As symmetrias P, C e T

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HANDS ON QUANTUM MECHANICS

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The discrete symmetries P, C, T and their breaking play a fundamental rôle in Particle Physics and Cosmology

The breaking of these symmetries is crucial for our understanding of nature and in particular the existence of matter in the Universe

Main References

"CP Violation" Gustavo C. Branco, Luis Lavoura, João P. Silva, Oxford U. Press (1999) Int. Ser. Monogr. Phys. 103

"Observation of Time Reversal Violation in the B^0 Meson System" BaBar Collaboration Phys. Rev. Lett. 109 (2012) 211801 arXiv: 1207.5832

"Time Reversal Violation from the entangled B^0-anti B^0 system" J. Bernabeu, F. Martinez-Vidal, P. Villanueva-Perez, JHEP 1208 (2012) 064 arXiv: 1203.0171

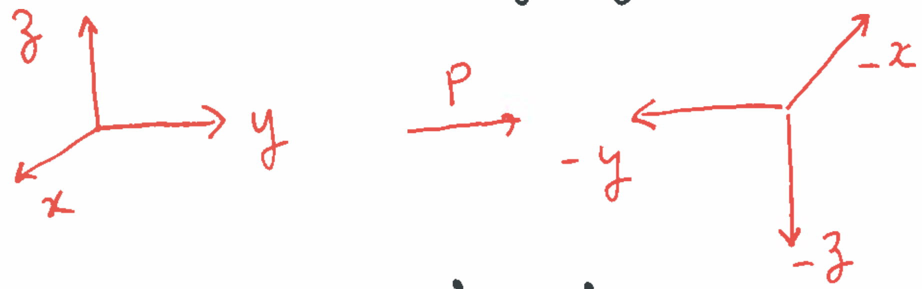
See also

"CP Violation" I. I. Bigi and
A. I. Sanda, Cambridge U. Press (2000)

"The Mystery of the missing Antimatter"
Helen R. Quinn and Yossi Nir
Princeton U. Press 2008

Parity symmetry, **usually called P**, **in classical Physics**, consists in the invariance of physics under a discrete transformation which changes the sign of the space coordinates x, y, z:

$$(x, y, z) \xrightarrow{P} (-x, -y, -z)$$



a right-handed coordinate system becomes left-handed under the parity transformation

Charge conjugation symmetry, **C**, **has no classical analogue**, C symmetry asserts that antiparticles behave in the same way as the corresponding particles

Time reversal transformation, **usually called T**, this consists of changing the sign of the time coordinate t. The genuine time-reversal transformation also interchanges final states and initial states

P and $\hat{T}$ transformations in classical physics

		P	$\hat{T}$	
Time	t	+	−	
Position	$\vec{r}$	−	+	
Energy	E	+	+	
Momentum	$\vec{p}$	−	−	$(\vec{v})$
Spin	$\vec{s}$	+	−	$(\vec{J})$
Helicity	h	−	+	
Electric Field strength	$\vec{E}$	−	+	
Magnetic Field strength	$\vec{B}$	+	−	
Magnetic dipole moment	d_m	+	+	$(-d_m \vec{s}\cdot\vec{B})$
Electric dipole moment	d_e	−	−	$(-d_e\, \vec{s}\cdot\vec{E})$
velocity	$\vec{v}$	−	−	
force	$\vec{F}$	−	+	

$$\vec{v} = \frac{d\vec{r}}{dt}$$

$$\vec{p} = m\vec{v}$$

$$\vec{J} = \vec{r} \times \vec{p}$$ angular momentum

$$\vec{F} = \frac{d\vec{p}}{dt}$$

$$\vec{F}_{Lorentz} = q(\vec{E} + \vec{v} \times \vec{B})$$

$$h = \frac{\vec{s}\cdot\vec{p}}{|\vec{s}||\vec{p}|}$$

The whole body of classical mechanics and electromagnetism is invariant under a parity transformation as well as a T transformation, the same is true for classical gravitational interactions

However at the macroscopic level there is a P and a T asymmetry

- left right asymmetry of the human body
- piece of wood burning down to ashes and smoke

These seemingly puzzling facts do not require microscopic P and T violation

"time arrow" is explained by statistical mechanics

About C

No one had imagined antimatter before the Dirac equation appeared (1928)

The existence of an antiparticle for every particle is a prediction of relativistic quantum theory (particles with the same mass but opposite "charges")

In 1930 Oppenheimer and Tamm working independently realised that Dirac equation predicted "annihilation" of particles with anti-particles into photons

This could be a disaster ...

and leads to the puzzle "why there is matter in the Universe?"

Historically there was a strong prejudice against the possibility of ever observing P and T violation due to the fact that all interactions known in nature conserved these symmetries. Weak interactions changed the picture

Violation of P, of C and of T, separately have been observed in nature. At first it was thought that CP would be conserved despite violation of P and C but its violation was also observed. T was the most difficult one to see.

It is assumed that CPT is conserved. There is a strong theoretical prejudice against the possibility that CPT is violated – "CPT theorem" – otherwise it is difficult to conceive a sensible relativistic quantum theory

T in QM is an anti unitary operator

Some history

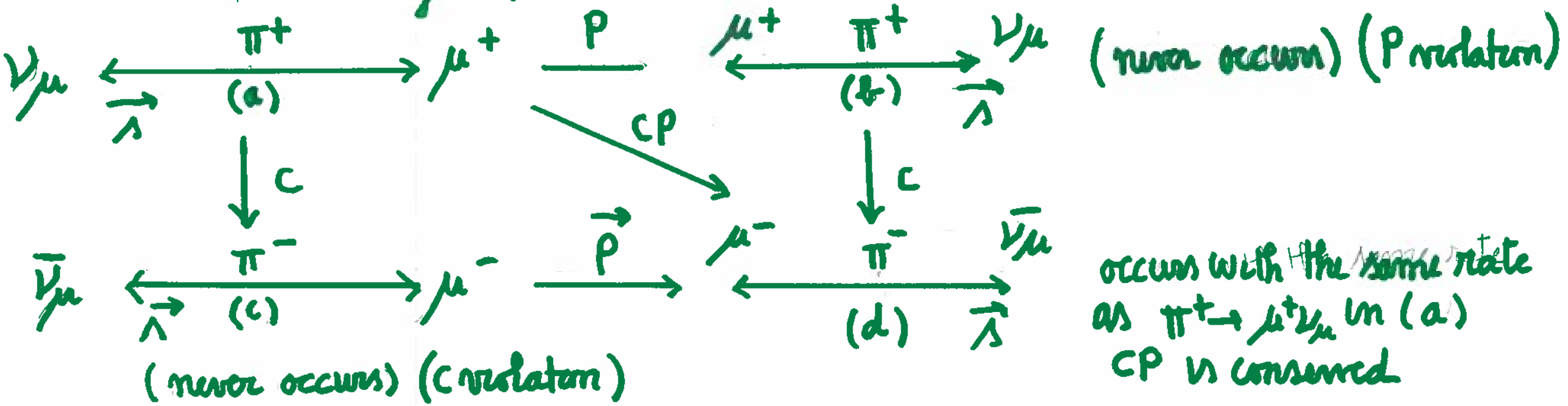
Lee and Yang (1956) concluded that parity invariance of weak interaction was not a confirmed experimental fact and proposed experiments to test P

Wu et al (1957) established parity violation experimentally

Goldhaber et al (1958) observed parity violation in another important experiment

In general one finds that C is violated with P in weak int.

π^+ decays predominantly to $\mu^+ \nu_\mu$



A thought experiment about C (T. D. Lee 1990)

Our civilization contacts another distant one via exchange of electromagnetic messages no charged particles are exchanged

Will the two civilization be able to meet without annihilation destroying both meeting parties?

It is not enough that C be violated, CP must be violated too in order that matter may be distinguished from antimatter

Clearly $\pi^{\pm}$ decays cannot provide a solution. We are unable to explain what we mean by a "positively charged pion" unless we could explain that it decays into a neutral particle with negative helicity, but we have no way to explain how we define the sign of the helicity

Only much later was CP discovered to be violated
Christenson et al (1964)

K_L is its own antiparticle
it decays both to $\pi^+ e^- \bar{\nu}_e$ and to the C-conjugate $\pi^- e^+ \nu_e$
However it decays slightly less often to the first than the second mode
implying C violation and CP violation

Indeed total decay rates involve integration over momenta of all particles in the decay and sum in spin which eliminates parity from consideration - differences in the two decay rates signals CP violation

We now have the solution to the thought experiment

- the decay that occurs less often gives rise to a pion with the same electric charge as the proton we are made of (this would define what we mean by matter)

On the importance of CP violation

Sakharov (1967) pointed out that in order to generate the observed baryon asymmetry of the Universe one needs a theory with

- baryon-number violation (possibility $B=0 \rightarrow B\neq 0$)
- C and CP violation (different rates for processes involving baryons and those involving anti-baryons)
- out of equilibrium dynamics (otherwise asymmetries in quantum numbers are erased)

SM of electroweak interactions cannot explain BAU

If BAU were taken as an initial condition from Big Bang, inflation would have erased it

The generation of the observed BAU remains an open question with very interesting possibilities

First direct observation of T violation through the exchange of initial and final states in transitions that can only be connect by a T-symmetry transformation : BaBar (2012)

CPT conservation together with $\not{CP}$ implies $\not{T}$

In the decay of $\Upsilon(4S)$ the two B meson are in an entangled antisymmetric state

The two body state is usually written in terms of flavour eigenstates B^0 and $\bar{B}^0$ but can be expressed in term of any two orthogonal states such as B_+ and B_- identified as

$B_+ \to J/\psi K_L^0$ $\quad B^- \to J/\psi K_S \quad K_S \to \pi\pi$ (used for CP tagging)

the flavour of B^0 and of $\bar{B}^0$ is identified as

$\bar{B}^0 \to \ell^- X$ and $B^0 \to \ell^+ X$

Let us use the notation (f_1, f_2) to indicate the process involved

ie f_1, f_2

ie f_1, f_2 indicate the flavour or CP eigenstates that are reconstructed at times t_1 and t_2

"B"$\to f_1$ first decay "B" to f_2 second decay

$\bar{B}^0 \to \ell^- X$ $\quad B^0 \to \ell^+ X$ $\quad B_+ \to J/\psi K_L^0$ $\quad B_- \to J/\psi K_S^0$

Example $(\ell^+ X, \; J/\psi K_S^0)$

at Time t_1 : $Y \to \ell^+ X$ meaning $Y = B^0$
therefore the remaining particle at time t_1 is $\bar{B}^0$

$t_2 > t_1$
at time t_2 : the product of decay is $J/\psi K_S^0$
therefore between t_1 and t_2 $\bar{B}^0$ evolved into B_-
ie $\bar{B}^0 \to B_-$

what is the time reversal Transition? $B_- \to \bar{B}^0$
this corresponds to $(J/\psi K_L, \; \ell^- X)$

we are left with B_- → ($J/\psi K_L$)
($\ell^- X$) ← B^- evolved into $\bar{B}^0$ at the Time of decay

Compare the rate of Transition to its T reversed -
- any difference in these two rates is evidence for T symmetry violation

There are four independent comparisons that came to be made

i) $(\ell^+ X, J/\psi K_S^0)$, $(J/\psi K_L^0, \ell^- X)$ $\quad \bar{B}^0 \to B_-$, $B_- \to \bar{B}^0$

ii) $(\ell^- X, J/\psi K_L^0)$, $(J/\psi K_S, \ell^+ X)$ $\quad B^0 \to B_+$, $B_+ \to B^0$

iii) $(\ell^+ X, J/\psi K_L^0)$, $(J/\psi K_S^0, \ell^- X)$ $\quad \bar{B}^0 \to B_+$, $B_+ \to \bar{B}_0$

iv) $(\ell^- X, J/\psi K_S^0)$, $(J/\psi K_L^0, \ell^+ X)$ $\quad B^0 \to B_-$, $B_- \to B^0$

$\bar{B}^0 \to \ell^- X \qquad B^0 \to \ell^+ X \qquad B_+ \to J/\psi K_L^0 \qquad B_- \to J/\psi K_S^0$

It should be noticed that T asymmetry is clearly different from Δt $(t_1 \leftrightarrow t_2)$ exchange and also from CP asymmetries

T exchange : exchange the in and out neutral B states
CP exchange : exchange B^0 and $\bar{B}^0$ states
CPT exchange : exchange B^0 and $\bar{B}^0$ states and in and out

exchange of in and out states is associated to anti-unitarity

Eight different combination

	T	CP	CPT
$\overline{B^0} \to B_-$	$B_- \to \overline{B^0}$	$B^0 \to B_-$	$B_- \to B^0$
$B_+ \to B^0$	$B^0 \to B_+$	$B_+ \to \overline{B^0}$	$\overline{B^0} \to B_+$
$\overline{B^0} \to B_+$	$B_+ \to \overline{B^0}$	$B^0 \to B_+$	$B_+ \to B^0$
$B_- \to B^0$	$B^0 \to B_-$	$B_- \to \overline{B^0}$	$\overline{B^0} \to B_-$

$B_- \to \overline{B_0}$

$B^0 \to B_+$

$B^+ \to \overline{B^0}$

$B^0 \to B_-$