Violation of Particle Anti-particle Symmetry

CERN Summer Student Lectures

1, 2 and 5 August 2002

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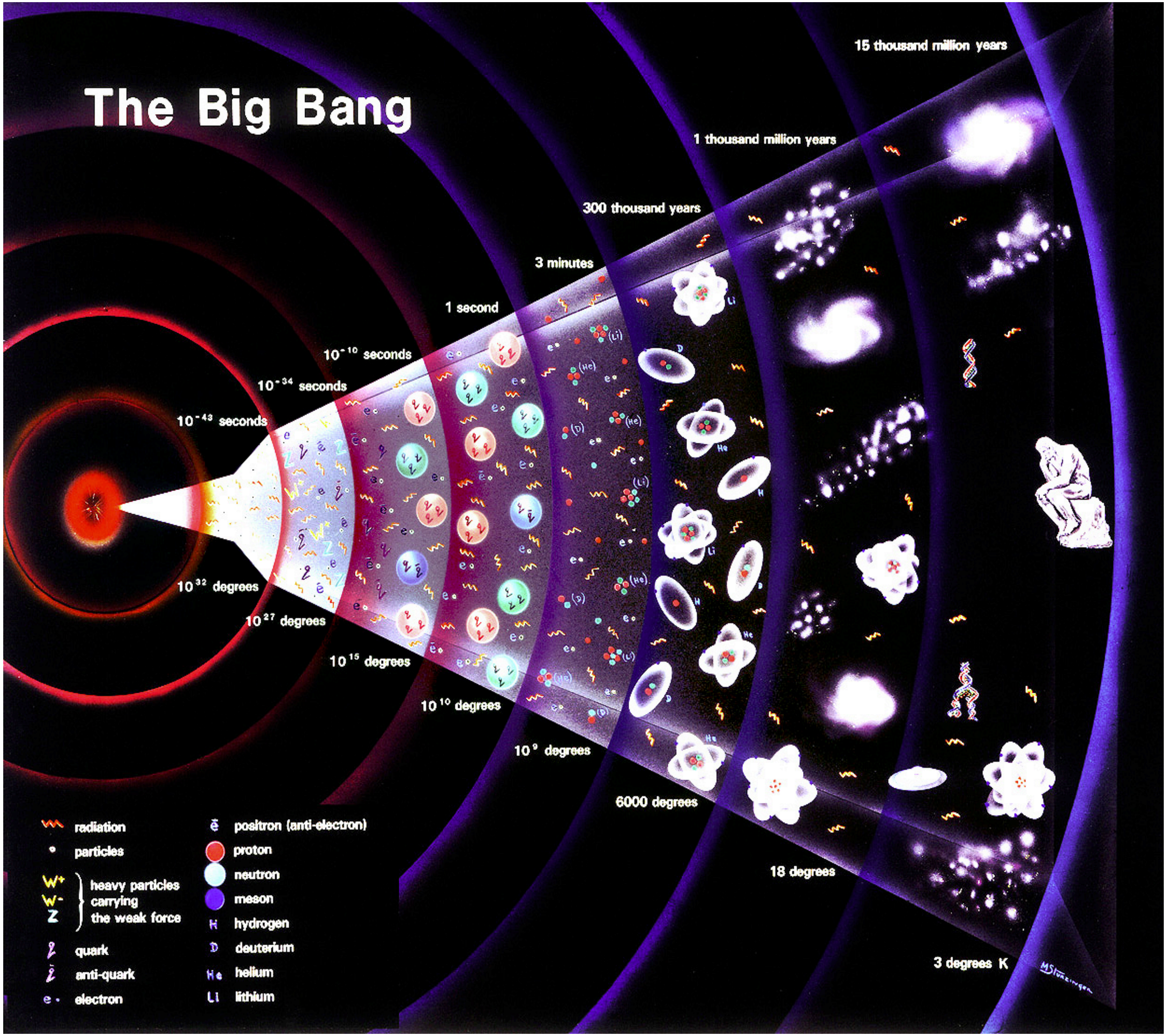

The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
e· electron
ē positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

Contents of the Lecture

☺ I
1) Concept of symmetries
2) P, T and C transformation
3) Conservation of symmetries
4) CP violation in the charged kaon system

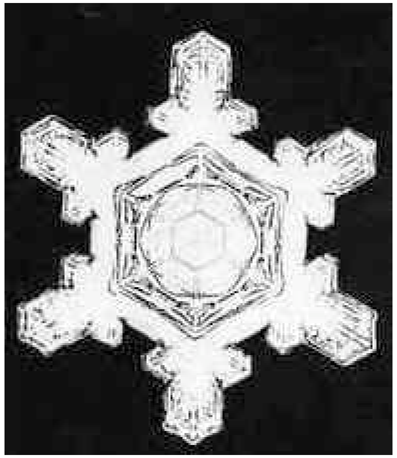
😐 II
5) CP violation in the neutral kaon system
6) Kaon interferometer

☹ III
7) Standard Model and CP violation (K, B)

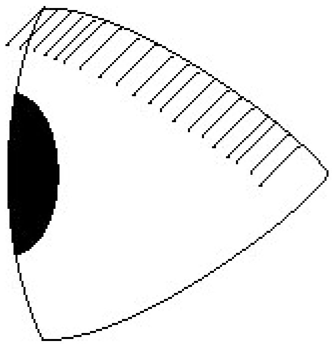
😐 IV
8) Baryogenesis and CP violation
9) Next experimental steps

1) Concept of symmetries

Symmetry



Nature

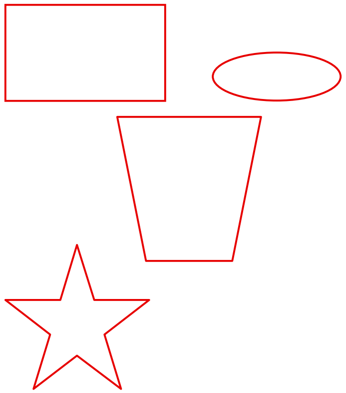


Observation

- regular pattern
- symmetry
- …

Recognition

Creating arts



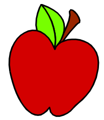
- regular pattern
- symmetry
- …

→

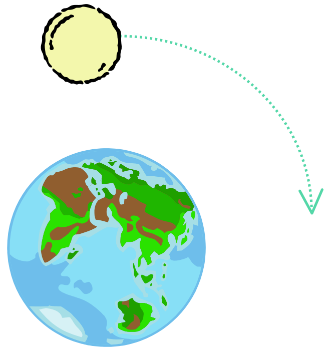
Concept

Realisation

Natural Science

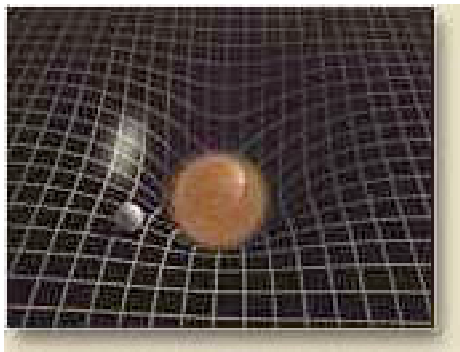


Observation



$$f = G\,\frac{m_1\,m_2}{r^2}$$

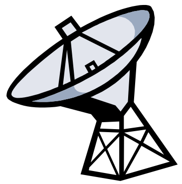
Generalising and making physical laws



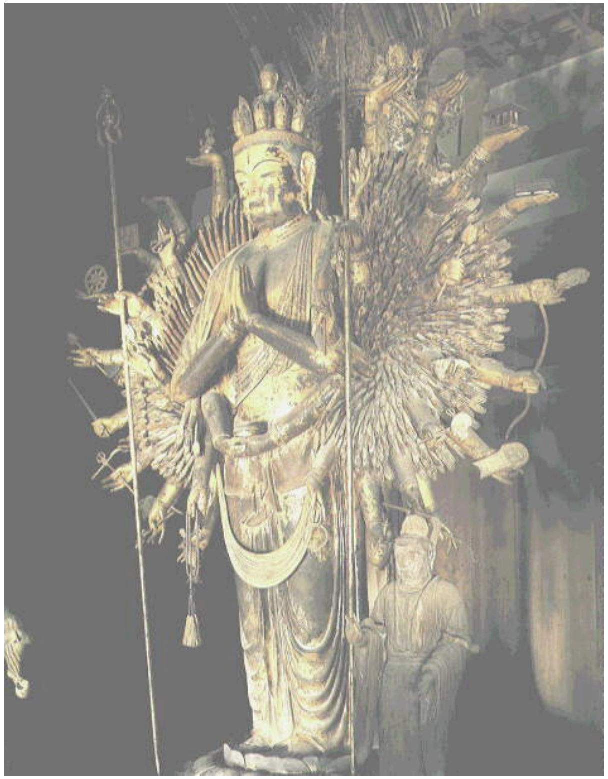
$g_{\square\square}g^{\square\square}$

Extracting more abstract concept

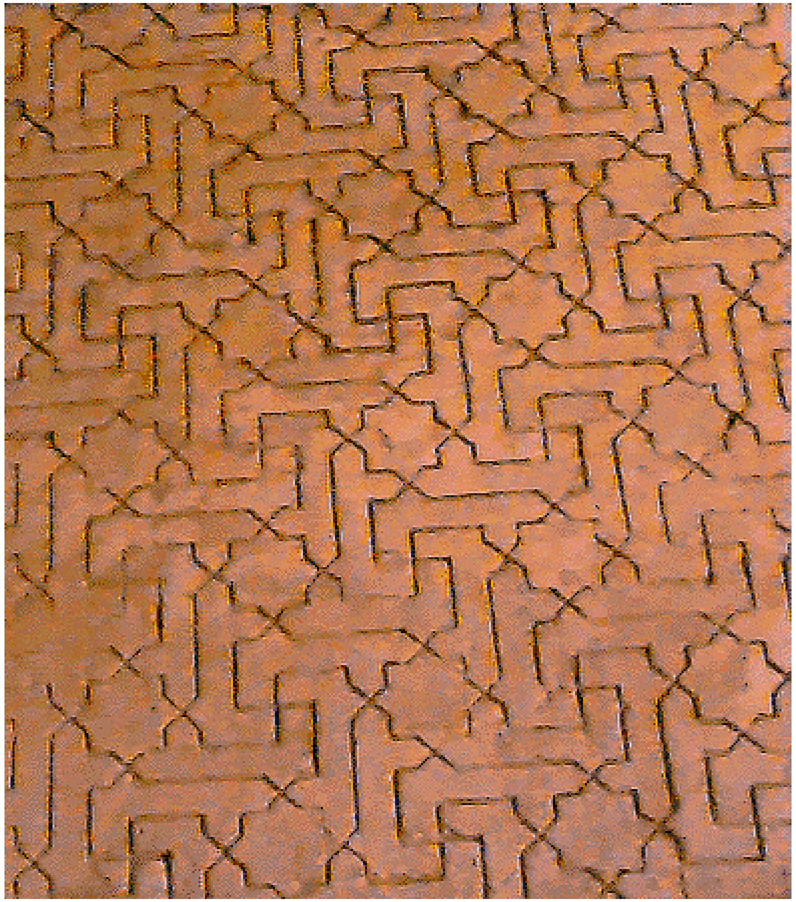
Postulating and predicting phenomena

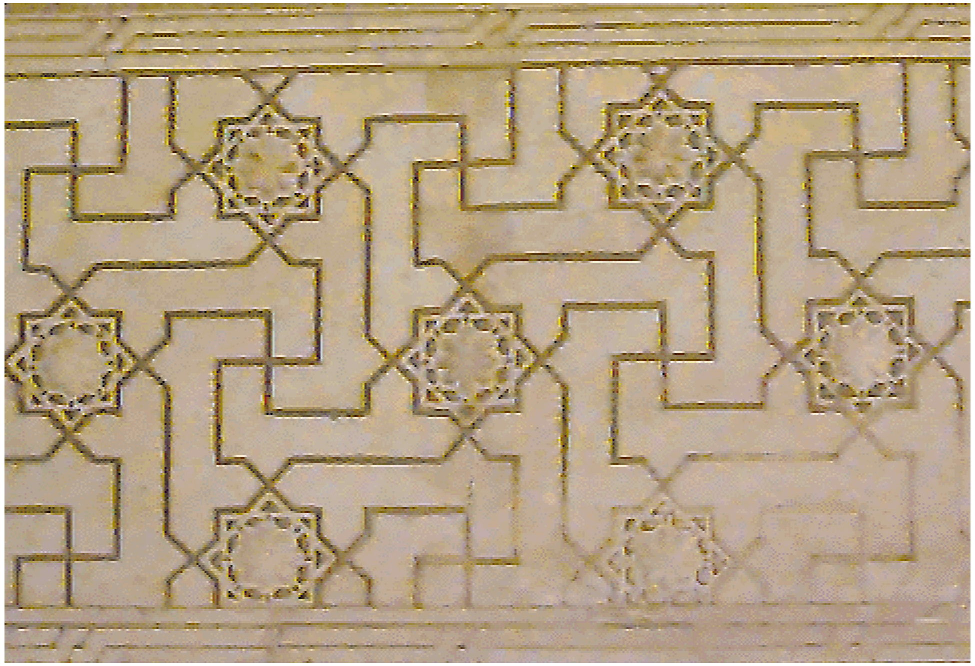


Observation



Other examples of symmetry



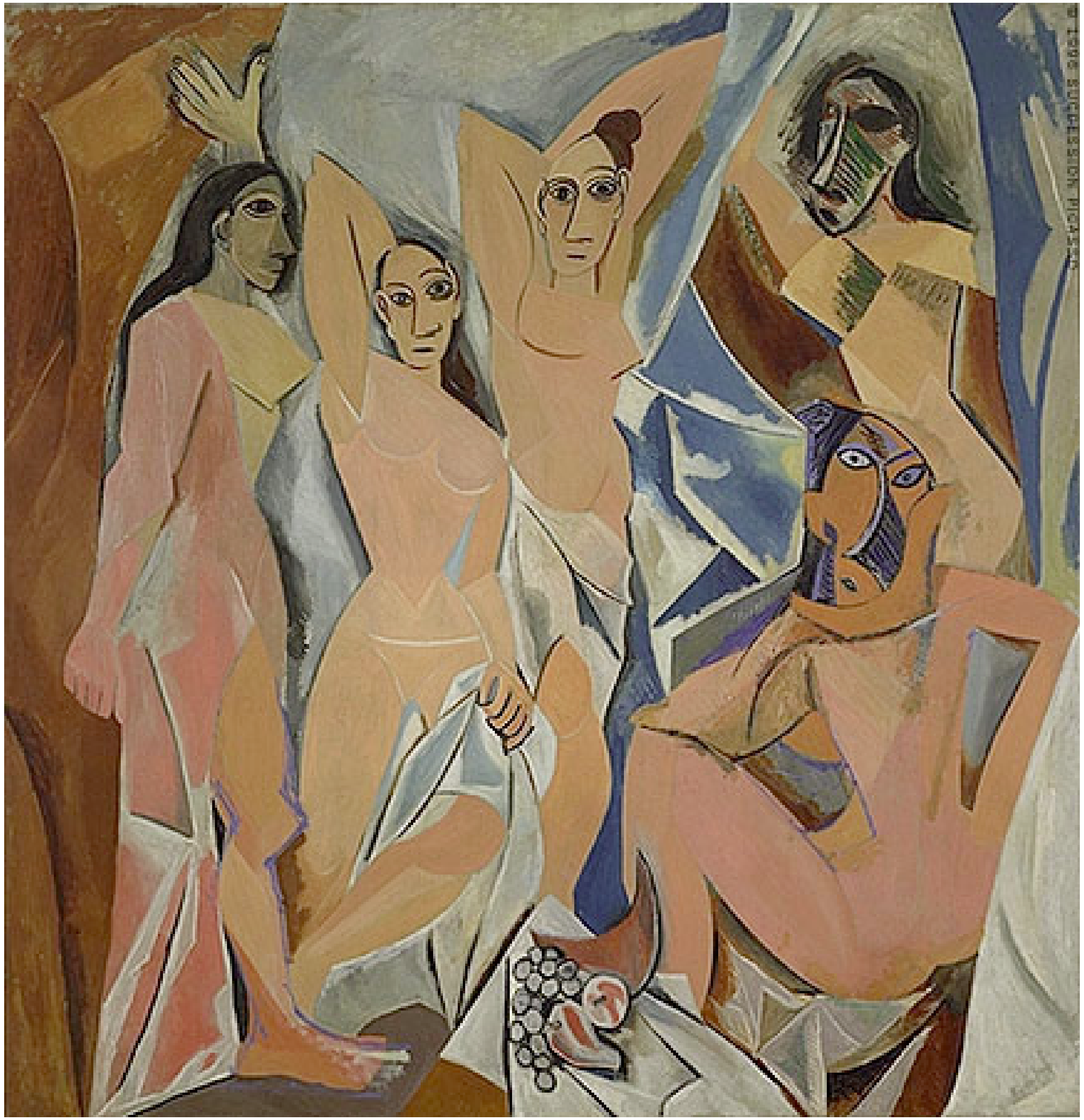


and patterns

Some asymmetry makes… more dynamic

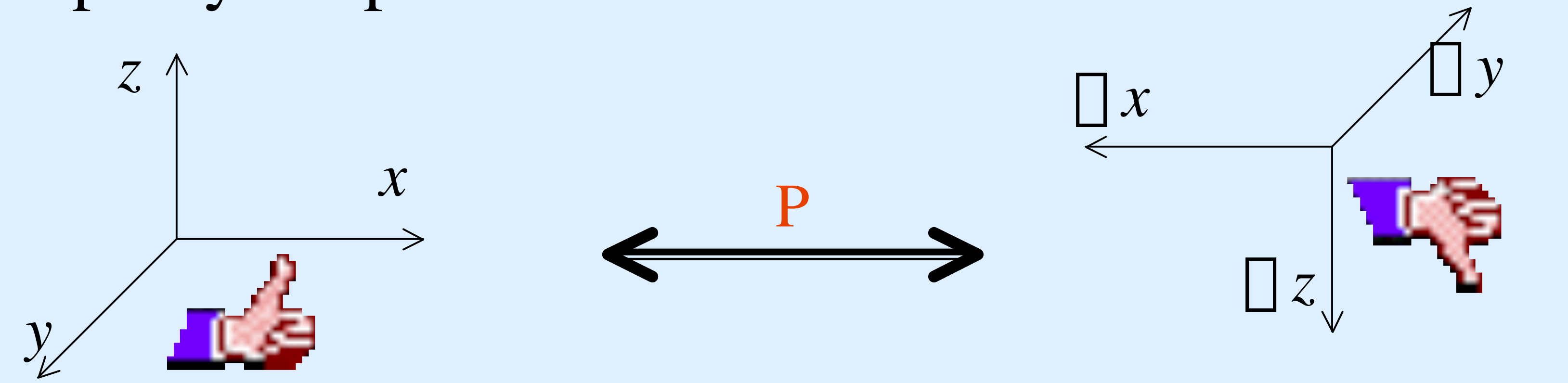

more beautiful

if not too much…?



2) P, T and C transformation

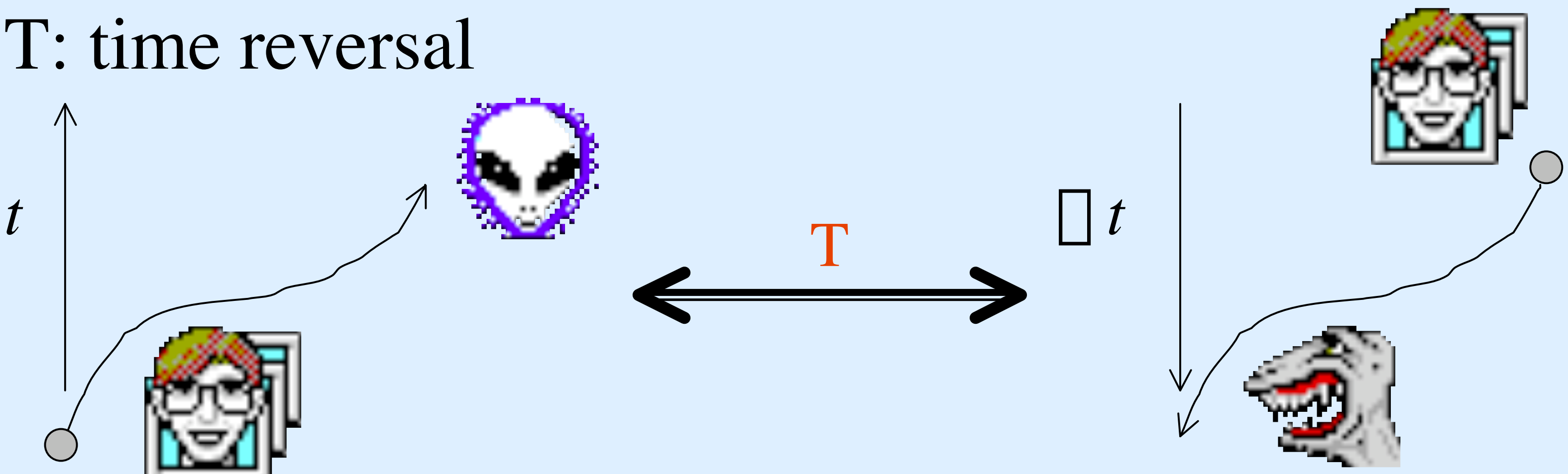
P: parity or space reflection



left handed system

right handed system

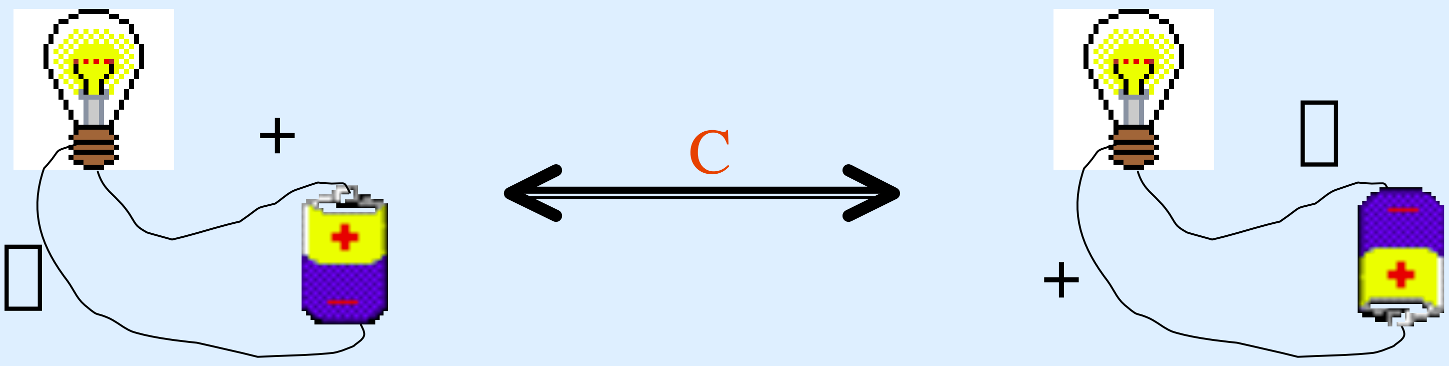
T: time reversal



forward moving

backward moving

C: charge conjugation



<u>In particle physics</u> reversing internal quantum numbers

charged states

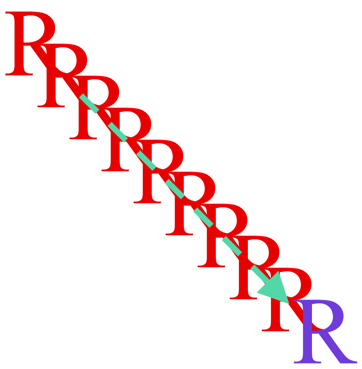
e^- (electron)	$\leftrightarrow$	e^+ (positron)
p (proton)	$\leftrightarrow$	$\bar{p}$ (anti proton)
π^+ (positive pion)	$\leftrightarrow$	π^- (negative pion)
u (u quark)	$\leftrightarrow$	$\bar{u}$ (anti u quark)

neutral states

n (neutron)	$\leftrightarrow$	$\bar{n}$ (anti neutron)
K^0 (k-zero meson)	$\leftrightarrow$	$\bar{K}^0$ (anti k-zero meson)
π^0 (neutral pion)	$\leftrightarrow$	π^0 (neutral pion)

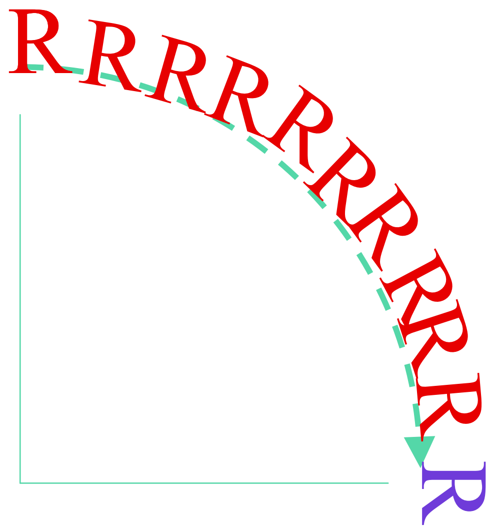
Discrete and continuous transformations

Translation



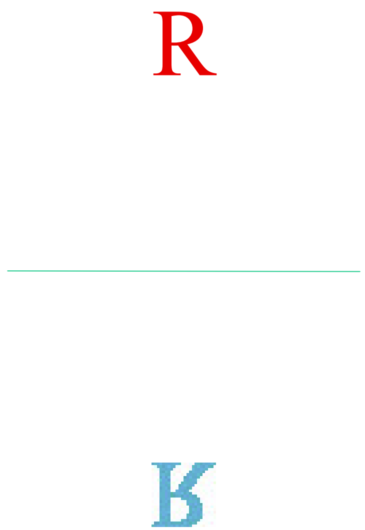
continuous

Rotation



continuous

Reflection
(parity)



discrete

3) Conservation of symmetries

If no difference seen between

"this world" and "space reflected world"

□ We say:

- parity is conserved,
- P symmetry is conserved,
- world is invariant under P transformation
- etc.

example

More "professional" description,

$\hat{H}$ Hamiltonian operator describing the world

$\hat{P}$ Parity transformation operator

$\hat{P}^{\dagger}\hat{H}\hat{P} = \hat{H}^{\mathrm{P}}$ parity transformation of Hamiltonian

If $\hat{H}^{\mathrm{P}} \neq \hat{H}$

Parity violation, Parity non-conservation etc. etc.

C and CP

Violation of Parity

World

90%

10%

Mirror World

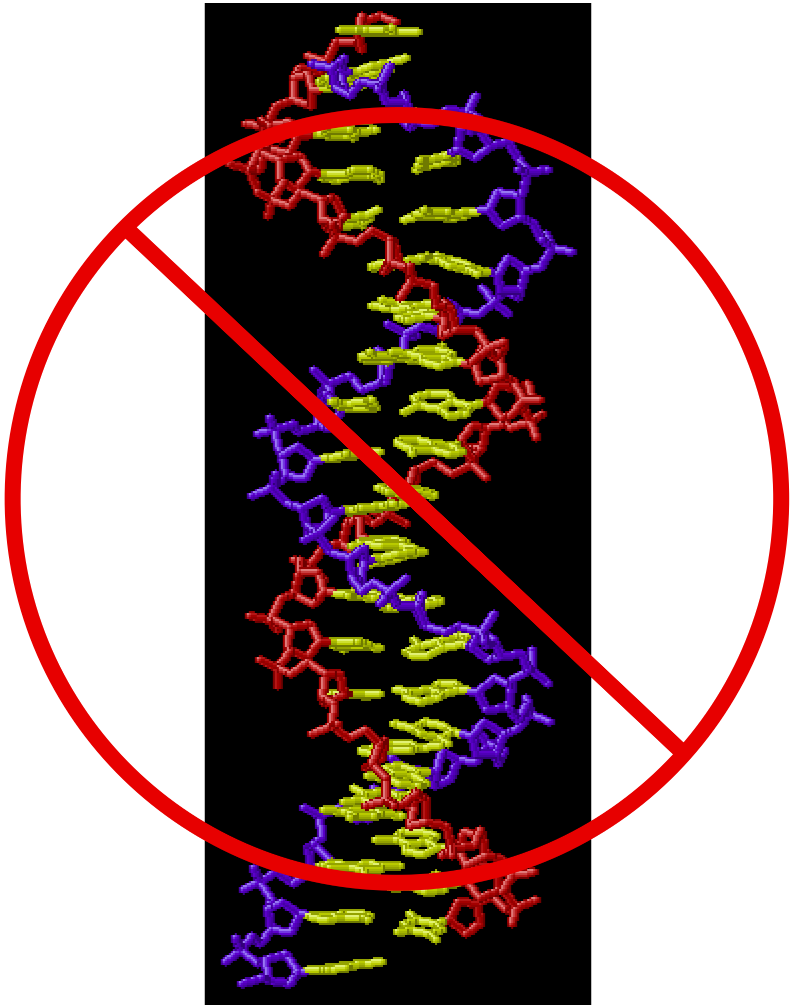
10%

90%

World ≠ Mirror World

(parity violation)

Even more with DNA



Parity is fully violated.

to formula

A similar terminology applies to C and T.

Strong and electromagnetic interactions conserve:
flavour quantum numbers,
C, P, T, CP, CT, PT and CPT

Particle physics example:

$\pi^0 \to \gamma\gamma$ but not $\gamma\gamma\gamma$

$\pi^0 = (u\bar{u}+d\bar{d})_{L=0,\,S=0} \Longrightarrow C(\pi^0) = +1$

$\vec{B}, \vec{E} \xrightarrow{C} -\vec{B}, -\vec{E} \Longrightarrow C(\gamma) = -1$

initial state $C(\pi^0) = +1$,
final state $C(\gamma\gamma) = +1$, $C(\gamma\gamma\gamma) = -1$
$\Rightarrow$ conservation of C in π^0 decays

Or... calculating decay amplitudes

$$A_{\square\square\square} = <\square\square\square|C^{\square 1} C\, H\, C^{\square 1} C|\square^0> = \square<\square\square\square|C\, H\, C^{\square 1}|\square^0>$$

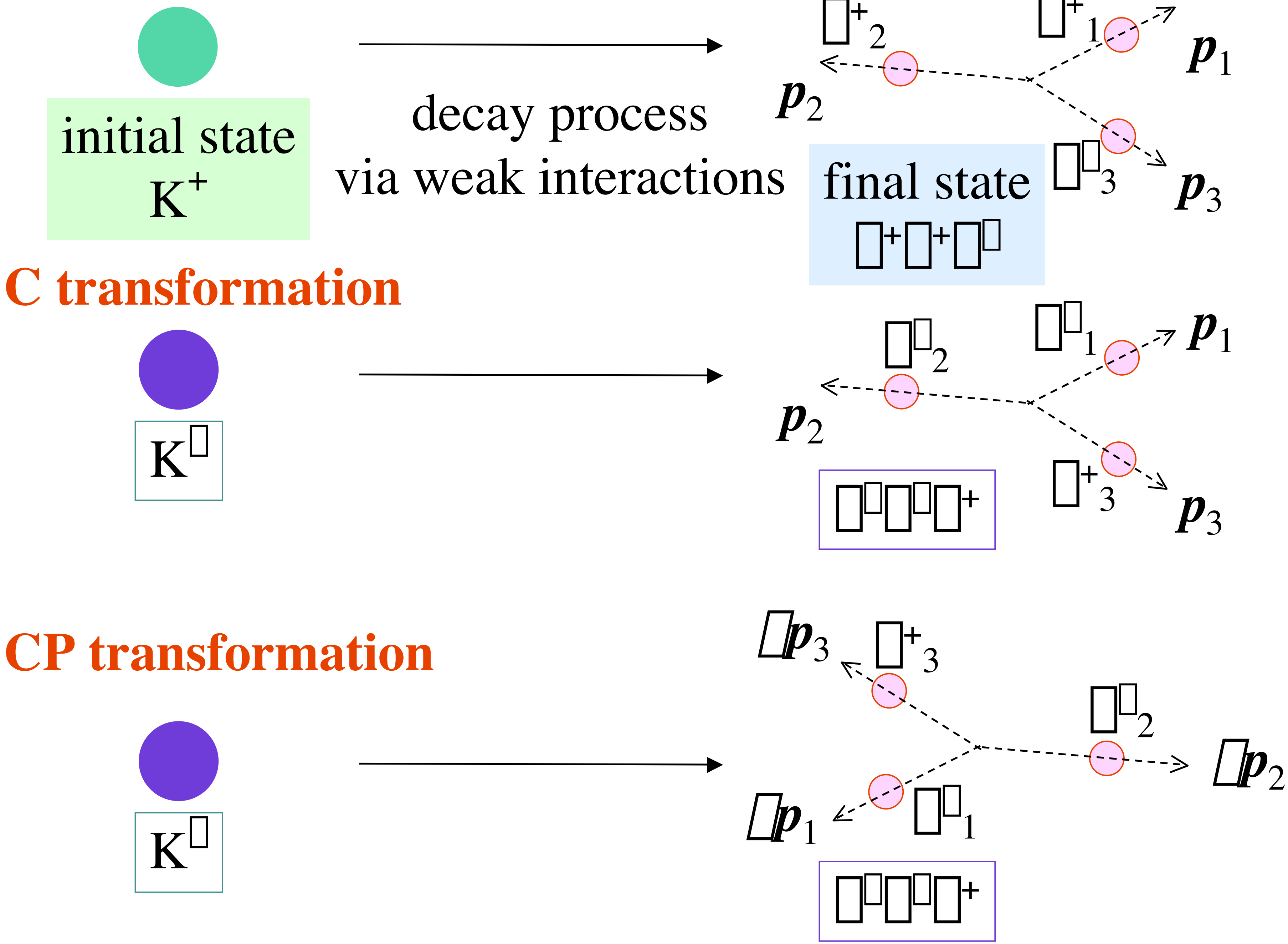
$$= \square<\square\square\square|\, H\, |\square^0> = \square A_{\square\square\square}$$

$$A_{\square\square\square} = 0$$

Weak interactions do not conserve:
flavour quantum numbers,
C, P, T, CP, CT and PT

The topic of this lecture series.

4) CP violation in the charged kaon system



Partial decay width for $K^+ \to \pi^+\pi^+\pi^-$

$$\Gamma_{K^+ \to \pi^+\pi^+\pi^-} = \int d^3p_1 \int d^3p_2 \int d^3p_3 \, \gamma_{\pi_1^+,\pi_2^+,\pi_3^-}(\vec{p}_1,\vec{p}_2,\vec{p}_3)$$

C transformed partial decay width

$$\Gamma^{C}_{K^+ \to \pi^+\pi^+\pi^-} = \int d^3p_1 \int d^3p_2 \int d^3p_3 \, \gamma_{\pi_1^-,\pi_2^-,\pi_3^+}(\vec{p}_1,\vec{p}_2,\vec{p}_3)$$

$$\equiv \Gamma_{K^- \to \pi^-\pi^-\pi^+}$$

CP transformed partial decay width

$$\Gamma^{CP}_{K^+ \to \pi^+\pi^+\pi^-} = \square \int d^3p_1 \int d^3p_2 \int d^3p_3 \, \gamma_{\pi_1^-,\pi_2^-,\pi_3^+}(-\vec{p}_1,-\vec{p}_2,-\vec{p}_3)$$

$$= \int d^3p_1 \int d^3p_2 \int d^3p_3 \, \gamma_{\pi_1^-,\pi_2^-,\pi_3^+}(\vec{p}_1,\vec{p}_2,\vec{p}_3)$$

$$= \Gamma_{K^- \to \pi^-\pi^-\pi^+}$$

Partial decay width: $\Gamma_{K^+\to\pi^+\pi^+\pi^-}$ and $\Gamma_{K^-\to\pi^-\pi^-\pi^+}$
are CP and C transformed to each other

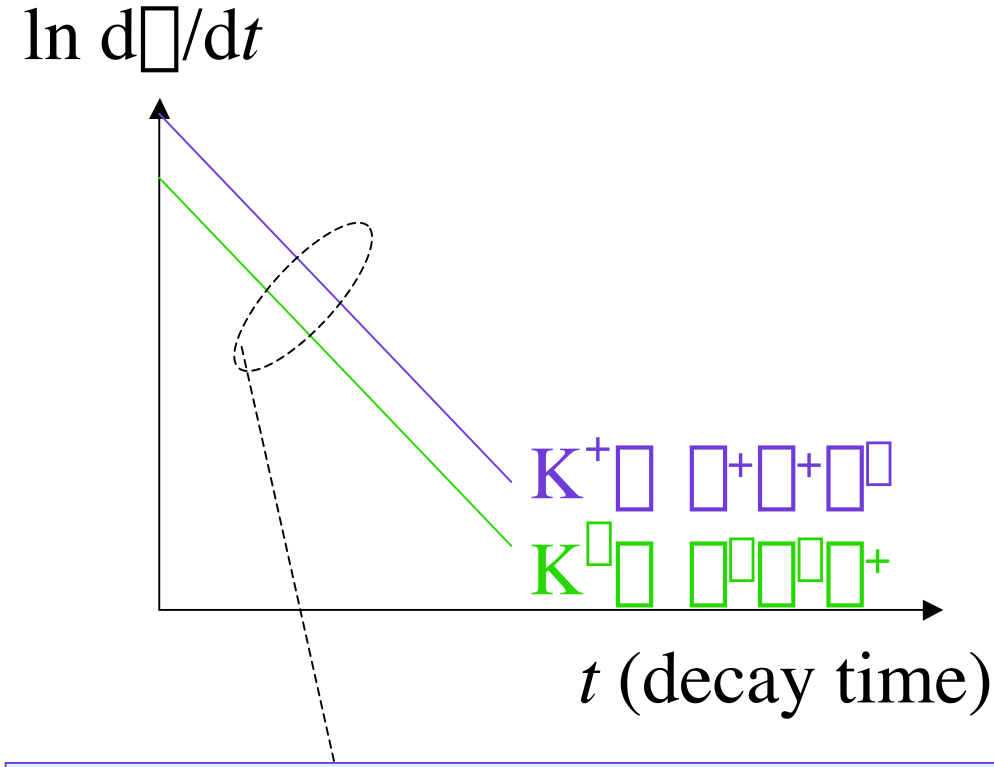
If $\Gamma_{K^+\to\pi^+\pi^+\pi^-} \neq \Gamma_{K^-\to\pi^-\pi^-\pi^+}$ $\Rightarrow$ $\not{C}\!\not{P}$ and $\not{C}$!

NB: these differences can appear in
Γ or $d\Gamma/dt$

In general,
$\not{C}$ and $\not{C}\!\not{P}$ are needed in order to generate partial decay widths differences between particles and anti particles.

Total widths between K^+ and K^- must be identical CPT

If there were $\not{C}P$ and $\not{C}$, we would observe



Not seen!

Exponential decays
(K$^\pm$ have definite masses and decay widths)
Sloops are given by the total decay widths:
CPT theorem guarantees that they are identical.