our rather limited statistics. We have fitted the mass spectrum of Fig. 2(a) between 2.80 and 3.05 GeV/c^2 with the superposition of a flat background and a Breit-Wigner shape modified by our expected resolution, which is typically $\sigma \approx 15$ MeV/c^2. We have also attempted to improve somewhat the mass resolution by subjecting the event sample to 5-C kinematic fits in which use is made of the photon energy and directional information. The results of the analysis are as follows:

$$M(\eta_c) = 2980 \pm 8 \text{ MeV}/c^2,$$

$$\Gamma(\eta_c) < 40 \text{ MeV}/c^2 \text{ (90\% confidence level).}$$

We have also made estimates of the branching ratio products for η_c decay into the final states listed in (2). The efficiencies for the Reactions (2a)–(2e) have been evaluated by Monte Carlo methods and range from 0.04 for (2e) to 0.24 for (2a). The results are given in Table I. It is worth noting that from isospin consideration one can obtain a value of branching-ratio products for $\psi' \to \gamma\eta_c$, $\eta_c \to K\bar{K}\pi$ of $(4.5^{+2.4}_{-1.8}) \times 10^{-4}$. Since the overall branching ratio estimate of the Crystal Ball Collaboration[3] for $\psi' \to \gamma\eta_c$ is 0.43%, the net $\eta_c \to K\bar{K}\pi$ branching fraction appears to be very substantial. In our efficiency determination we have assumed the photon angular distribution appropriate to Reaction (1b), namely $1 + \cos^2\theta$. The data are completely compatible with this distribution but the statistics are too small to consider this as a confirmation of the η_c interpretation.

In summary, we have presented evidence for the existence of the $\eta_c(2980)$ as a product of the radiative decay of the ψ', and have given estimates of its branching ratios into several hadronic channels.

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