MITP Workshop on T violation and CPT tests in neutral-meson systems

Mainz, 15 - 16 April 2013

First some very basic considerations:

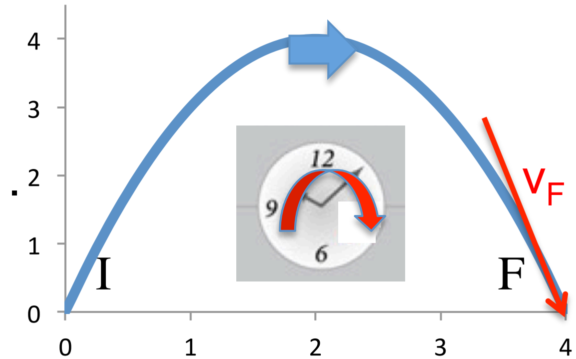
Time is not reversible. Time always runs in only one direction.

Our experience of the „arrow of time“ is valid in the macro- and the microcosmos.

We explain it by the 2nd law of thermodynamics in multi-particle systems and by causality in few-particle systems (an event can never influence an earlier one.)

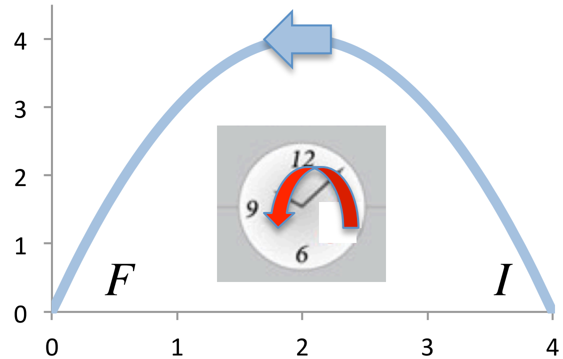
What do we understand by time-reversal? Let me start with classical mechanics, a two-body system, ball and earth:

Motion of a ball on the earth:



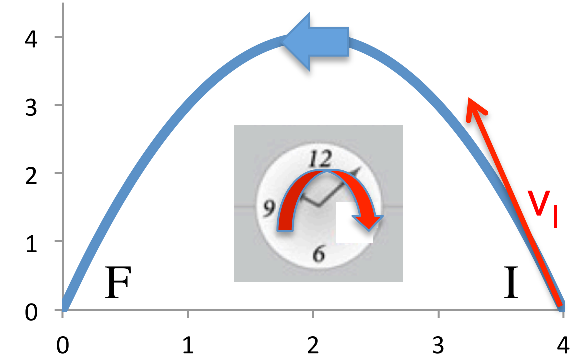
We record motion and clock

and replay it backwards:



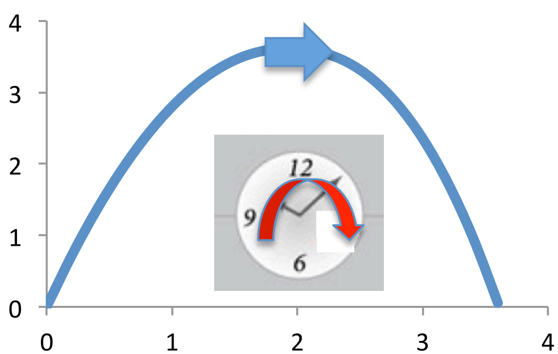
This is unobservable

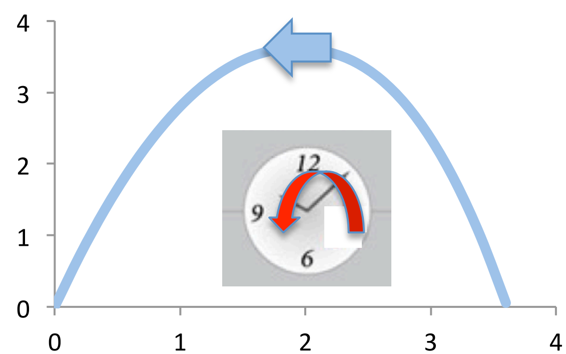
But with I ↔ F and $v_I = - v_F$:

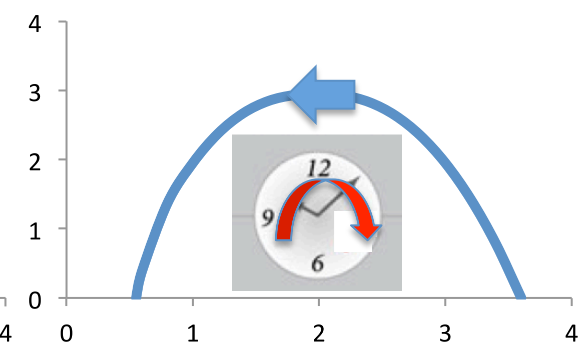


Observed reversed motion

When the orbit of the reversed motion coincides with that of the original motion, we have motion reversal symmetry. It follows from time-reversal (T) symmetry of the law for the motion; here: $m\ddot{\vec{x}} = m\vec{g}$. This is invariant under the exchange t → - t. Now modify the law of motion to $m\ddot{\vec{x}} = m\vec{g} - m\dot{\vec{x}}$ which is not invariant under t → - t:





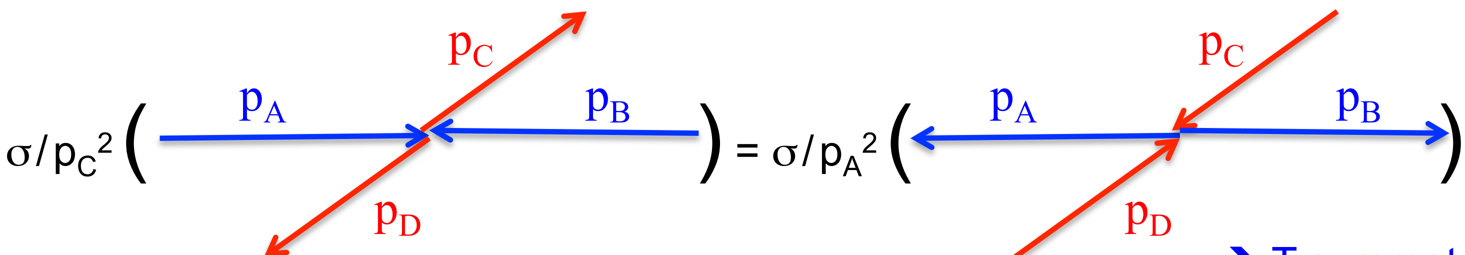


Time is not reversible. Also not in quantum mechanics. Examples for T symmetry tests:

- Reactions between stable particles
- Transitions beween stable particles
- Transitions between unstable particles
- Why is instability a problem?
- Tests of T symmetry in transitions between unstable particles

First example: Comparing the nuclear reactions $A + B \rightarrow C + D$ and $C + D \rightarrow A + B$,

Richter, v.Brentano, v.Witsch 1968 $^{27}Al(p,\alpha)^{24}Mg$ and $^{24}Mg(\alpha,p)^{27}Al$



for spinless particles and integration over all angles

➔ T symmetry better than 1 %.

2nd example: Neutrino-“Oscillations“ with three ν species

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{ij} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P(\nu_e \rightarrow \nu_\mu) = \left| \sum_{j=1}^{3} U_{ej} U_{\mu j}^{*} \, \mathrm{e}^{-im_j^2 L/2E} \right|^2 , P(\nu_\mu \rightarrow \nu_e) = \left| \sum_{j=1}^{3} U_{\mu j} U_{ej}^{*} \, \mathrm{e}^{-im_j^2 L/2E} \right|^2$$

If the two rates are different, $J(U_{ij}) \neq 0$ and T is violated.

3rd example: Transitions between unstable particles, $K^0 \leftrightarrow \bar{K}^0$, Niebergall et al 1974.

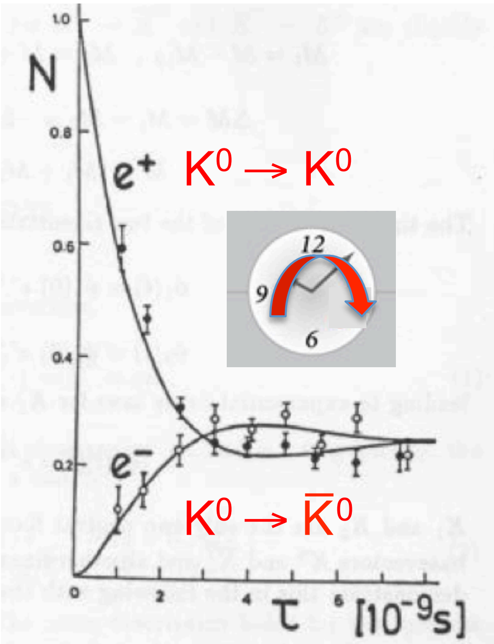
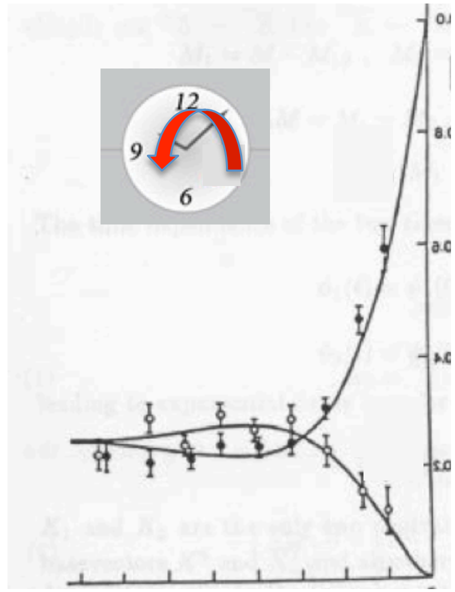
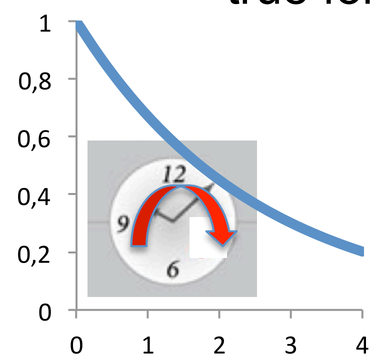


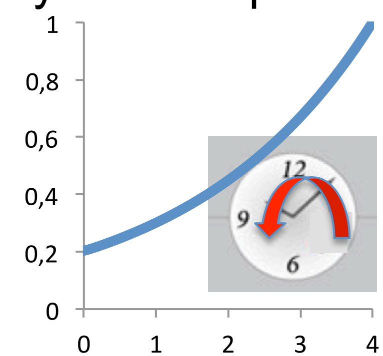
Fig. 3: Time dependence of $\pi^- e^+ \nu$ and $\pi^+ e^- \bar{\nu}$ decays of an initial K^0 state, from [2].

If we record the rate pattern and replay it backwards:

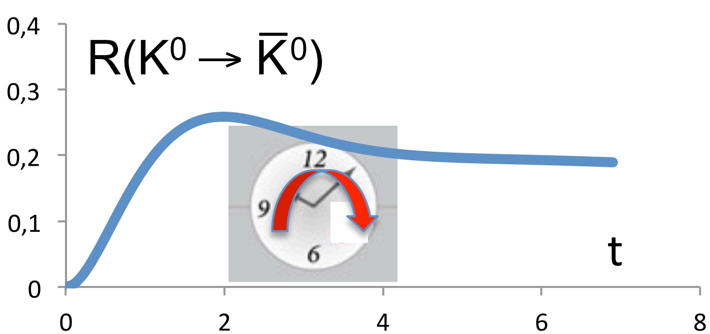


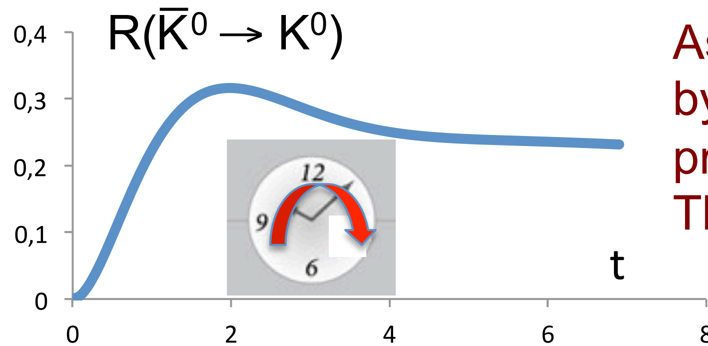
The increase of $K^0 \rightarrow K^0$ is only seen in the backward-played video, not in reality. But it would be wrong to conclude T violation in the transition interaction from that. The same is true for any instable particle:





Reason: This pseudo time-reversal forgets that an unstable particle must be produced. For „pseudo-stable“ particles, we can test T invariance of the transition by exchanging initial and final state $\psi_i \leftrightarrow \psi_f$ and setting $v_i = -v_f$ as in classical mechanics on p.2. Since we are in the C.M. system, $v_i = -v_f = 0$ and:





As measured 1999 by CPLEAR and presented today by Thomas Ruf

The observation of motion reversal, i.e. exchange $\psi_i \leftrightarrow \psi_f$ and reversal of all momenta and spins without reversing $t \rightarrow -t$, tests time reversal T, i.e. the symmetry of the responsible dynamics for the observed process under the reversal $t \rightarrow -t$.

T symmetry ➔ motion reversal symmetry.

Observation of motion reversal asymmetry ➔ T symmetry is violated.

We desscribe the observed T violation in the Wigner-Weisskopf approximation with a Schrödinger eqn. for the evolution of $\Psi = \psi_1 K^0 + \psi_2 \overline{K}^0$:

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = \left[\begin{pmatrix} m_{11} & m_{12}\\ m_{21} & m_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma_{21} & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$$

Condition: The weak interaction is so weak that linearity is good enough. (How good?)

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}=\left[\begin{pmatrix}m_{11} & m_{12}\\ m_{21} & m_{22}\end{pmatrix}-\frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma_{21} & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$$

Two solutions with exponential decay laws:

$$K_S^0(t)=\left[p\cdot\sqrt{1+2\delta}\cdot K^0+q\cdot\sqrt{1-2\delta}\cdot\bar{K}^0\right]\cdot e^{-\Gamma_S t/2-\mathrm{i}m_S t}$$

$$K_L^0(t)=\left[p\cdot\sqrt{1-2\delta}\cdot K^0-q\cdot\sqrt{1+2\delta}\cdot\bar{K}^0\right]\cdot e^{-\Gamma_L t/2-\mathrm{i}m_L t}$$

$p/q=(1+\varepsilon)/(1-\varepsilon)$ and ε and δ small:

$$K_S^0(0)=\left[(1+\varepsilon+\delta)\cdot K^0+(1-\varepsilon-\delta)\cdot\bar{K}^0\right]/\sqrt{2}$$

$$K_L^0(0)=\left[(1+\varepsilon-\delta)\cdot K^0-(1-\varepsilon+\delta)\cdot\bar{K}^0\right]/\sqrt{2}$$

$$\Delta m=m_L-m_S\approx 2|m_{12}|>0,\quad \Delta\Gamma=\Gamma_L-\Gamma_S\approx -2|\Gamma_{12}|<0,$$

$$\mathrm{Re}\,\varepsilon=\frac{\mathrm{Im}(m_{12}^*\Gamma_{12})}{(\Delta m)^2+|\Gamma_{12}|^2},\quad \delta=-\frac{1}{2}\cdot\frac{\delta m-\mathrm{i}\delta\Gamma/2}{\Delta m-\mathrm{i}\Delta\Gamma/2}\quad \text{with}\quad \begin{matrix}\delta m=m_{11}-m_{22}\\ \delta\Gamma=\Gamma_{11}-\Gamma_{22}\end{matrix}$$

$$R_1(K\to K)=e^{-\Gamma t}\left[\cosh(\Delta\Gamma t/2)+4\,\mathrm{Re}\,\delta\cdot\sinh(\Delta\Gamma t/2)+\cos\Delta mt-4\,\mathrm{Im}\,\delta\cdot\sin\Delta mt\right]/2$$

$$R_2(\bar{K}\to\bar{K})=e^{-\Gamma t}\left[\cosh(\Delta\Gamma t/2)-4\,\mathrm{Re}\,\delta\cdot\sinh(\Delta\Gamma t/2)+\cos\Delta mt+4\,\mathrm{Im}\,\delta\cdot\sin\Delta mt\right]/2$$

$$R_3(K\to\bar{K})=e^{-\Gamma t}(1-4\,\mathrm{Re}\,\varepsilon)\left[\cosh(\Delta\Gamma t/2)-\cos\Delta mt\right]/2$$

$$R_4(\bar{K}\to K)=e^{-\Gamma t}(1+4\,\mathrm{Re}\,\varepsilon)\left[\cosh(\Delta\Gamma t/2)-\cos\Delta mt\right]/2$$

δ Violates CP &CPT

ε Violates CP & T

Measurements of δ and Re ε since 1970 using the Bell-Steinberger relation, discussed today by Giancarlo d'Ambrosio; measurements of δ (B^0) and Re ε (B^0) by Luigi Li Gioi.

Observation of violated motion reversal symmetry will then be discussed by Jose Bernabeu in the special situation of creating ($\alpha\, B^0 + \beta\, \bar{B}^0$) states by breaking entangled $B^0 \bar{B}^0$ pairs. Here, the unstable particle ($\alpha\, B^0 + \beta\, \bar{B}^0$) is not produced by a strong-interaction reaction like $\pi^+\pi^- \to \rho^0$ or $p\,\bar{p} \to K^0 K^- \pi^+$ but spontanuously by the decay of another particle which changes the entangled 2-particle state into a 1-particle state (the same as in KLOE). Hans-Jürg Gerber will add some pedagogical comments.

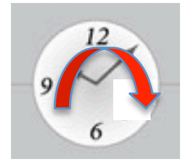
Why this workshop? I had two motivations for proposing it to MITP, both originating in the BABAR 2012 publication on T violation as proposed and discussed here by J. B.

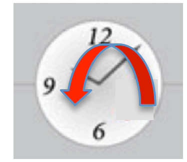
1) This is not the first observation of T violation in neutral-meson systems.
   What is different? Is it worth to write a review of all the observations up to now?

2) Which basic T- and CPT- violating parameters of the dynamics determine the observed motion-reversal asymmetry?
   q/p, δ, and Okun‘s 1984 complex amplitudes A and B? How well is CPT tested?

The 2nd contributions of T. R. and the contribution of Pablo Villanueva-Perez will bring us an answer on (2) or will bring us close to it. More discussion Tue afternoon.

Tue also contributions on future experiments: Antonio di Domenico and Adrian Bevan.





$\pm \neq \approx \leftrightarrow \rightarrow B^0\ \bar{B}^0\ B_-\ B_+\ 10^{-4}$

$\psi\ \varepsilon\ \delta\ K^+\ \pi^-\ \Gamma\ \Upsilon\ \ell^-$