Observation of the Radiative Decay $\eta' \to \omega\gamma$ in the Reaction $\pi^- p \to \pi^+\pi^- 3\gamma n$†

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We have obtained 68 ± 9 events of the previously unseen radiative decay $\eta' \to \omega\gamma$ ($\omega \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$) in a charged- and neutral-particle spectrometer. Simultaneously, 1505 events of the decay $\eta' \to \eta\pi^+\pi^-$ ($\eta \to \gamma\gamma$) were collected in the same apparatus, allowing a direct measurement of this branching ratio. We find $(\eta' \to \omega\gamma)/(\eta' \to \eta\pi^+\pi^-) = (6.8 \pm 1.3)\%$ and use published data to derive $(\eta' \to \rho\gamma)/(\eta' \to \omega\gamma) = 9.9 \pm 2.0$, in excellent agreement with predictions based on vector meson dominance.

Although it is expected from vector meson dominance that the radiative decay $\eta' \to \omega\gamma$ should occur at about $\frac{1}{10}$ the rate of the relatively copious decay $\eta' \to \rho\gamma$, only an upper limit[1] for this branching ratio presently exists. We report here the first measurement of the $\eta' \to \omega\gamma$ decay rate relative to that for the dominant decay $\eta' \to \eta\pi\pi$. A value for the $(\eta' \to \omega\gamma)/(\eta' \to \rho\gamma)$ branching ratio is then obtained from existing data on the $(\eta' \to \rho\gamma)/(\eta' \to \eta\pi\pi)$ ratio.

Data for both the $\omega\gamma$ and $\eta\pi^+\pi^-$ decays were collected simultaneously with the same apparatus, thereby greatly reducing the impact of systematic errors. The experiment was performed with the charged and neutral spectrometer at the Argonne National Laboratory zero-gradient synchrotron using a π^- beam of 8.4 GeV/c. The vector momenta of both outgoing charged pions and all detected γ's were measured for the reactions

$$\pi^- p \to \omega\gamma n,\quad \omega \to \pi^+\pi^-\pi^0,\quad \pi^0 \to \gamma\gamma \tag{1}$$

and

$$\pi^- p \to \eta\pi^+\pi^- n,\quad \eta \to \gamma\gamma. \tag{2}$$

The recoil neutron was not detected.

A plan view of the charged and neutral spectrometer is shown in Fig. 1; it has been described in more detail elsewhere.[2-4] The charged particles were detected in a conventional forward spectrometer consisting of five magnetostrictive readout spark chambers on each side of a large-aperture magnet. All detected γ rays were required to convert in a 1.6-radiation-length sheet of lead behind the last spectrometer chamber. Immediately following this lead sheet were three closely spaced spark chambers that measured the position of each shower. γ-ray energies were measured using a 56-element lead-glass Cherenkov array positioned immediately downstream of the γ-ray chambers. An anticoincidence system of alternate layers of lead and scintillator surrounding the target and framing the downstream aperture rejected events with extra charged particles and/or γ's which would go undetected by the rest of the apparatus. Scintillator hodoscopes downstream of the charged spectrometer (H2) and on either side of the lead converter (GHF, GHR) were used in the trigger to demand at least two charged particles and at least two showers.

The initial sample of candidates for Reaction (1) consisted of all events with three reconstructed showers, each with at least 300 MeV of energy, and two charged particles of opposite sign, each with a momentum of at least 400 MeV/c; these cuts were imposed to avoid reconstruction problems for soft particles. The three γ's for each event in this sample were ordered such that γ_1 and γ_2 were the pair with effective mass closest

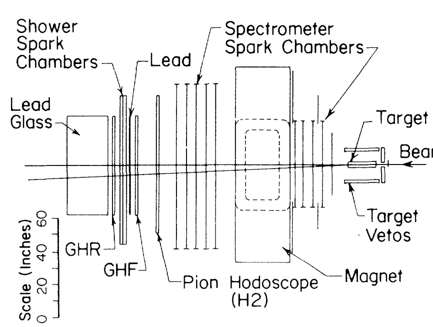

FIG. 1. Plan view of the charged and neutral spectrometer.

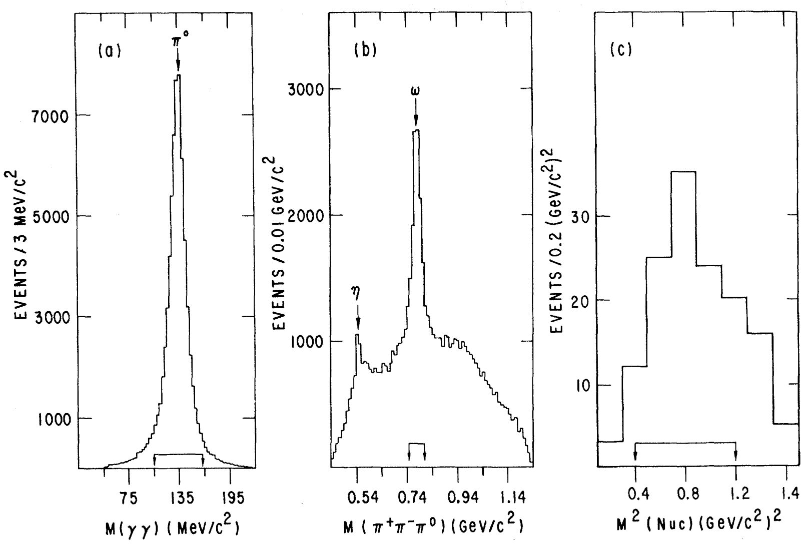

FIG. 2. (a) $\gamma_1\gamma_2$ effective mass distribution. The arrows indicate the 105–165 MeV/c^2 π^0 mass cut (71 318 events). (b) $\pi^+\pi^-\pi^0$ effective mass spectrum, showing the 750–810 MeV/c^2 ω mass cut (68 962 events). (c) Plot of square of the mass of the recoil nucleon for $\omega\gamma$ events within 30 MeV/c^2 of the η' mass. The cuts for the final data sample are indicated (144 events).

to the π^0, with γ_1 having the higher energy. The $\gamma_1\gamma_2$ mass spectrum[5] is shown in Fig. 2(a). For those events having $\gamma_1\gamma_2$ mass between 105 and 165 MeV/c^2 the γ_1 and γ_2 energies were constrained to give the π^0 mass, and a missing mass for the recoil nucleon and effective mass for the $\pi^+\pi^-\pi^0$ combination were then calculated. This $\pi^+\pi^-\pi^0$ mass is plotted in Fig. 2(b); a prominent ω peak and a smaller η signal are seen.

Events for which the $\pi^+\pi^-\pi^0$ mass was between 0.75 and 0.81 GeV/c^2 and the square of the nucleon mass was between 0.40 and 1.20 (GeV/c^2)^2 were then subjected to a three-constraint fit to the hypothesis $\pi^- p \to \omega\gamma n$, the natural width of the ω being ignored.

A comparison between the γ energy spectra predicted by a Monte Carlo simulation of Reaction (1) and those actually observed suggested that much of the background was coming from events with soft γ's. The following cuts were therefore applied to the data: $E_{\gamma_2} > 0.6$ GeV; $1.0 < E_{\gamma_3} < 2.4$ GeV; $1.0 < E_{\gamma_1} + E_{\gamma_2} < 4.5$ GeV. The strong E_{γ_3} cut removed about 25% of the good events but greatly suppressed the background. An additional cut on the momentum transfer, $|t'| < 0.4$ (GeV/c)^2, was imposed to take advantage of the peripherality of η' production. The $\omega\gamma$ mass spectrum with these cuts is shown in Fig. 3(a). There is a clear enhancement in the η' mass region which we associate with the $\eta' \to \omega\gamma$ radiative decay.

In Fig. 2(c) we display the distribution of the square of the missing mass for events which have $\omega\gamma$ mass within 30 MeV/c^2 of that of the η'. For this plot the cut on the square of the missing mass described above was not applied. It is clear that only a small background of inelastic events is present[6] in the interval of our neutron cut, 0.4 to 1.2 (GeV/c^2)^2.

The events in Fig. 3(a) are those from the "best"

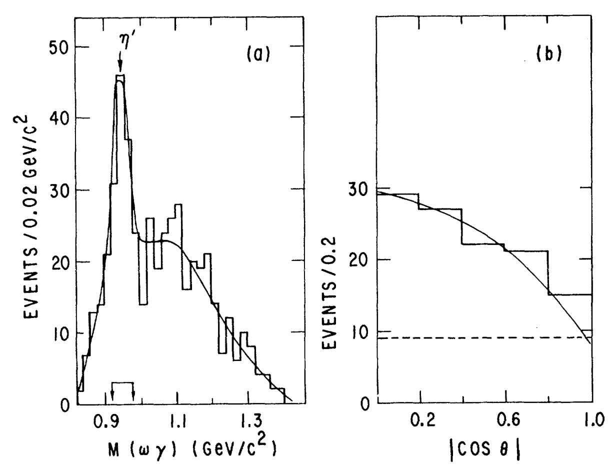

FIG. 3. (a) $\omega\gamma$ effective mass distribution with all the applied cuts. The curve is the result of the two-parameter fit described in the text (478 events). (b) Distribution in $|\cos\theta|$ for the 114 events between the arrows in (a). A small acceptance correction has been applied. The curves are described in the text.

γ pairings, $\gamma_1\gamma_2$. Spectra subject to the same cuts were also examined for the other combinations, and also for a sample of 4γ events. Although a small η' signal was seen, the relative background was so much worse that these combinations were not included in the final sample, but rather a small correction (10%) was made for the events thus excluded.

We believe that most of the remaining background in Fig. 3(a) results from $\omega\pi^0$ events in which one γ was not detected because of geometric acceptance or failure to convert in the lead sheet. We have therefore fitted this mass spectrum with the sum of two terms: (a) a background represented by Monte Carlo–generated, acceptance-corrected $\omega\pi^0$ phase-space events from which one γ of the four was randomly deleted, and (b) the η' peak parametrized by a Gaussian of central mass 955 MeV/c^2 and instrumental width 50 MeV/c^2. This width was obtained by adjusting the spectrometer measurement errors to describe accurately the widths of the π^0 (20 MeV/c^2), ω (40 MeV/c^2), and nucleon [0.8 (GeV/c^2)^2] peaks in Fig. 2. The solid curve in Fig. 3(a) is the result of this two-parameter fit. The fit has a confidence level of 75%, and yields 68 ± 9 $\eta' \to \omega\gamma$ events above background.

We now present evidence that the peak in Fig. 3(a) is consistent with the $\omega\gamma$ decay of a 0^- object, as the η' is believed to be.[7] Such a $0^- \to 1^-\,\gamma$ process is expected to be a magnetic dipole decay, for which angular momentum conservation requires the ω to have helicity ± 1. Consequently, the angle θ between the decay plane normal and the γ direction in the ω rest frame should follow a $1-\cos^2\theta$ distribution.[8] In Fig. 3(b) we show the distribution (corrected for acceptance) in $|\cos\theta|$ of events within ± 30 MeV/c^2 of the η' mass. Events from a control region above the η' have an angular distribution consistent with isotropy. The dotted line in Fig. 3(b) represents the background subtraction of 45 events obtained from the fit shown in Fig. 3(a). The events above this background are described very well by a $1-\cos^2\theta$ distribution, as shown by the solid curve which represents the best fit by the form $a+b(1-\cos^2\theta)$.

Corrections were made for the fraction of $\eta' \to \omega\gamma$ events removed by each of the mass cuts as follows: π^0 mass cut [$(3.0\pm 2.8)\%$], ω mass cut [$(13.7\pm 2.5)\%$], square of the neutron mass cut [$(28.9\pm 7.8)\%$]; and for a small Δ background under the neutron [$(-1.5\pm 0.5)\%$]. The effects of the energy cuts were included in the Monte Carlo acceptance program.

Our results for Reaction (2), the $\eta\pi^+\pi^-$ decay of the η', are presented elsewhere.[9] The data used here to normalize our $\omega\gamma$ data come from preliminary analysis of half the eventual sample. These $\eta\pi^+\pi^-$ data are characterized by a clean η' peak 16 MeV/c^2 wide, with a background of 5% under the peak. A correction of $(11\pm 1)\%$ was applied for events lost by cuts on the tails of the η', η, and nucleon peaks. There are 1505 events in the same interval of momentum transfer [$|t| < 0.4$ (GeV/c)^2] and they correspond to a beam exposure half as large as the one used for $\omega\gamma$.

The geometric acceptances of the apparatus for Reactions (1) and (2) were calculated by a Monte Carlo program which also simulated losses from pion decays and interactions, γ conversion in the target and spark chambers, and the effects of the energy cuts described above. The acceptances for both (1) and (2) vary slowly with $|t|$ between 0.0 and 0.4 (GeV/c)^2, between 0.11 and 0.044 for (1), and between 0.30 and 0.24 for (2). We believe that the ratio of the acceptances is known to at least 5% of itself.

Many systematic errors are common to both (1) and (2) and therefore cancel in the ratio. The most important experimental efficiency which does not cancel is that for converting the third γ, 0.671 ± 0.030. The ratio of all these inefficiencies for (1) relative to (2) is 0.68 ± 0.05. After applying these corrections, and also correcting for unseen decay modes[1] of the ω and η, we obtain the measured branching ratio $(\eta'\to\omega\gamma)/(\eta'\to\eta\pi^+\pi^-) = (6.8\pm 1.3)\%$. Using the published values[1] for the branching ratio $(\eta'\to\eta\pi^+\pi^-)/(\eta'\to \text{all}) = \frac{2}{3}(67.6\pm 1.7)\%$, where the factor $\frac{2}{3}$ is for the unseen $\eta\pi^0\pi^0$ decay, we obtain the branching ratio $(\eta'\to\omega\gamma)/(\eta'\to\text{all}) = (3.07\pm 0.60)\%$. Finally, making use of the known[1] branching ratio $(\eta'\to\rho\gamma)/(\eta'\to\text{all}) = (30.4\pm 1.7)\%$, we find the branching ratio

$$(\eta'\to\rho\gamma)/(\eta'\to\omega\gamma) = 9.9\pm 2.0.$$

The latter result is in excellent agreement with the predictions of many theoretical models,[10-15] which typically obtain values of 9–11, largely as a consequence of vector meson dominance and quite independent of other detailed dynamical assumptions.

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[5]A $\gamma\gamma$ mass plot which includes all three pairings (not shown) has a similar π^0 peak superimposed on a background; the ratio of peak to background at the π^0 peak is 4:1.

[6]Similar plots of square of the missing mass for events outside the η' peak do not show a clean nucleon peak, but rather a monotonically rising spectrum. This is consistent with our belief that most of the "$\omega\gamma$" events which are not η''s are really $\omega\pi^0$ events with an undetected γ.

[7]A recent experiment by the Amsterdam-CERN-Nijmegen-Oxford Collaboration has unambiguously established the spin and parity of the η' as 0^-: S. O. Holmgren *et al.*, CERN Report No. CERN/EP/PHYS 76-37, 1976 (to be published).

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Estimate of the Pseudoscalar Decay Constant

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We calculate the weak decay constant of paracharmonium (η_c) using a linear potential model. The result is somewhat larger than, but of the order of, F_π and depends on the universal Regge slope α'. A number of amusing features are noted.

The weak decay constants of the pseudoscalar mesons are extremely interesting dynamical quantities which also play a fundamental role in the discussion of the *strong* interactions of these particles at low energies. Unfortunately, it has been very difficult to compute them reliably from basic considerations. For example, to get F_π one would have to solve the highly relativistic bound-state problem for the pion in terms of its constituents.

However, there is one pseudoscalar for which we do have a hope of getting a reasonably reliable estimate of the decay constant. This is the η_c which, on the basis of the success of the charmonium picture[1] for ψ/J, would be an s-wave nonrelativistic bound state of a heavy charmed quark and its antiparticle. η_c is of course distinguished by the fact that it is the only pseudoscalar which does not contain (to lowest order) any light quark. We will carry out this calculation here and find that $F(\eta_c)$ is in fact of the same order as F_π and F_K. Some observations and speculations on the reason for this will be discussed later.

For convenience we use a field-theoretic notation. A pseudoscalar-meson bound state B of a