AN IMPROVED UPPER LIMIT ON THE ν_τ-MASS FROM THE DECAY $\tau^- \to \pi^-\pi^-\pi^-\pi^+\pi^+\nu_\tau$

ARGUS Collaboration

H. ALBRECHT, U. BINDER [1], P. BÖCKMANN, R. GLÄSER, G. HARDER, A. KRÜGER, A. NIPPE, M. SCHÄFER, W. SCHMIDT-PARZEFALL, H. SCHRÖDER, H.D. SCHULZ, F. SEFKOW, R. WURTH, A. YAGIL [2,3]

DESY, D-2000 Hamburg, Fed. Rep. Germany

R.D. APPUHN, J.P. DONKER, A. DRESCHER, D. KAMP, H. KOLANOSKI, U. MATTHIESEN, H. SCHECK, G. SCHWEDA, B. SPAAN, J. SPENGLER, A. WALTHER, D. WEGENER

Institut für Physik, Universität Dortmund [4], D-4600 Dortmund, Fed. Rep. Germany

J.C. GABRIEL, T. RUF, K.R. SCHUBERT, J. STIEWE, K. STRAHL, R. WALDI

Institut für Hochenergiephysik, Universität Heidelberg [5], D-6900 Heidelberg, Fed. Rep. Germany

K.W. EDWARDS [6], W.R. FRISKEN [7], D.J. GILKINSON [8], D.M. GINGRICH [8], H. KAPITZA [6], P.C.H. KIM [8], R. KUTSCHKE [8], D.B. MACFARLANE [9], J.A. McKENNA [8], K.W. McLEAN [9], A.W. NILSSON [9], R.S. ORR [8], P. PADLEY [8], J.A. PARSONS [8], P.M. PATEL [9], J.D. PRENTICE [8], H.C.J. SEYWERD [8], J.D. SWAIN [8], G. TSIPOLITIS [9], T.-S. YOON [8], J.C. YUN [6]

Institute of Particle Physics [10], Canada

R. AMMAR, S. BALL, D. COPPAGE, R. DAVIS, S. KANEKAL, N. KWAK

University of Kansas [11], Lawrence, KS 66045, USA

B. BOŠTJANČIČ, G. KERNEL, P. KRIŽAN

Institut J. Stefan and Oddelek za fiziko, Univerza v Ljubljani [12], 61111 Ljubljana, Yugoslavia

L. JÖNSSON

Institute of Physics, University of Lund [13], S-223 62 Lund, Sweden

A. BABAEV, M. DANILOV, B. FOMINYKH, A. GOLUTVIN, I. GORELOV, V. LUBIMOV, V. MATVEEV, V. RYLTSOV, A. SEMENOV, V. SHEVCHENKO, V. SOLOSHENKO, V. TCHISTILIN, I. TICHOMIROV, Yu. ZAITSEV

Institute of Theoretical and Experimental Physics, 117 259 Moscow, USSR

R. CHILDERS, C.W. DARDEN, R.C. FERNHOLZ and Y. OKU

University of South Carolina [14], Columbia, SC 29208, USA

Received 15 December 1987

For footnotes see next page.

0370-2693/88/$ 03.50 © Elsevier Science Publishers B.V.
(North-Holland Physics Publishing Division)

Using the ARGUS detector at the e^+e^- storage ring DORIS II, we have observed the decay $\tau^- \to \pi^-\pi^-\pi^-\pi^+\pi^+\nu_\tau$ in tau-pair events produced at center-or-mass energies between 9.4 and 10.6 GeV. From the 5π invariant mass distribution we derive an upper limit of $m(\nu_\tau) < 35$ MeV/c^2 at the 95% confidence level. The branching ratio for this decay channel is found to be $(0.064 \pm 0.023 \pm 0.01)$%.

Leptons are believed to be elementary particles. For the electron and muon, and their associated neutrinos, this is a well-tested hypothesis. However, for the tau and tau-neutrino the experimental measurements are considerably less stringent. In particular, improved constraints on the mass of the tau-neutrino would be welcome. Previous limits have been derived from either (a) studies of the energy spectrum of leptonic tau-decays [1], or the decays $\tau^- \to \pi^-\nu_\tau$ [#1] [2], and $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ [3,4], or (b) the invariant mass distribution at the phase-space limit of the hadrons in the decays $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ [5], $\tau^- \to K^+K^-\pi^-\nu_\tau$ [6], $\tau \to 2\pi^+3\pi^-\nu_\tau$ [7,8] and $\tau^- \to 2\pi^+3\pi^-\pi^0\nu_\tau$ [7]. The best limit [3] is 70 MeV/c^2 at the 95% confidence level. In this paper we report a new upper limit obtained from a study of the 5π invariant mass distribution in the decay $\tau^- \to \pi^-\pi^-\pi^-\pi^+\pi^+\nu_\tau$.

The study was performed using the ARGUS detector at the electron–positron storage ring DORIS II. Data were collected at centre-of-mass energies between 9.4 GeV and 10.6 GeV, and correspond, for this analysis to an integrated luminosity of 197 pb^{-1}. The detector, its trigger and particle identification capabilities are discussed in ref. [9]. A search was made for tau-pair events, corresponding to the combination of decays

$$e^+e^- \longrightarrow \tau^+\tau^- \longrightarrow \pi^-\pi^-\pi^-\pi^+\pi^+\nu_\tau \quad \llcorner\!\!\to e^+\nu_e\bar{\nu}_\tau,\ \mu^+\nu_\mu\bar{\nu}_\tau,\ \pi^+\bar{\nu}_\tau \text{ or } K^+\bar{\nu}_\tau , \qquad (1)$$

which leads to a final state with six charged particles and no photons. A preselection of events was first made using the following cuts:

- six charged particles originating from the main vertex,
- total charge zero,
- transverse momentum of each charged particle, $p_T > 0.06$ GeV/c,
- no photon with an energy $E_\gamma > 0.08$ GeV detected in the electromagnetic calorimeter. The tau-pairs are produced back-to-back, and with sufficient boost so that their decay products are typically in opposite hemispheres. This characteristic 1 versus 5 topology was selected by requiring the angle θ_{1i} between one prong and the remaining 5 pions satisfy $\cos\theta_{1i} < -0.3$, $i = 2, 3, ..., 6$.

These cuts reduce the event sample from about 2 million multihadron events to just 224 events. Backgrounds still remain from two-photon and $q\bar{q}$-interactions, as well as from doubly radiative bremsstrahlung events where both photons converted. In addition, some small fraction of events containing other tau-decay modes, such as $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$, also pass these cuts. A detailed study of events inside and outside the normal vertex fiducial volume showed the contributions from beam–gas and beam–wall events to be negligible.

To reject the doubly radiative Bhabha events, the following additional cuts were applied:

- invariant mass of opposite charged pairs, assumed to be electrons, greater than 0.1 GeV/c^2,
- opening angle between same-sign charged pairs to $\cos\theta_{\pm\pm} < 0.996$.

[1] Present address: CERN, CH-1211 Geneva 23, Switzerland.
[2] Weizmann Institute of Science, 76100 Rehovot, Israel.
[3] Supported by the Minerva Stiftung.
[4] Supported by the Bundesministerium für Forschung und Technologie, Fed. Rep. Germany, under contract number 054DO51P.
[5] Supported by the Bundesministerium für Forschung und Technologie, Fed. Rep. Germany, under contract number 054HD24P.
[6] Carleton University, Ottawa, Canada K1S 5B6.
[7] York University, Downsview, Canada M3J 1P3.
[8] University of Toronto, Canada M5S 1A7.
[9] McGill University, Montreal, Canada H3A 2T8.
[10] Supported by the Natural Sciences and Engineering Research Council, Canada.
[11] Supported by the US National Science Foundation.
[12] Supported by Raziskovalna skupnost Slovenije, the Internationales Büro KfA, Jülich, and DESY, Hamburg.
[13] Supported by the Swedish Research Council.
[14] Supported by the US Department of Energy, under contract DE-AS09-80ER10690.
[#1] References in this paper to a specific charged state are to be interpreted as also implying the charge conjugate state.

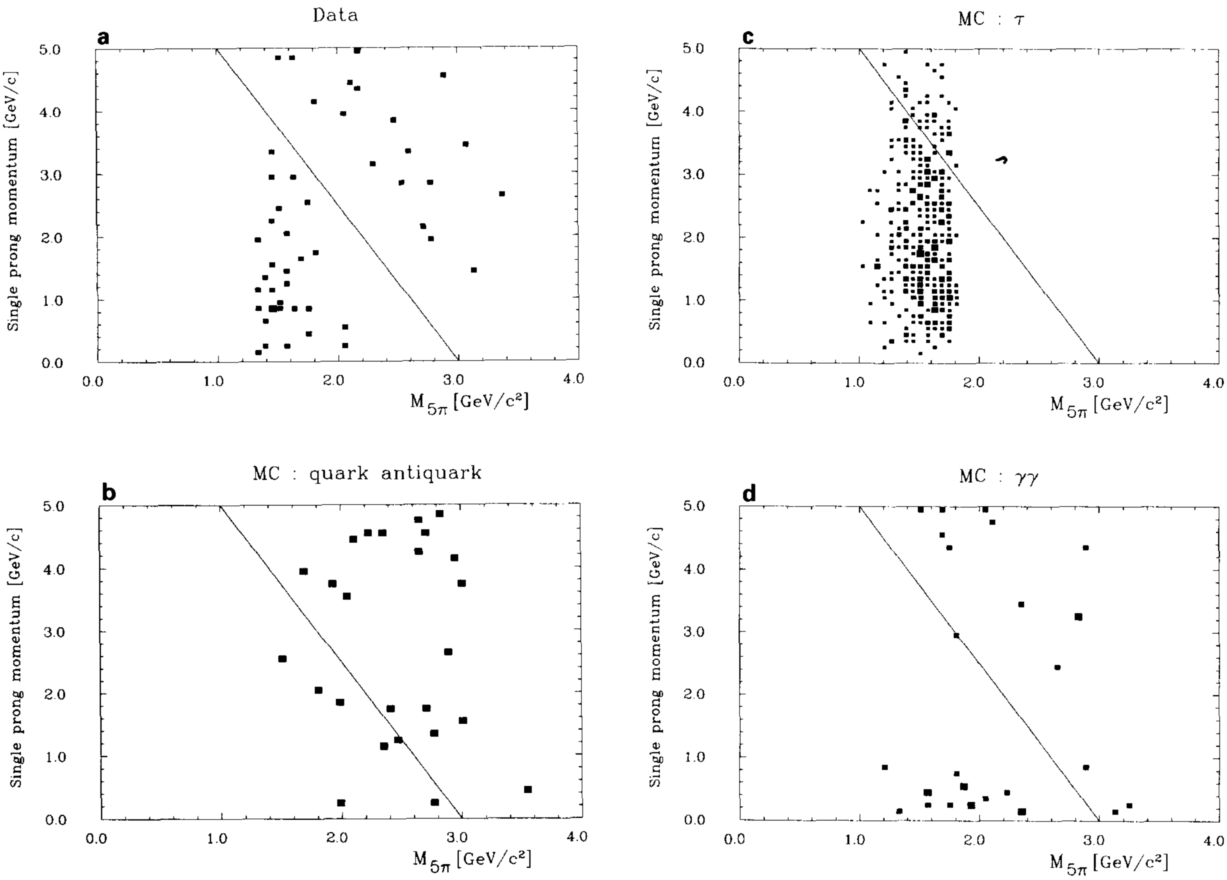

Fig. 1. Single-prong momentum versus 5π mass: (a) data, (b) q$\bar{q}$ Monte Carlo, (c) τ Monte Carlo and (d) γγ Monte Carlo. The solid line corresponds to the cut described in the text. Events above this line are rejected.

In fig. 1a the momentum of the single particle is plotted versus the invariant mass of the five-prong, for the selected events. Monte Carlo studies of q$\bar{q}$ events (fig. 1b) and two-photon interactions (fig. 1d) demonstrate that an appreciable amount of this background is rejected by the cut indicated in fig. 1a, while most of the tau-pair events pass this cut (fig. 1c). In order to reject the remaining background events we exploit the fact that for tau-decays the missing momentum is large. Therefore the following further cuts were applied:

– direction of the missing momentum of the event must point into the barrel region to ensure a good detection efficiency: $\cos\theta(\boldsymbol{P}_{\mathrm{miss}})| < 0.8$,

– missing momentum must be larger than 1.7 GeV/c: $|\boldsymbol{P}_{\mathrm{miss}}| > 1.7$ GeV/c.

These requirements effectively limit the total transverse momentum of the detected particles to $P_{\mathrm{T}} > 1$ GeV/c and eliminate two-photon, as well as initial-state radiation events, both of which typically have missing momentum along the beam tube.

The resulting invariant mass spectrum of the 5π system is shown in fig. 2. Twelve events remain, all in the tau-mass region. The background in the sample has been determined to be smaller than 1 event, as discussed below.

The effectiveness of the background suppression has been studied by applying the same cuts to well-defined samples of background events obtained either directly from the collected data or by Monte Carlo simulation. The available number of generated events was always large compared to data. For example, the

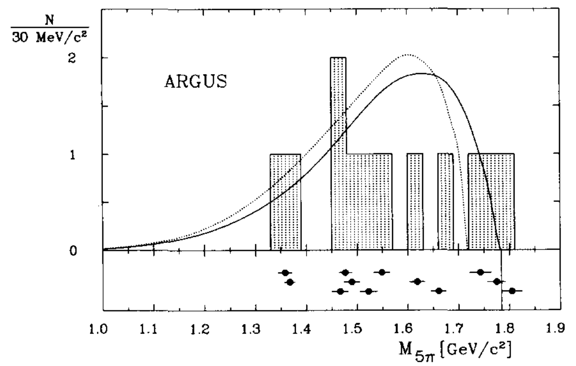

Fig. 2. Measured 5π mass spectrum after all cuts. The solid curve corresponds to the expected shape of a pure phase-space decay with $m(\nu_\tau)=0$ MeV/c^2. The dashed curve corresponds to the expected shape of a pure phase-space decay with $m(\nu_\tau)=70$ MeV/c^2. Underneath, the mass and error on mass for every event are shown. The τ- mass is indicated by the solid line.

cuts rejecting radiative Bhabhas with converted photons were applied to selected singly radiative Bhabha events

$$e^+e^- \longrightarrow e^+e^-\gamma \quad . \\ \hookrightarrow e^+e^-$$

From this analysis the rejection efficiency was determined and, when used to project the doubly radiative rate, leads to the conclusion that no Bhabha event remains in the final sample.

The rejection of two-photon events was studied by Monte Carlo simulation. The following channels were considered:

$$e^+e^- \longrightarrow$$

$$\gamma\gamma e^+e^-$$

$$\longrightarrow 3\pi^+3\pi^-,\ 3\pi^+3\pi^-\pi^0,\ 2\pi^+2\pi^-,\ 2\pi\pi^0\ .$$

$$\longrightarrow K^+2\pi^+3\pi^-K^0_L,\ 2\pi^+2\pi^-\ K^0_S\,K^0_L$$

From the analysis of these channels if follows that background from two-photon events in the final data sample is negligible.

In addition, the contribution of the decay $\tau^-\to\pi^-\pi^-\pi^+\pi^0\nu_\tau$, where the π^0 produces an e^+e^- pair either by a Dalitz decay or by conversion of one of its decay photons, was considered. It was found to be smaller than 0.1 events. Finally, possible contributions from $e^+e^-\to q\bar{q}$ interactions were studied using the Lund fragmentation model as an event generator [10]. As can be seen in fig. 1b, not all of the $q\bar{q}$-events are removed by the cut indicated by the full line. After all requirements described above, 3 out of 2×10^6 generated events survived. The five-prong mass of the events is $m(5\pi)>2.3$ GeV/c^2, considerably larger than the tau-mass. No event of this type is observed in the data. In summary these studies established that the background to the 12 data events is much smaller than 1 event [11].

The upper limit of the tau-neutrino was determined by a maximum likelihood method, which considered the mass resolution of each event, the expected mass distribution of the 5π system and the mass dependence of the acceptance. For each event the likelihood, depending on the mass of the tau-neutrino, is determined from a convolution of these distributions. The expected shape of the mass-resolution function has been determined by Monte Carlo simulations [12] and is well described by a gaussian distribution with a typical width of about 20 MeV/c^2 (fig. 2). Both a simple phase-space model, and a phase-space distribution weighted by a weak matrix element [13], were used to describe the 5π invariant mass distribution (fig. 2). However, the result does not depend on which model is used, because the limit is more sensitive to the shift in the kinematical threshold due to a finite tau-neutrino mass than to the actual shape of the distribution. By this means, we find an upper limit on the tau-neutrino mass of 25 MeV/c^2 at the 95% confidence level. Possible sources of systematic error are added in quadrature, including underestimation of the mass resolution, uncertainty in the momentum scale and uncertainty in the tau-mass [14,15]. To consider uncertainties of the background simulation we decided to remove the event with the highest 5π mass from the sample analysed and hence arrive at a conservative upper limit of 35 MeV/c^2 at 95% confidence level, well below the best existing bound of 70 MeV/c^2 [3].

In addition, we have used the sample to determine the branching ratio for the decay $\tau^-\to\pi^-\pi^-\pi^-\pi^+\pi^+\nu_\tau$. For this measurement, further background contribution from the decays

$$\tau^-\to3\pi^+3\pi^-\pi^0\nu_\tau \text{ and } \tau^-\to K^{*-}K^0_S\nu_\tau$$

must be considered. These backgrounds have been determined by a Monte Carlo calculation, using the measured branching ratios [16,6] for these channels [11], to be 1 ± 1 and 0.14 ± 0.14 events, respectively.

The branching ratio for the decay $\tau^- \to \pi^-\pi^-\pi^-\pi^+\pi^+\nu_\tau$ is then given by

$$\mathrm{Br} = \frac{N_5}{2N_{\tau\tau}\mathrm{Br}(\tau^- \to \text{single prong})\epsilon_{\text{faked}}\epsilon_{\text{cut}}}, \qquad (2)$$

where N_5 is the observed number of 5π decays after subtraction of background and $N_{\tau\tau}$ is the number of tau-pairs produced. The branching ratio for one-prong tau-decays, $\mathrm{Br}(\tau^- \to \text{single prong})$, includes a correction for the feeddown of single-prong tau-decays containing π^0's. Using average branching ratios given in ref. [15], this has been determined to be $(48.9 \pm 1.4)\%$. The efficiency, ϵ_{faked}, accounting for the loss of events introduced by noise in the calorimeter due to the requirement that there be no photon with $E_\gamma > 0.08$ GeV, has been determined from an analysis of cosmic-ray events to be $(91.6 \pm 1.0)\%$. The efficiency for the combination of decays in eq. (1) to pass all selection cuts, ϵ_{cut}, was determined to be $(9.1 \pm 0.63 \pm 0.9)\%$. Using these values, we find a branching ratio of

$$\mathrm{Br}(\tau^- \to \pi^-\pi^-\pi^-\pi^+\pi^+\nu_\tau) = (0.064 \pm 0.023 \pm 0.01)\% .$$

This in good agreement with the present world aversage [15] $(0.07 \pm 0.03)\%$.

In summary we have obtained an improved upper limit of $m(\nu_\tau) < 35$ MeV/c^2 at the 95% confidence level. In comparing limits on the tau- and electron-neutrino masses, one can use the following proposed relation [17]:

$$m(\nu_\tau)/m(\nu_e) = m^2(\tau)/m^2(e) , \qquad (3)$$

with the implication that present attempts to determine the tau-neutrino mass already reach about the same sensitivity to new physics as that derived from electron-neutrino-mass experiments [18]. Using this model, this new limit of 35 MeV/c^2 corresponds to an electron-neutrino-mass upper limit of about 3 eV/c^2, well below the existing limit of 18 eV/c^2 [18]. The measured branching ratio, $(0.064 \pm 0.023 \pm 0.01)\%$, agrees with the value determined by other groups [15].

Acknowledgement

It is a pleasure to thank U. Djuanda, E. Konrad, E. Michel and W. Reinsch for their competent technical help in running the experiment and processing the data. We thank Dr. H. Nesemann, B. Sarau and the DORIS group for the excellent operation of the storage ring. The visiting groups wish to thank the DESY directorate for the support and kind hospitality extended to them.

References

[1] DELCO Collab., W. Bacino et al., Phys. Rev. Lett. 42 (1979) 749.
[2] MARK II Collab., C.A. Blocker et al., Phys. Lett. B 109 (1982) 119.
[3] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 163 (1985) 404.
[4] CLEO Collab., S.E. Csorna et al., Cornell preprint CLEO 86-13.
[5] MARK II Collab., C. Matteuzzi et al., Phys. Rev. Lett. 52 (1984) 1869; Phys. Rev. D 32 (1985) 800.
[6] DELCO Collab., G.B. Mills et al., Phys. Rev. Lett. 54 (1985) 624.
[7] HRS Collab., S. Abachi et al., Phys. Rev. Lett. 56 (1986) 1039;
S. Abachi et al., Purdue preprint PU-86-581 (1986).
[8] MARK II Collab., P.R. Burchat et al., Phys. Rev. Lett. 54 (1985) 2489.
[9] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 134 (1984) 137.
[10] B. Andersson et al., Phys. Rep. 97 (1983) 31.
[11] B. Spaan, thesis University of Dortmund (1988), in preparation.
[12] H. Gennow, SIMARG: A program to simulate the ARGUS detector, DESY internal report DESY F15-85-02 (1985).
[13] Y.S. Tsai, Phys. Rev. D 4 (1971) 2821;
F.J. Gilman and D.H. Miller, Phys. Rev. D 17 (1978) 1846.
[14] DELCO Collab., A. Bacino et al., Phys. Rev. Lett. 41 (1978) 13.
[15] Particle Data Group, M. Aguilar-Benitez et al., Review of particle properties, Phys. Lett. B 170 (1986) 1.
[16] HRS Collab., B.G. Beltrami et al., Phys. Rev. Lett. 54 (1985) 1775.
[17] M. Gell-Mann et al., in: Supergravity, ed. P. van Nieuwenhuizen (North-Holland, Amsterdam, 1979) p. 315.
[18] S. Boris et al., Phys. Rev. Lett. 58 (1987) 2019;
M. Fritschi et al., Phys. Lett. B 173 (1986) 485.