Study of the Five-Charged-Pion Decay of the τ Lepton

D. Gibaut,[1] K. Kinoshita,[1] B. Barish,[2] M. Chadha,[2] S. Chan,[2] D.F. Cowen,[2] G. Eigen,[2] J.S. Miller,[2] C. O'Grady,[2] J. Urheim,[2] A.J. Weinstein,[2] D. Acosta,[3] M. Athanas,[3] G. Masek,[3] H.P. Paar,[3] J. Gronberg,[4] R. Kutschke,[4] S. Menary,[4] R.J. Morrison,[4] S. Nakanishi,[4] H.N. Nelson,[4] T.K. Nelson,[4] C. Qiao,[4] J.D. Richman,[4] A. Ryd,[4] H. Tajima,[4] D. Sperka,[4] M.S. Witherell,[4] M. Procario,[5] R. Balest,[6] K. Cho,[6] M. Daoudi,[6] W.T. Ford,[6] D.R. Johnson,[6] K. Lingel,[6] M. Lohner,[6] P. Rankin,[6] J.G. Smith,[6] J.P. Alexander,[7] C. Bebek,[7] K. Berkelman,[7] K. Bloom,[7] T.E. Browder,[7*] D.G. Cassel,[7] H.A. Cho,[7] D.M. Coffman,[7] D.S. Crowcroft,[7] P.S. Drell,[7] R. Ehrlich,[7] P. Gaidarev,[7] R.S. Galik,[7] M. Garcia-Sciveres,[7] B. Geiser,[7] B. Gittelman,[7] S.W. Gray,[7] D.L. Hartill,[7] B.K. Heltsley,[7] C.D. Jones,[7] S.L. Jones,[7] J. Kandaswamy,[7] N. Katayama,[7] P.C. Kim,[7] D.L. Kreinick,[7] G.S. Ludwig,[7] J. Masui,[7] J. Mevissen,[7] N.B. Mistry,[7] C.R. Ng,[7] E. Nordberg,[7] J.R. Patterson,[7] D. Peterson,[7] D. Riley,[7] S. Salman,[7] M. Sapper,[7] F. Würthwein,[7] P. Avery,[8] A. Freyberger,[8] J. Rodriguez,[8] R. Stephens,[8] S. Yang,[8] J. Yelton,[8] D. Cinabro,[9] S. Henderson,[9] T. Liu,[9] M. Saulnier,[9] R. Wilson,[9] H. Yamamoto,[9] T. Bergfeld,[10] B.I. Eisenstein,[10] G. Gollin,[10] B. Ong,[10] M. Palmer,[10] M. Selen,[10] J. J. Thaler,[10] K.W. Edwards,[11] M. Ogg,[11] A. Bellerive,[12] D.I. Britton,[12] E.R.F. Hyatt,[12] D.B. MacFarlane,[12] P.M. Patel,[12] B. Spaan,[12] A.J. Sadoff,[13] R. Ammar,[14] S. Ball,[14] P. Baringer,[14] A. Bean,[14] D. Besson,[14] D. Coppage,[14] N. Copty,[14] R. Davis,[14] N. Hancock,[14] M. Kelly,[14] S. Kotov,[14] I. Kravchenko,[14] N. Kwak,[14] H. Lam,[14] Y. Kubota,[15] M. Lattery,[15] M. Momayezi,[15] J.K. Nelson,[15] S. Patton,[15] D. Perticone,[15] R. Poling,[15] V. Savinov,[15] S. Schrenk,[15] R. Wang,[15] M.S. Alam,[16] I.J. Kim,[16] B. Nemati,[16] J.J. O'Neill,[16] H. Severini,[16] C.R. Sun,[16] M.M. Zoeller,[16] G. Crawford,[17] C. M. Daubenmier,[17] R. Fulton,[17] D. Fujino,[17] K.K. Gan,[17] K. Honscheid,[17] H. Kagan,[17] R. Kass,[17] J. Lee,[17] R. Malchow,[17] Y. Skovpen,[17†] M. Sung,[17] C. White,[17] F. Butler,[18] X. Fu,[18] G. Kalbfleisch,[18] W.R. Ross,[18] P. Skubic,[18] M. Wood,[18] J.Fast ,[19] R.L. McIlwain,[19] T. Miao,[19] D.H. Miller,[19] M. Modesitt,[19] D. Payne,[19] E.I. Shibata,[19] I.P.J. Shipsey,[19] P.N. Wang,[19] M. Battle,[20] J. Ernst,[20] L. Gibbons,[20] Y. Kwon,[20] S. Roberts,[20] E.H. Thorndike,[20] C.H. Wang,[20] J. Dominick,[21] M. Lambrecht,[21] S. Sanghera,[21] V. Shelkov,[21] T. Skwarnicki,[21] R. Stroynowski,[21] I. Volobouev,[21] G. Wei,[21] P. Zadorozhny,[21] M. Artuso,[22] M. Goldberg,[22] D. He,[22] N. Horwitz,[22] R. Kennett,[22] R. Mountain,[22] G.C. Moneti,[22] F. Muheim,[22] Y. Mukhin,[22] S. Playfer,[22] Y. Rozen,[22] S. Stone,[22] M. Thulasidas,[22] G. Vasseur,[22] X. Xing,[22] G. Zhu,[22] J. Bartelt,[23] S.E. Csorna,[23] Z. Egyed,[23] and V. Jain[23]

(CLEO Collaboration)

[1] *Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061*

[2] *California Institute of Technology, Pasadena, California 91125*

[3] *University of California, San Diego, La Jolla, California 92093*

[4] *University of California, Santa Barbara, California 93106*

[5] *Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213*

[6] *University of Colorado, Boulder, Colorado 80309-0390*

[7] *Cornell University, Ithaca, New York 14853*

[8] *University of Florida, Gainesville, Florida 32611*

[9] *Harvard University, Cambridge, Massachusetts 02138*

[10] *University of Illinois, Champaign-Urbana, Illinois, 61801*
[11] *Carleton University, Ottawa, Ontario K1S 5B6 and the Institute of Particle Physics, Canada*
[12] *McGill University, Montréal, Québec H3A 2T8 and the Institute of Particle Physics, Canada*
[13] *Ithaca College, Ithaca, New York 14850*
[14] *University of Kansas, Lawrence, Kansas 66045*
[15] *University of Minnesota, Minneapolis, Minnesota 55455*
[16] *State University of New York at Albany, Albany, New York 12222*
[17] *Ohio State University, Columbus, Ohio, 43210*
[18] *University of Oklahoma, Norman, Oklahoma 73019*
[19] *Purdue University, West Lafayette, Indiana 47907*
[20] *University of Rochester, Rochester, New York 14627*
[21] *Southern Methodist University, Dallas, Texas 75275*
[22] *Syracuse University, Syracuse, New York 13244*
[23] *Vanderbilt University, Nashville, Tennessee 37235*
(April 21, 1994)

Abstract

The branching fractions for the five-charged-particle decays of the τ lepton have been measured in e^+e^- annihilations using the CLEO II detector at CESR. Assuming all charged particles to be pions, the results are $B(3\pi^-2\pi^+ \geq 0 \text{ neutrals } \nu_\tau) = (0.097 \pm 0.005 \pm 0.011)\%$, $B(3\pi^-2\pi^+\nu_\tau) = (0.077 \pm 0.005 \pm 0.009)\%$, $B(3\pi^-2\pi^+\pi^0\nu_\tau) = (0.019 \pm 0.004 \pm 0.004)\%$, and $B(3\pi^-2\pi^+2\pi^0\nu_\tau) < 0.011\%$ at the 90%CL. $B(3\pi^-2\pi^+\pi^0\nu_\tau)$ is measured for the first time by exclusive π^0 reconstruction. The results are compared with the predictions from PCAC and CVC assuming isospin invariance.

13.35.Dx, 14.60.Fg

Typeset using REVTEX

---

*Permanent address: University of Hawaii at Manoa

†Permanent address: INP, Novosibirsk, Russia

The decay of the τ lepton provides a test of the Standard Model prediction of the hadronic weak current. The branching fraction into the five-pion final state can be calculated using current algebra and the partially conserved-axial-current hypothesis (PCAC). [1] The six-pion branching fraction is related to the e^+e^- cross section for the production of six pions by the conserved-vector-current hypothesis (CVC). A measurement of this branching fraction tests the absolute prediction of CVC while the shape of the six-pion mass spectrum tests CVC as a function of Q^2 $(= M_{6\pi}^2)$. The branching fractions for the five-charged-particle final states have been measured previously with limited statistics. [2] Presented in this Letter is a new result on the inclusive five-charged-particle decay with the assumption that all charged particles are pions. Also included are measurements of the exclusive branching fractions for the decays [3] $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ and $\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$ with much improved precision. The first limit on the decay $\tau^- \to 3\pi^-2\pi^+2\pi^0\nu_\tau$ is also presented.

The data used in this analysis have been collected from e^+e^- collisions at a center-of-mass energy of $\sqrt{s} \sim 10.6$ GeV using the CLEO II detector [4] at the Cornell Electron Storage Ring (CESR). The total integrated luminosity of the sample is $1.70 fb^{-1}$, corresponding to the production of 1.56×10^6 $\tau^+\tau^-$ events. CLEO II is a general purpose spectrometer with excellent charged particle and electromagnetic energy detection.

Each $\tau^+\tau^-$ candidate event is required to contain six charged tracks with zero net charge. Each track must project back to the e^+e^- interaction point and be in the central region of the detector. The former requirement suppresses the "migration" background from τ decays with a $K_S \to \pi^+\pi^-$ or photon conversion. The K_S background is further reduced by rejecting events containing a detached vertex with a $\pi^+\pi^-$ mass consistent with the nominal K_S mass. [5] Photon candidates are required to have a minimum energy of 60 MeV in the barrel region ($|\cos\theta| < 0.80$) and 100 MeV in the endcap region ($0.80 < |\cos\theta| < 0.95$) and a lateral profile of energy deposition consistent with that expected for a photon. The photon candidates must also be isolated from the charged tracks. The event is divided into two hemispheres using the plane perpendicular to the thrust axis of the event [6]; there must be one charged particle in one hemisphere recoiling against five charged particles in the other (1 vs. 5 topology). The total momentum vector of the particles in each hemisphere must be in the barrel region. The event is required to have a minimum shower energy of $0.15\sqrt{s}$.

The dominate sources of background are hadronic events and τ migration events from $\tau^- \to \pi^-\pi^+\pi^- n\pi^0\nu_\tau (n \geq 1)$ with a photon conversion or Dalitz decay. The migration events are suppressed by requiring a minimum invariant mass of 40 MeV/c^2 for all pairs of oppositely charged tracks in the 5-prong hemisphere, unless an electron candidate is identified, in which case the pair mass cut is 150 MeV/c^2 on all combinations with this track. The hadronic background is suppressed with several selection criteria. The number of photons in the 1-prong hemisphere is restricted to be two or fewer. For the case of two photons, both must be in the barrel and have an invariant mass within 20 MeV/c^2 of the nominal π^0 mass. The total momentum of the particles in the 5-prong hemisphere is required to be greater than $\frac{1}{3}\sqrt{s}$. The total invariant mass of the particles in each hemisphere must satisfy $M_1 < 1.2$ and $M_5 < 1.7$ GeV/c^2. The 5-prong hemisphere must have a positive pseudo-neutrino mass-squared:

$$M_\nu^2 = M_\tau^2 + M_5^2 - 2M_\tau E_5^* > 0 \quad ,$$

where M_τ is the τ mass and E_5^* is the energy of the 5-prong system in the τ rest frame, assuming that the τ has the full beam energy by ignoring initial state radiation and that the τ direction is given by the momentum vector of the 5-prong hemisphere. This cut selects events with tau-like kinematics, suppressing both the hadronic background and the τ migration background from lower multiplicity decays where the 5-prong momentum is not a good approximation of the τ direction. These selection criteria yield a sample of 495 inclusive events.

A subset of events in which the track in the 1-prong hemisphere is identified as a lepton is selected from this inclusive sample. This subset has smaller hadronic contamination than the 1-prong tag sample and thereby provides a verification of the background calculation. An electron candidate must have an energy deposition in the calorimeter consistent with the measured momentum and a specific ionization in the drift chamber consistent with that expected for an electron. A muon candidate must penetrate more than three absorption lengths of iron.

Candidates for the three exclusive decay modes are identified from the inclusive sample according to the photon information in the 5-prong hemisphere. For 5π decay candidates, no photons are allowed. For $5\pi\pi^0$ ($2\pi^0$), there must be two (four) photons in the barrel and no photons in the endcap. In the case of one (three) photon(s), an additional lower quality photon with an energy above 30 MeV is sought. If more than one low quality photon is found, the photon with the best combination of energy and isolation from the charged tracks is used. This increases the detection efficiency while minimizing the dependence on the modeling of hadronic interactions. The mass spectra of the candidates for two exclusive decays are shown in Fig. 1(a) and 1(c). An excess of events above the hadronic background for $M_5 < M_\tau$ is observed. This excess is greatly enhanced for the events selected with a lepton tag as shown in Fig. 1(b) and 1(d). The invariant mass spectrum of the two photons from the $5\pi\pi^0$ candidates is shown in Fig. 2. A π^0 signal is evident, corresponding to the first direct observation of the $5\pi\pi^0$ decay. The number of π^0 candidates is extracted by fitting this mass spectrum with a Gaussian plus a second order polynomial background. The mass and width are constrained to the Monte Carlo expectations. No $5\pi2\pi^0$ events are observed with two exclusive $\gamma\gamma$ pairs having an invariant mass within 20 MeV/c^2 ($\sim 3\sigma$) of the nominal π^0 mass. [7] The number of events in each decay mode, together with the hadronic background calculated from the data, τ migration predicted from Monte Carlo, and resulting branching fractions are shown in Table I.

The hadronic background is calculated empirically using a sample of 1 vs. 5 hadronic events obtained from the data. The hadronic sample is selected using the criteria described above, except that $1.7 < M_1 < 2.5$ GeV/c^2 and, to increase statistics, the number of photons is allowed to be as large as six. A few percent correction to the hadronic sample is made to account for contamination from τ decays. Assuming that M_1 and M_5 are not strongly correlated, the M_5 thus obtained should reproduce the hadronic background component in the τ sample. The hadronic mass spectra are superimposed in Fig. 1, normalized to the same number of events for $M_5 > 2.0$ GeV/c^2. The general shape of the background spectrum is reproduced.

The detection efficiency and migration background are calculated using a Monte Carlo technique. The KORALB program is used to generate pairs according to the standard electroweak theory, including α^3 radiative corrections. [8] The GEANT program [9] is used to simulate the detector response. The five-pion mass spectrum has been adjusted to fit the data. The six-pion spectrum is extracted from the e^+e^- cross section into six pions using CVC. [8] No intermediate resonance is assumed in the decay processes.

The branching fractions for the decays are extracted from the data by normalizing to the luminosity $\mathcal{L}$ and cross section σ,

$$B = \frac{N - N_{mig} - N_{q\bar{q}}}{2\mathcal{L}\sigma B_1 \epsilon},$$

where N, N_{mig}, and $N_{q\bar{q}}$ are the number of events in the data, migration from other τ decays, and hadronic background, respectively. $B_1 = (85.82 \pm 0.25)\%$ [2] is the branching fraction of the 1-prong tag and ϵ is the detection efficiency.

The systematic errors in the measurements are summarized in Table II. The systematic error from the uncertainty in the photon detection efficiencies is estimated by varying the photon selection criteria. This estimate has been checked [11] by performing similar analyses on other decay modes, $\pi^\pm 2\pi^0$, $3\pi^\pm$, $3\pi^\pm\pi^0$, and $\pi^\pm\omega$. Another indication of the reliability of the efficiency calculation is that the two exclusive branching fractions do not oversaturate the inclusive measurement. The systematic error in the tracking efficiency has been investigated by relaxing the track quality requirements and by comparing the observed momentum spectrum of the tracks with the Monte Carlo. Potential biases in the hadronic background estimate due to possible correlations in the total invariant masses of the two hemispheres have been investigated by varying the requirements on M_1 and the 1-prong photon multiplicity. The hadronic background has also been estimated using continuum Monte Carlo events [12] and 3 vs. 5 events from the data. All results are consistent within the statistical errors. The consistency of the branching fractions between the 1-prong and lepton tags indicates the validity of the hadronic background calculation. The systematic error in the modeling of the five- and six-pion decays is estimated by comparing the observed $\pi^+\pi^-$ mass spectrum with the Monte Carlo expectation. The systematic error in the migration background due to the uncertainties in τ decay branching fractions is estimated by changing the branching fractions within the reasonable ranges allowed by their uncertainties. [2] Also included in Table II is the systematic error in the luminosity [13] and cross section and the uncertainty in the detection efficiency due to limited Monte Carlo statistics. The final branching fractions from the 1-prong tag, with the systematic errors added in quadrature, are:

$$\begin{aligned}
B(3\pi^-2\pi^+ \geq 0 \text{ neutrals } \nu_\tau) &= (0.097 \pm 0.005 \pm 0.011)\%, \\
B(3\pi^-2\pi^+\nu_\tau) &= (0.077 \pm 0.005 \pm 0.009)\%, \\
B(3\pi^-2\pi^+\pi^0\nu_\tau) &= (0.019 \pm 0.004 \pm 0.004)\%, \\
B(3\pi^-2\pi^+2\pi^0\nu_\tau) &< 0.011\% \text{ @ } 90\%\text{CL},
\end{aligned}$$

where the first error is statistical and the second is systematic. These measurements are consistent with the world averages, [2] but the inclusive branching fraction is significantly smaller than the recent result from OPAL. [14] Combining $B(3\pi^-2\pi^+\nu_\tau)$ with our results [11,15] for $B(\pi^-4\pi^0\nu_\tau)$ and $B(2\pi^-\pi^+2\pi^0\nu_\tau)$ yields the total five-pion branching fraction of $(0.65 \pm 0.06 \pm 0.08)\%$. This is somewhat smaller than the prediction from PCAC of $\sim 1\%$. [1] The measurement of $B(3\pi^-2\pi^+\pi^0\nu_\tau)$ is consistent with the prediction [16] from isospin invariance and CVC, $B(3\pi^-2\pi^+\pi^0\nu_\tau) \geq (0.03 \pm 0.01)\%$, based on the e^+e^- cross section for six-pion production measured by M3N. [17] However, it is significantly smaller than the prediction [16] of $B(3\pi^-2\pi^+\pi^0\nu_\tau) \geq (0.07 \pm 0.01)\%$ based on the measurement by $\gamma\gamma 2$. [18] The CVC prediction of the $5\pi\pi^0$ mass spectrum (Fig. 3), based on combining the two measurements, is independent of the absolute normalization and reproduces the data.

In conclusion, the branching fractions for the 5-prong decays of the τ lepton have been measured. The $5\pi\pi^0$ branching fraction is measured for the first time by exclusive π^0 reconstruction. The sum of $B(3\pi^-2\pi^+\nu_\tau)$ and $B(3\pi^-2\pi^+\pi^0\nu_\tau)$ saturates the inclusive branching fraction and the first limit on $5\pi 2\pi^0$ has been set. The results are consistent with the world averages [2] and are significantly more precise than other experiments.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Dept. of Energy, the Heisenberg Foundation, the SSC Fellowship program of TNRLC, and the A.P. Sloan Foundation.

REFERENCES

[1] T.N. Pham, C. Roiesnel, and T.N. Truong, Phys. Lett. **78B**, 623 (1978).

[2] K. Hikasa *et al.*, Phys. Rev. **D45** (1992).

[3] In this Letter, charge conjugate states are implied.

[4] Y. Kubota *et al.*, Nucl. Instr. Method **A320**, 66 (1992).

[5] The remaining migration background from $\tau^- \to \pi^- K^0 \bar{K}^0 \nu_\tau$ is negligible ($\sim 0.3\%$).

[6] Both charged particles and photons are used in the calculation of kinematic variables.

[7] The π^0 sidebands contain five entries, consistent with the expectation of 4.0 ± 1.3 entries from $5\pi\pi^0$ and hadronic backgrounds.

[8] S. Jadach and Z. Was, Comp. Phys. Comm. **36**, 191 (1985); *ibid.* **64**, 267 (1991); S. Jadach, J. H. Kuhn, and Z. Was, *ibid.* **64**, 275 (1991).

[9] R. Brun *et al.*, CERN Report No. CERN-DD/EE/84-1, 1987 (unpublished).

[10] The detection efficiencies and migration backgrounds for the inclusive, 5π, and $5\pi\pi^0$ events are calculated assuming that the branching fraction for the $5\pi 2\pi^0$ decay is negligible.

[11] M. Procario *et al.*, Phys. Rev. Lett. **70**, 1207 (1993).

[12] T. Sjostrand and M. Bengtsson, Comp. Phys. Comm. **43**, 367 (1987).

[13] G. Crawford *et al.*, Cornell Univ. preprint CLNS 94/1268, 1994 (to be published in Nucl. Instrum. Meth.).

[14] P.D. Acton *et al.*, Phys. Lett. **288B**, 373 (1992).

[15] D. Bortoletto *et al.*, Phys. Rev. Lett. **71**, 1791 (1993).

[16] S.I. Eidelman and V.N. Ivanchenko, Phys. Lett. **257B**, 437 (1991).

[17] G. Cosme *et al.*, Nucl. Phys. **B152**, 215 (1979).

[18] C. Bacci *et al.*, Nucl. Phys. **B184**, 31 (1981).

FIGURES

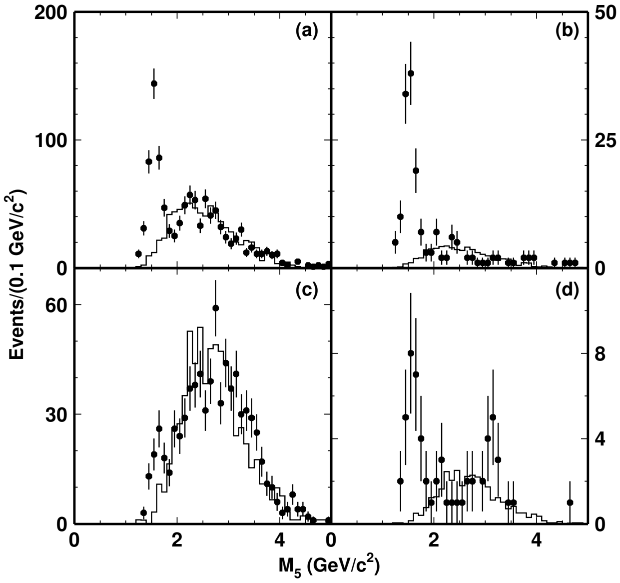

FIG. 1. The mass spectra of the (a) 5π and (c) $5\pi\pi^0$ candidates selected with the 1-prong tag. The M_ν cut, which suppresses the hadronic background by $\sim 50\%$, has been removed because it is unphysical for $M_5 > M_\tau$. The histograms show the hadronic background, normalized for $M_5 > 2.0$ GeV/c^2. The invariant mass of the photon pair forming the π^0 must be within 20 MeV/c^2 of the nominal π^0 mass. (b) and (d) are the corresponding spectra selected with the lepton tags.

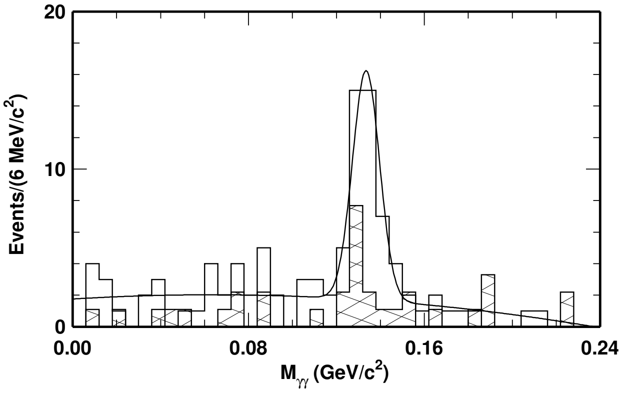

FIG. 2. The invariant mass spectrum of the two photons of the $5\pi\pi^0$ candidates. The curve shows a fit to the data (see text). The hatched histogram shows the hadronic background.

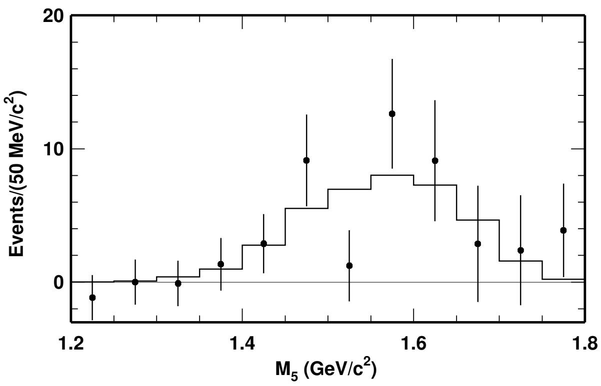

FIG. 3. The mass spectra of the $5\pi\pi^0$ candidates selected with the 1-prong tag together with the CVC prediction (histogram). The background contamination has been subtracted.

TABLES

TABLE I. Summary of the signal, background, detection efficiency, and branching fraction for each decay mode. All errors are statistical only. The upper limit is at the 90%CL.

	Inclusive		5π		$5\pi\pi^0$		$5\pi 2\pi^0$
Tag	1-prong	Lepton	1-prong	Lepton	1-prong	Lepton	1-prong
Data	495 ± 22	159 ± 13	335 ± 18	105 ± 10	38 ± 7	14.9 ± 4.2	0
$e^+e^- \to q\bar{q}$	60 ± 8	5 ± 1	26 ± 6	3 ± 1	7 ± 3	0.8 ± 0.3	–
Migration	16 ± 3	7 ± 2	14 ± 2	8 ± 1	–	–	–
ϵ(%)	16.1 ± 0.2	14.3 ± 0.3	14.2 ± 0.2	12.7 ± 0.3	5.9 ± 0.2	5.4 ± 0.2	0.9 ± 0.1
B(10^{-4})	9.7 ± 0.5	9.0 ± 0.8	7.7 ± 0.5	6.7 ± 0.7	1.9 ± 0.4	2.3 ± 0.7	< 1.0

TABLE II. Summary of systematic errors in percent (relative). The migration of $5\pi 2\pi^0$ into $5\pi\pi^0$ corresponds to a 68% upper limit.

	Inclusive	5π	$5\pi\pi^0$	$5\pi 2\pi^0$
ϵ (photon)	5	7	15	20
ϵ (tracking)	7.5	7.5	7.5	7.5
ϵ (stat)	1.2	1.5	3.0	10
Background (stat)	2.0	2.1	10.8	–
$e^+e^- \to q\bar{q}$ (sys)	4.3	2.7	6.9	–
Decay model	4.0	4.0	4.0	–
Migration (sys)	1.4	1.6	$^{+1.1}_{-5.1}$	–
$\mathcal{L}$	1.0	1.0	1.0	1.0
σ	1.0	1.0	1.0	1.0
Total	11	12	22	24