Exclusive Branching-Fraction Measurements of Semileptonic τ Decays into Three Charged Hadrons, into $\varphi\pi^- \nu_\tau$, and into $\varphi K^- \nu_\tau$

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Using a data sample corresponding to an integrated luminosity of 342 fb^{-1} collected with the *BABAR* detector at the SLAC PEP-II electron-positron storage ring operating at a center-of-mass energy near 10.58 GeV, we measure $\mathcal{B}(\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau(\mathrm{ex}.K^0_S)) = (8.83 \pm 0.01 \pm 0.13)\%$, $\mathcal{B}(\tau^- \to K^- \pi^- \pi^+ \nu_\tau(\mathrm{ex}.K^0_S)) = (0.273 \pm 0.002 \pm 0.009)\%$, $\mathcal{B}(\tau^- \to K^- \pi^- K^+ \nu_\tau) = (0.1346 \pm 0.0010 \pm 0.0036)\%$, and $\mathcal{B}(\tau^- \to K^- K^- K^+ \nu_\tau) = (1.58 \pm 0.13 \pm 0.12) \times 10^{-5}$, where the uncertainties are statistical and systematic, respectively. These include significant improvements over previous measurements and a first measurement of $\mathcal{B}(\tau^- \to K^- K^- K^+ \nu_\tau)$ in which no resonance structure is assumed. We also report a first measurement of $\mathcal{B}(\tau^- \to \phi\pi^- \nu_\tau) = (3.42 \pm 0.55 \pm 0.25) \times 10^{-5}$, a new measurement of $\mathcal{B}(\tau^- \to \phi K^- \nu_\tau) = (3.39 \pm 0.20 \pm 0.28) \times 10^{-5}$ and a first upper limit on $\mathcal{B}(\tau^- \to K^- K^- K^+ \nu_\tau(\mathrm{ex}.\phi))$.

The weak interaction coupling strength between the first and second quark generations [1] can be probed with unprecedented precision in hadronic τ decays having net strangeness of unity in the final state using $e^+ e^- \to \tau^+ \tau^-$ data collected at the $e^+ e^-$ *B* factories. Inclusive measurements of the strange spectral function, obtained from τ lepton decays to final states containing kaons, provide a direct determination of the strange quark mass and Cabbibo-Kobayashi-Maskawa (CKM) matrix mixing element $|V_{us}|$ [2]. A significant improvement on the precision of $\mathcal{B}(\tau^- \to K^- \pi^- \pi^+ \nu_\tau)$ in particular, where one measurement [3] disagrees by more than 2 standard deviations from the others [4,5], will have the most immediate impact on the determination of these two fundamental Standard Model (SM) parameters using τ decays [6]. Measurements of $\tau^- \to \phi\pi^- \nu_\tau$ and $\tau^- \to \phi K^- \nu_\tau$ provide an interesting laboratory for studying Okubo-Zweig-Iizuka (OZI) suppression [7].

Significant improvements on measurements of $\mathcal{B}(\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau)$, $\mathcal{B}(\tau^- \to K^- \pi^- \pi^+ \nu_\tau)$, and $\mathcal{B}(\tau^- \to K^- \pi^- K^+ \nu_\tau)$ are reported together with a first measurement of $\mathcal{B}(\tau^- \to K^- K^- K^+ \nu_\tau)$ without resonance assumptions (charge conjugate decays are implied). The data sample corresponds to an integrated luminosity of $\mathcal{L} = 342$ fb^{-1} recorded at a center-of-mass (c.m.) energy ($\sqrt{s}$) near 10.58 GeV using the *BABAR* detector at the SLAC PEP-II asymmetric-energy $e^+ e^-$ storage ring. With a luminosity-weighted average cross-section of $\sigma_{e^+ e^- \to \tau^+ \tau^-} = (0.919 \pm 0.003)$ nb [8,9], this corresponds to the production of 3.16×10^8 τ-pair events.

The *BABAR* detector [10] has a silicon vertex tracker (SVT), drift chamber (DCH), ring-imaging Cherenkov detector (DIRC), and electromagnetic calorimeter (EMC) all contained in a 1.5-T solenoid. The iron flux return of the solenoid is instrumented to identify muons.

τ-pair events are simulated with higher-order radiative corrections using the KK2F Monte Carlo (MC) generator [8] with τ decays simulated with TAUOLA [11,12] using measured rates [13]. The detector response is simulated with GEANT4 [14]. Simulated events for signal as well as SM background processes [8,11,12,15,16] are reconstructed in the same manner as data. The MC samples are used for selection optimization and systematic error studies. The number of simulated nonsignal events is comparable to the

number expected in the data, with the exception of Bhabha and two-photon events, which are not simulated. Data studies demonstrate that these backgrounds are negligible.

The basic analysis strategy is to select a pure sample of $\tau^- \to h^- h^- h^+ \nu_\tau$ decays from $e^+ e^- \to \tau^+ \tau^-$ events by requiring the partner τ^+ to decay leptonically. Within this sample, each of the $h^\pm$ mesons is uniquely identified as a charged pion or kaon and the decay categorized as $\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau$, $\tau^- \to K^- \pi^- \pi^+ \nu_\tau$, $\tau^- \to K^- \pi^- K^+ \nu_\tau$, or $\tau^- \to K^- K^- K^+ \nu_\tau$. An efficiency migration matrix, $\mathcal{E}_{ij}$, initially obtained from MC simulations, is used to correct for efficiency losses from all stages of event selection and includes cross feed between the four signal channels where i (j) is the selected (true) decay mode index. The $\mathcal{E}_{ij}$ matrix is modified using data control samples of kaons and pions from $D^{*+} \to \pi^+ D^0$, $D^0 \to \pi^+ K^-$ decays to account for small differences between MC calculations and data. The number of decay mode j signal events measured in the sample, $\mathbf{N}^{\mathrm{Sig}}_j$, is then

$$\mathbf{N}^{\mathrm{Sig}}_j = \sum_i (\mathcal{E}^{-1})_{ji}(\mathbf{N}^{\mathrm{Data}}_i - \mathbf{N}^{\mathrm{Bkg}}_i) \qquad (1)$$

where $\mathbf{N}^{\mathrm{Data}}_i$ is the number of data events selected in decay channel i and $\mathbf{N}^{\mathrm{Bkg}}_i$ is the estimated number of background events in decay channel i arising from sources other than $\tau^- \to h^- h^- h^+ \nu_\tau$. The branching fraction for decay mode j is then $\mathcal{B}_j = \frac{\mathbf{N}^{\mathrm{Sig}}_j}{2\mathcal{L}\sigma_{e^+ e^- \to \tau^+ \tau^-}}$.

The $\tau^- \to h^- h^- h^+ \nu_\tau$ sample is obtained by selecting events with four well reconstructed tracks having zero total charge, where none of the tracks originate from the conversion of photons in the material of the detector. All four tracks are required to lie within the geometrical acceptance of the EMC and DIRC and, to ensure the tracks can reach the DIRC, are required to have a transverse momentum of at least 250 MeV/c. If any two photons in the event are identified as coming from $\pi^0 \to \gamma\gamma$, the event is removed from the sample. The event is divided into hemispheres in the c.m. by a plane perpendicular to the thrust axis [17]. One of the hemispheres, the "leptonside," is required to contain a $\tau \to e\nu\bar{\nu}$ or $\tau \to \mu\nu\bar{\nu}$ decay. If the hemisphere with an electron (muon) has any neutral particles with more than 1.0 (0.5) GeV, the event is not selected. The $e^+ e^- \to q\bar{q}$ backgrounds are further reduced to ~0.1% of

TABLE I.   Diagonal elements of $\mathcal{E}_{ij}$ excluding particle identification, numbers of selected, background, and signal events determined using Eq. (1). The branching-fraction results for this work are presented in the fifth line where the first error is statistical and the second systematic. The PDG average branching fractions or limit [13] are presented in the sixth line.

	$\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau$	$\tau^- \to K^- \pi^- \pi^+ \nu_\tau$	$\tau^- \to K^- \pi^- K^+ \nu_\tau$	$\tau^- \to K^- K^- K^+ \nu_\tau$
ϵ	0.028	0.031	0.035	0.039
N^{Data}	$(1.5953 \pm 0.0013) \times 10^6$	$(6.956 \pm 0.0026) \times 10^4$	$(1.819 \pm 0.013) \times 10^4$	275 ± 17
N^{Bkg}	$(0.0642 \pm 0.0002) \times 10^6$	$(0.2263 \pm 0.0064) \times 10^4$	$(0.0145 \pm 0.0008) \times 10^4$	2.5 ± 1.5
N^{Sig}	$(55.59 \pm 0.05) \times 10^6$	$(171.5 \pm 1.2) \times 10^4$	$(84.71 \pm 0.66) \times 10^4$	$(9.93 \pm 0.84) \times 10^3$
$\mathcal{B}$ (this work)	$(8.83 \pm 0.01 \pm 0.13)\%$	$(0.273 \pm 0.002 \pm 0.009)\%$	$(0.1346 \pm 0.0010 \pm 0.0036)\%$	$(1.58 \pm 0.13 \pm 0.12) \times 10^{-5}$
$\mathcal{B}$ (PDG average)	$(9.13 \pm 0.05 \pm 0.46)\%$ [4]	$(0.33 \pm 0.05)\%$	$(0.154 \pm 0.009)\%$	$<3.7 \times 10^{-5}$@90%C.L.

the $\tau^- \to h^- h^- h^+ \nu_\tau$ sample by requiring a thrust magnitude >0.85.

Backgrounds from Bhabha and $e^+e^- \to \mu^+\mu^-$ events with photon conversions are suppressed by requiring the momentum of the leptonside track to be less than 80% of $\sqrt{s}/2$ and a requirement that none of the three signalside tracks pass an electron identification algorithm. Remaining non-τ background events, including those from two-photon processes, are reduced by requiring the event missing c.m. transverse momentum to be $>0.009\sqrt{s}$.

The remaining background in the sample is predominantly from other τ decays containing π^0 and K_S^0 mesons. Events containing a K_S^0 are identified and removed. Residual backgrounds from decays having a π^0 are reduced by requiring the total energy in the signalside hemisphere deposited in the EMC which is unassociated with the three charged hadron tracks to be <200 MeV. With these requirements, contributions from $\tau^- \to h^- n\pi^0 \nu$ and $\tau^- \to h^- h^- h^+ 2\pi^0 \nu$ are negligible.

A track in the $\tau^- \to h^- h^- h^+ \nu_\tau$ sample is classified as a kaon using a likelihood approach to combine information from the DIRC, DCH, and SVT with a characteristic kaon identification efficiency of $\sim 80\%$ and pion misidentification rate of $\sim 1\%$. If the track fails to be identified as a kaon, it is classified as a pion. Events are selected if the signalside decays are identified as $\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau$, $\tau^- \to K^- \pi^- \pi^+ \nu_\tau$, $\tau^- \to K^- \pi^- K^+ \nu_\tau$, or $\tau^- \to K^- K^- K^+ \nu_\tau$ with decays having a wrong charge combination removed.

The diagonal elements of $\mathcal{E}_{ij}$ excluding particle identification (ϵ), numbers of selected, background and signal events determined using Eq. (1) are shown in Table I for all modes. The increase in ϵ with number of kaons in the decay is associated primarily with the transverse momentum requirement and the K_S^0 veto. The background fraction from τ decays to $\pi^- \pi^- \pi^+ \pi^0 \nu$ ($K^- \pi^- \pi^+ \pi^0 \nu$, $K^- \pi^- K^+ \pi^0 \nu$, $K^- K^- K^+ \pi^0 \nu$) in the $\pi^- \pi^- \pi^+$ ($K^- \pi^- \pi^+$, $K^- \pi^- K^+$, $K^- K^- K^+$) candidate sample is estimated to be $(3.6 \pm 0.3)\%$ $((2.3 \pm 0.4)\%$, $(0.4 \pm 0.1)\%$, $<5.0\%)$. Non-τ backgrounds comprise less than 0.5% of each channel's final event sample.

The component of $\mathcal{E}_{ij}$ associated with the particle identification, M_{ij}, is shown in the first four rows of Table II.

Note that this matrix includes efficiency losses associated with cross feed of the wrong charge combinations and small factors associated with data control sample corrections to the MC cross-feed efficiencies; therefore, the columns of the table are not expected to sum to 100%.

Systematic uncertainties are assigned for the following: luminosity; cross section; migration matrix elements, which includes MC statistical and systematic errors associated with the efficiency and particle identification; signal-mode modeling; modeling of the EMC and tracking response including scale and resolution uncertainties, the sensitivities of the measurements to the modeling of hadronic and electromagnetic showers in the EMC, and tracking efficiency; modeling of the trigger; and modeling of the backgrounds, including uncertainties on cross-sections and branching fractions. These are summarized in Table III along with the total error correlation matrix. The absolute normalization is a significant source of the correlations.

The branching-fraction results of this analysis are presented in Table I together with the world average values or limit published by the Particle Data Group (PDG) [13], with which they are consistent and significantly more precise. In all four channels, the results where the leptonside has an electron are consistent with those where it has a muon. Our measurement of $\mathcal{B}(\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau)$ is also consistent with a precision $\mathcal{B}(\tau^- \to \pi^- \pi^- \pi^+ (\mathrm{ex}.\omega))$ measurement [18] after accounting for the ω. Our measurement of $\mathcal{B}(\tau^- \to K^- \pi^- \pi^+ \nu_\tau)$ is in agreement with [3] and disagrees by more than 2 standard deviations from

TABLE II.   Component of the efficiency migration matrix associated with pion-kaon particle identification, M_{ij}, in percent. The $\tau^- \to \phi\pi^- \nu_\tau$ and $\tau^- \to \phi K^- \nu_\tau$ study employs a higher-efficiency–lower-purity kaon selection algorithm.

Candidates	Decay modes			
	$\pi\pi\pi$	$K\pi\pi$	$K\pi K$	KKK
$\pi\pi\pi$	97.40	22.49	4.73	1.02
$K\pi\pi$	1.42	74.87	16.43	6.38
$K\pi K$	0.01	0.49	59.63	25.54
KKK	$\cdots$	$\cdots$	0.26	50.87
$\phi\pi$			72.54	19.20
ϕK			0.83	66.06

TABLE III. Upper: Systematic uncertainties (%). Lower: Correlation matrix from stat. ⊕ syst. covariance matrix.

	$\pi\pi\pi$	$K\pi\pi$	$K\pi K$	KKK
$\mathcal{L}$	0.9	0.9	0.9	0.9
$\sigma_{e^+e^-\to\tau^+\tau^-}$	0.3	0.3	0.3	0.3
M_{ij} and particle ID	0.4	3.0	1.9	4.9
signal modeling	0.2	0.2	1.3	2.0
EMC and DCH response	0.8	0.9	0.8	1.2
trigger	0.1	0.1	0.1	0.1
backgrounds	0.4	0.7	0.4	5.5
Total	1.4	3.4	2.7	7.8
$\pi\pi\pi$		0.544	0.390	0.031
$K\pi\pi$			0.177	0.093
$K\pi K$				0.087

[4,5]. We report a first measurement of $\mathcal{B}(\tau^- \to K^-K^-K^+\nu_\tau)$ in which no resonance structure is assumed and which has a significance in excess of 8σ.

A $\phi(1020)$ contribution is seen in both the $\tau^- \to K^-\pi^-K^+\nu_\tau$ and $\tau^- \to K^-K^-K^+\nu_\tau$ decay modes. The use of a kaon selection algorithm with higher efficiency, but less purity, provides significantly higher signal-to-background for $\tau^- \to \phi K^-\nu_\tau$. The $\tau^- \to \phi\pi^-\nu_\tau$ ($\tau^- \to \phi K^-\nu_\tau$) signal has a 5.7σ (9.8σ) level of significance. The last two rows of Table II lists the M_{ij} matrix for this higher efficiency selection. The K^+K^- invariant mass distributions for the $\tau^- \to K^-\pi^-K^+\nu_\tau$ ($\tau^- \to K^-K^-K^+\nu_\tau$) mode using this sample is shown in Fig. 1 and 2. Below 1.09 GeV (1.15 GeV), after background subtraction of the non-K^+K^- events, the K^+K^- invariant mass distribution
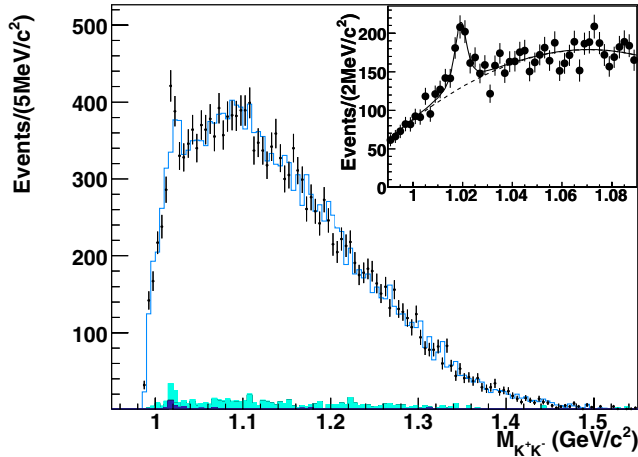
from the $\tau^- \to \phi\pi^-\nu_\tau$ ($\tau^- \to \phi K^-\nu_\tau$) decay is well described by a Breit-Wigner function convoluted with a Gaussian resolution function for the signal and a third-order polynomial (function in [19]) for the background and is used to fit for the number of events. A binned maximum likelihood fit yields 344 ± 42 (274 ± 16) $\tau^- \to \phi\pi^-\nu_\tau$ ($\tau^- \to \phi K^-\nu_\tau$) candidates. MC estimates of the subtracted $q\bar{q}$ background events with a ϕ contribute a 5.2% (0.7%) uncertainty. The $\phi\pi^-$ candidate sample has an additional 4.3% uncertainty arising from potentially peaking $\tau^- \to \phi\pi^-n\pi^0\nu_\tau$ background. The fit parameterization contributes a 1.0% (2.0%) error. Accounting for $\mathcal{B}(\phi \to K^+K^-)$ [13], $\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau) = (3.42 \pm 0.55 \pm 0.25) \times 10^{-5}$ and $\mathcal{B}(\tau^- \to \phi K^-\nu_\tau) = (3.39 \pm 0.20 \pm 0.28) \times 10^{-5}$ with a correlation of -0.07. From the fit, we find no evidence for $\tau^- \to K^-K^-K^+\nu_\tau$ without a ϕ and set a first upper limit on $\mathcal{B}(\tau^- \to K^-K^-K^+\nu_\tau(\mathrm{ex}.\phi)) < 2.5 \times 10^{-6}$ at 90% C.L.

This is the first measurement of $\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau)$. It is consistent with a CLEO limit [20] and larger than the $(1.20 \pm 0.28) \times 10^{-5}$ value predicted by a vector meson dominance model [7]. Our $\mathcal{B}(\tau^- \to \phi K^-\nu_\tau)$ measurement is consistent with a recent Belle result [21]. Recent calculations using a meson dominance model [22] agree with our $\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau)$ and $\mathcal{B}(\tau^- \to \phi K^-\nu_\tau)$ measurements and with the ratio $\frac{\mathcal{B}(\tau^-\to\phi\pi^-\nu_\tau)}{\mathcal{B}(\tau^-\to\phi K^-\nu_\tau)} = 0.99 \pm 0.21$. Our measurements of $\mathcal{B}(\tau^- \to K^-\pi^-\pi^+\nu_\tau)$ and $\mathcal{B}(\tau^- \to K^-K^-K^+\nu_\tau)$, when combined with improved measurements of the other strange decays, will constrain the CKM element $|V_{us}|$ better than unitarity bounds [6,23].
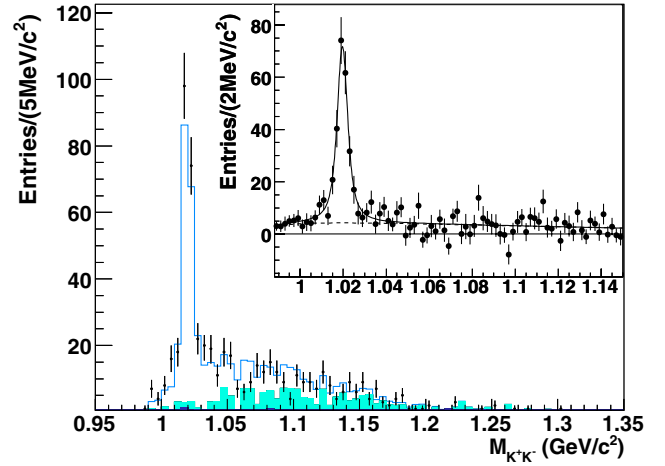

FIG. 1 (color online). K^+K^- invariant mass in $\tau^- \to K^-\pi^-K^+\nu_\tau$ decays. Data are represented by points with error bars, MC of $\tau^- \to K^-\pi^-K^+\nu_\tau$ by the open histogram, cross feed from other $\tau^- \to h^-h^-h^+\nu_\tau$ channels by the light shaded histogram, and non-τ backgrounds by the dark shaded histogram. The inset shows the background-subtracted data with the fit (solid line) and nonresonant component (dashed line).

FIG. 2 (color online). K^+K^- invariant mass in $\tau^- \to K^-K^-K^+\nu_\tau$ decays with two entries per event. Data are represented by points with error bars, the open histogram is the MC calculation of $\tau^- \to \phi K^-\nu_\tau$, the light shaded histogram is the cross feed from the other $\tau^- \to h^-h^-h^+\nu_\tau$ channels, primarily from $\tau^- \to K^-\pi^-K^+\nu_\tau$, and non-$\tau$ backgrounds by the dark shaded histogram. The inset shows the background-subtracted data with the fit (solid line) and nonresonant component (dashed line).

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