Inclusive γ-Ray Spectra from $\psi(3095)$ and $\psi'(3684)$ Decays*

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Inclusive γ-ray spectra from $\psi(3095)$ and $\psi'(3684)$ decays have been observed with segmented arrays of NaI(Tl) in an e^+e^- colliding-beam experiment. Three major peaks are seen in the ψ' spectrum corresponding to $\psi' \to \chi\gamma$ with $m_\chi = 3561$, 3511, and 3413 MeV/c^2 and with branching fractions of (7.0 ± 2.0), (7.1 ± 1.9), and $(7.2 \pm 2.3)\%$, respectively. Enhancements in the ψ' spectrum at higher energies are consistent with decays $\chi \to \psi\gamma$. The ψ spectrum shows no statistically significant structure.

Following the discovery of the $\psi(3095)$ and $\psi'(3684)$ several related states, populated by γ-ray transitions, were predicted.[1-4] The first evidence for such states (designated by χ) was obtained at DORIS[5] and SPEAR,[6] while an experiment[7] using NaI(Tl) detectors at SPEAR placed upper limits of about 6% on the branching fraction of $\psi' \to \gamma\chi$, subject to certain assumptions about χ decay modes. Two subsequent experiments being prepared to run at SPEAR were accordingly merged and expanded to search for these monoenergetic γ rays.

Figure 1 is a schematic view of the apparatus. γ-ray energies and points of impact are measured above and below the colliding beams by NaI(Tl) arrays consisting of nineteen hexagonal modules each 50 cm long and 15 cm between opposite vertices. The seven modules in the side array are used only for triggering purposes. Charged-particle directions are measured to an accuracy of $\pm 3°$ in approximately orthogonal directions by 219 square proportional tube counters arranged in four layers near the interaction region and by two sets of three horizontal planes of multiwire proportional chambers close to the NaI(Tl) arrays. The tube counters and each of these multiwire proportional chambers cover 90% and 16% of the total solid angle, respectively. An event trigger requires deposition of greater than 110 MeV in any one of the three NaI(Tl) crystal arrays and the presence of at least two charged particles in the tube counters as defined by the observation of multiple hits in two or more of 32 distinct sectors. The total integrated luminosity is approximately 600 nb^{-1} at the ψ' and 100 nb^{-1} at the ψ.

The energy resolution provided by the NaI(Tl) arrays is limited by nonlinearities and quantizing effects in the electronic digitizers, by energy losses in the 20-mil stainless-steel container

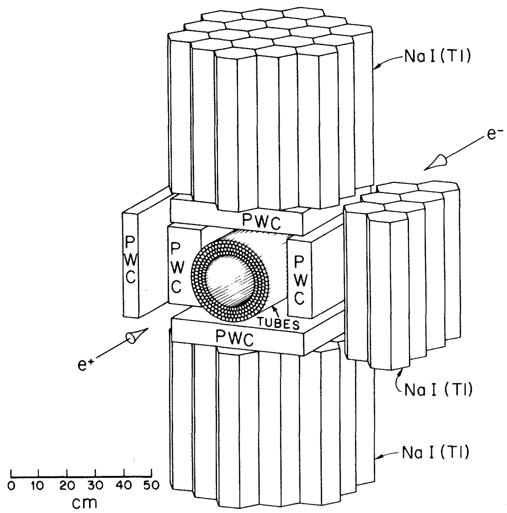

FIG. 1. Schematic of the apparatus used for the inclusive γ-ray experiment. The tube counters provide azimuthal coordinates for charged-particle trajectories, while the proportional wire chambers (PWC) yield coordinates along the beam direction. The hexagonal NaI(Tl) modules are 20 radiation lengths thick.

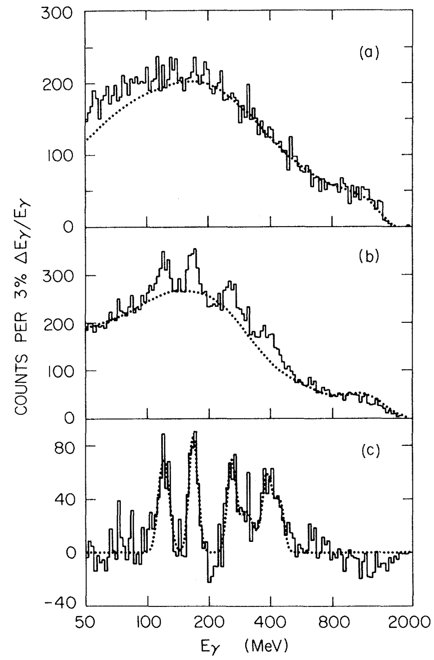

FIG. 2. The inclusive γ-ray distribution as a function of $\ln E_\gamma$ for (a) the ψ(3095) and (b) the ψ'(3684); (c) the difference between the data and the continuum in (b). See text for description of the dotted-line fits.

walls, and by transverse energy leakage from the arrays. A Monte Carlo shower simulation code is used to correct for the wall-loss effect, and also to show that transverse energy leakage is unimportant if at least 10% of the total shower energy is deposited in the inner seven modules of the nineteen-module arrays. This latter requirement restricts the effective solid angle subtended by one such crystal array to about 8% of 4π. The individual crystal calibrations are determined by observing $e^+e^- \to e^+e^-$ events, and vertical cosmic-ray muons are used to monitor short-term variations in the calibrations. The overall energy resolution (σ/E) varies from 2.5% at 1500 MeV to 5% at 200 MeV.

Events with candidate showers are selected by requiring that two or more charged tracks from the interaction region reconstruct in the tube counter and that greater than 140 MeV of energy be deposited somewhere in the crystal arrays other than in the candidate shower. The latter requirement eliminates the direct effect of the electronic trigger threshold on the γ-ray energy spectrum. A shower qualifies as a candidate γ ray if the energy deposited in a cluster of contiguous crystals in an array is such that at least 10% of the cluster energy is in the central seven crystals, more than 70% is in a single crystal (with the remaining energy in adjacent crystals), and there are no overlapping charged-particle trajectories. Background due to π^0 decay is suppressed by rejecting candidate γ rays if another neutral cluster is present in the same array. Remaining cosmic-ray events are suppressed using arrival time and topological criteria, and a final background spectrum is estimated by studying out-of-time events. This background has a peak near 280 MeV, the expected muon energy loss, with a width (σ/E) of 17% and contains 15 ± 5 events in a 3% energy interval at the peak for the ψ' data.

The inclusive γ-ray spectra, after cosmic-ray background subtraction, are shown as histograms in Figs. 2(a) and 2(b) for the decays of the ψ and ψ', respectively. Whereas the ψ spectrum has no significant narrow structure, the ψ' spectrum shows considerable structure, with at least four peaks. Both spectra display a shoulder at the high-energy end of the spectrum as a result of unresolved multiple γ-ray clusters hitting an array.

For ψ decay the background γ-ray spectrum is estimated with a Monte Carlo (MC) program based on an all-pion invariant–phase-space model.[8] The pion multiplicity and neutral fraction have previously been adjusted to agree with charged-particle momenta and multiplicities measured in the SPEAR magnetic detector. After smoothing by a cubic spline fit and normalization to the ψ data above 150 MeV, the prediction of this MC program for the present experiment is shown in Fig. 2(a) as the dotted line. While this MC spectrum matches the shape of the ψ data above about 150 MeV, it disagrees at lower energies. The ψ' MC spectrum is generated similarly, except that the decays[9] $\psi' \to \psi\pi\pi$, $\psi\eta$, and $\chi\gamma$ are included, and the radiative decay γ rays associated with the χ states are excluded from the final MC spectrum. To correct the ψ' MC spectrum for the discrepancy exhibited by the ψ MC spectrum at low γ-ray energies, the ψ' MC results are scaled by the ratio of the ψ data to the ψ MC results. This adjusted ψ MC spectrum is plotted in Fig. 2(b) as the dotted line.

In order to estimate branching fractions corresponding to the peaks in the ψ' γ-ray spectrum, the data are fitted by a model which includes the three well-established states (those with approximate masses of 3550, 3500, and 3410 MeV/c^2 [6,10]). The widths of the three lowest-energy peaks are therefore set at values determined by the resolution of the NaI(Tl) arrays at the appropriate energies. For the corresponding cascade γ rays ($\chi \to \psi\gamma$), the widths used are obtained by combining the resolution of the NaI(Tl) arrays with Doppler broadening. Thus, the ψ' spectrum is fitted by the function

$$a_0 F(\ln E_\gamma) + \sum_{i=1}^{6} a_i (2\pi\sigma_i)^{-1/2} \times \exp[\tfrac{1}{2}(\ln E_\gamma - \ln E_i)^2/\sigma_i^2].$$

Here $F(\ln E_\gamma)$ is the MC background spectrum, and the width σ_i of each Gaussian distribution is fixed as described above. The continuum normalization parameter a_0 and the amplitude a_i and energy E_i of each peak are adjusted to minimize χ^2 over the fitted region (50 to 1000 MeV). This fit yields energies for the monoenergetic γ rays and their cascade partners which are consistent, within errors, with each other and with previous measurements.[6,10] The sum of the Gaussian peaks is plotted as the dotted line in Fig. 2(c).

The branching fractions for the corresponding transitions are calculated by taking ratios of the number of γ rays in each peak to the number in the continuum, using efficiencies determined from the MC program appropriate to each energy and to the continuum. Most systematic errors cancel in this method. It is assumed that the hadronic decays of the ψ' and χ are similar to those of the ψ apart from the larger phase space and multiplicity. The MC program produces an average π^0 multiplicity of 2.8 for ψ hadronic decays. The uncertainty in the overall γ-ray multiplicity[11,12] from hadronic decays contributes a 20% systematic normalization error which applies equally to all the branching-fraction determinations. This error is combined with statistical and background-subtraction errors in the results presented in Table I. An isotropic γ-ray decay distribution is assumed. For the $\chi(3413)$, the branching fraction under the more likely assumption of a $1+\cos^2\theta$ angular distribution[13] is also shown, where θ is the angle of the γ ray with respect to the e^+e^- beam. The resulting $\psi' \to \chi(3413)\gamma$ branching ratio agrees well with a previously reported value of $(7.5\pm2.6)\%$[10] for the corresponding $1+\cos^2\theta$ assumption. A report based on a preliminary analysis of our data[4] listed branching fractions for the isotropic case only.

In conclusion, we find three major radiative decays of the $\psi'(3684)$ with comparable branching fractions, constituting approximately 20% of the ψ' decay rate. A broad enhancement at $E_\gamma \sim 410$ MeV is consistent with the Doppler-broadened radiative decays, $\chi \to \psi\gamma$, for the two highest-mass χ states. A sixth transition, having the largest width of all, may be present at the expected energy (303 MeV) for the radiative decay of the

TABLE I. γ-ray energies and rates from the fit shown in Fig. 2(c) and resultant masses and branching fractions relative to all ψ' decays. The three lowest-energy γ rays are assumed to come from $\psi' \to \chi\gamma$ and the three highset-energy γ rays from $\chi \to \psi\gamma$ in order to specify widths (σ_i) and calculate m_χ.

Fit parameters				Branching
σ_i ($\Delta E/E$)	E_i (MeV)	a_i (events)	m_χ (MeV/c^2)	fraction (%)
0.06	120.9(1.3)[a]	360(50)[a]	3561 ± 7[b]	7.0 ± 2.0[b]
0.05	169.2(1.4)	367(47)	3511 ± 7	7.1 ± 1.9
0.05	260.6(2.9)	290(44)	3413 ± 9	5.5 ± 1.8
				7.2 ± 2.3[c]
0.07	309.5(8.0)	180(45)	3420 ± 14	3.3 ± 1.7
0.06	390.7(4.7)	297(38)	3511 ± 13	5.0 ± 1.5
0.045	449.9(6.3)	137(31)	3577 ± 14	2.2 ± 1.0

[a]Quantities in parentheses are rms statistical errors from the fitting process.

[b]Errors in both m_χ and the branching fractions include systematic errors.

[c]Branching fraction for the $\chi(3413)$ if a $1+\cos^2\theta$ decay angular distribution is assumed as in Ref. 10.

$\chi(3413)$, but the fit is of marginal statistical significance. At the 90% confidence level we find that there are no monoenergetic γ rays in the $\psi(3095)$ spectrum between 50 and 1000 MeV with branching fractions larger than 2.0%. Upper limits in other channels are 1.7% for $\chi(3095) \to \chi(2850)\gamma$,[15] 1.0% for $\psi'(3684) \to \chi(2850)\gamma$, and 2.5% for $\psi' \to \chi(3455)\gamma$, all at the 90% confidence level. There is some evidence for this last χ state in the exclusive channel $\psi' \to \chi(3455)\gamma$, $\chi \to \psi\gamma$, with a branching-ratio product of $(0.8 \pm 0.4)\%$.[10]

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[1]M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

[2]G. C. Callan *et al.*, Phys. Rev. Lett. 34, 52 (1975).

[3]T. Appelquist, A. De Rújula, and H. D. Politzer, Phys. Rev. Lett. 34, 365 (1975).

[4]E. Eichten *et al.*, Phys. Rev. Lett. 34, 369 (1975).

[5]W. Braunschweig *et al.*, Phys. Lett. 57B, 407 (1975).

[6]G. J. Feldman *et al.*, Phys. Rev. Lett. 35, 821 (1975).

[7]J. W. Simpson *et al.*, Phys. Rev. Lett. 35, 699 (1975).

[8]G. J. Feldman and M. L. Perl, Phys. Rep. 19C, 233 (1975). We are indebted to G. J. Feldman for providing a computer program for generating Monte Carlo events.

[9]G. J. Feldman, SLAC Report No. SLAC-PUB-1851, 1976 (unpublished).

[10]J. S. Whitaker *et al.*, Phys. Rev. Lett. 37, 1596 (1976).

[11]R. Baldini-Celio *et al.*, Phys. Lett. 58B, 471 (1975).

[12]J. S. Whitaker, Lawrence Berkeley Laboratory Report No. LBL-5518, 1976 (unpublished).

[13]G. Goldhaber, in *Proceedings of the International Conference on Production of Particles with New Quantum Numbers, Madison, Wisconsin, 1976*, edited by D. B. Cline and J. J. Kalonko (Univ. of Wisconsin, Madison, Wis., 1976).

[14]D. H. Badtke *et al.*, in Proceedings of the Eighteenth International Conference on High Energy Physics, Tbilisi, U. S. S. R., 15–21 July 1976 (to be published).

[15]B. Wiik, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California, 1975*, edited by W. T. Kirk (Stanford Linear Accelerator Center, Stanford, Calif. 1976), p. 69; J. Heintze, *ibid.*, p. 97.

Isotope Effects in Molecular Scattering by Electrons*

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Recent improvement in electron-beam resolution has made possible the direct study of isotope effects in differential cross sections in H_2 and D_2. The observation of the reduced-mass dependence ($\mu^{-1/2}$) of vibrational ($v = 0 \to 1$) cross sections and isotopic independence of rotational cross sections at 4 eV has been understood using the frame-transformation theory. Generalization and limitation of the theory are discussed. Specific predictions are made for cross sections in HD, HT, DT, and T_2.

Scientific investigations involving isotopes in molecules have been a subject of current interest in many different fields. Typical examples are interstellar molecules, thermal neutron scattering, laser isotope separation, and the nuclear fusion problem. Of particular importance is the substitution of deuterium or tritium for hydrogen, because the effects are more pronounced as a result of the greater change of the reduced mass. For the nuclear fusion problem one needs explicit cross sections for D_2, DT, and T_2 while most electron impact cross sections[1] have been measured only in H_2.

Conventionally isotopic substitution in molecules