

Measurement of the Decay $\tau^- \rightarrow \pi^- \pi^+ \pi^- 2\pi^0 \nu_\tau$

D. Bortoletto,¹ D. N. Brown,¹ J. Fast,¹ R. L. McIlwain,¹ T. Miao,¹ D. H. Miller,¹ M. Modesitt,¹ S. F. Schaffner,¹ E. I. Shibata,¹ I. P. J. Shipsey,¹ P. N. Wang,¹ M. Battle,² J. Ernst,² H. Kroha,² S. Roberts,² K. Sparks,² E. H. Thorndike,² C. H. Wang,² J. Dominick,³ S. Sanghera,³ T. Skwarnicki,³ R. Stroynowski,³ M. Artuso,⁴ D. He,⁴ M. Goldberg,⁴ N. Horwitz,⁴ R. Kennett,⁴ G. C. Moneti,⁴ F. Muheim,⁴ Y. Mukhin,⁴ S. Playfer,⁴ Y. Rozen,⁴ S. Stone,⁴ M. Thulasidas,⁴ G. Vasseur,⁴ G. Zhu,⁴ J. Bartelt,⁵ S. E. Csorna,⁵ Z. Egyed,⁵ V. Jain,⁵ P. Sheldon,⁵ D. S. Akerib,⁶ B. Barish,⁶ M. Chadha,⁶ S. Chan,⁶ D. F. Cowen,⁶ G. Eigen,⁶ J. S. Miller,⁶ C. O'Grady,⁶ J. Urheim,⁶ A. J. Weinstein,⁶ D. Acosta,⁷ M. Athanas,⁷ G. Masek,⁷ B. Ong,⁷ H. Paar,⁷ M. Sivertz,⁷ A. Bean,⁸ J. Gronberg,⁸ R. Kutschke,⁸ S. Menary,⁸ R. J. Morrison,⁸ S. Nakanishi,⁸ H. N. Nelson,⁸ T. K. Nelson,⁸ J. D. Richman,⁸ A. Ryd,⁸ H. Tajima,⁸ D. Schmidt,⁸ D. Sperka,⁸ M. S. Witherell,⁸ M. Procaro,⁹ S. Yang,⁹ R. Balest,¹⁰ K. Cho,¹⁰ M. Dauodi,¹⁰ W. T. Ford,¹⁰ D. R. Johnson,¹⁰ K. Lingel,¹⁰ M. Lohner,¹⁰ P. Rankin,¹⁰ J. G. Smith,¹⁰ J. P. Alexander,¹¹ C. Bebek,¹¹ K. Berkelman,¹¹ D. Besson,¹¹ T. E. Browder,¹¹ D. G. Cassel,¹¹ H. A. Cho,¹¹ D. M. Coffman,¹¹ P. S. Drell,¹¹ R. Ehrlich,¹¹ M. Garcia-Sciveres,¹¹ B. Geiser,¹¹ B. Gittelman,¹¹ S. W. Gray,¹¹ D. L. Hartill,¹¹ B. K. Heltsley,¹¹ C. D. Jones,¹¹ S. L. Jones,¹¹ J. Kandaswamy,¹¹ N. Katayama,¹¹ P. C. Kim,¹¹ D. L. Kreinick,¹¹ G. S. Ludwig,¹¹ J. Masui,¹¹ J. Mevissen,¹¹ N. B. Mistry,¹¹ C. R. Ng,¹¹ E. Nordberg,¹¹ M. Ogg,^{11,*} J. R. Patterson,¹¹ D. Peterson,¹¹ D. Riley,¹¹ S. Salman,¹¹ M. Sapper,¹¹ H. Worden,¹¹ F. Würthwein,¹¹ P. Avery,¹² A. Freyberger,¹² J. Rodriguez,¹² R. Stephens,¹² J. Yelton,¹² D. Cinabro,¹³ S. Henderson,¹³ K. Kinoshita,¹³ T. Liu,¹³ M. Saulnier,¹³ F. Shen,¹³ R. Wilson,¹³ H. Yamamoto,¹³ M. Selen,¹⁴ A. J. Sadoff,¹⁵ R. Ammar,¹⁶ S. Ball,¹⁶ P. Baringer,¹⁶ D. Coppage,¹⁶ N. Coptly,¹⁶ R. Davis,¹⁶ N. Hancock,¹⁶ M. Kelly,¹⁶ N. Kwak,¹⁶ H. Lam,¹⁶ Y. Kubota,¹⁷ M. Lattery,¹⁷ J. K. Nelson,¹⁷ S. Patton,¹⁷ D. Perticone,¹⁷ R. Poling,¹⁷ V. Savinov,¹⁷ S. Schrenk,¹⁷ R. Wang,¹⁷ M. S. Alam,¹⁸ I. J. Kim,¹⁸ B. Nemati,¹⁸ J. J. O'Neill,¹⁸ H. Severini,¹⁸ C. R. Sun,¹⁸ M. M. Zoeller,¹⁸ G. Crawford,¹⁹ C. M. Daubenmier,¹⁹ R. Fulton,¹⁹ D. Fujino,¹⁹ K. K. Gan,¹⁹ K. Honscheid,¹⁹ H. Kagan,¹⁹ R. Kass,¹⁹ J. Lee,¹⁹ R. Malchow,¹⁹ F. Morrow,¹⁹ Y. Skovpen,^{19,†} M. Sung,¹⁹ C. White,¹⁹ J. Whitmore,¹⁹ P. Wilson,¹⁹ F. Butler,²⁰ X. Fu,²⁰ G. Kalbfleisch,²⁰ M. Lambrecht,²⁰ W. R. Ross,²⁰ P. Skubic,²⁰ J. Snow,²⁰ P. L. Wang,²⁰ and M. Wood²⁰

(CLEO Collaboration)

¹Purdue University, West Lafayette, Indiana 47907

²University of Rochester, Rochester, New York 14627

³Southern Methodist University, Dallas, Texas 75275

⁴Syracuse University, Syracuse, New York 13244

⁵Vanderbilt University, Nashville, Tennessee 37235

⁶California Institute of Technology, Pasadena, California 91125

⁷University of California, San Diego, La Jolla, California 92093

⁸University of California, Santa Barbara, California 93106

⁹Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

¹⁰University of Colorado, Boulder, Colorado 80309-0390

¹¹Cornell University, Ithaca, New York 14853

¹²University of Florida, Gainesville, Florida 32611

¹³Harvard University, Cambridge, Massachusetts 02138

¹⁴University of Illinois, Champaign-Urbana, Illinois 61801

¹⁵Ithaca College, Ithaca, New York 14850

¹⁶University of Kansas, Lawrence, Kansas 66045

¹⁷University of Minnesota, Minneapolis, Minnesota 55455

¹⁸State University of New York at Albany, Albany, New York 12222

¹⁹Ohio State University, Columbus, Ohio 43210

²⁰University of Oklahoma, Norman, Oklahoma 73019

(Received 6 July 1993)

The decay $\tau^- \rightarrow \pi^- \pi^+ \pi^- 2\pi^0 \nu_\tau$ has been observed in e^+e^- annihilation using the CLEO II detector at the Cornell Electron Storage Ring. In a data sample collected at $\sqrt{s} \sim 10.6$ GeV, 668 ± 38 decay candidates have been identified by exclusively reconstructing two π^0 's accompanying three charged particles, which are assumed to be pions. Normalizing to the number of τ pairs detected with one charged particle recoiling against three charged particles, this yields a branching ratio of $B_{3\pi^2\pi^0} = (0.48$

$\pm 0.04 \pm 0.04\%$. A signal of 430 ± 33 events for the decay $\tau^- \rightarrow \pi^- \omega \pi^0 \nu_\tau$ has also been observed, corresponding to a branching ratio of $B_{\pi\omega\pi^0} = (0.39 \pm 0.04 \pm 0.04)\%$.

PACS numbers: 13.35.+s, 14.60.Jj

The decay of the τ lepton provides a good laboratory for studies of the hadronic weak current. Its large mass allows the τ to decay to a variety of final hadronic states while the $V-A$ coupling of the hadronic weak current restricts the allowed quantum numbers of these states. The decay modes with high multiplicity in the final state are of particular interest because of their high sensitivity to the τ neutrino mass. In this Letter, we report the observation of the decay mode [1] $\tau^- \rightarrow \pi^- \pi^+ \pi^- 2\pi^0 \nu_\tau$. The decay is identified by exclusively reconstructing two π^0 's accompanying three charged particles, which are assumed to be pions. An ω signal has also been observed in the $\pi^+ \pi^- \pi^0$ invariant mass spectrum of the decay, corresponding to a new decay mode $\tau^- \rightarrow \pi^- \omega \pi^0 \nu_\tau$.

The data used in this analysis have been collected with the CLEO II detector [2] at the Cornell Electron Storage Ring (CESR). CLEO II is a general purpose spectrometer with excellent charged particle and shower energy detection. Charged particles are measured with three cylindrical drift chambers between 5 and 95 cm from the e^+e^- interaction region (IR), with a total of 67 layers. These are surrounded by a scintillation time-of-flight system and a CsI(Tl) calorimeter with 7800 crystals. These detector systems are installed inside a 1.5 T superconducting solenoidal magnet, surrounded by a proportional tube muon chamber with iron absorbers.

The data sample was collected from e^+e^- collisions at a center-of-mass energy $\sqrt{s} \sim 10.6$ GeV ($E_{c.m.}$). The total integrated luminosity of the sample is 1.6 fb^{-1} , corresponding to $\sim 1.4 \times 10^6$ τ events produced. The selection criteria for the τ events are similar to those described in a previous Letter [3]; we briefly recount the criteria here. Each τ event is required to contain four charged tracks with zero net charge. To ensure that the event is well measured, we demand the distance of closest approach of each track to be within 1 cm of the IR in the xy plane and 10 cm in z (the beam direction). These criteria also reject τ events with a K_S or photon conversion; in addition no more than one track may be identified as an electron. QED backgrounds such as radiative Bhabha and two-photon interactions are suppressed by requiring that the total energy of the event be greater than $0.30E_{c.m.}$ and the total shower energy be less than $0.75E_{c.m.}$. The QED and hadronic ($e^+e^- \rightarrow q\bar{q}$) backgrounds are further reduced by requiring the missing mass of the event to be between 0.5 and 7.0 GeV/c^2 , computed from the visible charged and neutral energy. The event is divided into two hemispheres by a plane perpendicular to the axis defined by the highest momentum track and there must be one charged particle in one hemisphere recoiling against three charged particles in the other hemisphere

(“1-3” topology). The total invariant mass of the charged and neutral particles in each hemisphere is required to be less than $1.7 \text{ GeV}/c^2$. The total momentum vector of the particles in each hemisphere is required to be in the barrel region of the electromagnetic calorimeter, $|\cos\theta| < 0.80$, where the polar angle θ is defined with respect to the beam direction. Photon candidates are required to have a minimum energy of 60 MeV in the barrel region and 100 MeV in the end-cap region ($0.80 < |\cos\theta| < 0.95$), and the crystal clusters forming the photons must not be associated with any charged track. Finally, we require exactly four such photons in the barrel in the 3-prong hemisphere; a sample of 2827 events satisfies these criteria.

We search for $2\pi^0$ candidates in these events. Figure 1 shows the invariant mass spectrum ($M_{\gamma\gamma}$) of one photon pair versus that of the other pair, for all three possible combinations. An enhancement at the π^0 mass is evident. The invariant mass spectrum of the $\pi^- \pi^+ \pi^- 2\pi^0$ events is shown in Fig. 2, where the invariant mass of both photon pairs forming the π^0 's is required to be $\pm 2.0\sigma$ ($\sigma = 6 \text{ MeV}/c^2$) of the nominal π^0 mass. The combinatoric background has been subtracted from the spectrum using the π^0 sidebands and the invariant mass cut on the 3-prong hemisphere has been removed. An excess of events over the expected hadronic background (described below) is observed.

The $2\pi^0$ signal is extracted by performing a binned maximum likelihood fit to the two-dimensional two-photon mass spectrum shown in Fig. 1, assuming Poisson statistics. The spectrum is parametrized using a Gauss-

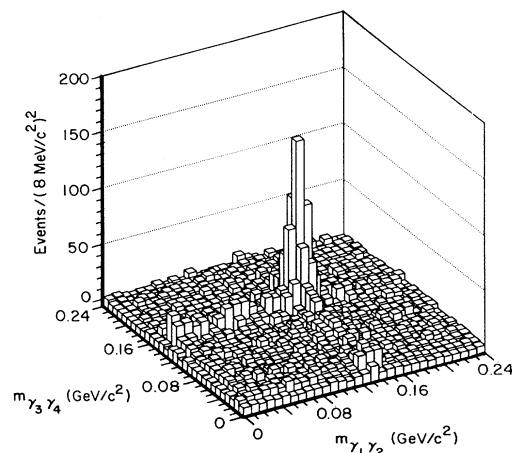


FIG. 1. The invariant mass of one photon pair versus that of the other in events with four photons in the 3-prong hemisphere.

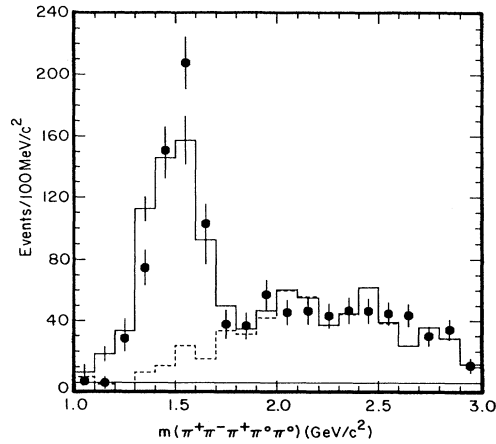


FIG. 2. The invariant mass spectrum of the $\pi^- \pi^+ \pi^- 2\pi^0$ system. The dashed histogram shows the hadronic background expectation (see text) and the solid histogram shows the Monte Carlo expectation including this background. For clarity, the statistical errors on the histograms have been omitted except the solid histogram with mass less than $1.7 \text{ GeV}/c^2$.

ian signal with a long low-mass tail and a Chebyshev polynomial background. With the mass and width of the Gaussian as free parameters, the fit yields a signal of $668 \pm 38 \text{ } 2\pi^0$ events, with a χ^2 of 388 for 393 degrees of freedom.

The dominant source of background in the data is hadronic events. This background is calculated empirically using a sample of 1-3 hadronic events obtained from the data. We select the hadronic sample using the criteria described above, but require the total invariant mass of the charged and neutral particles in the 1-prong hemisphere to be greater than $1.8 \text{ GeV}/c^2$, kinematically excluding τ -pair events. Assuming that the total invariant masses of the particles in the two hemispheres are not correlated, the mass spectrum of the 3-prong hemisphere thus obtained should reproduce the hadronic background component in the τ sample. The mass spectra of the $3\pi 2\pi^0$ candidates for the two samples are superimposed in Fig. 2, normalized so as to contain the same number of events above $2.0 \text{ GeV}/c^2$. The agreement in the shapes of the spectra in the normalization region indicates the reliability of this background calculation. By performing a similar fit for the $2\pi^0$ signal in the hadronic sample, the background fraction in the τ sample with the $1.7 \text{ GeV}/c^2$ mass cut is estimated to be $(7.2 \pm 2.9)\%$.

The detection efficiency is calculated using a Monte Carlo technique. We use the KORALB program to generate $\tau^+ \tau^-$ pairs according to the standard electroweak theory, including α^3 radiative corrections [4]. The GEANT program [5] is used to simulate the detector response. Backgrounds not associated with $e^+ e^-$ annihilation events are modeled by embedding random trigger events into the Monte Carlo events. The decay τ^-

TABLE I. Summary of the signal, background, and detection efficiency. All errors are statistical only.

	$3\pi 2\pi^0$	$\pi\omega\pi^0$	1-3
Data	668 ± 38	430 ± 33	142542 ± 378
τ migration	38 ± 8	18 ± 4	5642 ± 48
$q\bar{q}$	48 ± 20	28 ± 16	8510 ± 151
$\gamma\gamma$	551 ± 87
ϵ (%)	4.9 ± 0.1	4.0 ± 0.1	37.3 ± 0.1

$\rightarrow \pi^- \pi^+ \pi^- 2\pi^0 \nu_\tau$ is modeled using a phase space distribution with a $V-A$ weak interaction. Within the statistical errors, the observed spectrum shown in Fig. 2 is consistent with this simple model [6]. Repeating the same analysis procedure on the Monte Carlo events yields the detection efficiencies and the "migration" backgrounds from other τ decay modes as shown in Table I. The dominant migration backgrounds arise from the decays $\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau$ with a photon conversion or Dalitz decay and $\tau^- \rightarrow \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ with two extra neutral showers forming a fake π^0 .

The branching ratio for $\tau^- \rightarrow \pi^- \pi^+ \pi^- 2\pi^0 \nu_\tau$ is calculated by normalizing to the number of "generic" 1-3 τ events. This method has the advantage that it is independent of precise knowledge of the luminosity and τ cross section and many systematic errors cancel in the ratio. The 1-3 τ events are selected with the same criteria, except that the number of photons in the 3-prong hemisphere is restricted to two or less to reduce hadronic contamination. In this normalization, the branching ratio for $\tau^- \rightarrow \pi^- \pi^+ \pi^- 2\pi^0 \nu_\tau$ is related to the 3-prong topological branching ratio B_3 by

$$\frac{B_{3\pi 2\pi^0}}{B_3} = \frac{N_{3\pi 2\pi^0} - N_{3\pi 2\pi^0}^b}{N_{1-3} - N_{1-3}^b} \frac{\epsilon_{1-3}}{\epsilon_{3\pi 2\pi^0}},$$

where $N_{3\pi 2\pi^0}$ and $N_{3\pi 2\pi^0}^b$ are the number of $3\pi 2\pi^0$ events in the data and background, respectively. N_{1-3} and N_{1-3}^b are the corresponding numbers for 1-3 events. $\epsilon_{3\pi 2\pi^0}$ and ϵ_{1-3} are the detection efficiencies for $3\pi 2\pi^0$ and 1-3 events. The detection efficiency and backgrounds for the 1-3 events are also listed in Table I. The two-photon background is estimated by using a Monte Carlo model for the process [7] $e^+ e^- \rightarrow e^+ e^- 2\pi^+ 2\pi^-$ and by comparing data and Monte Carlo distributions for kinematic variables which are sensitive to two-photon processes such as transverse momentum and visible energy [8]. Using the results in Table I yields the ratio $B_{3\pi 2\pi^0}/B_3 = 0.034 \pm 0.002$, where the error is statistical only.

We have searched for substructure in the $\pi^- \pi^+ \pi^- 2\pi^0$ system. Figure 3 shows the $\pi^+ \pi^- \pi^0$ invariant mass spectrum for all four possible combinations, where the invariant mass of both photon pairs forming the π^0 's is required to be within $\pm 20 \text{ MeV}/c^2$ of the nominal π^0 mass. A clear enhancement at the ω is observed [9], corresponding to a new decay mode $\tau^- \rightarrow \pi^- \omega \pi^0 \nu_\tau$. We measure

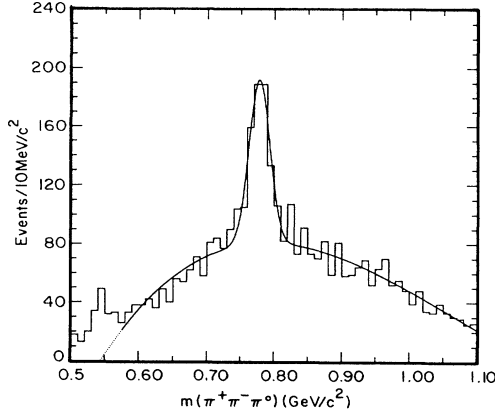


FIG. 3. The $\pi^+\pi^-\pi^0$ mass spectrum of the $3\pi 2\pi^0$ candidates in the τ sample. The curve shows the fit to the data.

the branching ratio for $\tau^- \rightarrow \pi^- \omega \pi^0 \nu_\tau$ by performing a maximum likelihood fit to the mass spectrum. The spectrum is parametrized using a Gaussian signal with a Chebyshev polynomial background. The width of the ω signal is constrained to the expectation from the Monte Carlo simulation [10]. The fit yields a signal of 430 ± 33 events, with a χ^2 of 51 for 46 degrees of freedom. We perform similar fits to the τ Monte Carlo and hadronic samples to determine the detection efficiency and backgrounds listed in Table I. Correcting for the detection efficiency and backgrounds, the branching ratio, normalized to B_3 , is $B_{\pi\omega\pi^0}/B_3 = 0.028 \pm 0.003$, where the error is statistical only. We have also searched for the ρ meson in the $3\pi 2\pi^0$ and $\pi\omega\pi^0$ events; no strong ρ signal is observed in either mode.

The dominant systematic error is the uncertainty in the relative detection efficiencies, which is estimated to be 8% by varying the photon selection criteria. This estimate has been checked by performing similar analyses on other decay modes, $\pi 2\pi^0$, 3π , $3\pi\pi^0$, and $\pi\omega$. The branching ratios measured are consistent with previously measured results [11]. The fitting procedure has been verified by performing a two-dimensional sideband subtraction instead of fitting the π^0 's by varying the $M_{\gamma\gamma}$ range over which the fit is performed, and by varying the definition of the π^0 used to reconstruct the $\pi^+\pi^-\pi^0$ mass spectrum for extracting the ω signal. The uncertainty in the Monte Carlo modeling of the ω width used in the fit has been investigated using $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ and $\tau^- \rightarrow \pi^-\omega\nu_\tau$. Potential biases in the hadronic background estimate due to possible correlations in the total invariant masses of the two hemispheres have been investigated by comparing the 1- and 3-prong mass spectra of hadronic events of 1-3, 1-5, and 3-3 topologies. From these studies, we assign a systematic error of 20% on the hadronic background fraction. We have verified the background calculation by measuring the branching ratios using a leptonic tag to suppress the hadronic background and obtain consistent

TABLE II. Summary of systematic errors in percent (relative).

	$3\pi 2\pi^0$	$\pi\omega\pi^0$
Efficiency (systematic)	8	8
Efficiency (statistical)	1	2
Fit	2	2
ω width	...	3
$q\bar{q}$ background (systematic)	2	2
τ migration	2	2
5π mass spectrum	2	2
Total	9	10

results: $B_{3\pi 2\pi^0}/B_3 = 0.034 \pm 0.003$ and $B_{\pi\omega\pi^0}/B_3 = 0.027 \pm 0.004$. The systematic error in the migration background [12] due to the uncertainties in τ decay branching ratios is estimated by changing the branching ratios within the reasonable ranges allowed by their uncertainties [11]. The sensitivity to the modeling of the five-pion mass spectrum is estimated by relaxing the cut on the total invariant mass of the 3-prong hemisphere. These systematic errors are summarized in Table II. Combining these errors in quadrature and using $B_3 = (14.06 \pm 0.25)\%$ from the Particle Data Group [11], the final results [13] are

$$B_{3\pi 2\pi^0} = (0.48 \pm 0.04 \pm 0.04)\%,$$

$$B_{\pi\omega\pi^0} = (0.39 \pm 0.04 \pm 0.04)\%,$$

where the second error is systematic, including the uncertainty in B_3 .

In conclusion, we have observed two new τ decay modes, $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ and $\tau^- \rightarrow \pi^-\omega\pi^0\nu_\tau$. The branching ratio for $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ is significantly larger than that of its isospin partner [11] $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^+\pi^-\nu_\tau$, $B_{5\pi} = (0.056 \pm 0.016)\%$. The large ω component might account for the enhancement. These decays provide a new technique for measuring the τ neutrino mass [14].

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. J.B. thanks the Vanderbilt University Research Council, J.P.A. and P.S.D. thank the PYI program of NSF, I.P.J.S. thanks the YI program of NSF, K.H. thanks the Alexander von Humboldt Stiftung, G.E. thanks the Heisenberg Foundation, K.K.G. and A.J.W. thank the SSC Fellowship program of TNRLC, K.K.G., H.N.N., J.D.R., and H.Y. thank the OJI program of DOE, and R.P. and P.R. thank the A.P. Sloan Foundation for support. This work was supported by the National Science Foundation and Department of Energy.

*Permanent address: Carleton University, Ottawa, Canada K1S 5B6.

†Permanent address: INP, Novosibirsk, Russia.

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- [13] We can also express the result as a ratio of the two branching ratios so that the systematic error in the detection efficiency cancels. The result is $B_{\pi\omega\pi^0}/B_{3\pi 2\pi^0} = (81 \pm 6 \pm 6)\%$.
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