FIRST OBSERVATION OF THE $\eta_c \to \rho^0\rho^0$ DECAY

DM2 Collaboration

D. BISELLO, G. BUSETTO, A. CASTRO, S. LIMENTANI, M. NIGRO, L. PESCARA, M. POSOCCO, P. SARTORI, L. STANCO
Dipartimento di Fisica dell'Università di Padova, e INFN, Sezione di Padova, I-35131 Padua, Italy

Z. AJALTOUNI, A. FALVARD, J. JOUSSET, B. MICHEL, J.C. MONTRET
Laboratoire de Physique Corpusculaire, Université de Clermont II, BP 45, F-63170 Aubière, France

R. BALDINI, S. CALCATERRA, G. CAPON
Laboratori Nazionali di Frascati dell'INFN, CP 13, I-00044 Frascati, Italy

J.-E. AUGUSTIN, G. COSME, F. COUCHOT, B. DUDELZAK, F. FULDA, G. GROSDIDIER, B. JEAN-MARIE, S. JULLIAN, D. LALANNE, V. LEPELTIER, F. MANE, C. PAULOT, R. RISKALLA, Ph. ROY and G. SZKLARZ
Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, F-91405 Orsay, France

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The decay $J/\psi \to \gamma\eta_c \to \gamma\pi^+\pi^-\pi^+\pi^-$ has been studied from the 8.6×10^6 J/ψ produced in the DM2 apparatus at DCI. A clear signal of (137 ± 23) events is observed in the η_c mass range. A partial wave analysis shows that the decay proceeds mainly through $\rho^0\rho^0$ dynamics with $BR(J/\psi\to\gamma\eta_c)\times BR(\eta_c\to\rho^0\rho^0)=(1.10\pm0.10\pm0.20)\times10^{-4}$. The observation of the $\eta_c\to\rho^0\rho^0$ decay gives the first high-statistics evidence of the pseudoscalar nature of the η_c.

1. Introduction. The pseudoscalar ${}^1S_0$ state of charmonium, called η_c, has been first observed by the Crystal Ball [1] and MARK II [2] experiments at a mass of (2984 ± 4) MeV/c^2. Its spin-parity has been measured to be 0^- by MARK III [3] and DM2 [4] Collaborations from clean, but statistically poor, samples of $\eta_c\to\phi\phi$ events (16 and 23 events respectively).

In a recent study of various η_c hadronic decays, MARK III [5] has reported an upper limit of 0.6×10^{-4} (90% CL) for the decay $J/\psi\to\gamma\eta_c\to\gamma\rho^0\rho^0$, whereas a relevant four charged pion decay branching ratio, $BR(J/\psi\to\gamma\eta_c)\times BR(\eta_c\to4\pi^\pm)$, was found.

In this paper we present the study of the decay $J/\psi\to\gamma\eta_c\to\gamma\pi^+\pi^-\pi^+\pi^-$ from the $(8.6\pm1.3)\times10^6$ J/ψ collected by the DM2 experiment at DCI. This result comes from an analysis of the full 4π mass spectrum from the $J/\psi\to\gamma\pi^+\pi^-\pi^+\pi^-$ decay [6,7], which will be published in a forthcoming paper. The peak observed at the η_c mass has been analysed in order to look for a $\rho^0\rho^0$ contribution. In contradiction with the MARK III result, the $\eta_c\to\pi^+\pi^-\pi^+\pi^-$ decay is found to be largely dominated by a $J^P=0^-$, $\rho^0\rho^0$ dynamics.

2. Detector. The DM2 detector [8], 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 in diameter and 3 m long solenoid with a $1X_0$ aluminium coil. Inside the magnet, proportional and drift chambers allow the measure of charged tracks over $87\%\times4\pi$ steradians with a momentum resolution of 3.5% at 1 GeV/c. The photon detector barrel ($5X_0$), divided into octants, is outside the coil:

it mainly consists of planes of streamer tubes with delay line interleaved with lead. The barrel covers $70\% \times 4\pi$ steradians with a resolution on the photon direction of 10 mrad in azimuth and 7 mrad in polar angle. The apparatus is fully efficient (> 96%) at the energy of the radiative photon in $J/\psi \to \gamma\eta_c$, and is able to recognize radiative photons from the products of pion interactions with the detector. Two end-cap photon detectors, of $5X_0$ each, are inside the magnetic field, covering 12% of the solid angle. Due to its bad angular resolution, this detector is used only as veto to define the requested topology.

3. Events selection. We have looked for events with one photon and four charged tracks; the tracks must belong to a common vertex inside a fiducial volume along the beam axis, and the total charge must be zero. Only one photon has to be detected in the barrel calorimeter, and no isolated tracks have to be found in the end-caps.

The missing energy of each event, in the hypothesis that all the tracks are pions, has to match the missing momentum within 200 MeV/c^2.

The selection of the radiative four pions events from the large five pions production is done by a cut on the variable $p_T^2 = 4p^2 \sin^2(\theta/2)$, where θ is the acollinearity angle between the photon and the direction of the missing momentum. Then a 3C fit is applied, where the kinematical parameters, except the unknown energy of the γ, are constrained by the energy–momentum conservation. The accepted events are required to have $p_T^2 \leqslant 1500$ (MeV/c)^2, and $\chi^2_{3C} \leqslant 9$.

The selected events are still contaminated by $J/\psi \to \pi^+\pi^-\pi^+\pi^-\pi^0$ events where the π^0 decays asymmetrically, the weak photon being undetected. However, the 5π contamination is found smoothly decreasing in the η_c mass range, as expected since the η_c is beyond the end point of the $4\pi^\pm$ phase space. Furthermore, $J/\psi \to \omega\pi^+\pi^-$ events are eliminated by a cut on the $\pi^+\pi^-\pi^0$ invariant mass, where the π^0 is associated to the missing momentum.

Background from $\gamma K^0_S K^\pm \pi^\pm$, $\gamma K^0_S K^0_S$, $K^0_S K^\pm \pi^\pm \pi^0$ events has also been eliminated by a cut on the $\pi^+\pi^-$ mass. These cuts are practically useless in the η_c mass range. More details on this analysis can be found in ref. [6].

The $4\pi^\pm$ invariant mass distribution of the surviving events in the η_c zone is shown in fig. 1a. Two clear peaks are present. The first, on the left, is easily identified to the η_c, while the second one comes from non-radiative $J/\psi \to 4\pi^\pm$ events, where a fake photon has been found. From the J/ψ peak the percentage of $\gamma\pi^+\pi^-\pi^+\pi^-$ with a fake photon can be evaluated to less than 3%, as expected from Monte Carlo: then events with more than one photon were not analysed.

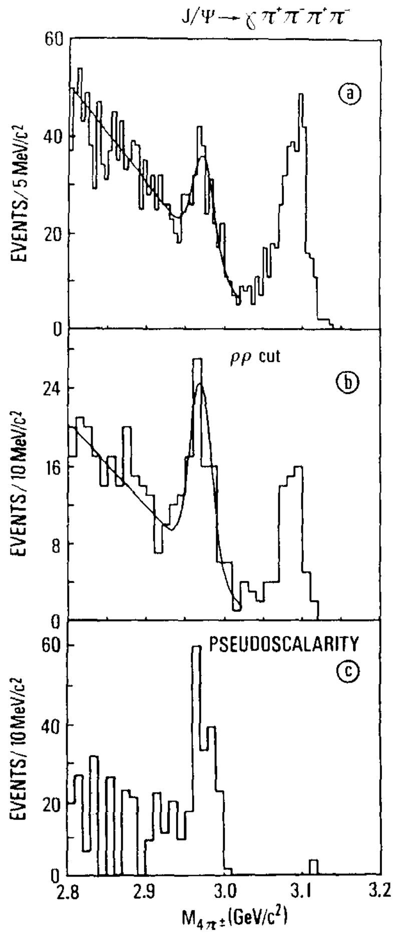

Fig. 1. $M_{4\pi}$ distribution in the η_c region. All the events (a). After the $R > 1/15$ cut (b). Pseudoscalar component (c).

4. Analysis. An unbinned fit to a polynomial added to a gaussian function over the $4\pi^\pm$ mass distribution (fig. 1a) gives the following η_c parameters:

$$m_{\eta_c} = 2973.3 \pm 2.7 \text{ MeV}/c^2 ,$$

$$\sigma_{\eta_c} = 14.8 \pm 2.4 \text{ MeV}/c^2 ,$$

the computed σ being in good agreement with the 13.3 MeV/c^2 mass resolution expected from Monte Carlo simulation. The efficiency at the η_c energy has been estimated from $\gamma 4\pi^\pm$ phase space Monte Carlo to be (12 ± 1)%: no relevant differences are found if a $\rho^0\rho^0$ dynamics is imposed. The corresponding branching ratio is

$$\mathrm{BR}(\mathrm{J}/\psi\to\gamma\eta_c)\times\mathrm{BR}(\eta_c\to4\pi^\pm)$$
$$=(1.33\pm0.22\pm0.20)\times10^{-4}\ ,$$

where the systematic error comes mainly from the normalisation. This value is in agreement with a previous measurement [5].

In order to evidentiate the possible $\rho^0\rho^0$ dynamics, different approaches have been used. First a simple $\rho^0\rho^0$ cut has been implemented using the quantity

$$R=\prod_{i=1,2}\frac{m_\rho^2\Gamma_\rho^2}{(m_i^2-m_\rho^2)^2+m_\rho^2\Gamma_\rho^2}\ ,$$

where m_i are the $\pi^+\pi^-$ invariant masses and m_ρ and Γ_ρ are the tabulated ρ meson mass and width. The $4\pi^\pm$ invariant mass distribution is shown in fig. 1b if $R>1/15$ for at least one of the two possible $\rho^0\rho^0$ combinations. The signal-over-background ratio at the η_c is increased, and the 3.1 GeV/c^2 fake peak is lowered. The fitted η_c parameters are fully consistent with the previous ones.

The $\rho^0\rho^0$ component in the $4\pi^\pm$ final state has been estimated using a maximum likelihood technique. Four populations, described by isotropic $\rho^0\rho^0$, $\rho^0\pi^+\pi^-$, $a_2\pi$, 4π phase space, have been assumed. Only the events with $\rho^0\rho^0$ dynamics show a resonant behaviour (fig. 2); their number accounts for the full $\eta_c\to4\pi^\pm$ decay.

In order to test that the observed peak is the η_c, a pseudoscalarity test has been performed. When the η_c decays into two identical vectors, as in this case, there are special angles which allow to distinguish between various spin-parity assignments. The most selective one is the angle χ between the decay planes of the two vectors [9]. Its distribution, integrated over the other angles, takes the form

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

where $\beta=0$ for J=odd, and $-1\leqslant\beta\leqslant1$ for J=even. In particular, $\beta=-1$ for a pseudoscalar (vector–vector) state. The DM2 angular acceptance is sufficiently flat so that the integration done to obtain the formula above is valid. In fig. 3, the χ angle distribution is shown, in three mass intervals, for all the events, and for those selected by the $\rho^0\rho^0$ cut. The η_c region exhibits a clear $\sin^2\chi$ behaviour which is emphasized by the $\rho^0\rho^0$ cut. A similar but smaller effect is present below the η_c reflecting the presence of a pseudoscalar $\rho^0\rho^0$ production at lower 4π masses [6,7].

The χ distribution of the events (fig. 1a), by 10 MeV/c^2 mass bin, has been fitted to the function $\mathrm{d}N/\mathrm{d}\chi=a+b\sin^2\chi$ in order to evaluate the fraction of pseudoscalar events per mass bin. The χ angle distribution of 5π has been checked to be flat by Monte

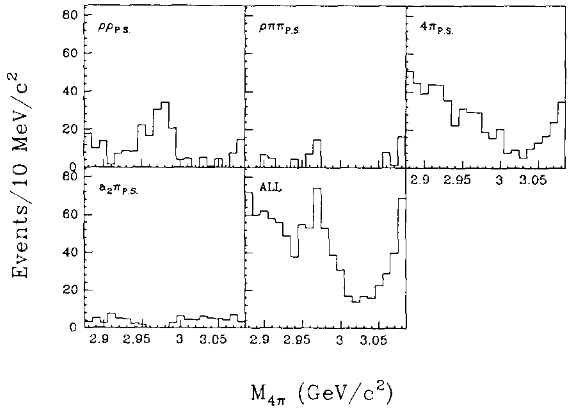

Fig. 2. $M_{4\pi}$ distributions in the η_c region for the four phase space channels, $\rho\rho$, $\rho\pi^+\pi^-$, $a_2\pi$, 4π.

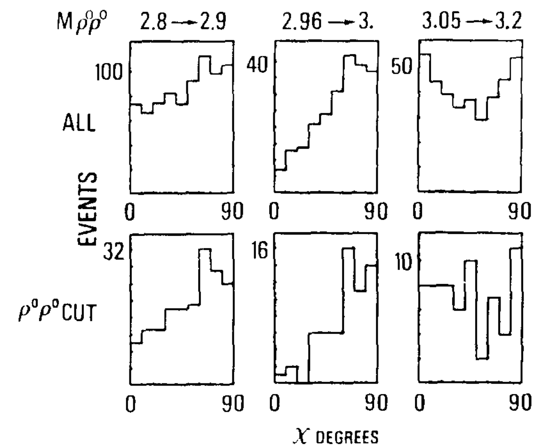

Fig. 3. The χ angle distribution for three $M_{4\pi}$ regions, below the η_c, at the η_c and in the J/ψ region. All the events (a). After the $R>1/15$ cut (b).

Carlo. The overall distribution is shown in fig. 1c.

Finally, in order to estimate the different contributions to the η_c signal a full partial wave analysis (PWA) [#1] has been developed. The multichannel analysis is based on the maximization process of a likelihood function, which takes care of various decay channels contributing to the $J/\psi \to \gamma 4\pi^{\pm}$ reaction. Ten different pure waves of the $(\rho^0\rho^0)$ system, with L, S values corresponding to a spin from $J=0$ to $J=2$, and four phase space channels, $\gamma 4\pi$, $\gamma\rho\rho$, $\gamma\rho\pi\pi$, $\gamma a_2\pi$, have been considered. The maximization gives the percentage of every channel and the x, y parameters which define the production helicity amplitudes, for a total of 26 free variables [6].

The result is shown in fig. 4. A clean peak appears in the 0^- $(\rho^0\rho^0)$ channel, demonstrating the existence of the $\eta_c \to \rho^0\rho^0$ decay. A fit to a gaussian function added to a polynomial one gives η_c parameters fuly consistent with the previous ones. On the contrary the 4π phase space does not exhibit a resonant behaviour: nevertheless a η_c contribution to this channel cannot be excluded. All the other channels are scarcely populated.

The analysis method has been checked in two different ways [#2]. First we have tested the capability to recognize single channel contribution by PWA. Large samples of Monte Carlo events have been generated for each channel. They have been divided into subsamples, numerically equivalent to the experimental events, which have passed through the same analysis as the data. The PWA method identifies all the pure waves and the $4\pi^+$ and $a_2\pi$ phase spaces at $(90\pm10)\%$ level, while isotropic $\rho^0\rho^0$ events are dis-

[#1] Pure wave analysis, in fact.

[#2] More than 5×10^7 events have been generated in order to perform a complete Monte Carlo control.

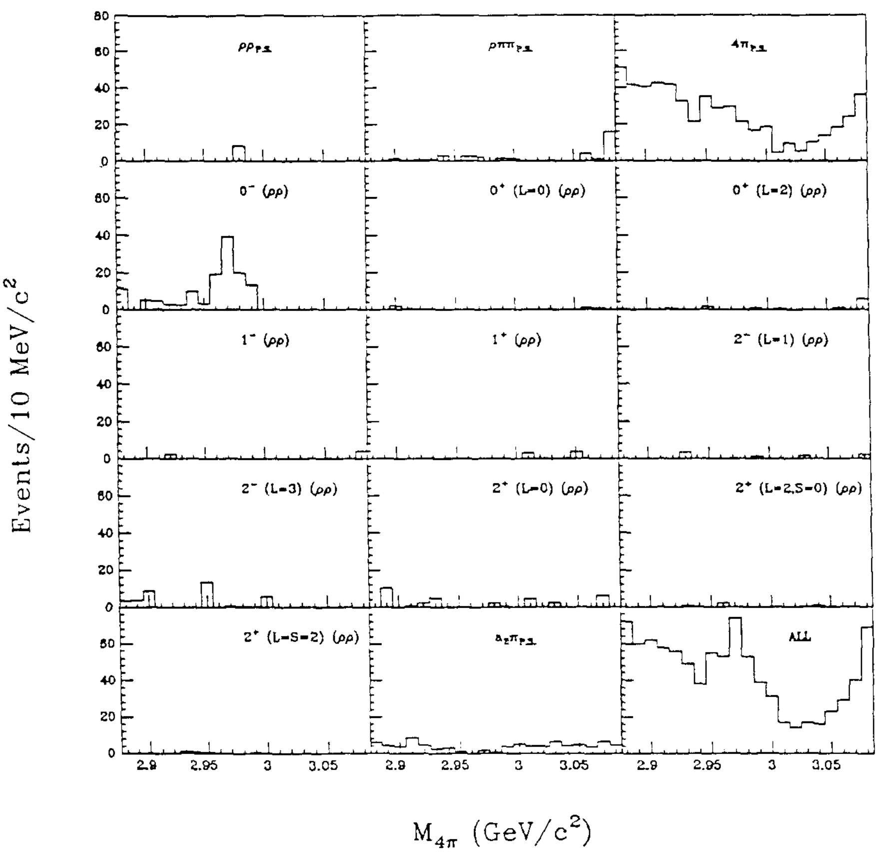

Fig. 4. $M_{4\pi}$ distribution obtained by the PWA method, for the 14 considered hypotheses.

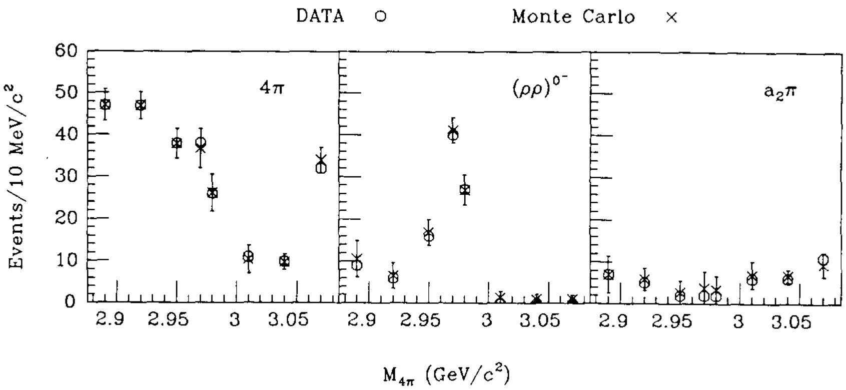

Fig. 5. (a) PWA results for samples of Monte Carlo $a_2\pi$, 4π and $\rho^0\rho^0 0^-$ events (white spots), mixed in the percentages found for the experimental data, compared with the fits to the experimental data (black points). The error bars include the statistical and PWA uncertainties.

tributed in the various $\rho^0\rho^0$ waves and isotropic $\rho\pi\pi$ events are mainly recovered in 4π (50%) and $a_2\pi$ (30%) channels.

Secondly, samples of 0^- $\rho^0\rho^0$, $a_2\pi$, $4\pi^\pm$ generated events, mixed in the same percentage as found in the experimental data, have been analysed by PWA; the imposed percentages have been reobtained (fig. 5). These results confirm that we have isolated a real 0^- $\rho^0\rho^0$ signal.

From the (113 ± 11) $\rho^0\rho^0$ 0^- events the estimated product branching ratio is

$$\mathrm{BR}(J/\psi\to\gamma\eta_c)\times\mathrm{BR}(\eta_c\to\rho^0\rho^0)$$
$$=(1.10\pm0.10\pm0.20)\times10^{-4}\ ,$$

where the systematic error includes the PWA method uncertainties. The η_c branching ratio into $\rho^0\rho^0$ can be calculated,

$$\mathrm{BR}(\eta_c\to\rho^0\rho^0)=(8.7\pm2.6\pm1.6)\times10^{-4}\ ,$$

if we take the inclusive Crystal Ball [1] measurement for the $(J/\psi\to\gamma\eta_c)$ decay.

This result is consistent with the branching ratio for $(\eta_c\to\phi\phi)$ [4,3] and with the upper limit for $(\eta_c\to\omega\omega)$ [10,11] obtained by DM2 and MARK III Collaborations, and does not support the suggested [5] $SU(3)_F$ breaking pattern in η_c decays.

5. Conclusion. The first observation of the $\eta_c\to\rho^0\rho^0$ decay is obtained. The $\rho^0\rho^0$ dynamics largely dominates the $4\pi^\pm$ decay of the η_c; the corresponding product branching ratio is

$$\mathrm{BR}(J/\psi\to\gamma\eta_c)\times\mathrm{BR}(\eta_c\to\rho^0\rho^0)$$
$$=(1.10\pm0.10\pm0.20)\times10^{-4}\ .$$

This value agrees with a quark flavour symmetry in the η_c decays. The first high statistics measurement of the pseudoscalar character offers the best evidence in identifying the state observed at this mass with the η_c, $^1S_0$ state of charmonium.

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