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First Observation of $\psi(3770) \to \gamma\chi_{c1} \to \gamma\gamma J/\psi^*$

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Abstract

We observe a highly significant signal for $\psi(3770) \to \gamma\chi_{c1}$, detected in two-photon cascade to J/ψ, followed by $J/\psi \to l^+l^-$. We determine $\sigma(e^+e^- \to \psi(3770)) \times \mathcal{B}(\psi(3770) \to \gamma\chi_{c1}) = (21.1 \pm 3.9 \pm 2.4)$ pb. Combining this result with the measurement of $\sigma(e^+e^- \to D\bar{D})$, we obtain $\mathcal{B}(\psi(3770) \to \gamma\chi_{c1}) = (3.3 \pm 0.6 \pm 0.4) \times 10^{-3}$. We also set 90% C.L. upper limits for the transition to χ_{c2}: $\sigma \times \mathcal{B} < 5.5$ pb and $\mathcal{B} < 0.9 \times 10^{-3}$, respectively. All results are preliminary.

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Transitions from $\psi(3770)$ to other charmonium states are interesting because they test models of $2^3S_1 - 1^3D_1$ mixing, and probe amplitudes for direct transitions from $1D$ to $1S$ or $1P$ states. The latter have been of considerable interest since the discovery of the narrow $X(3872)$ state in $\pi^+\pi^-$ transitions to $J/\psi(1S)$ [1, 2] and its possible interpretation as a 1^3D_2 state, competing with the $D\bar{D}^*$ molecule hypothesis. Measurement of hadronic transitions between $\psi(3770)$ and $J/\psi(1S)$ is a subject of a separate paper [3]. In this article, we present preliminary analysis of photon transitions between $\psi(3770)$ and $\chi_{cJ}(1P)$ states, followed by another photon transition to J/ψ, with J/ψ annihilating to e^+e^- or $\mu^+\mu^-$.

The data were acquired at a center-of-mass energy of 3773 MeV with the CLEOc detector [4] operating at the Cornell Electron Storage Ring (CESR), and correspond to an integrated luminosity of 281 pb^{-1}. The CLEOc detector features a solid angle coverage of 93% for charged and neutral particles. The cesium iodide (CsI) calorimeter attains photon energy resolutions of 2.2% at $E_\gamma = 1$ GeV and 5% at 100 MeV. For the data presented here, the charged particle tracking system operates in a 1.0 T magnetic field along the beam axis and achieves a momentum resolution of 0.6% at p = 1 GeV/c.

We select events with exactly two photons and two oppositely charged leptons. The leptons must have momenta of at least 1.4 GeV. We distinguish between electrons and muons by their energy deposition in the calorimeter. Electrons must have a high ratio of energy observed in the calorimeter to the momentum measured in the tracking system ($E/p > 0.7$). Muons are identified as minimum ionizing particles, and required to leave $150 - 550$ MeV of energy in the calorimeter. Stricter lepton identification does not reduce background in the final sample, since all significant background sources contain leptons. Each photon must have at least 60 MeV of energy and must be detected in the barrel part of the calorimeter, where the energy resolution is best. The invariant mass of the two photons must be at least 3 standard deviations away from the nominal π^0 or η mass. The total momentum of all photons and leptons in each event must be balanced to within 50 MeV. The invariant mass of the two leptons must be consistent with the J/ψ mass within ± 40 MeV. The measured recoil mass against two photons is required to be within -4 and $+3$ standard deviations from the J/ψ mass. The average resolution of the recoil mass is 16 MeV. To reduce Bhabha background in the dielectron sample we require an average of the cosine of the angle between the electron (positron) direction and the direction of the electron (positron) beam to be less than 0.5. The event selection efficiency is 30% (24%) for the χ_{c1} (χ_{c2}) state for $\gamma\gamma\mu^+\mu^-$ events, and 18% (14%) for $\gamma\gamma e^+e^-$ events, respectively.

After all selection cuts, we employ kinematic fitting of events to improve resolution on the photon energy. We constrain the total energy to twice the beam energy and total momentum to zero. We also impose a J/ψ mass constraint. These constraints improve energy resolution for the first transition photon by 20%.

The photon energy distribution for the less energetic photon in the event is plotted in Fig. 1. We fit this distribution with two Gaussian peaks representing the $\psi(3770) \to \gamma\chi_{c1,2}$ signals on top of smooth background represented by a quadratic polynomial. The widths of the signal peaks are fixed to the values predicted by the Monte Carlo simulations ($\sigma_{E_\gamma} = 8.1$ MeV). Peak amplitudes and energy of the χ_{c1} peak are free parameters in the fit. The energy of the χ_{c2} peak is constrained to the latter minus the mass difference between these two states.

In addition to $e^+e^- \to \psi(3770)$, $\psi(3770) \to \gamma\chi_{c1,2}$, also $e^+e^- \to \gamma\psi(2S)$, $\psi(2S) \to \gamma\chi_{c1,2}$ can contribute to the observed peaks. The cross-section for the latter process peaks for small energies of the initial state radiation photon. Hence the produced $\psi(2S)$ mass from

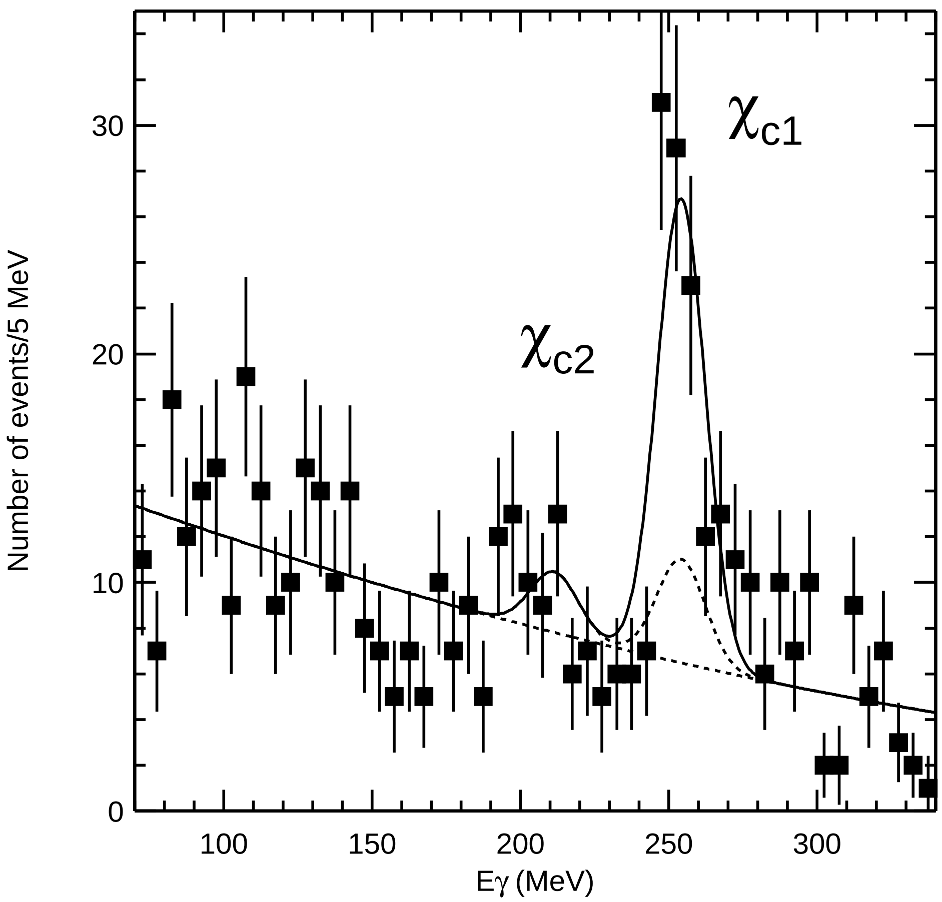

FIG. 1: Energy of the lower energy photon for the selected $e^+e^- \to \gamma\gamma J/\psi$, $J/\psi \to l^+l^-$ events at the $\psi(3770)$ resonance. The solid line shows the fit. The dashed lines show the smooth background and the expected background peaks from radiatively produced tail of the $\psi(2S)$ resonance (see the text). The latter saturates the χ_{c2} contribution. The excess of data over the χ_{c1} peak indicated with the dashed line represents the evidence for $\psi(3770) \to \gamma\chi_{c1}$ transitions.

the high-mass tail of this resonance peaks at the center-of-mass energy. This makes the $\psi(2S)$ background indistinguishable from the $\psi(3770)$ signal. We estimate the size of this background from the theoretical formulae [5], which fold in radiative flux, the Breit-Wigner shape of $\psi(2S)$, the branching ratio for $\psi(2S) \to \gamma\chi_{c1,2} \to \gamma\gamma J/\psi \to \gamma\gamma l^+l^-$ [6] at the $\psi(2S)$ peak and a phase-space factor rescaling the latter to the actually produced mass of $\psi(2S)$ at its resonance tail. Estimation of the $\psi(2S)$ background is discussed more fully in Ref. [3]. The phase-space factor is $(E_\gamma/E_\gamma^{peak})^3$ [7], where E_γ and E_γ^{peak} are the energies of the photon in $\psi(2S) \to \gamma\chi_{c1,2}$ transition at the $\psi(2S)$ resonance tail and peak, respectively. The $\psi(2S)$ resonance parameters in the Breit-Wigner formula are fixed to the world average values [8]. The effect of our selection cuts is to limit energy of the radiative photon in $e^+e^- \to \gamma\psi(2S)$ to less than 50 MeV. Integrating the theoretical cross-section in this range, and multiplying it by the event selection efficiencies given previously, we estimate that the $\psi(2S)$ background contributes 18.5 and 10.7 events to the χ_{c1} and χ_{c2} peaks, respectively. The systematic uncertainty in these estimates is 25%. We represent these background peaks in the fit to the energy spectrum (Fig. 1) by Gaussians with the same energy and widths as the signal peaks and the amplitudes fixed to the estimated number of events.

The fitted signal amplitudes are 64 ± 12 and 0^{+7}_{-0} events for χ_{c1} and χ_{c2}, respectively. The statistical significance of the evidence for χ_{c1} signal is 6.5 standard deviations as estimated from the change of the fit likelihood when this component is excluded in the fit. The fitted peak energy, 254.2 ± 1.3 MeV (statistical error only), is in good agreement with the value expected from the center-of-mass energy and the χ_{c1} mass (253.6 MeV).

The systematic error in luminosity measurement is 1%. The systematic error in efficiency simulation is 4%. Variations in the fit range, order of the background polynomial, bin size and the signal width result in a variation of the χ_{c1} signal yield by 5%, while the systematic uncertainty in the subtraction of the $\psi(2S)$ background contributes 7%. To obtain an upper limit on χ_{c2} transition rate, we combine statistical and systematic errors in quadrature. The results for $\sigma(e^+e^- \to \psi(3770)) \times \mathcal{B}(\psi(3770) \to \gamma\chi_{cJ})$ are $(21.1 \pm 3.9 \pm 2.4)$ pb for χ_{c1} and < 5.5 pb (at 90% C.L.) for χ_{c2}. The branching ratios for $J/\psi \to l^+l^-$ and $\chi_{cJ} \to \gamma J/\psi$ used in the calculations of the results given above are taken from our own measurements [6].

Using $\sigma(e^+e^- \to \psi(3770)) = (6.4{\pm}0.2)$ nb, based on our recent measurement of $\sigma(e^+e^- \to D\bar{D})$ [9] and accommodating the measured non-$D\bar{D}$ decays of $\psi(3770)$ [6, 10] (the latter are predicted to be less than 2% [11] of all decays), we obtain following branching ratio results: $\mathcal{B}(\psi(3770) \to \gamma\chi_{c1}) = (3.3 \pm 0.6 \pm 0.4) \times 10^{-3}$ and $\mathcal{B}(\psi(3770) \to \gamma\chi_{c2}) < 0.9 \times 10^{-3}$ (90% C.L.).

We turn the branching ratio results to transition widths using $\Gamma_{tot}(\psi(3770)) = (23.6{\pm}2.7)$ MeV [8]. This leads to: $\Gamma(\psi(3770) \to \gamma\chi_{cJ}) = (78 \pm 14 \pm 13)$ keV for χ_{c1} and < 20 keV (90% C.L.) for χ_{c2}. These results agree well with most of the theoretical predictions[11–13] as shown in Table I.

Combining this measurement with our determination of the $\pi^+\pi^-$ rate [3] we obtain $\Gamma(\psi(3770) \to \gamma\chi_{c1})/\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) = 1.75 \pm 0.38 \pm \pm 0.21$. The transition widths measured for $\psi(3770)$, which is predominantly the 1^3D_1 state, are theoretically related to the expected widths for the 1^3D_2 state. The ratio above is expected to be a factor 2-3.5 larger for the 1^3D_2 state with a mass of 3872 MeV than for the $\psi(3770)$ [12, 14, 15]. In view of the Belle's upper limit $\Gamma(X(3872) \to \gamma\chi_{c1})/\Gamma(X(3872) \to \pi^+\pi^- J/\psi) < 0.9$ (90 % C.L.) [1], the 1^3D_2 interpretation of $X(3872)$ is strongly disfavored, which is also supported by other recent Belle's results[16].

All results presented here are preliminary.

TABLE I: Our measurements of the photon transitions widths (statistical and systematic errors have been added in quadrature) compared to theoretical predictions.

	$\Gamma(\psi(3770) \to \gamma\chi_{cJ})$ in keV	
	$J=2$	$J=1$
CLEO data	< 20	78 ± 19
Rosner[11]	24 ± 4	73 ± 9
Eichten-Lane-Quigg[12]		
naive	3.2	183
with coupled-channels corrections	3.9	59
Barnes-Godfrey-Swanson[13]		
non-relativistic potential	4.9	125
relativistic potential	3.3	77

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