# Measurement of $\psi(3097)$ and $\psi'(3686)$ Decays into Selected Hadronic Modes

M. E. B. Franklin, G. J. Feldman, G. S. Abrams, M. S. Alam,[a] C. A. Blocker,[b] A. Blondel,[c] A. M. Boyarski, M. Breidenbach, D. L. Burke, W. C. Carithers, W. Chinowsky, M. W. Coles, S. Cooper,[d] W. E. Dieterle,[e] J. B. Dillon, J. Dorenbosch,[f] J. M. Dorfan, M. W. Eaton,[b] G. Gidal, G. Goldhaber, G. Hanson, K. G. Hayes,[f] T. Himel,[f] D. G. Hitlin,[g] R. J. Hollebeek, W. R. Innes, J. A. Jaros, P. Jenni,[f] A. D. Johnson,[h] J. A. Kadyk, A. J. Lankford, R. R. Larsen, M. Levi, R. E. Millikan, V. Lüth, M. E. Nelson, C. Y. Pang, J. F. Patrick,[i] M. L. Perl, B. Richter, A. Roussarie,[j] D. L. Scharre, R. H. Schindler,[g] R. F. Schwitters,[b] J. L. Siegrist,[f] J. Strait,[k] H. Taureg,[f] M. Tonutti,[l] G. H. Trilling, E. Vella,[f] R. A. Vidal,[i] I. Videau,[c] J. M. Weiss,[m] and H. Zaccone[j]

*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720*

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Measurements of $\psi(3097)$ and $\psi'(3686)$ branching fractions for selected hadronic decays are presented. The ratio of $\psi'$ to $\psi$ branching fractions for these decays is consistent with the ratio of branching fractions to lepton pairs, with the exception of the decays to $p\pi$ and $K^*K$ for which this ratio is substantially smaller.

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Applequist and Politzer[1] calculate, using perturbative QCD, that the width of the nonrelativistic charmed quark-antiquark bound-state (charmonium) decay to three gluons is proportional to its leptonic width. Both depend on the mass and the wave function at the origin of the charmonium system. The ratio of branching fractions of $\psi$ and $\psi'$ decays to three gluons can be written in terms of their total and leptonic widths,[2] $\Gamma_t$ and $\Gamma_{ee}$:

$$\frac{B(\psi'\to ggg)}{B(\psi\to ggg)}=\frac{\Gamma(\psi'\to e^+e^-)\Gamma_t(\psi)}{\Gamma(\psi\to e^+e^-)\Gamma_t(\psi')}=(12.2\pm 2.4)\%.$$

The calculation of the width to three gluons assumes that the charmonium system is nonrelativistic, that the strong-coupling constant $\alpha_s \ll 1$, that $\alpha_s(\psi)=\alpha_s(\psi')$, and that charmonium systems decay to hadrons predominantly via a pointlike annihilation into three gluons.

In this Letter we present measurements of the branching fractions from the $\psi$ and $\psi'$ to five exclusive hadronic final states. We compare the theoretical prediction for $B(\psi'\to ggg)/B(\psi\to ggg)$ with the measured ratio $B(\psi'\to X)/B(\psi\to X)$, where $X$ is an exclusive hadronic final state. We note that the prediction is made for the total width for three-gluon decay, not for the partial widths of exclusive final states. We expect the partial widths to be functions of the wave function at the origin of the charmonium states as well since the exclusive decay proceeds through a three-gluon annihilation in this model. However, there are other factors associated with each exclusive mode (such as multiplicity) which are disregarded by this prediction and therefore we do not expect the agreement between calculation and experiment to be perfect.

The data were taken with the MARK II detector at the SPEAR $e^+e^-$ storage ring located at the Stanford Linear Accelerator Center. The data sample corresponds to 427 000 produced $\psi$'s and $1.02\times10^6$ produced $\psi'$'s. The MARK II detector has been described in detail elsewhere.[3] Briefly, charged particles are tracked by a sixteen-layer cylindrical drift chamber in a 4.1-kG axial magnetic field. The momentum resolution is $\delta p/p = [(0.015)^2+(0.005p)^2]^{1/2}$, where $p$ is the momentum in gigaelectronvolts. Time-of-flight scintillation counters are used for particle identification. The timing resolution is 300 ps for hadrons. This provides $\pi/K$ separation for charged tracks of momenta below 1.2 GeV and proton identification below 2 GeV. Liquid-argon calorimeters with an energy resolution $\sigma/E=12\%/\sqrt{E}$ (where $E$ is the photon energy) are used to find photons and to discriminate hadrons from electrons. A system of steel interlaced with planes of proportional tubes is used to identify muons. This is done by detecting charged particles and ranging out all those which interact in the steel.

We have made measurements of the branching ratios from the $\psi$ and the $\psi'$ to the final states $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $2\pi^+2\pi^-\pi^0$, and $3\pi^+3\pi^-\pi^0$ on the basis of the following general event selection criteria.

In all cases we require that at least two photons with energies greater than 150 MeV be detected in the liquid-argon modules. We define a photon as a signal in the liquid-argon shower counter with no associated charged track in the central tracking chamber. To exclude events with fake photon signals made by the coincidence of noise in the liquid-argon and hadronic tracks, photons found within 36 cm of a charged track (at the entrance to the shower counter) were not used. We require that the total charge of the event be zero. A charged track is used only if it is associated with an acceptable time-of-flight measurement, which must be consistent to within 600 ps with the time expected given the chosen mass hypothesis and the reconstructed path length. Corrections are made for energy lost by the charged particles in the material before they enter the drift volume. Charged tracks identified as muons are excluded. Decays of the $\psi'$ which occur via the $\psi$, such as $\psi' \to \pi^+\pi^-\psi$, $\psi \to \pi^+\pi^-\pi^0$, or via the $\chi$ states are excluded. Each event is totally reconstructed which allows such radiative decays to be recognized easily and rejected.

In all analyses a kinematic fit with four constraints is performed on each event and a cut made on the $\chi^2$ of the fit. For example when we look at the decay $\psi \to p\bar{p}\pi^0$, the fit hypothesis is $\psi \to p\bar{p}\gamma\gamma$. By not constraining the two-photon invariant mass to the $\pi^0$ mass we are able to make a background subtraction beneath the $\pi^0$ in the two-photon invariant-mass spectra. Finally we require that a $\pi^0$, defined as $115 < M(\gamma\gamma) < 135$ MeV/$c^2$, be present. Detection efficiencies are calculated by Monte Carlo simulation. These efficiencies range from 0.1% to 12%, and are typically greater for decays of the $\psi'$ because of the 20% mass increase over the $\psi$. The errors in all branching fractions quoted below are the statistical and systematic errors added in quadrature.

The decay $\psi \to \pi^+\pi^-\pi^0$ is measured to be consistent with its proceeding almost entirely through the $\rho\pi$ intermediate state. Figure 1 shows the observed invariant-mass distribution of $\pi^+\pi^-$ pairs in events that satisfy the $\pi^+\pi^-\pi^0$ hypothesis. Note that there is very little continuum $3\pi$ production between 1.0 and 1.8 GeV/$c^2$. This is also true for the charged decay mode $\psi \to \rho^\pm\pi^\mp$. We require a $\rho$, defined as $530 < M(\pi\pi) < 1010$ MeV/$c^2$, in each event. Figure 2 shows the fitted two-photon invariant-mass spectrum for the decay $\psi \to \rho\pi$. The good resolution of the $\pi^0$ mass reflects the precision with which we have measured the angles of the photons, rather than their energies. We observe a $\rho\pi$ signal of 149.7 events (background subtracted) combining the neutral and charged modes. For the decay $\psi' \to \rho\pi$, with the same selection criteria, one event is seen which yields

$$B(\psi' \to \rho\pi)/B(\psi \to \rho\pi) < 0.6\% \quad \text{(90\% confidence level).}$$

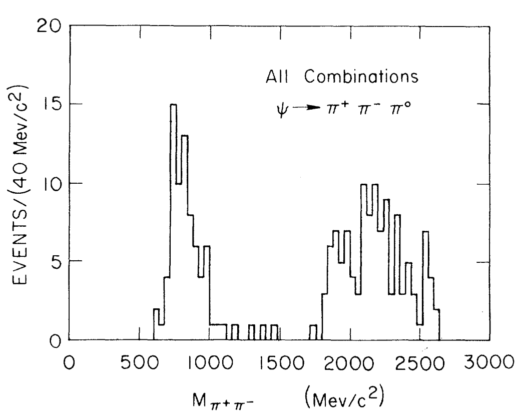


FIG. 1. $\pi^+\pi^-$ invariant-mass distribution for events $\psi \to \pi^+\pi^-\pi^0$. A $\rho^0$ peak and a charged-$\rho$ reflection are evident.

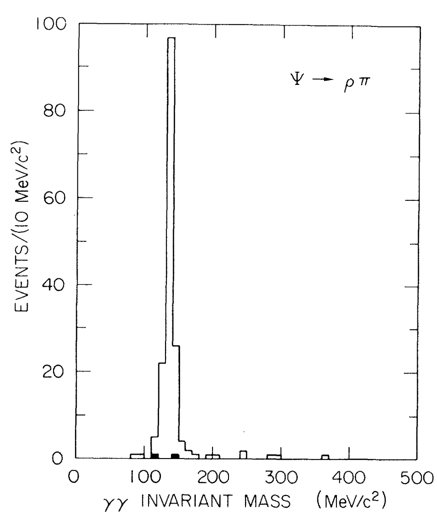


FIG. 2. Two-photon invariant-mass spectrum for decays $\psi \to \rho\pi$ and $\psi' \to \rho\pi$ (shaded).

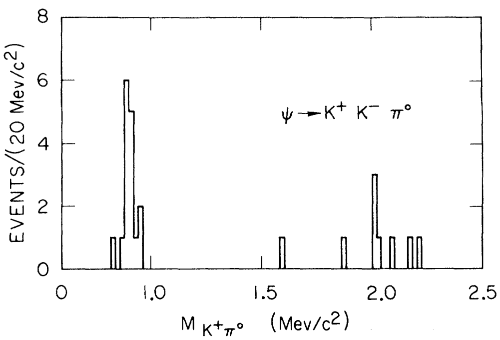


FIG. 3. $K^+\pi^0$ invariant-mass distribution for events $\psi \to K^+K^-\pi^0$. A $K^*(892)$ peak is evident.

If we relax the requirement that each event contain a $\rho$, then we find 170 events from the $\psi$ and 4 events from the $\psi'$. Regarding these as signal events with a negligible background we measure the ratio of branching fractions to be

$$B(\psi' \to \pi^+\pi^-\pi^0)/B(\psi \to \pi^+\pi^-\pi^0) = (0.58 \pm 0.40)\%.$$

The decay $\psi \to K^+K^-\pi^0$ is found to proceed predominantly through the intermediate state $K^*(892)\bar{K}$. Figure 3 shows this $K^*$ signal in the invariant-mass distribution of the $K^+\pi^0$. We require that a $K^*(892)$ be present in the final state by making a cut on the invariant mass of the $K\pi$ system such that $780 < M(K\pi^0) < 1000$ MeV/$c^2$. We observe a $\pi^0$ signal of 24 events with no background. We observe no such events in the corresponding decay of the $\psi'$. An upper limit on the ratio of branching ratios is

$$\frac{B(\psi' \to K^*K)B(K^* \to K\pi^0)}{B(\psi \to K^*K)B(K^* \to K\pi^0)} < 2.07\% \text{ (90\% C.L.)}.$$

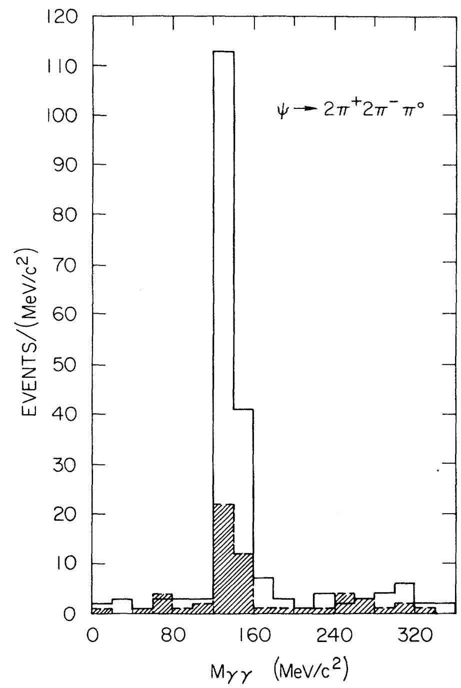


FIG. 4. Two-photon invariant-mass spectrum for decays $\psi$, $\psi'$(shaded)$\to 2\pi^+2\pi^-\pi^0$.

For the decays $\psi$ ($\psi'$)$\to p\bar{p}\pi^0$ we find 16 (9) events

TABLE I. Branching-ratio measurements for decay modes analyzed in the present experiment and for three modes analyzed previously (Refs. 4–6).

| Mode | Number of events | Efficiency (%) | $B(\psi\to X)$ (%) | Number of events | Efficiency (%) | $B(\psi'\to X)$ (%)[a] | $B(\psi'\to X)/B(\psi\to X)$ (%) |
|---|---|---|---|---|---|---|---|
| $p\bar{p}$[b] | | | (0.22±0.02) | | | (0.019±0.005) | 8.6±2.4 |
| $p\bar{p}\pi^+\pi^-$[b] | | | (0.53±0.06) | | | (0.08±0.02) | 15.1±4.1 |
| $K^+K^-\pi^+\pi^-$[b] | | | (0.72±0.23) | | | (0.16±0.04) | 22.2±9.0 |
| $p\bar{p}\pi^0$ | 16 | 3.72 | $(1.0\pm0.3)\times10^{-1}$ | 9 | 6.2 | $(1.4\pm0.5)\times10^{-2}$ | 14.0±6.3 |
| $2\pi^+2\pi^-\pi^0$ | 147.5 | 1.09 | (3.2±0.4) | 42 | 1.39 | (0.30±0.08) | 9.5±2.7 |
| $3\pi^+3\pi^-\pi^0$ | 11 | 0.09 | (2.8±0.9) | 6 | 0.17 | $(3.5\pm1.6)\times10^{-1}$ | 13.0±7.0 |
| $K^+K^-\pi^0$ inclusive | 25 | 2.13 | $(2.8\pm0.8)\times10^{-1}$ | 1 | 4.2 | $<8.9\times10^{-3}$ | <3.2 |
| $K^{\pm *}K^{\mp}$ $\hookrightarrow K^{\pm}\pi^0$ | 24 | 2.13 | $(2.6\pm0.8)\times10^{-1}$ | 0 | 4.2 | $<5.4\times10^{-3}$ | <2.07 |
| $\pi^+\pi^-\pi^0$ inclusive | 166 | 2.68 | (1.5±0.2) | 4 | 4.6 | $(8.5\pm4.6)\times10^{-3}$ | 0.6±0.4 |
| $\rho\pi$ | 149.7 | 2.68 | (1.3±0.3) | 1 | 4.6 | <0.0083 | <0.63 |

[a]All mimits set at 90% confidence level.

[b]These modes were measured elsewhere (Refs. 4–6).

which satisfy the event selection criteria, yielding $B(\psi' \to p\bar{p}\pi^0)/B(\psi \to p\bar{p}\pi^0) = (14.0 \pm 6.3)\%$. For the decays $\psi$ $(\psi') \to 2\pi^+2\pi^-\pi^0$ we find 152 (30) events which satisfy the selection criteria. Figure 4 shows the fitted two-photon invariant-mass spectrum for these decays. In both cases there is a clear $2\pi^+2\pi^-\pi^0$ signal. The ratio of branching ratios for these two processes is

$$B(\psi' \to 2\pi^+2\pi^-\pi^0)/B(\psi \to 2\pi^+2\pi^-\pi^0) = (9.5 \pm 2.7)\%.$$

For the decays $\psi(\psi') \to 3\pi^+3\pi^-\pi^0$ we see 11 events from the $\psi$ and 6 events from the $\psi'$ with no background. The ratio of branching fractions is

$$B(\psi' \to 3\pi^+3\pi^-\pi^0)/B(\psi \to 3\pi^+\pi^-\pi^0) = (13 \pm 7)\%.$$

Table I summarizes the results of branching-ratio measurements for all decay modes analyzed and for three modes, $\psi, \psi' \to p\bar{p}$, $p\bar{p}\pi\pi$, and $K^+K^-\pi^+\pi^-$ analyzed in previous experiments.[4-6] The table includes the number of events and the efficiency for each decay mode. The branching fractions measured in this experiment are consistent with measurements of previous experiments. Of the five decay modes studied and the three measured previously, six give values of the ratio of branching fractions of the $\psi'$ to the $\psi$ consistent with the prediction of perturbative QCD for inclusive hadrons and two do not. Those two states are $\rho\pi$ and $K^*K$. We find little significant evidence for these decays from the $\psi'$. This is a striking deviation from our naive expectations discussed above and as yet there is no theoretical explanation.

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[a]Present address: Vanderbilt University, Nashville, Tenn. 37235.

[b]Present address: Harvard University, Cambridge, Mass. 02138.

[c]Present address: Laboratoire de Physique Nucléaire et Hautes Energies, Ecole Polytechnique, F-91128 Palaiseau, France.

[d]Present address: DESY, D-2000 Hamburg 52, Federal Republic of Germany.

[e]Present address: University of Arizona, Tucson, Ariz. 85721.

[f]Present address: CERN, CH-1211 Geneva 23, Switzerland.

[g]Present address: California Institute of Technology, Pasadena, Cal. 91125.

[h]Present address: University of California at Santa Cruz, Santa Cruz, Cal. 95064.

[i]Present address: Fermi National Accelerator Laboratory, Batavia, Ill. 60510.

[j]Present address: Centre d'Etudes Nucléaires de Saclay, F-91190, Gif-Sur-Yvette, France.

[k]Present address: University of Massachusetts, Amherst, Mass. 01003.

[l]Present address: Physikcalisches Institut, Physikzentrum, D-5100 Aachen, Germany.

[m]Present address: Argonne National Laboratory, Argonne, Ill. 60439.

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