TAU LEPTON PHYSICS AT A TAU-CHARM FACTORY*

Martin L. Perl

Stanford Linear Accelerator Center

Stanford University, Stanford, California 94309

ABSTRACT

A two-day workshop, "The Tau-Charm Factory in the Era of B-factories and CESR," was held at SLAC in August, 1994. This paper summarizes the important research on the tau lepton which could be done at a tau-charm factory in the next decade. It is based on the presentations by the speakers and on the discussions by participants, as well as on published papers.

* This work was supported by the Department of Energy, contract DE-AC03-76SF00515.

TABLE OF CONTENTS

A. INTRODUCTION

On August 15 and 16, 1994, a group of experts on tau lepton physics, charm quark physics and charmonium physics gathered at a Workshop at SLAC to consider the physics potential of a tau-charm factory which might be built during the next six or more years (Zheng 1994, Wu 1994). Thus, this tau-charm factory would come into operation after a great deal of new tau and charm physics research had been carried out at CESR, LEP I, fixed target experiments at Fermilab and BEPC; this research having been added to that which exists at present. In addition, two B-factories will be in operation and there might be new fixed target charm experiments at Fermilab.

My task is to summarize in the area of tau lepton physics the presentations and discussions of the Workshop participants. It is difficult to try to look a decade ahead in particle physics and so my summary contains comparisons of the various techniques, some conclusions, quite a few guesses, and many suggestions for further studies of the potential for tau research at a tau-charm factory. Overall, the tau research carried out at a tau-charm factory will broaden and deepen our knowledge of the physics of the tau, because the tau-charm factory provides unique methods for studying the tau (Zheng 1994, Huang 1994).

Much of the tau discussions at the Workshop and the contents of the summary were based upon the detailed review of tau research using the CLEO II detector at CESR by Besson (1994) and the detailed review of tau research at LEP by Harton (1994). The discussions on beam polarization and CP violation in τ decays were based on the papers by Tsai (1994) and Prepost (1994). The paper on tests of tau lepton universality by Rizzo (1994) was also valuable. I use for general reference the rapporteur talk of Patterson (1994) and the reviews of Weinstein and Stroynowski (1993) and Perl (1993b).

Most of my references for a tau-charm factory machine and detector come from the Proceedings of the Third Workshop on the Tau-Charm Factory (Kirkby and Kirkby 1994) held at Marbella, Spain in June, 1993.

In this summary, I mainly compare the tau physics potential of a tau-charm factory with the present and projected tau research of CESR and LEP I and with the projected tau research at the B-factories now under construction in Japan and the United States. CESR refers to the present and future upgrades of the CESR collider and the CLEO detector including CP violation B physics. I use the term B-factory to mean the asymmetric B-factories being built in Japan and the United States.

B. TAU-CHARM COLLIDER AND DETECTOR PARAMETERS: COMPARISON WITH OTHER TAU RESEARCH FACILITIES

B.1 Luminosity and Tau Pair Production

At a tau-charm factory (Kirkby 1994, Fan 1994) there are three preferred energies for tau research:

$$\begin{aligned} &\text{Just above threshold at } E_{cm} = 3.56 \text{ GeV} : \sigma_{\tau\tau} = 0.5\,\text{mb} \\ &\text{Just below the } \psi' \text{ at } E_{cm} \quad = 3.67 \text{ GeV} : \sigma_{\tau\tau} = 2.4 \text{ mb} \\ &\text{Maximum } \sigma_{\tau\tau} \text{ at } E_{cm} \quad = 4.25 \text{ GeV} : \sigma_{\tau\tau} = 3.5 \text{ mb} \quad . \end{aligned} \tag{1a}$$

The design luminosity of a tau-charm factory is

$$\mathcal{L} = 10^{33}\text{cm}^{-2}\text{s}^{-1} \tag{1b}$$

at $E_{cm} \sim 4$ GeV. Ultimate luminosities 3 or 4 times larger have been discussed (Le Duff, 1994) but for the first years of operation $10^{33}\text{cm}^{-2}\text{s}^{-1}$ is a substantial goal.

Using $\mathcal{L} = 10^{33}\text{cm}^{-2}\text{s}^{-1}$ and a 10^7s data acquisition year, the number of produced τ pairs, $N_{\tau\tau}$ will be

$$\begin{aligned} &E_{cm} = 3.56 \text{ GeV} , N_{\tau\tau/\text{year}} = 0.5 \times 10^7/\text{year} \\ &E_{cm} = 3.67 \text{ GeV} , N_{\tau\tau/\text{year}} = 2.4 \times 10^7/\text{year} \\ &E_{cm} = 4.25 \text{ GeV} , N_{\tau\tau/\text{year}} = 3.5 \times 10^7/\text{year} \quad . \end{aligned} \tag{1c}$$

B.2 Comparisons with LEP, CESR and B-Factory Tau Pair Production

The tau pair cross section at CESR or a B-factory operating in the 10.6 GeV upsilon energy region is

$$\sigma_{\gamma\gamma} = 0.78 \text{ mb} \quad . \tag{2a}$$

At present CLEO (Patterson 1994) has

$$\mathrm{N}_{\tau\tau} = 2.5 \times 10^6 \quad , \tag{2b}$$

and by the year 2000 is projected (Besson 1994) to have

$$\mathcal{L} > 1 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1} \quad , \tag{2c}$$

$$\begin{gathered} \int \mathcal{L} \mathrm{dt} \cong 30 \text{ fb}^{-1} \\ \mathrm{N}_{\tau\tau}(\text{total}) = 2.3 \times 10^7 \quad . \end{gathered} \tag{2d}$$

Beyond the year 2000 CESR is projected (Besson 1994) to reach $\mathcal{L} = 3 \times 10^{33}$. Once a B-factory or CESR reaches the luminosity of $3 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, a 10^7s data acquisition year will yield

$$\mathrm{N}_{\tau\tau}/\text{year} = 2.3 \times 10^7/\text{year} \quad . \tag{2e}$$

Turning to LEP, at present

$$\mathrm{N}_{\tau\tau}/\text{experiment} \sim 9 \times 10^4 \quad , \tag{3a}$$

and this is projected (Harton 1994) to reach

$$\mathrm{N}_{\tau\tau}/\text{experiment} \sim 1.9 \times 10^5 \text{ to } 2.4 \times 10^5 \tag{3b}$$

when research using LEP I is concluded.

B.3 Decay Mode Selection Efficiency

It is not enough to compare the $N_{\tau\tau}$ values in Eqs. 1c, 2d, 2e and 3b, we must take account of the efficiency $\epsilon(x)$ for selecting a τ decay mode, $\tau \rightarrow x$, where the selection criteria include identifying the mode and reducing the contamination from other τ decay modes and from events which are not τ pairs.

The LEP experiments (Harton 1994) have large ϵ's

$$\begin{aligned} \epsilon(\nu_\tau \ell^- \overline{\nu}_\ell) &\simeq .5 - .7 \ , \ \ell = \text{e or } \mu \\ \epsilon(\text{semileptonic}) &\simeq .25 - .6 \quad . \end{aligned} \tag{4}$$

These ϵ's are large because the "back-to-back" τ pair events are easily separated from other events at the Z°.

In the CLEO II detector the ϵ's are smaller, usually

$$\epsilon \leq .2 \quad , \tag{5a}$$

decreasing to

$$\epsilon < .1 \tag{5b}$$

for complicated semileptonic modes. The ϵ's are smaller for τ research in the upsilon region because stronger criteria must be used to remove backgrounds.

At a tau-charm factory the ϵ's are expected to be larger than those in Eq. 5. As discussed by Kirkby (1991), it should be possible to single tag τ pair events at $E_{cm} = 3.56$ GeV and $E_{cm} = 3.67$ GeV by using the purely leptonic mode signatures: e + missing energy energy, μ + missing energy. Kirby (1991) estimates an efficiency of .5 for single tagging of τ pair events. Of course, this must be multiplied by the efficiency for selecting individual decay modes of the other τ. Detailed studies should be done to determine the ϵ's for the research in the 3.56 and 3.67 GeV energy regions and, as discussed next, the expected uncertainty in the ϵ's should also be estimated.

In high statistics measurements of the branching fraction B(x) for $\tau \rightarrow x$, a major error is the uncertainty, $\delta\epsilon(x)$, in $\epsilon(x)$. Quoting Besson (1994), "At CLEO, $\epsilon_{(MC)}$ vs. ϵ_{data} (is)

increasingly the dominant error." The precise determination of ϵ requires, in part, testing ϵ_{MC} using actual track which cover the full range of vector momenta as well as the various particle types. The very high rate of events from the ψ and $\psi\prime$ will be very useful here.

B.4 Tau Pair Spin Correlations and Tau Polarization

Since the work of Tsai (1971) it has been known that the τ spins are correlated. Close to threshold the spin components sum to $+1$ or -1 along an axis parallel to the incident e^+, e^- directions. When the τ's are relativistic the spin components sum to $+1$ or -1 along the τ line of flight. Thus, if the spin direction of one tau is known statistically through a decay channel, then the spin direction, that is the polarization, of the other τ is known statistically.

A more effective way to know the τ polarization is to produce polarized τ's by giving longitudinal polarization to the incident e^- beam, to the incident e^+ beam, or to both beams (Prepost 1994, Tsai 1994, Skrinsky 1994). A polarization of up to

$$P_\tau = 92\% \tag{6}$$

can be obtained by either injecting a transversely polarized beam into the collider or allowing the beam in the collider to become transversely polarized. Spin rotating devices must then be put on either side of the interaction region to produce longitudinal polarization (Prepost 1994, Tsai 1994, Zholents 1992).

Direct τ polarization has two advantages compared to the use of τ spin correlations. First, any polarization dependent measurement will be diluted statistically by a factor of 10 to 100 compared to the same measurement using fully longitudinally polarized τ's. Second, when looking for small effects caused by new physics, a 10^{-2} to 10^{-3} asymmetry for example, the ability to reverse or turn off the polarization, gives much better error control.

Longitudinally polarized beams can be produced in LEP, in CESR, in a B-factory, or in a tau-charm factory; and of course a longitudinally polarized e^- beam is used in the SLC. If such a beam is not eventually introduced in CESR or the B-factories, and it seems unlikely that it will be done, then the tau-charm factory is the best hope for studying τ physics using longitudinally polarized beams.

Before concluding this section, note that the reaction:

$$e^+ + e^- \rightarrow Z^\circ \rightarrow \tau^+ + \tau^-$$

produces τ's with an average longitudinal polarization of 15%. This has been used extensively at LEP (Harton 1994, Weinstein and Stroynowski 1993). However, in view of Eq. 6 and comparative luminosities, the tau-charm factory is much better than LEP I for studying polarized τ physics.

B.5 Reduction of Energy Spread

In the standard design of a tau-charm factory, the standard deviation in E_{cm} is

$$\sigma_{E_{cm}} \simeq .4 \times 10^{-3}\ E_{cm} \quad , \tag{7a}$$

which is larger at the ψ and $\psi\prime$ than the resonance width

$$\Gamma_\psi = 86\ \text{keV}\ ,\ \Gamma_{\psi'} = 278\ \text{keV} \quad . \tag{7b}$$

The peak cross sections are

$$\sigma_\psi(\text{peak}) \sim 3,000\ \text{nb}\ ,\ \sigma_\psi(\text{peak}) \sim 600\ \text{nb} \quad . \tag{7c}$$

However, there are proposals (Zholents 1992, Alexahin 1994) for reducing $\sigma_{E_{cm}}$ to

$$\sigma_{E_{cm}} \sim 100\ \text{keV} \tag{8a}$$

at the ψ and $\psi\prime$ yielding

$$\sigma_\psi(\text{peak}) \sim 20,000\ \text{nb}\ ;\ \sigma_{\psi\prime}(\text{peak}) \sim 5000\ \text{nb} \quad . \tag{8b}$$

In Eq. 8 the $\psi\prime$ width is set by its natural width. For the

$$\psi\prime \rightarrow \tau^+ + \tau^- \tag{8c}$$

decay mode

$$\sigma_{\tau\tau} \text{ (from } \psi\prime) = \sigma_{\psi\prime} \text{ (peak) } B_{ee}\beta_\tau \left(\frac{3-\beta_\tau^2}{2}\right) \quad , \tag{9a}$$

where B_{ee} is the branching fraction for $\psi\prime \to e^+e^-$ and B is the τ velocity. Then

$$\sigma_{\tau\tau} \sim 20 \text{ nb} \quad . \tag{9b}$$

Thus there is a large $\sigma_{\tau\tau}$ at the $\psi\prime$, but it will be difficult to do τ physics with a 200 times larger non-τ cross section. Another use for the reduced $\sigma_{E_{cm}}$ in τ physics is discussed in Section J.

C. PRECISELY CALCULABLE DECAY MODES: $\nu_\tau e^- \overline{\nu}_{\tau me}, \nu_\tau \mu^- \overline{\nu}_\mu, \nu_\tau \pi^-, \nu_\tau K^-$

C.1 Precisely Calculable Decay Modes and Branching Fractions

The decay width and all observable kinematic distributions of the purely leptonic modes

$$\begin{aligned} \tau^- &\to \nu_\tau + e^- + \overline{\nu}_e \\ \tau^- &\to \nu_\tau + \mu^- + \overline{\nu}_\mu \end{aligned} \tag{10}$$

are precisely determined by weak interaction theory. The decay widths of the modes

$$\begin{aligned} \tau^- &\to \nu_\tau + \pi^- \\ \tau^- &\to \nu_\tau + K^- \end{aligned} \tag{11}$$

are precisely determined by the $\pi^- \to \mu^- + \overline{\nu}_\mu$ and $K^- \to \mu^- + \overline{\nu}_\mu$ measured decay widths. Therefore, the ratios

$$B_\mu/B_e \ , \ B_\pi/B_e \ , \ B_K/B_e \tag{12}$$

provide a clear test of measurement with theory and hence a way to look for new physics in τ decays.

How well will these B's be measured? Presently at LEP the average over the four experiments is:

$$B_e = (17.55 \pm 0.13)\%$$

and Harton (1994) projects the error at the end of LEP I research to be $\pm 0.08\%$ giving a

$$\delta B_e / B_e = 0.005 \quad . \tag{13a}$$

The corresponding numbers for B_μ are

$$B_\mu = (17.11 \pm 0.12)\%$$

with the ultimate error $\pm 0.07\%$ giving

$$\delta B_\mu / B_\mu = 0.004 \quad . \tag{13b}$$

The most recent measurement from CLEO II (Akerib *et al.* 1994) is

$$B_e = (17.97 \pm 0.14 \pm 0.23)\% \quad , \tag{14a}$$

where the first error is statistical and the second is systematic. The fractional systematic error can be reduced to 0.01 (Weinstein 1994), so that with sufficient statistics

$$\delta B_e / B_e \approx 0.01 \quad . \tag{14b}$$

The B-factories will have about the same fractional systematic errors for B_e and B_μ. Eventually further reduction in $\delta\ B_\ell / B_\ell$ might be accomplished.

Kirkby (1991) has calculated that

$$\delta B_e / B_e \approx 0.002 \ , \ \delta B_\mu / B_\mu \approx 0.002 \tag{15}$$

might be achieved using a tau-charm factory. This will require an excellent detector, clear and efficient tagging, and a very well understood Monte Carlo simulation for the detector.

Turning to the modes in Eq. 11, the present world average measurements (Patterson 1994) are

$$\mathrm{B_h} = \mathrm{B}(\tau^- \to \nu_\tau \mathrm{h}^-) = (12.03 \pm 0.20)\% \quad , \tag{16a}$$

where $\mathrm{h} = \pi$ or K, and (Alamany 1994)

$$\mathrm{B}_K = (0.68 \pm 0.056)\% \quad . \tag{16b}$$

Thus

$$\mathrm{B}_\pi = (11.35 \pm 0.19)\% \tag{16c}$$

and

$$\delta\mathrm{B}_\pi/\mathrm{B}_\pi = 0.017 \tag{17a}$$

$$\delta\mathrm{B}_K/\mathrm{B}_K = 0.08 \quad . \tag{17b}$$

The final results from the LEP I experiment and further work at CESR will reduce

$$\delta\mathrm{B}_\pi/\mathrm{B}_\pi \approx 0.01 \quad . \tag{17c}$$

Improvements on $\delta\mathrm{B}_\pi/\mathrm{B}_\pi$ using the tau-charm factory depend on the factors listed after Eq. 15.

The large present error on B_K (Eq. 17b) is about half due to limited statistics and about half due to uncertainties in π/K separation. There will not be much improvement from LEP I, perhaps $\delta\mathrm{B}_K/\mathrm{B}_K \approx 0.06$ (Harton 1994). The larger improvement will come from CESR and the B-factories and will depend jointly on increased statistics and better π/K separation systems in the detectors. For example, suppose we desire $\delta\mathrm{B}_K/\mathrm{B}_K = 0.01$ and the statistical error should only contribute 0.025, then the required number of produced τ pairs is

$$\mathrm{N}_{\tau\tau} = 4 \times 10^4/(2\mathrm{B}_K\epsilon_K) = 3 \times 10^6/\epsilon_K \quad . \tag{18}$$

I believe there is an opportunity here for a detector with good π/K separation to contribute not only to the measurement of B_K but to the entire area of K decay modes of the τ:

$$\tau^- \to \nu_\tau + K^{*-}$$

$$\tau^- \to \nu_\tau + K^{*-} + n\pi^\circ, n > 0$$

$$\tau \to \nu_\tau + K^- + K^\circ \quad ,$$

and so forth.

C.2 Comparison of B_l τ_τ, and m_τ

The present world average for the τ lifetime (Timmermans 1994) is

$$\tau_\tau = 291.6 \pm 1.7 \text{ fs} \quad . \tag{19a}$$

The LEP I and SLD experiment can probably reduce the average error to 1 fs, giving

$$\delta\tau_\tau/\tau_\tau \approx 0.003 \quad . \tag{19b}$$

Weinstein (1994) and Gan (1991) have estimated that CESR and B-factories might also achieve $\delta\tau_\tau/\tau_\tau \approx 0.003$ although Weinstein (1994) thinks 0.005 might be more realistic. At present (Timmermans 1994):

$$\frac{g_\tau^2}{g_\mu^2} = \left[\frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 B_e\right] = 0.990 \pm 0.008 \quad , \tag{20}$$

so that the fractional error is 0.008. This error could be reduced by a factor of 2 if $\delta\tau_\tau/\tau_\tau$ in Eq. 19b is attained and if δB_e is reduced. A measurement of B_e or B_μ at a tau-charm factory could be of help. Incidentally, m_τ has already been measured very well by the BES Collaboration, but Fan (1994) has shown that m_τ can be measured with a statistical error of 0.1 MeV c^2 at a tau-charm factory!

D. DYNAMICS OF LEPTONIC DECAYS

The dynamics of τ leptonic decays are described by ten complex constants (Fetscher 1990), but since we are in the infancy of studying the dynamics we limit our consideration to four combinations of these constants, the Michel parameters:

$$\begin{aligned} \rho &: 3/4 \\ \eta &: 0 \\ \xi &: 1 \\ \delta &: 3/4 \end{aligned} \tag{21}$$

The associated numbers are the parameter values if both the $\tau - \nu_\tau - w$ vertex and the $\ell - \nu_\ell - w$ vertex are V−A. Deviations from the values in Eq. 21 will mean that the τ is *not* a standard lepton; hence new physics.

Ignoring radiative effects, the leptonic spectrum is given by

$$\begin{aligned} \frac{d\Gamma}{dx\, d\cos\theta} \;\alpha\; x^2 \Big\{ & 12(1-x) + \rho\left(\frac{32\, rmx}{3} - 8\right) \\ & + \eta\, \frac{m_\ell}{m_\tau}\, \frac{24(1-x)}{x} - P_\tau \xi \cos\theta \left[4(1-x) + \delta\left(\frac{32x}{3} - 8\right)\right]\Big\} \end{aligned} \tag{22}$$

Here $x = 2E_\ell/m_\tau$ and θ is the angle between the τ spin and ℓ momentum, both in the τ rest frame. P_τ is the τ polarization. The parameters ρ and γ can be determined from $d\Gamma/dx$. The parameters ξ and δ require either directly polarized τ's or the use of the τ spin correlation as discussed in Section B4.

Present world average values (Patterson 1994) are

$$\begin{aligned} \rho &= .757 \pm 0.024 \\ \eta &= 0.03 \pm 0.22 \\ \xi &= 1.03 \pm 0.12 \\ \delta &= 0.75 \pm 0.17 \quad . \end{aligned} \tag{23}$$

Harton (1991) projects the following ultimate errors from the combined LEP I experiments:

$$\begin{aligned} \rho &\quad \pm 0.025 \\ \eta &\quad \pm 0.07 \\ \xi &\quad \pm 0.10 \text{ or better} \\ \delta &\quad \pm 0.10 \text{ or better} \quad . \end{aligned} \tag{24a}$$

I do not know what the ultimate systematic errors on these parameters will be from CESR and the B-factories.

However, the tau-charm factory will have two advantages in measuring these parameters precisely. First, quoting Weinstein (1994): "A TCF will have a great advantage working near $\tau^+\tau^-$ threshold, where taus decay at rest in the lab. There will be no boost smearing the Michel spectrum, no backgrounds, near perfect particle identification, and good momentum resolution at low momentum." The second advantage will be polarized beams with P_τ = 92%. ξ and δ in Eq. 22 can be directly disentangled from ρ and γ.

Fan (1994) has calculated that at a tau-charm factory a fractional error on ρ of

$$\delta\rho/\rho = 0.005 \quad , \tag{24b}$$

can be achieved, leading to an error on ρ of

$$\delta_\rho \approx \pm 0.004 \quad . \tag{24c}$$

This is an order of magnitude smaller than the error expected from LEP I, Eq. 24a.

E. SEMILEPTONIC DECAYS

E.1 Present Values of Branching Fractions

I use the notation h for $\pi^\pm$ or $K^\pm$. The present world average values of B_i are:

Mode	B_i in %	$\delta B_i / B_i$
$\nu_\tau h\pi^\circ$	25.29 ± 0.37	0.015
$\nu_\tau h2\pi^\circ$	9.08 ± 0.27	0.03
$\nu_\tau h3\pi^\circ$	1.27 ± 0.16	0.1
$\nu_\tau h4\pi^\circ$	0.16 ± 0.07	0.4
$\nu_\tau 3h$	8.91 ± 0.34	0.04
$\nu_\tau 3h\pi^\circ$	4.25 ± 0.15	0.04
$\nu_\tau 3h\pi^\circ$	0.48 ± 0.06	0.1
$\nu_\tau 5h$	0.07 ± 0.01	0.14
$\nu_\tau 5h\pi^\circ$	0.02 ± 0.01	0.5

These are primarily based on results from CESR, ARGUS and the four LEP experiments (Patterson 1994).

The completion of LEP I, future measurements from CESR and SLD, and the contributions of the B-factories will certainly reduce $\delta B_i/B_i$ for all of these modes. Tau-charm factory experiments will contribute by further reducing the systematic errors in δB_i.

E.2 Summation of B_i's

Since the work of Gilman and Rhie (1985), the field of τ research has been concerned with the quantities

$$\begin{aligned} \Delta_1 &= B_1 - \sum_i B_i(1-\text{prong}) \\ \Delta_3 &= B_3 - \sum_i B_i(3-\text{prong}) \quad . \end{aligned} \tag{26a}$$

At present (Patterson 1994)

$$\begin{aligned} \Delta_1 &= (0.7 \pm 0.6)\% \\ \Delta_3 &= (1.0 \pm 0.4)\% \quad . \end{aligned} \tag{26b}$$

Thus there is no statistical proof of discrepancies. I do not know if measurements at a tau-charm factory or CESR or B-factories will be able to add additional precision to this test.

E.3 Careful Examination of Multi-Hadron Decay Modes

I think it will be very useful at a tau-charm factory for the experimenters to carefully examine the events which apparently comprise a decay mode. The goal would be to look for new physics. For example, suppose we have a few "new physics" events of the form

$$\tau^- \to \nu_\tau + x^- + 3\gamma \ , \ x = e \ , \ \mu, \pi, \text{ or } K \quad . \tag{27a}$$

Has this event been classified as

$$\tau^- \to \nu_\tau + h^- + 2\pi^\circ \tag{27b}$$

with a γ assumed undetected or has it been classified as

$$\tau^- \to \nu_\tau + h^- + \pi^\circ + \text{fake } \gamma \qquad ? \tag{27c}$$

Perhaps it is "new physics" and not the modes in Eqs. 27b or 27c.

As another example is the "new physics" decay mode

$$\tau^- \rightarrow \nu_\tau + e^- + h^+ + h^- \tag{28a}$$

being buried in

$$\tau^- \rightarrow \nu_\tau + h^- + h^+ + h^- \quad ? \tag{28b}$$

E.4 Quantum Chromodynamics

In the next decade we expect substantial progress in the technologies of quantum chromodynamic calculations in the few GeV energy region. The semileptonic decays of the τ listed in Eq. 25 will be the best place to apply those techniques because the initial state is simply a virtual W. The techniques will be applied not just to the branching fractions, but more important to the kinematic distributions. This will require clear event selection with small contamination and small distortion of the kinematic distributions. Data taken at the $E_{cm} = 3.56$ and 3.67 GeV energy points at a tau-charm factory will meet these requirements.

F. RARE DECAY MODES

Large $N_{\tau\tau}$'s are and will be available at CESR, will be available at the B-factories, and will be available at a tau-charm factory (Section B1). This allows searches for rare but allowed decay modes. I give some examples.

The seven-prong decay mode has the measured upper limit

$$B(\tau^- \rightarrow \nu_\tau 4h^- 3h^+ m\pi^\circ, m \geq 0) \leq 1.9 \times 10^{-4} \quad , \tag{29}$$

What is the size of this B?

The three-charged lepton, two-neutrino decay modes are predicted to have the branching fractions (Dicus and Vega 1994)

$$\begin{aligned} B(\tau^- \rightarrow \nu_\tau e^- e^- e^+ \overline{\nu}_e) &= 4 \times 10^{-5} \\ B(\tau^- \rightarrow \nu_\tau \mu^- e^- e^+ \overline{\nu}_\mu) &= 2 \times 10^{-5} \\ B(\tau^- \rightarrow \nu_\tau \mu^- \mu^- \mu^+ \overline{\nu}_\mu) &= 1 \times 10^{-7} \quad , \end{aligned} \tag{30}$$

Will measurement agree with theory?

Most interesting is the second-class current decay mode

$$\tau^- \rightarrow \nu_\tau + \pi^- + \eta \quad . \tag{31a}$$

The standard model predicts (Bramon *et al.* 1987)

$$B(\tau^- \rightarrow \nu_\tau \pi^- \eta) \approx 1.5 \times 10^{-5} \quad . \tag{31b}$$

There are no obvious "new physics" interactions which will increase B above that in Eq. 31b.

The present measured upper limit is (Artuso *et al.* 1992)

$$B(\tau^- \to \nu_\tau \pi^- \eta) < 3.4 \times 10^{-4} \quad , \quad 95\%\text{CL} \tag{31c}$$

A method of looking for $\tau^- \to \nu_\tau \pi^- \eta$ at CESR or a B-factory has been discussed by Lingel *et al.* (1993). They suggest using $\eta \to 2\gamma$ so that

$$\tau^- \to \nu_\tau + \pi^- + \eta \to \nu_\tau + \pi^- + \gamma + \gamma \quad . \tag{32a}$$

The backgrounds are from

$$\tau^- \to \nu_\tau + \pi^- + \pi^\circ \, , \; \tau^- \to \nu_\tau + \pi^- + 2\pi^\circ \quad . \tag{32b}$$

The larger angle between the γ's at a tau-charm factory compared to CESR or a B-factory may make it easier to find $\tau^- \to \nu_\tau \pi^- \eta$ at the tau-charm factory. Comparative studies should be done.

G. FORBIDDEN DECAY MODES

There are two types of forbidden τ decay modes: (a) those without neutrinos such as

$$\begin{aligned} &\tau^- \to e^- + \gamma \\ &\tau^- \to \mu^- + \gamma \\ &\tau^- \to e^- + e^+ + e^- \\ &\tau^- \to e^- + \mu^+ + \mu^- \end{aligned} \tag{33}$$

in which the τ mass can be reconstructed from the final state; and (b) those with at least one non-detected weekly interacting particle, X°:

$$\begin{aligned} &\tau^- \to e^- + X^\circ \\ &\tau^- \to \mu^- + X^\circ + X^\circ \quad . \end{aligned} \tag{34}$$

For most of the neutrinoless decay modes, CLEO II has found an upper limit of (Besson, 1994)

$$B \leq 3 \text{ to } 10 \times 10^{-6} \quad . \tag{35}$$

For $\tau^- \to e^- + \gamma$ there is an ARGUS upper limit of $B \leq 10^{-5}$.

For forbidden decays of the type in Eq. 34 the measured limits (Albrecht *et al.* 1990) are

$$\begin{aligned} B(\tau^- \to e^- + X^\circ) &\leq 3.2 \times 10^{-3} \\ B(\tau^- \to \mu^- + X^\circ) &\leq 5.6 \times 10^{-3} \end{aligned} \tag{36}$$

for X° having spin zero and mass <100 MeV. (The limits increase as m_{X° increases above 100 MeV.)

Alemany *et al.* (1993) have studied the potential of a tau-charm factory and of CESR or B-factories for finding forbidden decay modes. For the neutrinoless decay modes they find the attainable limits for a 10^7 s year are

Mode	Tau-Charm Factory	CESR or B-Factory
$\tau \to e\gamma$	10^{-7}	10^{-6}
$\tau \to \mu\gamma$		
$\tau \to \mu\mu\mu$		
$\tau \to \mu ee$	10^{-7}	10^{-7}
$\tau \to e\mu\mu$		
$\tau \to eeee$		

(37)

The search for $\tau^- \to e^- X^\circ, \mu^- X^\circ$ is limited by the leptonic decay modes $\tau^- \to \nu_\tau + e^- + \overline{\nu}_e, \nu_\tau + \mu^- + \overline{\nu}_\mu$. The $\nu_\tau \overline{\nu}_\ell$ combination is interpreted as a particle X° with the appropriate mass. Therefore, these forbidden modes must be found by looking for a deviation from the standard model lepton spectrum. Alemany *et al.*(1993) found the attainable limits to be

Mode	Tau-Charm Factory	CESR or B-Factory
$\tau \to eX^\circ$	10^{-5} to 10^{-6}	5×10^{-3}
$\tau \to \mu X^\circ$	10^{-3} to 10^{-4}	5×10^{-3} .

(38)

Thus in searching for forbidden decay modes the tau-charm factory has definite advantages over CESR or B-factories.

H. TAU NEUTRINO MASS

The present upper limit on the ν_τ mass is

$$m_{\nu_\tau} < 31 M/c^2 \tag{39}$$

(Aguilar–Benitez *et al.* 1994). There have been numerous projections of the smallest m_{ν_τ} which could be explored at CESR, at a B-factory or a tau-charm factory. A comparative discussion has been given by Gomez–Cadenas (1994). He discusses the use of the different decay modes:

$$\tau^- \to \nu_\tau + \pi^- + K^- + K^+ \tag{40a}$$

$$\tau^- \rightarrow \nu_\tau + 3\pi^- + 2\pi^+ \tag{40b}$$

$$\tau^- \rightarrow \nu_\tau + 2\pi^- + \pi^+ + 2\pi^\circ \tag{40c}$$

The ν_τ mass or its upper limit is found from

$$m_{\nu_\tau} \leq m_\tau - E_{\mathbf{hadrons,max}} \quad , \tag{41}$$

where $E_{\mathbf{hadrons,max}}$ is the maximum observed energy of the hadronic system. Gomez–Cadenas finds that the sensitivity to m_{ν_τ} in tau-charm factory experiments is 2.0 MeV/c^2 and in CESR or B-factory experiments is 2.5 MeV/c^2, assuming in both cases the data set contains 10^8 tau pairs.

Fan (1994) reported on the progress of a new study of the measurement limits on m_{ν_τ} at a tau-charm factory. He reports that the mode in Eq. 40a will yield a sensitivity of about 5 MeV/c^2 in agreement with the estimate of Gomez–Cadenas (1994). This study is continuing.

I find the tau-charm factory provides a more definitive search because there are greater background problems in the CESR or B-factory experiment and unremoved background events could fill in the $m_\tau - E_{\mathbf{hadrons,max}}$ thus concealing an $m_{\nu_\tau} > 0$.

The m_{ν_τ} sensitivity projections given above may be optimistic, for example, Weinstein (1994) projects a sensitivity of 15 MeV/c^2 for CLEO.

I. SEARCH FOR CP VIOLATION IN TAU DECAY

One of the most exciting discussions at the Workshop centered on the idea of searching for CP violation in the decay of the tau using polarized τ's (Tsai 1994). C. A. Nelson, in a series of papers (Nelson *et al.*1993, Nelson 1993), has discussed searches for CP violation in τ decays using the τ spin correlations discussed in Section B4.

A tremendous amount of theoretical and experimental work has been devoted to CP violation physics in the decay of hadrons, but very little work has devoted to CP violation physics in the decay of leptons. The semileptonic decays of the τ provide the opportunity to look for CP violation in the leptonic sector. For example, Nelson *et al.* (1993) has discussed looking for CP violation using the spin correlations in the double ρ decay

$$
\begin{aligned}
& e^+ + e^- \rightarrow \tau^+ + \tau^- \\
& \tau^- \rightarrow \overline{\nu}_\tau + \rho^-, \rho^- \rightarrow \pi^- + \pi^\circ \\
& \tau^+ \rightarrow \nu + \rho^+, \rho^+ \rightarrow \pi^+ + n^\circ \quad .
\end{aligned} \tag{42}
$$

Such studies will be very valuable but the requirement for double decays limits the statistics and makes the determination of systematic errors difficult. Thus, as discussed by Tsai (1994) there will be a great advantage to CP violation searches using polarized e^- and/or e^+ beams at a tau-charm factory. Then the τ's are polarized and CP violation signatures can be sought separately for each τ decay.

By the way, the CP violation possibility I have just discussed should be distinguished from searches for CP violation in τ pair production

$$e^+ + e^- \rightarrow \gamma \rightarrow \tau^+ + \tau^- \tag{43a}$$

$$e^+ + e^- \rightarrow Z^\circ \rightarrow \tau^+ + \tau^- \quad . \tag{43b}$$

As summarized in a paper by Bernreuther *et al.* (1993), such a CP violation is quantified by giving the τ an electric dipole momen d_τ^γ or a weak interaction dipole moment d_τ^Z. Bernreuther *et al.* (1993) show that for a specified number of τ pairs produced by unpolarized e^+ or e^- beams, the sensitivity to d_τ^γ or d_τ^Z increases with E_{cm} Therefore, tau-charm factory experiments will not be useful in searching for CP violation in τ pair production.

J. TAU PAIR PRODUCTION CROSS SECTION AND $\tau^+\tau^-$ ATOMS

The last measurement of the behavior of the τ pair production cross section, $\sigma_{\tau\tau}$, from threshold to $E_{cm} = 4$ GeV was made 16 years ago in the DELCO experiment at SPEAR (Bacino *et al.*1978). The theory of $\sigma_{\tau\tau}$ in this threshold region is now well understood (Smith and Voloshin 1994). I believe it will be interesting to make a precision study of the ratio $\sigma_{\tau\tau}(\text{measured})/\sigma_{\tau\tau}(\text{theory})$ as a function of E_{cm}.

The study might proceed as follows. Suppose there is some energy $E_{cm,0}$ where there has been a precision determination of some of the major branching functions: $B_e, B_\mu, B_\pi, B_\rho$. The

determination of a B assumes $\sigma_{\tau\tau}$(measured) = $\sigma_{\tau\tau}$(theory), since by definition of the B's $\sigma_{\tau\tau}$(measured)/$\sigma_{\tau\tau}$(theory) = 1 at $E_{cm,0}$. The question is: does $\sigma_{\tau\tau}$(measured)/$\sigma_{\tau\tau}$(theory) deviate from 1 whe $E_{cm} \neq E_{cm,0}$? Such a deviation would signify that

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \tag{44}$$

can occur through a process other than photon exchange or that the $\tau - \gamma - \tau$ vertex is not standard. I do not know how precisely $\sigma_{\tau\tau}$(measured)/$\sigma_{\tau\tau}$(theory) can be determined in the threshold region.

When the collider of a tau-charm factory is functioning well and $10^{33}\text{cm}^{-2}\text{s}^{-1}$ luminosity has been achieved, it may be possible to look for the production of $\tau^+\tau^-$ atoms just below threshold. Perl (1993a) has reviewed the atomic structure and decay process of $\tau^+\tau^-$ atoms, as well as the cross section for

$$e^+ + e^- \rightarrow \gamma \rightarrow \tau^+\tau^-\text{atom} \quad . \tag{45}$$

The 1^3S_1 ground state which is 24 KeV below threshold has a peak cross section and width (Perl 1993a)

$$\begin{aligned} \sigma_{\tau\tau\text{atom}}(\text{peak}) &\approx 2.4 \times 10^{-28}\text{cm}^2 \\ \Gamma &= 2.9 \times 10^{-2}\text{eV} \quad . \end{aligned} \tag{46}$$

The observed peak cross section depends upon $\sigma_{E_{cm}}$, the spread in E_{cm}, as follows

$$\begin{aligned} \sigma_{E_{cm}} &= 1 \text{ MeV} \ , \ \sigma_{\tau\tau\text{atom}}(\text{peak}) \approx 0.003 \text{ nb} \\ \sigma_{E_{cm}} &= 100 \text{ KeV} \ , \ \sigma_{\tau\tau\text{atom}}(\text{peak}) \approx 0.03 \text{ nb} \quad . \end{aligned} \tag{47}$$

Skrinsky (1994), in his paper in these proceedings entitled "Charm/Tau Factory", has shown the fascinating behavior of $\sigma_{\tau\tau\ \text{atom}}$ if $\sigma_{E_{cm}}$ can be reduced to 20 KeV or 5 KeV in a future upgrade of the collider. If $\sigma_{E_{cm}}$ = 20 KeV $\sigma_{\tau\tau\ \text{atom}}$(peak) $\approx$ 0.1 nb, and there is a measurable change in $\sigma_{\tau\tau}$ below threshold. If $\sigma_{E_{cm}}$ = 5 KeV $\sigma_{\tau\tau\ \text{atom}}$(peak) $\approx$ 0.5 nb, and there is a resonant peak in $\sigma_{\tau\tau}$, 24 KeV below threshold.

As noted by Perl (1993), there is still the "deeper question of what physics we can do with $\tau^+\tau^-$ atoms."

K. CONCLUSIONS

At different stages of the operation and upgrading of a tau-charm facility, there are different types of tau physics to be done. The facility has three parts: the collider, the detector, and the data analysis system. I will comment on the required stages in the conclusions.

- Precisely Calculable Decay Modes

A well-developed tau-charm facility will provide reduced errors on B_e, B_μ, B_π, B_K and will provide improved comparisons with theory and with τ_τ. Precise B_π and B_K measurements will require good π/K separation.

- Dynamics of Lepton Decays

Quite early in the operation of a tau-charm factory, improved measurements of the Michel parameters will be provided. When longitudinal polarization is introduced, there will be new ways to study the dynamics of the leptonic decay.

- Semileptonic Decays

When the luminosity reaches 2 to $5 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ and the detector and data analysis system attain good quality decay mode separation and identification, there will be two areas for semileptonic decay research. One area is the detailed comparison of QCD theory with the measured kinematic distributions in a multihadron decay. The other area is a speculative search through the known semileptonic decay modes for an unknown, "new physics" decay mode.

- Rare Decay Modes

As the luminosity rises to $10^{33}\text{cm}^{-2}\text{s}^{-1}$ a tau-charm facility can contribute to the studies of rare, but not forbidden, decay modes with branching fractions in the range of 10^{-5} to 10^{-7}. At present we cannot project how many of these studies will have been carried out at CESR or B-factories.

- Forbidden Decay Modes

From the beginning of operations, the tau-charm facility will provide a new search range for forbidden decays which include a non-detected weekly interacting particle.

- Tau Neutrino Mass

A tau-charm facility is certainly competitive with CESR and B-factories with respect to the sensitivity to m_{ν_τ}. Since the tau-charm facility provides smaller and measurable backgrounds, the search is more reliable.

- Search for CP Violations in Tau Decay

From the beginning of operations, the tau-charm facility can provide the data for an initial search for CP violation in tau decay based on the correlations of τ spins. The unique contribution to this CP violation search will come when a longitudinally polarized beam is available in the collider. Both types of searches require precise knowledge of the detector efficiencies and acceptances.

- Tau Pair Production Cross Section and $\tau^+\tau^-$ Atoms

At the beginning of operations of a tau-charm facility, a careful study can be carried out of the energy dependence of $\sigma_{\tau\tau}$ from threshold to 4 GeV. Such a study might reveal new physics. On the other hand, an entrance to the physics of $\tau^+\tau^-$ atoms requires a very well developed facility and very small $\sigma_{E_{cm}}$.

REFERENCES

Acton, P. D. *et al.*, 1992, Phys. Lett. **B281,** 405.

Aguilar–Benitaz *et al.*, 1994, "Review of Particle Properties," Phys. Rev. **D50,** 1173.

Akerib, D. S. *et al.*, 1992, Phys. Rev. Lett. **69** 3610; **71** 3395.

Albrecht, H. *et al.*, 1990, Phys. Lett. **B246,** 278.

Alemany, R. 1994, "Tau Decays Into Kaons," 27th Int. Conf. High Energy Phys. (Glasgow, 1994), to be published.

Alemany, R. *et al.*, 1993, CERN-PPE/93-49.

Alexahin, Y. I. 1994, Proc. Third Workshop on the Tau-Charm Factory (Editions Frontieres, Gif-sur-Yvette, 1994), Eds. J. Kirkby and R. Kirby, p. 571.

Artuso, M. *et al.*, 1992 Phys. Rev. Lett. **69,** 3278.

Bacino, W. *et al.*, 1978, Phys. Rev. Lett. **42,** 749.

Bernreuther, W. *et al.*, 1993, Phys. Rev. **48,** 78.

Besson, D. 1994, "Tau Physics at CESR," Proc. Tau-Charm Factory in the Era of B-Factories and CESR (Aug. 15–16, 1994, Stanford, California), SLAC-Report 451, Eds. L. V. Beers and M. L. Perl.

Bramon, A. *et al.*, 1987, Phys. Lett. **B196,** 543.

Buskulic D. *et al.*, 1992, Phys. Lett. **B297,** 459.

Dicus, D. A. and Vega, R. 1994 CPP-93-30, hep-ph/9402262.

Fan, X. 1994, "Monte Carlo Studies of Tau-Charm Factory," Proc. Tau-Charm Factory in the Era of B-Factories and CESR (Aug. 15–16, 1994, Stanford, California) SLAC-Report 451, Eds. L. V. Beers and M. L. Perl.

Fetscher, W. 1990, Phys. Rev. **42,** 1544.

Gan, K. K. 1991, Proc. Workshop on Physics and Detectors for KEK Asymmetric B-Factory (Tsukuba, 1991), Eds. H. Ozaki and N. Sato, p. 333.

Gilman, F. J. and Rhie, S. H. 1985, Phys. Rev. **D31,** 1666.

Gomez–Cadenas, J. J. 1994, Proc. Third Workshop on the Tau-Charm Factory (Editions Frontieres, Gif-sur-Yvette, 1994), Eds. J. Kirkby and R. Kirkby, p. 97.

Harton, J. 1994, "Tau Physics at LEP: Present Status and Potential," Proc. Tau-Charm Factory in the Era of B-Factories and CESR (Aug. 15–16, 1994, Stanford, California), SLAC-Report 451, Eds. L. V. Beers and M. L. Perl.

Huang, T. 1994, "Physics Prospects at th Tau-Charm Factory," Proc. Tau-Charm Factory in the Era of B-Factories and CESR (Aug. 15–16, 1994, Stanford, California), SLAC-Report 451, Eds. L. V. Beers and M. L. Perl.

Kirkby, J. 1994, Proc. Third Workshop on the Tau-Charm Factory (Editions Frontieres, Gif-sur-Yvette, 1994), Eds. J. Kirkby and R. Kirkby, p. 805.

Kirkby, J. 1991, Proc. Workshop on Tau Lepton Physics (Editions Frontieres, Gif-sur-Yvette, 1991), Eds. M. Davier and B. Jean–Maie, p., 453.

Kirkby, J. and Kirkby, R. 1994 (Eds.), Proc. Third Workshop on the Tau-Charm Factory (Editions Frontieres, Gif-sur-Yvette, 1994).

Le Duff, J. 1994, Proc. Third Workshop on the Tau-Charm Factory (Editions Frontieres, Gif-sur-Yvette, 1994), Eds. J. Kirkby and R. Kirkby, p. 797.

Lingel, K. *et al.*, 1993, CLNS-91-1043-REV.

Nelson, C. A. 1993, Proc. Second Workshop on Tau Lepton Physics (World Scientific, Singapore, 1993), Ed. K. K. Gan, p. 353; also SUNY BING 8/16/93.

Patterson, R. 1994, "Weak and Rare Decays," 27th Int. Conf. High Energy Phys. (Glasgow, 1994), to be published.

Perl, M. L. 1993a, Proc. Second Workshop on Tau Lepton Physics (World Scientific, Singapore, 1993), Ed. K. K. Gan, p. 483.

Perl, M. L. 1993b, Proc. 20th SLAC Summer Inst. Particle Physics, SLAC-Report-412, Ed. L. Vassilian, p. 213.

Prepost, R. 1994, "Polarized Beams at SPEAR and a Tau-Charm Factory," Proc. Tau-Charm Factory in the Era of B-Factories and CESR (Aug. 15–16, 1994, Stanford, California), SLAC-Report 451, Eds. L. V. Beers and M. L. Perl.

Smith, B. H. and Voloshin, M. B. 1994, Phys. Lett. **B324,** 117; Ibid **B333,** 564.

Skrinsky, A. 1994, "Charm/Tau Factory," Proc. Tau-Charm Factory in the Era of B-Factories and CESR (Aug. 15–16, 1994, Stanford, California) SLAC-Report 451, Eds. L. V. Beers and M. L. Perl.

Timmermans, J. 1994, "Measurements of τ Mass Lifetime and Leptonic Branching Ratios," 27th Int. Conf. High Energy Physcis (Glasgow 1994), to be published.

Tsai, Y.–S. 1994, "New Physics with Polarized Electron-Proton Beams at a Tau-Charm Factory," Proc. Tau-Charm Facotry in the Era of B-Factories and CESR (Aug. 15–16, 1994, Stanford, California), SLAC–Report 451, Eds. L. V. Beers and M. L. Perl.

Tsai, Y.–S. 1971, Phys. Rev. **D4,** 2821.

Weinstein, A. J. 1994, Proc. Third Workshop on the Tau-Charm Factory (Editions Frontieres, Gif-sur-Yvette, 1994), Eds. J. Kirkby and R. Kirkby, p. 11.

Weinstein, A. J. and Stroynowski, R. 1993, Ann. Rev. Nucl. Part. Sci. **43,** 457.

Wu, Y. 1994, "A Tau-Charm Factory at BEPC," Proc. Tau-Charm Factory in the Era of B-Factories and CESR (Aug. 15–16, 1994, Stanford, California), SLAC-Report 451, Eds. L. V. Beers and M. L. Perl.

Zheng, Z. 1994, "The Consideration of Tau-Charm Factory Construction in China," Proc. Tau-Charm Factory in the Era of B-Factories and CESR (Aug. 15–16, 1994, Stanford, California), SLAC-Report 451, Eds. L. V. Beers and M. L. Perl.

Zholents, A. 1992, CERN SL/92-27 (AP).