T-REVERSAL NON-INVARIANCE IN THE NEUTRAL KAON SYSTEM

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July 29, 2003

OUTLINE

- Introduction
- Arrow of time
- T-Reversal
  - Definition
  - Past Experimental Tests
- CPLEAR Experiment at CERN
  - Method
  - Experiment
  - Results – First direct observation of T violation
- Discussion
- Conclusions

ARROWS OF TIME

MACRO WORLD

> 3 DEFINITIONS OF ARROW OF TIME

1. THERMODYNAMIC ARROW OF TIME

2nd LAW OF THERMODYNAMICS
In any closed system entropy always increases!

2. COSMOLOGICAL ARROW OF TIME

Our Universe expands in time!

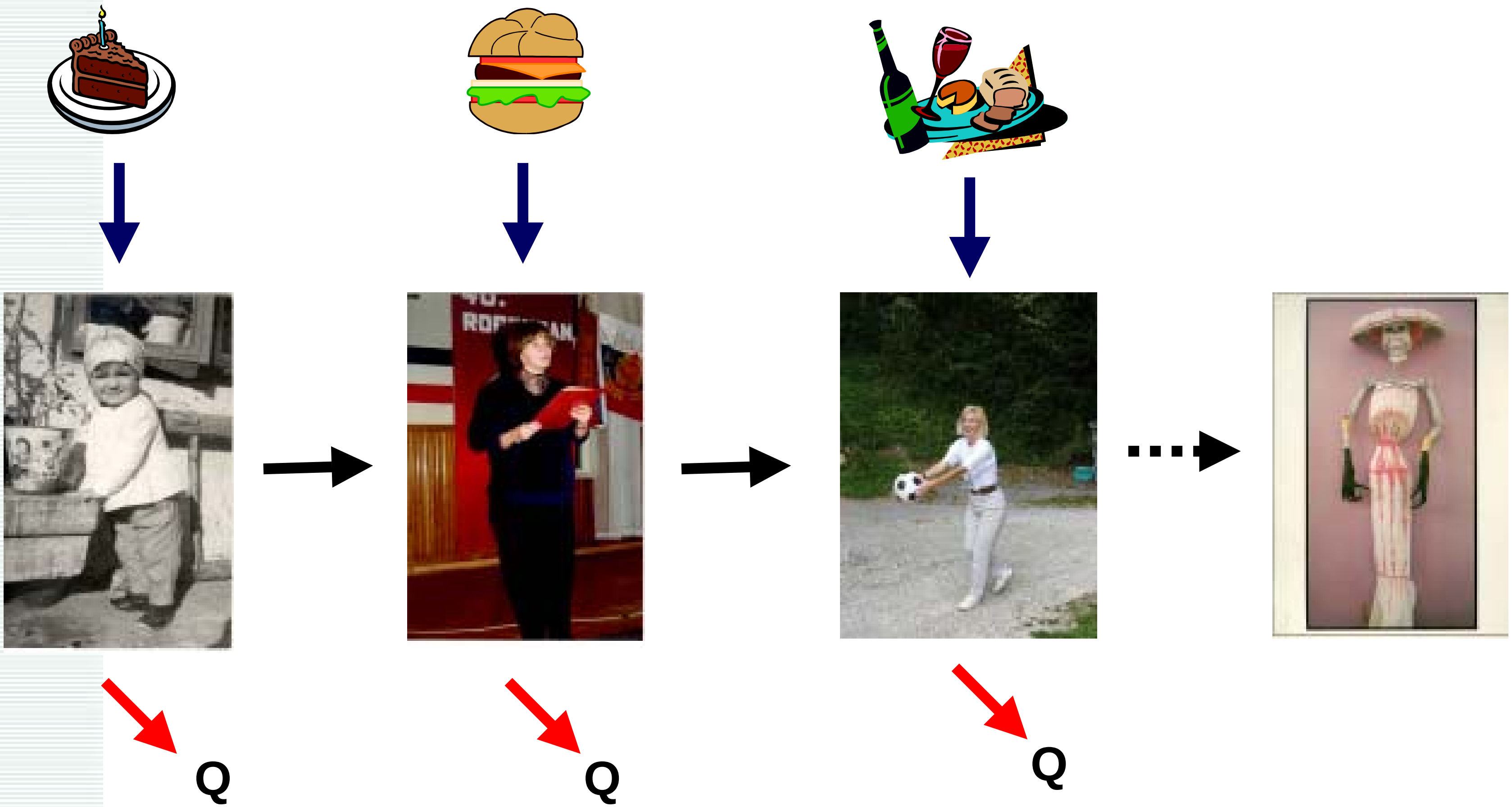
3. PSYCHOLOGIGAL ARROW OF TIME

We remember the past and not the future!

ALL ARROWS OF TIME SEEM TO POINT IN THE SAME DIRECTION!

DIFFICULT (OR IMPOSSIBLE) TO EXPLAIN!

ARROWS OF TIME



ARROWS OF TIME

MICRO WORLD

- **NO T-REVERSAL NON-INVARIANT PROCESS WAS MEASURED TILL CPLEAR EXPERIMENT**
- **THE LAWS OF PHYSICS DO NOT DISTINGUISH BETWEEN THE PAST AND THE FUTURE**

EXAMPLE

$$p + \gamma \rightarrow \Delta^{+} \rightarrow \pi^{+} + n$$
$$p + \gamma \leftarrow \Delta^{+} \leftarrow \pi^{+} + n$$

Both processes are possible and occur with the same probability at the same energy.

T-REVERSAL INVARIANCE WAS NEVER TESTED WITH HIGH PRECISION

EXPERIMENTAL TESTS OF T-REVERSAL

Before CPLEAR

INDIRECT TESTS

1. **EDM**

   - A non-zero value requires P and T violation

   - Most sensitive test seems to be EDM of neutron

$d < 6.3 \times 10^{-26}$ e cm

P.G. Harris et al., Phys. Rev Lett. **82** (1999) 904.

2. **NEUTRAL KAON SYSTEM**

   - Interference between
   $K_S \rightarrow \pi^0 \pi^0$ and $K_L \rightarrow \pi^0 \pi^0$ decays

   - Assumption:
   UNITARITY!
   Disappeared kaons had decayed into observable states

   - Most serious but indirect test!

J.C. Chollet et al., Phys. Lett. **B31** (1970) 658.

K.R. Schubert et al., Phys. Lett. **B31** (1970) 662.

EXPERIMENTAL TESTS OF T-REVERSAL

Before CPLEAR

DIRECT TESTS

TEST OF DETAILED BALANCE IN NUCLEAR REACTIONS

- Some attempts in late sixties

For example:

U. Wimmersperg et al., Phys. Lett. **B33** (1970) 291.

BUT

- Experiments were very difficult

- Have to measure 2 different reactions

- Have to deal with different phase space

- Accuracy was poor

TIME REVERSAL

MICRO WORLD

WHAT IS T – REVERSAL INVARIANCE?

INITIAL AND FINAL QUANTUM MECHANICAL STATES ARE INTERCHANGED WITH IDENTICAL POSITIONS AND OPPOSITE VELOCITIES UNDER T – REVERSAL

$$T < \Psi^{out}(t_f) \mid \Phi^{in}(t_i) > \; = \; < \Phi^{out}(t_f) \mid \psi^{in}(t_i) >$$

EXAMPLE

$K^0 \rightarrow \bar{K}^0$

$\bar{K}^0 \rightarrow K^0$

IF T – REVERSAL INVARIANCE HOLDS

$$| < \Psi^{out}(t_f) \mid \Phi^{in}(t_i) > |^2 = | < \Phi^{out}(t_f) \mid \psi^{in}(t_i) > |^2$$

$$P(t) = P(-t)$$

TIME REVERSAL

MICRO WORLD

WHERE TO SEARCH FOR T – VIOLATION

- **WE BELIEVE IN CPT CONSERVING WORLD**

THERE IS NO EXPERIMENTAL EVIDENCE OF CPT VIOLATION SO FAR!

- **EM AND STRONG INTERACTIONS ARE CP CONSERVING**

NO T – VIOLATION EXPECTED!

- **CP VIOLATION WAS OBSERVED IN WEAK INTERACTIONS**

T – VIOLATION IS EXPECTED!

TIME REVERSAL

- **KABIR TEST**

  - Comparison of $K^0 \rightarrow \bar{K}^0$ and $\bar{K}^0 \rightarrow K^0$

  - Probability to find a $\bar{K}^0$ (from initial K^0) and a K^0 (from initial $\bar{K}^0$) should be equal.

  - A measured asymmetry is a direct signature of T violation independent of CPT.

P.K. Kabir, Phys. Rev. **D2** (1970) 540.

- **IDEA WAS ELABORATED BY TANNER AND DALITZ**

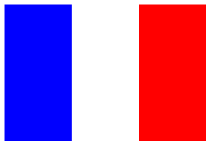
  - No symmetric source of $\bar{K}^0$ and K^0 existed!

  - Experiment became possible with LEAR at CERN

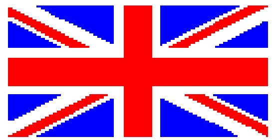
N.W. Tanner, R.H. Dalitz,
Ann. of Phys. **171** (1986) 463.

CPLEAR EXPERIMENT AT CERN MEASURED THE PROBABILITIES OF A KAON TRANSFORMING TO AN ANTIKAON AND VICE VERSA WITH HIGH PRECISION.

CPLEAR COLLABORATION



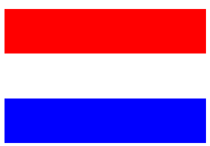
Saclay
Orsay
Marseille



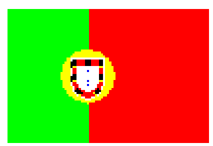
Liverpool

Athens
Ioannina
Thessaloniki

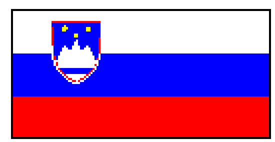
~ 100 physicists



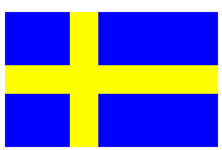
Delft



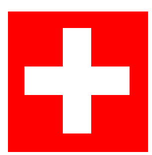
Coimbra



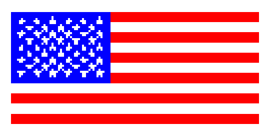
Ljubljana



Stockholm



Basel
ETHZ
Fribourg
PSI



Boston

CPLEAR PRINCIPLE

Principles of the CPLEAR Experiment

Measurement of time dependent decay rate asymmetries:

$$A_f(\tau) = \frac{R_{\overline{K}^0 \to \overline{f}}(\tau) - R_{K^0 \to f}(\tau)}{R_{\overline{K}^0 \to \overline{f}}(\tau) + R_{K^0 \to f}(\tau)}$$

acceptances cancel

$f = \overline{f}$	Measurement of $\mathcal{CP}$ violation $f = 2\pi,\ 3\pi$
$f = \overline{K}^0,\ \overline{f} = K^0$	Direct measurement of $\mathcal{T}$ violation
$f = K^0,\ \overline{f} = \overline{K}^0$	Direct measurement of $\mathcal{CPT}$ violation

Production and Tagging:

		BR
$p\overline{p}$ (at rest) $\to$	$K^-\pi^+K^0$	$2 \cdot 10^{-3}$
	$K^+\pi^-\overline{K}^0$	$2 \cdot 10^{-3}$

The Strangeness of the neutral kaon K^0 ($\overline{K}^0$) at time $\tau = 0$ is defined by the charged kaon K^- (K^+).

Tagging at decay time:

$$K^0 \to e^+\nu\pi^- \qquad \overline{K}^0 \to e^-\overline{\nu}\pi^+$$

The Strangeness of the neutral kaon K^0 ($\overline{K}^0$) at the decay time is defined by the charge of the lepton ($\Delta S = \Delta Q$).

CPLEAR PROGRAMME

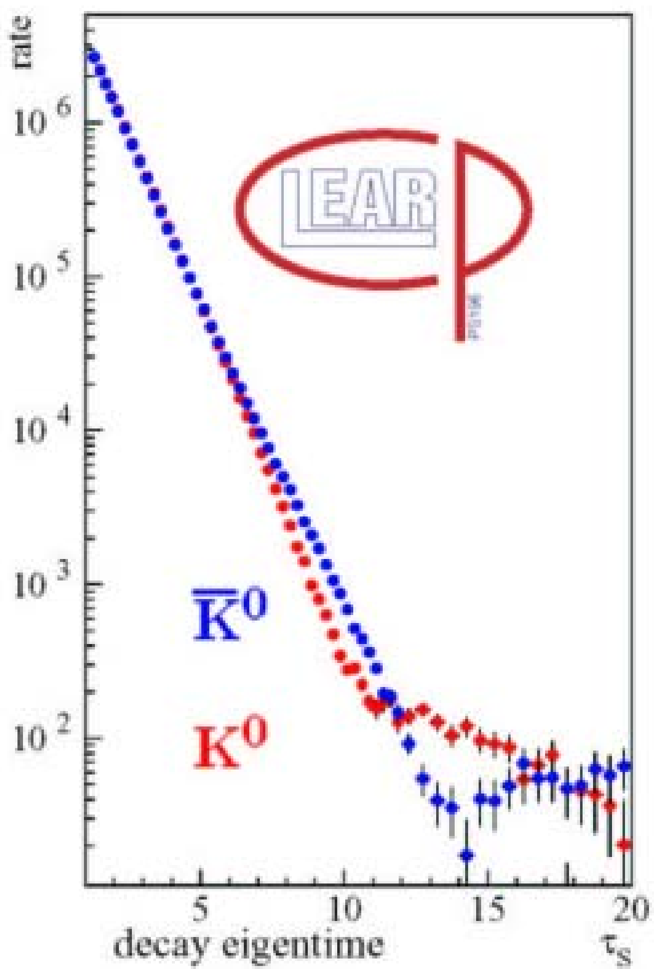
- **CP VIOLATION**
  - $\pi^+\pi^-$ decay channel
  - $\pi^0\pi^0$ decay channel
  - $\pi^+\pi^-\pi^0$ decay channel
  - $\pi^0\pi^0\pi^0$ decay channel

- **TESTS OF CPT INVARIANCE**
  - Direct
  - Indirect
  - K^0 - $\bar{K}^0$ mass and decay width difference

- **DIRECT TEST OF T INVARIANCE**
  - semileptonic decay channels

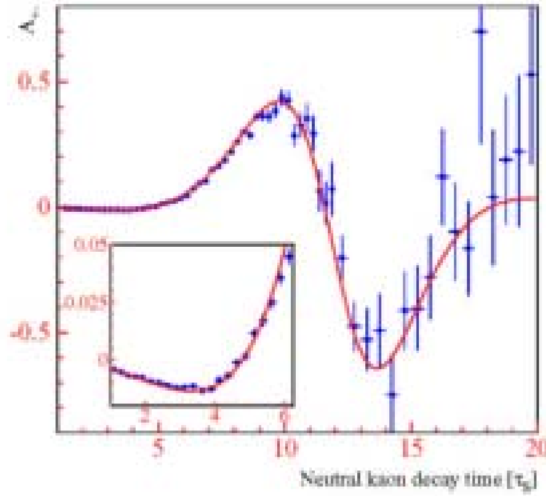
- **MISCELANEOUS**
  - Δm - semileptonic decay channel
  - $\Delta S = \Delta Q$ rule - semileptonic decay channel
  - Equivalence principle
  - EPR paradox
  - Test of QG

CPLEAR – KAON DECAY RATES



Acceptance and background corrected neutral kaon decay rates

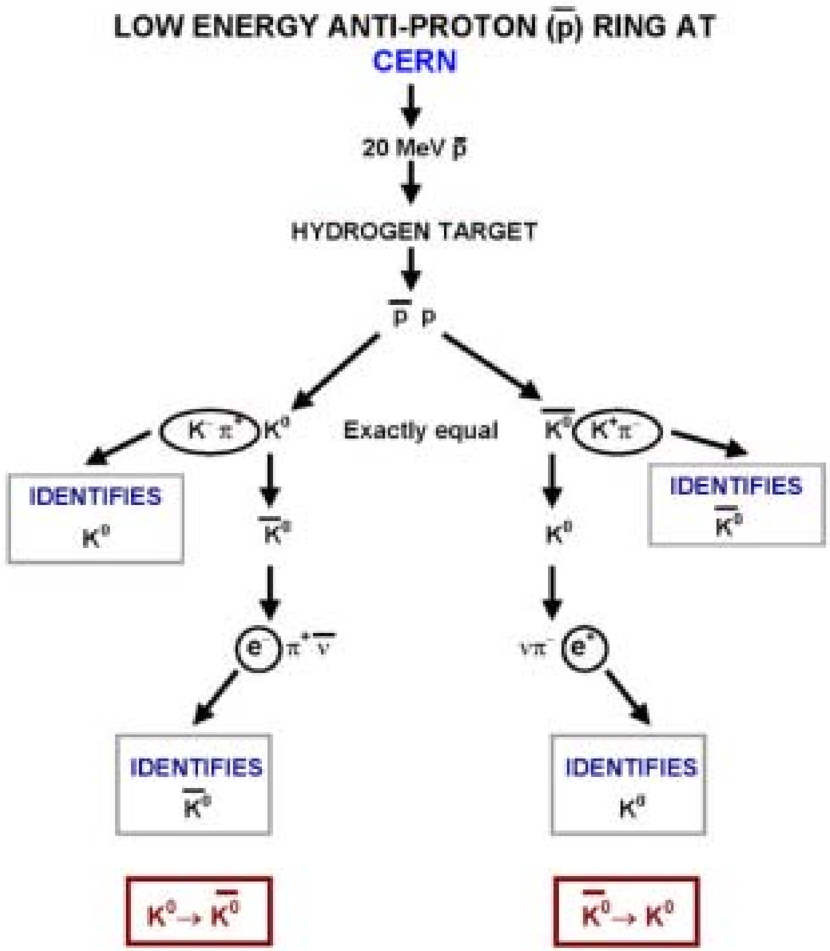
$$A_{+-}(t) = \frac{R_{\overline{K}^0 \to \pi^+\pi^-} - R_{K^0 \to \pi^+\pi^-}}{R_{\overline{K}^0 \to \pi^+\pi^-} + R_{K^0 \to \pi^+\pi^-}} = 2\frac{|\eta_{+-}| e^{\frac{1}{2}(\Gamma_S - \Gamma_L)t} \cos(\Delta m t - \varphi_{+-})}{1 + |\eta_{+-}|^2 e^{\frac{1}{2}(\Gamma_S - \Gamma_L)t}}$$



$$|\eta_{+-}| = (2.254 \pm 0.024_{stat} \pm 0.024_{syst}) \times 10^{-3}$$

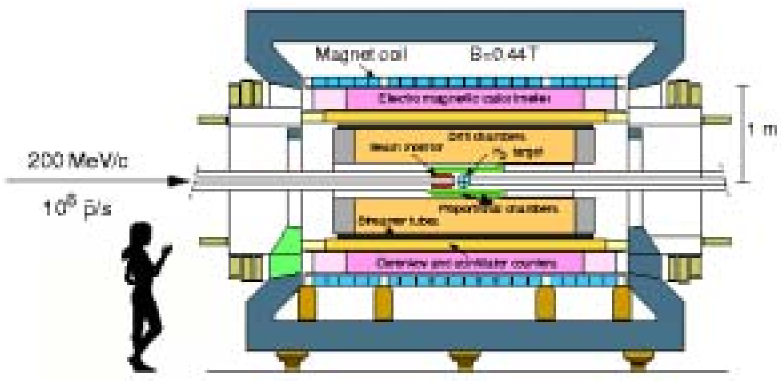
$$\varphi_{+-} = 43.63^\circ \pm 0.54^\circ_{stat} \pm 0.23^\circ_{syst} \quad (\pm 0.42^\circ_{\Delta m})$$

TIME REVERSAL - CPLEAR METHOD

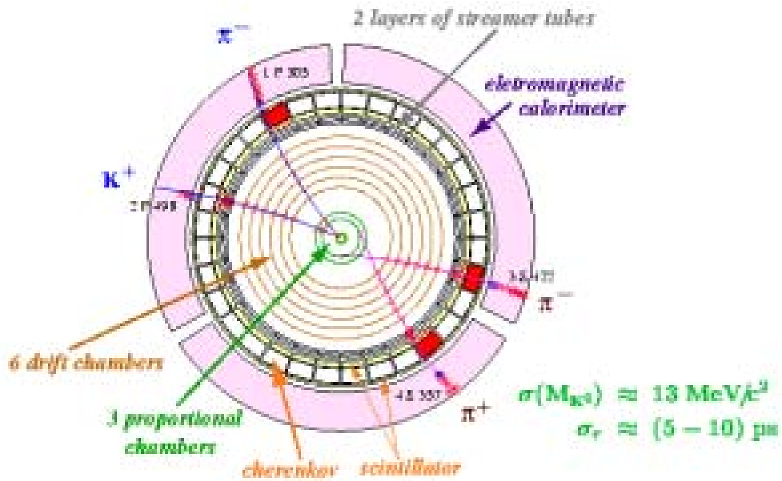


- **K/π separation**
  strangeness tag at production
- **e/π separation**
  strangeness tag at decay
- **Measure p and vertices**
  decay time in volume about 20 τ_s
- **Sophisticated trigger**
  $\bar{p}$ rate ~ 1 MHz

CPLEAR DETECTOR

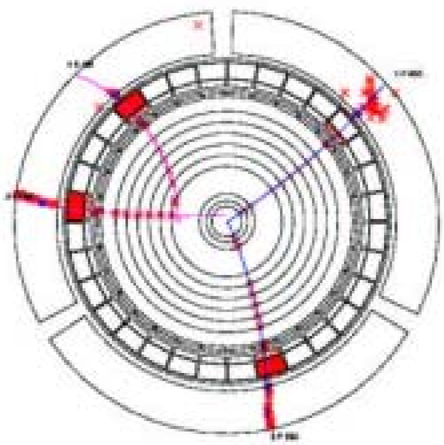


- 1985 – experiment approved
- 1990 – start of data taking
- 1992 – full trigger
- 1995 – upgrade – double statistics
- 1996 – regeneration measurements
- 1996 – end of data taking

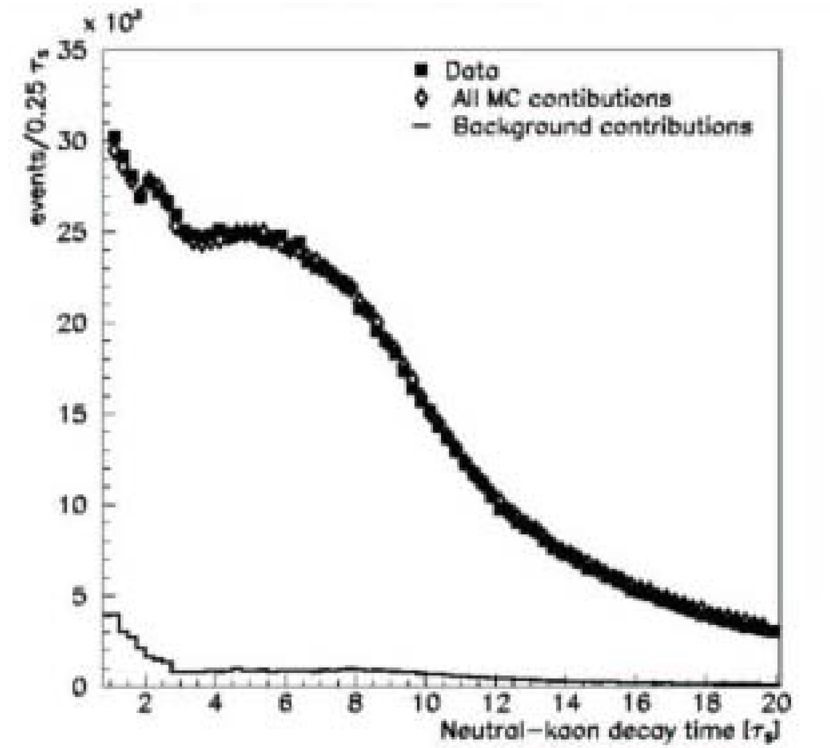


- ~ 100 M $\bar{K}^0$, K^0 decays entering analysis
- ~ 70 M $K^0 \rightarrow \pi^+\pi^-$ decays with $\tau > 1\ \tau_s$
- ~ 1.3 M $K^0 \rightarrow \pi e \nu_e$ decays with $\tau > 1\ \tau_s$
- ~ 0.5 M $K^0 \rightarrow \pi^+\pi^-\pi^0$ decays
- ~ 2 M $K^0 \rightarrow \pi^0\pi^0$ decays
- ~ 17 k $K^0 \rightarrow \pi^0\pi^0\pi^0$ decays

ANALYSIS OF SEMILEPTONIC DECAYS



~ 1.3 M $K^0 \rightarrow \pi e \nu_e$ decays with $\tau > 1\ \tau_s$



- **Kinematical constraints**
- **Electron identification based on:**
  - **dE/dx in scintillators**
  - **Number of photoelectrons in Čerenkov counters**
  - **Number of hits in calorimeter**

Background: badly reconstructed $\pi^+ \pi^-$ and $\pi^+ \pi^- \pi^0$ decays, amount determined by simulation

MEASUREMENT OF T VIOLATION

$$A_T = \frac{R(K^0 \to \bar{K}^0) - R(\bar{K}^0 \to K^0)}{R(K^0 \to \bar{K}^0) + R(\bar{K}^0 \to K^0)}$$

DIRECT TEST OF TIME REVERSAL

WHAT DID CPLEAR MEASURE?

- **CPLEAR is sensitive to electrons only**
- **Measure four rates: initial strangeness and final lepton charge**

$$R^+ = R(K^0(\tau) \to e^+\pi^-\nu) \qquad R^- = R(K^0(\tau) \to e^-\pi^+\bar{\nu})$$
$$\bar{R}^- = R(\bar{K}^0(\tau) \to e^-\pi^+\bar{\nu}) \qquad \bar{R}^+ = R(\bar{K}^0(\tau) \to e^+\pi^-\nu)$$

- **Acceptances cancel for asymmetries**

MEASUREMENT OF T VIOLATION

BUT

CPLEAR DETECTOR WAS NOT MADE OF EQUAL PARTS OF MATTER AND ANTIMATTER

Need to correct for relative detection efficiencies of:

- **Primary Kπ pair:** $\xi = \varepsilon(K^+\pi^-) / \varepsilon(K^-\pi^+)$
- **Secondary eπ pair:** $\eta = \varepsilon(\pi^+e^-) / \varepsilon(\pi^-e^+)$

Measured asymmetry A_T changes to:

$$A_{T,CPLEAR} = \frac{\eta\bar{R}^+ - \xi R^-}{\eta\bar{R}^+ + \xi R^-}$$

MEASUREMENT OF T VIOLATION

- η **from calibaration data:** $\eta = 1.014 \pm 0.002$
- ξ **from** $\pi^+\pi^-$ **decays:** $\alpha = \xi[1 + 4Re(\varepsilon_T - \delta_{CPT})]$
- **For the translation of** $\alpha \rightarrow \xi$ **need external information on** $Re(\varepsilon_T - \delta_{CPT})$
- **Semileptonic electron asymmetry**

  $\delta(e) = 2Re(\varepsilon_T - \delta_{CPT}) - 2Re(x_-) - 2Re(y)$

  $\delta(e) = (3.27 \pm 0.12) \times 10^{-3}$
- **With CPT conserved in semileptonic decays**

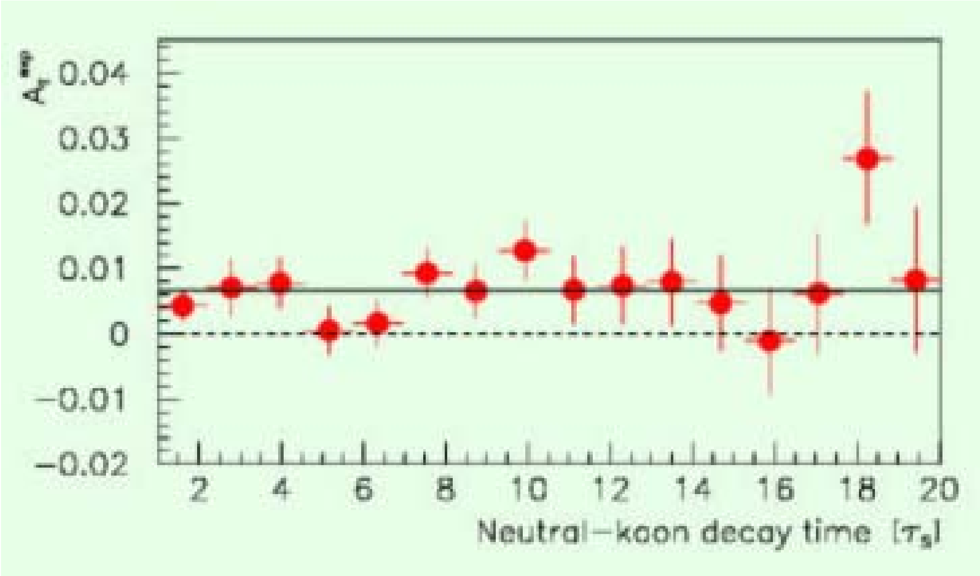
  $\delta(e) = 2Re(\varepsilon_T - \delta_{CPT})$

$$\langle\xi\rangle = 1.12023 \pm 0.00043$$

Correction done on event-by-event basis according to primary pair kinematics

CPLEAR RESULT ON T VIOLATION

EXPERIMENTAL ASYMMETRY FROM COMPLETE DATA SET



$$\langle A_{T,CPLEAR} \rangle_{(1-20)\tau_S} = (6.6 \pm 1.3_{stat} \pm 1.0_{syst}) \times 10^{-3}$$

4σ DIRECT MEASUREMENT OF T VIOLATION

CPLEAR RESULTS ON T VIOLATION

SYSTEMATIC ERRORS

Source	Known precision	$< A_{T,CPLEAR} >$ $[10^{-3}]$
background level	$\pm 10\%$	± 0.03
background asymmetry	$\pm 1\%$	± 0.02
ξ	$\pm 4.3 \times 10^{-4}$	± 0.2
η	$\pm 2.0 \times 10^{-3}$	± 1.0
decay-time resolution	10%	negligible
regeneration	-	± 0.1
Total syst.		± 1.0

A. Angelopoulos et, al., Phys. Lett. **B444** (1998) 43.

CPLEAR RESULT ON T VIOLATION

POSSIBLE QUESTIONS:

- **What if CPT is violated in semileptonic decays (parameter y)?**
- **What if $\Delta Q = \Delta S$ and CPT is violated in semileptonic decays (parameter x_-)?**

PHENOMENOLOGY

$$A_{T,CPLEAR} = \{[4Re(\epsilon_T - y - x_-)]e^{-\Gamma_L\tau} + [4Re(\epsilon_T - y - x_-)]e^{-\Gamma_S\tau} - [(8Re(\epsilon_T - y) - 4Re(x_-))\cos(\Delta m\tau) - 4Im(x_+)\sin(\Delta m\tau)]e^{-\frac{\Gamma_S+\Gamma_L}{2}\tau}\} \{e^{-\Gamma_L\tau} + e^{-\Gamma_S\tau} - 2\cos(\Delta m\tau)e^{-\frac{\Gamma_S+\Gamma_L}{2}\tau}\}^{-1}$$

$$A_{T,CPLEAR} \sim 4\,[Re\,\varepsilon_T - Re(y - x_-)] \qquad \text{for } \tau \gg \tau_S$$

- **Whith the $\alpha \rightarrow \xi$ transition using $\delta(e)$ and by not assuming CPT invariance an additional term $-2Re(x_-) - 2Re(y)$ entered into $A_{T,CPLEAR}$**

CPLEAR RESULT ON T VIOLATION

The final result for $\tau \gg \tau_S$ is:

$$A_{T,CPLEAR} = (6.6 \pm 1.3_{stat} \pm 1.0_{syst}) \times 10^{-3} \sim 4\,[Re\,\varepsilon_T - Re(y - x_-)]$$

$Re(y - x_-)$

was determined from Bell-Steinberger relation

RESULT

$Re(y - x_-) = (-0.2 \pm 0.3) \times 10^{-3}$

$Re\,\varepsilon_T = (1.649 \pm 0.025) \times 10^{-3}$

A. Apostolakis et, al., Phys. Lett. **B456** (1999) 297.

FIRST DIRECT MEASUREMENT OF T VIOLATION

MEDIA COVERAGE

Seite V2/18 / Süddeutsche Zeitung Nr. 253

Dienstag, 3. November 1998

Aus der Traum von der Zeitreise

Physiker beweisen, daß die Welt nicht rückwärts läuft

Ein mikroskopischer Unfall

Philosophische Fragen

PATRICK ILLINGER

Le Monde

VENDREDI 13 NOVEMBRE 1998

Au CERN de Genève, les physiciens des particules violent le temps

Jean-François Augereau

INTERPRETATION

CPLEAR CLAIMED FIRST DIRECT MEASUREMENT OF T VIOLATION

SCEPTICISM

- L. Wolfenstein, Phys. Rev. Lett. **83** (1999) 911.
- P.K. Kabir, Phys. Lett. **B459** (1999) 335.
- I.I. Bigi, A.I. Sanda, Phys. Lett. **B466** (1999) 33.

CONFIRMATION

- L. Alvarez-Gaumé et al., Phys. Lett. **B458** (1999) 347.
- J. Ellis, N.E. Mavromatos, Phys. Rep. **320** (1999) 341.

And references therein.

INTERPRETATION

OUR MAIN ARGUMENTS

- **Direct measurements of δ_{CPT} by CPLEAR Collaboration**

  $\delta_{CPT} \sim 10^{-4}$

- **x_- is expected to be small**

  $\Delta S = -\Delta Q$ **and CPT violation**

- **What we expect for y?**

  – no CPT violation theory

  – $y \sim \delta_{CPT}$ **or** $y < \delta_{CPT}$

PRESENT AND FUTURE EXPERIMENTS

PAST

KTeV

- **Measurement of rare $K_L \to \pi^+\pi^- e^+e^-$ decay**
- **T violation manifests in a subtle way through the measurement of angular distribution of a T-odd variable**
- **T violation was observed (5σ effect)**

A. Alavi-Harati et al., Phys. Rev Lett. **84** (2000) 408.

INDIRECT TEST

PRESENT

KEK-PS E246

- **Measurement of T violating transverse muon polarization in the decay $K^+ \to \mu^+ \nu\gamma$**
- **Result consistent with no T violation**
- **Sensitivity ~ 10^{-2}**

V.V. Anisimovsky et al., Phys. Lett. **B562** (2003) 166.

INDIRECT TEST

FUTURE

K SECTOR - DAΦNE

B SECTOR – BELLE, BABAR, LHC

NEW DIRECT TESTS ???

DISCUSSION

CPLEAR RESULTS

- **FIRST DIRECT MEASUREMENT OF T-REVERSAL NON-INVARIANCE**
- **CPT INVARIANCE WAS TESTED WITH A PRECISION OF ~ 10^{-4}**
- **RESULTS IN AGREEMENT WITH:**
  - **CP VIOLATION**
  - **T VIOLATION**
  - **CPT INVARIANCE**

DISCUSSION

ANTIMATTER → MATTER

$$\bar{K}^0 \rightarrow K^0$$

MORE PROBABLE THAN

MATTER → ANTIMATTER

$$K^0 \rightarrow \bar{K}^0$$

IT SEEMS LIKE THE ARROW OF TIME IN MICROCOSM POINTS TOWARDS THE DISAPEARANCE OF ANTIMATTER.

DISCUSSION

WHAT HAVE WE LEARNED

- **FIRST MEASUREMENT OF IREVERSIBILITY OF A PROCESS IN THE MICROWORLD**
- **LAWS OF PHYSICS ARE NOT SYMMETRIC WITH RESPECT TO T-REVERSAL**
- **DOES NOT EXPLAIN THE ARROW OF TIME IN MICROCOSM**

CONCLUSIONS

When you carry out an experiment there are two possible outcomes:either you confirm the theoretical expectations, and in this case you made a **measurement**, or you don't, and in this case you made a **discovery**.

Enrico Fermi