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A MEASUREMENT OF $\eta_c \to \phi\phi$ IN THE RADIATIVE DECAY OF THE J/ψ

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A total of 8.6 million J/ψ produced in the DM2 experiment at DCI have been analyzed looking for the η_c in the reaction $J/\psi \to \gamma\eta_c \to \gamma\phi\phi$, both ϕ's decaying into two charged kaons. The η_c is observed, with $m = (2968 \pm 5 \pm 7)\mathrm{MeV}/c^2$ and with a product branching ratio for $J/\psi \to \gamma\eta_c \to \gamma\phi\phi$, $\mathrm{BR} = (0.39 \pm 0.09 \pm 0.09) \times 10^{-4}$. The spin–parity analysis confirms the 0^- assignment obtained by a previous experiment.

Introduction. The existence of the pseudoscalar partner of the J/ψ, the η_c, predicted by the charmonium model, is since long established: the first observation was made by the MARK II [1] and Crystal Ball [2] experiments. In order to measure its quantum numbers, the decay $\eta_c \to \phi\phi$ was looked for, as this channel provides a clear test of the spin and parity of the η_c [3].

In a study of the radiative decay $J/\psi \to \gamma\phi\phi$, MARK III [4] observed a clean peak in the $(\phi\phi)$ mass at the η_c. The angular analysis of these events indicated that the spin–parity for the observed peak was 0^-, and strongly supported the η_c assignment.

In this paper we present results from a study of the same decay done by the DM2 detector at DCI. An enhancement of 23 events is present at the η_c mass, together with a lower $(\phi\phi)$ mass production. A specific study of the low mass $(\phi\phi)$ production will be developed in a forthcoming paper. The decay angular distribution confirms the 0^- assignment for the η_c. The adjacent events at lower $(\phi\phi)$ mass do not fit with this hypothesis.

Experimental set-up. The DM2 detector [5], operated at DCI, the Orsay e^+e^- colliding ring, is a large solid angle spectrometer. A 0.5 T field is produced by a 2 m diameter and 3 m length solenoid with a 1 X_0 aluminium coil.

Two thin proportional chambers surrounding the $1.18 \times 10^{-2}\, X_0$ titanium beam pipe contribute to the tracking and to the first level trigger. The drift chamber system measures charged tracks over 87% of the

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total solid angle with a momentum resolution of 3.5% at 1 GeV/c.

A system of 36 2 cm thick scintillators covering 80% of the solid angle, measures the time-of-flight with a resolution $\sigma = 540$ ps including 440 ps from the beam time spread, and provides a 3σ π/K separation up to 450 MeV/c.

Outside the coil there is the photon detector barrel (5 X_0), divided in 8 octants. Each octant consists of 14 planes of delay line streamer tubes interleaved with lead, and 5 planes of 3 scintillators. The barrel covers 70% of the solid angle with a detection efficiency greater than 96% for $E_\gamma \geqslant 110$ MeV; the resolution in the photon direction is 10 mrad in azimuth and 7 mrad in polar angle. Two end-cap photon detectors, for a total of 5 X_0, are inside the magnetic field, covering 12% of the solid angle. They consist of 2 × 122 elementary cells built up by 12 planes of wire chambers in semi-proportional regime, interleaved with lead sheets. The angular acceptance of the cells varies from (57 × 25) mrad^2 at 8°, to (113 × 30) mrad^2 at 29° with respect to the beam line.

Events selection. The data sample used in this analysis is the whole 8.6 million collected J/ψ. This number was calculated from a study of the J/$\psi \to \rho\pi$ channel, using for its branching ratio a world average value of $(1.42 \pm 0.2) \times 10^{-2}$.

The J/$\psi \to \gamma\phi\phi$ candidates were selected identifying both ϕ's in their K$^+$K$^-$ decays. The events were required to have four well reconstructed tracks, coming from a common vertex inside the fiducial region along the beams, with zero total charge. The kaons are tracked even if they decay inside the drift chamber as soon as the transerve flight is greater than 60 cm.

The missing energy of each event, in the hypothesis that all the tracks are kaons, has to match the missing momentum within 200 MeV:

$$|E_{\mathrm{miss}} - p_{\mathrm{miss}}| \leqslant 200 \text{ MeV}.$$

A loose time-of-flight condition is then applied. Each event is required to have at least one measured TOF and all the measured TOF's consistent with the kaon assignment within 3σ (1.7 ns). In order to select $\phi\phi$ events, the two independent K$^+$K$^-$ pair masses have to match the ϕ mass within 20 MeV/c^2:

$$|m_{\mathrm{KK}} - m_\phi| \leqslant 20 \text{ MeV}/c^2.$$

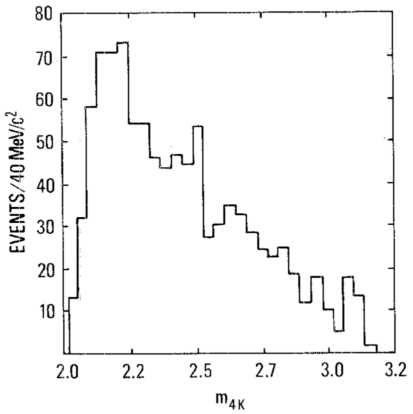

Fig. 1. Four-kaon invariant mass at the first events selection level (GeV/c^2).

The invariant four-kaon mass distribution of the accepted events is shown in fig. 1. At the top edge of a large smooth background, a small signal is present at the expected η_c mass, close to a peak of non-radiative events corresponding to the J/ψ.

The η_c analysis. In order to isolate the η_c peak, we have asked for more stringent conditions which improve the signal over background ratio, and do not reduce the statistical significance of the peak.

All the events with more than one gamma in the photon detector, including the end-caps, were rejected. The products of the interactions of the charged particles into the detector, which mimic real photons, were identified by pattern recognition and TOF's measurements in the octants and discounted.

At the η_c mass more kaons tag the time-of-flight counters than at lower ($\phi\phi$) mass and, consequently, the spread of this measurement is reduced, since the probability for a kaon to decay is low. Then we have required at least two measured time-of-flights, and each measured TOF consistent with the kaon hypothesis within 2σ (1.2 ns).

Finally a one-constraint kinematical fit was applied; the radiative photon information was not used, because events with zero detected gamma were accepted too. Only the events with $\chi^2 < 5$ were retained.

The final distribution of the four-kaon invariant mass is given in fig. 2 for the selected events. A clear enhancement appears at the η_c mass at the end of a large lower mass spectrum; the peak at the J/ψ, be-

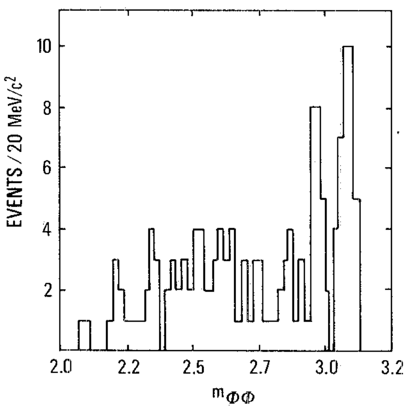

Fig. 2. $\phi\phi$ invariant mass for the $\gamma\phi\phi$ candidates (GeV/c^2).

longing to non-radiative events, still remains.

The scatter plot of the mass of the first (K^+K^-) pair which in the analysis falls in the ϕ window against the mass of the other pair, figs. 3a, 3b, shows the evidence for the ($\phi\phi$) dynamics for the η_c events, and for the events at lower mass. The uniform distribution of the (K^+K^-) mass for the events at the J/ψ, fig. 3c, indicates that here we are dealing with ϕK^+K^- events, as expected since the $J/\psi \to \phi\phi$ decay is forbidden by C invariance.

The reconstructed total energy of the $J/\psi \to \phi K^+K^-$ events agrees well with the Monte Carlo simulation. The resolution, σ = 20 MeV, obtained after the kinematical fit, excludes any background from the J/ψ peak under the η_c (< 0.3 events).

Background can originate from a non-resonant $\gamma\phi\phi$ production and from channels which mimic $\gamma\phi\phi$ events. The latter effect was evaluated from the events with one K^+K^- mass into the ϕ mass window and the other one into the adjacent window:

$$20\ \mathrm{MeV}/c^2 < (m_{KK} - m_\phi) \leqslant 60\ \mathrm{MeV}/c^2,$$

or with both the masses inside this adjacent window. Those events were independently selected and analyzed like the candidate events: the few which survive the analysis (10, for $m_{\phi\phi} > 2680$ MeV) are distributed all over the ($\phi\phi$) mass spectrum. Then an overall contribution from the two effects has been calculated by fitting the experimental ($\phi\phi$) mass distribution with a polynomial plus a gaussian function (fig. 4): at the η_c mass the background has been evaluated to 4 ± 2 events, and has been subtracted. A gaussian function was used because the observed width of the η_c, σ = (17 ± 3) MeV/c^2, is consistent with the experimental mass resolution.

We found for the η_c mass a value of (2968 ± 5 ± 7) MeV/c^2, in agreement with previous measurements. No information on the η_c width can be inferred from these data.

The efficiency estimated by Monte Carlo for the sequential decay

$$J/\psi \to \gamma\eta_c \to \gamma\phi\phi \to \gamma(K^+K^-)(K^+K^-)$$

is (5.7 ± 0.3)%, for a 0^- intermediate particle. This value does not change appreciably for different spin–parity assignment. The major losses in efficiency are due to the solid angle coverage, and the decays in flight of the kaons. From the 19 events in the η_c signal, we

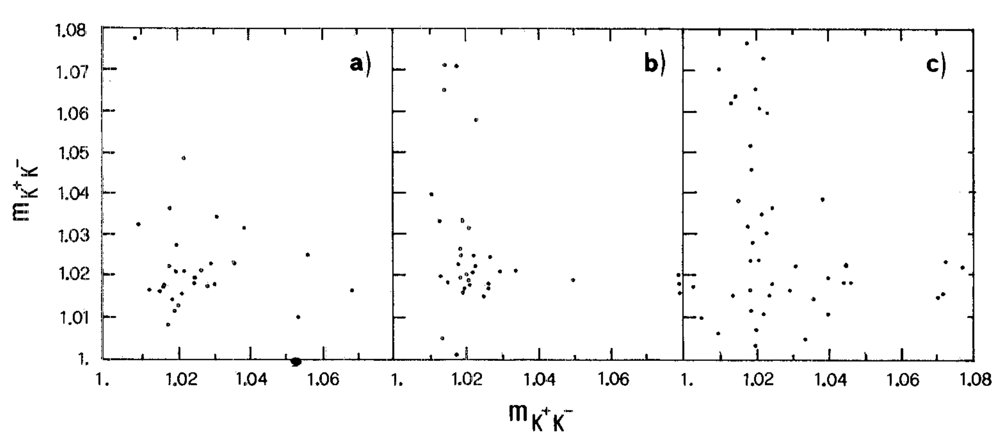

Fig. 3. First K^+K^- mass in the ϕ window (GeV/c^2) versus the opposite one for the events with invariant mass: (a) $2900 < m_{\phi\phi} <$ 3000 MeV/c^2, (b) $2700 < m_{\phi\phi} <$ 2900 MeV/c^2, (c) $m_{\phi\phi} >$ 3000 MeV/c^2.

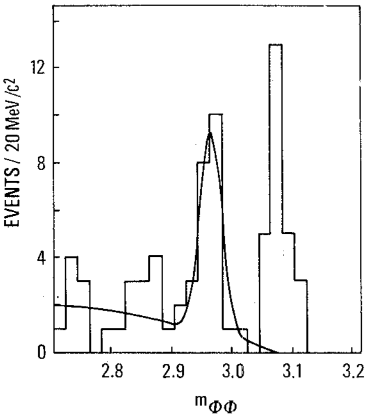

Fig. 4. Final $\phi\phi$ invariant mass distribution (GeV/c^2). The fit is overplotted.

obtain

$$\mathrm{BR}(J/\psi \to \gamma\eta_c) \times \mathrm{BR}(\eta_c \to \phi\phi)$$

$$= (0.39 \pm 0.09 \pm 0.09) \times 10^{-4},$$

where the first quoted error is statistical and the second is systematic, arising from the uncertainties in the efficiency and the number of analyzed J/ψ. This value is 2σ below the MARK III [4] measurement. Using the Crystal Ball result [2] for the branching ratio $\mathrm{BR}(J/\psi \to \gamma\eta_c) = (1.27 \pm 0.36) \times 10^{-2}$ we obtain

$$\mathrm{BR}(\eta_c \to \phi\phi) = (3.1 \pm 0.7 \pm 0.4) \times 10^{-3}.$$

Spin–parity assignment of the η_c. The angular distribution of the four kaons and the gamma, identified with the missing momentum, can be used to determine the spin and parity of the intermediate ($\phi\phi$) state. The analysis is similar to the one of ref. [4]. A straightforward extension of the Yang's parity test [6] for the π^0 gives that the two ϕ decay planes are preferentially orthogonal or parallel according to whether they are produced by an odd-parity or an even-parity intermediate state, respectively. This analysis of the ($\phi\phi$) system was generalized by Trueman [3] for an intermediate state of arbitrary spin. Seven angles describe completely the sequential decay, but three angles are the most sensitive to the ($\phi\phi$) spin and parity: the angle χ, between the ϕ decay planes, and the two polar angles, θ_1 and θ_2, of the K^+'s in their respective rest frame relative to the ϕ momenta in the η_c rest frame.

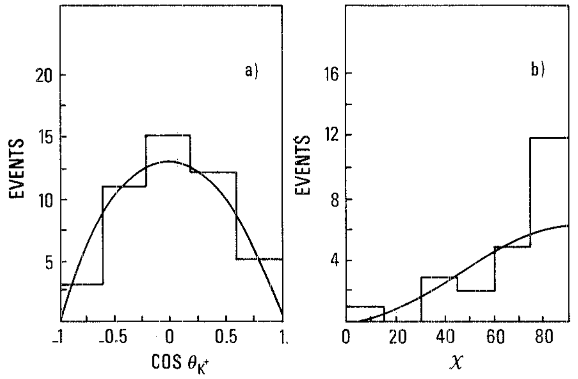

Fig. 5. Experimental distribution for χ (angles) and $\cos\theta_K$ for the η_c events. The expected 0^- shapes are overplotted.

The resulting distribution for a full acceptance detector and an (even J)–(odd parity) assignment has the form

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

Table 1
Likelihood ratios of 0^- with respect to J^P for η_c and background events.

J^P	$L_{\phi\phi}$	$S_{\phi\phi}$	β	Likelihood ratio, χ angle		Likelihood ratio, χ, θ_1, θ_2 angles	
				η_c events	background	η_c events	background
0^-	1	1	−1	1	1	1	1
2^-	3	1	−0.6	26	2.0×10^{-4}	150	2.0×10^{-6}
2^-	1	1	−0.4	192	1.8×10^{-4}	1.3×10^4	1.2×10^{-6}
$1^{+(-)}$	2(1)	2(1)	−0	2.8×10^4	9.4×10^{-4}	–	–
2^+	0	2	0.07	8.3×10^4	1.6×10^{-3}	–	–
0^+	2	2	0.333	1.0×10^7	2.3×10^{-2}	–	–
0^+	0	0	0.667	1.2×10^{12}	10	–	–

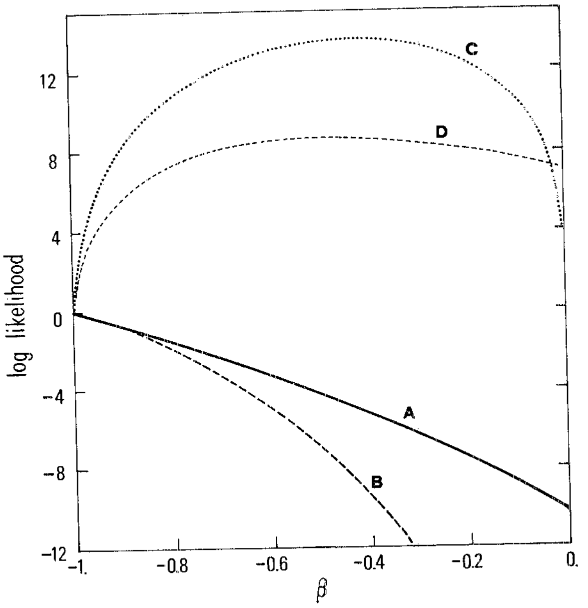

Fig. 6. Log likelihoods, relative to $\beta = -1$, of the (χ, θ) joint distribution (line A) and χ distribution (line B) for the η_c events. The same distributions (lines C and D) for the events with invariant mass below the η_c.

The coefficient β depends only on the spin and parity of the $(\phi\phi)$ system and is independent of its polarisation. The physical values of β range from −1 to 1, and its sign gives the parity of the $\phi\phi$ system. In particular, β is zero for odd spin and nonzero for even spin, with $\beta = -1$ for a pseudoscalar intermediate state.

Integration over all the angles, except χ, leads to the distribution

$$\mathrm{d}n/\mathrm{d}\chi = 1 + \beta \cos 2\chi, \qquad (2)$$

which is correct for any J^P assignment.

The DM2 detector has an angular acceptance sufficiently uniform so that the integration done to obtain the distributions (1) and (2), respectively, are valid.

Figs. 5a, 5b show the experimental χ and $\theta_{1,2}$ distributions, relative to the η_c events, with the expected 0^- shapes overplotted: the data agree well with this hypothesis. Then the value preferred by the data is $\beta = -1$. Fig. 6 shows the log likelihood relative to $\beta = -1$ hypothesis, for the $(\chi, \theta_{1,2})$ joint distributions and for the χ distribution alone (lines A and B, respectively).

The ratios of the likelihood of the 0^- to other spin and parities are given in table 1 (columns 5 and 7), for the two distributions respectively. The χ distribution is sufficient to assign an odd parity to the η_c; the joint $(\chi, \theta_{1,2})$ distributions indicate that the 0^- assignment is strongly preferred over 2^-, if the two ϕ's are produced in a pure P or F wave. Possible mixing of these two angular states has not been considered. The remaining angular distributions are consistent with 0^- as well.

The same analysis was performed for 23 events, below the η_c, with $2680 < m_{\phi\phi} < 2900$ MeV/c^2. The log likelihoods, relative to $\beta = -1$, for the joint $(\chi, \theta_{1,2})$ distributions and for the χ distribution alone are reported in fig. 6, lines C and D, respectively. The ratios of the likelihood of the 0^- to other spins and parities are given in table 1 (columns 6 and 8), for the two distributions, respectively.

No assignment can be given for the spin and parity of these events, but the 0^- hypothesis is strongly depressed.

Conclusions. We have observed a clean $(\phi\phi)$ production in the radiative decays of the J/ψ. The invariant mass distribution of the $(\phi\phi)$ system shows an enhancement at the η_c mass and the production of lower $(\phi\phi)$ masses. The angular distributions strongly suggest the presence of an intermediate pseudoscalar state at the η_c mass. The adjacent events at lower $(\phi\phi)$ mass do not fit with this hypothesis. In summary, the decay $J/\psi \to \gamma\phi\phi$, at 2968 MeV/$c^2$, proceeds via an intermediate resonant state with a branching ratio $(0.39 \pm 0.09 \pm 0.09) \times 10^{-4}$. The 0^- assignment is clearly favoured by the data and gives confirmation for the identification of this state to the η_c.

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