FROM THE CURRENT LITERATURE

Present status of the τ lepton

Ya. I. Azimov and V. A. Khoze

V. P. Constantinov Institute of Nuclear Physics, Academy of Sciences of the USSR, Leningrad

Usp. Fiz. Nauk **132**, 379–386 (October 1980)

A brief review is given of the present information about the heavy τ lepton and its associated neutrino ν_τ, and also the prospects for further research on these particles.

PACS numbers: 14.60. – z, 14.60.Gh, 13.10. + q

CONTENTS

The first experimental indications of the τ lepton appeared in 1975,[1] and its existence was not firmly established until 1978, after the discovery of anomalous events in the ψ' peak.[2] Nevertheless, many properties of $\tau^\pm$ are already well known. Such rapid progress was achieved owing to the intensive research of some dozen experimental groups at installations with colliding e^+ and e^- beams, **SPEAR** at Stanford, **DORIS** and **PETRA** at Hamburg. The present information about the τ lepton is based on statistics corresponding to the production of tens of thousands of $\tau^+\tau^-$ pairs.

Interest in the τ lepton, as in the other leptons, has also become stronger because the existence of quarks has become generally accepted. In the Glashow-Weinberg-Salam theory, and all the more in models of the "grand unification" of the strong, weak, and electromagnetic interactions, quarks and leptons are objects on the same level of the microscopic world, and many of their properties must be interrelated.

Here we give a brief description of new results on the τ lepton and of prospects of further research on it. Many theoretical processes associated with $\tau^\pm$ and its status up to the end of 1977 were given in an earlier review[2] (see also Ref. 4). There are surveys[5,6] devoted to the currently available data.

1. GENERAL PROPERTIES

a) The masses of τ and ν_τ

The energy dependence of the yield of events caused by the reaction

$$e^+e^- \to \tau^+\tau^-, \tag{1}$$

gives as the present most accurate value of the mass[7]

$$M_\tau = 1782^{+3}_{-4}\ \text{MeV}. \tag{2}$$

Information about the mass of the neutrino ν_τ associated with τ is obtained from the spectra of secondary particles. The spectra of electrons from the decay of $\tau^\pm$ give[8]

$$M_{\nu_\tau} < 250\ \text{MeV}. \tag{3}$$

If ν_τ is stable, cosmological arguments give a much stricter limit (cf., e.g., Ref. 9):

$$M_{\nu_\tau} \lesssim 30\ \text{eV}.$$

b) The spins of τ and ν_τ

The energy dependence of the reaction (1), which has been measured over a wide range of energies from the threshold to $s^{1/2} = 2E_{\text{beam}} = 32$ GeV, also leads to the conclusion[7] that the spin of the τ lepton is

$$S_\tau = 1/2. \tag{4}$$

An additional check on the value of S_τ and a determination of S_{ν_τ} are obtained from comparison of the widths of the decays $\tau^- \to \pi^-\nu_\tau$ and $\tau^- \to e^-\nu_e\nu_\tau$. The experimental value[6]

$$\Gamma(\tau^- \to \pi^-\nu_\tau)/\Gamma(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = 0.52 \pm 0.07 \tag{5}$$

agrees well with the theoretically expected value 0.6 for $S_\tau = S_{\nu_\tau} = 1/2$. The possibility that one or both of these spins could be 3/2 is completely excluded.

c) The structure of the electromagnetic vertex

If we assume that for the τ lepton the vertex differs from a point vertex by the factor

$$F_\tau(q^2) = 1 \mp q^2/(q^2 - \Lambda_\pm^2), \tag{6}$$

then from the behavior of the cross section for the reaction (1) right up to $s^{\frac{1}{2}} = 32$ GeV it follows that[10]

$$\Lambda_+ > 67\ \text{GeV} \qquad \Lambda_- > 74\ \text{GeV}. \tag{6a}$$

Accordingly, for the τ lepton quantum electrodynamics is confirmed at least down to distances $\sim 10^{-16}$ cm. The $e-\mu-\tau$ universality of the electromagnetic interactions is confirmed down to these same distances.

d) The structure of the weak vertex

The experimentally observed[8] spectrum of electrons from the decay $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ agrees well with the $V-A$ structure of the τ, ν_τ vertex, and excludes the $V+A$ form. The measured value of the Michel parameter is

$$\rho_{\mathrm{exp}} = 0.72 \pm 0.15. \tag{7}$$

Theoretically, $\rho_{V-A} = 0.75$ and $\rho_{V+A} = 0$. The types V or A with $\rho_{V,A} = 0.375$ are improbable. That the $V-A$ type is to be preferred is confirmed by measurements of the quantity (E_e/E_{beam}).[8] Assuming this type, one gets from this spectrum the restriction (3) on M_{ν_τ}.

e) The lifetime

A standard calculation (cf., e.g., Ref. 3) from the measured value of M_τ gives the theoretical lifetime

$$T_\tau \approx 2.8\cdot 10^{-13}\ \mathrm{sec}. \tag{8}$$

From the limits on the decay width at SPEAR and DORIS energies it could be concluded[8] that

$$T_\tau < 23\cdot 10^{-13}\ \mathrm{sec}. \tag{9}$$

Measurements on the PETRA machine at $s^{1/2} = 30$ GeV give[10]

$$T_\tau < 14\cdot 10^{-13}\ \mathrm{sec}. \tag{9a}$$

If we introduce the constant $g_{\tau\nu_\tau}$ for the coupling $\tau\nu_\tau W$, the limit (9a) can be expressed in the form

$$g^2_{\tau\nu_\tau} > 0.2g^2, \tag{10}$$

where g is the usual coupling constant between W and $e\nu_e$ or $\mu\nu_\mu$.

With increase of the initial energy in the reaction (1) the decay length of $\tau^\pm$ increases. It can be hoped that in the range of energies of PETRA and of the PEP machine which has begun operation at Stanford the range of the τ particles will be sufficient even for measuring T_τ at the level of the expected value (8).

2. THE DECAYS OF $\tau^\pm$

As is well known, the main decays of the heavy lepton can be rather reliably calculated (see, for example, Ref. 3). They all, and also some rarer decays, have now been studied experimentally. Most of them have even been measured by several groups.

The present results, averaging the data of various groups, are presented in Table I (see Refs. 5, 6, 11–13). This table also gives theoretical expectations based on the calculations of Ref. 3 for $M_\tau = 1.78$ GeV and $\gamma_\rho^2/4\pi = 2.3$ (the constant γ_ρ gives the coupling of the ρ meson and the photon). They correspond to the standard set of assumptions: Universality of the weak interactions, a new lepton quantum number for τ and ν_τ, conservation of vector current, chiral symmetry, and so on.[1] Obviously, there is good correspondence of experiment with theory.

TABLE I. Relative probabilities of decays of τ leptons.

Decay channel	Experimental value, %	Theoretical expectation, %
$e^-\bar{\nu}_e\nu_\tau$	17.5 ± 1.1	18.5
$\mu^-\bar{\nu}_\mu\nu_\tau$	18.5 ± 1.2	18
$\pi^-\nu_\tau$	9.1 ± 1.1	11
$K^-\nu_\tau$	<1.6	0.7
$\rho^-\nu_\tau$	20.9 ± 3.7	24
$K^{*-}\nu_\tau$	1.26 ± 0.49	1.3
$A_1^-\nu_\tau$	10.8 ± 3.4	9
$\pi^-\pi^-\pi^+\nu_\tau$ (without $\rho^0\to\pi^-\pi^+$)	<1.4	
$\pi^-\rho^0\nu_\tau$ ($J^P(\pi^-\rho^0)=1^-, 0^-$)	<1.6	
$\nu_\tau+(\geqslant$ 3 charged particles $)+(\geqslant 0\,\pi^0)$	28 ± 6	17

We shall make some more detailed comments on the τ decays.

1) The observed fractional probability of $\tau^- \to l^-\bar{\nu}_l\nu_\tau$ is close to the naive estimate $\sim 1/5$, which is obtained by assuming that the two lepton decays and three quark decays $\tau^- \to e^-\bar{\nu}_e\nu_\tau$, and $\tau^- \to \overline{du}\nu_\tau$ (allowing for three color states of the quarks) are equally probable. When the interaction of the quarks is taken into account by means of quantum-chromodynamical corrections of the order of α_s/π, the quark decays are enhanced, lowering the fractional probabilities of the lepton channels.[15]

2) The ratio of the decays to e^- and μ^- agrees with $e-\mu$ universality of the weak interactions, which leads to

$$B(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)/B(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = 0.97. \tag{11}$$

3) The ratio of the decays $\tau^- \to \pi^-\nu_\tau$, $\tau^- \to K^-\nu_\tau$, and $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ is the one calculated most reliably; it requires only the assumption that the weak decays are universal and knowledge of the probabilities of the decays $\mu^- \to e^-\bar{\nu}_e\nu_\mu$, $\pi^- \to \mu^-\nu_\mu$, and $K^- \to \mu^-\nu_\mu$. Therefore the good agreement of the mean global value of $B(\tau \to \pi\nu_\tau)$ with theory demonstrates the correctness of the general ideas about the new leptons τ and ν_τ, in particular about their spins (see Sec. 1). The limit on the probability of the decay $\tau \to K\nu_\tau$ found by the DASP group[12] also does not contradict the expected value.

4) The decay $\tau^- \to \nu_\tau(3\pi)^-$ gives previously unobtainable information about the weak axial current of hadrons. In particular, study of the channel $\tau^- \to \nu_\tau(\pi\rho)^-$ allows solution of the old problem of the A_1 resonance with $J^{PG} = 1^{+-}$, whose existence one could not reliably establish in purely hadronic processes.

The results of the PLUTO group[11] show that the final state $\nu_\tau\pi^-\pi^-\pi^+$ comes mainly from the cascade $\tau^- \to \tau^- \to \nu_\tau\pi^-\rho^0$, $\rho^0 \to \pi^-\pi^+$. Here the system $\pi^-\rho^0$ is predominantly in the S state, i.e., $J^{PG} = 1^{+-}$. The spectrum of masses of the $\pi\rho$ system gives evidence in favor of a resonance with mass $M \sim 1$ GeV and width $\Gamma \sim 0.4$–0.5 GeV. This agrees with the values usually accepted for the A_1 resonance.[16] It can be expected that the question of the existence of A_1 will be completely settled in the very near future.

---

[1] For references to earlier calculations see Ref. 3. New calculations[14] agree with values given in Table I. The discrepancies between different calculations show the degree of theoretical uncertainty.

5) The decay $\tau \to K^* \nu_\tau$ has been observed only by the group MARK-II .[13] The ratio of its probability to that of the decay $\tau \to \rho\nu_\tau$ agrees with the value $\sim tg^2\theta_c \approx 0.06$ which is expected in the usual Cabibbo scheme.

6) No one has succeeded in observing any exotic decays of τ, i.e., decays that are absent in the standard model. Examples are the decays $\tau^- \to e^-(\mu^-)\gamma$, $e^-e^-e^+$, etc. According to the existing data the probability of such decays is not more than 1–2 percent. For a more complete summary of the experimental limits on exotic decays see Ref. 6.

3. OTHER LEPTONS AND THE NATURE OF τ and ν_τ

We list a number of results relating to the nature of the new leptons.

1) The new neutrino ν_τ can not be identical with one of the "old" neutrinos, ν_e or ν_μ. If it were, the probabilities of the decays $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ and $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ would be different by a factor 2, and the $\tau\nu_\tau$ vertex would have the $V+A$ structure. Both of these are in contradiction with experiment (see Secs. 1, 2).

2) The τ lepton is not produced in the interaction of a ν_μ beam with matter. If we introduce a constant $g_{\tau\nu_\mu}$ for the vertex $\tau\nu_\mu W$, then[17]

$$g^2_{\tau\nu_\mu} < 0.025 g^2. \tag{12}$$

A comparison of Eq. (12) with Eq. (10) shows that ν_τ cannot be identical with ν_μ.

3) Comparison of the restrictions (10) and (12) with the results of the test of e–μ universality in the decays of π mesons excludes models in which $M_{\nu_\tau} > M_\tau$ and the decay of τ occurs owing to an admixture of ν_τ and ν_μ to ν_τ (see, for example, Ref. 5). The same result is obtained if instead of (12) we use the universality of G_F in μ decay and in β decays of hadrons.

4) The possibility that ν_τ is identical with ν_e is so far not excluded in principle. (The small probability of the decay $\tau \to e\gamma$ does not contradict this statement; see the discussion in Ref. 3.) One could hope to exclude this possibility with experiments on ν_e beams. But there is another way, by using the production of τ in hadron collisions (for example, owing to the production of heavy quarks and the appearance of $\tau\nu_\tau$ pairs in their weak decays). The neutrino events caused by such ν_τ neutrinos have characteristic peculiarities by which they can be distinguished from the usual events caused by ν_μ or ν_e.[18] Recently, the group CHARM , working in CERN, presented preliminary results[19] of an experiment on the detection of direct neutrinos when a proton beam is absorbed by a target (the so-called proton-dump experiment). Possibly these results already contain indications of the appearance of ν_τ. Confirmation of this result would be a graphic demonstration that the τ lepton possesses a new lepton number.

5) Searches for a still heavier charged lepton τ' have so far given no positive results. Under the standard assumptions about its decays one gets from experiments with the DORIS machine the limit

$$M_{\tau'} > 4.3 \text{ GeV}. \tag{13}$$

Measurements on the PETRA machine up to energies $s^{1/2} \sim \text{GeV}^{10}$ make it improbable that new leptons exist with masses clear up to

$$M_\tau \sim 14 \text{ GeV}. \tag{13a}$$

6) Searches are also being made for neutral heavy leptons N_0. For example, the possibility has been discussed that a decay $\tau^- \to \nu_\tau N_0 e^-$ might occur and be followed by decay of N_0 into three leptons[20] or into $l^\pm\pi^\mp$.[20,21] In both cases comparison with the data excludes the range of masses $M_N \lesssim 1.2$ GeV. Searches for neutral leptons are also being conducted in other processes, for example in neutrino reactions (see, for example, Ref. 22).

7) Summarizing all the data, we can say that $\tau^\pm$ most probably has a new lepton quantum number, and otherwise is analogous to the electron and the muon. The question naturally arises, just how many types of leptons are there in nature? Theory so far gives no answer to this question, but there are already some arguments. Thus, present cosmological ideas permit not more than four to six types of stable neutrinos (see, for example, Ref. 9), three of which are already known. In the framework of the Glashow-Weinberg-Salam theory and its simplest generalizations this must be the number of charged leptons, and also the number of doublets of quarks. In these types of theory the numbers of quarks and leptons must be equal in order to avoid the so-called triangle anomaly.[23] Therefore independent considerations limiting the number of quarks are also of interest for lepton physics. One of them comes from the conditions for securing the asymptotic freedom of the strong interactions (see the review articles, Ref. 24). It requires that the number of quark doublets be not larger than eight. All such arguments indicate that the number of different leptons (and quarks) in nature is probably small.

4. FURTHER PROSPECTS

As can be seen from the foregoing, the degree to which the τ lepton has been studied already approaches that for the "old" leptons. However, there are still many interesting questions that require more detailed investigation. We shall list some of them.

1) The lifetime T_τ must be measured. It could be either larger or smaller than the standard value (8). The former could be the case, for example, if a mixing of leptons affects the decay. If, on the other hand, ν_τ and τ^- do not form a spinor representation in the Glashow-Weinberg-Salam theory, but instead appear along with some doubly charged lepton in a vector representation $(\nu_\tau, \tau^-, L^{--})$,[25] T_τ would be only half the value (8).

2) More precise determinations are also needed for such properties as the masses of τ and ν_τ, the structure of the weak vertex, the electromagnetic vertex (in particular, the anomalous magnetic moment) and so on. All these problems can be solved by means of characteristic features of the spectra of secondary particles (see, for example, Ref. 26).

3) More exact measurements of the probabilities of ordinary and exotic decays are also necessary. For example, it is interesting to compare the decays $\tau \to K\nu_\tau$ and $\tau \to \pi\nu_\tau$. In the standard model their widths

can be calculated very reliably. But if the weak interactions go not only via the exchange of "ordinary" $W^\pm$ bosons, but also via Higgs bosons $H^\pm$, the decay to $K\nu_\tau$ is enhanced more than that to $\pi\nu_\tau$.[27] There could be an analogous (and, generally speaking, different) enhancement of the decay $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ in comparison with $\tau^- \to e^-\bar{\nu}_e\nu_\tau$. In all previously studied processes the Higgs exchange might not appear owing to the small masses of the "old" leptons and quarks.

A search for exotic decays of τ would help to clear up the problem of the connections between leptons of different "generations" (lepton quantum numbers, lepton mixing, etc.).

4) It would be interesting to detect a manifestation of a neutral weak current in the reaction (1).

5) In the hadronic decays of τ one can distinguish the contributions of vector and axial hadron currents. The former produces an even number of π mesons, the latter, an odd number. The study of the vector current will make it possible to check the hypothesis of conserved vector current in much more detail than before. The contribution of the axial current contains completely new evidence about hadrons not previously accesible to direct experimental study. One of the first problems here is a careful investigation of the A_1 meson.

The study of the contributions of the two currents is also interesting for testing the influence of quantum chromodynamics on the quark decays of τ. For example, sufficiently accurate measurements, in particular the determination of $B(\tau \to l\bar{\nu}_l\nu_\tau)$ to about one-percent precision, would clearly make it possible to distinguish the so-called power corrections associated with the structure of the vacuum in quantum chromodynamics.[28]

6) By studying the two-photon production of $\tau^+\tau^-$ pairs in the reaction $e^+e^- \to e^+e^-\tau^+\tau^-$ one could test whether the propagator of the τ lepton deviates from the usual Dirac form.

7) The search for new heavy leptons remains a standard problem. In the case of charged leptons $L^\pm$ one could proceed as for the $\tau^\pm$, by looking for anomalous $e\mu$ events in e^+e^- annihilation (~3.5 percent of all events L^+L^- over a wide range of masses $M_{L^\pm}$), and also events of the type

$$e^+e^- \to l^\pm + \text{jet of hadrons}$$

(~40 percent of all events). In looking for neutral leptons it is convenient to use readily observable decays, for example $N_0 \to l^\pm\pi^\mp$. There may possibly be significant progress in the search for new leptons, both charged and neutral, when experiments in the Z-boson peak become feasible.

8) There is much interest in new sources of τ leptons. One of them might be the decay of Higgs bosons. For example, if the charged boson $H^\pm$ exists, then over a wide range of masses M_H there is a high probability (30 to 50 percent) of the decay $H^\pm \to \tau^\pm\nu_\tau$ the decay $H^0 \to \tau^+\tau^-$ should also be appreciable.

It would be very interesting to find τ leptons in decays of new heavy hadrons. For example, the decays $F^+(c\bar{s}) \to \tau^+\nu_\tau$ and $B_c^-(b\bar{c}) \to \tau^-\bar{\nu}_\tau$ might not be small in comparison with other decays of such mesons and could be quite appreciable. Their widths are determined by the constants f_F and f_B, analogous to the well known constant f_π which appears in the amplitude for the decay $\pi \to \mu\nu$. Measurement of f_F and f_B and comparison of them with f_π and f_K would give new information about the quark structure of mesons. From the estimate of f_F described in Ref. 3 it follows that $B(F \to \tau\nu_\tau) \approx 3$ percent, in agreement with Ref. 18. An analogous estimate for F_B gives $B(B_c \to \tau\nu_\tau) \approx 6$ percent. There are also other estimates in the literature that lead to still larger probabilities for decays of heavy hadrons into $\tau\nu_\tau$ (for example, Ref. 29). It may be that these are the decays that are the source of direct ν_τ particles (see Sec. 3). The decay $F^+ \to \tau^+\nu_\tau$ is also of interest because, owing to the small energy release, it could give a good limit on the mass of ν_τ.

The writers are grateful to A.D. Dolgov, A.N. Rozanov, V.D. Khovanskiĭ, and M.A. Shifman for useful discussions.

[1] M. Pearl *et al.*, Phys. Rev. Lett. **35**, 1489 (1975); Phys. Lett. **63B**, 466 (1976).
[2] R. Brandelik *et al.*, Phys. Lett. **73B** 109 (1978).
[3] Ya. I. Azimov, L. L. Frankfurt, and V. A. Khoze, Usp. Fiz. Nauk **124**, 459 (1978) [Sov. Phys. Uspekhi **21**, 225 (1978)].
[4] M. Perl, Nature **275**, 273 (1978) [Russ. Transl. Usp. Fiz. Nauk **129**, 671 (1979)].
[5] G. Flügge, Invited talk at the EPS Conference on High Energy Physics, Geneva, 1979; Preprint DESY 79/37, July, 1979.
[6] J. Kirkby, Invited talk at International Symposium on Lepton and Photon Interactions at High Energies, Batavia, 1979; Preprint SLAC-PUB-2419, October, 1979.
[7] W. Bacino *et al.*, Phys. Rev. Lett. **41**, 13 (1978).
[8] W. Bacino *et al.*, Phys. Rev. Lett. **42**, 749 (1979).
[9] A. D. Dolgov and Ya. B. Zel'dovich, Usp. Fiz. Nauk **130**, 559 (1980) [Rev. Mod. Phys. **53**, 1 (January 1981)].
[10] R. Brandelik *et al.*, Preprint DESY 80/12, February, 1980.
[11] W. Wagner *et al.*, Preprint DESY 79/66, December, 1979.
[12] S. Yamada, Invited talk at International Symposium on Lepton and Photo Interactions at High Energies, Hamburg, 1977.
[13] Y. Dorfan, Preprint SLAC-PUB-2429, November, 1979.
[14] F. Gilman and D. Miller, Phys. Rev. **D17**, 1846 (1978). F. Gilman, Preprint SLAC-PUB-2226, 1978. N. Kawamoto and A. I. Sanda, Preprint DESY 78/14, 1978.
[15] C. S. Lam and T. M. Yan, Phys. Rev. **D16**, 703 (1977).
[16] Particle Data Group, Phys. Lett. 75B, No. 1 (1978).
[17] A. M. Cnops *et al.*, Phys. Rev. Lett. **40**, 144 (1978).
[18] C. Albright and R. Schrock, Phys. Lett. **84B**, 123 (1979).
[19] H. Wachsmuth, Invited Talk at International Symposium on Lepton and Photon Interactions at High Energies, Batavia, 1979.
[20] Ya. I. Azimov, L. L. Frankfurt, and V. A. Khoze, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 373 (1976) [JETP Lett. **24**, 338 (1976)].
[21] D. Meyer, H. Nguen, *et al.*, Phys. Lett. 70B, 469 (1977).
[22] V. I. Konyushko *et al.*, Preprint IFVE (Inst. of High Energy Phys.) 79–117, Serpukhov, 1979.
[23] J. S. Bell and R. Jackiw, Nuovo Cimento **60A**, 47 (1969). S. L. Adler, Phys. Rev. **177**, 2226 (1969).
[24] H. D. Politzer, Phys. Rep. **14C**, 129 (1974); V. B. Berestetskiĭ, Usp. Fiz. Nauk **120**, 439 (1976) [Sov. Phys. Uspekhi **19**, 934 (1976)].

[25] H. Georgi and S. Glashow, Preprint HUTP 79/A027.

[26] Ya. I. Azimov and V. A. Khoze, in book: Neĭtrino-77 (Neutrino 77), Moscow, Nauka 1978, Vol. 2, p. 236. Ya. I. Azimov, V. A. Khoze, and R. Raito, Z. Phys. 2C, 49 (1979).

[27] G. Kane, Preprint SLAC-PUB-2326, May, 1979.

[28] M. A. Shifman, A. I. Vaĭnshteĭn, and V. I. Zakharov, Nucl. Phys. **B147**, 385, 448, 519 (1979).

[29] S. S. Gershteĭn and M. Yu. Khlopov, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 374 (1976) [JETP Lett. **23**, 338 (1976)]; H. Georgi and M. Machacek, Phys. Rev. Lett. **43**, 1639 (1979).

Translated by W. H. Furry