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A Perspective On Tau Physics

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A Perspective On Tau Physics *‡

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It will soon be the twenty fifth anniversary of the discovery of the tau lepton. It has been an amazing twenty five years for tau physics and for the strong interaction physics that can be deduced from studies of tau decays. The discovery of the tau was based on the elucidation of the nature of about one hundred tau pairs. At this Fifth International Workshop on Tau Lepton Physics new results in tau physics are based on hundreds of thousands or even millions of tau pairs. In the next two decades we will see the data on tau pairs increase by at least a factor of ten. The theoretical work and theoretical understanding of tau physics and tau neutrino physics has also expanded enormously, and this theory will continue to grow in its reach and its depth. Given the vastness of this field and the recognition that there is always great uncertainty in predicting future directions and accomplishments in a scientific field; any perspective of the future of a scientific field is substantially dependent on the author's opinions and guesses. I have limited this talk to seven topics: tau research facilities in the next decades, searching for unexpected tau decay modes, searching for additional tau decay mechanisms, radiative tau decays, tau decay modes of the *W*, *B*, and *D*, searching for CP violation in tau decay, and rethinking the Tau-Charm factory.

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1. A PERSONAL VIEW ON THE PRACTICE OF SCIENCE

Contrary to textbooks on the scientific method, in spite of the claims of the philosophers of science, there is no one best way to practice science. Indeed, it is the diversity of the ways of doing science that brings excitement and progress to science. I will tell you my personal rules for practicing experimental science, and it is these rules that have led me to my perspective on the future of tau physics. Others will have different perspectives because their ways of doing science are different.

These are my rules for practicing experimental science:

a. The experimenter must take account of his or her personality in choosing problems to work on, apparatus to build and experiments to do. I like to work using relatively simple concepts and hence I am most interested in the simpler parts of tau physics.

b. It is best to use your own ideas in experiments. I stay away from those parts of tau physics that are dependent on complicated theoretical work by others.

c. For every good idea expect to have five or ten or twenty bad ideas. Hence I am willing to risk wasting time and energy on speculative searches in tau physics. One of those searches may be a good idea.

d. To get started in a new experiment don't wait until you fully understand what to do, just start.

e. You have to learn the art of obsession in experimental science, when to work obsessively, when to keep pressing to improve a measurement and when to give up. I am still obsessed with the idea that detailed studies of tau physics may lead to radically new insights into the nature of elementary particles. I may be wrong, it could be time to give up this obsession. But I am not yet prepared to do so; hence much of this perspective has to do with searches for new insights into particle physics.

I briefly discuss tau neutrino research. The recent important experimental results on neutrino oscillations and their possible implications are well known, and they are thoroughly reviewed and discussed in this Workshop.

I apologize for not having the time to talk about the use of the tau to study the physics of hadrons, a vast and fruitful research area. This area is also thoroughly reviewed and discussed in this Workshop.

I have taken much of the material in this talk from my June 1998 tau physics review at the Fifth International WEIN Symposium.

I often use the same notation for neutrinos and antineutrinos, for the sake of notational simplicity.

The plan of this paper is as follows:

Sec.2: Tau Research Facilities in the Next Decades.
Sec. 3: Searching for Unexpected Tau Decay Modes.
Sec. 4: Searching for Additional Tau Decay Mechanisms.
Sec. 5: What Can We Learn from Radiative Tau Decays?
Sec. 6: What Can We Learn from the Tau Decay Modes of the *W*, *B*, and *D*?
Sec. 7: Is There CP Violation in Tau Decay?
Sec. 8: The Tau Neutrino.
Sec. 9: Rethinking the Tau-Charm Factory

2: TAU RESEARCH FACILITIES IN THE NEXT DECADES

2.1. Present tau data

The status of existing collections of tau data is as follows:

CLEO (10 GeV): 1.1×10^7 τ pairs collected, ongoing analysis, (decay mode selection efficiency usually less than 20%)

BEPC (~4 GeV): about 10^5 τ pairs collected, ongoing analysis

ARGUS (10 GeV): analysis completed

ALEPH, DELPHI, L3, OPAL, SLD (Z^0): several $\times 10^5$ τ pairs collected, analysis mostly completed, (decay mode selection efficiency as high as 70%)

ALEPH, DELPHI, L3, OPAL (>100 GeV): small number of events

2.2.Data expected in next decades

The three B-factories:
CLEO III-CESR III (10 GeV symmetric), *BELLE- KEKB* (10 GeV asymmetric), and *BABAR-PEP II* (10 GeV asymmetric), will provide greatly increased amounts of tau data. I assume 1.5×10^7 seconds/year for data acquisition. Then each of these facilities with initial luminosities of 1×10^{33} cm^{-2}s^{-1} will yield 1.5×10^7 τ pairs/year.

Once the design luminosities of 3×10^{33} cm^{-2}s^{-1} are 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.

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 180GeV, 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 of

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

at this very high energy.

What about a Tau-Charm factory in the next decades? Until recently there was the hope that a firm decision would have been made by now to construct a Tau-Charm factory in Beijing, China. But no such decision has been made. With three B-factories soon going into operation time, it would be wise to study again and perhaps to revise the purposes of, and designs for, a Tau-Charm factory. This is briefly discussed in Sec. 9.

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 1 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.

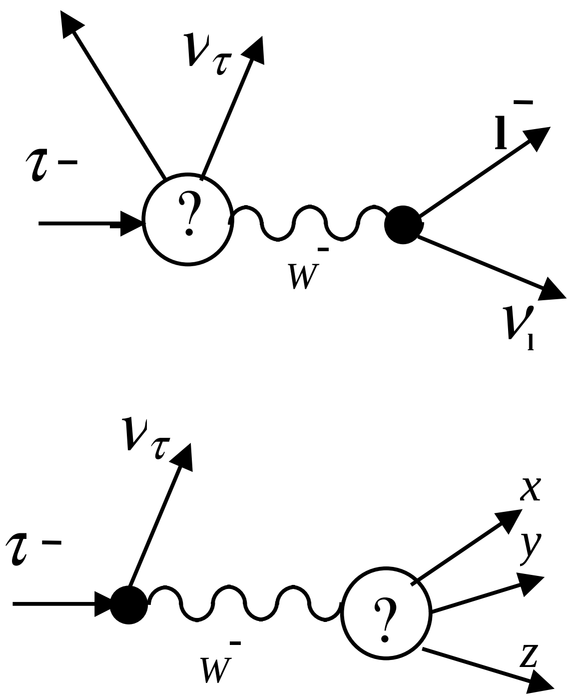


Figure 1. Unexpected decay modes of the tau. In this paper I use ν to represent a neutrino and an antineutrino.

However at present there are no unexpected decay modes. 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%.
- Lepton number violation such as $\tau\to\mu\gamma$ has not been observed. CLEO experimenters [1] have set the branching fraction upper limit $B(\tau\to\mu\gamma) < 3\times10^{-6}$ s. Other lepton number violating modes have similar almost as 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 [2] $B=3\times10^{-5}$.

Still I continue to think about the possible existence of unexpected decay modes, and whether there other ways to search for such modes. I don't have a good idea for a new search method.

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. 2? For the sake of brevity the discussion and examples in this section are limited to the pure leptonic decays.

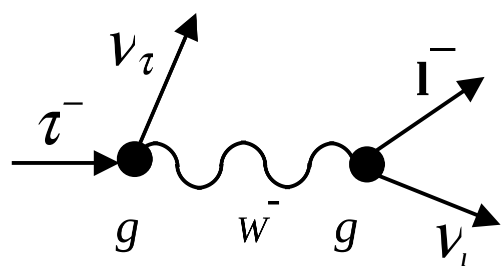


Figure 2. Standard decay route for tau.

The well known matrix element for this process is:

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

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

I use the nomenclature of Fetscher [3] where V means a vector interaction and the LL means that both neutrinos are left handed. The weak coupling constant is g.

In the realm of new physics, a scalar interaction, Fig. 3, might exist.

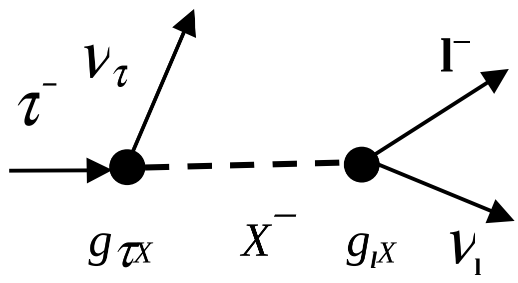


Figure 3. Possible scalar interaction in tau decay to leptonic modes.

The matrix element would be:

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

The only constraint on $m^S{}_{LL}$ is a constraint on an additive combination of $|m^S{}_{LL}|^2$ and $|m^V{}_{LL}|^2$ [4], hence a small amount of this scalar interaction is certainly possible

There could also be a small second vector interaction, Fig. 4..

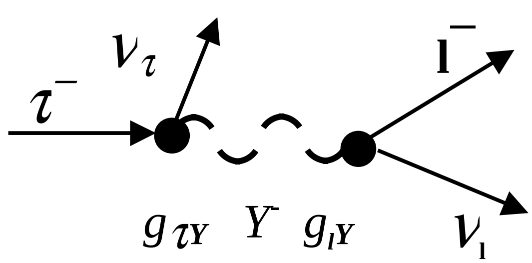


Figure 4. Possible additional vector interaction in tau decay to leptonic modes.

The matrix element would be:

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

From measurements of the τ lifetime and leptonic branching fractions, we derive a leptonic width, *Γ(lep,meas),* and compare it with *Γ(lep,theor)* using standard V-A theory. This limits $m^{V'}{}_{LL}$ as follows:

$$|m^{V'}{}_{LL}/\, m^V{}_{LL}| < 5 \times 10^{-3}$$

Hence there are constraints on the coupling constants in Fig. 4 and on the mass of the *Y*.

Thus in searching for additional decay mechanisms:

(a) we can continue to improve measurements of leptonic decay parameters,

(b) we can continue to improve measurements of the τ lifetime and leptonic branching fractions,

(c) and in addition we should 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.

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 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

$$\tau^- \to \nu_\tau + e^- + \bar{\nu}_e + \gamma$$
$$\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu + \gamma \qquad (1)$$

and the semileptonic decays

$$\tau^- \to \nu_\tau + \pi^- + \gamma$$
$$\tau^- \to \nu_\tau + \rho^- + \gamma \qquad (2)$$

The conventional theory of radiative leptonic decays of charged leptons is well established [5-7]. Therefore these decays, Eq. 1, are good for looking for unexpected tau decay phenomena. The semileptonic decays, Eq. 2, will be valuable for the study of *W*-hadron vertices [8]. In this talk I will concentrate on the radiative leptonic decays.

The standard diagrams for radiative leptonic decay are given in Fig. 5. 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 $(M_\tau/M_W)^2$ [9,10].

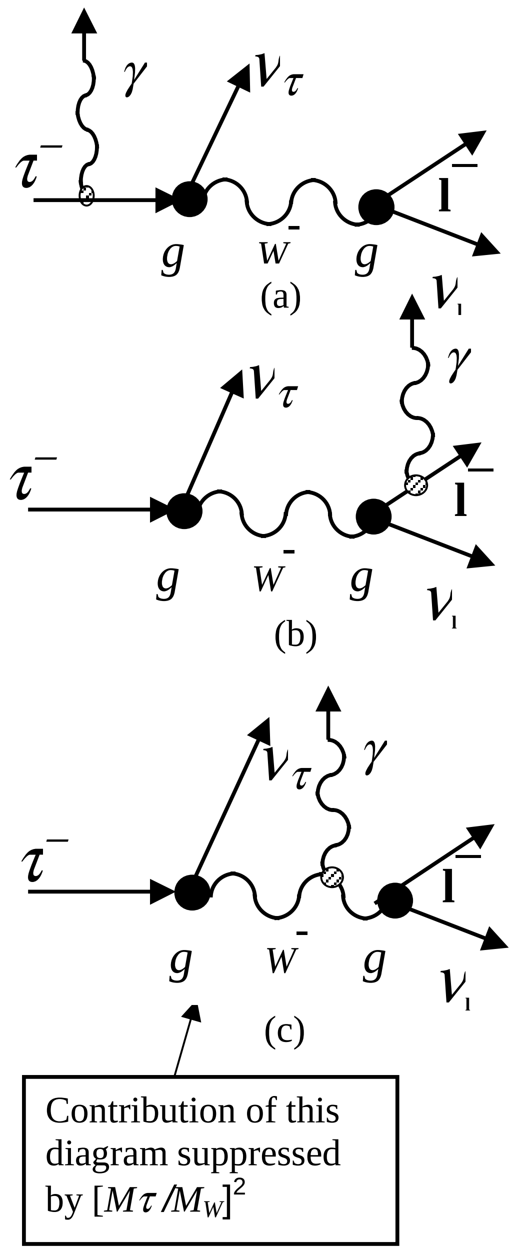
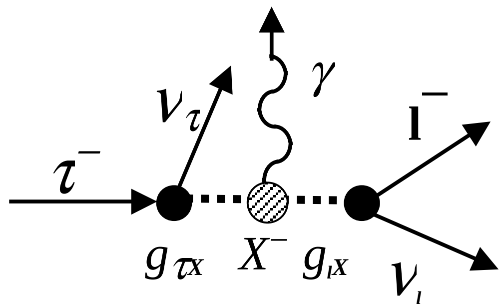
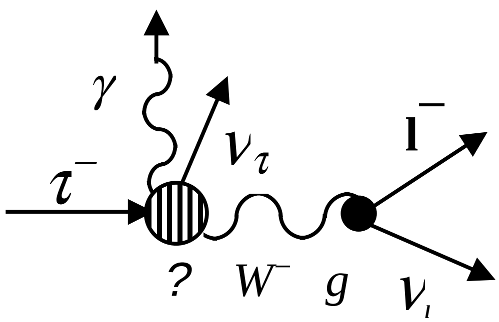


Figure 5. Diagrams for radiative tau decay. The symbol l means *e* or μ.

There are two types of anomalous, radiative, leptonic decay process that might exist, that we might dream about. As shown in Fig. 6a, there might be an unknown particle X that can also be exchanged in leptonic tau decays. Figure 6b points out the possibility



(a)



(b)

Figure 6. Possible types of anomalous, radiative, leptonic decays: (a) radiation from the exchange of particle X and (b) anomalous radiation from the τ-W vertex.

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 it's 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. On the other hand we require that the X be not yet detected in studies of non-radiative leptonic decays of the tau. In term of the coupling constants and m_X this requires

$$\left|\frac{g_{\tau x}g_{\ell x}}{m_x^{\;2}}\right| << \left|\frac{g^2}{m_W^2}\right| \qquad (3)$$

The radiative, muonic decay of the τ has been studied by the OPAL experimenters [11], they find:

$$B(\tau\to\nu_\tau\mu\ \nu_\mu\,\gamma) = (3.0\pm0.4\pm0.5)\times10^{-3}$$

for γ energies above 20 MeV in the τ rest frame. No anomalous behavior was found. CLEO experimenters [12] are now studying the electronic and muonic radiative decays radiative decays.

The major background in these studies is

$$e^+ + e^- \to \tau^+ + \tau^- + \gamma, \qquad (4)$$

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. 7, 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. 5 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 $e^+e^- \rightarrow \tau^+\tau^-\gamma$ radiation.

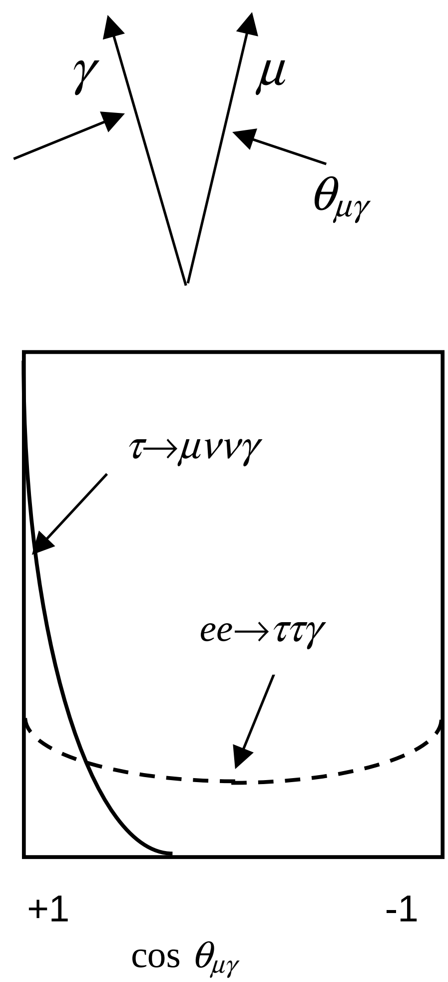


Figure 7. Schematic comparison of $\tau\rightarrow\mu\nu\nu\gamma$ signal and $e^+e^- \rightarrow \tau\tau\gamma$ background.

We will have to find some new ways to explore the radiative decays of the tau.

6. WHAT CAN WE LEARN FROM THE TAU DECAY MODES OF THE *W*, *B*, AND *D*?

6.1. $W \rightarrow l + \nu_l$

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 [13] gives the following branching fractions:

$B(W \rightarrow e + \nu_e) = 0.109 \pm 0.004$
$B(W \rightarrow \mu + \nu_\mu) = 0.102 \pm 0.005$
$B(W \rightarrow \tau + \nu_\tau) = 0.113 \pm 0.008$

It will be difficult to improve the precision of these measurements.

6.2. $D \rightarrow \mathrm{l} + \nu_l$, $B \rightarrow \mathrm{l} + \nu_l$

The decay widths for

$D^+ \rightarrow \mathrm{l}^+ + \nu_l$, $D_s^+ \rightarrow \mathrm{l}^+ + \nu_l$, $B^+ \rightarrow \mathrm{l}^+ + \nu_l$

are given by

$$\Gamma\left(M^+ \rightarrow \nu_\ell + \ell^+\right) = \frac{G_F^2}{8\pi\hbar} f_M^2 V_{qq'}^2 m_M m_\ell^2 \left[1 - \left(\frac{m_\ell}{m_M}\right)^2\right]^2 \qquad (5)$$

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 1, I give the branching fractions using Eq. 5, assuming $f_M = 200$ MeV.

Table 1. Branching fraction for the purely leptonic decay, $M \to l + \nu_l$, 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 2. Comparison with theory of the measured branching fraction for the purely leptonic decay, $M \to l + \nu_l$, of a D or B meson. The meson decay constant f_M 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}
$D_s \to \mu\nu$	$(4.0\pm2.1) \times 10^{-3}$	3×10^{-3}
$D_s \to \tau\nu$	$(7\pm4) \times 10^{-2}$	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}

Table 2 presents a comparison with theory of the measured branching fraction for the purely leptonic decay, $M \to l + \nu_l$, 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 we cannot hope to find new physics by looking for small differences between calculated and measured values of $B(M \rightarrow l\ \nu_l)$ for a particular decade mode. However large differences between calculated and measured values of $B(M \rightarrow l\ \nu_l)$ for a particular decade mode 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 2 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. $B \rightarrow \tau^+ + \tau^-$

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

$$B_d^0 \rightarrow \tau^+ + \tau^-$$
$$B_s^0 \rightarrow \tau^+ + \tau^-$$

Grossman et. al. [14] predict a branching fraction of 10^{-6} to 10^{-8}. Not easy. The present measured upper limits are a few per cent.

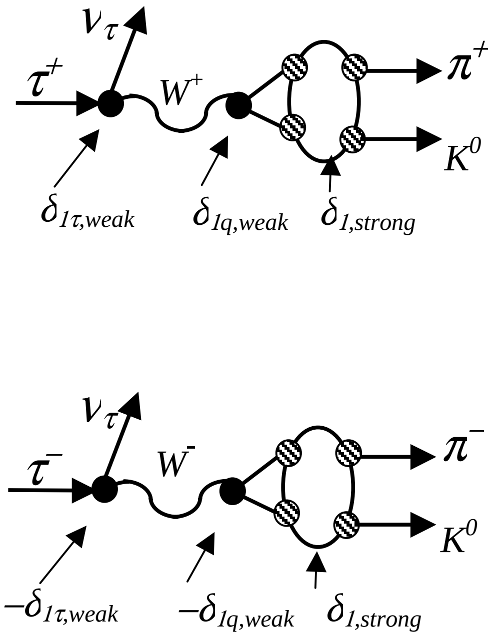
7. IS THERE CP VIOLATION IN TAU DECAY?

Nature is cruel! For several reasons it is difficult to search for CP violation in the decays of the tau. [15-17]

- 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 tau decays generally requires the existence of a second exchange process. This is good news in the sense that the detection of CP violation in tau decay means 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 tau decay may be very small.

- CP violation may be detected by using polarized taus or unpolarized taus. 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^-.



***W* exchange = Amplitude 1**

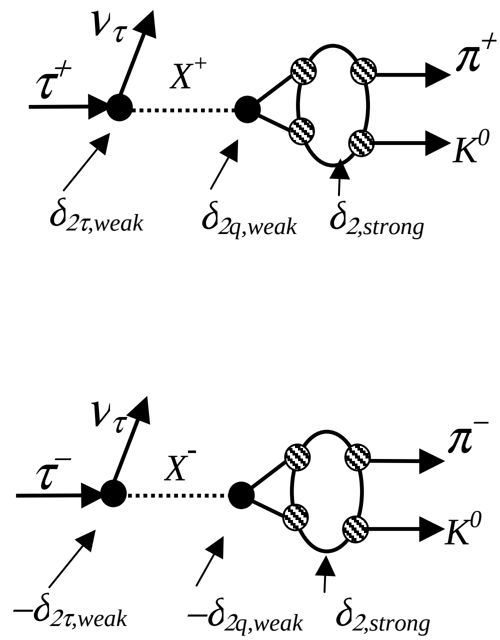
Figure 8. Diagrams for the decays $\tau^\pm \to \nu_\tau + \pi^\pm + K^0$ through *W* exchange showing the phases.

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. 8 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 shows the same decay occurring through an as yet unknown exchange particle *X*, called amplitude 2.



***X* exchange = Amplitude 2**

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

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 [18] using mainly the decay mode:

$\pi^+ K_S^0$ compared to $\pi^- K_S^0$.

The CLEO experimenters did not find any asymmetry in the angular distributions between the + and – charge states.
The null result set the following upper limit on CP violation in these tau decays:

$$g_{CPviolation} \sin \theta_{CP\ violation} < 1.7\ g_W$$

Here $g_{CP\ violation}$ is the coupling constant for the a CP violating effect, $\theta_{CP\ violation}$ is a corresponding phase difference in the amplitudes and g_W is the standard weak coupling constant. This experiment is discussed in further detail by Kass [19] at this Workshop.

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 and better K-π separation 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 [17,20]:

$$B \rightarrow \tau + \nu_\tau + \text{hadrons}$$

as well as

$$B \rightarrow \mu + \nu_\mu + \text{hadrons}$$

using τ or μ decay to measure polarization. I do not have the space to discuss these interesting experimental proposals. The τ experiment can be carried out using the B-factory detectors as now constructed. The μ^- experiment requires an addition to these detectors to detect $\mu \rightarrow e\ \nu_e\ \nu_\mu$

8. THE TAU NEUTRINO

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 unstable?

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

8.1 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 [21], 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.

8.2 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 mass in the range of 20 to 30 MeV/c^2 [22-24].

In the discussions of τ and ν_τ physics to be carried out at new electron-positron colliders, one often sees arguments that the ν_τ mass can be probed down to a few MeV/c^2 using multiparticle hadronic decays. I have probably made those arguments myself. But as I watched the struggles that achieved the aforementioned upper limits, I began to wonder if a few MeV/c^2 can be attained. There are uncertainties having to do with the expected kinematic distributions when the visible energy of the hadronic decay is close to the tau mass, and there are uncertainties in how to correct for contamination by events from other types of tau decays.

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

8.3 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 [25]. 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

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

Direct measurements give mass(ν_τ) < 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, than the ν_τ mass is of the order of 0.1 eV/c^2 or less.

Continuing with the idea that these observations [25] 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.

It should be noted that this first substantial progress in ν_τ physics has been made, not using an electron-positron collider, not using an accelerator produced neutrino beam, but using a cosmic ray detector. I will return to this point in Sec. 9.

8.4 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, might the ν_τ be unstable?

We cannot make much progress in answering such questions until we can directly study the interactions of the ν_τ, Sec. 8.1. 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 [13] 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. As you know no anomalies have been found in these quantities.

9. RETHINKING THE TAU-CHARM FACTORY

The stimulating talks and discussions at this Fifth International Workshop on Tau Lepton Physics turned my thoughts to the decade old concept of a Tau-Charm factory. Should we explore again the physics potential, accelerator requirements, and detector requirements for a Tau-Charm factory?

9.1 The Tau-Charm factory concept

The Tau-Charm factory concept was invented by J. Kirkby [26] and J. Jowett [27]. It consists of a two ring electron-positron collider and specially designed detector. The initial design luminosity was $10^{33}cm^{-2}s^{-1}$, some recent studies considered $3\times10^{33}cm^{-2}s^{-1}$ Figure 10 shows the proposed energy range. There is a great deal of information in the proceedings of the half dozen workshops on the Tau-Charm factory [28].

9.2 τ physics at the Tau-Charm factory

In the original concept, tau physics would be studied at three energies shown in Fig. 10:

- τ data acquired just above the τ pair threshold, 3.57 GeV, would be used for special studies.
- τ data acquired just below the Ψ',3.67 GeV, would be free of contamination from charm meson decays. In addition any unconventional τ decay phenomenon detected at 3.67 GeV could be checked for

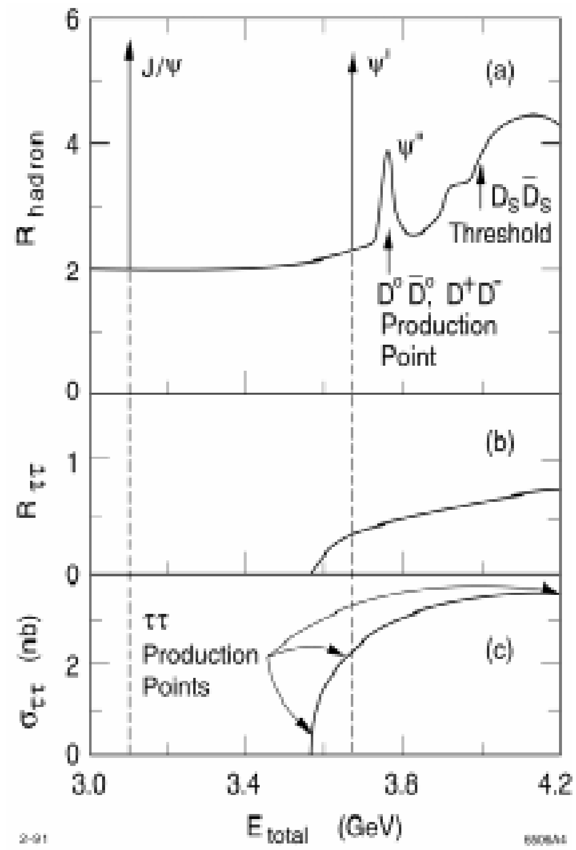


Figure 10. Energy range and major operating points for the Tau-Charm factory.

hadronic contamination by running just below the τ pair threshold. The hadronic background would be almost constant between those two energies. The τ pair production cross section here is 2.4 nb. Most τ studies would occur at this energy.

- The τ pair cross section reaches its maximum value of 3.5 nb at 4.25 GeV, but at this energy there is substantial charm particle production and decay. Hence this is not a clean region for tau studies, its only virtue is the large cross section.

9.3 *D* physics at the Tau-Charm factory

In the original Tau-Charm factory concept, charm physics would be studied at the two energy regions shown in Fig. 10.

• At the Ψ'' the *D* mesons are produced in pairs:

$$e^+ + e^- \rightarrow D^+ + D^-$$

$$e^+ + e^- \rightarrow D^0 + D^0$$

These are simple quantum mechanical states compared to the *D* states produced at higher energies or from *B* decays.

• The energy region from the Ψ'' to 4.2 GeV is made up of a complicated set of charm physics thresholds. Past studies of the *D* physics at a Tau-Charm factory argued for the value of studying this energy region in detail.

9.4 Rethinking the Tau-Charm factory.

New generations of experimenters are now working in tau physics. Will these experimenters be able to carry out all their tau physics dreams using the B-factories. To answer this question it is important to restudy the value and purpose of a Tau-Charm factory. I have a number of comments and questions that such a study should consider.

• In the ten years since the invention of the Tau-Charm factory idea, many additional collider, detector and physics goal have been added; the concept has lost its focus. I begin with some examples.

• Is it still worthwhile to design a Tau-Charm factory to operate in the upper energy range of Fig. 10, above 3.8 GeV? As I already noted the tau physics in the upper energy range is not clean, and I wonder if the charm physics is worth the effort. Would reducing the maximum energy to about 3.8 GeV reduce collider costs?

• Going further, perhaps the Tau-Charm factory should be just a Tau factory? This would make a more efficient facility because in a Tau-Charm factory one cannot simultaneously do tau physics and charm physics. Does the elimination of charm physics simplify the detector? Can charm physics be done just as well at a B-factory or in a fixed target experiment?

• I believe it was an unwise proposal that the Tau-Charm factory be designed with the option of a nearly monochromatic energy spread for enhanced luminosity at the Ψ.

• On the other hand I like the proposal for a longitudinally polarized electron beam.

• More study should probably be devoted to the physics that can be done by operating the Tau-Charm factory at, and just below, the τ pair threshold. For example, it may be possible to detect the formation of the τ^+-τ^- atoms.

• A new study of the tau physics possibilities at a Tau-Charm factory should pay more attention to two data analysis questions. How clean will be the separation of a τ pair event from an $ee \rightarrow$ hadrons event? How serious is the contamination of one tau decay mode by another tau decay mode?

• In connection with the first of these two questions some thought should be given to the idea of an asymmetric Tau-Charm factory. Detection of the τ decay vertex would definitely identify a τ pair when the energy is too low for charm pair production.

• A new study should explore the differences in tau, and perhaps charm, physics potential between the Tau-Charm factory and the B-factories. Here I am thinking by analogy about the recent great success of the Super Kamiokanda experimenters. If the recent results are correct [25] they have made the most important elementary particle physics discovery in more than a decade. And they accomplished this by *not* following the present popular path of building higher energy colliders, they built a unique scientific instrument. In the same way a Tau-Charm factory *may* be a unique scientific instrument. The overall goal of a new study of the Tau-Charm factory concept should be to determine if it *will* be a unique scientific instrument.

10. FINAL REMARKS.

There is a tremendous amount of grand τ physics that will be done at the B-factories and at the CESR-CLEO facility; and, if it is built, at a Tau-Charm factory. But it will require new ideas, new techniques, work and patience. This is summed up in two proverbs of Spain:

No hay atajo sin trabajo.

De los arroyos chicos se hacen los grandes ríos.

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