Observation of the Decay $\eta_c \to \phi\phi$ and Determination of the η_c Spin and Parity

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In a study of 2.7 million J/ψ decays with the Mark III, a new magnetic detector at SPEAR, we have observed the sequential decay $J/\psi \to \gamma\eta_c$, $\eta_c \to \phi\phi$. The product branching fraction is $(1.02 \pm 0.25 \pm 0.14) \times 10^{-4}$, where the quoted errors are statistical and systematic, respectively. Analysis of the final-state angular distributions provides the first experimental determination that the spin and parity of the η_c are 0^-.

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The pseudoscalar state associated with the J/ψ, the η_c, was an immediate prediction of the charmonium model. The first observations of an η_c candidate state with mass (2984 ± 4) MeV/c^2 were published by the Crystal Ball[1] and Mark II[2] collaborations. The Crystal Ball collaboration observed this state in the inclusive photon spectra of both the J/ψ and the ψ' and also obtained evidence for its decay into $\eta\pi^+\pi^-$. The Mark II collaboration obtained evidence for this state in ψ' decays by combining several hadronic modes. Although these observations of this state at 2984 MeV/c^2 were consistent with its being a pseudoscalar, there have been no direct tests of its spin and parity. It has been suggested[3] that $\phi\phi$ would be a clean channel for observing the η_c and would also provide a powerful test[4,5] of its spin and parity. Searches in fixed-target experiments[6] for the η_c in this mode have been unsuccessful.

This paper presents results from a high-statistics study of J/ψ decays with a new detector, the Mark III, at SPEAR. We have obtained events from the previously unobserved decay sequence

$$\begin{array}{l} J/\psi \to \gamma\eta_c \\ \quad\quad \hookrightarrow \phi\phi \\ \quad\quad\quad \hookrightarrow K^+K^- \\ \quad\quad\quad \hookrightarrow K^+K^-, \end{array} \qquad (1)$$

and have measured the spin and parity of the η_c by analysis of the decay angular distributions.

The Mark III is a general purpose solenoidal detector[7] optimized for reconstruction of exclusive hadronic final states produced in the SPEAR energy range. A low-mass inner drift chamber surrounding the beryllium beam pipe provides tracking and a first level trigger. The main drift chamber system, in a 0.4-T magnetic field, measures momenta of charged tracks with a resolution of 2% at 1 GeV/c over 84% of the solid angle. Charged particle identification is obtained with a system of 48 time-of-flight (TOF) counters of 5-cm-thick scintillator. These counters, which cover 80% of the solid angle, have a time resolution of approximately 190 psec for hadrons. Between the TOF counters and the solenoid coil is a highly segmented gas sampling calorimeter consisting of 24 layers of alternating $\frac{1}{2}$-radiation-length lead sheets and proportional counters. End-cap shower counters of similar design extend the photon detection to 94% of the solid angle. For 100-MeV photons, the shower counters are fully efficient, and have an angular resolution of 10 mrad and an energy resolution of $0.17E^{1/2}$, where E is in gigaelectronvolts.

The data sample used in this analysis corresponds to $(2.7 \pm 0.23) \times 10^6$ produced J/ψ's. This number was calculated from the number of observed hadronic events and the J/ψ triggering efficiency which was measured to be 93% with a sample of $\psi' \to \psi\pi^+\pi^-$ decays from a separate run.

In the Mark III detector, ϕ mesons are easily identified via their K^+K^- decay mode with use of TOF. The $J/\psi \to \gamma\phi\phi$ events were selected as follows. Events were required to have four well-reconstructed tracks. Pions and kaons are separated at the 3σ level by the TOF counters below 800 MeV/c, which is the relevant range for the kaons in Reaction (1). Events with tracks having TOF information consistent with the pion hypothesis ($|t_{\text{measured}} - t^{\pi}_{\text{predicted}}| \leq 3\sigma$) were rejected. In addition, each K^+K^- pair was required to contain at least one track with positive TOF kaon identification ($|t_{\text{measured}} - t^{K}_{\text{predicted}}| \leq 3\sigma$). Events with small missing mass, e.g., $\gamma 4K$, were selected by requiring $|E_{\text{miss}} - P_{\text{miss}}| \leq 0.15$ GeV, where the missing energy and momentum are computed from the charged tracks only. Evidence for $\phi\phi$ production is given in Fig. 1 which shows the scatter plot of the mass of one K^+K^- pair versus the mass of the other pair.

The decay $J/\psi \to \gamma\phi\phi$ has no background from $J/\psi \to \phi\phi$ or $J/\psi \to \phi\phi\pi^0$ since both are forbidden by charge conjugation invariance. Hence even without shower counter measurement of the photon, a clean sample of $\gamma\phi\phi$ events can be obtained by requiring both K^+K^- pairs to have the ϕ mass. These events, selected on the basis of charged-track information only, were then required to have a shower counter signal from the associated photon. The events in the η_c region were all found to have photon signals. Finally, a four-constraint (4C) kinematic fit by $J/\psi \to \gamma K^+K^-K^+K^-$ was applied. The resulting $\phi\phi$ mass spectrum, Fig. 2, shows a prominent signal in the $\eta_c(2980)$ region. Our mass resolution of 20 MeV/c^2 and the low statistics do not permit us to improve on previous measurements of the mass and width of this state. A maximum-likelihood fit to the data with a Gaussian yields a mass of 2976 ± 8 MeV/c^2, which is consistent with previous measurements.[1,2] The observed width is consistent with our resolution. The estimated background is 1–2 events.

To calculate the branching fraction for the sequential decay (1), we estimated the reconstruction efficiency by Monte Carlo technique to be $(5.8 \pm 0.6)\%$, including the branching ratio for $\phi \to K^+K^-$. The major losses in efficiency are due to the solid angle coverage and the decays in flight of the kaons. Decays in flight cause the efficiency to fall rapidly at lower values of the $\phi\phi$ mass.

From the sixteen events in the η_c signal we obtain

$$B(J/\psi \to \gamma\eta_c) \times B(\eta_c \to \phi\phi) = (1.02 \pm 0.25 \pm 0.14) \times 10^{-4},$$

where the first error quoted is statistical and the second is systematic, arising from the uncertainties in the efficiency and the number of produced J/ψ's. Using the Crystal Ball result[1] for the branching ratio $B(J/\psi \to \gamma\eta_c) = (1.27 \pm 0.36) \times 10^{-2}$, we obtain $B(\eta_c \to \phi\phi) = (8.0 \pm 2.0 \pm 2.5) \times 10^{-3}$.

The angular distributions of the final-state particles in Reaction (1) can be used to determine the spin and parity of the intermediate $\phi\phi$ state. In a generalization of Yang's parity test[8] for the π^0, Chang and Nelson[4] pointed out that a $\phi\phi$ decay mode of the η_c would provide a maxima parity signature for a spin-0 particle. That is, the ϕ decay planes are preferentially orthogonal for odd parity and parallel for even parity. The analysis of the $\phi\phi$ system was extended by Trueman[5] for arbitrary

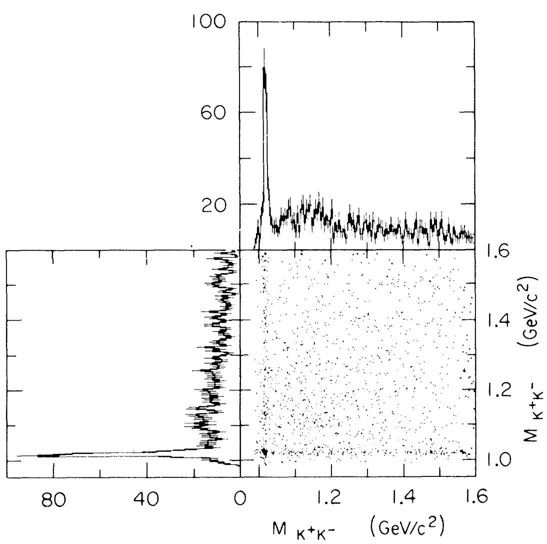

FIG. 1. The mass of one K^+K^- pair vs the mass of the other pair. There are two entries per event if both combinations satisfy the TOF requirement.

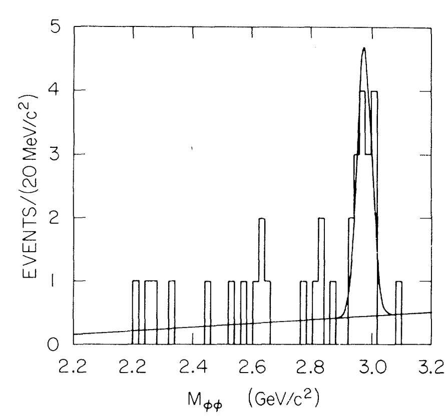

FIG. 2. The $\phi\phi$ mass spectrum. The curve is a fit by a Gaussian with a linear background.

TABLE I. Likelihood ratios of 0^- with respect to J^P.

J^P	$L_{\phi\phi}$	β	Likelihood ratio (χ)	Likelihood ratio (χ, θ_1, θ_2)
0^-	1	-1	1	1
0^+	0	$+0.667$	1.8×10^8	...
1^-	1	0	2200	...
1^+	2	0	2200	...
2^+	0	$+0.07$	5100	...
2^-	1	-0.4	55	4400
2^-	3	-0.6	12	120

spin.

Seven angles are required for a complete description of this decay, if the e^+e^- beams are unpolarized. However, the azimuthal angle between the ϕ decay planes, χ, provides the greatest sensitivity to the $\phi\phi$ spin and parity. When integrated over the other angles, this distribution takes the form[4]

$$dn/d\chi = 1+\beta\cos(2\chi), \tag{2}$$

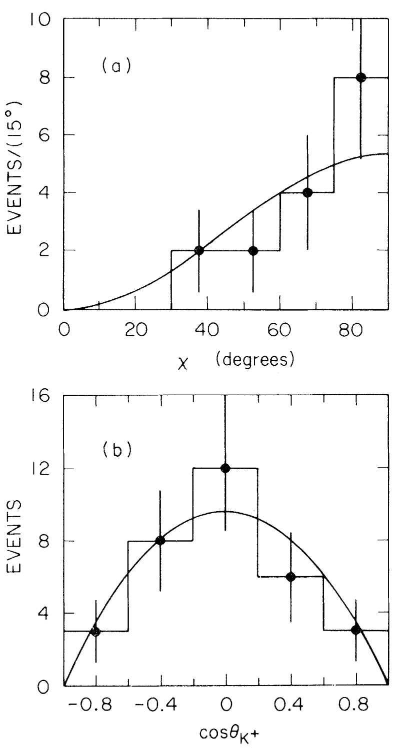

FIG. 3. (a) The distribution of events as a function of the angle between the ϕ decay planes. (b) The polar angle of the K^+ in the ϕ rest frame. The curve is the 0^- prediction in both plots.

where, if the acceptance is sufficiently uniform, the coefficient β is a constant which depends only on the spin and parity of the $\phi\phi$ system and is independent of its polarization. Values of β, which range from -1 to 1, are given in Table I for $J \leqslant 2$ for the lowest allowed values of $L_{\phi\phi}$, the relative orbital angular momentum of the ϕ's. As emphasized by Trueman,[5] β is zero for odd spin, and nonzero for even spin. Its sign is the parity of the $\phi\phi$ system.

The acceptance of the Mark III detector is flat in χ and is sufficiently uniform in the other angles so that the integration over them in (2) is valid. The χ distribution is shown in Fig. 3(a) overplotted with the pseudoscalar prediction, which corresponds to $\beta=-1$. The data agree well with this prediction. The value of β prefered by the data is -1. The logarithm of the likelihood relative to $\beta=-1$ is shown as the solid line in Fig. 4. This negative value of β implies that the $\phi\phi$ system is in a J^P (even)$^-$ state. The ratios of the likelihood of 0^- to other spins and parities as determined from this distribution are given in the Table I.

Further discrimination between the 0^- and the 2^- hypotheses is obtained by including in the description of the decay the polar angles, θ_1, θ_2, of the two K^+'s in their respective ϕ rest frames relative to the ϕ momenta in the η_c rest frame. The data, with two entries per event, are shown in Fig. 3(b) along with the prediction for 0^-. For this case the prediction is simply $\sin^2\theta$ since the ϕ's are polarized along their direction of motion. To combine the information given by the χ distribution with that of θ_1 and θ_2, we consider the joint distribution of these three angles, which for even spin and odd

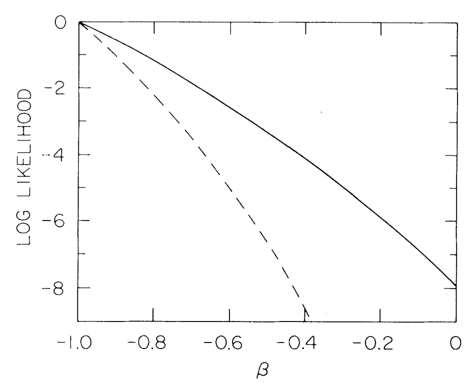

FIG. 4. The logarithm of the likelihood relative to $\beta=-1$. The solid curve corresponds to the χ distribution [Eq. (2)]. The dashed curve corresponds to the joint distribution of χ, θ_1, θ_2 [Eq. (3)].

parity is given by

$$\frac{d^3 n}{d\chi \, d\cos\theta_1 \, d\cos\theta_2} = -\beta \sin^2\theta_1 \sin^2\theta_2 \sin^2\chi + \tfrac{1}{2}(1+\beta)(\sin^2\theta_1 \cos^2\theta_2 + \cos^2\theta_1 \sin^2\theta_2 + \tfrac{1}{2}\sin 2\theta_1 \sin 2\theta_2 \cos\chi). \quad (3)$$

The preferred value of β is again -1. The logarithm of the likelihood function relative to 0^- is shown as the dashed curve in Fig. 4. The likelihood ratio of 0^- to 2^-, as computed from this distribution, is 4400, assuming $L_{\phi\phi}=1$. However, a $J^P=2^-$ state can also have an F-wave component. A pure F-wave state would have $\beta=-0.6$ and for this we find a likelihood ratio of 120. (The P wave and F waves could interfere and produce a β ranging from -1 to 0.) Aside from this possible mixing, the addition of the polar angles thus confirms that 0^- is preferred over 2^-. The remaining angular distributions have been examined and were found to be consistent with 0^-, but do not significantly change the likelihood ratios.

In summary, we have observed the decay $J/\psi \to \eta_c$, $\eta_c \to \phi\phi$ with a product branching fraction of $(1.02 \pm 0.25 \pm 0.14)\times 10^{-4}$. We find that the pseudoscalar assignment of this state is strongly favored. This provides confirmation for the identification of this state as the ${}^1S_0$ state of charmonium.

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