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Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.59.751

Experimental Limit on the Decay $\tau^- \to \nu_\tau K^- K^0$

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(Received 16 April 1987)

We set an upper limit on the branching fraction $B(\tau^- \to \nu_\tau K^- K^0) < 0.26\%$ at the 95% confidence level. The data sample was obtained with the TPC/Two-Gamma detector facility at the SLAC e^+e^- storage ring PEP. The process $\tau^- \to \nu_\tau K^- K^0$ is related via SU(3) to the second-class-current decay $\tau^- \to \nu_\tau \pi^- \eta$. Our limit is nearly 20 times smaller than the recently reported branching fraction $B(\tau^- \to \nu_\tau \pi^- \eta)$ of $(5.1 \pm 1.0 \pm 1.2)\%$, whereas SU(3) symmetry predicts the ratio of $\pi\eta$ to $K\bar{K}$ production to be at most 5:1. We also measure the branching fraction $B(\tau^- \to \nu_\tau K^{*-}) = (1.5 \pm 0.4 \pm 0.4)\%$.

PACS numbers: 13.35.+s, 14.60.Jj

Several authors[1-3] have pointed out the value of the decays $\tau^- \to \nu_\tau \pi^- \eta$ and $\tau^- \to \nu_\tau \pi^- \omega$ as tests for the presence of second-class currents[4] in weak interactions. While Albrecht *et al.* have recently set a limit on the second-class axial-vector current in τ decays by studying the decay $\tau^- \to \nu_\tau \pi^- \omega$,[5] Derrick *et al.* (HRS Collaboration) have presented evidence for a second-class vector-current interaction by measuring a branching ratio of $(5.1 \pm 1.0 \pm 1.2)\%$ for the decay $\tau^- \to \nu_\tau \pi^- \eta$.[6] Such a second-class current should also give rise to a $\nu K\bar{K}$ final state.[7,8] With good charged-particle identification this final state is easily reconstructed and relatively background free. In this Letter we present an upper limit on the branching fraction $B(\tau^- \to \nu_\tau K^- K^0)$. Our result limits the size of the second-class vector current.

The data were recorded with the TPC/Two-Gamma facility at the SLAC e^+e^- storage ring PEP operating at $\sqrt{s} = 29$ GeV. The time-projection chamber[9] (TPC) was used to reconstruct and identify charged particles over 87% of 4π. Data were taken with two different detector configurations: an initial sample of 74 pb^{-1} with the TPC operating in a 4-kG magnetic field generated by a normal solenoid, and a more recent sample of 70 pb^{-1} with a 13.25-kG superconducting coil. The higher field and the addition of a gating system to reduce space-charged–induced distortions in the TPC resulted in a substantial improvement in momentum resolution for the second sample, $(\sigma_p/p)^2=(1.5\%)^2+[(0.65\%)p]^2$ (p in GeV/c), as compared with $(\sigma_p/p)^2=(6\%)^2+[(3.5\%)p]^2$ for the earlier sample. Charged particles are identified by simultaneous measurement of ionization energy loss (dE/dx) and momentum. The ionization of each track is sampled up to 183 times, and the information is summarized by forming the mean of the 65% lowest pulse heights, resulting in a typical dE/dx resolution of 3.7%.[9]

We look for τ decays proceeding through the chain $\tau^- \to \nu_\tau K^- K_S^0$, $K_S^0 \to \pi^+\pi^-$, which results in three charged tracks. To isolate a clean sample of three-prong τ decays, we select events containing one charged prong recoiling against the three candidate tracks. The criteria for selection of events of this type have been described in detail elsewhere.[10] Briefly stated, the τ_{1+3} selection requires that an event contain exactly four well measured tracks that point toward the event vertex, and that their charges sum to zero. One track must be separated from each of the other three by at least 140°. Beam-gas interactions and two-photon events are suppressed by the requirements that the scalar sum of the track momenta be greater than 4.5 GeV/c, that the invariant mass of all four tracks be greater than 3.0 GeV/c^2, and that the invariant mass of the three nonisolated tracks be less than 2.0 GeV/c^2, where the invariant masses are calculated on the assumption that all the particles are pions. Bhabha and radiative Bhabha events that shower in the detector are rejected by the requirements that the scalar sum of track momenta be less than 24 GeV/c, that the isolated track form an acollinearity angle of at least 2° with each of the other tracks, and that none of the three nonisolated tracks be identified as an electron by dE/dx.[9] The τ_{1+3} selection yields a sample of 1372 events, of which 71 are estimated to be background. The primary source of background is $e^+e^- \to$ hadrons.

On the three-prong side of events displaying the 1+3 topology, we make loose cuts to identify the decay $K_S^0 \to \pi^+\pi^-$. We select K_S^0 candidates by searching for two oppositely charged tracks that meet at a secondary vertex further than 1 cm from the primary event vertex; a detailed description of the algorithm is given by Aihara *et al.*[11] The vector momentum sum of those tracks must point within 5° of the primary vertex and both tracks must have dE/dx consistent with the pion hypothesis. The invariant masses of all combinations that meet these requirements are plotted in Fig. 1(a). All pairs of tracks in this figure with an invariant mass within ±80 MeV/c^2 of the K_S^0 mass (the shaded region) are labeled as K_S^0 candidates. This mass cut is quite loose in view of our typical K_S^0 mass resolutions of 35 and 16 MeV/c^2 in the low- and high-field data sets, respectively.

We now measure the number of events in which the track accompanying the K_S^0 candidate is a charged kaon. The isolated track and the tracks that form the K_S^0 are removed from consideration. Events in which the remaining track has a small number of dE/dx wire samples or whose momentum is not measured well enough to permit reliable particle identification are rejected. Figure 2 shows the dE/dx and $\ln(p)$ of the remaining track on the three-prong side of each surviving event, as well as the expected curves for several particle species. All the tracks are consistent with the pion hypothesis. To bound the number of kaons consistent with our data, we use an extended maximum-likelihood fit.[12,13] The fit uses as input the momentum, momentum error, dE/dx, and dE/dx resolution of each track. Tracks whose momenta fall in the region where the pion and kaon bands cross are cut away by our requiring momentum less than 0.9 GeV/c, or greater than 1.4 GeV/c. The best fit to the number of kaons in the remaining sample of 37 tracks is zero and the maximum-likelihood fit yields a 95%

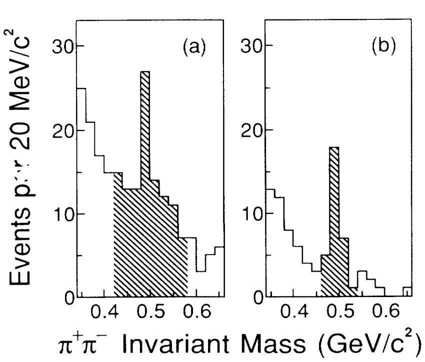

FIG. 1. Invariant mass of the $\pi^+\pi^-$ system. The entries in (a) have the loose secondary-vertex cuts used in the $K\bar{K}$ analysis, while those entries in (b) have the tight cuts used in the K^* analysis. The shaded areas represent the entries selected as K_S^0 candidates.

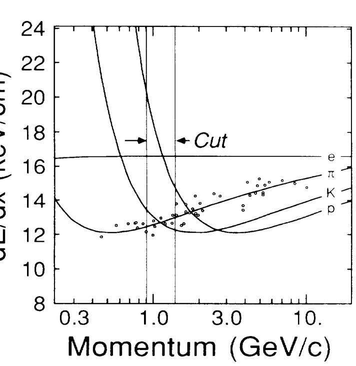

FIG. 2. Scatter plot of dE/dx vs $\ln(p)$ for well measured tracks accompanying K_S^0 candidates on the three-prong side of events in the τ_{1+3} sample. The solid lines represent the expected curves for various particle types.

confidence level upper bound of 4.4 charged kaons. This limit is insensitive to the values of the cuts used to identify K_S^0 candidates or to select well-measured tracks accompanying the K_S^0.

The branching fraction is computed by our comparing the number of candidate decays to the number of events in the τ_{1+3} sample, taking into account the effects of our K_S^0 reconstruction efficiency and K^- identification cuts. These effects were evaluated with a Monte Carlo program. The program simulates τ production and decay, including initial- and final-state radiation,[14] as well as subsequent momentum and dE/dx measurement errors in the TPC, nuclear and electromagnetic interactions in the material in front of the TPC, and track-finding inefficiencies. In addition, we use the Monte Carlo to correct for slight differences in even selection efficiences among the various hadronic final states. With the predicted K_S^0 reconstruction efficiency and K^- identification efficiency (both typically 70%) and a three-prong τ branching fraction of 13.4%,[15] the limit of 4.4 events in a τ_{1+3} data sample of $1372-71=1301$ events corresponds to

$$B(\tau^- \to \nu_\tau K - K_S^0) < 0.13\% \qquad (1)$$

or

$$B(\tau^- \to \nu_\tau K^- K^0) < 0.26\% \qquad (2)$$

at the 95% confidence level (C.L.).

We check our efficiency estimates by measuring the branching function of the decay $\tau^- \to \nu_\tau K^{*-}$ and comparing to the world average of $(1.4 \pm 0.4)\%$.[15-17] We measure this branching fraction by observing the decay chain $K^{*\pm} \to \pi^\pm K_S^0$, $K_S^0 \to \pi^+\pi^-$, which tests our ability to identify K_S^0 in τ_{1+3} events. K_S^0 candidates are selected by the procedure described above, with tighter decay-distance (>3 cm) and momentum-vector-alignment ($<2°$) cuts applied to reduce the number of accidental combinations. The resulting invariant-mass combinations are plotted in Fig. 1(b). Combinations with invariant masses within ± 40 MeV/c^2 of the K_S^0 mass (the shaded region) are selected as K_S^0 candidates. Each K_S^0 candidate is combined with the remaining charged track in the same hemisphere and the invariant mass computed. A clear K^* peak with a width consistent with the expected width is visible in the resulting invariant mass distribution, shown in Fig. 3. The eighteen combinations with invariant masses between 0.8 and 1.1 GeV/c^2 are labeled as K^* candidates, of which 3 ± 3 are estimated to be background. This leads to a measured branching fraction $B(\tau^- \to \nu_\tau K^{*-})$ of $(1.5 \pm 0.4 \pm 0.4)\%$, where the errors are statistical and systematic, respectively. The systematic error is dominated by uncertainty in the background estimation. Our measurement agrees with the world average.

Consistency between our limit Eq. (2) and the HRS result[6,18] on $\tau^- \to \nu_\tau \pi^- \eta$ would require a ratio

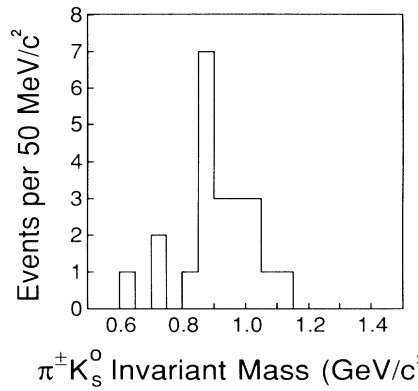

FIG. 3. Invariant mass of the $\pi^\pm K_S^0$ combinations used in the K^* analysis.

$$\mathcal{R} \equiv \frac{B(\tau^- \to \nu_\tau \pi^- \eta)}{B(\tau^- \to \nu_\tau K^- K^0)} > 19. \qquad (3)$$

However, theoretical models for these decays predict a significantly smaller ratio. The largest predicted ratio, obtained when both $K\bar{K}$ and $\pi\eta$ are produced predominantly through the $a_0(980)$ resonance, is[8]

$$\mathcal{R} = 5.1. \qquad (4)$$

This estimate is obtained under the assumption that SU(3) symmetry is broken only by final-state phase space, and with the η treated as a pure octet state. Equation (4) is consistent with observed a_0 branching fractions.[19] If the η is considered to be a mixed state and the nonet assumption[20] is used to relate the octet and singlet amplitudes, cancellations between those amplitudes tend to reduce the $\nu\pi\eta$ branching fraction and hence $\mathcal{R}$.[21] Nonresonant production lessens the phase-space suppression of $K\bar{K}$ imposed by the a_0, and results in predictions for the value of $\mathcal{R}$ near 2. Allowed production of $K\bar{K}$ in a p wave via a first-class vector current would also reduce $\mathcal{R}$.

We can use our limit on $\tau^- \to \nu_\tau K^- K^0$ to set limits on several processes that can proceed only through a second-class current.

(1) If we assume that the $K\bar{K}$ and $\pi\eta$ modes are the only important decay modes of the $a_0(980)$, then Eq. (4) implies a branching ratio $B(a_0 \to K\bar{K}) > 16\%$, and our limit Eq. (2) leads to

$$B[\tau^- \to \nu_\tau a_0^-(980)] < 1.6\%. \qquad (5)$$

(2) Using the same assumptions, we establish a limit on the a_0 decay constant f_{a_0}, defined by $\langle 0 | J_\mu^{\mathrm{II}-} \times | a_0^+(p)\rangle = f_{a_0} p_\mu$, where $J_\mu^{\mathrm{II}-}$ is the hadronic second-class vector current defined in Ref. 1. Using Eq. (1) of Ref. 1, Eq. (5) above, and the most recent values of the τ

mass, the a_0 mass, and $B(\tau^- \to \nu_\tau \pi^-)$,[15] we arrive at

$$f_{a_0}^2/f_\pi^2 < 0.3. \tag{6}$$

(3) In order to account for scalar hadronic final states in τ decays, one can introduce a hypothetical scalar part S of the effective four-fermion interaction that links the τ to hadrons[8]:

$$\mathcal{H}_{\rm int} = (G/\sqrt{2})\{[\bar{d}\gamma_\lambda(1-\gamma_5)u][\bar{\nu}_\tau\gamma^\lambda(1-\gamma_5)\tau] + \epsilon_s(\bar{d}u)[\bar{\nu}_\tau(1+\gamma_5)\tau]\} + \text{H.c.} \tag{7}$$

The total hadronic decay rate of the τ through the scalar interaction is related to the electronic decay rate by

$$\frac{\Gamma(\tau^- \to \nu_\tau(\text{hadrons})^-_{\text{scalar}})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = \tfrac{3}{8}\epsilon_s^2 \times (\text{phase-space factor}) \simeq 0.2\epsilon_s^2. \tag{8}$$

Assuming that the $\pi\eta$ and $K\bar{K}$ modes saturate the decay of $(u\bar{d})_s$,[22] we can limit the strength of a such a scalar contribution. Using the experimental value $B(\tau^- \to \nu_\tau e^- \bar{\nu}_e) = 17.4\%$ (Ref. 15) and the conservative value for $\mathcal{R}$ given in Eq. (4), we find

$$\epsilon_s^2 < 0.5. \tag{9}$$

Finally, we note that, as no cuts were made to eliminate events containing neutral energy, our sample may contain such decays as $\tau^- \to \nu_\tau K^- K^0 \pi^0$, which is allowed to proceed via the $\rho(1600)$. The experimental acceptance for this mode is the same as that for the decay $\tau^- \to \nu_\tau K^- K^0$, and so the limit implied by our study takes the same value:

$$B(\tau^- \to \nu_\tau K^- K^0 \pi^0) < 0.26\% \text{ (95\% C.L.)}. \tag{10}$$

In conclusion, we have established the 95%-confidence-level upper limit $B(\tau^- \to \nu_\tau K^- K^0) < 0.26\%$. This decay can proceed through a forbidden second-class vector current or through an allowed first-class current; therefore, our null result effectively limits the size of the second-class vector in τ decay. The HRS Collaboration's reported branching ratio of $\tau^- \to \nu_\tau \pi^- \eta$ is nearly a factor of 20 above our limit on $B(\tau^- \to \nu_\tau K^- K^0)$, whereas SU(3) symmetry broken by phase-space effects predicts a factor of no more the 5.1. These results are clearly inconsistent. In addition, we present the new measurement $B(\tau^- \to \nu_\tau K^{*-}) = (1.5 \pm 0.4 \pm 0.4)\%$.

We acknowledge the efforts of the PEP staff, and of the engineers, programmers, and technicians, who made this work possible. We are especially grateful to Professor Mahiko Suzuki and to Dr. Michael Chanowitz for helpful discussions. This work was supported by the U.S. Department of Energy, the National Science Foundation, the Joint Japan–U.S. Collaboration in High-Energy Physics, and the Foundation for Fundamental Research on Matter in The Netherlands.

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