**DIRECT OBSERVATION AND PARTIAL-WIDTH MEASUREMENT
OF $\gamma\gamma$ DECAY OF CHARMONIUM STATES**

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ABSTRACT

As part of the charmonium formation experiment at the CERN Intersecting Storage Rings, we studied the reaction $p\bar{p} \rightarrow c\bar{c} \rightarrow \gamma\gamma$ in an antiproton momentum scan through the η_c , χ_1 , and χ_2 regions. We report events observed in the η_c and χ_2 regions, whilst no event was observed in the χ_1 region, as expected for a spin-1 state.

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1. INTRODUCTION

The interest in studying the $\gamma\gamma$ decays of charmonium states is well known. Potential models [1], as well as QCD sum rules [2], can be tested by measuring these decays. In addition, since the ratio $\Gamma(R \rightarrow \gamma\gamma)/\Gamma(R \rightarrow \text{hadrons})$ (where R is the resonant state) is directly related to the running coupling constant $\alpha_s(Q^2)$ of QCD, the measurement of this ratio allows the validity of perturbative QCD calculations to be checked in this range of Q^2 .

When this experiment began to take data, only upper limits for this decay mode of the η_c and χ_2 states were available [3]. Meanwhile, new experimental results have been published: in photon-photon interactions at PETRA, the PLUTO Collaboration [4] have observed a bump in the $K^0 K^\pm \pi^\mp$ mass spectrum, with a mass about 3 GeV. A natural interpretation of this bump is given by the reaction $\gamma\gamma \rightarrow \eta_c \rightarrow K^0 K^\pm \pi^\mp$. Using the 1984 Particle Data Group branching ratio $\text{BR}(\eta_c \rightarrow K^0 K^\pm \pi^\mp)$, they obtained the value of the partial width $\Gamma(\eta_c \rightarrow \gamma\gamma) = (14 \pm 12) \text{ keV}$. This gives an experimental indication of a coupling of the η_c to $\gamma\gamma$, but the partial width is still quite uncertain. Later, the TASSO Collaboration [5] observed a signal in the same process, giving $\Gamma(\eta_c \rightarrow \gamma\gamma) = (50 \pm 40) \text{ keV}$. More recently, at PEP, the MARK II Collaboration [6] observed four events above background in the same channel. The value derived for $\Gamma(\eta_c \rightarrow \gamma\gamma)$ is $(8.0 \pm 5.0 \pm 2.0) \text{ keV}$. The Crystal Ball Collaboration at SPEAR [7] have observed the $\gamma\gamma$ decays of the χ_0 and χ_2 states, and give the partial width $\Gamma(\chi_2 \rightarrow \gamma\gamma) = (2.8 \pm 2.0) \text{ keV}$.

We report the results obtained by the R704 Collaboration at the CERN Intersecting Storage Rings (ISR) for the reaction

$$p\bar{p} \rightarrow \gamma\gamma \quad (1)$$

studied in the mass region of the η_c , χ_1 , and χ_2 states of the $(c\bar{c})$ system.

2. EXPERIMENTAL SET-UP

A detailed description of the experimental technique and of the apparatus has been given in previous publications [8]. The proton-antiproton annihilations were produced, in ring 2 of the ISR, by intersecting a cooled coasting antiproton beam with a molecular hydrogen jet.

The detector (fig. 1) was a non-magnetic spectrometer with two detection arms set symmetrically relative to the beam axis. Each arm had a charged-particle tracking section, including sets of scintillation hodoscopes, a threshold Cherenkov counter for tagging electrons, and a transversally and longitudinally segmented electromagnetic calorimeter. For $\gamma\gamma$ detection, the calorimeter is the essential part of the apparatus and has to provide a high π^0/γ rejection factor in order to be able to isolate the $\gamma\gamma$ signal over the large multineutral hadronic background. The calorimeter was set up to optimize

- i) the efficiency of detection of the low-energy γ 's,
- ii) the $\gamma\gamma$ spatial resolution,
- iii) the energy resolution.

Each calorimeter had four parts:

- 1) The γ converter, or precalorimeter. This was made of lead/scintillator sandwiches amounting to a total length of $4.7X_0$. The transverse segmentation consisted of 29 vertical strips and 14 horizontal wedge-shaped strips.
- 2) The analog chambers. These consisted of four identical (X, Y) chambers with analog readout of the cathodic strips (10 mm pitch).
- 3) The shower hodoscope. This consisted of 14 vertical scintillator strips (NE110, 1 cm thick) used for triggering.

- 4) The lead-glass wall was made of 66 blocks of F2 glass with the dimensions $15 \times 15 \times 30.5 \text{ cm}^3$. The length of the blocks (30.5 cm or $10X_0$) ensured full shower containment.

A system of guard counters completely surrounded the two arms, covering most of the remaining solid angle. This guard system was composed of scintillation counters followed by segmented lead/scintillator sandwich counters ($4.7X_0$). Its aim was to detect charged particles and/or γ -rays outside the detection arms and therefore to set multiparticle or multi- γ veto conditions.

The fast trigger (200 ns) for the $\gamma\gamma$ final state was implemented using the guard system and shower hodoscope information.

A slow trigger (450 μs) made use of a fast processor, which read the calorimeter fast ADCs, calculated the energy deposited in the precalorimeter and the lead glass, and performed a cut on the total energy deposited. The trigger rate was a few events per second. Triggering for the $\pi^0\pi^0$ final state was also obtained at the same time. The ability of the detector to reconstruct π^0 's is shown in fig. 2, which displays the reconstructed mass for the γ pairs.

3. DATA TAKING

The energy scan was done around the η_c , χ_1 , and χ_2 regions. The energies and luminosities are given in table 1. The χ_1 scan was performed to constrain the background level in the χ_2 sample.

Owing to the presence of the multi- γ veto condition, the largest background (from hadronic multineutrals) is coming from the $\pi^0\pi^0$ channel, which simulates an exclusive $\gamma\gamma$ final state from symmetric π^0 decays inside the angular resolution or from very asymmetric π^0 decays where the low-energy γ escapes detection. In order to evaluate the multi- γ background to reaction (1), we have also studied the reaction

$$p\bar{p} \rightarrow \pi^0\pi^0 \quad (2)$$

in the same mass regions.

4. DATA ANALYSIS

The selection of $\gamma\gamma$ final-state candidates in reaction (1) was based on the single γ -shower topology, the energy deposit, and the two-body kinematics.

As a first step we used the following criteria in order to obtain an intermediate sample of a reasonable size suitable for a detailed study of the final analysis cuts:

- no charged particle entering the detector;
- total energy deposited in the calorimeters, $> 0.8E_{\text{tot}}$;
- only one electromagnetic shower per arm, with $E > 150 \text{ MeV}$;
- an effective mass of these two showers $> 75\%$ of the centre-of-mass energy (i.e. $> 2.2 \text{ GeV}$ for the η_c);
- extra energy deposited in the detector, $< 50 \text{ MeV}$.

This first step of the analysis led to a total sample of 1173 $\gamma\gamma$ candidate events out of 2.6 million triggers (all data taken at the η_c , χ_1 , and χ_2 states). Their centre-of-mass $\cos \theta^*$ distributions are shown in fig. 3a ($s \approx 9 \text{ GeV}^2$) and fig. 3b ($s \approx 12 \text{ GeV}^2$). The corresponding c.m. angular distributions of $\pi^0\pi^0$ events (4 γ converted in the calorimeters) are shown in figs. 3c and 3d. A comparison of figs. 3a and 3c indicates that in the η_c region there is an important $\pi^0\pi^0$ background in the $\gamma\gamma$ sample, since we expect an isotropic angular distribution for the $\eta_c \rightarrow \gamma\gamma$ decay. In order to reduce this background, we disregarded for the η_c state the region $\cos \theta^* > 0.35$, where the $\pi^0\pi^0$ -induced background is the highest. For the χ_1 and χ_2 states, where the $\pi^0\pi^0$ angular distribution flattens and there is no definite expectation for the $\chi_2 \rightarrow \gamma\gamma$ angular distribution, we have considered data up to $\cos \theta^* = 0.5$ so as to avoid edge effects at the limit of the acceptance.

The final step of the data analysis was based on

- i) restricted kinematical constraints using the shower position measurements given by the analog chambers for which angular resolution was obtained using the exclusive J/ψ sample [8, 9] ($p\bar{p} \rightarrow J/\psi \rightarrow e^+e^-$);
- ii) longitudinal and transverse shower development characteristics; these were derived also by the analysis of the exclusive J/ψ sample;
- iii) no possible π^0 reconstruction using the main shower correlated with a very low energy deposit.

The efficiency of this analysis is about 60%. This has been derived by reanalysing the exclusive J/ψ sample, disregarding the charged-particle tracking section and Cherenkov information.

The final results of the analysis chain are reported in table 1.

5. RESULTS

5.1 The η_c sample

Figure 4 displays the c.m. angular distribution for the $\gamma\gamma$ candidates in the η_c region. The hatched event (corresponding to a mass of 3023.5 MeV), far from the central mass value of the resonance, is considered as a background event. The excitation function in this η_c mass region is shown in fig. 5. The curve is the result of a fit obtained with a maximum likelihood method, described in ref. [10]. The total width Γ_{tot} , the mass, the branching ratios, and the background level were free parameters^{*)}. An energy-dependent background was used. The best fit parameters are

$$m_{\eta_c} = (2982.6 \pm 2.7) \text{ MeV}; \quad \Gamma_{\text{tot}} = (7.0 \pm 7.5) \text{ MeV};$$

$$\text{BR}(\eta_c \rightarrow p\bar{p}) \times \text{BR}(\eta_c \rightarrow \gamma\gamma) = (0.68 \pm 0.42) \times 10^{-6};$$

$$\sigma_{\text{back}} = (100 \pm 100) \text{ pb}.$$

This cross-section takes into account the efficiency and acceptance corrections ($\epsilon = 0.05$) and corresponds to the value of the background at the η_c mass.

If we use the published value of $\text{BR}(\eta_c \rightarrow p\bar{p}) = (1.1 \pm 0.6) \times 10^{-3}$ [12], we obtain the following branching ratio,

$$\text{BR}(\eta_c \rightarrow \gamma\gamma) = (0.6 \pm 0.4 \pm 0.4) \times 10^{-3},$$

and partial width

$$\Gamma(\eta_c \rightarrow \gamma\gamma) = (4.3 \pm 3.4 \pm 2.4) \text{ keV}.$$

The first errors come from the maximum likelihood fit. The last errors correspond to the uncertainties in the other parameters. These uncertainties are composed quadratically.

We have checked the stability of our results with respect to the different cuts used in the analysis. The results are stable for slight variations of these cuts^{**)}.

^{*)} If Γ_{tot} is fixed at $(11 \pm 4) \text{ MeV}$ [11], the best-fit parameters are:

$m_{\eta_c} = (2982.4 \pm 2.6) \text{ MeV}$, $\text{BR}(\eta_c \rightarrow p\bar{p}) \times \text{BR}(\eta_c \rightarrow \gamma\gamma) = (0.57 \pm 0.26) \times 10^{-6}$, $\sigma_{\text{back}} = (90 \pm 140) \text{ pb}$,
giving the following branching ratio:

$$\text{BR}(\eta_c \rightarrow \gamma\gamma) = (0.5 \pm 0.2 \pm 0.3) \times 10^{-3}$$

and partial width:

$$\Gamma(\eta_c \rightarrow \gamma\gamma) = (5.7 \pm 2.6 \pm 3.7) \text{ keV}.$$

^{**) In particular, the maximum likelihood method applied to the reduced sample corresponding to $\cos \theta^* < 0.3$ leads to the following results:}

No. of events in the η_c mass intervals of table 1: 0/9/0.

$m_{\eta_c} = (2980.7 \pm 2.1) \text{ MeV}$, $\Gamma_{\text{tot}} = (7.2 \pm 7.7) \text{ MeV}$, $\sigma_{\text{back}} < 80 \text{ pb}$ (84% CL),
 $\text{BR}(\eta_c \rightarrow \gamma\gamma) = (0.7 \pm 0.7 \pm 0.4) \times 10^{-3}$, $\Gamma(\eta_c \rightarrow \gamma\gamma) = (5.3 \pm 3.9 \pm 2.9) \text{ keV}$.

Table 2 summarizes our results. The value of the partial width is in agreement with the theoretical expectations [2, 13] and is consistent with the upper limit given by the Crystal Ball [3] and with the values given by PLUTO [4], TASSO [5], and MARK II [6]. Table 3 shows our results and the present published values for this partial width.

5.2 The χ_1 and χ_2 samples

The χ_1 and χ_2 samples are given in table 1. No candidate event is found in the χ_1 region.

A likelihood maximization has been performed using the two samples. In this case, the mass, the total width of the χ_2 , and the $\text{BR}(\chi_2 \rightarrow p\bar{p})$ are as determined in ref. [10]. So we have only two free parameters: the branching ratio $\text{BR}(\chi_2 \rightarrow \gamma\gamma)$ and the background cross-section. The $\chi_2 \rightarrow \gamma\gamma$ c.m. angular distribution is strongly dependent on the helicity amplitudes of the initial and final states and is not likely to be isotropic. However, in the absence of any experimental result for this angular distribution, we consider it as isotropic and give results in this framework. These results are

$$\text{BR}(\chi_2 \rightarrow p\bar{p}) \times \text{BR}(\chi_2 \rightarrow \gamma\gamma) = (0.99^{+0.46}_{-0.33}) \times 10^{-7},$$

$$\sigma_{\text{back}} < 70 \text{ pb.}$$

This upper limit (90% confidence level) for the background also takes into account the efficiency and acceptance corrections ($\epsilon = 0.07$). Using

$$\text{BR}(\chi_2 \rightarrow p\bar{p}) = (0.9^{+0.4}_{-0.3}) \times 10^{-4}$$

we get

$$\text{BR}(\chi_2 \rightarrow \gamma\gamma) = (1.1^{+0.5}_{-0.4} \pm 0.4) \times 10^{-3},$$

which, for a total width $\Gamma_{\text{tot}} = (2.6^{+1.4}_{-1.0}) \text{ MeV}$, gives the following width:

$$\Gamma(\chi_2 \rightarrow \gamma\gamma) = (2.9^{+1.3}_{-1.0} \pm 1.7) \text{ keV}.$$

The branching ratio $\text{BR}(\chi_2 \rightarrow \gamma\gamma)$ agrees with the theoretical expectation: 1.2×10^{-3} [14]. In addition, these values of branching ratio and partial width are consistent with the values measured by the Crystal Ball Collaboration [7]. All these results are also summarized in tables 2 and 3.

In the χ_1 region, the above value for σ_{back} provides an upper limit for the decay rate $\chi_1 \rightarrow \gamma\gamma$. Using the lower limit 0.5×10^{-4} (ref. [10]), for $\text{BR}(\chi_1 \rightarrow p\bar{p})$, we obtain $\text{BR}(\chi_1 \rightarrow \gamma\gamma) < 8 \times 10^{-4}$, consistent with the spin-1 assignment for the χ_1 state.

6. CONCLUSIONS

In an experiment (R704) performed at the CERN ISR, we have observed $\gamma\gamma$ decays of η_c and χ_2 charmonium states directly formed in $p\bar{p}$ annihilations. New determinations of total and partial widths are obtained, which are consistent with the values given by previous experiments at e^+e^- colliders.

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Table 1

Candidate events, mass range, and luminosity

Mass range (MeV)	No. of events	Luminosity (nb ⁻¹)
2963–2969	0	96
2975–2987	12	511
3023–3025	1	98
3509–3516	0	494
3552–3564	6	821

Table 2

Resonance parameters from R704

	η_c	χ_2
Mass (MeV)	$2982.6^{+2.7}_{-2.3}$	$3556.9 \pm 0.4 \pm 0.5^b)$
Total width (MeV)	$7.0^{+7.5}_{-7.0}$	$2.6^{+1.4^b)}_{-1.0}$
$\text{BR}(R \rightarrow p\bar{p}) \times$ $\text{BR}(R \rightarrow \gamma\gamma) \times 10^6$	$0.68^{+0.42}_{-0.31}$	$0.099^{+0.046}_{-0.035}$
$\Gamma(R \rightarrow \gamma\gamma)$ (keV)	$4.3^{+3.4}_{-3.7} \pm 2.4$	$2.9^{+1.3}_{-1.0} \pm 1.7$
$\text{BR}(R \rightarrow \gamma\gamma) \times 10^3$	$0.6^{+0.4}_{-0.3} \pm 0.4^a)$	$1.1^{+0.5}_{-0.4} \pm 0.4^c)$

a) From ref. [12]: $\text{BR}(\eta_c \rightarrow p\bar{p}) = (1.1 \pm 0.6) \times 10^{-3}$.

b) From ref. [10].

c) From ref. [10]: $\text{BR}(\chi_2 \rightarrow p\bar{p}) = (0.9^{+0.4}_{-0.3}) \times 10^{-4}$.

Table 3

Summary of partial widths (in keV)

	η_c	χ^2
R704	$4.3^{+3.4}_{-3.7} \pm 2.4$	$2.9^{+1.3}_{-1.0} \pm 1.7$
PLUTO [4]	14 ± 12	
TASSO [5]	50 ± 40	
MARK II [6]	$8.0 \pm 5.0 \pm 2.0$	
Crystal Ball [7]		2.8 ± 2.0

Figure captions

Fig. 1 Schematic view of the experimental apparatus.

Fig. 2 Effective mass spectrum for two photons in the same arm.

Fig. 3 The $\cos \theta^*$ angular distributions for the first-step $\gamma\gamma$ sample:

a) at $s \approx 9 \text{ GeV}^2$ (η_c sample),

b) at $s \approx 12 \text{ GeV}^2$ (χ_2 sample),

and $\cos \theta^*$ angular distribution for $\pi^0\pi^0$,

c) at $s \approx 9 \text{ GeV}^2$,

d) at $s \approx 12 \text{ GeV}^2$.

Fig. 4 The $\cos \theta^*$ angular distribution for the final η_c sample.

Fig. 5 Excitation curve in the η_c mass region. The curve is the result of the maximum likelihood procedure described in the text. The dashed line is the background contribution parametrized by the expression $\sigma_{\text{back}} = \sigma_b[1 - 0.0024 (p_{\text{beam}} - 3635)] \text{ pb}$ obtained from the study of the $\pi^0\pi^0$ sample (σ_b is the parameter used in the maximum likelihood fit; p_{beam} is in MeV).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5