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Tau Physics at Future Facilities*

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This paper discusses and projects the tau research which may be carried out at CESR, at BEPC, at the SLC, in the next few years at LEP I, at the asymmetric B-factories under construction in Japan and the United States and, if built, a tau-charm factory. As the size of tau data sets increases, there is an increasing need to reduce the effects of systematic errors on the precision and search range of experiments. In most areas of tau physics there is a large amount of progress to be made, but in a few areas it will be difficult to substantially improve the precision of present measurements.

CONTENTS

1. INTRODUCTION

The τ was discovered two decades ago. In this paper I look ahead to the next two decades of τ research. I begin in Section 1.1 by estimating the number of τ pairs, $N_{\tau\tau}$, which may be produced at ongoing and future τ research facilities, and I note special properties of these facilities. But $N_{\tau\tau}$ by itself is not sufficient for forecasting future research, and so in Section 2 I discuss detector properties and systematic errors, $\sigma_{\rm sys}$. In the next eight sections I apply the discussion of $N_{\tau\tau}$ and $\sigma_{\rm sys}$ to the newer areas of τ physics, comparing where we are now to where we might go in τ research. In the course of this comparison, I note possible new directions in physics and techniques. After the year 2000 the facilities with large $N\tau\tau$ production per year will be CESR, the asymmetric B-Factories (ABF) at KEK and SLAC, and perhaps a tau-charm factory (TCF). Therefore I particularly compare CESR, the ABFs and a possible TCF.

There is always uncertainty in predicting human activities. The list

- Roulette wheel
- Stock market
- Technology trends
- Economic trends
- Population growth

goes from the unpredictable to something which can be predicted a decade ahead. Where is forecasting high energy physics research on this list? It is probably at the level of forecasting economic trends. But there is also an analogy between forecasting technological trends and forecasting τ research. A new technique that drastically reduces $\sigma_{\rm sys}$ or enables the finding of a deviation from the standard model in τ physics will change τ research, just as fiber optics changed communications technology. Therefore the most useful way to use this paper is that I provide information on $N_{\tau\tau}$ and $\sigma_{\rm sys}$ and the like, and let the reader do the forecasting.

The data used in this paper is taken from this Workshop [1], from the 1994 Review of Particle Properties [2], and from the review talk of R. Patterson [3]. I do not discuss tau neutrino physics other than the ν_τ mass.

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Some conventions used in this paper are: B means decay fraction, δB/B means the fractional error in B, and a data acquisition year is 10^7's.

2. FUTURE FACILITIES

I begin with the low energy facilities.

2.1 CESR

If almost all future data acquisition at CESR is at or close to the Υ(4S), the τ pair cross section is

$$\sigma_{\tau\tau} = 0.78 \text{ nb} \quad . \tag{1a}$$

At present, the CLEO collaboration has accumulated [4]

$$\mathrm{N}_{\tau\tau}(1994) \approx 2.5 \times 10^6 \quad , \tag{1b}$$

and by the year 2000 it is expected that

$$\mathrm{N}_{\tau\tau}(2000) \approx 2 \times 10^7 \tag{1c}$$

$$\mathcal{L}(\mathrm{CESR}) \approx 1 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1} \tag{1d}$$

$$\mathrm{N}_{\tau\tau}/\mathrm{yr} \approx 8 \times 10^6/\mathrm{yr} \quad . \tag{1e}$$

Beyond 2000, $\mathcal{L}$(CESR) may increase above $3 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and then $\mathrm{N}_{\tau\tau}$/yr will exceed 2×10^7.

2.2 Asymmetric B-Factories (ABF)

Two asymmetric B-factories are under construction: the KEK B-Factory in Japan with $3.5 \bigoplus 8.0$ GeV and the SLAC B-Factory, PEP-II, with $3.1 \bigoplus 9.0$ GeV. There is one experiment at each facility. These colliders will begin operation for data acquisition about the year 2000 with:

$$\mathcal{L} \approx 1 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1} \rightarrow 3 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1} \tag{2a}$$

$$N_{\tau\tau}/\mathrm{yr} \approx 8 \times 10^6/\mathrm{yr} \rightarrow 2.3 \times 10^7/\mathrm{yr} \quad . \tag{2b}$$

The second $\mathcal{L}$ value is $\mathcal{L}$ design. Eventually these facilities might attain

$$\mathcal{L} \approx 1 \times 10^{34} \text{ cm}^{-2}\mathrm{s}^{-1} \tag{2c}$$

$$\mathrm{N}_{\tau\tau}/\mathrm{yr} \approx 10^8/\mathrm{yr} \quad . \tag{2d}$$

2.3 BEPC

The BES Collaboration at the Beijing Electron Position Collider (BEPC) has collected [5]

$$\mathrm{N}_{\tau\tau}(1994) \approx 90,000 \quad . \tag{3a}$$

The luminosity of BEPC is being upgraded [5,6] to

$$\mathcal{L} \approx 1.5 \times 10^{31} \text{ cm}^{-2}\mathrm{s}^{-1} \tag{3b}$$

which will yield

$$\mathrm{N}_{\tau\tau}/\mathrm{yr} \approx 4 \times 10^5/\mathrm{yr} \quad . \tag{3c}$$

2.4 Tau-Charm Factory (TCF) [7,8]

In August 1994 a Workshop [9] jointly organized by physicists from the Stanford Linear Accelerator Center (SLAC), the Institute for High Energy Physics (IHEP) in Beijing, and the BEC Collaboration and entitled "The Tau-Charm Factory in the Era of B-Factories and CESR" was held at SLAC.

The participants discussed the tau, charm, and charmonium physics which would be studied at a TCF that began operation on or after the year 2000. TCF designs were presented for sites at IHEP in Beijing [5,10], Argonne National Laboratory [11], the Budker Institute in Novosibirsk [12] and at IHEP in Dubna [13]. In all these presentations the design luminosity was

$$\mathcal{L} \approx 1 \times 10^{33} \text{ cm}^{-2}\mathrm{s}^{-1} \quad . \tag{4a}$$

At the usual proposed three operating points for τ research [7]

$$\mathrm{E}_{\mathrm{cm}} = 3.56 \text{ GeV}: \quad \sigma_{\tau\tau} = 0.5 \text{ nb}, \mathrm{N}_{\tau\tau}/\mathrm{yr} = 0.5 \times 10^6/\mathrm{yr} \tag{4b}$$

$$\mathrm{E}_{\mathrm{cm}} = 3.67 \text{ GeV}: \quad \sigma_{\tau\tau} = 2.4 \text{ nb}, \mathrm{N}_{\tau\tau}/\mathrm{yr} = 2.4 \times 10^7/\mathrm{yr} \tag{4c}$$

$$\mathrm{E}_{\mathrm{cm}} = 4.25 \text{ GeV}: \quad \sigma_{\tau\tau} = 3.5 \text{ nb}, \mathrm{N}_{\tau\tau}/\mathrm{yr} = 3.4 \times 10^7/\mathrm{yr} \ . \tag{4d}$$

An advanced upgraded TCF might achieve [14] $\mathcal{L} = 4 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Next I consider high energy facilities.

2.5 TRISTAN

At the present TRISTAN energy [15] of 58 GeV

$$\mathcal{L} \approx 4 \times 10^{31} \mathrm{cm}^{-2} \mathrm{s}^{-1} \tag{5a}$$

$$\sigma_{\tau\tau} \approx 20 \text{ pb} \tag{5b}$$

$$\mathrm{N}_{\tau\tau}/\mathrm{yr}, \text{ experiment} \approx 8 \times 10^3/\mathrm{yr} \quad . \tag{5c}$$

Thus the main τ research is the study [16] of $\gamma - \mathrm{Z}^0$ interference.

2.6 LEP I

At present [17], each of the four LEP experiments has

$$\mathrm{N}_{\tau\tau}(1994)/\text{experiment} \approx 9 \times 10^4 \quad , \tag{6a}$$

and at the conclusion of LEP I

$$\mathrm{N}_{\tau\tau}(1996)/\text{experiment} \approx 1.9 \times 10^5 \text{ to } 2.4 \times 10^5 \quad . \tag{6b}$$

2.7 SLC

By the end of the present data acquisition period the SLD Collaboration using the SLAC Linear Collider (SLC) will have acquired

$$\mathrm{N}_{\tau\tau}(1994) \approx 5 \times 10^3 \quad . \tag{7a}$$

If a total of $10^6 \mathrm{Z}^0$'s are produced

$$\mathrm{N}_{\tau\tau} \rightarrow 2 \times 10^4 \quad . \tag{7b}$$

These τ pairs have the special property that they are produced using an e^- beam that is 70% to 80% longitudinally polarized [18].

2.8 LEP II

At $\mathrm{E}_{\mathrm{cm}} = 180$ GeV

$$\sigma_{\tau\tau} \approx 8 \text{ pb} \quad , \tag{8a}$$

and it is expected that LEP II will give an integrated luminosity

$$\int \mathcal{L} dt \approx 500 \text{ pb}^{-1} \quad . \tag{8b}$$

Then

$$\mathrm{N}_{\tau\tau}/\text{experiment} = 4 \times 10^3 \quad . \tag{8c}$$

About half of these events will be from the radiative tail of the Z^0 and may not be useful. Thus at LEP II and at an $\mathrm{e}^-\mathrm{e}^+$ linear collider, $\mathrm{N}_{\tau\tau}$ is small and τ research is restricted (see Section 10).

2.9 Electron-Positron Linear Collider

Far above the Z^0 energy

$$\sigma_{\tau\tau} \approx \frac{0.1}{s} \text{ pb, s in TeV}^2 \quad . \tag{9a}$$

At $\mathrm{E}_{\mathrm{cm}} = 0.5$ TeV and

$$\mathcal{L} = 10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1} \quad , \tag{9b}$$

$$\mathrm{N}_{\tau\tau}/\mathrm{yr} = 4 \times 10^3/\mathrm{yr} \quad . \tag{9c}$$

2.10 Longitudinal Polarization of $\mathrm{e}^-\mathrm{e}^+$ Beams

A substantial amount of present day τ research makes use of τ spin distributions through τ spin – τ spin correlations .[19-22].

The sensitivity of such research can be substantially increased by using a longitudinally polarized e^- or e^+ beam in the collider [23], but it is not necessary to polarize both beams.

There are already longitudinally polarized e^- beams at the SLC [18] and HERA [24]. Longitudinally polarized beams are under discussion for LEP, and such beams might be considered for CESR and the ABFs. A very suitable candidate is a tau-charm factory [12,14,26].

Radiative transverse polarization [25] cannot be used at a TCF unless wigglers are inserted in the ring [12]. Otherwise the polarization time is too long. A separate small radius ring may however be used with the polarized e^- injected into the TCF. An attractive alternative is to use a linear accelerator with a polarized e^- source as the TCF injector. In all cases spin rotators must be used before and after the interaction point so that the e^- beam is longitudinally polarized at the interaction point, but transversely polarized in the ring.

2.11 Tau production at Hadron Colliders

There are two ways in which τ's can be produced at hadron colliders [27]. At a pp collider

$$\begin{aligned} p + p &\rightarrow \mathrm{D_s \text{ or } B} + \ldots \\ \mathrm{D_s \text{ or } B} &\rightarrow \tau + \nu_\tau \quad . \end{aligned} \tag{10}$$

A more practical way is to use a heavy ion collider, RHIC or LHC, and the two virtual photon reactions [28-31]

$$\begin{aligned} &\mathrm{ion + ion \rightarrow ion + ion} + \gamma_{\mathrm{virtual}} + \gamma_{\mathrm{virtual}} \\ &\gamma_{\mathrm{virtual}} + \gamma_{\mathrm{virtual}} \rightarrow \tau^+ + \tau^- \quad . \end{aligned} \tag{11}$$

The ions would not be disrupted and the event would be quite clean.

A Pb-Pb collision at the LHC gives

$$\sigma_{\mathrm{PbPb}\tau\tau} \approx 1 \text{ mb} \quad , \tag{12a}$$

and with

$$\mathcal{L} \approx 10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1} \tag{12b}$$

$$\mathrm{N}_{\tau\tau}/\mathrm{yr} = 10^8/\mathrm{yr} \quad . \tag{12c}$$

However event detections may be difficult because the transverse momentum of the τ's is less than m_τ.

3. DETECTORS, EFFICIENCIES AND SYSTEMATIC ERRORS

A large $\mathrm{N}_{\tau\tau}$ is not enough, the significance of the measurement depends upon many properties of the experiment: event selection efficiency, backgrounds, detector simulation quality, systematic errors. Valuable comparisons of many of these experiment properties have been carried out by Weinstein [32] and Burchat [33].

3.1 Efficiencies and Backgrounds

It has been known for quite [4,32,33] a while and was emphasized again at this meeting [1] that τ data analyses at the Γ(4S) compared to τ data analyses at the Z^0 involve smaller efficiencies, ϵ, for event acceptance and larger fractional backgrounds $\mathrm{f_b}$. The ϵ's and $\mathrm{f_b}$'s will be about the same at ABFs as they are at CESR. One of the goals of a TCF project is to design a detector so that at the smaller τ physics operating points [7,8], 3.56 and 3.67, the $\mathrm{f_b}$'s are smaller, and then the ϵ's can be larger.

3.2 Systematic Errors

In the past few years (and even more so at this meeting [1]) in many measurements the systematic errors, σ_{sys}, are larger than the statistical error, σ_{stat}. The determination of a systematic error is often a complicated process, and there is always some nervousness in the way we combine them quadratically

$$\sigma_{\mathrm{sys,tot}} = \left[\sum_i \sigma_{\mathrm{sys,i}}^2 \right]^{1/2} \quad . \tag{13}$$

As $\mathrm{N}_{\tau\tau}$ increases, the future of τ research depends upon reducing systematic errors such as $\sigma_{\mathrm{sys},\epsilon}$ and $\sigma_{\mathrm{sys,f_b}}$. Reduction of $\sigma_{\mathrm{sys,f_b}}$ requires in part improvements in particle identification as sketched next.

3.3 The μ/π Separation

The separation of μ's from π's becomes difficult for momentum below about 0.5 GeV/c. This is not a problem at the Z^0 energy and above, it is a problem at CESR and the ABFs, and is even more of a problem at the TCF [34].

3.4 The π/K Separation

The problem of π/K separation behaves in the opposite way versus energy. At LEP only the DELPHI experiment [35] permits event-by-event separation of π's from K's, the other experiments will continue with statistical π/K separation. On the other hand, there will be powerful event-by-event π/K separation in the CLEO III detector [4,36] and the ABF detectors [37,38]. It is easier to achieve π/K separation over most of the momentum range at CESR compared to the ABFs, and it is easiest at a TCF (Table 1).

Table 1
Maximum π and K momentum from τ decays

Collider	Maximum π and K momentum (GeV/c)
TCF at 3.56 GeV	0.8 to 0.9
TCF at 3.67 GeV	1.1
CESR	5.1
PEP II	8.7

3.5 The γ and π^0 Detection

Substantial reduction of systematic errors in the detection of γ's and π^0's will be necessary for substantial improvement in research on semileptonic decay modes, radiative decay modes and rare decay modes. The LEP I experiments will conclude in a few years, hence the reduction of $\sigma_{\mathrm{sys},\gamma}$ and $\sigma_{\mathrm{sys},\pi^0}$ must be carried out at CESR, the ABF's and perhaps a TCF. Detection problems include (a) the rejection of false γ's from "split-offs" from hadronic interactions in the electromagnetic calorimeter, (b) the efficiency for detecting low energy γ's, and (c) the efficiency for reconstructing π^0's. The CsI calorimeter of the CLEO II detector gives

$$\sigma_{\mathrm{sys},\pi^0}/\mathrm{B_i} \approx .01 - .02 \tag{14}$$

per π^0 in decay modes with π^0's and reduction in $\sigma_{\mathrm{sys}}, \pi^0$ requires further tuning of the π^0 simulation programs using data from known, non-τ events containing π^0's.

The ABF detectors will have about the same $\sigma_{\mathrm{sys},\gamma}$ and $\sigma_{\mathrm{sys},\pi^0}$ as CLEO II unless the electromagnetic calorimeters are improved by using longitudinal segmentation of the CsI crystals.

At a TCF the electromagnetic calorimeter must detect smaller energy γ's compared to CESR and the ABF's. As a compensation the ψ and $\psi\prime$ decays such as

$$\begin{aligned} \psi &\to \pi^+\pi^-\pi^0 \ , \ \mathrm{B} = 1.5\% \\ \psi\prime &\to 2(\pi^+\pi^-)\pi^0 \ , \ \mathrm{B} = 3.4\% \end{aligned} \tag{15}$$

are a copious source of calibration π^0's.

4. PRECISELY CALCULABLE DECAY MODES

The decay widths and dynamics of the modes

$$\tau^- \to \nu_\tau + \mathrm{e}^- + \overline{\nu}_\mathrm{e} \tag{16a}$$

$$\tau^- \to \nu_\tau + \mu^- + \overline{\nu}_\mu \tag{16b}$$

$$\tau^- \to \nu_\tau + \pi^- \tag{16c}$$

$$\tau^- \to \nu_\tau + \mathrm{K}^- \tag{16d}$$

are predicted precisely from weak interaction theory and well measured quantities such as the π^- lifetime and the $\mathrm{K}^- \to \mu^-\overline{\nu}_\mu$ decay width. How well can we expect to compare prediction with measurement?

4.1 Ratio of $\mathrm{B_i}$'s

How well can and will we be able to measure

$$\mathrm{B}_\mu/\mathrm{B_e} \ , \ \mathrm{B}_\pi/\mathrm{B_e} \ , \ \mathrm{B_K}/\mathrm{B}_\pi \quad ? \tag{17}$$

As the first example consider $\mathrm{B_e}$. Including the new data presented at this meeting the world average value is [39,40]

$$\mathrm{B_e(wa)} = (17.79 \pm 0.09)\% \tag{18a}$$

which is heavily weighted by the $\mathrm{B_e}$'s from the LEP experiment, particularly

$$\mathrm{B_e(ALEPH)} = (17.76 \pm 0.13)\% \quad . \tag{18b}$$

According to Harton [17], by the end of LEP I we might expect that the average of the LEP experiments has the errors on $\mathrm{B_e}$

$$\sigma_{\mathrm{stat}} = 0.05\% \ , \ \sigma_{\mathrm{sys}} = 0.06\% \sigma_{\mathrm{tot}} = 0.08\% \tag{19c}$$

which is not much better than the present value. Thus from the LEP experiments the final fractional error will be

$$\delta\mathrm{B_e}/\mathrm{B_e} \approx 0.005 \quad . \tag{18d}$$

The fractional error on B_μ will be similar. Hence

$$\delta\left(\frac{\mathrm{B}_\mu}{\mathrm{B_e}}\right) \Big/ \left(\frac{\mathrm{B}_\mu}{\mathrm{B_e}}\right) \approx 0.007 \quad . \tag{18e}$$

Improvements in precision will have to come from CESR, the ABF's and, if built, a TCF. A two-year-old CLEO II measurement [41] gives

$$\mathrm{B_e(CLEO\ II)} = (17.97 \pm 0.14 \pm 0.23)\% \quad . \tag{18f}$$

As $\mathrm{N}_{\tau\tau}$ increases, σ_{stat} can certainly be reduced to $\sigma_{\mathrm{stat}}/\mathrm{B_e} \approx 0.001$; the question is how much σ_{sys} can be reduced at CESR or the ABF's? Can experimenters at these colliders attain $\sigma_{\mathrm{sys}}/\mathrm{B_e} \to 0.002$? Can they attain $\sigma_{\mathrm{sys}}/\mathrm{B}_\mu \to 0.002$?

Initial studies for a TCF [42,43] indicate that 0.002 might be attained for $\sigma_{\rm sys}/{\rm B_e}$ and $\sigma_{\rm sys}/{\rm B}_\mu$ by using the special properties of the $\rm E_{cm}$ = 3.56 operating point.

Heltsley [44] gives the new world average values

$$\rm B(\tau^- \to \nu_\tau h^-, wa) = (11.76 \pm 0.14)\% \quad (19a)$$

$$\rm B_K(wa) = (0.68 \pm 0.04)\% \ . \quad (19b)$$

By subtraction

$$\rm B_\pi(wa) = (11.08 \pm 0.15)\% \quad . \quad (19c)$$

Thus at present

$$\delta {\rm B}_\pi/{\rm B}_\pi \approx 0.014 \quad (19d)$$

$$\delta {\rm B_K}/{\rm B_K} \approx 0.06 \quad . \quad (19e)$$

Weinstein [32] predicts that CESR and the ABF's will reduce $\sigma_{\rm sys}$ in $\rm B_\pi$ to give

$$\delta {\rm B}_\pi/{\rm B}_\pi \to 0.01 \quad . \quad (19f)$$

This is not a brick wall limit, as $\rm N_{\tau\tau}$ increases $\delta {\rm B}_\pi/{\rm B}_\pi$ could decrease further.

Thus future reductions in $\delta {\rm B_e}/{\rm B_e}$, $\delta {\rm B}_\mu/{\rm B}_\mu$, $\delta {\rm B}_\pi/{\rm B}_\pi$ and probably $\delta {\rm B_K}/{\rm B_K}$ will be by factors of 2 to 4, but not by a factor of 10. One or more radically new techniques will be needed to reduce the fractional errors by a factor of 10.

There is an additional reason for new measurements of Be, $\rm B_\mu$, $\rm B_\pi$, and $\rm B_K$. At this meeting [1] Hayes [45] and Smith [46] have shown that τ branching fractions such as $\rm B_\rho$ and $\rm B_1$ have changed over time beyond the range of the *world average* $\sigma_{\rm sys}$ errors. Might the same happen for Be, $\rm B_\mu$, $\rm B_\pi$, or $\rm B_K$?

4.2 Comparison of τ_τ, $\rm B_\ell$ and $\rm M_\tau$

At present the world average value of the tau lifetime [40] is

$$\tau_\tau({\rm wa}) = 291.6 \pm 1.6 \ {\rm fs} \quad , \quad (20a)$$

based primarily on

$$\begin{aligned} \tau_\tau({\rm CLEO}) &= 291 \pm 7.6 \ {\rm fs} \\ \tau_\tau({\rm ALEPH}) &= 292.5 \pm 3.2 \ {\rm fs} \\ \tau_\tau({\rm DELPHI}) &= 295.2 \pm 4.2 \ {\rm fs} \\ \tau_\tau({\rm L3}) &= 296.4 \pm 7.8 \ {\rm fs} \\ \tau_\tau({\rm OPAL}) &= 288.8 \pm 2.6 \ {\rm fs} \quad . \end{aligned} \quad (20b)$$

Thus at present

$$\delta\tau_\tau/\tau_\tau \approx 0.005 \quad . \quad (20c)$$

This represents amazing improvement in the last four years, but I do not think that the LEP I experiments can improve much more.

Reduction of δ_τ will have to come from the CLEO experiment when the new vertex detector is introduced and from the ABF detectors. In the CLEO τ_τ measurement [47] the largest $\sigma_{\rm sys}$ are from (a) vertexing and tracking and (b) background. Certainly (a) will be drastically reduced.

Using

$$\rm B_e = \left(\frac{m_\tau}{m_\mu}\right)^5 \left(\frac{\tau_\tau}{\tau_\mu}\right)(1+c) \quad (21)$$

with c a small correction term [19,48]. Stroynowski [39] finds Eq. 21 confirmed within one standard deviation.

As is the case with $\rm B_e$ and $\rm B_\mu$, the sensitivity of this comparison cannot be much improved unless radically new techniques are used to decrease $\delta\tau_\tau/\tau_\tau$ in Eq. 20c.

In this section I have taken some space to show how we try to forecast future precision in τ measurements from our knowledge of present errors. From now on I will be more concise.

Table 2
The τ Michel parameters ρ, η, δ, ξ. The first row gives the expected values for a Dirac charged lepton. The second row gives the world average values. The third row gives the projected total errors from LEP I experiments. The next two rows give the projected statistical errors for CESR, ABF's and a TCF. The bottom row gives the projected total error for a TCF. The ρ, δ and ξ values and errors are averaged over the e and μ decay modes. The η values and errors are only for μ decay mode.

	ρ	η	ξ	δ	Ref
Dirac charged lepton	3/4	0	1	3/4	
World average	0.732 ± 0.024	-0.01 ± 0.14	$1.04 \pm .010$	0.70 ± 0.15	40
Projected LEP I total errors	$\leq$0.025	$\approx$0.07	$\leq$0.10	$\leq$0.10	17
Projected CESR or ABF statistical errors	$\approx$0.002	$\approx$0.03	$\approx$0.01	$\approx$0.01	21
Projected TCF statistical errors at 4 GeV	$\approx$0.002	$\approx$0.03	$\approx$0.02	$\approx$0.02	21
Projected TCF total errors at 3.56 GeV	≈ 0.003		≈ 0.001	≈ 0.01	43

5. DYNAMICS OF LEPTONIC DECAYS

Table 2 gives the τ Michel parameters ρ, η, δ, ξ (a) the world average values, (b) the final projected errors from LEP I experiments, and (c) projected errors for CESR, ABF's, and a TCF. For simplicity, $e - \mu$ universality has been used. In contrast to the discussion in the previous section, the future will bring substantial reductions in the errors on the Michel parameters.

All the measurements and projections in Table 2 are for unpolarized e^- and e^+ beams and use τ spin$-\tau$ spin correlations [21,49]. We expect even further reduction in the errors on δ and ξ when a longitudinal polarized e^- or e^+ beam is used in a collider (Section 2.10).

6. SEMILEPTONIC DECAY MODES

Table 3 lists world averages for B_i and $\delta B_i/B_i$ for semileptonic decay modes as given by Patterson [3].

Once the LEP I experiments are concluded the burden of reducing $\delta B_i/B_i$ falls on the CLEO, ABF and BES collaborations, and perhaps on a TCF collaboration. I look at three examples from CLEO II analysis to illustrate the larger sources of σ_{sys}.

First consider [32,50]

$$\tau^- \to \nu_\tau + h^- + \pi^0 \quad . \tag{22a}$$

Using three different topologies, l vs. ρ, ρ vs. ρ, and 3-prong vs. ρ

$$\begin{aligned} B(\tau \to \nu_\tau h \pi^0) &= (25.87 \pm 0.12 \pm 0.42)\% \\ \sigma_{sys}/B &= 0.016 \quad . \end{aligned} \tag{22b}$$

Table 3
Branching fractions B_i and errors, δB_i, in percent for semileptonic decay modes from Patterson.[3] $\delta B_i/B_i$ is the fractional error.

Mode	$B_i \pm \delta B_i$ in %	δB_i / B_i
ν_τ h π^0	25.20 ± 0.37	0.015
ν_τ h $2\pi^0$	9.08 ± 0.27	0.030
ν_τ h $3\pi^0$	1.27 ± 0.16	0.13
ν_τ h $4\pi^0$	0.16 ± 0.07	0.4
ν_τ 3h	8.91 ± 0.34	0.038
ν_τ 3h π^0	4.25 ± 0.15	0.035
ν_τ 3h $2\pi^0$	0.48 ± 0.06	0.1
ν_τ 5h	0.07 ± 0.01	0.1
ν_τ 5h π^0	0.02 ± 0.01	0.5

The largest contributions to $\sigma_{\rm sys}/{\rm B}$ in Eq. 22b are 0.009 for π^0 reconstruction, 0.009 for extra shower veto and 0.005 to 0.010 for acceptance.

The second example from CLEO II [51] is

$$\begin{aligned} {\rm B}(\tau \to \nu_\tau 3{\rm h}\pi^0) &= (4.25 \pm 0.09 \pm 0.26)\% \\ \sigma_{\rm sys}/{\rm B} &= 0.06 \quad , \end{aligned} \tag{23}$$

the analysis used e and μ tags. The largest contribution to $\sigma_{\rm sys}/{\rm B}$ are .041 to .048 for cuts, .03 for π^0 reconstruction, and .025 for tracking efficiency.

The third example from CLEO II [50] is

$$\begin{aligned} {\rm B}(\tau \to \nu_\tau 5{\rm h}\pi^0) &= (0.019 \pm 0.004 \pm 0.004)\% \\ \sigma_{\rm sys}/{\rm B} &= 0.21 \quad . \end{aligned} \tag{24}$$

The major contributors to $\sigma_{\rm sys}/{\rm B}$ are π^0 reconstruction, tracking and backgrounds.

I do not see how to predict the reductions in $\sigma_{\rm sys}$ for the semileptonic decay modes width which will be accomplished by the CLEO, ABF, and BES collaborations. Certainly experience, larger $N_{\tau\tau}$'s, new analysis ideas, and improved detectors will bring reductions in $\sigma_{\rm sys}$, but will $\delta B_i/B_i < 0.01$ be attained?

Conversely, do we need $\delta B_i/B_i < 0.01$ for semileptonic decay modes? Accurate comparisons with theory and other data can only be made for decay modes with even numbers of π's. And these comparisons using CVC and $e^+ e^-$ annihilation cross section data are limited in their accuracy by the $e^+ e^-$ data. Thus to compare with Eqs. 22a and 23 Eidelman reports [52]

$$\begin{aligned} &{\rm B}(\tau \to \nu_\tau \pi\pi^0 \ , \ \text{CVC prediction}) \\ &\quad = (24.9 \pm 0.07)\% \end{aligned} \tag{24a}$$

$$\begin{aligned} &{\rm B}(\tau \to \nu_\tau 3\pi\pi^0 \ , \ \text{CVC prediction}) \\ &\quad = (4.20 \pm .29)\% \quad , \end{aligned} \tag{24b}$$

and Sobie gives [53]

$$\begin{aligned} &{\rm B}(\tau \to \nu_\tau \pi\pi^0 \ , \ \text{CVC prediction}) \\ &\quad = 24.3 \pm 1.1)\% \quad . \end{aligned} \tag{24c}$$

(Add .5% for $\tau^- \to \nu_\tau K^- \pi^0$ to B in Eqs. 24a and 24c to compare with Eq. 22b.) Reduction of the errors in the predicted B's in Eqs. 24 requires better $e^+ e^-$ cross section data in the energy region $2m_\pi < E_{\rm cm} < m_\tau$. Such data can be obtained at the VEPP-2M e^+e^- collider which has $E \leq 1.4$ GeV and, if it is built, from a tau-charm factory.

As has been emphasized by Kühn [54] at this meeting, there is much more to semileptonic decays than branching fractions. The hadronic resonances contained in the modes, the kinematic distributions, the measurement of form factors, the great variety of modes containing hadrons; all this data provides the best highway to the study of hadron physics for $E_{\rm cm} < 1.8$ GeV. Large values of $N_{\tau\tau}$ will be of great help in providing precise data.

Improvements will also be required in π/K separation, π^0 reconstruction, and in removal of backgrounds. In particular, it will be important to avoid using cuts which distort kinematic distributions.

Finally, I come to the question of what might be hidden in the semileptonic modes. Since the sum of the exclusive mode B_i's is within 1% of 100% [39,44] there are no mysterious modes with $B \gtrsim 1\%$. But are there mysterious modes with $B \approx 10^{-3}$ or $B \approx 10^{-4}$. Can we begin to use our detectors as bubble chambers which were once used to pick out a few "new physics" events out of thousands of ordinary events? For example, is there a mysterious decay

$$\tau^- \to \nu_\tau + x^- + 3\gamma \tag{25}$$

which does not come from

$$\tau^- \to \nu_\tau + h^- + \pi^0 + \text{fake } \gamma$$

or

$$\tau^- \to \nu_\tau + h^- + 2\pi^0 (\gamma \text{ lost})$$

or

$$\tau^- \to \nu_\tau + e^- + \overline{\nu}_e + 3\gamma \quad ?$$

7. RARE DECAYS, FORBIDDEN DECAYS, AND LEPTON NONCONSERVATION IN TAU PRODUCTION

There will be tremendous progress in research on rare τ decays, forbidden τ decays, and lepton number nonconservation in τ pair production as

$$\mathrm{N}_{\tau\tau} \rightarrow 10^8 \tag{26}$$

at CESR, ABFs, and perhaps a TCF.

7.1 Second-Class Current Rare Decays

Most interesting is the search for the second-class current decay mode [19,55]

$$\tau^- \rightarrow \nu_\tau + \pi^- + \eta \tag{27a}$$

for which the standard model predicts

$$\mathrm{B}(\tau^- \rightarrow \nu_\tau \pi^- \eta) \approx 10^{-5} \text{ to } 10^{-6} \tag{27b}$$

and the present upper limit [56] is

$$\mathrm{B}(\tau^- \rightarrow \nu_\tau \eta^- \eta) < 3.4 \times 10^{-4} \ , \ 95\% \text{ CL} \tag{27c}$$

The best signature uses $\eta \rightarrow \gamma + \gamma$ hence

$$\tau^- \rightarrow \nu_\tau + \pi^- + \gamma + \gamma \quad . \tag{27d}$$

The backgrounds are

$$\tau^- \rightarrow \nu_\tau + \pi^- + \pi^0 \ , \ \nu_\tau + \pi^- + 2\pi^0 \tag{27e}$$

so that once again π^0 and γ detection and selection is crucial.

The second-class current decay mode

$$\tau^- \rightarrow \nu_\tau + \pi^- + \omega \text{ via } \mathrm{b}_1(1235) \tag{28}$$

will be more resistant to demonstration because it must be proven that the $\pi^-\omega$ come from the b_1.

7.2 Other Rare Decays

There is a variety of rare decay modes which will be a challenge to detect and study although they are not of special theoretical interest. Examples are the higher multiplicity Cabibbo suppressed decays and the seven-prong decay

$$\tau^- \rightarrow \nu_\tau + 4\mathrm{h}^- + 3\mathrm{h}^+ + \mathrm{n}\pi^0 \ , \ \mathrm{n} \geq 0 \quad . \tag{29}$$

Another example is the five particle leptonic decays

$$\mathrm{B}(\tau^- \rightarrow \nu_\tau \mathrm{e}^- \mathrm{e}^- \mathrm{e}^+ \overline{\nu}_\mathrm{e} \ , \ \text{predicted}) = 4 \times 10^{-5}$$

$$\mathrm{B}(\tau^- \rightarrow \nu_\tau \mu^- \mathrm{e}^- \mathrm{e}^+ \overline{\nu}_\mu \ , \ \text{predicted}) = 2 \times 10^{-5}$$

$$\mathrm{B}(\tau^- \rightarrow \nu_\tau \mu^- \mu^- \mu^+ \overline{\nu}_\mu \ , \ \text{predicted}) = 1 \times 10^{7} \ , \tag{30}$$

the branching fractions have been calculated by Dicus and Vega [57].

7.3 Forbidden Decays Without Neutrinos

The search for τ decay modes which do not contain neutrinos, such as

$$\tau^- \rightarrow \ell^- + \gamma \tag{31a}$$

$$\tau^- \rightarrow \ell^- + \ell^+ + \ell^- \tag{31b}$$

$$\tau^- \rightarrow \ell^- + (\text{hadrons})^0 \tag{31c}$$

with $\ell = \mathrm{e}$ or μ, will of course greatly benefit from very large $\mathrm{N}_{\tau\tau}$. The smallest upper limits on the $\mathrm{B_i}$'s are [55,58]

$$\mathrm{B_i} \leq \text{ few } \times 10^{-6} \tag{31d}$$

based on $\mathrm{N}_{\tau\tau} \approx 1.5 \times 10^6$ from CLEO II. As $\mathrm{N}_{\tau\tau}$ goes to 10^7 and then 10^8 at CESR and the ABF's, experimenters can attain sensitivity 1/10 and then 1/100 of Eq. 31d, if backgrounds can be suppressed. Looking at existing search data [55,58] the search for forbidden modes containing hadrons, Eq. 31c, are most likely to suffer from backgrounds. Table 4 from Alemany et al. [59]. gives projected sensitivity limits.

Table 4
Attainable limits for the branching fractions for forbidden, neutrinoless τ decays. The TCF is assumed to have $N_{\tau\tau} = 2.4 \times 10^7$ at 3.67 GeV. CESR or the ABF is assumed to have $N_{\tau\tau} = 0.9 \times 10^7$.

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

7.4 Forbidden Decays with an Undetectable Particle

There is no recent progress in the search for

$$\tau^- \to l^- + x^0 \qquad (32a)$$

with ℓ = e or μ and x^0 a weakly interacting particle. In 1990 Albrecht et al. [60] reported with a 95% C.L.

$$B(\tau^- \to e^- x^0) < 0.003 \ , \ m_{x^0} < 100 \text{ MeV} \quad (32b)$$

rising to 0.009 at m_{x^0} = 500 MeV. The limits [59] on $B(\tau^- \to \mu^- x^0)$ are similar. The problem is that these forbidden modes cannot be distinguished from the corresponding leptonic modes

$$\tau^- \to \nu_\tau + l^- + \overline{\nu}_l \quad , \qquad (32c)$$

if m_x^0 equals the invariant mass of the $\nu_\tau \overline{\nu}_l$ combination. Indeed the search method requires that the x^0 be detected as a bump above the $\nu_\tau \overline{\nu}_l$ mass spectrum. Alemany et al [59]. have shown that a TCF will permit a more sensitive search than CESR or ABF's particularly for the $\tau^- \to e^- x^0$ mode, Table 5.

Table 5
Attainable limits for the branching fractions for forbidden τ decays with a weakly interacting particle. The TCF is assumed to have $N_{\tau\tau}$ = 2 to 5 $\times 10^6$ at 3.56 GeV. CESR or the ABF is assumed to have $N_{\tau\tau} = 9 \times 10^6$ (from Ref. 59).

Mode	Tau-Charm Factory	CESR or B-Factory
$\tau \to e x^0$	10^{-5} to 10^{-6}	5×10^{-3}
$\tau \to \mu x^0$	10^{-3} to 10^{-4}	5×10^{-3}

7.5 Lepton Nonconservation in Tau Pair Production

Vorobiev [61] has reviewed the upper limits

$$\begin{aligned} e^+ + e^- &\to e^\pm + \tau^\mp \\ e^+ + e^- &\to \mu^\pm + \tau^\mp \quad . \end{aligned} \qquad (33a)$$

The smallest 95% C.L. upper limit at the Z^0 is from the L3 experiment with

$$\begin{aligned} B(Z^0 \to e\tau) &< 0.9 \times 10^{-5} \\ B(Z^0 \to \mu\tau) &< 1.1 \times 10^{-5} \quad . \end{aligned} \qquad (33b)$$

To my knowledge, the smallest upper limit measured below the Z^0 is [62]

$$\begin{aligned} \sigma(e^+e^- \to e^\pm\tau^\mp)/\sigma(e^+e^- \to \mu^+\mu^-) &< 1.2 \times 10^{-3} \\ \sigma(e^-e^- \to \mu^\pm\tau^\mp)/\sigma(e^+e^- \to \mu^+\mu^-) &< 4.1 \times 10^{-3} \end{aligned} \qquad (33c)$$

with 95% C.L. at 29 GeV.

The sensitivity to $B(Z^0 \to e\tau)$ and B $(Z^0 \to \mu\tau)$ can probably be extended to 5×10^{-6} at LEP I [61], but that is not a significant increase in sensitivity. I do not know how much the sensitivity can be improved at CESR, the ABF's or a TCF over that in Eq. 33c.

8. CP VIOLATION IN TAU PRODUCTION AND DECAY

8.1 CP Violation in Tau Production

At this meeting Stahl [63] has reviewed the search for CP violation in

$$e^+ + e^- \to Z^0 \to \tau^+ + \tau^- \qquad (34a)$$

using τ spin–τ spin correlations. The upper limits on a weak dipole moment, d_τ^z, from LEP I experiments are [63]

$$\begin{aligned} |\mathrm{Re}(d_\tau^Z)| &< 6.4 \times 10^{-18} \text{ e cm} \\ |\mathrm{Im}(d_\tau^Z)| &< 4.5 \times 10^{-17} \text{ e cm} \quad . \end{aligned} \qquad (34b)$$

Table 6 from Bernreuther et al. [22] gives projected 1 σ accuracies for measurement of d_τ^Z and d_τ^γ using τ spin–τ spin correlations. The bottom row shows that as $N_{\tau\tau} \to 2 \times 10^5$ (Eq. 6b), there will be some increase in sensitivity at the Z^0.

Sensitivity to the electric dipole moment, d_τ^γ, is given in the top three rows of Table 6. Weinstein and Stroynowski [19] have reviewed other ways to find d_τ^γ. Present upper limits on d_τ^γ are [2]

$$|d_\tau^\gamma| < \text{ few } \times 10^{-16} \text{ ecm} \quad . \qquad (35)$$

Table 6
Projected 1σ accuracies for measurement of the CP violating electric dipole moment of d_τ^γ and weak dipole moment d_τ^Z for various E_{cm} and certain $N_{\tau\tau}$. The upper value is for $|\,\mathrm{Re(d)}\,|$ and the lower value is for $|\,\mathrm{Im(d)}$ from Bernreuther et al.[22]

E_{cm} (GeV)	$N_{\tau\tau}$	d_τ^γ (e cm)	d_τ^Z (e cm)
3.67	2.4×10^7	2×10^{-16} 1×10^{-16}	
4.25	3.5×10^7	4×10^{-17} 2×10^{-17}	
10.58	5×10^7	1×10^{-18} 3×10^{-18}	
91.2	3.3×10^5		2×10^{-18} 3×10^{-17}

Ananthanarayan and Rindani [64] have discussed using a longitudinally polarized e^- beam to search for CP violation in τ pair production.

The τ provides almost the only way to search for CP violation in the decay of leptons. At this meeting Nelson [49] described the theory of using τ spin–τ spin correlations to search for CP violation.

An alternative method of searching for CP violation in τ decay is to use a longitudinally polarized e^- beam or e^+ beam as discussed by Tsai [23] at the Workshop [9] on "The Tau-Charm Factory in the Era of B-Factories and CESR." There are two advantages. First, the search will be more sensitive by a factor of 10 or more. Second, the experimenter will be able to reverse the beam polarization or set it to zero, thus obtaining better control of the systematic errors in the required asymmetry measurements.

9. TAU NEUTRINO MASS

As reviewed by Cerutti [65] the present upper limits on m_{ν_τ} with 95% C.L. are

$$\begin{aligned} \text{ALEPH} &: 23.8 \text{ MeV} \\ \text{ARGUS} &: 31.0 \text{ MeV} \\ \text{CLEO} &: 32.6 \text{ MeV} \\ \text{OPAL} &: 74.0 \text{ MeV} \quad . \end{aligned}$$

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 [66]. He discusses the use of the different decay modes:

$$\begin{aligned} &\tau^- \to \nu_\tau + \pi^- + K^+ + K^- \\ &\tau^- \to \nu_\tau + 3\pi^- + 2\pi^+ \\ &\tau^- \to \nu_\tau + 2\pi^- + \pi^+ + 2\pi^0 \quad . \end{aligned} \qquad (36)$$

He 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. These projections may be optimistic, for example, Weinstein [32] predicts a sensitivity of about 15 MeV for CESR. On the other hand, the new two-dimensional search technique introduced by ALEPH experimenters [65] may also be helpful at CESR and ABF's.

10. ELECTROMAGNETIC PROPERTIES OF THE TAU

10.1 Radiative Decays

There is much work to be done on the radiative decays of the τ such as:

$$\tau^- \to \nu_\tau + l^- + \overline{\nu}_l + \gamma \ , \ l = \mathrm{e}, \mu \qquad (37a)$$

$$\tau^- \to \nu_\tau + \pi^- + \gamma \qquad (37b)$$

$$\tau^- \to \nu_\tau + \rho^- + \gamma \quad . \qquad (37c)$$

There are three physics issues. First, precise comparisons of the measured ratios $\mathrm{B}_\pi/\mathrm{B}_\mathrm{e}$ zand $\mathrm{B}_\mathrm{K}/\mathrm{B}_\mathrm{e}$ with theory require calculation of radiative corrections [67]. Second, as discussed by Decker and Finkemeir [68] and the references they give, we can learn about internal bremsstrahlung and structure-dependent radiation from distribution such as the γ energy spectrum and the $\pi\gamma$ invariant mass spectrum in Eq. 37b. Third, can there be "new physics" in radiative decays?

To my knowledge, there are only two experiments on radiative tau decays [69,70].

10.2 Tau Magnetic Moment

If the τ is a conventional Dirac charged particle, its magnetic moment is given [71] by

$$\mu_\tau = \mathrm{g}_\tau \frac{\mathrm{e}\hbar}{2\mathrm{m}_\tau \mathrm{c}} \qquad (38a)$$

$$\frac{\mathrm{g}_\tau - 2}{2} = \frac{\alpha}{2\pi} + \mathrm{O}(\alpha^2) = \mathrm{a}_\tau \ , \qquad (38b)$$

where

$$\frac{\alpha}{2\pi} = 1.16 \times 10^{-3} \qquad (39a)$$

is the Schwinger term. In Eq. 38b[71]

$$\mathrm{a}_\tau = 1.177 \times 10^{-3} \qquad (39b)$$

As calculated by Escribano and Masso [72] from LEP I experimental data

$$-8 \times 10^{-3} \leq \mathrm{a}_\tau(\mathrm{measured}) \leq 10 \times 10^{-3} \ . \quad (39c)$$

Thus measured limits are ten times larger than the expected value. Can we eventually measured a_τ so as to test the τ? Laursen et al. [73] have suggested a method using the leptonic radiative decays in Eq. 37a.

10.3 Tau Cross Section Near Threshold

The last measurement of the behavior of the τ pair production cross section, $\sigma_{\tau\tau}$, from threshold to $\mathrm{E}_\mathrm{cm} = 4$ GeV was made 16 years ago in the DELCO experiment at SPEAR [74]. The theory of $\sigma_{\tau\tau}$ in this threshold region is now well understood.[75] I believe it will be interesting to make a precision study of the ratio $\sigma_{\tau\tau}$(measured) $/\sigma_{\tau\tau}$(theory) as a function of E_cm.

10.4 $\tau^+\tau^-$ Atom

I have reviewed [27] the atomic structure and decay process of $\tau^+\tau^-$ atoms, as well as the cross section for

$$\mathrm{e}^+ + \mathrm{e}^- \to \gamma \to \tau^+\tau^-\mathrm{atom} \quad . \qquad (40)$$

The $1^3\mathrm{S}_1$ ground state which is 24 KeV below threshold has a peak cross section and width

$$\begin{aligned} \sigma_{\tau\tau\mathrm{atom}}(\mathrm{peak}) &\approx 2.4 \times 10^{-28}\mathrm{cm}^2 \\ \Gamma &= 2.9 \times 10^{-2}\mathrm{eV} \quad . \end{aligned} \qquad (41)$$

The observed peak cross section depends upon $\sigma_{\mathrm{E}_\mathrm{cm}}$, the spread in E_cm, as follows

$$\begin{aligned} \sigma_{\mathrm{E}_\mathrm{cm}} &= 1 \text{ MeV} \ , \ \sigma_{\tau\tau\mathrm{atom}}(\mathrm{peak}) \approx 0.003 \text{ mb} \\ \sigma_{\mathrm{E}_\mathrm{cm}} &= 100 \text{ KeV} \ , \ \sigma_{\tau\tau\mathrm{atom}}(\mathrm{peak}) \approx 0.03 \text{ mb} \quad . \end{aligned} \qquad (42)$$

Skrinsky [12] has shown the fascinating behavior of $\sigma_{\tau\tau\mathrm{atom}}$ if $\sigma_{\mathrm{E}_\mathrm{cm}}$ can be reduced to 20 KeV or 5 KeV in a future upgrade of a tau-charm factory. If $\sigma_{\mathrm{E}_\mathrm{cm}} = 20$ KeV $\sigma_{\tau\tau\mathrm{atom}}(\mathrm{peak}) \approx$ 0.1 mb, and is $\sigma_{\mathrm{E}_\mathrm{cm}} = 5$ KeV $\sigma_{\tau\tau\mathrm{atom}}(\mathrm{peak}) \approx$ 0.5 mb. There is still the deeper question of what physics can we do with $\tau^+\tau^-$ atoms?

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