MEASUREMENT OF $\mathcal{B}(J/\psi \rightarrow \eta_c \gamma)$ AT KEDR*

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 (for KEDR collaboration[†])

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We present a study of the inclusive photon spectrum from 6.3 million J/ψ decays collected with the KEDR detector at the VEPP-4M e^+e^- collider. We measure the branching fraction of the radiative decay $J/\psi \rightarrow \eta_c \gamma$, η_c width and mass. Taking into account an asymmetric photon line shape we obtain: $M_{\eta_c} = (2978.1 \pm 1.4 \pm 2.0) \text{ MeV}/c^2$, $\Gamma_{\eta_c} = (43.5 \pm 5.4 \pm 15.8) \text{ MeV}$, $\mathcal{B}(J/\psi \rightarrow \eta_c \gamma) = (2.59 \pm 0.16 \pm 0.31)\%$.

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1. Introduction

$J/\psi \rightarrow \eta_c \gamma$ decay is a magnetic dipole radiative transition with photon energy ω about 114 MeV, and a relatively large branching fraction of about 2%. This is a transition between $1S$ states of charmonium and its rate can be easily calculated in potential models. The transition does not change a spatial part of the wave function and its matrix element in the leading approximation equals one. A simple calculation without relativistic corrections gives the result¹ $\mathcal{B}(J/\psi \rightarrow \eta_c \gamma) = 3.05\%$. It was expected that relativistic corrections are of order 20-30%, similarly to the case of the electric dipole transitions in charmonium. Therefore, it was surprising when in 1986 the Crystal Ball Collaboration measured this branching fraction in the inclusive photon spectrum and obtained $(1.27 \pm 0.36)\%^2$. There are a lot of theoretical predictions for this decay rate³, based on QCD sum rules, lattice QCD calculations and so on, but as a rule they give values approximately twice as large as the Crystal Ball result.

This puzzle remained for more than twenty years. Only in 2009 the CLEO Collaboration published⁴ the result of a new measurement of this branching fraction

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using analysis of 12 exclusive decay modes of η_c . The obtained value $\mathcal{B}(J/\psi \rightarrow \eta_c \gamma) = (1.98 \pm 0.09 \pm 0.30)\%$ is closer to theory. Combining the Crystal Ball and CLEO results, PDG⁵ got $\mathcal{B}(J/\psi \rightarrow \eta_c \gamma) = (1.7 \pm 0.4)\%$ with a scale factor of 1.6. In this work we report a result of the new independent measurement.

2. Photon spectrum

The photon spectrum in $J/\psi \rightarrow \eta_c \gamma$ decay can be written as¹

$$\frac{d\Gamma(\omega)}{d\omega} = \frac{4}{3} \alpha \frac{e_c^2}{m_c^2} \omega^3 |M|^2 BW(\omega). \quad (1)$$

Here $M = \langle \eta_c | j_0(\omega r/2) | J/\psi \rangle$ is the matrix element of the transition, $j_0(x) = \sin(x)/x$, e_c and m_c are c-quark charge (in electron charge units) and mass while $BW(\omega)$ is a Breit-Wigner function taking into account a nonzero η_c width. The matrix element tends to unity when ω tends to zero and decreases slowly with the photon energy increase.

CLEO found that the photon line shape of this transition is asymmetric, and a Breit-Wigner function alone provides a poor fit to data. Its modification with ω^3 improves the fit around the peak, but gives a diverging tail at higher photon energies. To suppress this tail, CLEO used in their fit $|M|^2 = \exp(-\frac{\omega^2}{8\beta^2})$ with $\beta = 65$ MeV, explaining it by the overlap of the ground state wave functions. However, such a form of the matrix element is valid for the wave functions of the harmonic oscillator only. In all other potentials, $|M|^2$ dependence will be proportional to some negative degree of ω when ω tends to infinity.

We tried to fit the CLEO data using another line shape: at photon energy ω near the resonance the decay probability $d\Gamma/d\omega$ is proportional to $\omega^3 BW(\omega)$, but at higher energies the factor ω^3 is replaced with ω . We found that the function $d\Gamma/d\omega \sim \frac{\omega^3 \omega_0^2}{\omega \omega_0 + (\omega - \omega_0)^2} BW(\omega)$, where $\omega_0 = \frac{M_{J/\psi}^2 - M_{\eta_c}^2}{2M_{J/\psi}^2}$, is also suitable. Here the correction factor $\frac{\omega_0^2}{\omega \omega_0 + (\omega - \omega_0)^2}$ is a smooth function near the resonance. Results of fits with the CLEO function and our function are shown in Table 1. One can see that results on the η_c mass, width, and decay rate are close, and the confidence level of the fit with our function is also good. Therefore, we use the latter function in the analysis of our data.

Table 1. Results of the fits to CLEO data using various decay probability functions. N_{1S}^{EXC} is the number of signal photons in the fit.

$d\Gamma/d\omega$	M_{η_c} , MeV/ c^2	Γ_{η_c} , MeV	N_{1S}^{EXC}	χ^2/ndf (C.L.)
$\sim \omega^3 \exp(-\frac{\omega^2}{8\beta^2}) BW(\omega)$	2982.4 ± 0.7	32.5 ± 1.8	6142 ± 430	$38.0/38$ (0.47)
$\sim \frac{\omega^3 \omega_0^2}{\omega \omega_0 + (\omega - \omega_0)^2} BW(\omega)$	2981.8 ± 0.5	33.6 ± 1.9	6494 ± 362	$39.1/39$ (0.47)

3. KEDR data

The experiment was performed at the KEDR detector⁶ of the VEPP-4M collider⁷.

The collider operates with a peak luminosity of about $1.5 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ near the J/ψ peak energy. Luminosity is measured with single Bremsstrahlung online and with small-angle Bhabha scattering offline. Two methods of beam energy determination are used: resonant depolarization with accuracy of $8 \div 30 \text{ keV}$ and IR-light Compton backscattering with accuracy $\sim 100 \text{ keV}$ ⁸.

This analysis is based on a data sample of $1.52 \pm 0.08 \text{ pb}^{-1}$ collected at the J/ψ peak. Three J/ψ scans were performed. Using a measured beam energy spread as well as known⁵ $\Gamma(J/\psi \rightarrow e^+e^-)$ and $\Gamma(J/\psi \rightarrow \text{hadrons})$, we calculate the J/ψ production cross section at the peak and get $N_{J/\psi} = (6.3 \pm 0.3) \cdot 10^6$.

Event selection was performed in two steps. At the first step, multihadron decays of J/ψ were selected with the following cuts: total energy in the calorimeters is greater than 0.8 GeV ; at least four clusters with the energy greater than 30 MeV in the calorimeters are detected; at least one central track in the drift chamber is reconstructed; there are no muon tubes activated in the third layer of the muon system. These cuts suppress background from the cosmic rays, beam-gas interactions and Bhabha events. At the second step, photons in these events were identified. A photon is a cluster in the liquid krypton calorimeter which is not associated with the reconstructed tracks in the drift chamber and has no time-of-flight (ToF) scintillation counters activated in front of it. According to the simulation, the photon detection efficiency with the above mentioned cuts is about 28% and is almost constant in the investigated range of the photon energies.

4. Data analysis

The inclusive photon spectrum and a fit to our data is shown in Fig. 1. The spectrum was fit with a sum of the signal having a shape $d\Gamma/d\omega \sim \frac{\omega^3 \omega_0^2}{\omega \omega_0 + (\omega - \omega_0)^2}$,

Fig. 1. Fit of the inclusive photon spectrum.

convolved with the calorimeter response function (logarithmic normal distribution⁹ with $\sigma_E = 7.4$ MeV at 110 MeV and $a = -0.33$), and background. The background shape was taken in the form $\ln(dN/d\omega) = a \cdot \exp(-\omega/b) + p_2(\omega) + c \cdot MIP(\omega)$, where the first term describes “fake” photons appearing due to nuclear interactions of hadrons in the calorimeter and usually having energies less than 60 MeV, the second term is the second-order polynomial describing photons arising mainly from π^0 decays, and $MIP(\omega)$ is the spectrum of charged particles (a charged particle can be also misidentified as a photon). The Breit-Wigner function of the form $BW(\omega) \sim s/((s - M_{\eta_c}^2)^2 + s\Gamma_{\eta_c}^2)$, where $s = M_{J/\psi}^2 - 2\omega M_{J/\psi}$, was used in the fit.

We also tried to fit our data using other line shapes. We used $BW(\omega)$ alone, $\omega^3 BW(\omega)$, the CLEO function, and our function. Again, as first noted by CLEO, we found that the $BW(\omega)$ function alone gives a shifted value of η_c mass compared to other functions: $M(\eta_c) = 2974.3 \pm 1.4$ MeV/c². The function $\omega^3 BW(\omega)$ leads to a large tail at higher photon energies, giving for the branching fraction $\mathcal{B}(J/\psi \rightarrow \eta_c \gamma) = (7.3 \pm 0.5)\%$ (here the decay probability function was integrated up to $M_{J/\psi}/2$). The last two functions give close fit results. Since the CLEO function has an exponential factor, the result for the branching fraction with this function can be considered as a lower limit. The difference between the results obtained with the two last functions is used to estimate a systematic error appearing due to the unknown line shape.

5. Systematic errors

Systematic errors of our measurements are listed in Table 2.

Table 2. Systematic errors.

Systematic error	M_{η_c} , MeV/c ²	Γ_{η_c} , MeV	$\mathcal{B}(J/\psi \rightarrow \gamma \eta_c), \%$
Line shape	0.7	2.3	0.15
η_c width	0.4		0.15
Background subtraction	0.8	15.6	0.17
Number of J/ψ produced			0.13
Photon efficiency			0.08
Photon energy scale	1.7		
Total	2.0	15.8	0.31

The uncertainty of the η_c width leads to an error, which we evaluated varying the η_c width in the fit by 2.2 MeV (the current PDG error). A systematic error related to the background subtraction was estimated by using in the fit a polynomial of the third order instead of the second-order one, varying ranges of the fit, and applying or not the ToF veto in photon selection. The error in the number of J/ψ produced was evaluated using the known uncertainty of the luminosity measurement. Since the cluster multiplicity is different in the simulation and experimental photon spectrum in J/ψ decays, the error due to the photon detection efficiency was estimated by

changing by 25% weights of events with small ($n < 4$) and large ($n > 3$) track multiplicities, and taking different MC generators for the η_c decays. The calibration of the photon energy scale was performed using $\pi^0 \rightarrow 2\gamma$ decays and $\psi' \rightarrow \gamma\chi_{cJ} \rightarrow \gamma J/\psi$ transitions.

6. Results and conclusions

A new direct measurement of $J/\psi \rightarrow \eta_c\gamma$ decay was performed. We measured the η_c mass, width, and branching fraction of $J/\psi \rightarrow \eta_c\gamma$ decay. The values of the branching fraction and η_c mass are sensitive to the line shape of the photon spectrum and it should be taken into account during analysis. Our results on the η_c mass and width are:

$$M_{\eta_c} = 2978.1 \pm 1.4 \pm 2.0 \text{ MeV}/c^2,$$

$$\Gamma_{\eta_c} = 43.5 \pm 5.4 \pm 15.8 \text{ MeV}.$$

Before our experiment these parameters were measured in J/ψ and B meson decays, as well as in $\gamma\gamma$ and $p\bar{p}$ collisions. Measurements of Crystal Ball, MARK3, BES, and KEDR were performed using the radiative J/ψ decays, therefore, a mass shift should be taken into account. Crystal Ball and KEDR made such a correction, but MARK3 and BES did not. Therefore we believe that MARK3 and BES results on the η_c mass should be corrected by approximately 4 MeV towards higher values.

Our result on the branching fraction of $J/\psi \rightarrow \eta_c\gamma$ decay is

$$\mathcal{B}(J/\psi \rightarrow \eta_c\gamma) = (2.59 \pm 0.16 \pm 0.31)\%.$$

It is consistent with that of CLEO, is higher than the old Crystal Ball value and close to theoretical predictions.

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