New particle in e^+e^- annihilation: the heavy lepton $\tau^{\pm}$

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A review is presented of experimental data that provide evidence for the existence of a heavy charged lepton $\tau^{\pm}$. The properties of the τ particle extracted from experimental data are compared with theoretical expectations. A summary of necessary further measurements is provided. The possible theoretical significance of the new particle is briefly discussed.

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CONTENTS

1. INTRODUCTION

The study of e^+e^- annihilation has proved to be remarkably fruitful for elementary particle physics. In a brief period, the study of this process revealed an entire family of ψ and χ particles with hidden charm, and also the recently discovered D particles with naked charm (see the reviews[1-4]). All these results are especially interesting in that, taken together, they are equivalent to the experimental discovery of a new species of quark and, thereby, to the final proof that quarks indeed exist.

But it turns out that this is not all. The study of the same process of e^+e^- annihilation has brought to light, and continues to do so, data that ever more clearly indicate the existence of a further new object. All its properties so far investigated indicate that this is a charge lepton with mass ~ 2GeV.[5-12] In the present review, we describe the state and possible development in the investigation of this lepton e^+e^- annihilation.

The "muon riddle" already long ago prompted the question of whether there do not exist in nature still heavier leptons (see, for example, Refs. 13-15). Even models of weak interactions containing an entire family of leptons, have been proposed by analogy with hadrons (for example, Ref. 16). An experimental search for heavy leptons, including one in e^+e^- annihilation (for example, Ref. 17), has also been discussed more than once.

A powerful stimulus for studying and looking for heavy leptons was the appearance of gauge models of the weak interaction of the Weinberg--Salam[18] type, in which the contribution of heavy leptons can help to make the theory renormalizable[19] (see also Ref. 20).[1)] At the present time, heavy leptons are discussed theoretically in connection with just such models. The inclusion in them of additional leptons makes it possible to obtain many interesting phenomena; for example, to introduce a CP violation in the fundamental lepton Lagrangian. Virtually any generalization of the Wein-

[1)] A more detailed discussion of the situation as it developed up to 1972–1974 can be found in reviews.[21,22] References to and a summary of results on searches for heavy leptons in various processes are given in Ref. 23.

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berg--Salam model that increases the symmetry of the interaction at short distances also requires an increase in the number of leptons. However, the question of the correct symmetry group and, hence, also of the number and properties of the leptons remains open from the theoretical point of view. This is hardly surprising if one remembers that the weak interactions are characterized by a scale $E_{cm} \sim G_F^{-1/2} \sim 300$ GeV, so that at present only very low energies, where we are restricted to phenomenology, are accessible.

Experimental searches for and the study of heavy leptons also encounter a number of serious difficulties. Let us mention only the most fundamental ones.

a) The presence in a decay of an undetected neutrino rules out the possibility of studying the mass spectrum of the system of final particles.

b) In the framework of the usual assumptions (see Sec. 2) a short lifetime ($\sim 10^{-13}$ sec) is expected if $M \sim$ 2 GeV. It is then very difficult to observe the track before the decay.

c) At the currently available energies, there are no intense sources of heavy leptons. For example, in contrast to μ and e, which are copiously produced in decays of π and K mesons, heavy leptons are produced only electromagnetically in hadron collisions. In addition, their observation in hadronic reactions and in photoproduction is made very difficult by the background conditions. And in neutrino reactions not all types of leptons can be produced (see below).

d) In the region of lepton masses $M \sim 2$GeV there is an additional (partly psychological) difficulty associated with the production (in the same mass region) of charmed particles having important semi-leptonic decays. Was the confused history of pions and muons really fortuitous?

Because of these and other difficulties, one must use rather indirect methods to look for heavy leptons, and this forces one to make conjectures about the properties of the sought for particles when one is proposing and interpreting experiments. All these difficulties also explain why the very existence of the heavy lepton can still be questioned. In what follows, we shall understand a lepton to be a point particle with spin $\frac{1}{2}$ that is subject only to weak and electromagnetic interactions; however, other variants have also been discussed in the literature (for example, cf. Refs. 24, 25).

Among the proposed variants of heavy leptons, it is convenient to distinguish the three simplest types, although they do not exhaust all possibilities (the terminology is not yet quite established, although it is already widely used by experimentalists).

1) Sequential Heavy Lepton $L^{\pm}$, which has a new lepton number and is associated with a new neutrino.[22] The name reflects the sequence of charged leptons carrying different lepton numbers, $-e$, μ, L. . . . .

2) Ortholeptons $e^{*\pm}$ or $\mu^{*\pm}$, carrying electron or muon number and having the same relation between the lepton number and charge as $e^{\pm}$ or $\mu^{\pm}$ (the name derives from "orthodox"[26]).

3) Paraleptons $E^{\pm}$ or $M^{\pm}$, which have electron or muon number but the "wrong" relationship between the lepton number and the charge (the lepton number of E^+ is the same as that of e^-; the name derives from "paradoxical"[26]).

In principle, ortho- and paraleptons could be produced in neutrino experiments, with characteristic manifestations (apparent violation of lepton number, different threshold effects, etc; cf. Refs. 20, 26, 27). Their absence experimentally leads to bounds on the masses of para- and orthomuons. Under the "standard" assumptions[20,28] concerning the coupling constants and the decay properties (see Sec. 2) the absence of the reaction $\nu_\mu N \to \mu^+$. . . gives $M_{\mu_+} > 8.3$ GeV,[29] and the absence of a threshold in the energy dependence of the usual reaction $\nu_\mu N \to \mu^-$. . . leads to the estimate $M_{\mu *} \gtrsim$ 5 GeV.[30] A study of the energy dependence of muonless neutrino events also leads to restrictions on the masses of ortho- and paramuons (see, for example, Ref. 26). As yet, there are no restrictions on the masses of ortho- and paraelectrons deduced from neutrino data.

In contrast, in e^+e^- annihilation phenomena have already been found (anomalous dileptonic events, anomalous inclusive production of leptons, etc; see Sec. 3) that taken together can be described only as a manifestation of a heavy lepton, which is denoted by $\tau^{\pm}$ (from *νρlτον*, the Greek for "third", i.e., the third charged lepton[31]). The aim of the present review is to describe the current situation with regard to the study of $\tau^{\pm}$. The review is structured as follows.

In Sec. 2, we consider the expected properties of decays of the simplest types of lepton. This makes it possible to formulate the expected manifestations of the $\tau^{\pm}$ lepton in e^+e^- annihilation.

In Sec. 3, wedescribethe existing experimental data and the properties of $\tau^{\pm}$ deduced from them. We also list the evidence for the existence of τ that follows from the characteristics of the reaction $e^+e^- \to$ hadrons with allowance for the production of charmed particles. The main conclusion at present drawn from the experiments is that $\tau^{\pm}$ is apparently a sequential heavy lepton with mass $M \approx 1.9$ GeV, and it belongs in the left-handed charged current together with a massless (new?) neutrino. However, other possibilities still cannot be ruled out (one of them could be that nature is showing us, not a lepton, but a very successful imitation of one).

In Sec. 4, we list the measurements that should be made for further verification of the existence of $\tau^{\pm}$ and its properties.

Finally, in Sec. 5 we briefly describe the theoretical problems that arise and are discussed in connection with the existence of heavy leptons.

2. EXPECTED PROPERTIES OF HEAVY LEPTONS

As we have already explained in the introduction, in an experimental study of heavy leptons one must first make a theoretical hypothesis and then test whether it matches the observed data. In the first place, this applies to the decay properties. Individual decays of leptons have been discussed by many authors (see, for example, Refs. 27, 32). In Refs. 20, 28 the whole complex of decays for the simplest types of lepton was considered for the first time, and this made it possible to find the relative probabilities of individual channels and to establish their dependence on the lepton mass. The assumptions made in Refs. 20, 28 have become "standard" for these types of leptons (for a more recent discussion of the calculations $M\sim 2$ GeV, cf. Refs. 33, 34).

In this section, we consider the decay properties of charged leptons, using the "standard" assumptions concerning their interactions. We shall discuss in more detail the expected properties of $\tau^{\pm}$ with $M\approx 1.9$ GeV and their manifestations in e^+e^- annihilation.

a) Decays of the sequential lepton

The simplest variant is the sequential heavy lepton $L^{\pm}$, which together with a new massless[2)] neutrino ν_L forms a doublet (L^-, ν_L) that interacts with the same intermediate vector bosons and with the same coupling constant as the doublets $(e^-, \nu e)$ and $(\mu^- \nu_\mu)$. Then the partial width of the decay

$$L^- \to \nu_L + X \tag{2.1}$$

reduces to the form

$$\Gamma_X \equiv \Gamma(L^- \to \nu_L + X) = \frac{G^2 M^4}{8\pi} \int_{t_{\min}}^{t_{\max}} dt\, |\mathbf{l}_X| \left[\rho_1^X(q^2)(1+t-2t^2) + \rho_2^X(q^2)(1-t)\right],$$
$$q^2 \equiv m_X^2, \quad t = q^2/M^2; \tag{2.2}$$

where M is the mass of L, $|\mathbf{l}_X|$ is the ν_L momentum in the L^- rest frame. The spectral functions $\rho_i^X(q^2)$ are related to the weak current J_μ^w (for example, see Refs. 20, 28):

$$\sum \langle 0 | J_\mu^{w+}(0) | X\rangle \langle X | J_\nu^w(0) | 0\rangle (2\pi)^3 \delta^{(4)}(q-p_X) = \rho_1^X(q^2)(q_\mu q_\nu - q^2 g_{\mu\nu}) + \rho_2^X(q^2) q_\mu q_\nu. \tag{2.3}$$

The summation is over all states of the system X for fixed mass m_X. Obviously, the contributions of the V and A currents enter ρ_i^X without interference:

$$\rho_i^X = \rho_{iV}^X + \rho_{iA}^X.$$

The following decays are possible

$$L^- \to \nu_L + e^- + \bar{\nu}_e, \tag{2.4a}$$
$$L^- \to \nu_L + \mu^- + \bar{\nu}_\mu, \tag{2.4b}$$
$$L^- \to \nu_L + \pi^-, \tag{2.4c}$$
$$L^- \to \nu_L + K^-, \tag{2.4d}$$
$$L^- \to \nu_L + \rho^-, \tag{2.4e}$$
$$L^- \to \nu_L + K^{*-}, \tag{2.4f}$$
$$L^- \to \nu_L + A_1^-, \tag{2.4g}$$
$$L^- \to \nu_L + Q^-, \tag{2.4h}$$
$$L^- \to \nu_L + \text{hadron continuum}, \tag{2.4i}$$

where the hadron continuum stands for the multihadronic system outside the listed resonances.

For the purely leptonic decays (2.4a) and (2.4b), neglecting m_e/M and m_μ/M[3)] we obtain $\rho_1^L = 1/6\pi^2$, $\rho_2^L = 0$, which gives the well-known expression

$$\Gamma_e = \Gamma_\mu = \Gamma^{(0)} \equiv \frac{G^2 M^5}{192\pi^3} \approx 3.46\cdot 10^{10} M^5 \ \text{sec}^{-1}\,\text{GeV}^{-5} \tag{2.5}$$

For the decays (2.4c) and (2.4d) we have

$$\rho_1^{\pi,K} = 0, \quad \rho_2^{\pi,K}(q^2) = (g^{\pi,K})^2 \delta(q^2 - m_{\pi,K}^2),$$
$$g^\pi = f_\pi \cos\theta_C, \quad g^K = f_K \sin\theta_C, \quad f_K \approx f_\pi, \tag{2.6}$$

where θ_C is the Cabibbo angle. We assume $\sin^2\theta_C \approx 0.055$, which does not contradict the recent evaluation.[38] From the data on the decays $\pi(K) \to \mu\nu$ we can extract the values

$$g^\pi \approx 0.92 m_\pi, \quad g^K \approx 0.25 m_\pi. \tag{2.7}$$

Substituting (2.6) in (2.2) and comparing with (2.5), we find

$$\frac{\Gamma_{\pi,K}}{\Gamma^{(0)}} = \left(\frac{4}{3}\pi \frac{g^{\pi,K}}{m_{\pi,K}}\right)^2 F_0\left(\frac{m_{\pi,K}^2}{M^2}\right), \tag{2.8}$$

where $F_0(x) = (27/4)x(1-x)^2$.

For the decays (2.4e)-(2.4h) in the approximation of resonances of zero width we have

$$\rho_2^X = 0, \quad \rho_1^X(q^2) = (g_X)^2 \delta(q^2 - m_X^2),$$
$$g_{\rho, A_1} = \sqrt{2}\frac{m_{\rho, A_1}}{\gamma_{\rho, A_1}} \cos\theta_C, \quad g_{K^*, Q} = \sqrt{2}\frac{m_{K^*, Q}}{\gamma_{K^*, Q}} \sin\theta_C, \tag{2.9}$$

so that, for example, for (2.4e)

$$\frac{\Gamma_\rho}{\Gamma^{(0)}} = 3\left(\frac{\pi g_\rho}{m_\rho}\right)^2 F_1\left(\frac{m_\rho^2}{M^2}\right), \tag{2.10}$$

where $F_1(x) = 4x(1-x)^2(1+2x)$.

The usual hypothesis of a conserved vector current (CVC), which relates the charged weak current to the electromagnetic current, enables one[23] to obtain from the $e^+e^- \to \rho^0 \to \pi^+\pi^-$ data[23]

$$\frac{\gamma_\rho^2}{4\pi} \approx 2.1. \tag{2.11}$$

The approach used to estimate the decays (2.4f)-(2.4h) is less reliable. The sum rule which expresses asymptotic $SU(3)$ symmetry for vector currents[39] gives in

[2)] We restrict ourselves here for simplicity to zero mass of ν_L and $V-A$ current, which does not contradict the experimental data for τ (see Sec. 3). The case of nonzero ν_L mass and arbitrary V, A structure of the current is considered in Refs. 20, 35. Note that cosmological arguments lead to stringent bounds on the mass of a stable neutrino[36] and on the number of species of such neutrinos.[37] According to current ideas, masses 10 eV $\lesssim m\nu_L \lesssim$ 2 GeV are ruled out. The current state of the question was discussed in the report by Ya. B. Zel'dovich, M. I. Vysotskiĭ, and A. D. Dolgov at the "Neutrino—77" conference.

[3)] We restrict ourselves to the region $M<1$ GeV since analysis of the data indicates that heavy charged leptons, at least sequential heavy leptons, with $M\lesssim 1$ GeV do not exist.[22]

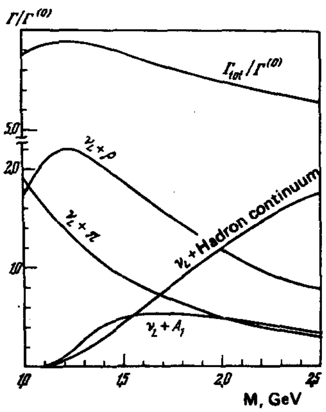

FIG. 1. Ratios of the partial widths and total width of decay of the sequential heavy lepton to the width of the lepton decay $\Gamma^{(0)}$ for different M.

the case of saturation by resonances

$$\frac{\gamma_{K^*}}{m_{K^*}}=\frac{\gamma_\rho}{m_\rho}. \tag{2.12}$$

From the sum rules that express asymptotic chiral symmetry (Weinberg sum rules[40]) in the case of saturation by resonances we obtain

$$\frac{\gamma_{A_1}}{m_{A_1}^2}=\frac{\gamma_\rho}{m_\rho^2}. \tag{2.13}$$

Equation (2.13) follows from the second Weinberg sum rule. The first sum rule gives numerically the same results. One can estimate γ_Q similarly. The use of all these relations gives for $\Gamma_X/\Gamma^{(0)}$ in the decays (2.4c), (2.4e), and (2.4g) the values shown in Fig. 1. The widths of the decays (2.4d), (2.4f), and (2.4h) are small basically because $\sin^2\theta_C$ is small. For example, $\Gamma_K/\Gamma^{(0)}<0.09$ for all M, and for K^* and Q the upper limits are even smaller. The strangeness changing decays (2.4i) are also small, and we ignore them.

For strangeness-conserving decay (2.4i) we obtain, using the CVC hypothesis,

$$\rho_{2V}^c=0,$$
$$\rho_{1V}^c(q^2)=\frac{1}{6\pi^2}R^1(q^2)\,\theta(q^2-m_V^2), \tag{2.14}$$

where $R^1(q^2)$ is the contribution of the isovector final state to $R(s)=\sigma(e^+e^-\to\text{hadrons})/\sigma(e^+e^-\to\mu^+\mu^-)$ for $s=q^2$. The θ function is introduced in order to achieve separation from the ρ resonance; to this end, one can choose $m_V\approx 1$ GeV. The data on e^+e^- annihilation for $\sqrt{s}>1$ GeV do not seem to contradict the value $R^1(q^2)\approx 3/2$ expected in the quark model.

Concerning the contribution of the axial current, nothing is yet known. Bearing in mind asymptotic chiral symmetry, we can set

$$\rho_{2A}^c=\rho_{2V}^c=0,\quad \rho_{1A}^c(q^2)=\frac{1}{6\pi^2}R^1(q^2)\,\theta(q^2-m_A^2). \tag{2.15}$$

Since the masses of the axial resonances are greater than those of the vector resonances, it is natural to take $m_A>m_V$. We choose $m_A=1.3$ GeV.

The results of such a calculation are shown in Fig. 1. Taken together, they enable us to find the relative probabilities of the decay channels (2.4). It must however be borne in mind that each of the relative probabilities is sensitive to the assumptions made about each channel, in contrast to the ratios of the partial widths to $\Gamma^{(0)}$. The extent to which the various quantities depend on the assumptions about the hadron continuum are discussed in Ref. 34.

It is interesting that the total width of the sequential heavy lepton in the entire range of masses $1\le M\le 2.5$ GeV is close to $5\Gamma^{(0)}$. Such a value corresponds to naive expectations. From the point of view of quarks, $L^\pm$ has five decay channels: the two leptonic (2.4a) and (2.4b) and the three (with allowance for three colors) quark decay channels

$$L^-\to\nu_L+\bar{u}+d' \tag{2.16}$$

(as usual, $d'=d\cos\theta_C+s\sin\theta_C$). If the masses of the u, d, and s quarks and the leptons e and μ are ignored, all the channels are equally probable, and this gives $\Gamma_{\text{tot}}\approx 5\Gamma^{(0)}$, $B_e=B_\mu=\Gamma^{(0)}/\Gamma_{\text{tot}}\approx 0.2$.

The quark hypothesis was not used in the calculations. Indeed, the value $R^1(q^2)\approx 3/2$ can be regarded as "experimental". The other assumptions (CVC, sum rules, experimental values of g^π, g^K, γ_ρ, θ_C) are not related explicitly to quarks at all, and even less to color. Therefore, an optimist can regard the relation $\Gamma_{\text{tot}}\sim 5\Gamma^{(0)}$ for sequential heavy leptons as one further argument in favor of the existence of colored quarks.

b) The case of very large mass

With increasing mass of the sequential heavy lepton, additional decay channels become possible. These could be channels of the type (2.4a) and (2.4b) with the formation of other lepton pairs. But an even greater contribution is expected from the production of charmed particles, which could become appreciable already at $M\sim 3$ GeV. It corresponds to the decay

$$L^-\to\nu_L+\bar{c}+s', \tag{2.17}$$

from which one expects a contribution $\sim 3\Gamma^{(0)}$, as from the decay (2.16). Such contributions reduce the probability of the leptonic decay (2.4a). If the additional contributions are restricted to the c quark and τ lepton, then the probability of the decay (2.4a) is reduced from ~20% to ~11%.

In order to get an idea how charmed particles come into the picture, we consider the decays

$$L^-\to\nu_L+F^-, \tag{2.18a}$$
$$L^-\to\nu_L+F^{*-}, \tag{2.18b}$$

where F^- and F^* are a pseudoscalar and vector meson of the type $(\bar{c}s)$. These decays are analogous to the decays (2.4c) and (2.4e) and are described by the same equations (2.6), (2.8) and (2.9), (2.10). To estimate f_F and γ_{F^*}, we use a naive quark model. For pseudoscalar and vector mesons P and V consisting of quarks a and b, we obtain

$$f_P^2\sim(m_a+m_b)^{-1}|\psi_{ab}(0)|^2,\quad \gamma_V^{-2}\sim(m_a+m_b)^{-3}|\psi_{ab}(0)|^2.$$

Data on the decay widths of ρ^0, ω, φ, J/ψ into e^+e^- indicate that $|\psi(0)|^2 \sim \mu^2$, where μ is the reduced mass. Taking

$$m_u \approx m_d \approx 300 \text{ MeV}, \quad m_s \approx 450 \text{MeV}, \quad m_c \approx 1.5 \text{ GeV},$$

we obtain

$$\frac{f_F^2}{f_\pi^2} \approx 1.6, \quad \frac{\gamma_{F*}^2}{\gamma_\rho^2} \approx 6.5. \tag{2.19}$$

The use of such estimates can be justified by the fact that for strange mesons they give f_K/f_π in good agreement with the experiments and γ_{K*}/γ_ρ in agreement with the relation (2.12).

Substitution of the values (2.19) in expressions of the type (2.8) and (2.10) shows that the decays (2.18) give for all M a very small contribution (we assume $m_F \approx$ 2 GeV):

$$\frac{\Gamma_F}{\Gamma^{(0)}} < 0.11, \quad \frac{\Gamma_{F*}}{\Gamma^{(0)}} < 0.30.$$

This may mean that, in contrast to ordinary quarks, saturation of the contribution of charmed quarks can possibly occur on account of the large number of states; for example, on account of the $\overline{D}K$ spectrum, which is possible only for $M > m_D + m_K \approx 2360$ MeV.

c) Other types of lepton

Decays of the type (2.4) must exist for all leptons. But various types of lepton have their own specific features.

1) Let us consider a paralepton (to be specific, the paramuon M^-). Then the decay (2.4b) is replaced by

$$M^- \to \mu^- \bar{\nu}_\mu \bar{\nu}_\mu \tag{2.20}$$

and $\Gamma_\mu^{(M)} = 2\Gamma^{(0)}$,[20] so that single muons appear in decays of M twice as often as electrons. If there are no decays of M^- with production of some new heavy neutrino M^0, then with allowance for the contribution of ordinary quarks

$$\Gamma_{\text{tot}} \approx 6\Gamma^{(0)}, \quad B_e \approx 1/6, \quad B_\mu \approx 1/3.$$

Another characteristic feature is that production of paramuons in neutrino experiments would lead to apparent nonconservation of lepton number: $\nu_\mu \to M^+ \to \mu^+$. As we have already said in the introduction, the neutrino data rule out the possibility that τ is a paramuon. A similar elimination of the paraelectron is at present impossible because of the absence of good ν_e beams.

2) For ortholeptons there is in principle the characteristic possibility of a radiative decay of the type

$$e^* \to e\gamma. \tag{2.21}$$

This is a magnetic dipole transition, and in renormalizable electrodynamics it cannot take place purely electromagnetically. However, it is possible through the combined influence of electromagnetic and weak interaction already in the first order in G. The probability of the decay (2.21) depends very strongly on the nature of the interaction.

For example, if there are no right-handed currents in the theory, and e^* forms a left-handed charged current with a heavy neutral lepton N, which is mixed with ν_e, then (see, for example, Refs. 41, 42)

$$\frac{\Gamma(e^* \to e\gamma)}{\Gamma(e^* \to \nu_e \mu \bar{\nu}_\mu)} \approx \frac{3}{32} \frac{\alpha}{\pi} \left(\frac{m_N^2}{m_W^2}\right)^2 \cos^2\theta, \tag{2.22}$$

where θ is the mixing angle of N and ν_e, and m_W is the mass of the intermediate vector boson. Note that both widths here contain $\sin^2\theta$, i.e., the effective coupling constant is $\sim G_F \sin\theta$.

The presence of right-handed currents may appreciably enhance the radiative decay. For example, in a vectorlike model for $m_N \ll m_W$[43,44]

$$\frac{\Gamma(e^* \to e\gamma)}{\Gamma(e^* \to \nu_e e \bar{\nu}_e)} \approx \frac{6\alpha}{\pi} \left(\frac{m_N}{m_{e*}}\right)^2. \tag{2.23}$$

It is easy to see that (2.22) and (2.23) may differ by many orders of magnitude. It is therefore clear that the discovery and investigation of radiative decays of leptons could give important information about the nature of the weak interaction. Another characteristic feature of ortholeptons is the possibility of decay due to the weak neutral current. The widths of such decays are also strongly model-dependent.

3) Hitherto, we have used the simplest assumptions about the structure of the weak interactions. Nature may be more complicated. There are models containing several charged or neutral intermediate vector bosons, leptons can be mixed, and so forth. Moreover, the effective coupling constants in the various decay channels may be different, and some channels may even be forbidden.

A discussion of decays in these cases requires the use of a definite model, and goes beyond the scope of the present review.

d) Expected properties of $\tau^\pm$

To conclude this section, we give a list of the expected properties of the τ leptons and their manifestations in e^+e^- annihilation for the case when τ is a sequential heavy lepton with mass $M \approx 1.9$ GeV. This subsection is intended for comparison with the experimental data (see Sec. 3).

1) The calculation described above gives for the τ lifetime

$$T_\tau \approx 2.1 \cdot 10^{-13} \text{ sec}. \tag{2.24}$$

The relative probabilities B_X of the various decay channels are given in Table I. Recall that we have restricted ourselves to the $V - A$ current variant and the case of a massless neutrino ν_L. Transition to the $V + A$ variant does not change the probabilities. If the ν_L mass does not exceed a few hundred MeV (see Sec. 3), then it too has little influence on Table I.

2) The process $e^+e^- \to \tau^+\tau^-$ with subsequent leptonic decays (2.4a) and (2.4b) generates the so-called anomal-

TABLE I. Expected relative probabilities of different decay channels of $\tau^{\pm}$ for $M_\tau = 1.9$ GeV.

Decay channel	B, %	Decay channel	B, %	Decay channel	B, %
$e^{\pm}+\nu_\tau+\nu_e$	18	$\rho^{\pm}+\nu_\tau$	23	ν_τ + hadron continuum	19
$\mu^{\pm}+\nu_\tau+\nu_\mu$	18	$K^{*\pm}+\nu_\tau$	1.3		
$\pi^{\pm}+\nu_\tau$	10	$A_1^{\pm}+\nu_\tau$	9	$\chi^{\pm}$ + neutrals	82
$K^{\pm}+\nu_\tau$	0.7	$Q^{\pm}+\nu_\tau$	0.4	$h^{\pm}$ + neutrals	45

ous $e\mu$ events:

$$e^+e^- \to e^{\pm}\mu^{\mp} + \text{"nothing"}. \tag{2.25}$$

Similarly, anomalous ee and $\mu\mu$ events must occur. Their energy dependence is determined by single-photon annihilation:

$$\sigma(e^+e^- \to \tau^+\tau^-) = \frac{v}{2}(3-v^2)\sigma(e^+e^- \to \mu^+\mu^-), \tag{2.26}$$
$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{14}{3}\pi\alpha^2/s = (86.8\ \text{nb}\cdot\text{GeV}^2)/s, \quad s \gg m_\mu^2,$$

where v is the velocity of the τ, and $\sqrt{s}$ is the total cms energy.

3) The yield of K mesons in $\tau^{\pm}$ decays is small and hence also in e^+e^- annihilation into $\tau^+\tau^-$. This is due to the small value of θ_C (in strangeness-changing decays) and the low production of $K\overline{K}$ pairs in the continuum (in particular, because of the phase volume).

4) The fraction of decays of the type

$$\tau^- \to \chi^- + \text{neutrals}, \tag{2.27}$$

where χ is any charged particle, is large. This applies to all the decays (2.4a)-(2.4e), two thirds of the decays (2.4f), half of the decays (2.4g), and one third of the decays (2.4h). The number of charged particles in the continuum depends on the detailed properties of the continuum. It appears reasonable to assume as an estimate that one third of the decays (2.4i) contains one charged particle. Then $B_\chi \approx 82\%$, $B_h \approx 45\%$ (h is a charged hadron).

5) Because of the decays (2.27), the production of $e^+e^- \to \tau^+\tau^-$ makes a contribution basically to two-prong events. An appreciable fraction in them are events of the type e_χ and μ_χ, i.e., for example,

$$e^+e^- \to e^{\pm}\chi^{\mp} \mp \text{neutrals}, \tag{2.28}$$

which has characteristic experimental properties. Events of the $e\mu$, e_χ, and μ_χ type are a convenient way of detecting heavy leptons with masses 1-2.5 GeV. At even higher masses, the fraction of events of this type may decrease.

6) Making assumptions about the properties of the lepton, one can calculate the spectra of secondary particles produced in the reaction $e^+e^- \to \tau^+\tau^-$. Detailed calculations for a general structure of the leptonic current and arbitrary mass of the new neutrino have been made for secondary leptons (for example, cf. Refs. 28, 33–35, 45–52) as well as for secondary hadrons[28,35,52] The spectra have a number of specific kinematic features, which in principle enables one to compare them with the experimental data (if they have sufficiently good statistics) and reliably establish the mass of ν_τ, and also draw conclusions about the structure of the $(\bar{\tau}, \nu_\tau)$ current, the vertex $\tau^+\tau^-\gamma$, and other characteristics.[34,35,49-52]

In Refs. 34, 35, manifestations of heavy leptons in different inclusive characteristics of e^+e^- annihilation and possibilities for the best separation of the contributions to these quantities are also discussed in detail.

3. EXISTING EXPERIMENTAL DATA ON $\tau^{\pm}$

In the preceding section, we have considered what properties heavy leptons could have and the experiments in which one could hope to "observe" them. These experiments (at least, the simplest of them) have in fact been performed, and it was they that indicated the existence of the new $\tau^{\pm}$ lepton. In this section, we shall describe more concretely the processes of e^+e^- annihilation in which searches were made for heavy leptons and what the results of these searches were. In particular, we shall indicate why other simple hypotheses (besides the leptonic one) cannot completely describe the so-called anomalous events. In the final part of this section we shall describe how the contributions of the τ leptons and charmed particles complement one another in the observed properties of the process $e^+e^- \to$ hadrons. This approach to the study of $\tau^{\pm}$ is more indirect since one must make a number of assumptions (as yet not fully verified) about the contributions of charmed and ordinary hadrons. Nevertheless, it reveals an important role of τ in a reasonable and consistent description of various aspects of e^+e^- annihilation and gives independent arguments for the existence of τ.

It should be borne in mind that the experimental situation described here is only an instantaneous photograph of a picture that is steadily being filled in.

a) Experimental evidence for production of $\tau^+\tau^-$ pairs

Despite the absence of serious theoretical arguments for the existence of charged heavy leptons, searches for them from 1970 onward became standard on facilities with colliding e^+e^- beams with maximal available energies. One of the reasons for this was the existence of an exceptionally sharp trigger for detection of these objects namely the reaction

$$e^+e^- \to e^{\pm} + \mu^{\pm} + \text{"nothing"} \tag{3.1}$$

("nothing" corresponds to undetectable neutrals), and to a considerable extent another was the optimism of the experimentalists who made these searches systematically for a number of years.

A series of measurements of the reaction (3.1) with ADONE (Frascati, Italy)[53] gave the lower bound $M > 1$ GeV on the mass of a charged heavy lepton.

Heavy leptons with masses $M \lesssim 2$ GeV were also sought at the Cambridge Electron Accelerator in the United States.[54,55] However, it was in this case impossible to obtain reliable results because of the low statistics.

A collaboration (led by M. Perl and G. Feldman) between the Stanford Linear Accelerator Center (SLAC) and the Lawrence Berkeley Laboratory (LBL) on SPEAR (colliding e^+e^- beams) began a search for heavy leptons soon after operation of SPEAR began.[56] The first results of the measurements of this group were not encouraging,[55] but already by June 1975 the SLAC-LBL group detected 24 events at total energy $\sqrt{s}=4.8$ GeV in the center of mass system of the initial particles corresponding to the reaction (3.1) (the expected background from known mechanisms was 4-6 events).

Here and in what follows, such events that cannot be explained by any background mechanisms will be called anomalous. At the present time, the statistics of anomalous $e^\pm\mu^\mp$ events is steadily increasing, and they have been observed not only by the SLAC-LBL group but also by the PLUTO and DASP groups using DORIS (Hamburg, West Germany[4)]).

In accordance with the theoretical expectations for the $\tau^\pm$ lepton (see section 2) it was also looked for by analyzing the inclusive production of anomalous leptons in the reactions

$$e^+e^- \to e^\pm + \chi^\mp + \text{photons} \quad (3.2)$$

$$e^+e^- \to \mu^\pm + \chi^\mp + \text{photons} \quad (3.3)$$

here, $\chi^\mp$ is a charged lepton or hadron. A detailed exposition of the criteria for selecting events used in studying the reactions (3.1)-(3.3), the methods for eliminating possible standard explanations for the observed lepton yields, and also the procedures for calculating the various backgrounds can be found in the original papers. We here only mention that to reduce various kinds of background mechanisms kinematic cutoffs were introduced in all experiments looking for anomalous leptonic events: a) with respect to the lepton momenta $p_{e,\mu}>p_{\text{cut}}^{e,\mu}$ (for better identification of the muons and/or electrons); b) with respect to the coplanarity angles between the charged tracks, $\theta_{\text{copl}}>\theta_{\text{copl}}^0$, and with respect to the square of the mass missing in the system $\mu^\pm(e^\pm)\chi^\mp$; $m^2>m_0^2$ (to reduce the contributions from standard processes of quantum electrodynamics). For various ongoing experiments, p_{cut}, θ_{copl}^0, and m_0^2 correspond to the values $p_{\text{cut}}^\mu=0.65-1.05$ GeV, $p_{\text{cut}}^e=0.1-0.65$ GeV, $\theta_{\text{copl}}^0=10°-20°$, $m_0^2=0.8-2.7$ GeV^2 (depending on the detector and the values of $\sqrt{s}$). Of course, the price to be paid for all these cutoffs is a lowering of the experimental statistics. Below, we list the data on anomalous events corresponding basically to the situation at the end of June 1977.

1) *Anomalous $e\mu$ Events*. 1a) Data obtained by means of the detector MARK-I of the SLAC-LBL group.[5,6,8,12,60,61] In the energy range $3.8\leqslant\sqrt{s}\leqslant7.8$ GeV, 190 such events have been accumulated (the expected background is 46). The cross sections for the production of anomalous $e^\pm\mu^\mp$ and the distributions with respect to the momenta of the leptons and the angle between them have been measured. An important characteristic of experiments with anomalous leptons, which determines their reliability, is the quantity $P_{h\to\mu}$ ($P_{h\to e}$), the probability that a hadron produced in annihilation could be identified as a muon (electron). In experiments using the magnetic detector MARK-I, the values of $P_{h\to\mu}$ and $P_{h\to e}$ averaged over the momenta are fairly large:

$$P_{h\to\mu}=19.8\pm0.7\%, \quad P_{h\to e}=18.3\pm0.7\%.$$

1b) Data obtained by the SLAC-LBL group using the muon tower.[31,61] In January 1975, the SLAC-LBL group began experiments with a special muon detector, the so-called muon tower, which augments the main magnetic detector MARK-I.[62] It considerably improves the identification of muons ($P_{h\to\mu}\approx3.3\%$[31]) and reduces the background at the price of a considerable reduction in the statistics.

By summer 1976, the tower had identified 13 $e\mu$ events with a background of 0.53 event.[31]

1c) Data obtained by means of the magnetic detector PLUTO.[10,63] Enthusiasts for the heavy lepton obtained important support from the experimentalists of the PLUTO group, who found 23 anomalous $e\mu$ events (expected background 2 ± 0.5 events) at energies $4\leqslant\sqrt{s}\leqslant5$ GeV. An important feature of these data is the much more favorable background situation:

with large solid angle and high detection efficiency for all particles, including photons. The measured yield of anomalous events and the distributions of the leptons with respect to momenta and angles agree well with the data of the SLAC-LBL group.

2) *Anomalous $\mu^\pm\chi^\mp$ and $e^\pm\chi^\mp$ Events*. 2a) Data obtained by means of the magnetic spectrometer of the MPP group (Maryland-Princeton-Pavia) on SPEAR.[64] This group discovered for the first time 13 events corresponding to the reaction (3.3) at $\sqrt{s}=4.8$ GeV. The yields of anomalous leptons were in good agreement with those expected for a sequential heavy lepton.[65,66] However, there are at present doubts (for example, Ref. 62) that the estimates given in Ref. 64 of the expected background are much too low.

2b) Data on anomalous $\mu^\pm\chi^\mp$ events obtained using the muon tower.[7,62] This experiment, in three energy ranges, $\sqrt{s}=3.9-4.3$ GeV, 4.3-4.8 GeV, 5.8-7.8 GeV, has revealed a clear signal corresponding to the reaction (3.3). Altogether, 136.9 ± 28.8 such events have been found (mainly in the region of maximal energies). The characteristics of the $\mu^\pm\chi^\mp$ events agree well with the hypothesis of a heavy lepton.

2c) Data on anomalous events obtained by the PLUTO group.[9,63] In this experiment, good statistics have been accumulated in observing the reaction (3.3) in the energy range $4.0\leqslant\sqrt{s}\leqslant5.0$ GeV (273 events at a background of 62 events). The data of Refs. 9,63 agree well with the results of the SLAC-LBL group and the hypothesis of the $\tau^\pm$ lepton.

2d) Data on anomalous $e^\pm\chi^\mp$ events obtained by means of the detector DASP.[11,67] In the energy range $3.99\leqslant\sqrt{s}\leqslant5.2$ GeV with $p_{\text{cut}}^e=0.2$ GeV there have been found

[4)]The detector MARK-I of the SLAC-LBL group is described in Ref. 58. The detectors of PLUTO and DASP are described, for example, in Ref. 59.

60 events corresponding to the reaction (3.2). Of them, 37 (at expected background 8.5 ± 2 events) were photonless. The event yields and the distributions with respect to the electron momenta agree well with the τ hypothesis.

2e) By means of the detector MARK-I, augmented with a special system of lead glass counters (LGW for lead glass wall)) for reliable identification of electrons and photons ($P_{h\to e} = 2 \pm 0.5\%$ at $p^e_{\text{cut}} = 0.4$ GeV/c) anomalous $e^{\pm}\chi^{\mp}$ events have been studied for different numbers of final photons.[12] The measurements were made in three energy ranges: $\sqrt{s} = 4.1$–4.2 GeV, 4.4–5.8 GeV, 6.4–7.4 GeV. A charged $\chi^{\pm}$ track was identified as $\mu^{\pm}$ or as a hadron $h^{\pm}$, which made it possible to compare the relative yields of $e^{\pm}\mu^{\mp}$ and $e^{\pm}h^{\mp}$ events. There were found 31 eh events (at background of 12.1 events) and 21 $e\mu$ events (background 0.4 events). The energy spectra of the leptons and hadrons were measured, together with the θ_{coll} distributions.

3. *Anomalous* $\mu^+\mu^-$ and e^+e^- *Events*. 3a) The SLAC–LBL group has investigated anomalous e^+e^- and $\mu^+\mu^-$ events in the energy range $3.9 \leq \sqrt{s} \leq 7.8$ GeV.[68] The existence of such events has been reliably established. The cross section for their production agrees with the cross section for $e\mu$ events within the framework of the hypothesis of a sequential lepton or ortholepton τ:

$$\frac{\sigma_{ee}}{\sigma_{e\mu}} = 0.52 \pm 0.10 \left(\begin{smallmatrix}+0.16\\-0.19\end{smallmatrix}\right), \quad \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = 0.63 \pm 0.10 (\pm 0.19).$$

In brackets, the systematic error is estimated. The momentum spectra and the distributions with respect to $\cos\theta_{\text{coll}}$ also do not contradict the τ hypothesis.

3b) The PLUTO group have also discovered anomalous $\mu^+\mu^-$ events.[10] For $4.0 \leq \sqrt{s} \leq 5.0$ GeV, they have found six events , and this agrees with the expectations for τ.

b) Basic properties of the experimental data and their correspondence to the τ lepton hypothesis

1) The apparent nonconservation of leptonic quantum numbers in the $e\mu$ events indicates that weak interactions participate at some stage of the process.

2) Two features of the data immediately indicate the production and decay of pairs of new particles as the source of these events. One of them is the existence of a clear threshold with respect to the energy $\sqrt{s}$: the $e\mu$ events are not observed at all for $\sqrt{s} \leq 3.6$ GeV.[8,10,60] (The same threshold is seen for $\mu\chi$ and $e\chi$ events.[9,11]) The other is the nature of the distributions with respect to the collinearity angle ($\cos\theta_{\text{coll}} = -\mathbf{p}_e\mathbf{p}_\mu/|\mathbf{p}_e||\mathbf{p}_\mu|$). The data clearly show that with increasing $\sqrt{s}$ the e and μ tracks become evermore collinear, as must be in the case of production and subsequent decay of a pair of particles with fixed mass. Figure 2 shows the distribution of $e\mu$ events with respect to $\cos\theta_{\text{coll}}$ measured by the SLAC–LBL group.[6,8] For comparison, we give curves corresponding to a pair of heavy leptons $\tau^+\tau^-$ for $M = 1.9$ GeV, $m_{\nu_\tau} = 0$, and $V-A$ decay vertex.

The energy dependence of the observed cross sections of the anomalous events (Fig. 3) agrees with the expected cross section for the production of a pair of point

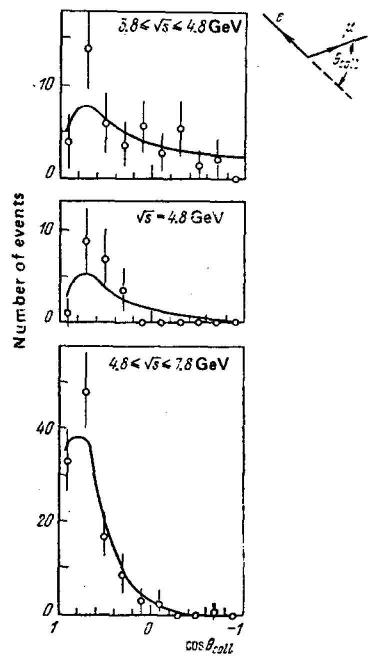

FIG. 2. Distribution of anomalous $e\mu$ events with respect to $\cos\theta_{\text{coll}}$ in three different ranges of the energy $\sqrt{s}$. The continuous curve corresponds to the expectations for τ with $M = 1.9$ GeV for $V-A$ current structure and $m_{\nu_\tau} = 0$.

fermions. It is evident that the presence of a form factor $F(s) \sim 1/s$ in the photon vertex is precluded (Fig. 3a).[8]

3) An important error in the identification of a $\tau^+\tau^-$ pair as the source of anomalous $e^{\pm}\mu^{\mp}$ events could be due to the fact that these events arise from processes of the type

$$e^+e^- \to e^{\pm} + \mu^{\mp} + (\text{hadrons or/and photons}), \tag{3.4}$$

when the accompanying particles avoid detection for some reason or another. Events of the type (3.4) can arise from semileptonic decays of pairs of the recently discovered charmed hadrons h_c, for example, processes of the form

$$\begin{array}{l} e^+ + e^- \to h_c^+ + h_c^- \\ \quad \left| \quad \ \ \llcorner\!\!\to \mu^-\tilde{\nu}_\mu + \text{hadrons}, \ \gamma \right. \\ \quad \llcorner\!\!\to e^+\nu_e + \text{hadrons}, \ \gamma \end{array} \tag{3.5}$$

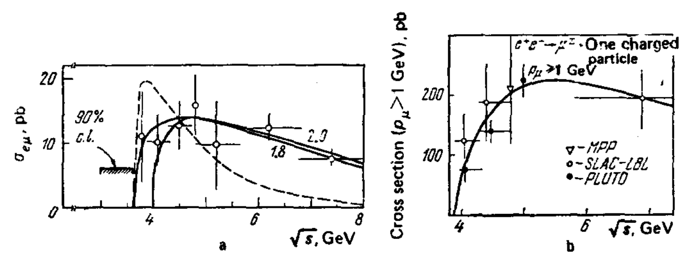

FIG. 3. a) Energy dependence of observed cross section $\sigma_{e\mu}$ for production of anomalous $e\mu$ pairs. (The continuous curves correspond to the expectations for the $\tau^{\pm}$ lepton (for $m_{\nu_\tau} = 0$ and $V-A$ current structure) with $M = 1.8$ and $M = 2$ GeV; the dashed curve corresponds to the case when the $\tau^+\tau^-\gamma$ vertex contains a form factor $F_\tau(s) \sim 1/s$. In the region $3.0 \leq \sqrt{s} \leq 3.6$ GeV, no $e\mu$ events are observed (before subtraction of the background); here, an upper limit is given for $\sigma_{e\mu}$); b) energy dependence of the cross section for the production of anomalous $\mu^{\pm}\chi^{\mp}$ pairs; the curve corresponds to the expectations for $\tau^{\pm}$ (with $M = 1.9$ GeV, $m_{\nu_\tau} = 0$, and for $V-A$ current structure). The data of the SLAC–LBL and MPP groups have been recalculated[11] to take into account the difference between the conditions of observation as compared with the PLUTO group).

One of the arguments against charmed hadrons as the main source of $e\mu$ events is that the yield of anomalous $e\mu$ is not apparently correlated with the structures in the $e^+e^- \to$ hadrons cross section,[60] whereas the yield of charmed particles does manifest such a correlation. Even more important is that, as detailed analysis made by the SLAC–LBL group[6,31] and especially the PLUTO group[10] (whose detector has larger solid angles and higher efficiency of photon detection) shows, the observed number of events of the type (3.4) with accompanying particles in different topologies is too small to explain the $e\mu$ events and the number agrees with the background.

Undetected hadrons in (3.4) could, for example, be K_L^0 from decays of charmed D mesons. Experimentally however the production of $e^\pm\mu^\mp$ pairs[6,10] (and also e^+e^- and $\mu^+\mu^-$ pairs[31]) accompanied by K_S^0 is very small. Under the natural assumption that the yields of K_S^0 and K_L^0 are the same in processes of the type (3.5), this rules out such a mechanism as the main source of $e\mu$ events. According to the present data,[6,10] not more than 9% of the $e\mu$ events can be explained by such a scheme; the contribution of events containing π^0 or η must be even smaller.[10]

Thus, the missing energy and momentum in the majority of the observed $e\mu$ events are carried away exclusively by undetected objects of the type of neutrinos (neutrons are rejected as the main possible carriers of the missing energy by an analysis of the spectra of the anomalous leptons; see below), which agrees well with the hypothesis of the τ lepton.

4) The data as a whole do not agree with the hypothesis that the particles generating the anomalous events have spin 0 or 1.

For example, Fig. 4 shows the momentum distributions in $e\mu$ events.[8] Use of the variable $r=(p_l-p_{\rm cut}^l)/(p_l^{\max}-p_{\rm cut}^l)$, where $p_l^{\max}(s)$ is the maximal kinematically possible momentum of the secondary lepton, and $p_{\rm cut}^l=0.65$ GeV, $0\leqslant r\leqslant 1$, here makes it possible to combine the results of measurements at different $\sqrt{s}$. The spectrum does not agree with the hypothesis of a two-particle leptonic decay of scalar[5)] or vector particles with or without spin effects, but it does agree with a three-particle decay of $\tau^\pm$. Note that the leptonic spectra in the reactions (3.1)–(3.3) agree with one another (i.e., do not depend on the final state). This is a further argument for a common source of all three reactions.

A three-particle decay of point scalar particles $\varphi^\pm$ is also ruled out; for suppose that the source of the anomalous events is the process $e^+e^-\to\varphi^+\varphi^-$. Since the cross section

$$\sigma(e^+e^-\to\varphi^+\varphi^-)=\frac{1}{4}v^3\sigma(e^+e^-\to\mu^+\mu^-) \tag{3.6}$$

is small compared with $\sigma(e^+e^-\to\tau^+\tau^-)$ (cf., (2.26)), the data of the PLUTO group[9] on the anomalous $\mu\chi$ events

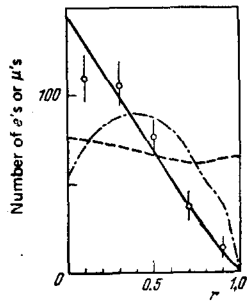

FIG. 4. Distribution of leptons in anomalous $e\mu$ events with respect to

$$r=\frac{p_1-0.65\ \text{GeV}}{(P_1)_{\max}-0.65\ \text{GeV}}$$

for $3.8\leqslant\sqrt{s}\leqslant 7.8$ GeV.[8] The continuous curve corresponds to the expectations for the decay of $\tau^\pm$ with $M=1.9$ GeV for $V-A$ current structure and $m_{\nu_\tau}=0$. The dashed curve corresponds to two-particle leptonic decays of bosons with $M=1.9$ GeV in the absence of spin effects; the chain curve corresponds to two-particle leptonic decays of bosons with spin 1 if they are produced only in states with zero helicity.

would require preferential decay of $\varphi^\pm$ through the muon channel, which, for example, contradicts the small yield of $\mu^+\mu^-$ pairs observed in the same experiment.[6)]

5) All data agree with the hypothesis that has become standard for the experimentalist: decays of a sequential heavy lepton coupled by $V-A$ interaction to a massless neutrino. Using the various distributions of the $e\mu$ events (for example, with respect to $\cos\theta_{\rm coll}$ and r) the SLAC–LBL group obtained in the framework of the standard hypothesis the mean value[8]

$$M=1.9\pm 0.10\,\text{GeV}, \tag{3.7}$$

where the error includes systematic uncertainties. Analysis of the spectra (Fig. 4) for $M=1.9$ GeV gives a bound on the neutrino mass: $m\nu_\tau<0.6$ GeV.[8] The results for M of other groups agree with (3.7). The PLUTO group, considering $\mu\chi$ events under the standard hypothesis, gives the estimate $m_{\nu_\tau}<0.5$ GeV.[9] In particular, such estimates rule out the neutron as one of the secondary neutral particles.

6) In the framework of the hypothesis of the sequential heavy $\tau^\pm$ lepton, all data of the SLAC–LBL group[6-8] lead to values of the relative probability B_1 of τ decay through one leptonic channel in good agreement with one another and the theoretical expectations (see Sec. 2). From the data on the $e\mu$ events[8] (under the assumption $B_e=B_\mu$)

$$B_e=18.6\pm 1\ (\pm 2.8)\%. \tag{3.8}$$

The results of other experiments[9-12] gives values of B_e that agree with (3.8) within experimental error.

7) Comparison of the yields of the anomalous $e^\pm\mu^\mp$, $\mu^\pm\chi^\mp$, and $\mu^+\mu^-$ events made by the PLUTO group[9,10] and also measurements of the ratios of the yields of anomalous $e^\pm\mu^\mp$, $\mu^+\mu^-$, and e^+e^- events made by

[5)] Under the usual assumptions about the weak interactions, decay of a scalar particle into $e\nu$ or $\mu\nu$ as a source of the $e\mu$ events is also ruled out by the equality and relatively large yields of the anomalous e^+e^-, $e^+\mu^-$, and $\mu^+\mu^-$ events.[68]

[6)] The hypothesis of Higgs scalar bosons can also be ruled out for a number of other reasons when confronted with modern experimental data.

the SLAC–LBL group[8,68] confirm the equality (within experimental error) of the relative probabilities of the leptonic decays of τ: $B_e \approx B_\mu$. This fact, which agrees well with the sequential heavy lepton hypothesis, rules out the possibility that τ is a paraelectron (for which one expects $B_e = 2B_\mu$[20]). We recall that according to the neutrino data (see the introduction) $\tau^\pm$ cannot be an ortho- or paramuon. The proximity of the B_e and B_μ values also favors, for example, a small possible contribution to the $\tau^\pm$ decays from nondiagonal neutral currents of the type $(\bar{e}^* e)$ if τ is an orthoelectron.

8) The fraction of single-prong τ decays measured by the PLUTO group,[9]

$$B_\chi = 70 \pm 10\%, \quad (3.9)$$

and the fraction of decays into one charged hadron

$$B_h = 45 \pm 19\%, \quad (3.10)$$

found by means of the LGW counters[12] also agree well with the theoretical expectations (cf Sec. 2).

9) The SLAC–LBL group also obtained bounds on the following relative probabilities of possible τ decays[8] (90% level of confidence):

$$B(\tau^- \to e^-\gamma) + B(\tau^- \to \mu^-\gamma) \leqslant 6.0\%, \quad (3.11)$$

$$B(\tau^- \to l^-l^+l^-) \leqslant 0.6\%, \quad (3.12a)$$

where $l^-l^+l^-$ denotes the sum over all possible combinations of e and μ. In addition, the PLUTO group gives the bound[9]

$$B(\tau^- \to 3 \text{ charged particles}) \leqslant 1\% \quad (95\% \text{ c.l.}) \quad (3.12b)$$

Comparison with (2.22) and (2.23) shows that the bound (3.11) is not yet sufficiently stringent to rule out radiative decay of $\tau^\pm$. But it can already impose restrictions on possible models. For example, if $\tau^\pm$ is an orthoelectron and (2.23) holds for it, then $m_N \lesssim 4$ GeV. Similar remarks also apply to (3.12).

10) The data as a whole favor the $V-A$ variant of the (τ, ν_τ) current. Transition to $V+A$ current worsens χ^2 in the description of the PLUTO data on $\mu\chi$ events[9] and leads to a loss of self-consistency in the description of various distributions for the $e\mu$ events measured by the SLAC–LBL group.[8] The agreement between the results of these groups is also worsened. Introduction of $m_{\nu_\tau} \neq 0$ for the $V+A$ variant only aggravates these difficulties. However, the comparatively meagre experimental statistics and the uncertainty with regard to systematic indeterminacies (see[8]) prevent one completely rejecting the $V+A$ variant as yet.

Thus, all the available data of the various groups on the anomalous $e\mu$, ee, $\mu\mu$, $\mu\chi$, and $e\chi$ events agree well with the hypothesis of the sequential heavy lepton $\tau^\pm$ coupled by $V-A$ current to a massless neutrino ν_τ.

At the present time, there are no facts known which contradict this hypothesis. Of course, other possibilities, in the first place that τ is an orthoelectron, still remain open.

c) Coexistence of τ and charm

As we already said in the introduction, the problem of reliable confirmation of the heavy lepton hypothesis encounters the (partly psychological) difficulty that it is precisely in this region of e^+e^- energies that one clearly observes production of pairs of charmed hadrons which have similar masses and significant ($B_e \sim 10\%$) semileptonic decay modes.[2,3]

The following facts demonstrate that in e^+e^- annihilation both types of these new objects are manifested simultaneously without there being any deep inner connection between them known at the present time.

1. In the experiments of the same groups, in particular DASP and SLAC–LBL, two classes of events are simultaneously and clearly recognized in measurements of the inclusive spectra of electrons and muons, respectively:

a) events with charged-particle multiplicity $n_{ch} = 2$ have a gently sloping momentum spectrum of the leptons e or μ; all their properties agree with the expectations for leptonic decays of $\tau^\pm$ (see the preceding section); in particular, they contain virtually no K mesons (in $e\chi$ events, 0.07 ± 0.06 $K^\pm$ per event[67]);

b) events with high multiplicity of the particles in the final state (in particular, with $n_{ch} \geqslant 3$) have a steep momentum spectrum of the leptons,[7,69,70] which disagrees strongly with the expectations for $\tau^\pm$, both as regards shape and magnitude. The properties of the events of this class, in particular, the shape of the momentum spectra, the K mesons in the final state (~0.90 ± 0.18 $K^\pm$ per electronic event[67]), the correlation between the energy dependence of the yield of inclusive e and the structures in the total cross section for $(e^+e^- \to \text{hadrons})$,[70] agree well with the expectations for semileptonic decays of charmed hadrons (see, for example, Refs. 2, 4).

All this confirms that in e^+e^- annihilation there are indeed two different sources of inclusive leptons, and these are apparently the heavy $\tau^\pm$ leptons and charmed hadrons.

2. According to the present canonical ideas, the branching ratio

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \quad (3.13)$$

measures the sum of the squares of the charges of the fundamental fermions: the quarks and possible heavy charged leptons (which have predominantly hadronic decay channels). In the GIM model (Glashow–Iliopoulos–Maiani model) with four colored quarks one expects only $R_{GIM} = 10/3$ (with possibly a small positive correction at nonasymptotic energies)[7)]. Therefore, the experimentally observed (at $\sqrt{s} \gtrsim 4.5$ GeV) values $R \approx 4.5$–5 offer the $\tau^\pm$ lepton (whose contribution is $R_\tau \sim 1$ far from the threshold) an excellent possibility to manifest itself and make up in a sensible way the clearly insufficient contribution of R_{GIM}.

3. Study of the energy dependence of the total cross section of two-prong events ($n_{ch} = 2$) in e^+e^- annihilation[73] had revealed a remarkable result: the fraction $\delta(2)$ of such events in the cross section $\sigma(e^+e^- \to \text{hadrons})$ is found to be fairly large (~35%) and virtually indepen-

[7)] This group of questions is discussed in more detail in, for example, Refs. 71, 72.

dent of $\sqrt{s}$. But according to the standard assumptions the contribution to $\delta(2)$ from annihilation into ordinary hadrons must die out rapidly with increasing energy, while the contribution from charmed hadrons is expected to be small. A reasonable description of the energy dependence of $\delta(2)$ can be obtained only if in addition to charmed hadrons new objects of the type $\tau^{\pm}$ (leading predominantly to final states with $n_{ch}=2$) are produced.[4]

4. A direct consequence of the model with a charmed quark is that events corresponding to the contribution of the production of a pair of charmed mesons to $\sigma(e^+e^- \to \text{hadrons})$ must contain a pair of K mesons, at least at energies not far from the threshold.

If the entire experimentally observed growth of R for $\sqrt{s} \gtrsim 3.8$ GeV were due solely to the production of charmed hadrons, then the difference $\Delta R = R - R_q$ (the subscript q corresponds to the values of R at energies $\sqrt{s}$ below the threshold, i.e., to the contribution of ordinary quarks) should be equal to the corresponding quantity

$$\Delta R_K = R_K - (R_K)_q$$

($R_K = \sigma_K/\sigma_{\mu^+\mu^-}$, where σ_K is the cross section of inclusive kaon production). But if not only charmed particles but also $\tau^+\tau^-$ pairs (in whose decay the production of K mesons is suppressed) are produced, then ΔR_K must correspond to $\Delta R - R_\tau(s)$. As follows from the measurements of inclusive production of $K^{\pm}$ and K^0_S made by the DASP group[74] and the PLUTO group,[63,75] the experimental data clearly favor the latter possibility.

5. The condition for selecting events with $n_{ch} \geq 3$ used in the SLAC–LBL collaboration[58] in the analysis of the behavior of the spectra of hadrons, the mean hadron momentum, and the fraction of the energy carried away by charged hadrons, greatly reduces the contribution to these quantities from $\tau^{\pm}$, so that in the variation of these observed quantities with increasing energy $\sqrt{s}$ the charmed hadrons are manifested more or less independently.[4,34]

Note that the arguments under headings 2–4 of the present subsection can be perfectly well regarded[4] as independent additional evidence supporting production of $\tau^+\tau^-$ pairs in e^+e^- annihilation.

4. FURTHER MEASUREMENTS NECESSARY IN e^+e^- ANNIHILATION IN CONNECTION WITH THE $\tau^{\pm}$

The mutual consistency of the experiments already performed within the framework of the hypothesis of the sequential heavy lepton already seems fairly convincing. However, all these experiments are much more indirect than is usually the case in the discovery of a new elementary particle (we have discussed the reasons for this in the introduction). It is therefore necessary to continue studying various properties of $\tau^{\pm}$ and to see if they remain consistent with one another and with the theoretical expectations.

Here, we give a (certainly incomplete) list of experiments that should be helpful in this connection.[76] We hope that the list will give the reader a better grasp of the subsequent development of the experimental situation. For convenience of exposition, we divide the experiments into groups, although the division is to some extent arbitrary.

a) Confirmation of the existence of the $\tau^{\pm}$ lepton

1) It is necessary to obtain more stringent restrictions on the hadron and photon accompaniment in $e\mu$ events.

2) A clearer verification that there is no correlation between the yield of anomalous events and structures in the cross section $\sigma(e^+e^- \to \text{hadrons})$. Note however that such a correlation could arise if at higher energies certain new hadrons are produced of which an appreciable fraction decay, for example, into $\tau\nu_\tau$.

3) Verification that the $\tau^+\tau^-\gamma$ vertex is pointlike. This can be done, for example, by determining more accurately the energy dependence of the $e\mu$ cross section and of other anomalous events. If the vertex $\tau^+\tau^-\gamma$ should be nonpointlike, then $\tau^{\pm}$ has an internal structure and participates not only in electromagnetic and weak interactions.

4) More accurate measurements are needed of the two-prong and $e(\mu)\chi$ events in e^+e^- annihilation, especially in the near-threshold region $\sqrt{s} \sim 3.8$ GeV (note that the threshold behavior of $D\bar{D}$ and $\tau^+\tau^-$ is different) at the positions of dips in R, where the production of charmed particles is apparently suppressed, and at the maximal attainable energies, where the requirement $n_{ch}=2$ must separate the τ contribution well from the hadronic contributions. It would also be interesting to establish which hadronic states are manifested in two-prong events.

All these experiments would make it possible to separate more clearly the contributions of the charmed hadrons and heavy leptons.

b) Elucidation of the nature of $\tau^{\pm}$

1) Measurement of the τ lifetime would make it possible to test whether the effective coupling constant is equal to G_F. However, the experiment may be very difficult (the expected value is $T_\tau \sim 2 \cdot 10^{-13}$ sec if $G = G_F$; the measurement of such times in e^+e^- annihilation is unrealistic).

2) Separation of the decays $\tau \to \nu_\tau \pi, \nu_\tau \rho$. They can be looked for either in "inclusive" events ($l = e, \mu$)

$$e^+e^- \to l^{\pm}\pi^{\mp} + \text{neutrals}\ ,$$

or in "exclusive" events

$$e^+e^- \to l^{\pm}\pi^{\mp} + \text{"nothing"},$$
$$e^+e^- \to l^{\pm}\pi^{\mp} + 2\gamma + \text{"nothing"}.$$

One can also use events with two charged hadrons in the final state. Note that the momentum spectrum of the $\pi(\rho)$ produced in the decays $\tau \to \nu_\tau \pi(\rho)$ has the flat profile characteristic of two-particle decays. The importance of observing these decays is due, in particular, to the fact that for the sequential heavy lepton the ratio of their widths to the leptonic width can be calculated theoretically with confidence (see Sec. 2).

3) Searches for radiative decays of $\tau^{\pm}$ in the events

$e^+e^- \to e^{\pm}\mu^{\mp} + 1\gamma +$"nothing".

4) Further verification of the equality $B_e = B_{\mu}$ for the leptonic decays (to within radiative corrections). A departure from this equality would, for example, indicate a nondiagonal neutral current of the type $(\tau, e(\mu))$ or lepton mixing.

c) More accurate determination of the properties of τ

1) An important role may be played by a detailed study of the e or μ spectra in anomalous events. From the position and energy dependence of the limit of the spectrum and its maximum one can accurately recover the τ and ν_{τ} masses.[34,49] From the energy dependence of the spectrum one can also test the absence of a form factor in the $\tau^+\tau\gamma$ vertex.

2) Study of the angular distributions of e or μ in anomalous events makes it possible to recover the angular distribution of the $\tau^+\tau^-$ pair and thus measure the $\tau^{\pm}$ spin, and also the anomalous magnetic moment (if it exists).[35,51]

3) Experiments with polarized initial beams and with measurement of the polarization of the final particles in $e\mu$ events would make it possible to establish all parameters of the $\tau^{\pm}$ leptonic decays with the same completeness as has already been done for $\mu^{\pm}$.[50]

d) Study of other problems

1) Study of the $\tau^{\pm}$ decays with an odd number of pions, for example, in the events

$e^+e^- \to l^{\pm}\pi^{\mp}\pi^+\pi^- +$"nothing",

would make it possible to separate the contribution of the axial hadronic current and, in particular, to settle the question of the existence and properties of the axial resonance A_1. Measurements of this kind have already been begun.[11]

2) Further searches for new heavy leptons, both charged and neutral are necessary (both in e^+e^- annihilation and in other processes).

5. THE PLACE IN THEORY ASSIGNED TO $\tau^{\pm}$

If $\tau^{\pm}$ really is a sequential heavy lepton, then we may find that a "τ riddle" has simply been added to the "muon riddle". But even in this case study of $\tau^{\pm}$ would have great theoretical interest. This is because, in particular, decays of heavy leptons provide a unique possibility for studying the axial hadronic current and obtaining the same information about it as we obtain in the vector current from the reaction $e^+e^- \to$ hadrons. But we can also hope that the importance of $\tau^{\pm}$ is not restricted to this.

At the present time it is usually considered that the basic leptonic characteristics such as the number of different lepton species, their masses, coupling constants, lifetimes, etc, must be determined by the structure of the weak interaction. Therefore, we shall here briefly sketch the group of problems in the theory of weak interactions that relate to the existence of heavy leptons and could be influenced by study of τ.

The progress achieved in recent years in the theoretical understanding of weak-interaction structure is largely related to the search for a group describing broken symmetries. This term is usually applied to symmetries which are exact only at short distances, where one can ignore the masses of particles in the original Lagrangian. As a concrete example, we can take models based on gauge theories of the Yang-Mills type with spontaneous breaking of the vacuum symmetry. The various models differ by the choice of the original group. Below, we shall give some examples as illustrations.

The currently most popular symmetry is $SU_L(2) \times U(1)$, in which the left-handed components of the fermions are grouped into doublets (or singlets) of the group $SU_L(2)$. The simplest variant is the Weinberg-Salam model,[18] which contains the doublets $(\nu_e, e)_L$ and $(\nu_{\mu}, \mu)_L$ and the singlets e_R and μ_R. If the symmetry of the weak interaction really is $SU_L(2) \times U(1)$, then in the absence of lepton mixing τ with its neutrino ν_{τ} must form a new doublet $(\nu_{\tau}, \tau)_L$. In this case, τ is a sequential heavy lepton, and it has a new lepton quantum number. It is this interpretation of the observed properties of τ that at present seems preferable on the basis of the available experimental data (see the discussion of the previous section).

It is to be noted that a gauge model based on the symmetry $SU_L(2) \times U(1)$ is not renormalizable if one restricts it to the leptons (ν_e, e), (ν_{μ}, μ), and (ν_{τ}, τ) and the quarks (u, d') and (c, s') because of the existence of the so-called triangle anomaly in such a model.[77] The condition for canceling of this anomaly requires the existence of new species of quarks and/or leptons and/or right-handed currents. The requirement that there be no triangle anomaly is the first purely theoretical argument indicating the possibility of an inner connection between leptons and quarks. Note that this argument is not based on the phenomenological theory of weak interactions since the nonrenormalizability of the model due to the triangle anomaly appears only in a fairly high (currently not observable) order of perturbation theory.

The fruitfulness of this argument seems to be confirmed experimentally. New data on the production of $\mu^+\mu^-$ pairs in pp scattering[78] apparently indicate the existence of a new heavy quark with mass ~5 GeV. On the other hand, the existing experiments on ν_{μ}, $\bar{\nu}_{\mu}$ scattering on hadrons[79] indicate that there is no appreciable contribution of right-handed currents. Both facts could be interpreted as an indication that the new quark occurs with ordinary quarks only in left-handed currents. But precisely this ensures the possibility of canceling the contribution of the τ to the triangle anomaly if the new quarks form a left-handed doublet!

The τ lifetime depends, in particular, on the ratio of the τ and ν_{τ} masses. If $M_{\tau} > m_{\nu_{\tau}}$, then the decays $\tau \to \nu_{\tau} + (\bar{\nu}_e e, \bar{\nu}_{\mu}\mu, q\bar{q})$ are predominant (here, the symbol q corresponds to the light quarks u, d, s). It is this decay variant that was discussed in Sec. 2. But if $M_\tau < m_{\nu_\tau}$, then the decay of $\tau^\pm$ is possible if the weak current contains a linear combination of ν_τ with ν_e and/or ν_μ. (The decays of strange particles in the standard theory are described similarly by introducing the Cabibbo angle.) Then if the mixing angle is small, the τ lifetime may be much longer than given by the calculation made in Sec. 2 (see, for example, Ref. 80). Note that if there is mixing of neutral leptons one obtains in a comparatively natural manner the decay $\mu \to e\gamma$ (see, for example, Refs. 41, 80-82), neutrino oscillations (see, for example Refs. 82, 83), etc.

The approach based on $SU_L(2)\times U(1)$ encounters difficulties when one attempts to describe the currently available experimental data on neutral currents. On the one hand, optical measurements of the rotation of the plane of polarization in bismuth[84] may indicate that there is no appreciable parity violation at the electron vertex (i.e., the absence of an axial component in the electron neutral current), while on the other hand the scattering of ν, $\bar{\nu}$ by hadrons and electrons indicates the presence of both V and A currents in the quark and lepton vertices.[85] If all these data are reliably confirmed, then taken together they rule out the Weinberg-Salam model based on the group $SU_L(2)\times U(1)$.

Attempts to overcome this difficulty essentially reduce at the present time to the introduction of right-handed currents into the original theory of weak interactions. Since it is well-known that the currently studied decays of hadrons and leptons do not reveal an appreciable contribution of right-handed currents, their introduction into the theory requires the existence of heavy leptons or some further quarks. The simplest variant, in which the left- and right-handed components of the leptons occur symmetrically in the interaction, the so-called vectorlike models,[86] lead to strangeness conserving neutral currents, and this apparently contradicts the experiments.[85] If the model is made a bit more complicated, for example, by going over to the symmetry $SU_L(2)\times SU_R(2)\times U(1)$ (see, for example,[87]), then the introduction of additional intermediate vector mesons and the concomitant increase in the number of parameters makes it possible to "loosen" the leptonic and the quark vertex and, as a result, to avoid contradictions between different experiments. (We recall that the neutrinos currently accessible to experiments have effectively left-handed polarization; therefore, neutrino experiments would not reveal $SU_R(2)$ symmetry even if it exists.) In this and other models like it, the τ alone is insufficient; one requires still more leptons (quarks). In this connection, we recall that preliminary experimental indications of the existence of additional heavy leptons have already appeared.[88,89]

These examples show that at the present time there is a serious arbitrariness in the construction of models, and they demonstrate once more, if that were needed, the insufficiency of our ideas about the weak interaction. It may be that we stand with regard to the weak interaction at the present time in about the same position as with regard to the strong interaction prior to the discovery of $SU(3)$ symmetry.

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SUPPLEMENT

(October 1977)

From August 25 to 31, 1977, the International Symposium on Lepton and Photon Interactions at High Energies was held at Hamburg. There, various experimental data on anomalous events were presented. The list of these data (Table II) illustrates how broad is the front on which this work advances. Below, we briefly discuss the most important results of the new measurements.

1. The e, μ events presented at this conference by the DASP group (see Table I) are very clean because DASP ensures good identification of charged particles and high photon detection efficiency.

2. For the first time, data were presented from the new detector DELCO (see Table II). It has a large solid angle for particle detection and identifies electrons very clearly ($P_{h\to e} \leqslant 0.1\%$).

3. According to the preliminary data from the detectors MARK-I (LGW) and DELCO anomalous $e\mu$ and $e\chi$ events are observed near the threshold of $D\bar{D}$ production in the region of the new resonance $\psi''(3772)$. There are arguments (M. Perl) suggesting that $D\bar{D}$ cannot be responsible for all these events. The presented data agree with the hypothesis of the τ lepton. If they are confirmed, then the τ mass lies in the range $1.8 \leqslant M \leqslant 1.875$ GeV.

4. The energy dependence of the yield of anomalous $e^\pm$ in events with $n_{ch} \geqslant 3$ measured by the DELCO group reveals very clear correlations in the total cross section $\sigma(e^+e^- \to \text{hadrons})$. In particular, one clearly observes peaks at $\sqrt{s} = 3.772$ GeV and $\sqrt{s} \sim 4.4$ GeV and a

TABLE II. New preliminary data on anomalous $e\mu$, $\mu\chi$, and $e\chi$ events.

Type of anomalous event	Detector	Range of s, GeV	p_l, p_μ, p_χ GeV	Number of anomalous events	Remarks
$e\mu$	DASP	4.0—5.2	>0.15 >0.7	11 (background 0.7)	High photon detection efficiency
	MARK-I (LGW)	3.760—3.784	>0.4 >0.65	8(background 2.3)	
$\mu\chi$	DASP	4.0—5.2	>0.7 >0.1	14 (background 2)	It follows from comparison of $\mu\chi$ and $e\chi$ data that $B_\mu/B_e = 0.8\pm0.3$
	MPP	7.0	$\geqslant 1.15$ >0.1		
$e\chi$	MARK-I (LGW)	3.760—3.784	>0.4 $\geqslant 0.65$		
	DELCO	3.7—7.4	$\geqslant 0.1$ $\geqslant 0.3$	≈ 230	Very clean identification of electrons: $P_{h\to e} \sim 0.1\%$ A total of 73 events detected at $\psi''(3772)$

TABLE III. Data on decays of $\tau^{\pm}$ lepton (the standard hypothesis is adopted: $M_\tau \approx 1.9$ GeV, $m_{\nu_\tau} = 0$, $V-A$ current structure).

Decay channel	B, %	Detector	Remarks
$e^{\pm}\nu_\tau\nu_e$, $\mu^{\pm}\nu_\tau\nu_\mu$	18.6±1.0 (±2.8) *)	MARK-I	$e\mu$ events
	17.5±2.7 (±3.0)	MARK-I	$\mu\chi$ events, $B_\chi = 0.85$ assumed
	22.4±3.2 (±4.4)	MARK-I (LGW)	$e\mu$ events, $B_e = B_\mu$ assumed
	14±3.4	PLUTO	$\mu\chi$ events and multiprong events with anomalous muons are compared
	16±6	PLUTO	From comparison of $\mu\chi$ and $e\mu$ events
	20±3	DASP	$e\mu$ events
	15	DELCO	$e\chi$ events
$\pi^{\pm}\nu_\tau$	2±2.5	DASP	For B_e=20% (90% confidence level)
$K^{\pm}\nu_\tau$	<1.6	DASP	
$\rho^{\pm}\nu_\tau$	24±9	DASP	For B_e=16%
$A_1^{\pm}\nu_\tau$	11±4 (±3)	PLUTO	
	~16	MARK-I	
$\chi^{\pm}$ + neutrals	70±10	PLUTO	
$h^{\pm}$ + neutrals	45±19	MARK-I (LGW)	
3 charged particles	<1	PLUTO	95% confidence level
3 leptons	<1	PLUTO	95% confidence level
	<0.6	MARK-I	90% confidence level
$(e+\gamma\text{'s})+(\mu+\gamma\text{'s})$	<12	PLUTO	90% confidence level
$e\gamma$	<2.6	MARK-I (LGW)	90% confidence level
$\mu\gamma$	<1.3	MARK-I (LGW)	90% confidence level

Note: The value of the systematic error is given in brackets.

structure at $\sqrt{s} \sim 4$ GeV, and also a strong dip at $\sqrt{s} \approx 4.25$ GeV, as in the total cross section for $e^+e^- \to$ hadrons. This fact reliably establishes that such events are due to decays of charmed hadrons.

On the other hand, in the yields of $e\mu$ and $e\chi$ events there are no clear indications of the existence of such correlations (in particular, in the region of $\psi''(3772)$). However, the situation here is much less definite, and to confirm the τ lepton hypothesis it is definitely necessary to make further measurements, above all in the region of $\psi''(3772)$. For example, the detection of anomalous events below the threshold of $D\bar{D}$ production, i.e., for $\sqrt{s} \lesssim 3.7$ Gev, would make it possible to separate the contributions of the τ lepton and charm. The detection of anomalous events at the peak $\psi'(3684)$ would make it possible to study well many properties of τ.

5. In analyzing events of the type $e^+e^- \to l^{\pm} + \pi^{\mp}\pi^{+}\pi^{-}$ + "nothing" ($l = e, \mu$) (see Sec. 4) the PLUTO group have obtained indications of observation of the decay $\tau^{\mp} \to A_1^{\mp}\nu_\tau(\bar{\nu}_\tau) \to \rho^0\pi^{\mp}\nu_\tau(\bar{\nu}_\tau)$ (Table III). In the case $l = e$ preliminary data on the decay $\tau \to A_1 + \nu_\tau$ have also been obtained with the detector MARK-I (see Table III). The DASP group have found indications of the decay $\tau \to \nu_\tau + \rho$ in measurements of the events $e^+e^- \to \pi^{\pm} + 2\gamma + \chi^{\mp}$ + "nothing". The observed values of the partial widths of the decays $\tau \to \nu_\tau A_1$ and $\tau \to \nu_\tau\rho$ (see Table III) agree well with the theoretical expectations for the τ lepton (see Sec. 2d).

6. Analyzing events of the type $e^+e^- \to e^{\pm}e^{\mp}$ + "nothing" and $e^+e^- \to \pi^{\pm}\chi^{\mp}$ + "nothing", the DASP group has not succeeded in detecting the decay $\tau \to \pi\nu_\tau$. The observed number of events corresponds to 2-3 standard deviations from the theoretical expectations. If this were confirmed, it would be a serious objection against the normal leptonic nature of τ. (In the framework of the existing assumptions about the weak interaction, the decays $\tau \to \nu_\tau A_1$, $\nu_\tau\pi$ are determined by the matrix element of one and the same axial hadronic current. Therefore, observation of the decay $\tau \to A_1\nu_\tau$ in the absence of the decay $\tau \to \pi\nu_\tau$ would indicate that other interactions besides the ordinary weak and strong interactions are involved in the process.) Note however that the PLUTO data on the $\mu\pi$ events (which have as yet a low statistics agree with the expectation for the decay $\tau \to \pi\nu_\tau$.

7. The PLUTO group has established an upper bound for the τ lifetime: $T_\tau \lesssim 10^{-11}$ sec (95% confidence level).

8. In Table III we give a list of the existing values of the relative probabilities of the different decays of τ, including the preliminary results presented at the Hamburg symposium (cf. Table I).

In the near future, we can expect the appearance of new data from the detectors DASP, PLUTO, and DELCO, and also from the new-generation detector MARK-II, which replaced MARK-I as from November 1977.

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