Observation of $\psi(3770) \rightarrow \gamma \chi_c0$

R. A. Briere,1 I. Brock,1 J. Chen,1 T. Ferguson,1 G. Tatischevili,1 H. Vogel,1 M. E. Watkins,1 J. L. Rosner,2 N. E. Adam,3 J. P. Alexander,3 K. Berkelman,3 D. G. Cassel,3 J. E. Duboscq,3 K. M. Ecklund,3 R. Ehrlich,3 L. Fields,3 R. S. Galik,3 L. Gibbons,3 R. Gray,3 S. W. Gray,3 D. L. Hartill,3 B. K. Heltsley,3 D. Hertz,3 C. D. Jones,3 J. Kandaswamy,3 D. L. Kreinick,3 V. E. Kuznetsov,3 H. Mahlke-Kruger,3 T. O. Meyer,3 P. U. E. Onyisi,3 J. R. Patterson,3 D. Peterson,3 J. Pivarski,3 D. Riley,3 A. Ryd,3 A. J. Sadoff,3 H. Schwarthoff,3 X. Shi,3 S. Stroiney,3 W. M. Sun,3 T. Wilksen,3 M. Weinberger,3 S. B. Athar,4 R. Patel,4 V. Potlia,4 H. Stoecck,4 J. Yeton,4 P. Rubin,5 C. Cawlfield,6 B. I. Eisenstein,6 I. Karliner,6 D. Kim,6 N. Lowrey,6 P. Naik,6 C. Sedlack,6 M. Selen,6 E. J. White,6 J. Wiss,6 M. R. Shepherd,7 D. Besson,7 T. K. Pedlar,9 D. Cronin-Hennessy,10 K. Y. Gao,10 D. T. Gong,10 J. Hietala,10 Y. Kubota,10 T. Klein,10 B. W. Lang,10 R. Poling,10 A. W. Scott,10 A. Smith,10 S. Dobbs,11 Z. Metreveli,11 K. K. Seth,11 A. Tomaradze,11 P. Zwerbe,11 J. Ernst,12 H. Severini,13 S. A. Dyttman,14 W. Love,14 V. Savinov,14 O. Aquines,15 Z. Li,15 A. Lopez,15 S. Mehrabyan,15 H. Mendez,15 J. Ramirez,15 G. S. Huang,16 D. H. Miller,16 V. Pavlunin,16 B. Sanghi,16 I. P. J. Shipsey,16 B. Xin,16 G. S. Adams,17 M. Anderson,17 J. P. Cummings,17 I. Danko,17 J. Napolitano,17 Q. He,18 J. Insler,18 H. Muramatsu,18 C. S. Park,18 E. H. Thorndike,18 T. E. Coan,19 Y. S. Gao,19 F. Liu,19 M. Artuso,20 S. Blusk,20 J. Butt,20 J. Li,20 N. Menaa,20 R. Mountain,20 S. Nisar,20 K. Randrianarivony,20 R. Redjimi,20 R. Sia,20 T. Skwarnicki,20 S. Stone,20 J. C. Wang,20 K. Zhang,20 S. E. Csorna,21 G. Bonvicini,22 D. Cinabro,22 M. Dubrovin,22 A. Lincoln,22 D. M. Asner,23 and K. W. Edwards23

(CLEO Collaboration)

1Carnegie Mellon University, Pittsburgh, Pennsylvania 15213
2Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637
3Cornell University, Ithaca, New York 14853
4University of Florida, Gainesville, Florida 32611
5George Mason University, Fairfax, Virginia 22030
6University of Illinois, Urbana-Champaign, Illinois 61801
7Indiana University, Bloomington, Indiana 47405
8University of Kansas, Lawrence, Kansas 66045
9Luther College, Decorah, Iowa 52101
10University of Minnesota, Minneapolis, Minnesota 55455
11Northwestern University, Evanston, Illinois 60208
12State University of New York at Albany, Albany, New York 12222
13University of Oklahoma, Norman, Oklahoma 73019
14University of Pittsburgh, Pittsburgh, Pennsylvania 15260
15University of Puerto Rico, Mayaguez, Puerto Rico 00681
16Purdue University, West Lafayette, Indiana 47907
17Rensselaer Polytechnic Institute, Troy, New York 12180
18University of Rochester, Rochester, New York 14627
19Southern Methodist University, Dallas, Texas 75275
20Syracuse University, Syracuse, New York 13244
21Vanderbilt University, Nashville, Tennessee 37235
Abstract

From $e^+e^-$ collision data acquired with the CLEO-c detector at CESR, we search for the non-$D\bar{D}$ decays $\psi(3770) \rightarrow \gamma \chi_{cJ}$, with $\chi_{cJ}$ reconstructed in four exclusive decays modes containing charged pions and kaons. We report the first observation of such decays for $J = 0$ with a branching ratio of $(0.73 \pm 0.07 \pm 0.06)\%$. The rates for different $J$ are consistent with the expectations assuming $\psi(3770)$ is predominantly a $1^3D_1$ state of charmonium, but only if relativistic corrections are applied.
Observation of the narrow X(3872) and Y(4260) states \[1\] above open charm threshold, and their possible interpretation as states beyond the traditional c\(\bar{c}\) model of charmonium \[2\], calls for thorough investigation of the lightest charmonium state above the \(DD\) threshold - \(\psi(3770)\). The common interpretation of the \(\psi(3770)\) assumes it is predominantly the \(1^2D_1\) c\(\bar{c}\) state, with a small admixture of \(2^3S_1\). Except for the large \(DD\) decay width and rough agreement with the potential model mass predictions, there have been no other experimental data to verify this assumption. Although decays of \(\psi(3770)\) to \(\pi^+\pi^- J/\psi\), \(\eta J/\psi\) and \(\eta J/\psi\) have been measured to be non-zero \([3, 4]\), such hadronic modes present a less sensitive probe of the charmonium model than rates for \(\psi(3770) \rightarrow \gamma \chi_{cJ}\) since they involve hadronization probabilities.

Previously, we have reported observation of \(\psi(3770) \rightarrow \gamma \chi_{c1}\) with \(\chi_{c1} \rightarrow \gamma J/\psi, J/\psi \rightarrow l^+l^-\) \([3]\). The branching ratio for \(\psi(3770) \rightarrow \gamma \chi_{c0}\) is predicted to be the largest \([3, 7, 8, 9]\), but the small branching ratio for \(\chi_{c0} \rightarrow \gamma J/\psi\) reduces the sensitivity so much that only a loose upper limit could be set in Ref. \([3]\). However, hadronic \(\chi_{c0}\) decays are copious and thereby offer complementary probes for these photon transitions. Backgrounds from \(DD\) decays and continuum processes are suppressed by full reconstruction of \(\chi_{cJ}\) decays to a few exclusive hadronic final states. We use the following decay modes: \(\chi_{cJ} \rightarrow K^+K^- (2K), \chi_{cJ} \rightarrow \pi^+\pi^-\pi^+\pi^- (4\pi), \chi_{cJ} \rightarrow K^+K^-\pi^+\pi^- (2K2\pi)\) and \(\chi_{cJ} \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^+\pi^- (6\pi)\). To minimize sensitivity to large uncertainties in branching fractions and resonant substructure for these channels, we measure the rates relative to those seen in \(\psi(2S)\) decays with the same detector,

\[R_J \equiv \frac{\mathcal{B}(\psi(3770) \rightarrow \gamma \chi_{cJ}) \times \mathcal{B}(\chi_{cJ} \rightarrow \pi^\pm, K^\pm)}{\mathcal{B}(\psi(2S) \rightarrow \gamma \chi_{cJ}) \times \mathcal{B}(\chi_{cJ} \rightarrow \pi^\pm, K^\pm)},\]

and normalize to \(\mathcal{B}(\psi(2S) \rightarrow \gamma \chi_{cJ})\) \([11]\), which was measured by fitting inclusive photon energy spectra. Thus, our results for \(\mathcal{B}(\psi(3770) \rightarrow \gamma \chi_{cJ})\) are not only independent of \(\mathcal{B}(\chi_{cJ} \rightarrow \pi^\pm, K^\pm)\), but also depend only on ratios of detection efficiencies for \(\psi(3770)\) and \(\psi(2S)\). The latter are almost independent of the resonant substructure and, therefore, can be more reliably determined.

The data were acquired at a center-of-mass energy of 3773 MeV with the CLEO-c detector \([11]\) operating at the Cornell Electron Storage Ring (CESR), and correspond to an integrated luminosity (number of resonant decays) of 281 pb\(^{-1}\) (1.80 ± 0.05 \times 10^6) at the \(\psi(3770)\) and 2.9 pb\(^{-1}\) (1.51 ± 0.05 \times 10^6) at the \(\psi(2S)\). The CLEO-c 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. Particle identification is performed using Ring-Imaging Cherenkov Detector (RICH) in combination with specific ionization loss (dE/dx) in the gaseous tracking volume.

We select events with exactly 6, 4 or 2 charged tracks and at least one photon candidate with energy above 60 MeV. The highest energy photon is considered to be the signal photon, while other neutral clusters in the calorimeter are considered fragments of hadronic showers, and therefore ignored. We separate pions and kaons using a log-likelihood difference, which optimally combines the dE/dX and RICH information. The track is considered a kaon if the kaon hypothesis is more likely. The RICH information is used only if the track momentum is above kaon radiation threshold (700 MeV) and the number of Cherenkov photons for the kaon hypothesis is required to be at least 3 in this case. We also impose 3\(\sigma\) consistency on dE/dx. Those tracks not identified as kaons become pion candidates if they satisfy 3\(\sigma\)
TABLE I: Efficiencies for $\psi(2S)/\psi(3770) \rightarrow \gamma \chi_{cJ}, \chi_{cJ} \rightarrow \pi^{\pm}, K^{\pm}$, based on Monte Carlo of phase-space $\chi_{cJ}$ decays (i.e. no intermediate resonances).

|                      | Efficiency (%) | J = 2 | J = 1 | J = 0 |
|----------------------|---------------|-------|-------|-------|
| $\psi(2S) \rightarrow \gamma \chi_{cJ}$ |               |       |       |       |
| $2\pi$               | 4\pi          | 33    | 35    | 34    |
| $2K2\pi$             |               | 25    | 27    | 28    |
| $6\pi$               |               | 23    | 25    | 27    |
| $2K$                 |               | 43    | 44    | 42    |
| $2\psi(3770) \rightarrow \gamma \chi_{cJ}$ |               |       |       |       |
| $4\pi$               |               | 35    | 36    | 34    |
| $2\pi$               |               | 29    | 30    | 29    |
| $6\pi$               |               | 27    | 28    | 27    |
| $2K$                 |               | 44    | 44    | 41    |

consistency with dE/dX. Events with odd numbers of kaons or pions are rejected. The total energy and Cartesian components of momentum of the selected charged particles and the photon must be consistent within ±30 MeV with the expected center-of-mass four-vector components, which take into account a small beam crossing angle. To improve resolution on the photon energy, we then constrain these quantities to the expected values via kinematic fitting of events. Selection efficiencies obtained with GEANT [12] based simulation of detector response are given in Table I.

The energy of the photon candidates is plotted for the data for different decay channels in Fig. 1 and Fig. 2. Fits used to extract signal amplitudes are also shown. Each photon line is represented by a detector response function, parameterized by the so-called Crystal Ball line (CBL) shape. CBL is a Gaussian (described by the peak energy, $E_0$, and energy resolution, $\sigma_E$) turning into a power law tail, $1/(E_0 - E + \text{const})^n$, at an energy of $E_0 - \alpha \sigma_E$. We fix $\alpha$ and $n$ to the values determined from the signal Monte Carlo. The peak amplitude ($A_{\psi(2S)}^{\text{in}}$), peak energy and widths are free parameters in the fit to the $\psi(2S)$ data. The smooth background is represented by a first order polynomial. In the fit to the $\psi(3770)$ data only the peak amplitudes ($A_{\psi(3770)}^{\text{in}}$) are free parameters, while the CBL parameters are fixed to the predictions from the signal Monte Carlo. In addition to the smooth backgrounds, represented by a second order polynomial, the $\psi(3770)$ data also contain radiatively produced $\psi(2S)$ background. After our selection cuts, the latter cannot be distinguished from the $\psi(3770)$ signal. They are explicitly represented in the fit by peaks with the amplitudes, $A_{\psi(2S)}^{\text{in}}$ ($A_{\psi(3770)}^{\text{in}}$), fixed to the values estimated from the $\psi(2S)$ data ($A_{\psi(3770)}^{\text{in}}$) and extrapolated to the $\psi(3770)$ beam energy with help of the theoretical formulae:

$$A_{\psi(3770)}^{\text{in}} = \mathcal{L}_{\psi(3770)} \cdot \epsilon_{\psi(3770)} \cdot B_X \cdot \Gamma_{ee}(\psi(2S)) \cdot I(s)$$

$$I(s) = \int_0^{x_{\text{cut}}} W(s, x) \cdot b(s'(x)) \cdot F_X(s'(x)) dx.$$  

Here, we are using the same notation as in Ref. [4]: $\mathcal{L}$ is the integrated luminosity; $\epsilon$ is the efficiency; $B_X$ is the branching ratio for $\psi(2S) \rightarrow \gamma \chi_{cJ} \rightarrow \gamma X$ ($X$ is the hadronic final state) at the $\psi(2S)$ resonance peak; $x$ is energy radiated in $e^+e^- \rightarrow \gamma \psi(2S)$ divided by its maximal possible value (i.e. by $E_{\text{beam}} = \sqrt{s}/2$); $s'$ is the mass-squared with which the $\psi(2S)$
FIG. 1: Distribution of photon energy for $4\pi$ (top) and $2K2\pi$ (bottom) decay samples in CLEO-c $\psi(2S)$ (left) and $\psi(3770)$ (right) data. Solid histogram is data, smooth curve is fit to the data. Dashed line shows radiative return background contribution from $\psi(2S)$ tail and dotted line is polynomial background.

is produced ($s'(x) = s(1-x)$); $W(s, x)$ is the initial state radiation probability (see Ref. [4] for the definition and discussion); $b(s')$ is the relativistic Breit-Wigner formula describing the $\psi(2S)$ resonance ($b(s') = 12\pi\Gamma_R/[(s' - \sqrt{s} R)^2 + \sqrt{s}^2 \Gamma_R^2]$); and $F_X(s')$ is the phase-space factor between the $\psi(2S)$ produced with $\sqrt{s'}$ mass and with its nominal mass, $M_R$. $F_X(s')$ is equal [13] to $(E_\gamma(s')/E_\gamma(M_R^2))^3$, where $E_\gamma$ is the photon energy in $\psi(2S) \rightarrow \gamma\chi_{cJ}$ decay. The $\psi(2S)$ nominal mass ($M_R$) and total width ($\Gamma_R$) are taken from PDG [14], while $\Gamma_{ee}(\psi(2S))$
FIG. 2: Distribution of photon energy for $6\pi$ (top) and $2K$ (bottom) decay samples in CLEO-c $\psi(2S)$ (left) and $\psi(3770)$ (right) data. Solid histogram is data, smooth curve is fit to the data. Dashed line shows radiative return background contribution from $\psi(2S)$ tail and dotted line is polynomial background.

is taken from the CLEO determination utilizing $e^+e^- \rightarrow \gamma\psi(2S)$ at $E_{CM} = 3773$ MeV with $\psi(2S)$ decaying to $J/\psi$ through a hadronic transition [4]. The radiative flux, $W(s,x)$, strongly peaks for $x \rightarrow 0$ making the $\psi(2S)$ background indistinguishable from the $\psi(3770)$ signal within our photon energy resolution. Unlike in our $X = \gamma J/\psi$ analysis [5], where we used the published CLEO results for $B_X$ and relied on the absolute value of the detection
TABLE II: Fitted signal yields for $\psi(2S)/\psi(3770) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to \pi^\pm, K^\pm$. The total number of the estimated $\psi(2S)$ background events in the $\psi(3770)$ data ($A_{\psi(2S)}^{in \psi(3770)}$) is also given. The errors on the latter quantities are systematic. All other errors are statistical.

| Decay Events | Mode $J = 2$ | $J = 1$ | $J = 0$ |
|-------------|-------------|--------|--------|
| $A_{\psi(2S)}^{in \psi(2S)}$ | 4$\pi$ | 534 ± 27 | 291 ± 19 | 981 ± 36 |
| | 2$K2\pi$ | 261 ± 16 | 187 ± 14 | 745 ± 29 |
| | 6$\pi$ | 469 ± 23 | 408 ± 21 | 744 ± 30 |
| | 2$K$ | 64 ± 8 | − | 346 ± 19 |
| | All | 1329 ± 40 | 886 ± 32 | 2816 ± 58 |
| $A_{\psi(2S)}^{in \psi(3770)}$ | All | 25 ± 6 | 12 ± 3 | 25 ± 6 |
| | 4$\pi$ | 9 ± 10 | 14 ± 9 | 112 ± 16 |
| | 2$K2\pi$ | 6 ± 8 | 25 ± 9 | 73 ± 14 |
| | 6$\pi$ | 5 ± 12 | 16 ± 11 | 65 ± 16 |
| | 2$K$ | 0 ± 1 | − | 24 ± 6 |
| | All | 20 ± 18 | 54 ± 17 | 274 ± 27 |

The results for the ratio of branching ratios, $R_J$, for individual decay modes are given in Table III. Average values are calculated using inverse-of-statistical-errors-squared for weights. To estimate the statistical significance of $\psi(3770) \to \gamma\chi_{cJ}$ signals, we fit the $\psi(3770)$ data with the background contribution alone and compare the fit likelihoods to our nominal fits. Combining likelihoods for all the channels, we obtain statistical significance of 1.3, 3.6 and 12.6 standard deviations for $J = 2$, 1 and 0, respectively. The sum of the photon spectra over the individual channels is shown for $\psi(2S)$ and $\psi(3770)$ data in Fig. 3. Since no significant signal is observed for $J = 2$, we set an upper limit for this state.

The upper range of integration in the definition of $I(s)$ is $x_{cut} \approx 30$ MeV/1887 MeV=0.016, because of our cuts on total energy and momentum. The signal yields in the $\psi(2S)$ and $\psi(3770)$ data are given in Table III. Average values are calculated using inverse-of-statistical-errors-squared for weights. To estimate the statistical significance of $\psi(3770) \to \gamma\chi_{cJ}$ signals, we fit the $\psi(3770)$ data with the background contribution alone and compare the fit likelihoods to our nominal fits. Combining likelihoods for all the channels, we obtain statistical significance of 1.3, 3.6 and 12.6 standard deviations for $J = 2$, 1 and 0, respectively. The sum of the photon spectra over the individual channels is shown for $\psi(2S)$ and $\psi(3770)$ data in Fig. 3. Since no significant signal is observed for $J = 2$, we set an upper limit for this state.

Various contributions to the systematic errors are listed in Table IV. We simulated signal events assuming various resonant substructures and compared the efficiency ratio to...
FIG. 3: Distribution of photon energy in CLEO-c $\psi(2S)$ (top) and $\psi(3770)$ (bottom) data summed over all analyzed modes (data points). The smooth curve shows the sum of the fits performed to the individual modes. The dashed curve shows the radiative tail from $\psi(2S)$. The dotted line shows the polynomial background.

As for our nominal values obtained with the phase-space model to evaluate the error in efficiency simulation. Including the systematic errors, our results for the ratio of branching ratios are: $R_0 = (7.9 \pm 0.8 \pm 0.6)\%$, $R_1 = (4.3 \pm 1.6 \pm 0.6)\%$ and $R_2 < 2.2\%$ (90% C.L.). The 3% uncertainty in the number of $\psi(2S)$ resonant decays contributes to the $R_1$ measurement, but cancels when multiplied by the inclusively measured $B(\psi(2S) \rightarrow \gamma \chi_{cJ})$ \[10\]. The results for $B(\psi(3770) \rightarrow \gamma \chi_{cJ})$ are $(0.73 \pm 0.07 \pm 0.06)\%$, $(0.39 \pm 0.14 \pm 0.06)\%$ and $< 0.20\%$ (90% C.L.)
TABLE III: The ratio $R_J = B(\psi(3770) \to \gamma\chi_{cJ}, \chi_{cJ} \to \pi^\pm, K^\pm)/B(\psi(2S) \to \gamma\chi_{cJ}, \chi_{cJ} \to \pi^\pm, K^\pm)$. Only statistical errors are given here.

| Decay mode | $R_J$ in % | $J=2$ | $J=1$ | $J=0$ |
|------------|------------|-------|-------|-------|
| $4\pi$     | $1.3 \pm 1.5$ | $3.8 \pm 2.6$ | $9.6 \pm 1.4$ |       |
| $2K2\pi$   | $1.7 \pm 2.4$ | $9.9 \pm 4.0$ | $8.2 \pm 1.7$ |       |
| $6\pi$     | $0.7 \pm 1.8$ | $2.9 \pm 2.2$ | $7.4 \pm 1.8$ |       |
| $2K$       | $0.0 \pm 1.4$ |       | $6.0 \pm 1.6$ |       |
| Average    | $0.8 \pm 0.8$ | $4.3 \pm 1.6$ | $7.9 \pm 0.8$ |       |

TABLE IV: Systematic errors and their sources.

| Source                             | Relative change in % | $J=2$ | $J=1$ | $J=0$ |
|-----------------------------------|----------------------|-------|-------|-------|
| Luminosity                        |                      | 1     | 1     | 1     |
| $\psi(3770)$ cross-section        |                      | 3     | 3     | 3     |
| Number of $\psi(2S)$ decays       |                      | 3     | 3     | 3     |
| Resonant substructure             |                      | 2     | <1    | <1    |
| $\pm 25\%$ change in $\psi(2S)$ bkg. |                    | 39    | 6     | 2     |
| Fit systematics                   |                      |       |       |       |
| $\pm 7\%$ change in $\sigma_E$   |                      | 10    | 8     | 4     |
| $\pm 10\%$ change in fit range   |                      | 17    | 5     | 1     |
| Using Gaussian signal shape       |                      | 9     | 2     | 1     |
| Decreasing bin-size to half       |                      | 15    | 3     | <1    |
| $\pm 1$ order of bkg. polynomial  |                      | 47    | 9     | 2     |
| Total fit systematics             |                      | 53    | 12    | 5     |
| Total systematic error on $R_J$   |                      | 66    | 14    | 7     |
| $B(\psi(2S) \to \gamma\chi_{cJ})$ |                    | 6     | 5     | 4     |
| Number of $\psi(2S)$ decays       |                      | −3    | −3    | −3    |
| Total systematic error on $B(\psi(3770) \to \gamma\chi_{cJ})$ |        | 66    | 15    | 8     |

for $J = 0, 1$ and 2, respectively. They are consistent with the results obtained previously by CLEO using $\chi_{cJ} \to \gamma J/\psi$ decays: $< 4.4\%$ (90\% C.L.), $(0.28 \pm 0.05 \pm 0.04)\%$ and $< 0.09\%$ (90\% C.L.), correspondingly. The two analyses are complementary. While this analysis offers much better sensitivity for $J = 0$, the previous analysis is more sensitive for $J = 1$ and 2. The $J = 1$ signal is observed in both analyses. Combining both analyses we obtain $B(\psi(3770) \to \gamma\chi_{cJ}) = (0.29 \pm 0.05 \pm 0.04)\%$.

We turn the branching ratio results to transition widths using $\Gamma_{\text{tot}} = (23.6 \pm 2.7) \text{ MeV}$ from PDG. The results are given in Table V where they are compared to theoretical values.
TABLE V: Our measurements of the photon transitions widths (statistical and systematic errors) compared to theoretical predictions. The $J=0$ measurement comes from this analysis. The $J=2$ upper limit comes from Ref. [5]. The $J=1$ measurement comes from the combination of this analysis and of the result in Ref. [5].

|                      | $\Gamma(\psi(3770)\rightarrow \gamma \chi_{cJ})$ in keV |
|----------------------|---------------------------------------------------------|
| Our results          | $<21\, 70\pm 17\, 172\pm 30$                           |
| Rosner (non-relativistic) [7] | $24\pm 4\, 73\pm 9\, 523\pm 12$                      |
| Ding-Qin-Chao [6]    |                                                         |
| non-relativistic     | $3.6\, 95\, 312$                                       |
| relativistic         | $3.0\, 72\, 199$                                       |
| Eichten-Lane-Quigg [8] |                                                         |
| non-relativistic     | $3.2\, 183\, 254$                                      |
| with coupled-channels corrections |                                                         |
| Barnes-Godfrey-Swanson [9] |                                                         |
| non-relativistic     | $4.9\, 125\, 403$                                      |
| relativistic         | $3.3\, 77\, 213$                                       |

predictions.

The theoretical predictions are based on potential model calculations [13] of the electric dipole matrix element $<1^3P_J|r|1^3D_1>$:

$$
\Gamma_J = \frac{4}{3} e_Q^2 \alpha E_3^2 C_J <1^3P_J|r|1^3D_1>,
$$

where $e_Q$ is the c quark charge and $\alpha$ is the fine structure constant. The spin factors $C_J$ are equal to $2/9$, $1/6$ and $1/90$ for $J = 0$, $1$ and $2$, respectively [15]. The phase-space factor ($E_3^2$) also favors the $J = 0$ transition. Together, the spin and phase-space factors predict enhancement of the $J = 0$ width by a factor of $\sim 3.2$ and $\sim 85$ over $J = 1$ and $J = 2$, respectively. In the non-relativistic limit, the matrix element is independent of $J$. The measured ratios of the widths, $\Gamma_0/\Gamma_1 = 2.5 \pm 0.6$ and $\Gamma_0/\Gamma_2 > 8$ (90% C.L.), are consistent with these crude predictions, therefore, providing further evidence that $\psi(3770)$ is predominantly a $1^3D_1$ state. A small admixture of $2^3S_1$ wave, necessary to explain the observed $\Gamma_{ee}(\psi(3770))$, is expected to increase $\Gamma_0$ and $\Gamma_2$ while making $\Gamma_1$ smaller [6, 7]. The large experimental and theoretical uncertainties in $\Gamma_J$ make testing of the mixing hypothesis via radiative transitions difficult.

As evident from Table V, the naive non-relativistic calculations tend to overestimate absolute values of the transition rates. Relativistic [6, 8] or coupled-channel [8] corrections are necessary for quantitative agreement with the data. The latter is not surprising since non-relativistic calculations also overestimate $\psi(2S) \rightarrow \gamma \chi_{cJ}$ transition rates [16].

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the A.P. Sloan Foundation, the National Science Foundation, the U.S. Department of Energy, and the Natural Sciences
and Engineering Research Council of Canada.

[1] Belle Collaboration, S. K. Choi et al., Phys. Rev. Lett. 91, 262001 (2003); BABAR Collaboration, B. Aubert et al., Phys. Rev. D73, 011101(R) (2006); CLEO Collaboration, T. E. Coan et al., Phys. Rev. Lett. 96, 162003 (2006).
[2] T. Appelquist, A. de Rujula, H. D. Politzer, Phys. Rev. Lett. 34, 43 (1975); C. G. Callan, R. L. Kingsley, S. B. Treiman, F. Wilczek, A. Zee, Phys. Rev. Lett. 34, 52 (1975); T. Appelquist, A. de Rujula, H. D. Politzer, Phys. Rev. Lett. 34, 365 (1975); E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane, T.-M. Yan, Phys. Rev. Lett. 34, 369 (1975).
[3] BES Collaboration, J.Z. Bai et al., Phys. Lett. B605, 63 (2005).
[4] CLEO Collaboration, N.E. Adam et al., Phys. Rev. Lett. 96, 082004 (2006).
[5] CLEO Collaboration, T. E. Coan et al., Phys. Rev. Lett. 96, 182002 (2006), arXiv:hep-ex/0509030.
[6] Y.-B. Ding, D.-H. Qin, K.-T. Chao, Phys. Rev. D 44, 3562 (1991).
[7] J. L. Rosner, Phys. Rev. D64, 094002 (2001); J. L. Rosner, Annals Phys. 319, 1 (2005), arXiv:hep-ph/0411003.
[8] E. J. Eichten, K. Lane and C. Quigg, Phys. Rev. D69, 094019 (2004).
[9] T. Barnes, S. Godfrey and E. S. Swanson, Phys. Rev. D 72, 054026 (2005), arXiv:hep-ph/0505002.
[10] CLEO Collaboration, S. B. Athar et al., Phys. Rev. D70, 112002 (2004).
[11] CLEO Collaboration, Y. Kubota et al., Nucl. Instrum. Methods Phys. Res., A320, 66 (1992); D. Peterson et al., Nucl. Instrum. Methods Phys. Res., A478, 142 (2002); M. Artuso et al., Nucl. Instrum. Methods Phys. Res., A554 147 (2005).
[12] R. Brun et al., GEANT 3.21, CERN Program Library Long Writeup W5013 (1993), unpublished.
[13] See e.g. Eq. (4.118) in N. Brambilla et al., arXiv:hep-ph/04112158 (unpublished).
[14] Particle Data Group, S. Eidelman et al., Phys. Lett. B 592, 1 (2004).
[15] See e.g., W. Kwong and J. L. Rosner, Phys. Rev. D 38, 279 (1988).
[16] T. Skwarnicki, Int. J. Mod. Phys. A 19, 1030 (2004).