Probing violation of CP & T invariance in the transitions of $\tau$ leptons

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My motto: "Crafted with Care"

Abstract

The SM predicts zero value for CP & T violation in the decays of $\tau$ leptons – except $\tau^- \rightarrow \nu K_S[\pi^-/\pi^-\pi^0...]$. Our community could establish impact of New Dynamics (ND) in a CP asymmetry in a semi-hadronic $\tau$ transition and later in a second one. To be ‘practical’, I suggest to our experimental colleagues to probe $\tau^- \rightarrow \nu K^0[\pi^-/\pi^-\pi^0/\pi^-\eta]$ and $\tau^- \rightarrow \nu K^-[\pi^0/\pi^0+\pi^-/\eta]$. While I had mostly given comments about CP violation in $\tau$ transitions, some theorists have shown how ND models could produce CP asymmetries; I will discuss these ones, although sometimes I am not a true theorist, but as a phenomenalist here. I can hardly ‘dream’ that CP asymmetry in $\tau$ decays could be connected with our huge asymmetry in ‘our’ matter vs. anti-matter.

1 Introduction to CP violation in $\Delta L \neq 0$ transitions

Old people like me often start with a ‘history’. In this case I first give a reference to my July 2021 book with two co-authors [1]. It is dedicated to Lev Okun, who said in his 1963 Russian book ‘we’ have to continue probing CP violation in $K_L \rightarrow \pi\pi$,

Furthermore the TAU2021 WS is dedicated to Prof. Simon Eidelman (1948 - 2021) – which him I had discussions for many years, and I had learnt & enjoyed – and Prof. Olga Igonkina (1973 - 2019), when I had listened to her excellent talks at Capri (Italy) and CERN.

My 2021 book [1] discusses CP asymmetries (plus strong CP violation, Axions, rare decays, Dark Matter, modern cosmology ...) about the transitions of hadrons & leptons in general. At this TAU2021 Workshop we have seen nice introduction talks about $\tau$ dynamics from Toni Pich & Bill Marciano including its ‘history’ (& future challenges) as one can see on their slides [2]. Now one can read Toni’s contribution to the Proceedings [3]. Furthermore, one can read several good talks about neutrino oscillations and EDMs.

Obviously I focus on CP violation in leptonic transitions. ‘My judgment’ said: With neutrino oscillations being established between three neutrinos ‘we’ will find CP asymmetries there; I would give the golden medal. Next I will give the silver medals for the

1Contributed talk for the TAU2021 WS at the University of Indiana (U.S.A.)
2I have ‘stolen’ it from a local pizza restaurant in Pearland (Texas).
EDMs for electrons, muons and tau, although these competitions are ‘close’. ‘We’ have candidates for the bronze medal; of course, I am biased, namely to probe CP asymmetries in \( \tau \) decays. I discuss next.

\section{CP asymmetries in \( \tau \) decays}

Mostly I am thinking about “leptogenesis” driving “baryogenesis”; however, CP violation in the decays of \( \tau \) leptons can hardly ‘dream’ about ”leptogenesis” leading to ”matter” \( \gg \) ”anti-matter” in ‘our’ Universe. On the other hand, it is a wonderful hunting area for the impact of ND on CP & \( T \) asymmetries (in the world of theorists). Their hadronic final states are enough ‘complex’ to show impact of non-perturbative QCD at least. It is not surprised that data of \( \tau^- \rightarrow \nu K_S \pi^- \) has shown signs of CP asymmetry. The SM predicts \( A_{CP}(\tau^- \rightarrow \nu K_S \pi^-)_{SM} = -(0.36 \pm 0.01)\% \) due indirect CP violation in \( K_S \rightarrow \pi^+\pi^- \). PDG2020 has accepted BaBar2012 analysis leading to \( A_{CP}(\tau^- \rightarrow \nu K_S \pi^-)_{PDG2020} = + (0.36 \pm 0.25)\% \): it is consistent with the SM prediction – or a sign of impact from ND.

\subsection{The theoretical ‘Landscape’}

‘We’ had listened a nice talk by Noel at the TAU2021 Workshop; one can read it in the Proceedings \cite{4, 5}. It is based on his article \cite{5}. His talk was clearer (in my view) than in his article about finding CP violation there, but also a sign of ND.

On my 2009 book \cite{6} one can find a reference \cite{341} on its page 406, namely non-minimal Higgs models. Those could reach the \( 10^{-3} \) level. SUSY models might go beyond that, in particular with broken \( R \) parity \cite{7}.

There is a list of articles by my colleague Morozumi & his team to discuss CP asymmetries in \( \tau^- \rightarrow \nu K[\pi/\eta/\eta'] \). It is not just an idea about CP asymmetries, but to analyze some models like two Higgs doublet models. These ones would produce impact on forward vs. backward transitions; furthermore these models could also produce CP asymmetries there \cite{8}. It is very interesting in principle; however, it suggested CP asymmetries on the level of \( \mathcal{O}(10^{-6}) \). Still one can learn lessons from failures of impact of ND. Anyway, none of these had been participants at the TAU2021 WS.

\subsection{Probing CP & \( T \) asymmetries in general}

Just above I had listed three candidates for ND to produce CP (\& T) asymmetries. However, I do not act as a true theorist here, but as a phenomenalist about CP violation in \( \tau \) decays. One example is the ”Sect.5 Dynamics of \( \tau \) leptons” in my Ref.\cite{9} with a small comment about future regional asymmetries from Belle II (and a possible Super Tau-Charm Factory); I will come back to that.

\footnote{My main point is the title: ”On the scalar \( \pi K \) form factor beyond the elastic region” both Noel’s talk \& his article \cite{5}. First he discussed the tools for analyzing data. The truly new stuff (in my view) is the end, namely to probe CP asymmetries in \( \tau \) decays.}
I have realized that my 2021 book has giving less than one page for CP asymmetry in τ decays, while around three pages in my 2009 book, see Ref.[10]. I make a better case (I hope) for continuing probing CP violation in τ decays.

Now I discuss CP asymmetries in τ decays with some details. To be realistic (from a theorist’s view) I talk about \( \tau^- \to \nu K^0 [\pi^0 / \pi^+ \pi^- / \eta] \) and \( \tau^- \to \nu \bar{K}^0 [\pi^- / \pi^0 / \pi^- / \eta] \) with somewhat similar branching ratios, see the PDG2020 data. However, the SM describes quite differently the ‘landscape’ for CP asymmetries.

Class (I)

\[
\begin{align*}
\text{BR}(\tau^- \to \nu K^- \pi^0) & = (4.33 \pm 0.15) \cdot 10^{-3} \\
\text{BR}(\tau^- \to \nu K^- \pi^+ \pi^-) & = (3.45 \pm 0.07) \cdot 10^{-3} \\
\text{BR}(\tau^- \to \nu \bar{K}^- \eta) & = (1.55 \pm 0.08) \cdot 10^{-4}
\end{align*}
\]

The SM gives zero CP violation in these channels.

Class (II)

\[
\begin{align*}
\text{BR}(\tau^- \to \nu \bar{K}^0 \pi^-) & = (8.38 \pm 0.14) \cdot 10^{-3} \\
\text{BR}(\tau^- \to \nu \bar{K}^0 \pi^- \pi^0) & = (3.82 \pm 0.13) \cdot 10^{-3} \\
\text{BR}(\tau^- \to \nu \bar{K}^0 \pi^- \eta) & = (0.94 \pm 0.15) \cdot 10^{-4}
\end{align*}
\]

The situation is more ‘complex’ with neutral kaon about CP asymmetries:

\[
\begin{align*}
A_{\text{CP}}(\tau^- \to \nu K^- \pi^-) & = + (0.36 \pm 0.25) \% \\
A_{\text{CP}}(\tau^- \to \nu K^0 \pi^-) & = - (0.36 \pm 0.01) \%
\end{align*}
\]

I give reference to two articles about CP asymmetry in \( \tau^- \to \nu \bar{K}_S \pi^- \) in the past [11].

Which lesson one can learn here?

- So far our community has not established impact of ND on \( A_{\text{CP}}(\tau^- \to \nu K_S^0 \pi^-) \); i.e., the SM prediction is consistent with the PDG2020 data within 3σ, see Eq.(8) vs. Eq.(7).

- The situations are very different between Class (I), where the SM predicts zero CP violation, and Class (II), where it predicts \( A_{\text{CP}}(\tau^- \to \nu K_S^0 \pi^-)\)\(_{\text{SM}} = - (0.36 \pm 0.01) \cdot 10^{-3} \). Actually this SM asymmetry is subtle: it is based on indirect CP violation in neutral \( K \to \pi^+ \pi^- \), although in general τ decays could show direct CP asymmetries.

- For phenomenalists the goals are to convince experiments not only to probe CP asymmetry in \( \tau^- \to \nu K_S \pi^- \) with accuracy, but also with a broader program: \( \tau^- \to \nu K_S^0 [\pi^- / \pi^0 / \pi^- / \eta] \) and \( \tau^- \to \nu K^- [\pi^0 / \pi^+ \pi^- / \eta] \).

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4I am not a super-fan of thinking about a connection between τ vs. \( D^+ \) transitions.
• A small comment: our community can probe CP asymmetry in Cabibbo favored transitions like $\tau^- \to \nu K^- K^0$ with the opposite sign in the SM; furthermore it could show impact of ND. Of course, one can compare the branching ratios:

$$\text{BR}(\tau^- \to \nu \pi^- \pi^0) = (25.49 \pm 0.09)\% \quad (9)$$

$$\text{BR}(\tau^- \to \nu K^- K^0) = (1.486 \pm 0.034) \cdot 10^{-3}. \quad (10)$$

At the TAU2012 workshop I had mostly focussed on $\tau^- \to \nu K \pi$’s, but I had mentioned FS with only $\pi$’s. [12].

The SM predicts zero CP asymmetries in $\tau^- \to \nu K^0[\pi^0/\pi^+\pi^-]$. The situations are somewhat similar for doubly Cabibbo suppressed $D^- \to K^-\pi^0/K^-\pi^+\pi^-$. Thus there are ‘hunting areas’ for impact of ND on CP asymmetries in $\tau$ & $D^-$ decays.

• Kiers in his TAU2012 talk had discussed both FS of $K\pi$’s and $\pi$’s [13]. For mostly practical reasons they had discussed CP asymmetries first in $\tau^- \to \nu \pi$’s; it had suggested that model with charged Higgs fields could hardly have impact on $\tau^- \to \nu \pi^- \pi^0$, but on $\tau^- \to \nu [3\pi/4\pi]$ [14].

• Again as a phenomenalist (in the world of quarks & leptons): I ‘paint’ the ‘landscape’: $\tau^- \to \nu s...\bar{u} \Rightarrow \nu K^-\pi^+\pi^-/\nu K^0\pi^-\pi^0$ etc. Somewhat similar situation with Cabibbo favored transition $\tau^- \to \nu d...\bar{u} \Rightarrow \nu K^- K^0$.

Due to $K^0 - \bar{K}^0$ the SM predicts

$$A_{CP}(\tau^- \to \nu K_S \pi^-) = + (0.36 \pm 0.01)\% = -A_{CP}(\tau^- \to \nu K_S K^-) \quad (11)$$

• ”Leptoquarks” (LQ) have been become as a ‘fashion’, in particular for the theoretical literature about their indirect impact. One can look at $\tau^- \to s’ LQ’ \nu \bar{u} \Rightarrow \nu \bar{K}^0\pi^-/\nu K^-\pi^+\pi^-$ or even $\tau^- \to d’ LQ’ \nu \bar{u} \Rightarrow \nu K^- K^0$ that could violate Eq.(11).

The situations about CP asymmetries in $\tau$ transitions are very different about CP violations in the decays of beauty, charm & strange mesons at least, where SM had predicted non-zero values. Here I am not talking about numbers or models or even classes of models. As a phenomenalist one would say in one channel that CP asymmetry has been established the impact of ND. However, one has to be realistic in our world with experimental data; one has to find possible patterns; thus I use again the word of ‘paintings’, see Figure [1].

My summarizing of the 2020 data:

• PDG2020 data are consistent with SM predictions including CP violation.

• However, the situation is ‘thin’ about CP violation in $\tau$ decays: PDG2020 gives only for $A_{CP}(\tau^- \to \nu K_S^0 \pi^-)_{PDG2020} = + (0.36 \pm 0.25)\%$.

It is important to probe CP asymmetry in different FS Eq.[1] - Eq.(6) (as listed above). I think it is an excellent candidate for the bronze medal.
At the TAU2021 WS ‘we’ had been told that the Belle II collaboration is ‘thinking’ about CP asymmetries in $e^+e^- \rightarrow \tau^+\tau^-$, which is good. What are the limits in different channels?

One can find a very nice 2013 review by Pich with the title “Precision Tau Physics” with 50 pages (except the list of References)\(^5\). When one looks at the ‘landscape’ of $\tau$ dynamics in a review, the ‘Sect.10 CP violation’ could be discussed in less than one page; however, 16 references were given there\(^6\).

3 Probing $\tau$ transitions with polarized electron beams

I list articles about CP violation in $e^+e^- \rightarrow \tau^+\tau^-$ with polarized $e^-$ beams, see Rets.\(^9\)\(^12\)\(^13\)\(^15\) or mentioned in Ref.\(^16\). It was pointed out by Bernabeu et al. in Ref.\(^17\) to focus on leptonic EDMs for good reasons, and I have to agree. Of course, it is a true challenge to produce $e^+e^-{\text{polar}} \rightarrow \tau^+\tau^-$. I tell about a ‘broader’ (but maybe not deeper) ‘landscape’, namely CP asymmetries in $\tau$ decays.

One can notice that the articles came from theorists. However, the situation has changed. We were able to listen very nice talks by X. Zhou about a possible Super Tau-Charm Factory in China\(^18\) and by D. Epifanov about a Russia one\(^19\)\(^20\). One can read some details in their contributions.

It would have rich programs in general; furthermore, it opens new ‘roads’ about fundamental dynamics in $\tau$ EDMs and CP asymmetries. I only somewhat disagree: ‘we’ should not focus only on CP asymmetries on $\tau^- \rightarrow \nu(K\pi)$; we have to probe also CP asymmetries in $\tau^- \rightarrow \nu K[\pi\pi/\eta/\pi\eta]$, as I said above including $e^+e^-{\text{polar}} \rightarrow \tau^+\tau^-$. Of course, the first goal is to find CP asymmetry in $e^+e^- \rightarrow \tau^+\tau^-$. Later one can use a $e^-{\text{polar}}$ beam: it is not about bragging rights about an experiment; one could find a deeper information about the underlying dynamics.

\(^{5}\)It gives a list of 601 references which helps readers to understand the underlying $\tau$ dynamics.

\(^{6}\)It is discussed also in Sect.9 ‘Electromagnetic and Weak Dipole Moments’
4 Lessons for the future

I give a short comment about CP asymmetries in the decays of strange baryons like for \( \Lambda \rightarrow p\pi^- \): I am a co-author in a 2018 article \[21\]. The SM situations of CP violation are very different between \( \tau^- \) and \( \Lambda \) (in principle; in real data one has to worry about uncertainties in the measured values):

\[
A_{\text{CP}}(\tau^- \rightarrow K^-[\pi^+'s]) = 0 \quad \text{vs.} \quad A_{\text{CP}}(\Lambda \rightarrow p\pi^-) \neq 0 ; \tag{12}
\]

so far we have no real SM prediction for \( A_{\text{CP}}(\Lambda \rightarrow p\pi^-) \). It was listed as an important goal for a future Super Tau-Charm Factory \[18\].

Mostly our literature about leptonic EDM’s is for electrons & muons; however it is important to probe \( \tau \) EDMs in a different ‘landscape’, as discussed in the 2021 Ref.\[22\] with the title ”Electric dipole moment of the tau lepton revisited”. On the other hand, I focus on CP asymmetries in \( \tau \) decays. The SM predicts zero CP asymmetries in \( \tau^- \) transitions (except CP violation in the decays of neutral kaons). As I had said above, CP asymmetries in semi-hadronic \( \tau^- \) decays are good candidate for the bronze medal. The hadronic FS are described including resonances: some are narrow, while other are broad. They are ‘complex’ in the world of quarks, see the ‘painting’ of s\( \bar{u} \) or d\( \bar{u} \) leading to two & three mesons (or even four ones).

I list three classes of \( \tau^- \) decays about CP asymmetries: (a) \( \tau^- \rightarrow \nu K^-[\pi^0/\pi^+\pi^-/\eta] \); (b) \( \tau^- \rightarrow \nu[\pi^-\pi^0/\pi^-\pi^+/\pi^-\eta] \); (c) \( \tau^- \rightarrow \nu K_S[\pi^-/\pi^-\pi^0/\pi^-\eta] \). The SM predicts zero CP asymmetries in classes (a) & (b), while non-zero value due to CP violation in the measured \( K^0 - \bar{K}^0 \) oscillations.

- CP violation is an excellent tool for finding ND due to an amplitude in \( \tau \) rates.
- The FS of semi-hadronic \( \tau \) decays have one, two, three ... mesons. ‘We’ have decent chance to find ND in CP asymmetries, in particular beyond \( \tau^- \rightarrow \nu h_1 h_2 \). For example: \( \tau^- \rightarrow \nu K^- \pi^+\pi^- \).

The situations about CP violation are very different between the \( \tau \) lepton vs. the strange, beauty & charm mesons already on the qualitative level.

- One can find models for CP asymmetries for \( \tau \) transitions (like with charged Higgs or leptoquarks fields) that can produce CP asymmetries, but my main points are: future experiments should probe CP violation in \( \tau^- \rightarrow \nu (h_1 h_2 h_3) \) decays with \( h_i \) mesons \[8\].

Once we get new limits or even better to get non-zero values, we can discuss what we have learnt about underlying dynamics like chiral symmetry. Thus it is crucial to use collaboration with members of HEP vs. Hadrodynamics \[9\] from different ‘cultures’.

\[7\] One could include \( \tau^- \rightarrow \nu K^0 K^- \).

\[8\] As usual, the hard work has to be done from experimenters.

\[9\] Hadrodynamics is a much better choice of words than MED.
5 Epilogue

One can go to old history: "Gods = Symmetries speak in Riddles." Or: "On seeing a missile shot by a catapult which had been brought them for the first time, a king from Sparta in the 4th century B.C. cried out: ‘By Heracles, this is the end of man’s valor’." Can a theorist see an analogy with computers?

Figure 2: Renaissance architecture & modern sculpture (picture taken by IIB)

I want to show an analogy of CP asymmetries in \( \tau \) transitions with ‘art’, see the Figure 2. It is wonderful connection of Renaissance architecture and modern sculpture. It is inside a building just south of the Main Market Square of the city Cracow (Poland). It is not easy to find it; thus I am proud of this picture.

Our understanding of fundamental dynamics is based on symmetries in many ways – although often that is not obvious. We can learn from paintings (or other arts). Some artists can have ‘visions’, not just describe the landscape: when one talks about triangles, quadrangles etc. in the different flavor dynamics of quarks and leptons, the paintings of the Russian artist Kandinsky come to mind: one can look at page 87 in Ref.\[1\] from Kandinsky’s 1923 paintings before quantum mechanics, see Figure 3.

Figure 3: "Composition VIII" (painted by V., Kandinsky in 1923)
Another example: this time from a Spanish painter, namely Salvador Dali. At my talk at the TAU2021 workshop I had shown his 1931 painting with the title ”Persistence of Memory”. Here I show his 1937 painting, see Figure 4.

Figure 4: ”Metamorphosis of Narcissus” (painted by S. Dali in 1937)

My final comment here: As I had said above theorists can produce models of ND that could be found CP asymmetries in $\tau^{\pm}$ transitions for the next decade. So far, I am not convinced by these models. I am happy to hear about CP asymmetries in $\tau$ decays by the LHCb and the Super-Tau-Charm Factory. However, ‘our’ community has to beyond $\tau^{-} \to \nu(K\pi)^{-}$ – it is very important. There is an analogy between ‘real art’ and ‘fundamental physics’.

Acknowledgements

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