Title
Observation of the Decay 00

Journal
Physical Review Letters, 49(9)

ISSN
0031-9007

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Publication Date
1982

DOI
10.1103/PhysRevLett.49.632

Observation of the Decay $\psi \to \gamma\rho^0\rho^0$

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(Received 28 June 1982)

The prompt photon decay $\psi(3095) \to \gamma\pi^+\pi^-\pi^+\pi^-$ has been studied with the Mark II detector at SPEAR. This channel is found to contain a $\gamma\rho^0\rho^0$ component with $\rho^0\rho^0$ masses concentrated between 1.4 and 2.0 GeV/c^2. The branching fraction for the $\psi \to \gamma\rho^0\rho^0$ decay with masses less than 2.0 GeV/c^2 is measured to be $(1.25 \pm 0.35 \pm 0.40) \times 10^{-3}$.

PACS numbers: 13.25.+m, 13.40.Hq, 14.40.Gx

The remarkably narrow width of the $\psi(3095)$ implies a strong Okubo-Zweig-Iizuka suppression of the three-gluon decay of the $^3S_1$ $c\bar{c}$ bound state. Prompt photons produced in ψ decays are therefore expected to be predominantly emitted from an initial charmed quark rather than from a final-state quark since this requires only two gluons to mediate the decay. The possibility that gluonic bound states might be observed in these decays has led to considerable experimental effort[1] at the SPEAR and DORIS electron-positron colliding beam facilities. We report in this Letter a study of the decay

$$\psi(3095) \to \gamma\pi^+\pi^-\pi^+\pi^-. \tag{1}$$

Likelihood fits to the four-pion system provide evidence for the decay

$$\psi(3095) \to \gamma\rho^0\rho^0, \tag{2}$$

with $\rho^0\rho^0$ invariant masses concentrated between 1.4 and 2.0 GeV/c^2. Enhancements in the $\rho^0\rho^0$ channel in this mass range have previously been reported in hadronic reactions[2] and observed in final states produced by photon-photon collisions.[3]

The data for this experiment were taken with the Mark II detector[4] at SPEAR and correspond to $\simeq 650\,000$ produced ψ mesons. Events were considered candidates for the prompt photon decay (1) if they contained four charged particles with zero net charge and at least one photon detected in the electromagnetic calorimeters with energy greater than 300 MeV. Candidate events were removed from further consideration if they contained a pair of tracks that formed a secondary vertex consistent with a K_s^0 decay, or if any of the prongs were determined by the time-of-flight system to be charged kaons. These cuts remove events of the type $K_s^0K\pi$ that come from the decay $\psi \to \gamma\iota(1440)$.[1] Conservation of energy was imposed on candidate events by requiring that the difference between the missing energy recoiling against the four-pion system and the magnitude of the corresponding missing momentum be less than 0.100 GeV. After these cuts the only significant background that remains is the decay $\psi \to \pi^+\pi^-\pi^+\pi^-\pi^0$. This is the largest hadronic decay of the ψ ($\simeq 4\%$), and asymmetric decays of the π^0 lead to events that are mistaken for the desired prompt photon signal. To estimate the size of this background we use a technique, developed for our study[5] of the decay $\psi' \to \gamma\eta_c$, that uses the measured direction of the observed photon. The transverse momentum of the hadronic system relative to the observed photon direction is defined by

$$p_{t\gamma}^2 \equiv 4p_{4\pi}^2 \sin^2(\chi/2), \tag{3}$$

where $p_{4\pi}$ is the magnitude of the momentum vector of the four-pion system, and χ is the acollinearity angle between the photon and the hadronic

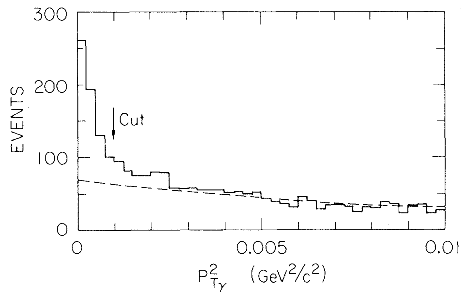

FIG. 1. The distribution of the square of the transverse momentum of the four-pion system relative to the observed photon direction. The dashed curve is the expected shape of the background from π^0 decays, and has been normalized to the data between 0.003 and 0.01 GeV^2/c^2.

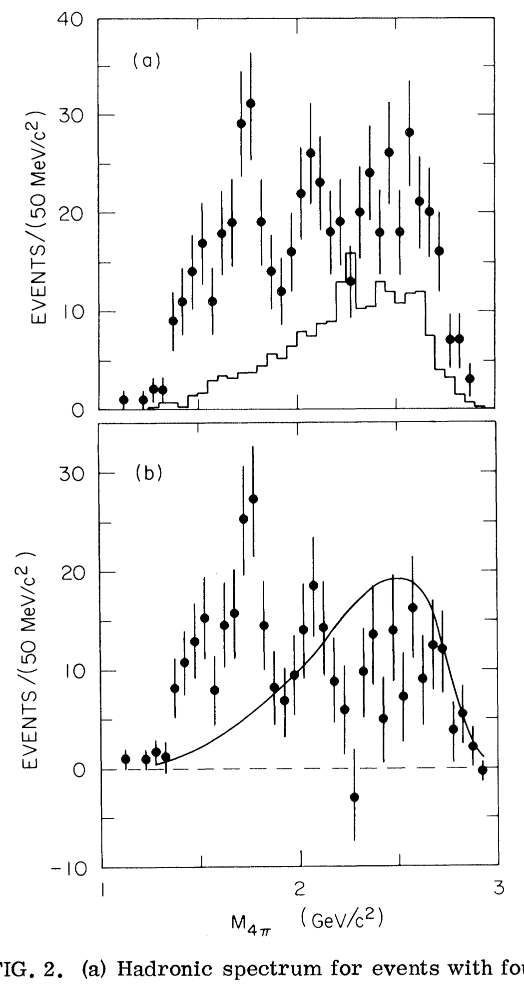

FIG. 2. (a) Hadronic spectrum for events with four observed pions and one observed photon. The histogram shows the estimated background from the decay of the ψ into five pions $\pi^+\pi^-\pi^+\pi^-\pi^0$. (b) The observed π^0-background-subtracted prompt photon signal $\psi\to\gamma\pi^+\pi^-\pi^+\pi^-$. The curve is the distribution expected if the decay proceeds via five-body phase space.

momentum vector. Conservation of momentum requires that, in the absence of measurement errors, this quantity vanish for real prompt photon decays. Decays of π^0's lead to a rather broad distribution of $p_{t\gamma}^2$. The observed distribution of $p_{t\gamma}^2$ is shown in Fig. 1 for all events that pass the previously stated criteria. The signal region is defined by $p_{t\gamma}^2 < 0.001\ \mathrm{GeV}^2/c^2$, and the π^0 background is estimated from the number of events in the region $0.003\ \mathrm{GeV}^2/c^2 \leq p_{t\gamma}^2 \leq 0.01\ \mathrm{GeV}^2/c^2$.

Figure 2(a) shows the hadronic mass distribution for events found in the signal region and also shows the estimated π^0 background. The detector acceptance falls smoothly by $\simeq 10\%$ as the mass increases from 1 GeV/c^2 to 2.5 GeV/c^2, but above 2.5 GeV/c^2 the 300-MeV cut on the measured photon energy removes events at an increasing rate. The π^0-background-subtracted prompt γ signal is shown in Fig. 2(b) and is compared with the distribution of four-pion masses expected to be observed if the decay proceeds via five-body Lorentz-invariant phase space.[6] The data are clearly inconsistent with this hypothesis.

Figure 3 shows the scatter plot of one $\pi^+\pi^-$ mass combination against another (two entries per event) for all signal events in Fig. 2(a). A significant $\rho^0\rho^0$ cluster is seen in this plot and evidence for $\rho^0\pi\pi$ events is also visible. To isolate the $\rho^0\rho^0$ component in the data sample, we

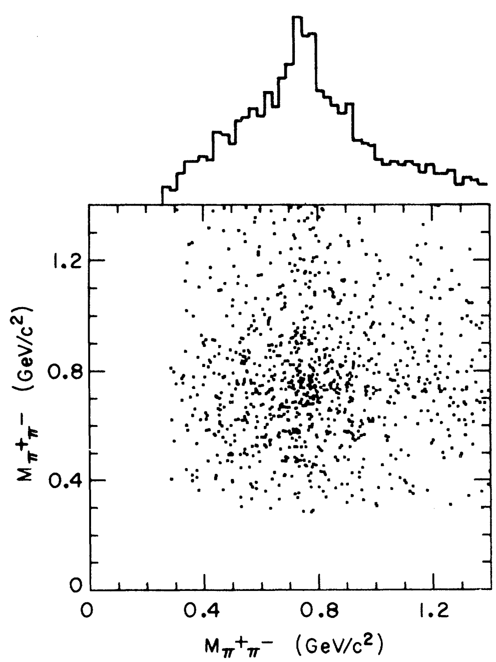

FIG. 3. Scatter plot of $\pi^+\pi^-$ pair masses. There are two entries per event.

have performed a series of likelihood fits. These fits were done by assigning to each event weights computed from the four-vectors of the observed pions. We first assumed that the 4π state consists of an incoherent superposition of four-body phase space and $\rho^0\rho^0$, and made a one-parameter fit to the fraction of events that are $\rho^0\rho^0$ for each of several four-pion mass bins. The $\rho^0\rho^0$ weight was the square of a properly symmetrized amplitude in the $\pi^+\pi^-$ pair masses, but all angular distributions were assumed to be isotropic. The signal region and the π^0 background region were separately fitted, and the appropriate background subtraction was made bin by bin in the hadronic mass. The π^0-background-subtracted $\rho^0\rho^0$ signal as determined by this fit is shown in Fig. 4 as a solid histogram. Since Fig. 3 indicates a possible $\rho^0\pi\pi$ component in the data, we have also done a two-parameter fit in which the 4π state included a $\rho^0\pi\pi$ three-body contribution as well as $\rho^0\rho^0$ and four-body phase space. The $\rho^0\rho^0$ signal from this fit is shown in Fig. 4 as points with errors. Although the limited statistics result in sizable errors in the two-parameter fit, the qualitative agreement with the previous result is good.

To check for possible biases in these results, a third fit was made that included the three contributions of the previous fit plus a πA_1 modification of the $\rho\pi\pi$ three-body final state. The A_1 was taken to have a mass of 1.2 GeV/c^2 and a width of 0.300 GeV/c^2 and was assumed to have a relativistic Breit-Wigner shape with constant width. This term was considered since, aside from the $\rho^0\rho^0$ state, it is the most likely two-body system that produces a threshold at $m_{4\pi} \simeq 1.4$ GeV/c^2. (See Fig. 2.) Although a sizable part of the $\rho\pi\pi$ final state was assigned to the πA_1 channel by this fit, the addition of the πA_1 term reduced the $\rho^0\rho^0$ component by only $\simeq 20\%$. The two-parameter fit has also been applied to Monte Carlo-generated $\rho^0\rho^0$ and $\rho^0\pi\pi$ events. The probability for identification of $\rho^0\rho^0$ events was found to be consistent with 100%, while $\lesssim 5\%$ of the $\rho^0\pi\pi$ events were systematically misidentified as $\rho^0\rho^0$ events.

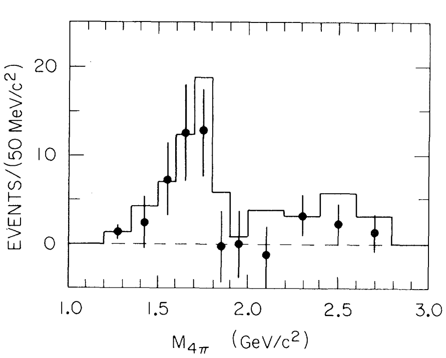

FIG. 4. The $\rho^0\rho^0$ mass spectrum as determined by likelihood fits to the spectra in Fig. 2(a). See text for descriptions of these fits. Notice that the bins in this plot are of variable size.

To estimate the size of the $\rho^0\rho^0$ signal we find that 76 ± 22 events with masses below 2.0 GeV/c^2 were assigned to this channel by the two-parameter fit. The acceptance of the detector for the $\gamma 4\pi$ final state has been determined by a Monte Carlo calculation to be $(9.7 \pm 2.0)\%$. The error is due to uncertainty in the angular distribution of the prompt photon; we have taken this distribution to be isotropic. From the number of produced ψ mesons, we then obtain

$$R(\psi \to \gamma\rho^0\rho^0(m_{\rho\rho} < 2.0 \text{ GeV}/c^2)) = (1.25 \pm 0.35 \pm 0.40) \times 10^{-3}, \tag{4}$$

where the first error is the statistical error from the two-parameter likelihood fit and the second error is the systematic uncertainty which includes 20% from the acceptance calculation, 10% from the normalization, and 20% from the variation in the number of events assigned to the $\rho^0\rho^0$ channel by the various likelihood fits. We similarly find from the data in Fig. 2(b) the branching fraction for the decay $\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$ (with $m_{4\pi}$ less than 2.5 GeV/c^2) to be $(4.85 \pm 0.45 \pm 1.20) \times 10^{-3}$.

We conclude that we observe a substantial $\psi \to \gamma\rho^0\rho^0$ signal with $\rho^0\rho^0$ invariant masses concentrated below 2.0 GeV/c^2. While a threshold enhancement may account for the observed signal, we can interpret the $\rho^0\rho^0$ spectrum obtained from the two-parameter likelihood fit as a combination of $\gamma\rho^0\rho^0$ phase space and a resonance described by a Breit-Wigner resonance with constant width. A fit gives a mass of 1.65 ± 0.05 GeV/c^2 and a width of 0.20 ± 0.10 GeV/c^2 for the resonance parameters. The branching fraction (4), which is given only for the case of two neutral ρ mesons, is comparable to that for the decay $\psi \to \gamma f(1270)$,[7] and if we assume that the $\rho^0\rho^0$ state is purely isoscalar (isovector is not possible), the total branching fraction for $\psi \to \gamma\rho\rho$ (with a factor of 3 to account for the $\rho^+\rho^-$ final state) may be as large as that for the decay $\psi \to \gamma\iota(1440)$.[1] We also note that a resonance θ with a mass of 1.640 ± 0.050 GeV/c^2 and width $\simeq 0.220$ GeV/c^2 has recently been observed[8] in the radiative decay $\psi \to \gamma\eta\eta$.

Comparison of the $\rho^0\rho^0$ spectrum presented here with previously reported[2,3] signals is complicated by the fact that the mass range of interest is near the $\rho^0\rho^0$ threshold and different production mechanisms lead to substantially different dynamical and phase-space considerations. Production of $\rho^0\rho^0$ states in nucleon-antinucleon annihilation has been reported[2] at masses $\simeq 1.4$ GeV/c^2 and $\simeq 1.7$ GeV/c^2 with widths that are perhaps more narrow than that seen in this experiment. These hadronic processes involve final states that include one or more pions in addition to the four pions that make up the $\rho^0\rho^0$ combination, and final-state interactions may play a role in determining the $\rho^0\rho^0$ line shapes. An enhancement in the $\gamma\gamma \rightarrow \rho^0\rho^0$ cross section has been observed[3] that is broader than the signal presented here and is peaked at a somewhat lower mass. This two-photon reaction most likely proceeds via vector dominance, and as such, the cross section may have additional hadronic flux factors modifying any possible threshold or Breit-Wigner behavior.

The authors wish to acknowledge useful discussions with G. Fox of the California Institute of Technology regarding aspects of this work. This work was supported in part by the U. S. Department of Energy under Contracts No. DE-AC03-76SF00515 and No. W-7405-ENG-48, the Universität Bonn, Federal Republic of Germany, the Centre d'Etudes Nucleaires de Saclay, France, and the Miller Institute for Basic Research in Science, Berkeley, California.

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