The Investigation of CP Violation through the Decay of Polarized Tau Leptons II

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Abstract

Under the assumption that CP violation is caused by exchange of a new boson, we propose to measure the magnitudes and CP-violating phases of the coupling constants of this boson to five different vertices in tau decay. This can be accomplished by studying the decay of polarized tau leptons produced at an $e^+ e^-$ collider whose beams are polarized. These five coupling constants could be used to construct a future theory of CP violation. If CP is violated in any channel of tau decay, it will imply that there exists a new charged boson other than the W boson responsible for CP violation. It will also imply that CP violation is much more prevalent than the standard theory predicts and this may enable us to understand the preponderance of matter over antimatter in the present universe.

The CP violation is known to occur only in K_L upto now and in a few years we would know whether it will occur in the B system from the B factories. In this paper we would like to propose experiments to investigate whether the CP violation occurs in leptonic sectors as well as ud and us vertices by using the decay of polarized taus. CP violation in the decay of tau is prohibited in the standard model for the following reasons. The standard theory assumes that the origin of the CP violation is the imaginary numbers in the mass matrix. These imaginary numbers cause the CKM matrix to have a complex phase that produces the observable CP violating effects. The matrix element in the mass matrix represents the coupling constants between the fermions and the vacuum expectation value of the scalar particle that was eaten by the massless gauge fermions to fatten them. Since neutrinos are massless in the standard theory these CP violating complex coupling constants must be zero for the mass matrix of the neutrinos and thus the CP violation in the leptonic sector is zero. Thus, the pure leptonic decay modes of tau cannot have any CP violation. In the semileptonic decay of tau the elements V_{ud} and V_{us} of the CKM matrix can be assumed to be real because their phases can be absorbed by suitably redefining the phases of quark wave functions. The same argument can also be used for the leptonic vertices as well. The last reason is that in the standard theory the weak charged current is carried solely by the W boson that is coupled to each fermion doublet by a single coupling constant. Thus even if this coupling constant is complex we shall not be able to see its phase because there is no other amplitude to interfere with it to produce the CP violating effects. For these reasons in order to have CP violation in tau decay we must assume the existence of another carrier of weak charged current called X boson having a complex coupling constant to quarks and leptons. We let the X exchange diagram interfere with the CP conserving standard model diagram with W exchange to produce CP violation. The X particle is assumed to be either spin one or spin zero. We also assume that all neutrinos to be massless in order to simplify the calculation. In contrast to the pure hadronic system our experiments can isolate the strong interaction effects such as the final state interaction effect and the hadronic form factors experimentally and obtain the CP violating phases unambiguously without relying on the QCD calculations. If CP violation is due to exchange of a new particle as speculated in this paper the CP violation would become much more universal than the standard model gives and thus we may be able to understand the predominance of matter over antimatter in our universe. We also no longer require the existence of at least three generations to have CP violation in nature. The test of CP violation in tau decay can be put into three categories:

1. **Use polarized electron and preferably also positron beams to investigate the semileptonic tau decay modes [1] with at least two final hadrons:** In this case it is relatively straight forward to interpret the result in terms of the strength and the phase of the CP violating coupling constant. Let us assume that CP violation is produced by an interference between two diagrams, A and B, where A is a CP conserving diagram and B is a CP violating diagram due to exchange of a new meson X with a complex coupling constant having a phase exp $(i\delta_t)$ for τ^- decay and exp $(-i\delta_t)$ for τ^+ decay. Let us further assume that the final state interactions for A and B involve quantum numbers j and j' with phases exp $(i\delta_j)$ and exp $(i\delta_{j'})$ respectively. Let us write for τ^- decay

$$A = \exp(i\delta_j)a, \tag{1}$$

$$B = \exp(i\delta_{j'} + i\delta_t)b; \tag{2}$$

and for τ^+ decay

$$A' = \exp(i\delta_j)a', \tag{3}$$

$$B' = \exp(i\delta_{j'} - i\delta_t)b'. \tag{4}$$

In the above the strong interaction phases are unchanged because they are invariant under charge conjugation, whereas the CP violating phase has a different sign because of the requirement of Hermiticity in the weak Hamiltonian that is one of the requirements of the validity of TCP theorem [1]. An equivalent way to see this is to assume the validity of TCP. Since under T i changes into -i , under CP δ_t must become - δ_t in order to preserve TCP invariance. The test of CP consists of comparing the interference between A and B with that between A' and B'.

$$F= A^+B+B^+A= \cos(\delta_{j'}-\delta_j+\delta_t)(a^+b+b^+a)+\sin(\delta_{j'}-\delta_j+\delta_t)(a^+b-b^+a), \tag{5}$$

$$F' = A'^+B'+B'^+A' = \cos(\delta_{j'}-\delta_j-\delta_t)(a'^+b' + b'^+a')+\sin(\delta_{j'}-\delta_j-\delta_t)(a'^+b' - b'^+a'). \tag{6}$$

In the absence of strong interactions we have $\delta_{j'}-\delta_j=0$ and F' is related to F by CP, namely $\delta_t\to-\delta_t$, all the momenta of the particles go into the negative of the momenta of the charge conjugate particles and the polarization vector of the spin $\frac{1}{2}$ particle becomes the polarization vector of its anti-particle without changing sign. Since $\cos(\delta_t)= \cos(-\delta_t)$, CP is conserved without the strong interaction for the cosine terms and thus the coefficients of cosine terms must be T even from the TCP theorem. On the other hand the coefficients of the sine terms must be T odd using similar argument. Thus for decay mode involving two hadrons, denoted by q_1 and q_2 for τ^- decay and q_1' and q_2' for τ^+ decay, we may write:

$$F= C\{\cos(\delta_{j'}-\delta_j+\delta_t)[\mathbf{W}\cdot\mathbf{q_1}f_1+\mathbf{W}\cdot\mathbf{q_2}f_2+f_3]+\sin(\delta_{j'}-\delta_j+\delta_t)\mathbf{W}\cdot(\mathbf{q_1}\times\mathbf{q_2})f_4 \}, \tag{7}$$

$$F'= C\{\cos(\delta_{j'}-\delta_j-\delta_t)[\mathbf{W}'\cdot\mathbf{q_1}'f_1' + \mathbf{W}'\cdot\mathbf{q_2}'f_2' + f_3']+\sin(\delta_{j'}-\delta_j-\delta_t)\mathbf{W}'\cdot(\mathbf{q}_1'\times\mathbf{q}_2')f_4'\}, \tag{8}$$

where $\mathbf{W}$ and $\mathbf{W}'$ are the polarization vectors of the τ^- and τ^+ respectively. We assume CP is conserved in the production of taus, in that case $\mathbf{W} = \mathbf{W}'$ in the center of mass system [1]. At energy of the tau/charm factory the production is almost all in the s wave, hence the polarization vectors of the taus are almost equal [1] to the effective beam polarization vector:

$$\mathbf{P}=\mathbf{e}_z(W_1+W_2)/(1+W_1W_2), \tag{9}$$

where $\mathbf{e}_z$ is the unit vector in the direction of the incident electron, W_1 and W_2 are longitudinal polarizations of electron and positron respectively in the z direction.

At energies far above the threshold, for example at Z_0 pole, the d-wave production becomes comparable to the s wave production. Only s and d wave production of tau pair is allowed for the parity conserving one photon exchange interaction, whereas p-wave is also allowed in the parity non conserving Z_0 exchange. The conservation of angular momentum prohibits higher partial waves. After integrating with respect to the production angle only the component of the polarization in the z direction comes in but with average magnitude less than the effective beam polarization, $\mathbf{P}$, given above when the energy is far above the threshold. [1]

f's are calculable functions of the dot products of various four momenta of the problem (See reference [1] for examples). In general they are functions of tau production angle but it can be integrated out easily. By reversing the polarization we can isolate the coefficients of $\mathbf{W}\cdot\mathbf{q_1}$, $\mathbf{W}\cdot\mathbf{q_2}$, $\mathbf{W}\cdot(\mathbf{q_1}\times\mathbf{q_2})$, $\mathbf{W}'\cdot\mathbf{q}_1'$, $\mathbf{W}'\cdot\mathbf{q}_2'$, and $\mathbf{W}'\cdot(\mathbf{q}_1'\times\mathbf{q}_2')$ from the experiment. These six equations can be used to solve for three unknowns: C, $\delta_{j'}$-δ_j, and δ_t in Equations (7) and (8) as functions of invariant mass of two hadrons. The CP violating phase δ_t is the sum of two terms, δ_τ for the tau-nu vertex and a similar thing for one of the four possible final states: δ_e for e-nu, δ_μ for mu-nu, δ_{ud} for the ud quarks, and δ_{us} for the us quarks. The fact that we can isolate the strong interaction effects, $\delta_{j'}$-δ_j and the form factor C, experimentally is very gratifying because it means that we do not have to rely upon QCD to calculate them.

I would like to make several important observations from the equations given in (7) and (8):

a. Two hadrons in A and B must be in two different quantum states, i.e. $j \neq j'$, in order to exhibit any CP violation. Proof: If $j = j'$ we have $\delta_{j'}$-δ_j=0 and cos(δ_t)= cos(-δ_t) thus CP can not be violated in the T-even terms. For T-odd terms if a and b represent the same quantum states they must be proportional to each other, hence $(a^+b-b^+a)= 0$, Q.E.D.

b. Thus decay channels such as $\tau \to \nu_\tau + \rho$, $\nu_\tau + K^*$, $\nu_\tau + \pi$, etc. can not exhibit CP violation, because each hadronic final state shown above has definite angular momentum and isospin quantum numbers. This shows that some of the CP violation discussed by Goozerat and Nelson [5] can not occur.

c. If we assume that CP violating diagram B is through the exchange of either spin-1 or spin-0 particle, and the diagram A involves only W exchange, then we can have only s-p interference for the CP violating terms. This fact has both advantage and disadvantage. The advantage is that s-p interference gives unique expressions for f_1, f_2 ... regardless of spin of exchanged particles so there is no ambiguity involved in what kind of expressions to use for these functions (See examples in [1]). The disadvantage is that this means we can not use the energy angular distribution to tell us the spin of the particle exchanged! [4] However if the exchanged particle is a Higgs it may have a larger coupling constant when coupled to heavier particles.

d. The CP violation is manifested by the difference in two cosine and sine functions shown in Equations (7) and (8):
The difference in cosine functions that is responsible for the CP violation in the T-even part

is

$\cos(\delta_{j'}-\delta_j+\delta_t)-\cos(\delta_{j'}-\delta_j-\delta_t)=2\sin(\delta_{j'}-\delta_j)\sin(\delta_t).$ (10)

The difference in sine functions that is responsible for the CP violation in the T-odd part is

$\sin(\delta_{j'}-\delta_j+\delta_t)-\sin(\delta_{j'}-\delta_j-\delta_t)=2\cos(\delta_{j'}-\delta_j)\sin(\delta_t).$ (11)

These two equations show that the CP violation in both cases are induced only by the imaginary part of the coupling constant, i.e. $\sin(\delta_t)$, as expected. The CP violation is absent in the T-even terms in the absence of strong final state interactions, i.e. $\delta_{j'}=0$ and $\delta_j=0$, in agreement with the TCP theorem. This shows that in the leptonic decay to be treated next, only the T odd terms can appear for the CP violation. From Equation (11) we note that in the T-odd terms, the CP violation is maximum when $\delta_{j'}-\delta_j=0$.

2. **The second category of experiments [2] deals with testing of CP violation in the pure leptonic decay modes such as muon decay of tau**. For this we require both polarized tau and detection of transverse polarization of muon. Since there is only one observable momentum in the final state, the momentum of the muon denoted by **q**, the rotationally invariant quantities we can form are: $\mathbf{W}\cdot\mathbf{q}$, $\mathbf{W}_\mu\cdot\mathbf{q}$, and $\mathbf{W}\cdot(\mathbf{q}\times\mathbf{W}_\mu)$. According to the TCP theorem the first two can not violate CP because they are T even and no strong interactions. The third term is T odd and hence must also violate CP without the final state interaction. This implies that If this term is C $\mathbf{W}\cdot(\mathbf{q}\times\mathbf{W}\mu)$ for τ^- decay then for τ^+ decay it must be $C\mathbf{W}'\cdot(\mathbf{q}'\times\mathbf{W}_\mu')$. Thus T violation and CP violation can be checked independently in this experiment. This experiment involves only leptons whereas the previous experiments involve leptons and hadrons. In [2] we showed that only spin 0 X boson contributes to T and CP violation for the pure leptonic decay of tau.

3. **For unpolarized Taus [3]**: In this case we measure the branching fraction of a semileptonic decay of τ^- with two or more hadronic final particles and compare it with that of the charge conjugate decay mode, for example:

$$\Gamma(\tau^-\to\pi^-+\pi^0+\nu_\tau)\neq\Gamma(\tau^+\to\pi^++\pi^0+\nu_{\bar{\tau}}) \text{ or}$$
$$\Gamma(\tau^-\to K^-+\pi^0+\nu_\tau)\neq\Gamma(\tau^+\to K^++\pi^0+\nu_{\bar{\tau}}).$$

If any of the inequality holds, it would indicate a CP violation. However, the result of such an experiment is not easily analyzable in terms of the CP violating coupling constant. For example [1] in the 2π mode shown above, if CP is violated 2π's from τ^- decay will have different energy-angle distributions from that from τ^+. This results in the difference in the rate of the inelastic final state interactions such as $2\pi \rightarrow 4\pi$. Thus part of the width of 2π mode is shuffled into that of 4π mode and vice versa differently resulting in different branching fractions for these modes. The total width as well as the partial widths of those channels without strong final state interactions are CP invariant. Since we do not know anything about the cross sections for $2\pi \rightleftharpoons 4\pi$, there is no way we can obtain the magnitude and the phase of the complex coupling constant responsible for the violation of CP using this method. Since CP violation discussed here is very indirect, we expect this effect to be small. In Equations (7) and (8), we have ignored such inelastic final state interactions.

Comments on Polarized beams at BTCF

The longitudinal polarization is the most important tool to select weak interaction events through the parity violating dot product $\mathbf{P}\cdot\mathbf{q}$ where $\mathbf{P}$ is defined by Eq. (9) and $\mathbf{q}$ is any momentum of the particle. We can obtain many such dot products as well as T odd products: $\mathbf{P}\cdot(\mathbf{q_1}\times\mathbf{q_2})$ and $\mathbf{P}\cdot(\mathbf{q}_\mu\times\mathbf{W}_\mu)$ to obtain the structure of weak interaction. In the electron-positron colliding beam the charge conjugate final state is readily available and by comparing the two we obtain parameters for CP violation. At the Beijing Tau/Charm Factory (BTCF) there will be two separate rings for electrons and positrons. The Sokolov-Ternov effect will most likely be used to first transversely polarize both beams with assistance from wigglers to speed up the polarization time to around 40 minutes for both beams [6] . Siberian snakes will be installed in both rings to rotate the beam polarization before and after the interaction to achieve the longitudinally polarized beams at the interaction region. The polarization achievable for each beam is around 70% without sacrifice to the luminosity if we avoid certain resonance energies of the machine [6]. The experiments I am proposing are not sensitive to the choice of energy except that the cross section must be large and the background must be minimal. The ideal energy is slightly below ψ'(3685) resonance that is slightly below the charm threshold. Below charm threshold all e-hadron, mu-hadron, and e-mu events are tau induced and thus the background is greatly reduced. It should be emphasized that polarizing both electron and positron beams have the following advantages [1]:

1. The effective polarization is increased from W_1 to $P= (W_1+W_2)/(1+W_1W_2)$. For example if $W_1=W_2= .7$ we have $P= .94$.

2. All cross sections, not just in the tau production, are increased by a factor $F= 1+W_1W_2$. For example $F= 1.49$ if $W_1=W_2= 0.7$. This means that it is advisable to have two beams polarized even when the polarization is not required. The longitudinal polarization does not affect any energy-angle distribution unless parity is violated, in other words, unless weak interaction is involved. Of course if a spin 0 particle is produced and decays subsequently

by weak interaction, the initial beam polarization will not affect the energy angle of the subsequent decay, because the spin zero particle has no ability to transfer the information of its parent's angular momentum.

The longitudinally polarized beams can also be used to investigate CP violation in $\Lambda \bar{\Lambda}$ and $\Xi \bar{\Xi}$ systems; we may also test whether right handed current and charged Higgs exchange play any role in $\tau \rightarrow \nu_\tau + \mu + \nu_\mu$ by measuring the longitudinal polarization of muons [5]. Please notice that the CP violation in muon decay of tau deals with the transverse polarization of the muon.

Future Outlook for CP Violation.

By year 2005 SLAC, KEK and Cornell probably would have found out whether one of the six unitarity triangles of the CKM matrix closes or not [8]. If it does not close, then the model in the standard model for CP violation is wrong. There are many possible reasons why the CKM matrix not being unitary. One possibility is the one conjectured in my work, namely, the mass matrix has nothing to do with the CP violation and thus CP violation is not prohibited by the smallness of neutrino mass and the number of generations has nothing to do with the CP violation. It has something to do with the exchange of a new particle or particles that couple to other particles with a complex coupling constant. Unitarity of KM matrix can also be violated by the existence of fourth generation fermions and yet CP violation still is caused by the complex coupling constants in the mass matrix and the W boson is still the only boson responsible for all the phenomena, including CP violation, associated with the weak charged current. Testing the CP violation in the tau decay can rule out the second possibility. Of course if CP violation is discovered in the decay of tau in any channel it will indicate directly the existence of a new boson other than the W boson and that CP violation is much more universal than that given by the standard model. The significance of such a discovery will be far reaching. Hopefully the Tau/Charm Factory will be finished by 2002 and some results on the CP violation will be available by 2005.

On the other hand if the B Factory experiment concludes that one of the unitarity triangle closes or almost closes, then in order to show the unitarity of the CKM matrix one has to check five other unitarity triangles and six normalization conditions which state that sum of the absolute square of each element of any row or column must be unity. This will take a long time to accomplish. In fact B Factories can not do this because we need the knowledge on the CP violation of the top quark. In this case at least one of the three B factories in the world should be persuaded to pursue the investigation of CP violation in tau decay.

CP violation in tau decay can also be investigated at the B factories if the incident beam or beams are polarized. This problem was discussed in Equation (4.12) of reference [1].

Roughly speaking the merit of the experiment is determined by three factors: 1. The luminosity. 2. The total production cross section and 3. The average tau polarization along the direction of the incident electron. The luminosity of a machine is roughly proportionate to the energy in the center of mass system. For the tau/charm factory (TCF) the energy for each beam is 2 Gev whereas for the B factory (BF) it is 5.5 Gev, so the luminosities of TCF and BF in the initial stage are 1×10^{33} and 3×10^{33} respectively and eventually these numbers can be increased by ten folds [9]. Multiplying the cross sections and the design luminosities given above at respective energies we obtain 3.4 ($1+W_1W_2$) and 2.14 ($1+W_1W_2$) tau pairs per second at the first stage of operation for TCF and BF respectively. After improvement these numbers probably can be increased by ten folds in both facilities. The average tau polarization in the incident electron direction at TCF is essentially given by P shown in Equation (9), but at BF for energy of 5.5 Gev the polarization of tau in the z direction is reduced by 22% due to increase in importance of the d-wave production.

The X particle responsible for CP violation is coupled to both the tau-nu vertex and the vertex for the final particles. Thus δ_t is sum of two terms one is due to CP violating phase δ_τ in the tau sector and the other is any one of the four possible final states for tau decay: δ_e, δ_μ, δ_{ud}, and δ_{us}. These five phase angles can not be separated out using the tau decay alone. We need CP violation from other sources. CP violation in the decays $K^\mp \to \pi^0 + \nu_\mu + \mu^\mp$ and the subsequent measurement of muon polarization can yield $\delta_\mu + \delta_{us}$, measurement of CP violation in $\mu \to \nu_\mu + \nu_e + e$ with subsequent measurement of electron polarization can yield $\delta_\mu + \delta_e$. We have more than enough equations to solve for five unknown phase angles. Measurement of δ_e is probably the most difficult because it involves measurement of the transverse polarization of an electron. Fortunately the knowledge of δ_e is not necessary to solve for the other four phase angles.

Suppose we are able to determine all five of the CP violating phases and the coupling constants for all the vertices in the tau decay. We should then be able to construct some theory to correlate all the data and predict the mass and spin of the particle exchanged. This would be analogous to what Weinberg did for the standard theory. If we assume δ_t's to be roughly $\pi/2$ and the coupling constants to be about the same as the electroweak coupling constants due to some symmetry, and the CP violation has roughly the magnitude of 2×10^{-3}, the same as the CP violation in K_L into 2π, we can estimate the mass of the particle responsible for CP violation:

$$M_X = M_W/\sqrt{2\times 10^{-3}} = 1.8 \text{ Tev}. \qquad (12)$$

On the other hand if the particle X exists it should also contribute to the total and partial width of Tau. Since the standard model can predict the width to about 2% accuracy, we can obtain the lower bound of the mass of such a particle:

$$M_X > M_w/\sqrt{0.02} = 560 \text{ Gev.} \tag{13}$$

If CP violation is transmitted by such a particle, then CP violation we are trying to detect is a 2% effect and we can see the effect with only about one million tau pairs that are obtainable within one year of operation of the Tau/Charm Factory. BTCF is designed to produce about 100 million tau pairs per year.

20 years from now we may be investigating the properties of this particle, similarly to the way we are investigating the properties of W's and Z_0 today. After that we may finally be able to understand why there is more matter than anti-matter in our universe.

Some of my friends asked me if I had any specific model which predicts the existence and the properties of the hypothetical X particle. My answer is that it is premature to play such a game. Weinberg could not have invented the standard theory of the electroweak interaction without the discovery of parity violation, V-A nature of the coupling, conserved vector current theory, Higgs mechanism, etc. We do not know enough about the phenomenology of CP violation to construct a credible theory yet. Therefore I believe the most useful thing to do now is to devise methods to accumulate more facts on the CP violation independent of any particular model. When devising methods to test CP violation we must remember that its strength is at most about 2% of the weak interaction as discussed in conjunction with Equation (13). Devising methods for testing CP violation that require CP violation to be as strong as electromagnetic interaction is waste of time. I believe testing the CP violation in the production mechanism of tau at low energies is such an example. In the appendix I give my reasons.

Comments on Possible Experiments

Let me comment on some of the possible experiments necessary to obtain the CP violating phases for five different vertices involved in tau decay:

1. $\tau^{\pm} \rightarrow K^{\pm} + \pi^0 + \nu_\tau$ and $\tau^{\pm} \rightarrow K^0 + \pi^{\pm} + \nu_\tau$

These modes are suppressed by the Cabibbo angle but may have larger CP violation than the item 2 if X is a Higgs boson. We obtain $\delta_\tau + \delta_{us}$ in this experiment.

2. $\tau^{\pm} \rightarrow \pi^{\pm} + \pi^0 + \nu_\tau$

This mode has the branching fraction of 25% that is the largest. We obtain $\delta_\tau + \delta_{ud}$ in this experiment.

3. $\tau^\pm \to \pi^\pm + \pi^+ + \pi^- + \nu_\tau$ and $\tau^\pm \to \pi^\pm + \pi^0 + \pi^0 + \nu_\tau$

Each of these two modes has roughly 7.5% branching fraction. The three body kinematics is determined by the strong interactions and hence the expressions for f's in (7) and (8) depend upon the strong interaction model. We obtain $\delta_\tau + \delta_{ud}$ in this experiment.

4. $\tau^\pm \to \mu^\pm + \nu_\mu + \nu_\tau$

This is a pure leptonic mode hence uniquely important. We need to measure the transverse polarization of muons. We obtain $\delta_\tau + \delta_\mu$ in this experiment. If this experiment shows CP violation then it will imply the existence of a spin zero X boson having complex coupling constants to tau-nu and mu-nu vertices. Whether this spin zero X boson is a charged Higgs can be decided by comparing the results of experiments 5 and 7.

5. $\tau^\pm \to e^\pm + \nu_e + \nu_\tau$

It is hopelessly difficult to measure the transversal polarization of electrons in this experiment; item 7 is slightly easier. Fortunately δ_e is not required to solve for other δ's.

6. $K^\pm \to \mu^\pm + \pi^0 + \nu_\mu$

We have to measure the polarization of the muon perpendicular to the muon-pion plain. This experiment will yield $\delta_\mu + \delta_{us}$, that can be used to solve for δ_μ , δ_τ , δ_{us} , and δ_{ud} using experiments 1, 2 and 4.

7. $\mu^\pm \to e^\pm + \nu_e + \nu_\mu$

We have to measure the transversal polarization of the electron from the decay of polarized muons, namely the T violating correlation $\mathbf{W}_\mu \cdot (\mathbf{p}_e \times \mathbf{W}_e)$. This experiment will measure $\delta_\mu + \delta_e$. Since δ_μ is obtainable from experiment 6 we can finally obtain δ_e.

Needless to say that any one of the seven experiments listed above is by itself a revolutionary experiment because it shows that a new boson, called X in this paper, exists and is responsible for CP violation in the charged current.

Appendix. Testing CP violation in the production of Tau

I have ignored the possibility of CP violation in the production of taus and considered only the CP violation in the decay. The reason is that I can not obtain the detectable magnitude of CP violation if we believe that CP violation in the production arises also from the interference between the standard one photon exchange diagram and a CP nonconseving diagram due to exchange of a charged X boson or a neutral Y boson somewhere in the diagram. There are two classes of diagrams that interfere with the lowest order one photon exchange diagram to produce CP violating effects. The first class is the vertex correction due to exchange of a neutral Higgs boson between the tau pair resulting in the electrical dipole moment of tau [10]. Now this diagram is similar to the one for calculating the anomalous magnetic moment of tau except that the photon is replaced by a Y propagator. Since the contribution of the anomalous magnetic moment to the cross section is approximately α/π [11], if we replace the photon propagator by a neutral Higgs boson propagator there must be another reduction factor of $(M_\tau/M_H)^2$. Using the value of M_X given by Equation (13) for M_H we obtain the contribution of tau electric dipole moment to the cross section to be at most 2.4×10^{-8} of the cross section, which is undetectable using 100 million taus. There are many papers written on the possible CP violation in the tau <u>production</u> due to the possible existence of an <u>intrinsic</u> electrical dipole moment of tau [12]. However I believe that the electric dipole moment of an elementary particle must arise from some T and P non-invariant interactions. Thus such possibility is excluded. In other words if the electric dipole moment of tau can give more than α/π contribution to the cross section it must be due to a force stronger than the electromagnetic force and this is impossible [13].

Another mechanism is the interference between one photon exchange diagram and a diagram consisting of exchange of a neutral Y boson between the electron pair and the tau pair. The Y boson cannot be a spin one particle unless its coupling to tau or electron has an electric dipole moment type of coupling, because hermiticity of the current forces the reality of the lowest order coupling for vector, axial vector, the anomalous magnetic moment, and the electric dipole terms. Only the electric dipole moment term has an opposite behavior from the other three under T. If the exchanged particle is a scalar particle the hermiticity of the interaction forces the scalar coupling to be real and T even and the pseudoscalar coupling to be pure imaginary and T odd. Thus the interference of the one photon exchange and the pseudo-scalar part of Y exchange coupling will produce the CP violation. Its contribution will be suppressed by a factor m_e/E because the one photon exchange and the scalar exchange diagrams do not interfere in the limit of zero electron mass. If the particle exchanged is a Higgs there will be another factor of m_e/M_W because Higgs particle's coupling to any particle is proportional to the mass of the particle. Thus for the Higgs particle exchange the effect is of order $(2Em_e^2)/(M_W M_H^2) \approx 10^{-13}$ for E=2 Gev which is completely unobservable. There are some papers which claim to obtain null results for detecting the CP violation in Tau production with about one percent accuracy [14]. In my opinion such an experiment can not even measure the effect due to the anomalous magnetic moment which will produce the kind of correlation they are looking for, but its magnitude is α/π=1/430.

However this does not have anything to do with CP violation, it is just the electromagnetic final state interaction mimicking the CP violation. This effect does not bother us, because the effect is the correlation between the decay product of τ^- and that of τ^+ which we are not advocating in our experiment. In conclusion I believe that CP violation in the tau <u>production</u> is undetectable at low energies even with the designed luminosity of the Tau/Charm Factory. Only CP violation in the tau <u>decay</u> there is a hope of detecting it using the Tau/Charm Factory or a B factory with polarized beam or beams. We have shown that the decay of polarized taus will tell us about the existence of a charged boson X that is responsible for the CP violation in the charged current. Its neutral partner, Y, that is responsible for the CP violation in the neutral current, must be a spin zero particle according to the discussion given above. This spin zero particle is rather difficult to search using the electron positron collider unless one knows its precise mass. It will most likely be discovered in conjunction with the Higgs boson search. Its signature will be the spin correlation of tau pairs in the decay of Y of the form $(\mathbf{p}_1 - \mathbf{p}_2).(\mathbf{s}_1 \times \mathbf{s}_2)$, where $\mathbf{p}_1$ and $\mathbf{s}_1$ are momentum and spin of τ^- respectively and $\mathbf{p}_2$ and $\mathbf{s}_2$ are those for τ^+. Since $\mathbf{s}_1$ and $\mathbf{s}_2$ are analyzed by the decay products of τ^- and τ^+ respectively, they can be replaced by the momenta of decay products from each tau. The detail of such a scheme has been worked by He, Ma and McKellar [15].

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