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Measurements of tau decays to three pions*

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ABSTRACT

We report the results of a study of tau decays with three pions in the final state ($\tau^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}\nu_{\tau}$ and $\tau^{\pm}\rightarrow\pi^{\pm}\pi^{\circ}\pi^{\circ}\nu_{\tau}$) from data accumulated with the MAC detector operating at the PEP storage ring. The branching fractions for these modes are measured to be $.070 \pm .003 \pm .007$ and, with assumptions discussed in the text, $.087 \pm .004 \pm .011$, respectively. Assuming that these final states result from the decay of the a_1 meson, we measure the resonant parameters of the a_1 with the three charged pion sample to be $m_{a_1} = 1166 \pm 18 \pm 11$ MeV and $\Gamma_{a_1} = 405 \pm 75 \pm 25$ MeV, and with the one charged plus two neutral pions sample to be $m_{a_1} = 1164 \pm 41 \pm 23$ MeV and $\Gamma_{a_1} = 419 \pm 108 \pm 57$ MeV.

The study of tau decays to $\pi^-\pi^+\pi^-\nu_\tau$ ($3\pi^\pm$) and $\pi^-\pi^\circ\pi^\circ\nu_\tau$ ($\pi 2\pi^\circ$) and their charge-conjugate decays is an investigation of the weak axial vector hadronic current under conditions such that the production mechanism and backgrounds are well understood. These decays are expected to be dominated by the a_1 meson through a $\rho\pi$ intermediate state. Improved measurements of the $\pi 2\pi^\circ$ mode may help resolve the discrepancy between the measured inclusive and sum of the exclusive branching fractions for 1-prong tau decays.[1] We present measurements of the branching fractions and mass spectra of these decays. The data for these measurements were accumulated with the MAC detector operating at a center-of-mass energy of 29 GeV at the e^+e^- storage ring PEP of the Stanford Linear Accelerator Center. The integrated luminosity for this sample is 216 ± 3 pb^{-1}.

The MAC detector consists of a cylindrical drift chamber inside a conventional solenoid coil, surrounded by a hexagonal array of electromagnetic and hadronic calorimeters, scintillation counters, and drift chambers for detection of muons. The detector is closed by end caps which complete the coverage of the detector to within about 10° of the beams.

The central drift chamber (CD) consists of ten cylindrical layers of cells, six of which are oriented at ±3° with respect to the beam axis. The 180 micron point resolution of the CD results in typical angular resolutions of 0.2° in azimuth (ϕ) and 0.7° in polar angle (θ), and in the 0.57-T axial magnetic field results in an inverse momentum resolution of $\sigma_{1/p} = 0.052 \sin\theta$ (GeV/c)$^{-1}$.

The central-section electromagnetic calorimeter is constructed of alternating layers of proportional wire chambers (PWC's) and lead sheets, segmented into 192 azimuthal sectors and three radial layers from which independent readouts are obtained. The end caps consist entirely of alternating layers of PWC's and iron plates. The energy resolutions for electromagnetic showers are $\sigma_E/E = 20\%/\sqrt{E(\mathrm{GeV})}$ in the central section and $45\%/\sqrt{E}$ in the end caps. The angular resolutions are $\sigma_\phi = 0.6^\circ$ and $\sigma_\theta = 1.2^\circ$ in the central section and $\sigma_\phi = 1.2^\circ$ and $\sigma_\theta = 1.5^\circ$ in the end caps. Additional details concerning the detector and the triggering requirements can be found elsewhere.[2]

The selection of τ decays to three charged pions or one charged plus two neutral pions begins with a sample of preselected tau pair events.[3] These events are divided into two hemispheres by a plane perpendicular to the charged particle thrust axis and are required to have an isolated CD track in one hemisphere (separated from others by at least 120°) and either one (1-1 topology) or three (1-3 topology) tracks in the other hemisphere. The most important selection criteria require that the total calorimetric energy be greater than 6 GeV and the electromagnetic shower energy be less than 23 GeV and that the sphericity of the event be less than 0.05.

For the $3\pi^\pm$ sample, events must have a 1-3 topology, and satisfy a number of further requirements. All tracks on the 3-prong side must be consistent with originating at the beam interaction point and each of the tracks on the 3-prong side must have a momentum greater than 0.5 GeV/c. We do not accept events with isolated electromagnetic showers (neutrals) with energy greater than 0.75 GeV in the same hemisphere as the 3-prong. For the $\pi 2\pi^\circ$ sample we allow both 1-1 and 1-3 topology and apply a different set of further requirements. One-prong tracks must have a momentum greater than 0.5 GeV/c, deposit at least 0.1 GeV in the calorimeters, and be associated with two neutrals, each within 26° of the reconstructed $\pi 2\pi^\circ$ momentum vector. One neutral must have energy greater than 0.5 GeV and the other greater than 1.0 GeV and the invariant mass of the neutrals must be greater than 0.20 GeV/c^2. Monte Carlo studies indicate that about 30% of $\pi 2\pi^\circ$ events have exactly two neutrals. These requirements result in 1566 events in the $3\pi^\pm$ sample and 815 events in the $\pi 2\pi^\circ$ sample.

Tau-pair production and decay and various background processes are simulated with Monte Carlo techniques.[3] All generated events are processed with the MAC detector simulation programs, which include all the physical and electronic properties of the detector and describe the data well. Monte Carlo events are required to pass the same criteria as the data, including a simulation of the trigger requirements.

The efficiencies, number of events in the samples, and amounts of backgrounds, estimated from the Monte Carlo calculations, are given in Table 1. Backgrounds not due to the process $e^+e^- \to \tau^+\tau^-$ are estimated to be about 2%. The major source of background in the $3\pi^\pm$ sample is the decay mode $\tau \to 3\pi^\pm\pi^\circ\nu_\tau$ (18%). This decay is assumed to be dominated by $\rho(1600)$, although a recent measurement indicates that about one-third of the $3\pi^\pm\pi^\circ$ events result from non-resonant $\omega\pi$ decays.[4] To estimate the *shape* of the background mass distribution, we use selected $3\pi^\pm\pi^\circ$ data events. Since the number and shape of these events agrees with the Monte Carlo prediction, the effect of assuming that the $3\pi^\pm\pi^\circ$ is dominated by $\rho(1600)$ is estimated to be small. For the $\pi 2\pi^\circ$ sample, the major sources of background are the decay modes $\tau \to \rho\nu_\tau$ (25%) and $\tau \to \pi 3\pi^\circ\nu_\tau$ (10%).[6] Since the MAC detector has no π/K separation capability, we also correct for small backgrounds from decay modes with kaons.

TABLE 1. Numbers relevant to the measurement of $B_{3\pi^\pm}$ and $B_{\pi 2\pi^\circ}$. The quoted errors are statistical only.

	N_{1-1}	N_{1-3}	$N_{3\pi^\pm}$	$N_{\pi 2\pi^\circ}$ (1-1)	$N_{\pi 2\pi^\circ}$ (1-3)
No. of observed events	4693	2342	1566	641	174
Efficiency(%)	$21.9 \pm .1$	$38.0 \pm .3$	$38.7 \pm .4$	$8.4 \pm .2$	$15.5 \pm .3$
Backgrounds (%)	2.2 ± 0.3	4.4 ± 1.1	22.0 ± 1.0	46.0 ± 2.4	44.9 ± 3.8

The branching fraction for the decay $\tau^\pm \rightarrow \pi^\pm \pi^+ \pi^- \nu_\tau$, $B_{3\pi^\pm}$, is extracted from the expression

$$B_{3\pi^\pm} = B_3 \cdot \frac{N_{3\pi^\pm}/\epsilon_{3\pi^\pm}}{N_{1-3}/\epsilon_{1-3}} ,$$

where B_3 is the tau 3-prong branching fraction,[7] $N_{3\pi^\pm}$ and N_{1-3} are, respectively, the number of events in the $3\pi^\pm$ and 1-3 samples after background subtraction, and $\epsilon_{3\pi^\pm}$ and ϵ_{1-3} are the efficiencies for detecting these types of events. With assumptions discussed below, we calculate $B_{\pi 2\pi^\circ}$, the branching fraction for the decay $\tau^\pm \rightarrow \pi^\pm \pi^\circ \pi^\circ \nu_\tau$, in a similar manner. The results are

$$\begin{aligned} B_{3\pi^\pm} &= .070 \pm .003 \pm .007 \\ B_{\pi 2\pi^\circ} &= .087 \pm .004 \pm .011 , \end{aligned}$$

where the first errors are statistical and the second are systematic.[8] The major sources of systematic uncertainty for both analyses are from neutral particle detection efficiencies and background subtractions. The systematic errors are determined by variation of the appropriate selection criteria.

The result for $B_{3\pi^\pm}$ is in good agreement with our previous measurement from a smaller data sample and simpler analysis[9] and other recent measurements.[10–12] For the above measurement of $B_{\pi 2\pi^\circ}$, we assume the branching fraction for the decay $\tau \rightarrow \pi 3\pi^\circ \nu_\tau$ to be .01, as expected from the conserved vector current (CVC) hypothesis and reliable measurements of $e^+e^- \rightarrow \pi^+\pi^+\pi^-\pi^-$.[13] We also assume tau decays with an η meson in the final state to be rare, as expected from data for the process $e^+e^- \rightarrow \eta\pi^+\pi^-$ and CVC.[15] However, measurements by the TPC and Mark II collaborations[16] find an unexpectedly large branching fraction for tau decays involving a charged particle and more than one neutral hadron. This has typically been interpreted in terms of a possible anomalously large contribution from tau decays involving η mesons as suggested in Ref. 1. A recent measurement by the HRS collaboration[17] finds the branching fraction for all tau decays involving η mesons to be less than .021 at the 90% confidence level, in agreement with theoretical expectations. The result for $B_{\pi 2\pi^\circ}$ given above, is somewhat smaller than that implied by the TPC and Mark II measurements, and somewhat larger than theoretical expectations (isospin arguments[1] require that $B_{\pi 2\pi^\circ} \leq B_{3\pi^\pm}$). However, our result is consistent with both the measurements favoring an excess of tau decays involving multiple neutrals and the theoretical prediction with no excess. Though the recent HRS measurement makes it unlikely that there is a large η contribution, we investigate the sensitivity to unexpectedly large branching fractions for tau decays involving η or other multiple-neutral final states by measuring $B_{\pi 2\pi^\circ}$ assuming different values for $B_{\eta\pi\pi^\circ}$. From these studies, we estimate that $B_{\pi 2\pi^\circ}$ would decrease by .016 if the 1-prong branching fraction for the decay $\tau \rightarrow \eta \pi^{\pm} \pi^{\circ} \nu_\tau$ or similar modes were increased by 0.02. This represents an additional systematic uncertainty associated with the theoretical assumptions.

We also have investigated the 3π invariant mass spectra for both samples. The analysis assumes that the 3π decay mode of the tau lepton is dominated by the $a_1(1270)$ meson (spin-parity $J^P = 1^+$), decaying to $\rho\pi$ (see below).[18] Specifically, we assume

$$
\begin{aligned}
&\tau^- \rightarrow a_1^- \nu_\tau \\
&\qquad \hookrightarrow \rho^\circ \pi^- \\
&\qquad\qquad \hookrightarrow \pi^+ \pi^-
\end{aligned}
$$

for the 3-prong mode and

$$
\begin{aligned}
&\tau^- \rightarrow a_1^- \nu_\tau \\
&\qquad \hookrightarrow \rho^- \pi^\circ \\
&\qquad\qquad \hookrightarrow \pi^- \pi^\circ
\end{aligned}
$$

for the 1-prong mode. The differential decay rate for tau decays to three pion final states can be expressed as[19]

$$
\frac{d\Gamma_{\tau \rightarrow a_1 \nu_\tau}}{dm^2} = \frac{G_F^2}{16\pi^2 m_\tau^3} \frac{f_{a_1}^2(m)}{m^2} (m_\tau^2 - m^2)^2 (m_\tau^2 + 2m^2) \frac{m_{a_1} \Gamma(m)}{(m_{a_1}^2 - m^2)^2 + m_{a_1}^2 \Gamma(m)^2} , \tag{1}
$$

where f_{a_1} is a form factor with units of m^2 and unknown mass dependence, which we take to be constant (the consequences of this assumption are discussed below).

The mass dependent width $\Gamma(m)$ is taken from Frazer *et al.*,[20]

$$\Gamma(m) \propto \frac{1}{m^3} \int F(s_1, s_2) ds_1 ds_2 \ , \qquad (2)$$

where s_1 and s_2 are the two unlike-sign-pion invariant masses and $F(s_1, s_2)$ is given in Ref. 20. A complete treatment of interference effects between the two unlike-sign pion combinations is included.

Evidence of the intermediate $\rho\pi$ state can be observed in both the $3\pi^{\pm}$ and $\pi 2\pi^{\circ}$ samples by subtracting the invariant mass distributions of like-sign pion pairs from those of unlike-sign pion pairs (two entries/event). These mass distributions for the data and Monte Carlo are shown in Fig. 1. The Monte Carlo spectrum is derived from the expression in Eq. (1) and includes experimental resolution, acceptance, and efficiency effects. The χ^2 of 24.8 for 26 bins from the $3\pi^{\pm}$ sample and 25.5 for 26 bins from the $\pi 2\pi^{\circ}$ sample (with no free parameters) indicate that the data are in good agreement with the hypothesis of a $\rho\pi$ intermediate state. The ARGUS collaboration (Ref. 18) has set a limit, at the 95% confidence level, of less than 10% for the non-$\rho^{\circ}\pi^{-}$ contribution to the $3\pi^{\pm}$ decay mode.

We perform least-squares fits in which the data are compared with the form of Eq. (1) (arbitrarily normalized), convoluted with a mass-dependent resolution function (determined from Monte Carlo samples) with Gaussian width $\sigma_m = a + bm$. We find these constants to be $a = -0.05 \pm 0.01$ and $b = 0.13 \pm 0.01$ for the $3\pi^{\pm}$ sample, and $a = -0.02 \pm 0.03$ and $b = 0.12 \pm 0.03$ for the $\pi 2\pi^{\circ}$ sample. The results of these fits are shown with the data in Fig. 2 for both samples. The

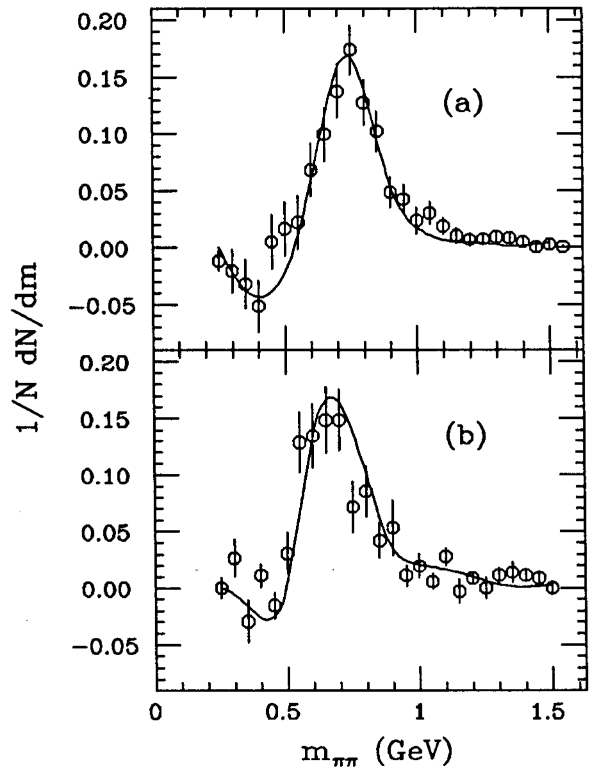

FIGURE 1. The invariant mass distributions of each unlike-sign pion pair (two entries/event) with the like-sign pairs subtracted. The data points and Monte Carlo predictions (solid lines) for (a) the $3\pi^{\pm}$ sample, and (b) $\pi 2\pi^{\circ}$ sample are shown.

resonant parameters determined from the fit are

$$m_{a_1} = \begin{cases} (1166 \pm 18 \pm 11) \text{ MeV} & (3\pi^{\pm} \text{ sample}) \\ (1164 \pm 41 \pm 23) \text{ MeV} & (\pi 2\pi^{\circ} \text{ sample}) \end{cases}$$

$$\Gamma_{a_1} = \begin{cases} (405 \pm 75 \pm 25) \text{ MeV} & (3\pi^{\pm} \text{ sample}) \\ (419 \pm 108 \pm 57) \text{ MeV} & (\pi 2\pi^{\circ} \text{ sample}) \ , \end{cases}$$

with $\Gamma_{a_1} \equiv \Gamma(m_{a_1})$. The systematic errors include uncertainties of the mass resolution and background subtraction. This is the first measurement of the mass spectrum of the $\pi 2\pi^{\circ}$ decay. We find good agreement with the $3\pi^{\pm}$ sample, though until the situation involving the 1-prong, multiple-neutral tau decays is resolved, the background subtraction remains uncertain.[21] The results for the $3\pi^{\pm}$ sample are in reasonable agreement with previous measurements[10–12] if allowance is made for the differences in the resonance parameterizations used.[22]

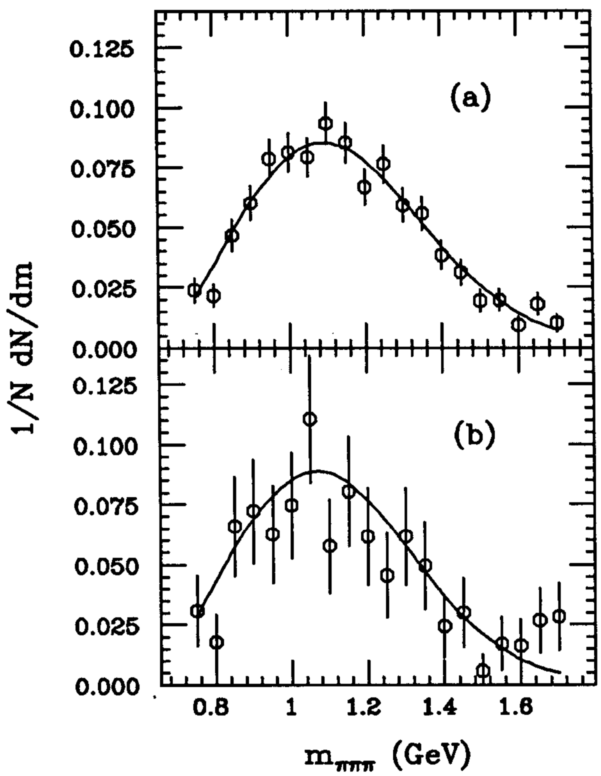

FIGURE 2. The 3π mass distributions for a) the $3\pi^{\pm}$ sample, and b) the $\pi 2\pi^{\circ}$ sample. The solid line is the best fit described in the text.

In conclusion, we have measured the $\tau \rightarrow \pi\pi\pi\nu_{\tau}$ branching fractions and are in agreement with previous measurements. However, since the measurements of $B_{3\pi^{\pm}}$ and $B_{\pi 2\pi^{\circ}}$ are also consistent with theoretical expectations, our data alone do not demand additional 1-prong tau decays with multiple neutrals beyond the expected modes. The mass spectra of both 3π modes indicate the existence of a $\rho\pi$ intermediate state. The resonance parameters found from the fits to the

$3\pi^{\pm}$ and $\pi 2\pi^{\circ}$ mass distributions imply a resonance which is broader and has lower mass than the $a_1(1270)$ observed in hadronic experiments,[23] confirming previous measurements from tau decays. Though there is some uncertainty in the correct parameterization, there appear to be significant discrepancies between the resonance parameters of the a_1 produced hadronically and those from tau decays.

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5. P. R. Burchat, in: *Proceedings of the XXIII International Conference on High Energy Physics*, ed. S. C. Loken (World Scientific, 1987), p. 756.
6. To estimate the amounts of backgrounds and their uncertainties, experimentally measured tau branching fractions are taken from Ref. 5: (ρ) .221 $\pm$

.011, $(3\pi^{\pm}\pi^{\circ})$ .052 ± .005, (K*) .014 ± .003, and (K) .007 ± .002. The assumptions for the $\pi 3\pi^{\circ}$ decay and those involving η mesons are discussed in the text.

7. For B_3, we use the value 0.131 ± 0.003 given in Ref. 5.

8. The values of $B_{\pi 2\pi^{\circ}}$ for the 1-1 and 1-3 samples are .085 ± .005 ± .010 and .090 ± .009 ± .011, respectively.

9. MAC Collab., E. Fernandez *et al.*, Phys. Rev. Lett. 54 (1985) 1624. This measurement did not attempt to correct for decays involving kaons.

10. DELCO Collab., W. Ruckstuhl *et al.*, Phys. Rev. Lett. 56 (1986) 2132.

11. Mark II Collab., W. B. Schmidke *et al.*, Phys. Rev. Lett. 57 (1986) 527.

12. ARGUS Collab., H. Albrecht *et al.*, Z. Phys. C 33 (1986) 7.

13. See references contained in Ref. 1.

14. Omega Photon Collab., M. Atkinson *et al.*, Z. Phys. C 30 (1986) 531.

15. F. J. Gilman, Phys. Rev. D 35 (1987) 3541. We assume that the only significant η mode is $\eta\pi^{\pm}\pi^{\circ}$ and that the branching fraction for this mode is .005, as would be expected from tau decaying to $\rho(1600)$ which in turn decays to $\eta\pi^{\pm}\pi^{\circ}$. A recent measurement (see Ref. 14) suggests that the $\eta\pi^{\pm}\pi^{\circ}$ decay mode of the $\rho(1600)$ may be smaller than had been measured previously.

16. TPC/Two-Gamma Collab., H. Aihara *et al.*, Phys. Rev. Lett. 57 (1986) 1836; Mark II Collab., P. R. Burchat *et al.*, Phys. Rev. D 35 (1987) 27; Mark II Collab., K. K. Gan *et al.*, SLAC Report No. SLAC-PUB-4110

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17. HRS Collab., S. Abachi *et al.*, contributed to the 1987 International Symposium on Electron and Photon Interactions at High Energies, Hamburg, Germany (1987) and D. H. Miller, private communication.

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19. Y. S. Tsai, Phys. Rev. D 4 (1971) 2821.

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21. When we allow $B_{\eta\pi\pi^0}$ to increase to .02 or .04, we find relatively small changes in the fitted mass, 1156 ± 41 and 1122 ± 68, respectively. However, the effect on the width is considerably larger and less certain, 491 ± 186 and 626 ± 251, respectively.

22. We find that if the power of m in Eq. 1 (Eq. 2) is changed by ± 1, the fitted mass (width) changes by ∓ 25 (∓ 45) MeV. In particular, for the parameterization of Ref. 11 (a change in the power of m in Eq. 1 of $+1$), we find $m_{a_1} = 1140 \pm 16$ MeV and $\Gamma_{a_1} = 401 \pm 75$ MeV.

23. The Particle Data Group, M. Aguilar-Benitez *et al.*, Phys. Lett. B 170 (1986), finds world average values $m_{a_1} = 1275 \pm 28$ MeV and $\Gamma_{a_1} = 316 \pm 45$.