## **CORFU SUMMER INSTITUTE** "Standard Model and Beyond"

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# **DISCRETE SYMMETRIES CP, T, CPT**



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#### **50 YEARS OF CP-VIOLATION**

On july 10<sup>th</sup> 1964 Cronin, Fitch, Christenson and Turlay submitted a paper to Phys. Rev. Lett. announcing the discovery of CP violation in the weak decays of neutral kaons.



The Nobel Prize in Physics 1980 James Cronin, Val Fitch

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#### The Nobel Prize in Physics 1980





James Watson Cronin Prize share: 1/2

Val Logsdon Fitch Prize share: 1/2

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch *"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"* 

Photos: Coovright © The Nobel Foundation

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PHYSICAL REVIEW LETTERS

27 July 1964

EVIDENCE FOR THE  $2\pi$  DECAY OF THE  $K_2^{\circ}$  MESON\*<sup>†</sup>

J. H. Christenson, J. W. Cronin,<sup>‡</sup> V. L. Fitch,<sup>‡</sup> and R. Turlay<sup>§</sup> Princeton University, Princeton, New Jersey (Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the  $2\pi$  decay of the  $K_2^0$  meson. Several previous experiments have served<sup>1,2</sup> to set an upper limit of 1/300 for the fraction of  $K_2^{0}$ 's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit. In this measurement,  $K_n^0$  mesons were pro-

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass,  $m^*$ , assuming each charged particle had the mass of the charged pion. In this detector the  $K_{e3}$  decay leads to a distribution in  $m^*$  ranging from 280 MeV to ~536 MeV; the  $K_{\mu3}$ , from 280 to ~516; and the  $K_{\pi3}$ , from 280 to 363 MeV. We emphasize

#### **CP-SYMMETRY BREAKING BY PARTICLE CONTENT IN SM**

#### **Progress of Theoretical Physics**

PTP is predecessor journal of Progress of Theoretical and Experimental Physics (PTEP)

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Oxford Journals > Progress of Theoretical Physics > Volume 49, Issue 2 > Pp. 652-657.

#### *CP*-Violation in the Renormalizable Theory of Weak Interaction

Makoto Kobayashi and Toshihide Maskawa

Author Affiliations

Received September 1, 1972.

#### Abstract

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

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The Nobel Prize in Physics 2008 Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa

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# The Nobel Prize in Physics 2008



Photo: University of Chicago Yoichiro Nambu Prize share: 1/2



Prize share: 1/4

© The Nobel Foundation Photo: U. Montan Toshihide Maskawa

Prize share: 1/4

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

Photos: Copyright © The Nobel Foundation

#### **CP-VIOLATION IN STANDARD MODEL**

In the Standard Model, charged weak interactions among quarks are codified in a 3 X 3 unitarity matrix: the CKM Mixing Matrix.

The existence of this matrix conveys the fact that the quarks which participate to weak processes are a linear combination of mass eigenstates

The unitarity conditions can be represented by triangles in the complex plane.

For the B-Bbar system, the unitarity triangle is given by

 $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ 

Flavour Mixing and CP-Violation are described with high precision in the SM.

The best measured CP-phase is

 $S = \sin(2 \beta) = 0.682 \pm 0.019$ 



#### THE CP ANGLES OF THE UNITARITY TRIANGLE



$$B_{d} \rightarrow '' \psi'' K_{L,S} \left[ b \rightarrow c \,\overline{c} \, s \right]$$
  
$$\beta = \left( 21.5^{+0.8}_{-0.7} \right)^{0} or \, \beta = \left( 68.5^{+0.7}_{-0.8} \right)^{0}$$
$$\bigcup$$
  
$$\cos(2\beta)?$$

$$B \rightarrow \pi^{+}\pi^{-} \Rightarrow \sin(2\alpha) = -0.65 \pm 0.06$$
  
[Direct CPV]:  $C_{\pi^{+}\pi^{-}} = -0.29 \pm 0.05$ 

[Interference Mixing-No mixing]

 $B^+ \rightarrow DK^+$  [Direct CPV] and related transitions: BaBar, Belle, LHCb  $\Rightarrow \gamma = (67 \pm 12)^0$ 

Ideal Experiment: From Entangled states, Equal time Decays ightarrow J /  $\psi$   $K_{_{
m S}}, \pi^+\pi^-$ 

#### Phenomenology of CPV is different in K, D, B and B<sub>s</sub> decays

#### RARE DECAY $B_s \rightarrow \mu \mu$

LHCb Collaboration, PRL (2013)



Penguin projected to a pseudoscalar

Helicity suppression

Proportionality with the mass of the lepton

Latest disappointment:

Prospects for new physics, thinking on: - Origin of Baryogenesis

- Essence of Dark Matter
- In addition, Z-penguin can induce NON DECOUPLING effects, providing information c EWSB mechanism.

first evidence for very rare decay  $B_s {\rightarrow} \mu^+ \mu^-$ 



$$B_d, B_s \rightarrow v v \gamma / b \rightarrow s v v$$

- > Box with the Penguin Vertex: Similar arguments for non-decoupling,
- But... no proportionality to v mass.
- > The point is that the penguin is **NOT projected to a pseudo-scalar**



BABAR, PRD (2012) : B<sub>d</sub>

Not proportional to v mass

```
Br < 4.7 x 10^{-5} , 90% CL
```

For LHC detectors: Is Displaced Vertex enough ?

 $B \rightarrow K^{(*)} \nu \nu$ 

Move the penguin away from the s-channel
 Non-decoupling again



# TIME REVERSAL VIOLATION

Why 48 years after CP Violation?



The Economist, September 2012

physic	Stoday / Volume 65 / Issue 11 / Search and Discove Previous Article   Next Article			
Home Print Edition	Daily Edition        Advertising          TWITTER       TWITTER         DR SS       E-M         Dysics has finally been clearly seen			
> 1964	CPV observed in the $K^0 - \overline{K}^0$ and $B^0 - \overline{B}^0$ systems: unstable particles.			
CPT-"Theorem"	TRV expected in these systems as well.			
1998	CPLEAR $K^0 \Leftrightarrow \overline{K}^0$ needs $\Delta\Gamma$ ; CP&T experimentally identical			
< 1999	L. Wolfenstein, R.G. Sachs,: "For a decaying state, its T-reverse is not a physical state" "Impossible" test of T-symmetry!?			
= 1999	Bypass to "No-Go" by means of Quantum Entanglement			
CONCEPT	M.C. Bañuls, J.B., PLB (1999), NPB (2000); scrutinized by L. Wolfenstein, IJMP(1999); H. Quinn, JPCS(2009): V. Rubakov; T. Nakada; F. Botella,			
METHOD	J.B., F. Martínez-Vidal, P. Villanueva-Pérez, JHEP (2012)			
EXPERIMENT	BABAR Collaboration, PRL (2012): 14 σ			
PERSPECTIVE 2013-14	Extension to any pair of decay channels? Orthogonality problem			

#### THE CONCEPTUAL BASIS - THE EXPERIMENT

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#### PHYSICS LETTERS B

Physics Letters B 464 (1999) 117-122

#### CP, T and CPT versus temporal asymmetries for entangled states of the $B_d$ -system

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FLSEVI



Although *CP* violation in the *B* meson system has been well established by the *B* factories, there has been no direct observation of time-reversal violation. The decays of entangled neutral *B* mesons into definite flavor states ( $B^0$  or  $\bar{B}^0$ ), and  $J/\psi K_L^0$  or  $c\bar{c}K_S^0$  final states (referred to as  $B_+$  or *B*), allow comparisons between the probabilities of four pairs of *T*-conjugated transitions, for example,  $\bar{B}^0 \to B$  and  $B \to \bar{B}^0$ , as a function of the time difference between the two *B* decays. Using  $468 \times 10^6 B\bar{B}$  pairs produced in Y(4*S*) decays collected by the *BABAR* detector at SLAC, we measure *T*-violating parameters in the time evolution of neutral *B* mesons, yielding  $\Delta S_T^+ = -1.37 \pm 0.14(\text{stat}) \pm 0.06(\text{syst})$  and  $\Delta S_T = 1.17 \pm 0.18(\text{stat}) \pm 0.11(\text{syst})$ . These nonzero results represent the first direct observation of *T* violation through the exchange of initial and final states in transitions that can only be connected by a *T*-symmetry transformation.

## WHAT IS "TIME REVERSAL"?

A symmetry transformation, T, that changes one physical system into another with an inverted sense of time evolution is called Time Reversal.

In classical mechanics, this corresponds to substituting

for each trajectory  $\vec{r} = \vec{r} (t)$  the trajectory  $\vec{r} = \vec{r} (-t)$ , to moving along the given trajectory with the opposite velocity at each point.



### **TIME REVERSAL INVARIANCE ?**

➢ If the original trajectory is dynamically possible, it is not necessary, in general, that the time reverse trajectory be so for the same dynamics.

One would need that the equation of motion remains invariant in form under the transformation

$$t \rightarrow -t, \ \vec{r} \rightarrow \vec{r}, \ \vec{p} \rightarrow -\vec{p}$$

In our elementary example, one would need to neglect velocity-dependent friction:

$$\frac{d \vec{p}}{d t} = \vec{F}(\vec{r}) \quad \text{INVARIANT;} \qquad \frac{d \vec{p}}{d t} = \vec{F}(\vec{r}, \overline{v}) \quad \text{VIOLATED}$$

➢ We are interested in the fundamental laws of Physics, from Newton's law to the behaviour of elementary constituents of matter and their interactions.

## SYMMETRIES IN THE LAWS OF PHYSICS

> In Quantum Mechanics, there is an operator  $U_T$  implementing the T-symmetry acting on the states of the physical system, such that

$$U_T \vec{r} U_T^+ = \vec{r}, \ U_T \vec{p} U_T^+ = -\vec{p}, \ U_T \vec{s} U_T^+ = -\vec{s}$$

By considering the commutator  $[r_j, p_K] = i\hbar \delta_{jK} I$ 

the operator  $U_T$  must be ANTI-UNITARY:

UNITARY- for conserving probabilities, ANTI- for complex conjugation



Similarly for ANTIUNITARY CPT which needs not only in  $\Longrightarrow$  out, but also  $i, f \rightarrow \overline{f}, \overline{i}$ 

#### WHAT IS T-TRANSFORMATION EXPERIMENTALLY ?

The problem is in the preparation and filtering of the appropriate initial and final meson states for a T-test



#### $\Delta S^{\pm}$ , $\Delta C^{\pm}$ ASYMMETRY PARAMETERS

 $I_{i}(\Delta t) \sim e^{-\Gamma \Delta t} \{ C_{i} \cos(\Delta m \Delta t) + S_{i} \sin(\Delta m \Delta t) + C'_{i} \cosh(\Delta \Gamma \Delta t) + S'_{i} \sinh(\Delta \Gamma \Delta t) \}$ 



### **EXPERIMENTAL RESULTS**

Parameter	Final result	SM expected val.	
$\Delta S_T^+$	$-1.37 \pm 0.14 \pm 0.06$	-1.36	
$\Delta S_T^-$	$1.17 \pm 0.18 \pm 0.11$	1.36	
$\Delta C_T^+$	$0.10 \pm 0.14 \pm 0.08$	0.	
$\Delta C_T^{-}$	$0.04 \pm 0.14 \pm 0.08$	0.	
$\Delta S_{CP}^+$	$-1.30 \pm 0.11 \pm 0.07$	-1.36	
$\Delta S_{CP}^{-}$	$1.33 \pm 0.12 \pm 0.06$	1.36	
$\Delta C_{CP}^{+}$	$0.07 \pm 0.09 \pm 0.03$	0.	
$\Delta C_T^{-}$	$0.08 \pm 0.10 \pm 0.04$	0.	
$\Delta S_{CPT}^{+}$	$0.16 \pm 0.21 \pm 0.09$	0.	
$\Delta S_{CPT}^{-}$	$-0.03 \pm 0.13 \pm 0.06$	0.	
$\Delta C_{CPT}^{+}$	$0.14 \pm 0.15 \pm 0.07$	0.	
$\Delta C_{CPT}^{2}$	$0.03 \pm 0.12 \pm 0.08$	0.	
$S^{+}_{\ell^{+},K^{0}_{S}}$	$0.55 \pm 0.09 \pm 0.06$	0.68	
$S^{-}_{\ell^+,K^0_S}$	$-0.66 \pm 0.06 \pm 0.04$	-0.68	
$C^{+}_{\ell^{+},K^{0}_{2}}$	$0.01 \pm 0.07 \pm 0.05$	0.	
$C^{-}_{\ell^+,K^0_{\rm S}}$	$-0.05 \pm 0.06 \pm 0.03$	0.	

#### **T-RAW ASYMMETRIES & SIGNFICANCE**



This Discovery was made possible thanks to the

spectacular quantum properties of EPR <u>entangled</u> states:

"The reality of two entangled B's is much more

than the sum of two separate B local realities"

The appropriate preparation of initial and final meson states

based on:

1) Entanglement

2) The two decays as Filtering Measurements

#### **PROSPECT: THE ORTHOGONALITY PROBLEM**

- 1. "Theoretical" Asymmetry in terms of initial and final **meson** states:  $S(P_1 \rightarrow P_2) \text{ vs. } S(TP_2 \rightarrow TP_1)$
- 2. Tag initial state from first decay to "f " in a Meson Factory:

 $\left| \boldsymbol{P}_{\not \to f} \right\rangle \boldsymbol{\alpha} \left[ \overline{\boldsymbol{A}}_{f} \left| \boldsymbol{P}^{0} \right\rangle - \boldsymbol{A}_{f} \left| \overline{\boldsymbol{P}}^{0} \right\rangle \right]$ using Entanglement of orthogonal states  $\boldsymbol{P}_{\not \to f} - \boldsymbol{P}_{\not \to f}^{\perp}$ Tagged-Filtered by the decay to "f "

- 3. After time-evolution, second decay and Reference  $P_{\not \Rightarrow f_1} \Rightarrow P_{\not \Rightarrow f_2}^{\perp}$ i.e., Experiment  $(f_1, f_2) \iff$  Theory  $(P_{\not \Rightarrow f_1}, P_{\not \Rightarrow f_2}^{\perp})$
- 4. T-reverse transition:  $P_{\neq f_2}^{\perp} \Rightarrow P_{\neq f_1}$ What is the decay channel such that: Given "f",  $\exists f : |P_{\neq f}\rangle = |P_{\neq f}\rangle$ ?

Flavour and CP-eigenstates privileged. Extension to any other pair of decay channels?

## **IS EPR-ENTANGLEMENT APPLICABLE?**

Proposed tests of separate CP, T, CPT symmetries in transitions based on EPR-Entanglement imposed by Particle Identity:

 $K^0, \overline{K}^0$  are two states of identical particles.

> The two states connected by C, so that  $C\mathcal{P} = + [\mathcal{P}: permutation operation]$ .

▶ In neutral meson factories,  $K^0 \to \overline{K}^0$  produced by  $\Phi$ -decay: J=1, S=0 → L=1→ C= →  $\mathscr{P}$ = -, antisymmetric wave function ↔ Time evolution (including the Mixing  $K^0 \to \overline{K}^0$ ) preserves  $K^0 \overline{K}^0$  terms only.

> What if the $K^0$ ,  $\overline{K}^0$  Identity is lost ?

The two particle system would not satisfy the requirement  $C\mathcal{P} = +$ . In perturbation theory, if still J=1, C=-,

 $|i\rangle = |antisymmetric\rangle + \omega |symmetric\rangle \longrightarrow$  the  $\omega$ -effect

 $\implies$  Time evolution:  $\omega K^0 K^0$  terms  $\leftrightarrow$  Demise of tagging

### ΤΗΕ ω-EFFECT

 $\succ$  Loosing the  $K^0, \overline{K}^0$  Identity...

In some Quantum Gravity models, matter propagation in topologically non-trivial space-time vacua suffers a possible <u>loss of quantum</u> <u>coherence</u> or "decoherence".

> Originated by space-time foam backgrounds? [Wheeler, Ellis et al.]

The matter quantum system is an open system, interacting with the "environment" of quantum gravitational d. o. f. → Apparent loss of unitarity for low-energy observers

> Not a well-defined S-matrix between asymptotic states → The CPT-operator is NOT well-defined [Wald]

► It should be disentangled from the case of effective theories for Lorentz violation, in which CPT breaking means [H<sub>eff</sub>, CPT] ≠ 0.
 ► The new CPT "Violation" would be an "intrinsic" microscopic time irreversibility, so that K<sup>0</sup> is not "well-defined" from K<sup>0</sup>. It implies:
 1) a modified single K<sup>0</sup> → K<sup>0</sup> evolution: α,β,γ parameterization [Lindblad].
 2) for entangled Kaon states in a Φ-factory, the ω-effect

#### **ω-EFFECT OBSERVABLES**



#### ➢ <u>Strategy:</u>

Choose a channel suppressed by  $\eta$ 's:  $X = Y = \overline{u}^+ \overline{u}^-$ , CP "forbidden"





### **MEASUREMENT OF \omega-EFFECT**

KLOE [Di Domenico et al.] obtained the first measurement of the

# $\begin{aligned} \omega \text{-parameter} & \text{Re}(\omega) = (-1.6 \,{}^{+3.0}_{-2.1_{stat}} \pm 0.4_{syst}) x 10^{-4} \\ \text{Im}(\omega) = (-1.7 \,{}^{+3.3}_{-3.0_{stat}} \pm 1.2_{syst}) x 10^{-4} \end{aligned} \Big\} \quad |\omega| < 1.0 \, \text{x} \, 10^{-3} \text{ at } 95\% \, \text{CL} \end{aligned}$

> At least one order of magnitude improvement is expected with KLOE-2 at the upgraded DA $\Phi$ NE.

> All decoherence effects, including the  $\omega$ effect, manifest as a DEVIATON from the QM prediction of the correlation I ( $\pi$ + $\pi$ -, $\pi$ + $\pi$ -;  $\Delta$ t=0)=0. Hence the reconstruction of events in the region near  $\Delta$ t≈0 is crucial  $\leftrightarrow$ -vertex resolution.

➢ In B-factories, there is no such privileged channel.

 With currently available data from BABAR and BELLE, the CPV semileptonic charge asymmetry, in equal sign dilepton channel
 I(I± I±; Δt), gives the bounds [Alvarez,J.B.,Nebot]
 -0.0084 ≤ Re(ω) ≤ 0.0100 at 95%CL



Monte Carlo simulation of I( $\pi$ + $\pi$ -,  $\pi$ + $\pi$ -;  $\Delta$ t), with the KLOE resolution  $\sigma_{\Delta t} \approx \zeta s$  and with the expected KLOE-2 resolution  $\sigma_{\Delta t} \approx 0.3 \zeta s$ 

#### CONCLUSION

- > CPV asymmetries well described by CKM-Mixing Matrix Mechanism.
- Current level of experimental accuracy and theoretical uncertainties leave room for additional sources of CPV.
- ➤ SM unable to explain the Matter-Antimatter Asymmetry of the Universe → New Physics!
- ➤T-tests for unstable systems?
  Bypass → Entanglement ⊕Decays as Filtering Measurements
- Flavour-CP channels in B decays ->
  Independent Asymmetries for each CP, T, CPT
- $\succ$  TRV observed at 14  $\sigma$  level, consistent with CPT invariance.
- CPTV search, ill-defined CPT?
  - in single K, B transitions: the  $\alpha$ ,  $\beta$ ,  $\gamma$  parameterization
  - for entangled states: the  $\omega$ -effect

#### **TWO VISIONS OF NEAR FUTURE**





### CAN TR BE TESTED IN UNSTABLE SYSTEMS?

#### THE FACTS

> Taking as Reference  $K^0 \to \overline{K}^0$  and calling (X,Y) the observed decays at times  $t_1$  and  $t_2$ , with  $\Delta t \equiv t_2 - t_1 > 0$ , the CP, T and CPT transformed transitions are

Transition	$K^0 \to \overline{K}^0$	$\overline{K}^0 \to K^0$	$\overline{K}^0 \to K^0$	$K^0 \to \overline{K}^0$	$K^0 \to \overline{K}^0$
(X,Y)	(I⁻, I⁻)	(l+, l+)	(I+, I+)	(ŀ-, ŀ-)	(ŀ, ŀ)
Transformation	Reference	СР	Т	CPT	Δt

No way to separate T and CP if T were defined.

T-operator is not defined for decaying states: its time reverse is not a physical state.

The Kabir asymmetry NEEDS the interference of CP mixing with the "initial state interaction" to generate the effect, directly proportional to  $\Delta\Gamma$ .

#### The decay plays an essential role

> The time evolutions of  $K^0 \rightarrow \overline{K}^0$  and  $\overline{K}^0 \rightarrow K^0$  are equal, the asymmetry is time independent.



> In the WW approach, the entire effect comes from the overlap of non-orthogonal  $K_L$ ,  $K_S$  states. If the **stationary** states were orthogonal  $\implies$  no asymmetry.

L. Wolfenstein: "it is not as direct a test of TRV as one might like".