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The Tau Lepton and the Search for New Elementary Particle Physics*

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Abstract

This Fifth International WEIN Symposium is devoted to physics beyond the standard model. This talk is about tau lepton physics, but I begin with the question: do we know how to find new physics in the world of elementary particles? This question is interwoven with the various tau physics topics. These topics are: searching for unexpected tau decay modes; searching for additional tau decay mechanisms; radiative tau decays; tau decay modes of the W, B, and D; decay of the Z^0 to tau pairs; searching for CP violation in tau decay; the tau neutrino, dreams and odd ideas in tau physics; and tau research facilities in the next decades.

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1 Do we know how to find new physics?

Over the years in elementary particle physics and to some extent in nuclear physics we have developed a set of rules as to the best ways to look for new physics. These rules are based on a set of axioms, perhaps better called *idées fixes*. I am probably as trapped as other physicists in these *idées fixes*, but it is still worthwhile to think about them. Perhaps we can loosen our minds a little or at least the younger practitioners of particle and nuclear physics can develop some skepticism about the wisdom of the elder practitioners.

- Look for more massive particles. The *idées fixes* are:
  - More massive particles exist.
  - Supersymmetric theory is relevant.
  - Mass is a significant property.
  - More massive particles can be produced with present technology.
- Look for unconventional interactions. The *idées fixes* are:
  - Unconventional interactions exist.
  - Sufficient experimental sensitivity can be obtained with present technology.
- Compare measured interaction and decay parameters with theory. The *idées fixes* are:
  - There is a deeper theory that will lead to deviations.
  - Sufficient experimental sensitivity can be obtained with present technology.
- Look for odd particles and peculiar phenomena. The *idées fixes* are:
  - Such particles or phenomena exist.
  - Sufficient experimental sensitivity can be obtained with present technology.

What other ways are there for new physics searches? I don't have any startling new ideas about how to look for new physics, but I have two somewhat different ideas. One idea is to go back and look with new technology at old and fully established laws of physics. Thus almost everyone believes there are no free elementary particles with fractional electric charge; quarks are not free. But my colleagues and I are using a highly automated version of the Millikan oil drop experiment to search for particles with fractional electric charge.[1],[2] Another contrary idea is that mass is not an important property of elementary particles, beyond the law of relativistic energy conservation that allows heavy particles to decay into light particles. I don't know how to do experiments specifically based on this speculation, but it does incline me to be content to experiment in the realms of smaller masses and lower energies.

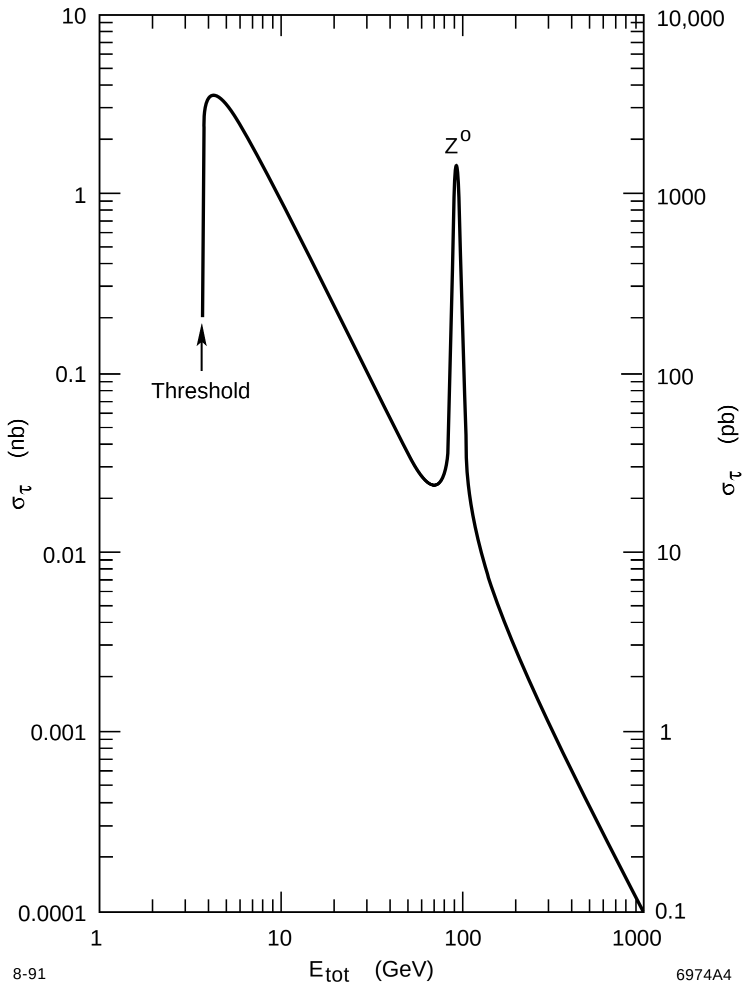

Figure 1: The energy dependence of the cross section for τ pair production.

2 Overview of tau physics.

Tau physics includes studying the properties of the tau lepton and the properties of the tau neutrino. This paper is primarily about the tau lepton but I briefly discuss tau neutrino research. The recent exciting and important experimental results from the Super-Kamiokanda experiment on neutrino oscillations and their possible implications for the tau neutrino are thoroughly reviewed and discussed in this Symposium.[3]

I will not talk about using the tau to study the physics of hadrons and quantum chromodynamics; the subject lies outside the scope of the Symposium. It is however a vast and fruitful research area.

The energy dependence of the cross section for τ pair production

$$e^+ + e^- \to \tau^+ + \tau^-$$

is given in Fig. 1. The discovery of the τ [4] and early τ research was carried out in the energy region of 3 to 7 GeV using the first generation of electron-positron colliders. The research continued with the next generation of colliders in the energy range from about 20 GeV to below the mass of the Z^0 (91 GeV). The most recent period of τ research has been carried out in two different energy regions. Experimenters at LEP and the SLC have used the Z^0 decay

$$e^+ + e^- \rightarrow Z^0 \rightarrow \tau^+ + \tau^-.$$

The other energy region, about 10 GeV, the region of B meson pair production, has been a prolific source of τ research, first at the DORIS collider and now at the CESR collider. This 10 GeV region will be the main source of future τ research as the CESR collider is upgraded and the B factories go into operation, see Sec. 11.

The τ has a great number of decay modes, summarized by the Particle Data Group.[5] About 85% of the time the τ decays into one charged particle, neutral particles, and of course the tau neutrino, ν_τ. The major one-charged-particle, decay modes are the pure leptonic modes:

$$\begin{array}{ll} \tau^- \rightarrow \nu_\tau + e^- + \nu_e & B = 17.8\% \\ \tau^- \rightarrow \nu_\tau + \mu^- + \nu_\mu & B = 17.3\% \end{array}$$

In this paper I use ν to denote a neutrino or an antineutrino. The branching fraction is denoted by B.

The major one charged particle, semileptonic, decay modes are:

$$\begin{array}{ll} \tau^- \rightarrow \nu_\tau + \pi^- & B = 11.1\% \\ \tau^- \rightarrow \nu_\tau + \rho^- & B = 25.3\% \\ \tau^- \rightarrow \nu_\tau + \pi^- + 2\pi^0 & B = 9.4\% \end{array}$$

Decay modes with a K meson are much smaller because of Cabibbo suppression.

In the decays with three charged particles, 9.6% are of the form:

$$\tau^- \rightarrow \nu_\tau + h^- + h^+ + h^-$$

where h is a π or a K. The remaining 5.2% have additional π^0 or K^0 mesons.

3 Searching for unexpected tau decay modes.

Some of us still dream about discovering unexpected decay modes of the tau, decay modes that would lead to the discovery of new physics. Figure 2 shows two possibilities. In the upper diagram the τ-W vertex has unexpected behavior, another particle, x, is emitted. The W materializes into a standard pure leptonic final state. In the lower diagram, the τ-W vertex is standard, but the W materializes into an unknown x, y, z final state.

But as yet there are no unexpected decay modes, all are explained by conventional theory. Thus for example:

- The total decay width of the tau is understood to better than 0.5%. Hence there are no undiscovered decay modes with branching fractions greater than 0.5%.

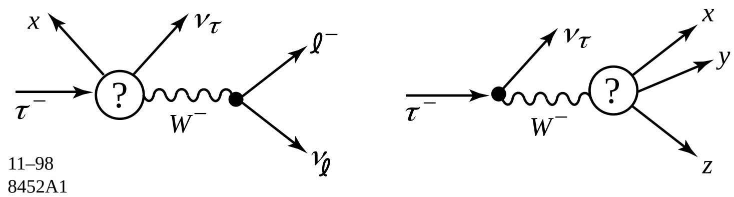

Figure 2: Unexpected decay modes of the tau.

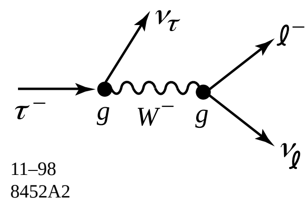

Figure 3: Standard decay route for tau.

- Lepton number violation such as $\tau \to \mu\gamma$ has not been observed. Experimenters using the CLEO detector[6] have set the branching fraction upper limit $B(\tau \to \mu\gamma) < 3 \times 10^{-6}$. Other lepton number violating modes have similar small upper limits.
- So far, expected modes with very small, branching fractions such as $\tau^- \to e^- e^+ e^- \nu_\tau \nu_e$ agree with theory. This decay mode has the branching fraction[7] $B = 3 \times 10^{-5}$.

Yet I continue to ask myself: Are there other ways to search for unexpected decay modes?

4 Searching for additional tau decay mechanisms.

Perhaps there are no unexpected decay modes of the tau, but is there a tau decay route other than through a virtual W with V-A coupling at both vertices, Fig. 3? The conventional theory for the leptonic decays based on W exchange is complete; hence it has been the clearest way to search for other exchange mechanisms. For the sake of brevity, the discussion and examples in this section are limited to the pure leptonic decays.

Assuming Lorentz invariance, local interactions, no derivative couplings, and lepton number conservation, the most general matrix element for these decays consists of four different scalar interactions, four different vector interactions, and two different tensor interactions. Each of these interactions can have a different complex coupling constant. I use the nomenclature of the classic paper of Fetscher.[8] The matrix elements, m, and coupling constants, g, are denoted by:

$$m^I_{LL'},\ m^I_{LR'},\ m^I_{RL'},\ m^I_{RR'};g^I_{LL'},\ g^I_{LR'},\ m^I_{RL'},\ m^I_{RR'}$$

where $I = S,\ V,\ T$ for scalar, vector, or tensor interaction; and the subscripts indicate whether the neutrinos are left-handed (L) or right-handed (R).

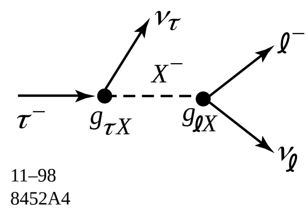

Figure 4: Possible scalar interaction in tau decay to leptonic maodes.

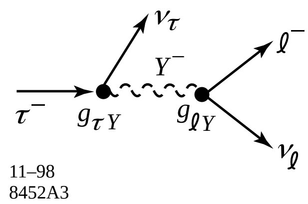

Figure 5: Possible additional vector interaction in tau decay to leptonic modes.

The matrix element for the V-A interaction of conventional theory is denoted by m^V_{LL}, where V means a vector interaction and the LL means that both neutrinos are left handed. This matrix element is of course

$$m^V_{LL} = \left(\frac{g}{2\sqrt{2}}\right)^2 \frac{1}{M_W^2} \left[\bar{u}(\nu_\tau)\gamma^\mu \left(1-\gamma^5\right) u(\tau)\right] \left[\bar{u}(\ell)\gamma_\mu \left(1-\gamma^5\right) \nu(\nu_\ell)\right] \tag{1}$$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

The weak coupling constant is written simply as g here and G_F is the Fermi coupling constant.

As an example in the realm of new physics, a scalar interaction occurring through the exchange of an unknown particle X, Fig. 4, might exist. The matrix element for the leptonic decays would be:

$$m^S_{LL} = \left(\frac{g_{\tau X} g_{\ell X}}{8M_X^2}\right) \left[\bar{u}(\nu_\tau) \left(1+\gamma^5\right) u(\tau)\right] \left[\bar{u}(\ell) \left(1-\gamma^5\right) \nu(\nu_\ell)\right] \tag{2}$$

The only constraint on m^S_{LL} is a constraint on an additive combination of $\left|m^S_{LL}\right|^2$ and $\left|m^V_{LL}\right|^2$,[9] hence a small amount of this scalar interaction is certainly possible. In Table 1 I summarize the present experimental limits on the possible τ coupling constants and compare these limits with the tighter limits on the μ coupling constants.[9]

As an example of how limits are set, consider a small second vector interaction occurring thorough an unknown new particle Y, see Fig. 5. The matrix element would be:

$$m^{V'}_{LL} = \left(\frac{g_{\tau Y} g_{\ell Y}}{8M_Y^2}\right) \left[\bar{u}(\nu_\tau)\gamma^\mu \left(1-\gamma^5\right) u(\tau)\right] \left[\bar{u}(\ell)\gamma_\mu \left(1-\gamma^5\right) \nu(\nu_\ell)\right]$$

Table 1: Comparison of 90% CL limits on $\left|g^I\right|$'s from measurements of $\mu \to e\nu_e\nu_\mu$ with combined measurements of $\tau \to e\nu_e\nu_\tau$ and $\tau \to \mu\nu_\mu\nu_\tau$.[9] Because of the normalization convention some $\left|g^I\right|$'s have a maximum value of 1, others have a maximum value of 2.[9] In the table the numbers 1, 2, and $1/\sqrt{3}$ are normalization limits, indicating there is no measured limit. In conventional V-A theory all g^I's are zero except for $g^V_{LL} = 1$.

	$\mu \to e\nu_e\nu_\mu$	$\tau \to e\nu_e\nu_\tau$ $\tau \to \mu\nu_\mu\nu_\tau$
$\left\|g^S_{RR}\right\|$	< 0.066	< 0.57
$\left\|g^S_{LR}\right\|$	< 0.125	< 0.70
$\left\|g^S_{RL}\right\|$	< 0.424	≤ 2
$\left\|g^S_{LL}\right\|$	< 0.55	≤ 2
$\left\|g^V_{RR}\right\|$	< 0.033	< 0.29
$\left\|g^V_{LR}\right\|$	< 0.060	< 0.35
$\left\|g^V_{RL}\right\|$	< 0.110	< 0.53
$\left\|g^V_{LL}\right\|$	> 0.96	≤ 1
$\left\|g^T_{LR}\right\|$	< 0.036	< 0.20
$\left\|g^T_{RL}\right\|$	< 0.122	$\leq 1/\sqrt{3}$

From measurements of the τ lifetime and the leptonic branching fractions, we can calculate the leptonic widths, and compare them with standard V-A theory. This comparison limits $m^{V'}_{LL}$ as follows:

$$\left|\frac{m^{V'}_{LL}}{m^{V}_{LL}}\right| < 5 \times 10^{-3}$$

Hence there are constraints on the coupling constants in Fig. 5 and on the mass of the Y.

More generally, as shown in Table 1, *no deviations from conventional physics have been found in the τ leptonic decays.* But the limits are not nearly as tight as they are for the corresponding coupling constants of the μ.

Future searches for additional τ decay mechanisms will take two directions:

- We can and will continue to improve measurements of leptonic decay parameters.
- In addition we should and do use probes that are intrinsically sensitive to small additional decay mechanism. I will discuss two such probes: radiative leptonic decays and searches for CP violation in τ decay.

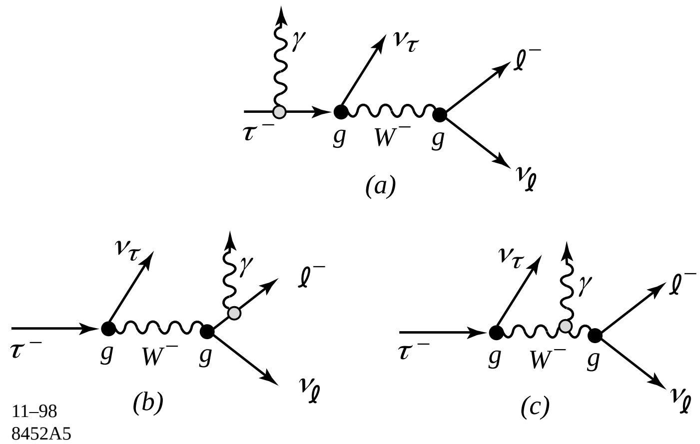

Figure 6: Diagrams for radiative, leptonic tau decays.

The first direction may soon reach its experimental limits, not because of statistics but because of measurement problems in large particle detectors. The second direction is newer and has further to go; there is more room for experimental progress.

5 What can we learn from radiative tau decays?

The radiation of a photon from a reaction offers the advantage that the photon has no final state strong interaction. Therefore the kinematic properties of the emitted photon directly reflect the inner dynamics of the reaction. There is, however, a disadvantage: photons are also emitted by the well-known but uninteresting process of bremsstrahlung from charged particles produced or annihilated in the reaction. These bremsstrahlung photons can lead to a serious background problem.

The radiative decays of the tau fall into two classes: the purely leptonic decays

$$\tau^- \to \nu_\tau + e^- + \nu_e + \gamma \tag{3}$$

$$\tau^- \to \nu_\tau + \mu^- + \nu_\mu + \gamma \tag{4}$$

and the semileptonic decays such as

$$\tau^- \to \nu_\tau + \pi^- + \gamma \tag{5}$$

$$\tau^- \to \nu_\tau + \rho^- + \gamma. \tag{6}$$

The conventional theory of radiative leptonic decays of charged leptons is well established.[10]–[12] Therefore the leptonic decays, Eq. 3–4, are valuable in looking for unexpected tau decay phenomena. The semileptonic decays, Eq. 5–6, will be valuable for the study of W-hadron vertices.[13] In this talk I will concentrate on the radiative leptonic decays.

The standard diagrams for radiative leptonic decay are given in Fig. 6. The dominant contributions are from diagrams a and b, radiation from the τ and radiation from the e or μ. Radiation from the W is suppressed by the very small factor $(M_\tau/M_W)^2$.[14],[15]

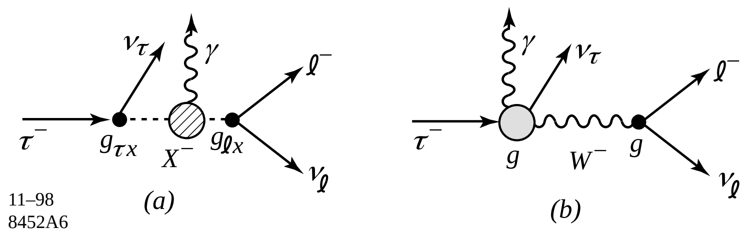

Figure 7: Possible types of anomalous, radiative, leptonic decays: (a) radiation from the exchange of particle X and (b) anomalous radiation from the τ-W vertex.

There are two types of anomalous, radiative, leptonic decay processes that might exist, that we might dream about. As shown in Fig. 7a, there might be an unknown particle X that is exchanged in leptonic tau decays and that radiates. Figure 7b points out the possibility of the τ-W vertex having anomalous photon radiation with a small branching ratio. I have no model for such anomalous vertex behavior but I think it is worth seeking.

Returning to radiation from X exchange, there are constraints on the properties of X and its coupling constants. The mass of X, m_X, must not be too large, otherwise the suppression factor $(M_X/M_W)^2$ will be so small that we will not be able to detect radiation from the X. In terms of the coupling constants and m_X this requires

$$\left|\frac{g_{\tau X} g_{\ell X}}{m_X^2}\right| << \left|\frac{g^2}{m_W^2}\right|. \tag{7}$$

The radiative, muonic decay of the τ has been studied by the OPAL experimenters,[16] they find:

$$B(\tau \to \nu_\tau \mu \nu_\mu \gamma) = (3.0 \pm 0.4 \pm 0.5) \times 10^{-3}$$

for γ energies above 20 MeV in the τ rest frame. No anomalous behavior was found. CLEO experimenters[17] are now studying the electronic and muonic radiative decays.

The major background in these studies is

$$e^+ + e^- \to \tau^+ + \tau^- + \gamma, \tag{8}$$

the γ being produced in the annihilation of the electron or positron, or in the production of one of the τ's. It is an unfortunate background because, as shown schematically in Fig. 8, it obscures what might be the most interesting region for searches for anomalous radiation. Consider the example of radiative muonic decay. We define $\theta_{\mu\gamma}$ as the angle in the laboratory frame between the μ and the γ. The radiation from the standard diagrams, (a) and (b), in Fig. 6 peaks near $\theta_{\mu\gamma} = 0$. Anomalous radiation might most easily be found when $\theta_{\mu\gamma} > 0$, but unless the anomalous radiation has a relatively large branching fraction, it will be hidden by the $e^+e^- \to \tau^+\tau^-\gamma$ radiation.

It will probably be difficult to substantially increase the precision of these τ radiative decay studies, even with greatly increased statistics. *We will have to find some new ways to explore the radiative decays of the τ.*

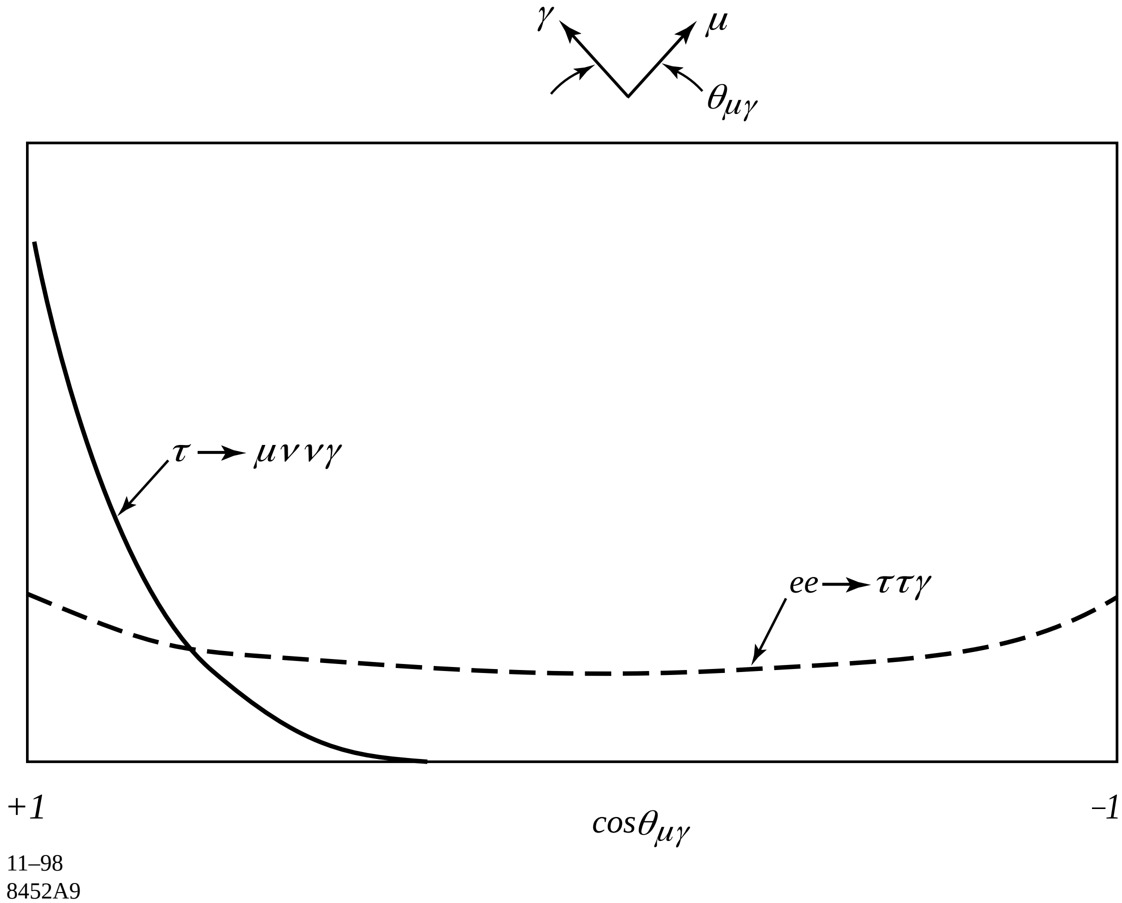

Figure 8: Schematic comparison of $\tau \to \mu\nu\nu\gamma$ signal and $e^+e^- \to \tau\tau\gamma$ background.

6 What can we learn from the tau decay modes of the $\boldsymbol{W}$, $\boldsymbol{B}$, and $\boldsymbol{D}$?

6.1 $W \to \ell + \nu_\ell$

Since the W mass is much larger than the lepton mass, we expect the same branching fraction for all three leptons unless there is a special connection between the W and the τ. The Particle Data Group[5] gives the following branching fractions:

$$B(W \to e + \nu_e) = 0.109 \pm 0.004$$

$$B(W \to \mu + \nu_\mu) = 0.102 \pm 0.005$$

$$B(W \to \tau + \nu_\tau) = 0.113 \pm 0.008$$

Thus there is no apparent special connection between the τ and the W. *I don't think the precision of this comparison can be improved substantially.*

Table 2: Branching fraction for the purely leptonic decay, $M \to \ell + \nu_\ell$ of a D or B meson. The meson decay constant f_M is assumed to equal 200 MeV and $V_{qq'}$ is the assumed CKM mixing matrix element.

M	$V_{qq'}$	$e\nu$	$\mu\nu$	$\tau\nu$
D	0.221	8×10^{-9}	4×10^{-4}	9×10^{-4}
D_S	0.974	7×10^{-8}	3×10^{-3}	3×10^{-2}
B	0.003	7×10^{-12}	3×10^{-7}	6×10^{-5}

Table 3: Comparison with theory of the measured branching fraction for the purely leptonic decay, $M \to \ell + \nu_\ell$, of a D or B meson. The meson decay constant is assumed to equal 200 MeV. Most measurements are upper limits.

Decay	Branching Fraction, Data	Branching Fraction, Theory ($f_M = 200$ MeV)
$D \to \mu\nu$	$< 7.2 \times 10^{-4}$	4×10^{-4}
$D \to \tau\nu$	?	9×10^{-4}
$D_S \to \mu\nu$	$(4.0 \pm 2.1) \times 10^{-3}$	3×10^{-3}
$D_S \to \tau\nu$	$(7 \pm 4) \times 10^{-2}$	3×10^{-2}
$B \to e\nu$	$< 1.5 \times 10^{-5}$	7×10^{-12}
$B \to \mu\nu$	$< 2.1 \times 10^{-5}$	3×10^{-7}
$B \to \tau\nu$	$< 5.7 \times 10^{-4}$	6×10^{-5}

6.2 $D \to \ell + \nu_\ell, B \to \ell + \nu_\ell$

The decay widths for

$$D^+ \to \ell^+ + \nu_\ell, \quad D_S^+ \to \ell^+ + \nu_\ell, \quad B^+ \to \ell^+ + \nu_\ell$$

are given by

$$\Gamma\left(M^+ \to \nu_\ell + \ell^+\right) = \frac{G_F^2}{8\pi\hbar} f_M^2 V_{qq'}^2 m_M m_\ell^2 \left[1 - \left(\frac{m_\ell}{m_M}\right)^2\right]^2 \tag{9}$$

Here M is a D or B meson, f_M is the meson decay constant and $V_{qq'}$ is the CKM mixing matrix element. In Table 2, I give the branching fractions using Eq. 9, assuming $f_M =$ 200 MeV.

Table 3 presents a comparison with theory of the measured branching fraction for the purely leptonic decay, $M \to \ell + \nu_\ell$, of a D or B meson. Most measurements are upper limits. I have the following comments:

(a) Eventually we may know quite well the magnitude of $V_{qq'}$ from other measurements, but there is no independent way to measure f_M. Calculated values of f_M can be used, particularly if the calculation method is checked against a measured value for a different M. Therefore while we cannot hope to find new physics by looking for small differences between calculated and measured values of $B(M \to \ell\nu_\ell)$ for a particular decay mode, large differences between calculated and measured values might indicate new physics.

(b) One can get around a poorly known value of f_M by using the ratio of two different leptonic decays of the same M. The accuracy of the calculated value of this ratio will of course depend upon how well the $V_{qq'}$'s are known.

(c) In the next decade there should be considerable progress in measuring the μ and τ decay modes of the D and D_S. The three charged particle decays of the τ will be most useful, but their use will require larger D and D_S data sets.

(d) The measurement of the conventional theory values of the branching fractions of B decays in Table 3 is beyond our present technology. Even the $\tau\nu$ mode is very difficult because a very large number of B pairs have to be tagged. *Still one can hope for new physics that drastically increases these branching fractions.*

6.3 $B \to \tau^+ + \tau^-$

Another difficult but interesting direction for seeking an unexpected connection between the B and the τ is the search for the decays

$$B_d^0 \to \tau^+ + \tau^-$$

$$B_s^0 \to \tau^+ + \tau^-$$

Grossman *et al.*[18] predict a branching fraction of 10^{-6} to 10^{-8}. Not easy to do. The present measured upper limits are a few percent.

7 Decay of the Z^0 to tau pairs.

A tremendous amount of research work has been done on the Z^0 decays

$$Z^0 \to e^+ + e^- \qquad \Gamma = 83.94 \pm 0.14 \text{ MeV} \tag{10}$$

$$Z^0 \to \mu^+ + \mu^- \qquad \Gamma = 83.84 \pm 0.20 \text{ MeV} \tag{11}$$

$$Z^0 \to \tau^+ + \tau^- \qquad \Gamma = 83.68 \pm 0.24 \text{ MeV} \tag{12}$$

Here Γ is the decay width from the combined results of measurements at LEP.[19] Thus in its overall interaction with the Z^0, the τ behaves exactly like the e and μ. There is no possibility of improving at LEP this already fine precision because there will be no more LEP operation at the Z^0. Perhaps some improvement may be made using the SLC linear collider. *But we cannot expect much improvement.*

Hence it is important to look for more subtle deviations from expected behavior in $Z^0 \to \tau^+\tau^-$. An example is the search for CP violation in $Z^0 \to \tau^+\tau^-$. No violation has been found.[20] The upper limit on any such CP violation is usually given as an upper limit on a weak dipole moment, d_τ^{weak}:[20]

$$\left|\mathrm{Re}(d_\tau^{weak})\right| < 3.6 \times 10^{-18}\mathrm{e\ cm}$$

$$\left|\mathrm{Im}(d_\tau^{weak})\right| < 1.1 \times 10^{-17}\mathrm{e\ cm}$$

The level of 10^{-17} to 10^{-18} e cm does not seem particularly small to me, since the equivalent size of a lepton is less than 10^{-16} cm.

In summary the extensive research on $Z^0 \to \tau^+\tau^-$ leaves the feeling that the tau is simply an ordinary lepton.

8 Searching for CP violation in tau decay.

We know that the violation of CP conservation occurs in the decays of the K mesons and there are strong reasons to believe that CP violation also occurs in the decays of the B mesons. It is usually believed that such CP violations can be explained by a theory that concern only the quarks, even though no one knows the correct theory. But if the violation of CP conservation also occurred in lepton decays, then we would need a more general and deeper theory of CP violation. It is possible to search for CP violation in μ and τ decays, with the latter offering many more opportunities for investigation.

Unfortunately, even in τ decays it is difficult to search for CP violation[21]–[23] for a number of reasons:

- The τ has charge, therefore direct CP violation, not mixing, is required.
- The detection of CP violation in decay generally depends upon the interaction of different phases. One cannot search for CP violation if the τ decays only through W exchange. Therefore the detection of CP violation in τ decays generally requires the existence of a second exchange process. This is good news in the sense that the detection of CP violation in τ decay would mean that new physics has been discovered. But it is bad news because there may not be a second exchange process, or if there is such a process its contribution to τ decay may be very small.
- CP violation may be detected by using polarized τ's or unpolarized τ's. In the latter case it is necessary to look for differences between the angular distributions of the decay products of the τ^+ and the τ^-.

I use the decays

$$\tau^\pm \to \nu_\tau + \pi^\pm + K^0$$

to illustrate the requirements for detecting CP violation with unpolarized taus. The W exchange diagram is shown in Fig. 9 and this is called amplitude 1. Under charge conjugation the weak interaction phases at the W vertices change sign, but the strong interaction phase of the final states $\pi^\pm K^0$ does not change sign.

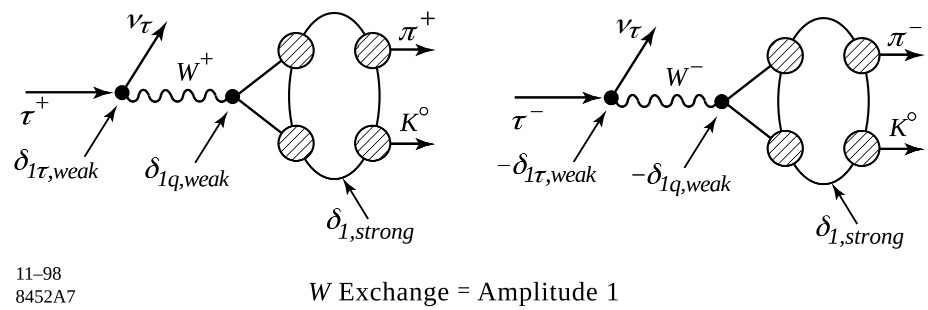

Figure 9: Diagrams for the decays $\tau \to \nu_\tau + \pi^\pm + K^0$ through W exchange showing the phases.

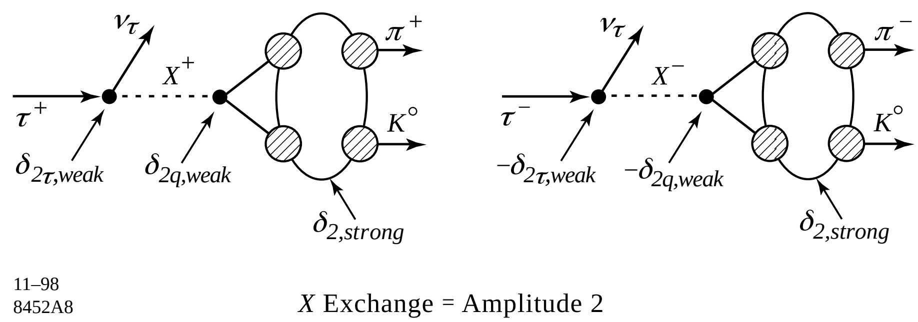

Figure 10: Diagrams for the decays $\tau^\pm \to \nu_\tau + \pi^\pm + K^0$ through X exchange showing the phases.

Figure 10 shows the same decay occurring through an as yet unknown exchange particle X, called amplitude 2. The interference of the X exchange amplitude 2 with the W exchange amplitude 1 can give an asymmetry between the angular distribution of the two charge states if amplitude 2 gives an angular distribution different from amplitude 1.

The first search for CP violation in τ decay has been carried out by CLEO experimenters[24] using mainly the decay mode $\pi^+ K^0_S$ compared to $\pi^- K^0_S$, with the addition of other decay modes. No asymmetry was found in the angular distributions. This null result set the following upper limit on CP violation in these tau decays:

$$g_{\text{CPviolation}} \sin\theta_{\text{CPviolation}} < 1.7g$$

Here $g_{\text{CPviolation}}$ is the coupling constant for the a CP violating effect, $\theta_{\text{CPviolation}}$ is a corresponding phase difference in the amplitudes and g is the standard weak coupling constant. Of course this is not a surprising upper limit. On the contrary we would be surprised if $g_{\text{CPviolation}}$ were anywhere near the size of g.

We should not be disappointed by the null result of this pioneer experiment. There are many improvements that can be made to increase the sensitivity. *With increased statistics in the next decade it will be possible to probe to 1/5 to 1/10 of the present limit.*

CP violation involving leptons can also be sought in the reactions: [23],[25]

$$B \rightarrow \tau + \nu_\tau + \text{hadrons}, \quad B \rightarrow \mu + \nu_\mu + \text{hadrons}$$

using τ or μ decay to measure polarization.

9 The tau neutrino, ν_τ.

The discovery of the tau and the recognition that a tau associated neutrino, ν_τ, also existed led to four questions about the properties of the ν_τ: does the ν_τ have conventional weak interactions; if the ν_τ has a non-zero mass, what is that mass; are there oscillations between the different types of neutrinos, and in particular, does the ν_τ partake in those oscillations; and does the ν_τ have any unusual properties, for example is it stable?

Experimenters have labored for twenty years to try to answer these questions, but we have had little success. It is only in the last year that we may have received positive evidence for a non-zero ν_τ mass and for ν_τ being involved in neutrino oscillations.

9.1 Interactions of the ν_τ?

We are probably about to get evidence about the interactions of the ν_τ with matter from experiments using a ν_τ beam. I have read that a few interactions of the ν_τ have been detected,[26] but there is no physics publication at present.

If other neutrinos oscillate into the ν_τ, higher-energy neutrino oscillation experiments may give us information about ν_τ interactions. Of course for the present we assume the interactions are conventional.

9.2 ν_τ mass.

The direct search for the ν_τ mass using multiparticle hadronic decays of the τ has been a frustrating business. Recent measurements give an upper limit to the ν_τ mass in the range of 20 to 30 MeV/c^2.[27]–[29] There are hopes that experimenters can probe down to the mass range of several MeV/c^2 using this same method of multiparticle hadronic decays with larger statistics. *I am pessimistic.*

Of course the alternate way to explore the ν_τ mass is to use neutrino oscillation phenomena, if they exist for the ν_τ.

9.3 Neutrino oscillations and the ν_τ.

The most exciting particle physics news of this year is the research by the experimenters using the Super-Kamiokande apparatus in Japan.[3] The deficit of muon neutrinos from cosmic ray interactions in the atmosphere can be interpreted as due to oscillations between ν_μ's and ν_τ's. This interpretation and the observations lead to

$$\left|\text{mass}^2(\nu_\tau) - \text{mass}^2(\nu_\mu)\right| = 10^{-2} \text{ to } 10^{-3}\text{eV/c}^2$$

Direct measurement of the ν_μ mass gives an upper limit of 170 keV/c^2; hence the ν_τ mass would have at least the same upper limit. If we think there is no reason for ν_μ and ν_τ to have very close large masses, then the ν_τ mass is of the order of 0.1 eV/c^2 or less.

Continuing with the idea that these observations[3] can be interpreted as due to oscillations between ν_μ's and ν_τ's, one also obtains the mixing angle:

$$\sin^2(2\theta) > 0.8,$$

an amazing result, the mixing being so close to its maximum possible value.

It looks like tau neutrino physics research finally has the needed tools. *We in the tau physics community look forward to verification and broadening of the observations made by the Super-Kamiokande experimenters, as more experiments are turned on in this field.*

9.4 Unconventional ν_τ properties?

Are there other unconventional properties of the ν_τ besides the possibility that it can oscillate into other neutrinos? For example, is the ν_τ stable?

We cannot make much progress in answering such questions until we can directly study the interactions of the ν_τ, see Sec. 9.1. But astrophysical calculations and observations have taught us some things. Other things about the ν_τ have been deduced from terrestrial research using beam dump experiments. The Particle Data Group[5] lists lower limits on the lifetime of the ν_τ and upper limits on the magnetic moment, the electric dipole moment, and the electric charge. The review by Gentile and Pohl[30] also discusses these limits. *As you probably know no anomalies have been found in these quantities.*

10 Dreams and odd ideas in tau research.

I conclude the physics discussions with three examples of the many odd ideas and dreams of the tau research community.

10.1 Tau magnetic moment.

Recall that the magnetic moment of a τ is expected to be[30]

$$\mu_\tau = \frac{g_\tau e h}{4\pi m_\tau}, \quad g_\tau = 2\left[1 + a_\tau\right], \quad a_\tau = \frac{\alpha}{2\pi} + O\left(\frac{\alpha}{\pi}\right)^2 + ...$$

The Schwinger term, $\alpha/2\pi$, in a_τ has the value

$$a_\tau = 0.0012.$$

It would be very nice to measure μ_τ with enough precision to check this, as it was checked for the e and the μ years ago. *At present such precision is a dream.* The best that has been done so far is to use the decay $Z^0 \rightarrow \tau^+ + \tau^- + \gamma$. Acciarri *et al.*[31] found the limits

$$a_\tau = 0.004 \pm 0.027 \pm 0.023;$$

thus the limits are an order of magnitude larger than the expected value.

10.2 Is τ decay exponential?

Alexander *et al.*[32] have examined the distribution of the decay time of individual τ's to test if the decay distribution is exponential. The τ, being a relatively heavy elementary particle, is a good specimen for such a test. They find that τ decay is quite ordinary; it is exponential to better than 10%.

10.3 A τ^+-τ^- atom and a τ^- nucleus atom?

One of my dreams is to make τ^+-τ^- atoms, in analogy to e^+-e^- atoms, positronium. This can be done just below τ pair threshold at a Tau-Charm factory.[33]–[37] It would be a *tour de force*; perhaps it might be a way to look for new physics, although I admit that is a very long shot. One can also think about making a τ-nucleus atom, in analogy to mu-mesic atoms; again a long shot.[33]

11 Tau research facilities in the next decade.

11.1 Present tau research facilities.

The major existing collections of tau data are:

- The CLEO experimenters have about 10^7 τ pairs collected at 10 GeV; the analysis of this data is continuing.

- The ALEPH, DELPHI, L3, OPAL and SLD have each collected about 10^5 or more τ pairs from Z^0 decays. The analysis is mostly completed; the SLD experimenters may collect more data. Note that the efficiency of using τ pairs in analysis is 2 to 5 times higher at 91 GeV, the Z^0 energy, compared to 10 GeV.

- The BEPC experimenters have about 10^5 τ pairs collected in the 4 GeV region.

11.2 Future tau research facilities.

In the next few years three very high luminosity B factories will begin full operation at about 10 GeV; these are: the symmetric CLEO III-CESR III facility in New York, the asymmetric Belle-KEKB facility in Japan, and the asymmetric BABAR-PEPII facility in California. Each of these facilities expect initial luminosities in full operation of 1×10^{33} cm^{-2}s^{-1}; this will yield 1.5×10^7 τ pairs/year. (I assume 1.5×10^7 seconds/year for data acquisition.) Once the design luminosities for these facilities of 3×10^{33} cm^{-2}s^{-1} is reached, each facility will yield 5×10^7 τ pairs/year. Another factor of 3 increase in τ pairs/year will be obtained if the perhaps dream luminosity of 1×10^{34} cm^{-2}s^{-1} is obtained.

Some final remarks. The upgrade of BEPC will yield about 3 to 5×10^5 τ pairs/year. Meanwhile there will be continual production of τ pairs at the LEP experiments for the next few years. Since the energy will be above 180 GeV, the number of τ pairs will be relatively small. Still it will be interesting to see if there is any anomaly in the cross section for $e^+ + e^- \to \tau^+ + \tau^-$ at this very high energy.

In the past decade there has been much work on the concept of a Tau-Charm factory: a high luminosity electron positron collider designed to operate primarily in the 3 to 4 GeV region.[34]–[37] The facility would include a detector designed specially for the study of tau physics and charm physics. At present there are no firm plans to build a Tau-Charm factory.

In conclusion:

- *In the next decade the amount of accumulated τ decay data will increase by a factor of ten and perhaps eventually by another factor of ten!*
- *Full and fruitful use of this increased statistics will require substantial improvements in increasing the precision and decreasing the bias of existing particle detectors.*
- *Tau physics has a marvelous future.*

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In this paper I have depended a great deal on some recent reviews of tau physics: Pich,[9] Gentile and Pohl,[30] and Weinstein and Stroynowski.[38] I recommend these reviews to the reader.

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