Elementary particle physics course

Lesson 7 PHY 1054 EP

Symmetry breaking in weak interactions

Mirrors would do well to think (reflect) a little more before returning their images

(Jean Cocteau)

PHY554 Exam

It will be an oral exam :

- Randomly one subject

- 40 minutes preparation

- 20 minute presentation

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Calculation of magnetic masses and moments

Matter and antimatter, what symmetries ?

Parity, a symmetry and an observable

Spin, parity and other quantic numbers.

Conservation and non-conservation in hadron decays

Oscillations of leptons and quarks

Lifetime and cross sections

Strong interactions

The weak interactions

Addition of spins

From fermion masses to hadron masses

The quark model, qualities and shortcomings

Spin, definition and applications

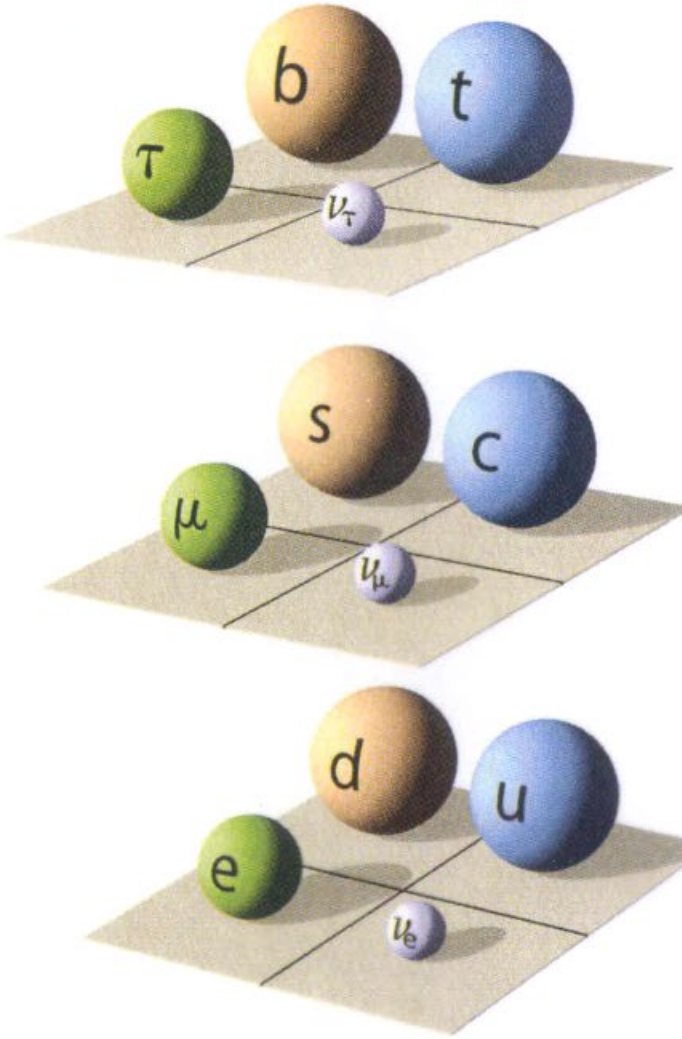
Neutrinos

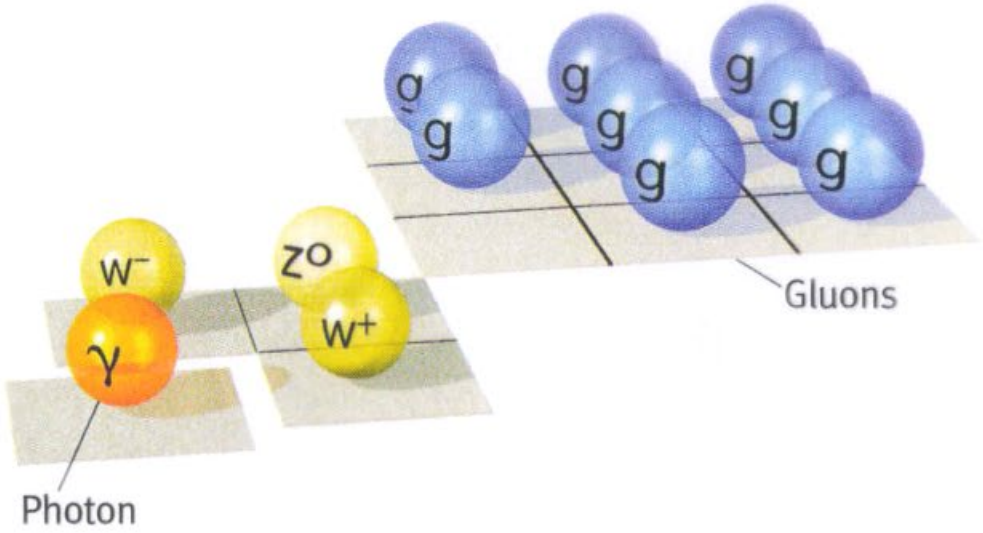
Differences between baryons and mesons in the quark model.

Symmetries and invariance. Examples

Symmetry breaking

The standard model





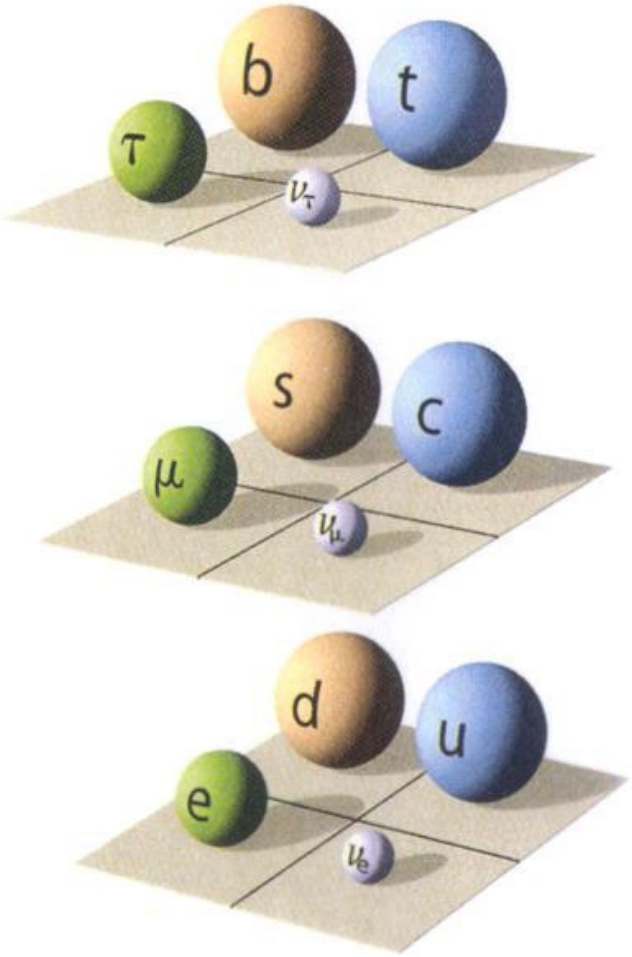
Forces (quanta)

Fundamental Constituents

Conservation Laws

Conserved quantities	Strong	Electro.	Weak
Energy-Momentum	✓	✓	✓
Angular momentum	✓	✓	✓
Electrical charge	✓	✓	✓
Leptonic number (L_e, L_μ, L_τ)	✓	✓	✓
Baryonic number B	✓	✓	✓
Flavor			
Charge Conjugation			
Parity			

Quark Flavors



Additional internal quantum number corresponding to the type of quarks

Quark Flavors

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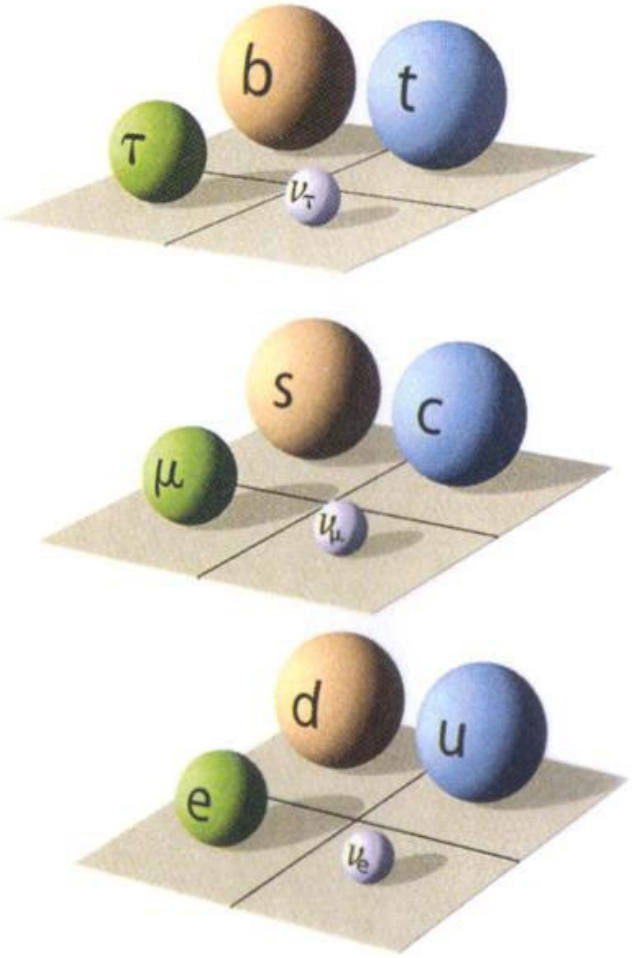


1) ***Strangeness S***

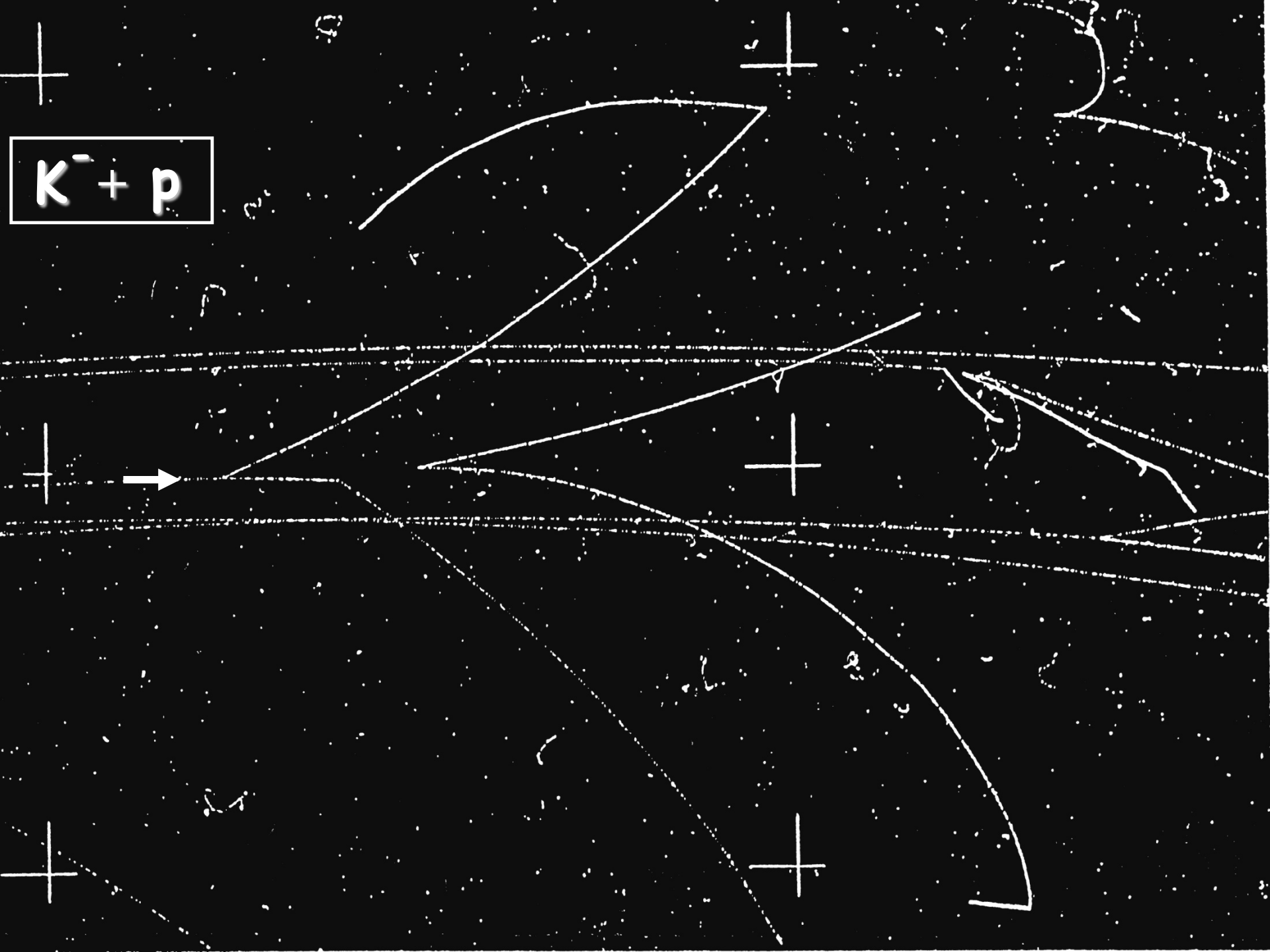
S = -1 for quark « s »
S = 0 for all other quarks

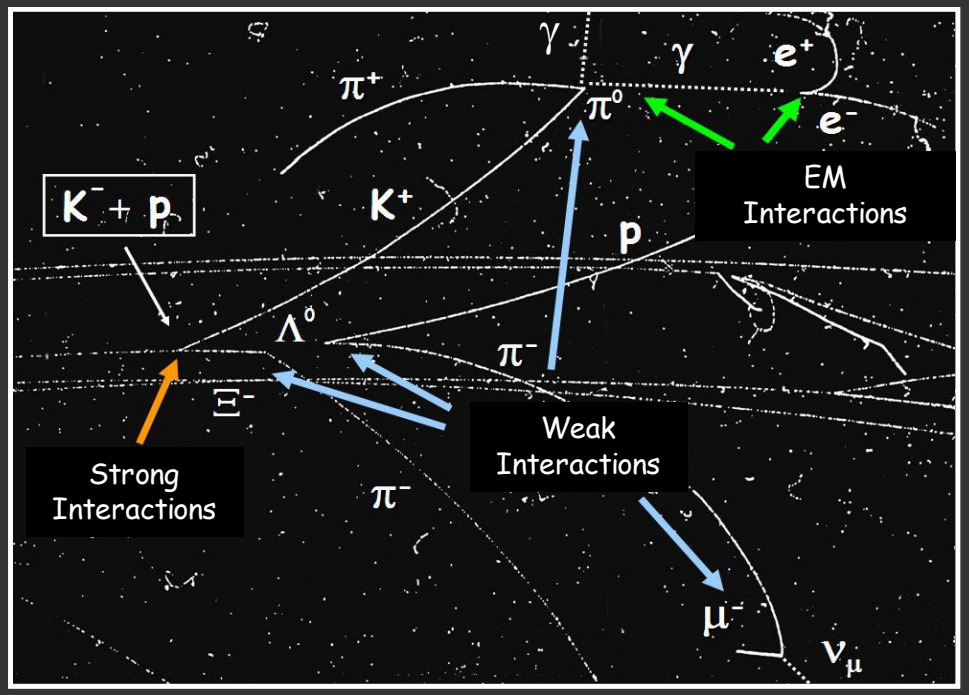
2) ***Charm C***

C = +1 for quark « c »
C = 0 for all other quarks

3) ***Beauty B***

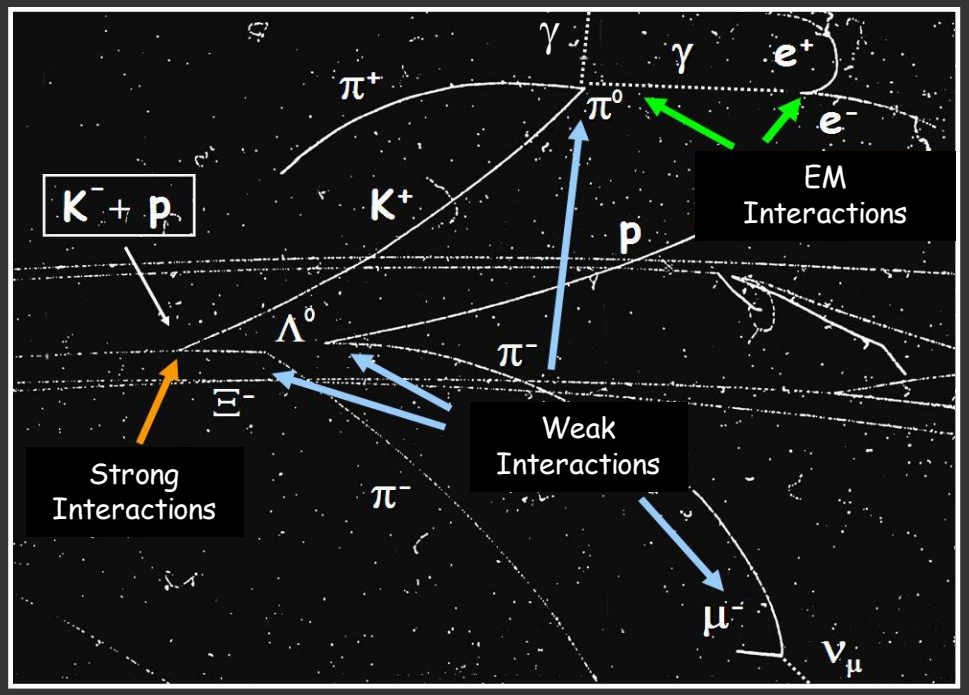
B = -1 for quark « b »
B = 0 for all other quarks


$K^- + p$



	quarks	charge	masse (MeV)	durée de vie (s)
p	uud	1	938	∞
n	udd	0	940	887
Λ	uds	0	1115	$2.6\ 10^{-10}$
Δ^{++}	uuu	2	1232	$\approx 10^{-23}$
Ξ^-	ssd	-1	1321	$1.6\ 10^{-10}$

	quarks	charge	masse (MeV)	durée de vie (s)
π^+	$u\bar{d}$	1	140	$2.6\ 10^{-8}$
π^0	$u\bar{u}$ ($d\bar{d}$)	0	135	$8.4\ 10^{-17}$
K^-	$s\bar{u}$	-1	494	$1.2\ 10^{-8}$
ϕ	$s\bar{s}$	0	1019	$\approx 10^{-23}$
D^0	$c\bar{u}$	0	1869	$1.0\ 10^{-12}$



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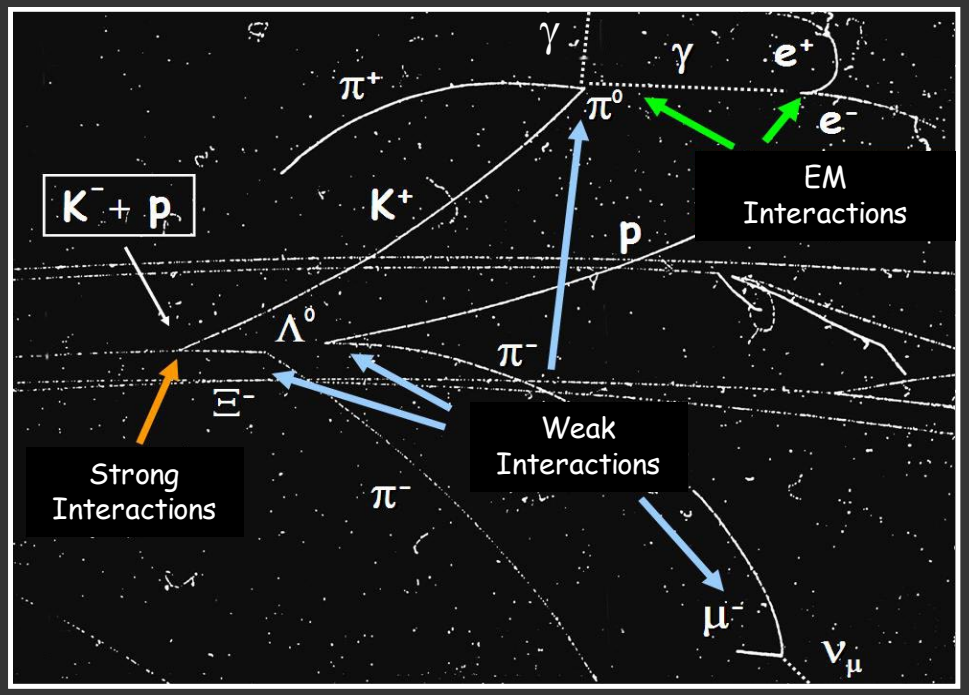
Production : $K^- + p \rightarrow \Xi^- + K^+$

strangeness S ?



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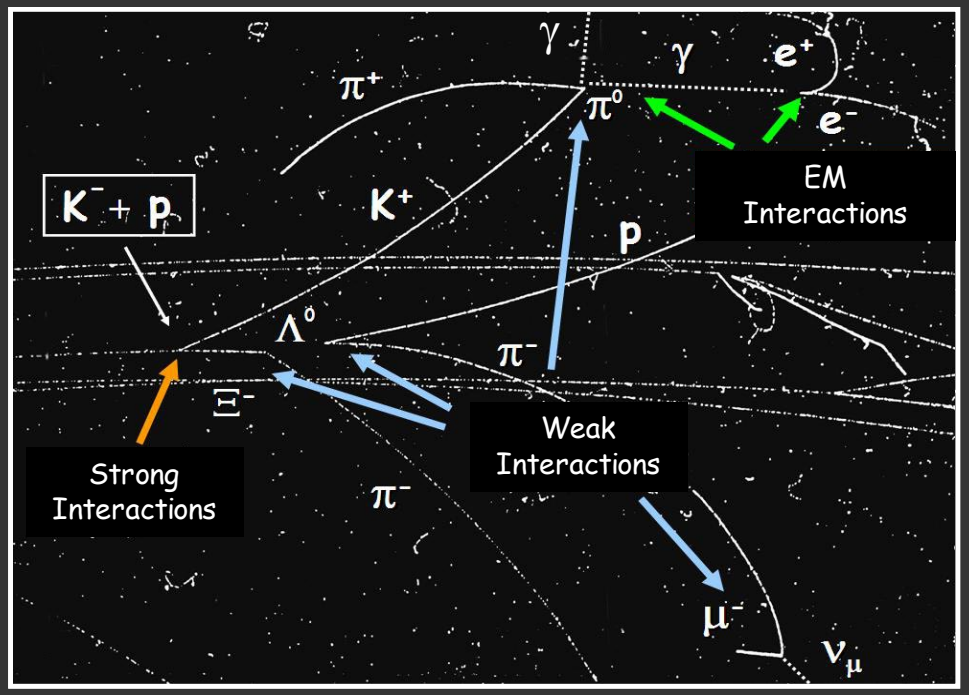
Production : $K^- + p \rightarrow \Xi^- + K^+$

strangeness S : $-1 + 0 \rightarrow -2 + 1$



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Production : $K^- + p \rightarrow \Xi^- + K^+$

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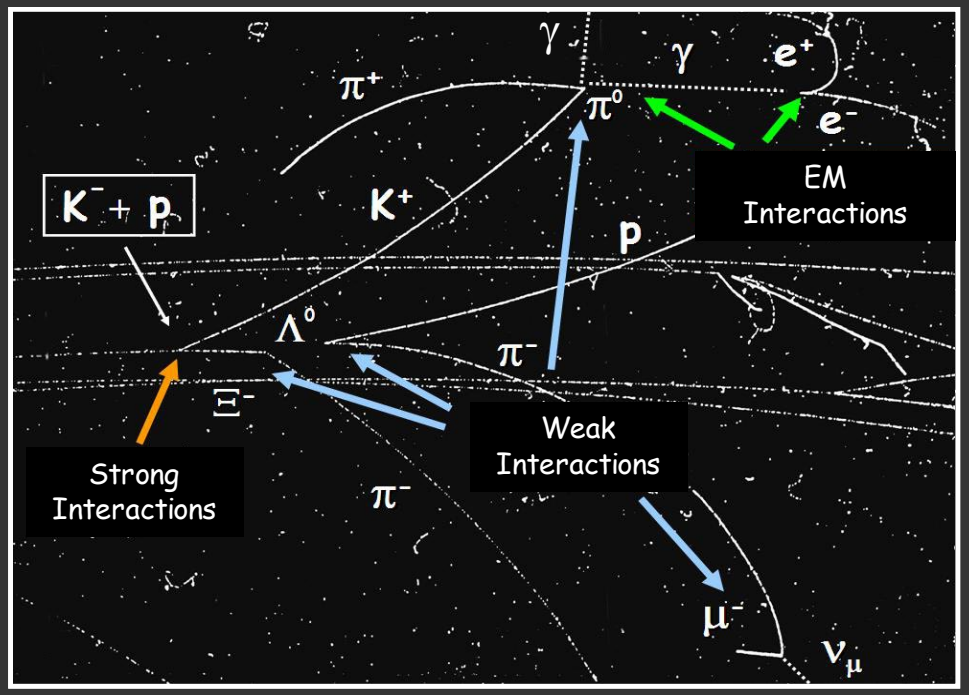
Disintegration : $K^+ \rightarrow \pi^+ + \pi^0$

strangeness S : $+1 \rightarrow 0 + 0$



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strangeness S : - 1 + 0 → - 2 + 1

Disintegration : $K^+ \rightarrow \pi^+ + \pi^0$

strangeness S : + 1 → 0 + 0

Disintegration : $\Lambda \rightarrow \pi^- + p$

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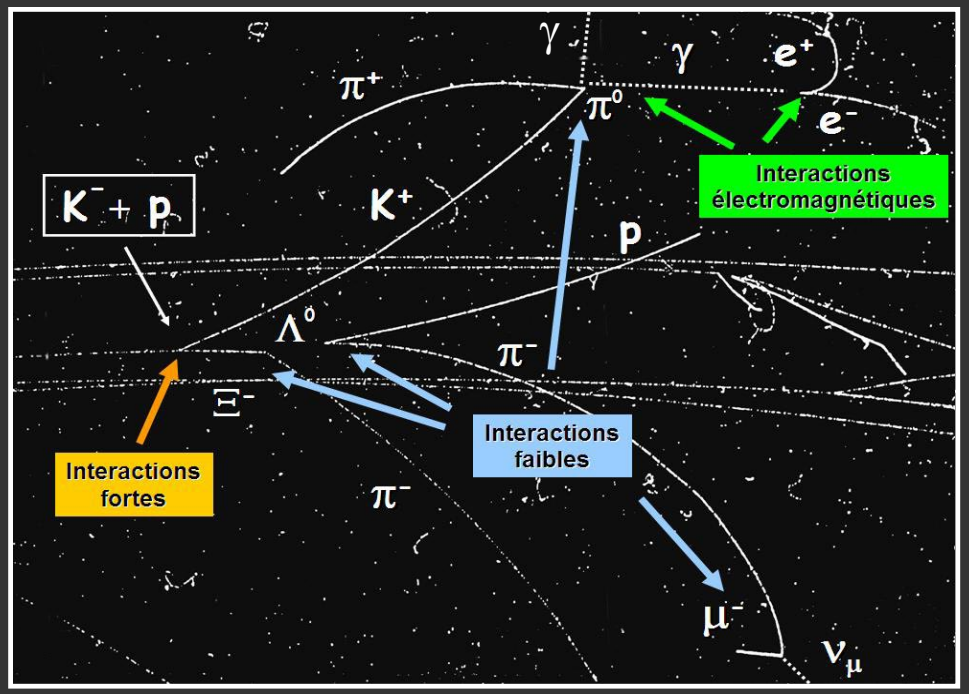

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$\Delta S = 0$

Disintegration : $K^+ \rightarrow \pi^+ + \pi^0$

strangeness S : + 1 → 0 + 0

Disintegration : $\Lambda \rightarrow \pi^- + p$

strangeness S : - 1 → 0 + 0

$\Delta S \neq 0$

Non-conservation of flavor in weak decays

Another example, the neutron decay
(radioactivity β^+)

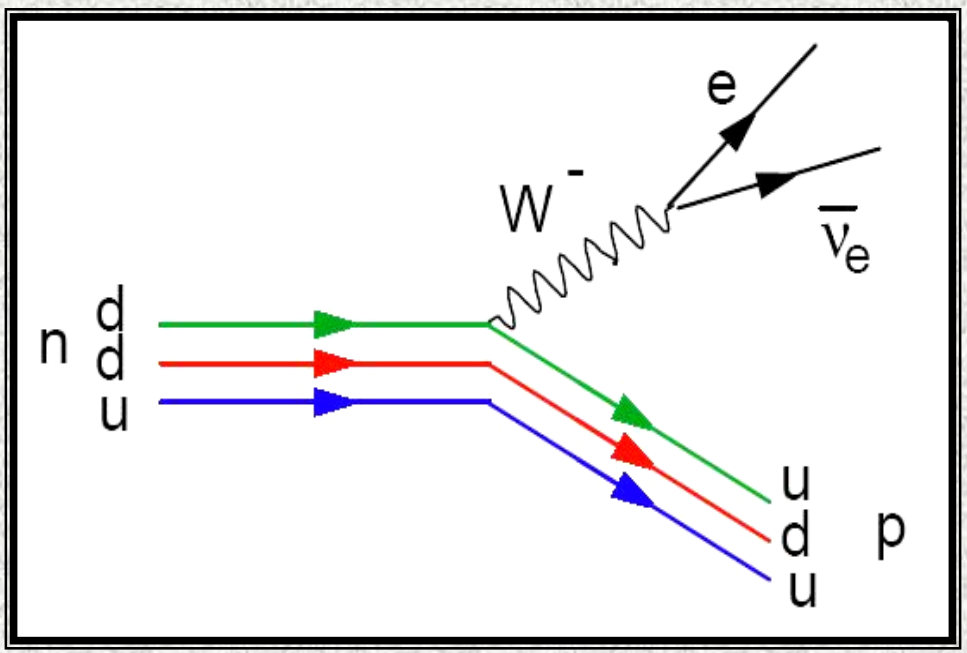
$$n \rightarrow p + e^- + \overline{\nu}_e$$

Non-conservation of flavor in weak decays

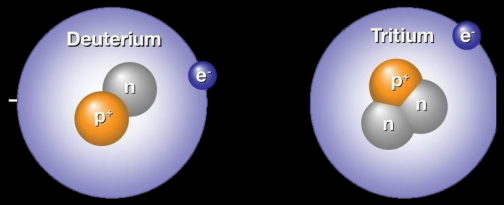
Another example, the neutron decay
(radioactivity β^+)

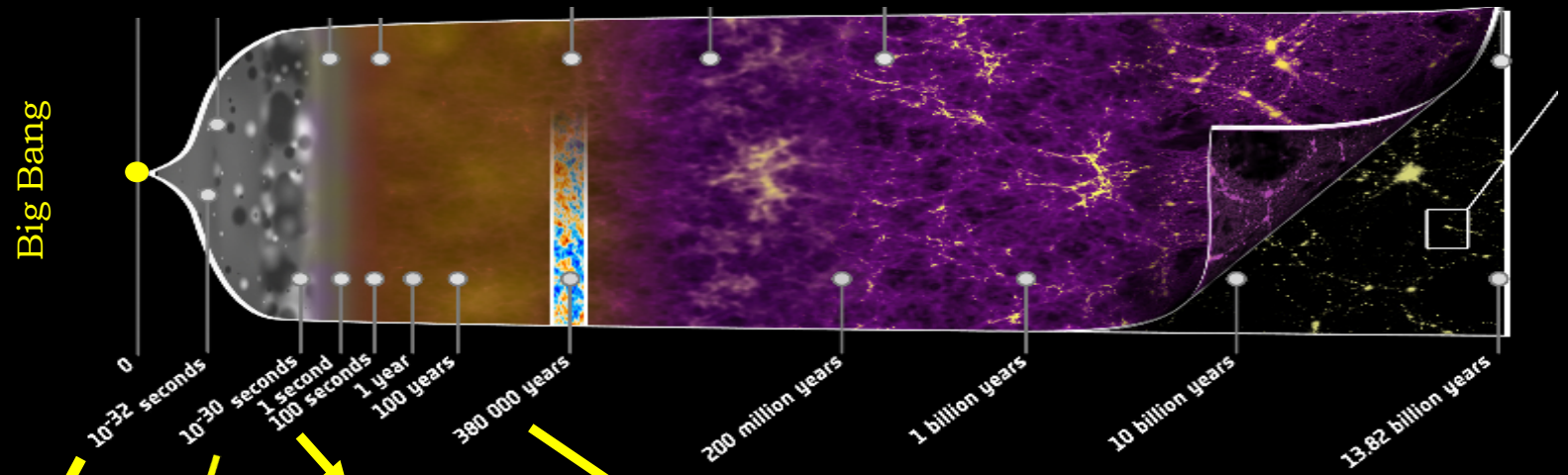
Free neutron's lifetime ≈ 15 minutes

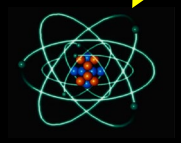
$$n \rightarrow p + e^- + \bar{\nu}_e$$



Primordial Nucleosynthesis







atom

orange

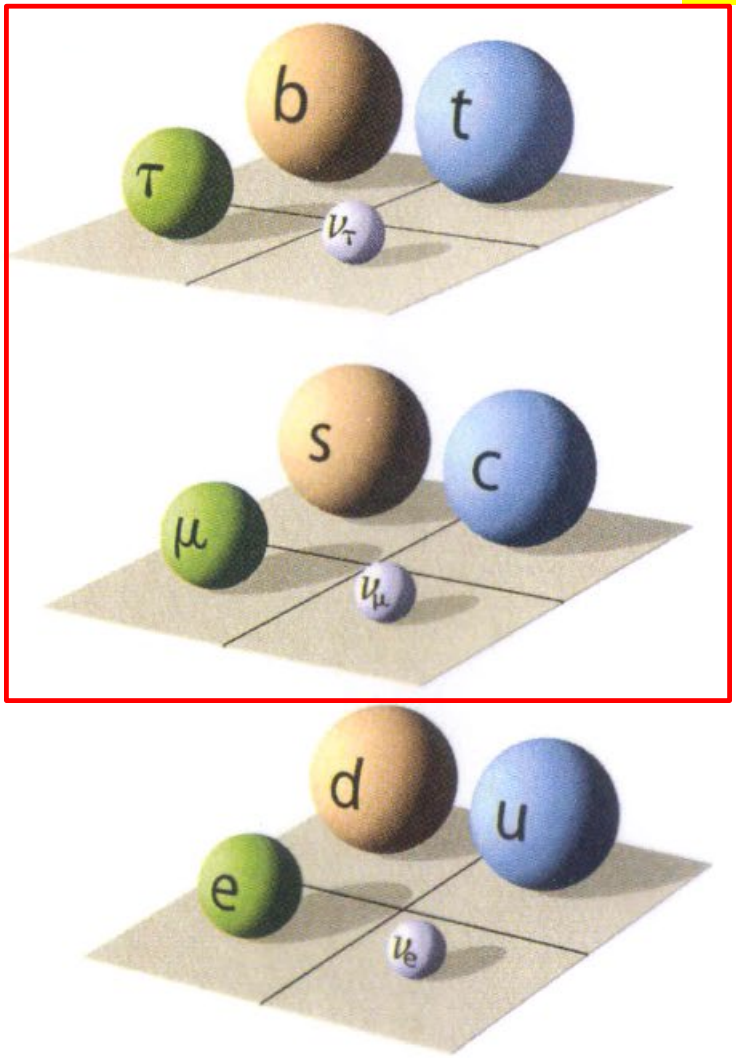
Solar system

800 galaxies

Billion = milliard

TODAY

The standard model



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Conservation Laws

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Baryonic number B	✓	✓	✓
Flavor	✓	✓	✗
Charge Conjugation			
Parity			

Charge Conjugation Operator : C

particules → antiparticules

$$C|\pi^+> = |\pi^->$$

$$C|e^+> = |e^->$$

$$C|p> = |\bar{p}>$$

Eigen Values and Eigen States ?

Charge Conjugation Operator : C

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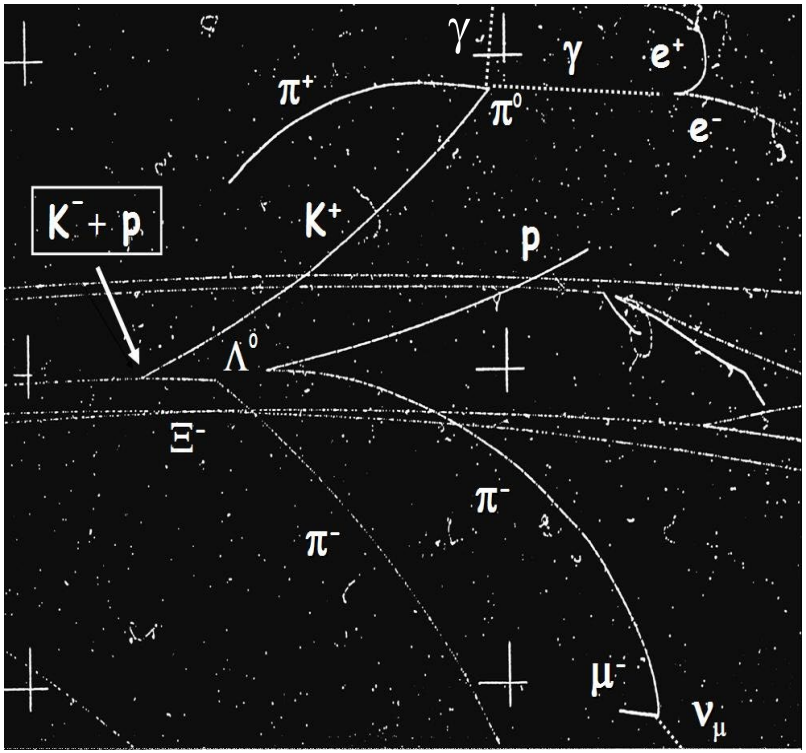
Eigen Values and Eigen States ?

$\eta_c = \pm 1$
(Charge Parity)

particules = antiparticules

$|\pi^0>$, $|J/Psi>$, $|\gamma>$, $|\phi>$, ...

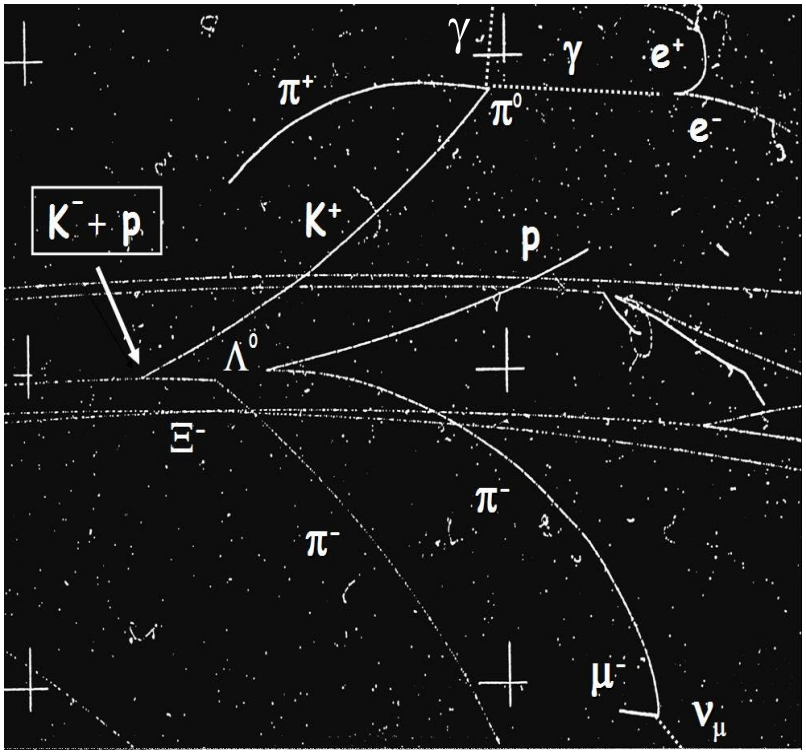
Charge Conjugation Operator : C



$$\pi^0 \rightarrow \gamma + \gamma$$

$$\eta_c(\gamma) = -1 \longrightarrow \eta_c(\pi^0) = +1$$

Charge Conjugation Operator : C



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Selection rule

$$\pi^0 \rightarrow \gamma + \gamma + \gamma$$ impossible

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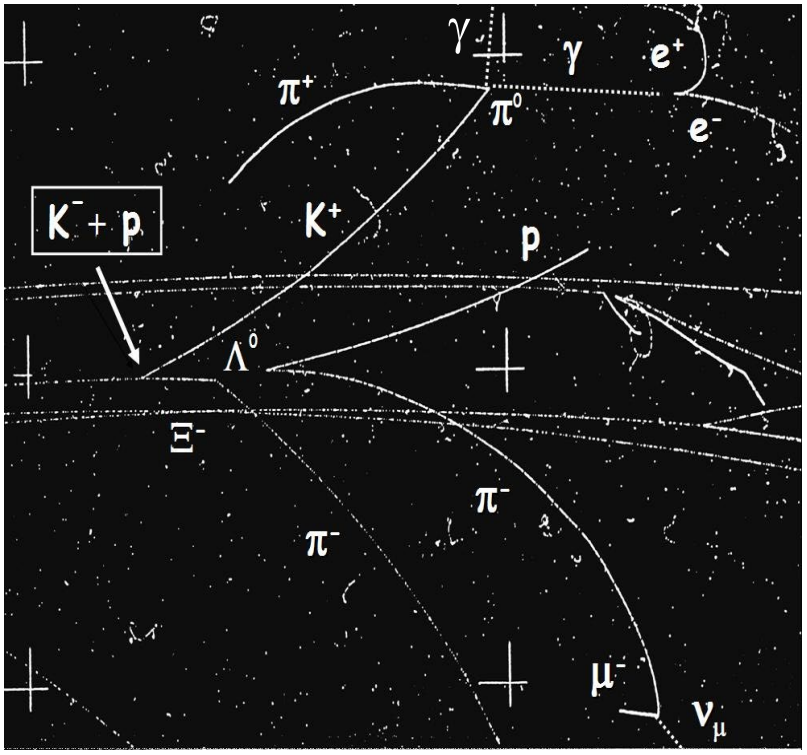

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Selection rule

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C ?

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Weak disintegration
Equivalent reactions

Charge Conjugation Operator : C

particules → antiparticules

$$C|\pi^+> = |\pi^->$$

$$C|e^+> = |e^->$$

$$C|p> = |\bar{p}>$$

$$[C, H_{strong}] = 0 \qquad [C, H_{electro.}] = 0 \qquad [C, H_{weak}] \neq 0$$

Eigen Values and Eigen States

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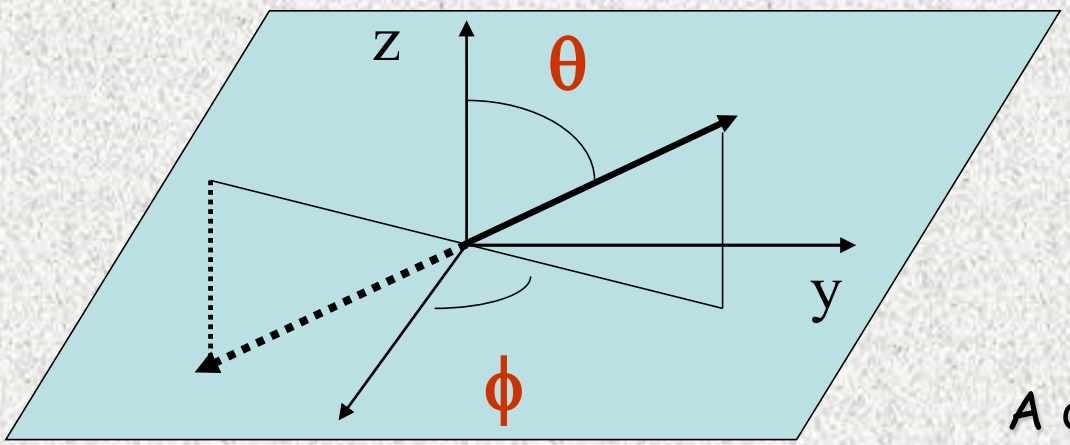
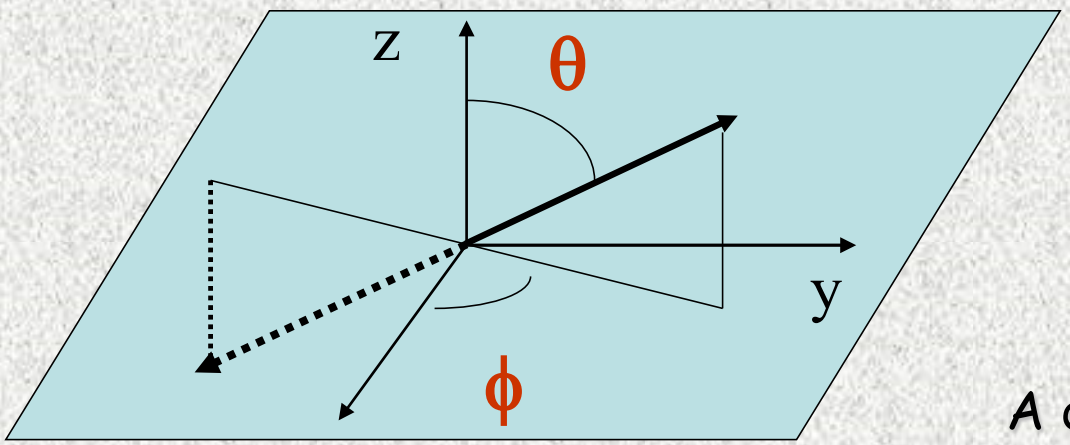


Parity Operator

$$P = P^{+} = P^{-1}$$

Eigen values $\eta = \pm 1$

A discrete symmetry operator



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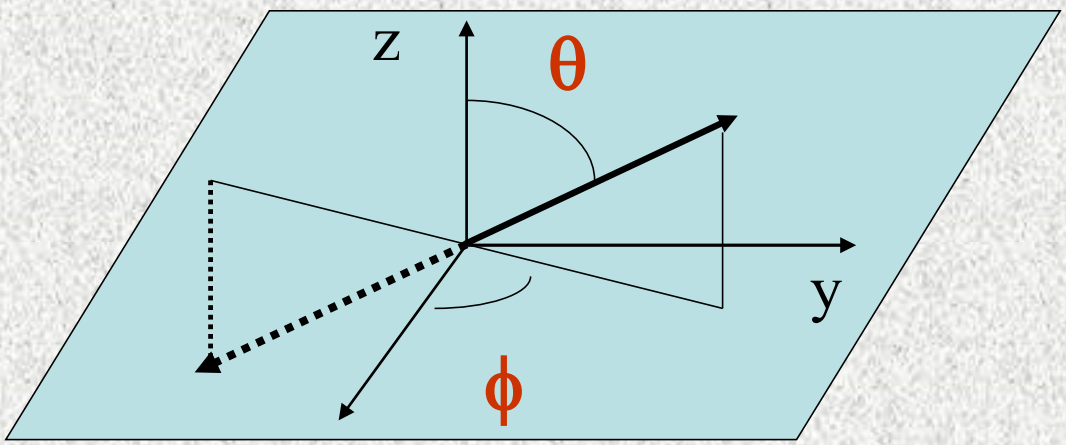
For many particules $P = P_1 \otimes P_2 \otimes P_3 \otimes \ldots$

η is a multiplicative quantum number → $\eta = \eta_1 \eta_2 \eta_3 \ldots$



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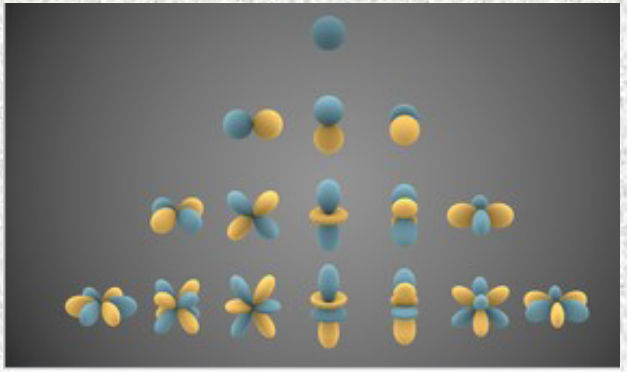
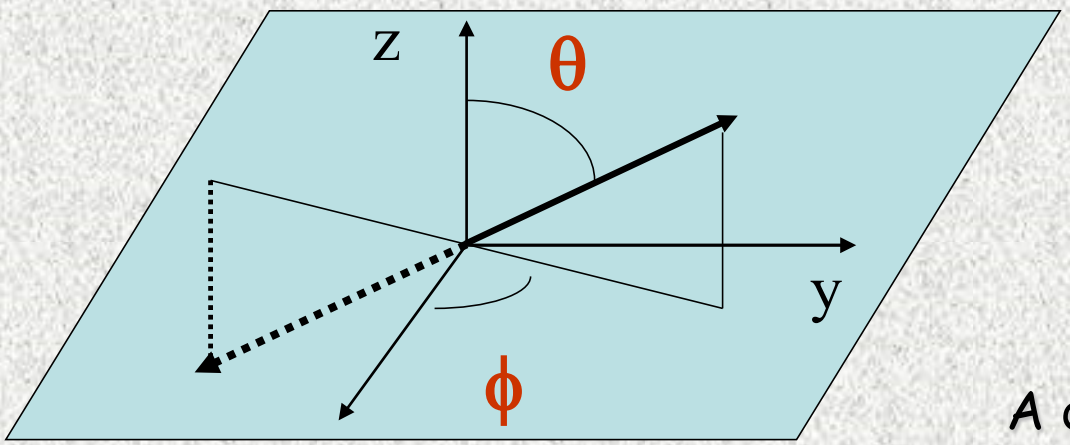


Visual representations of the first few real spherical harmonics. Blue portions represent regions where the function is positive, and yellow portions represent where it is negative The distance of the surface from the origin indicates the absolute value of $Y_\ell^m(\theta,\varphi)$ in angular direction (θ,φ).

Total parity for a system of 2 particles (a, b) $\eta_{tot} = \eta_a \eta_b (-1)^l$

Intrinsic Parity (a,b), l is the relative orbital angular momentum



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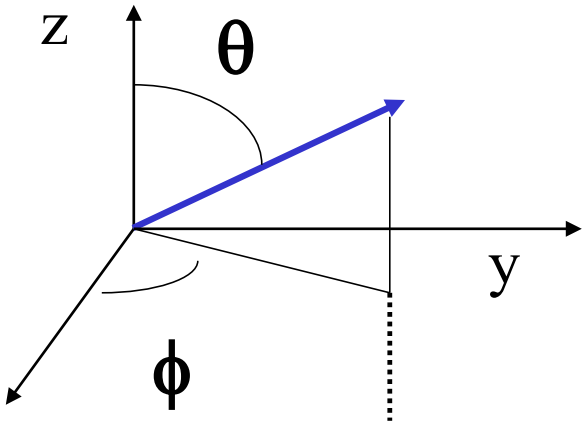
$[H, P] = 0$ → Parity conservation, η has a constant value

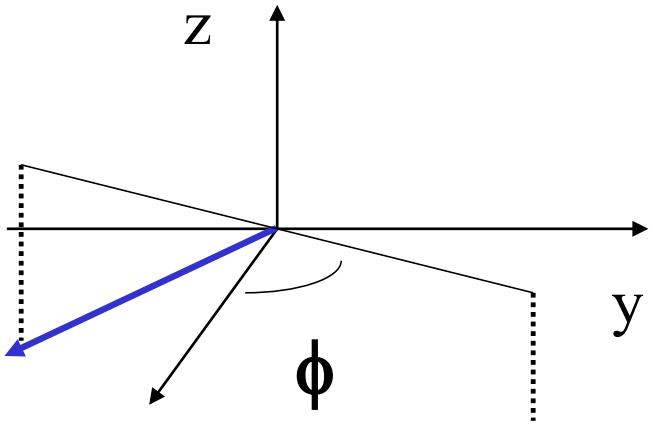
Real Vectors

Position $\vec{r}$

Momentum $\vec{p}$



Parity



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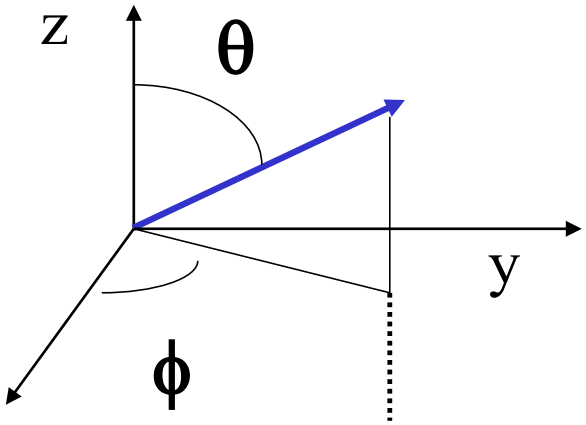
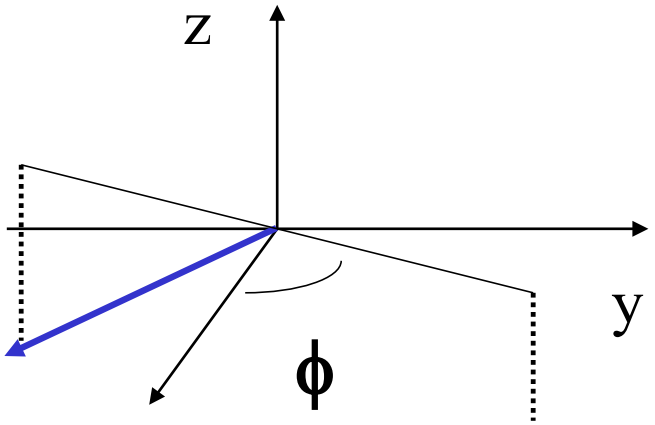


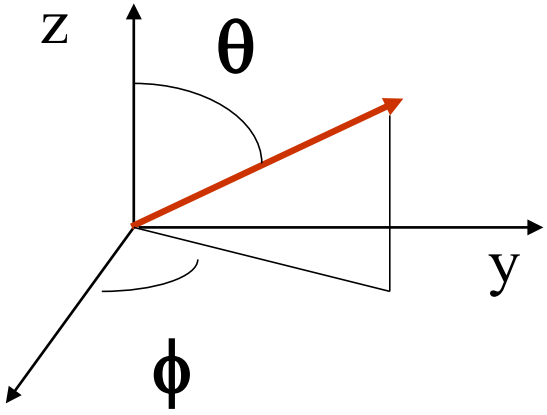
Parity



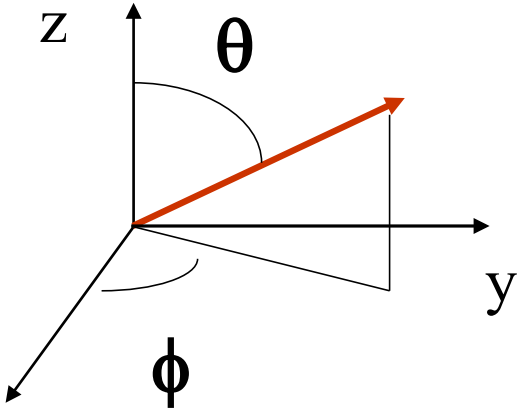
Pseudo Vectors

Magnetic Field $\vec{B}$

Angular Momentum $\vec{J}$

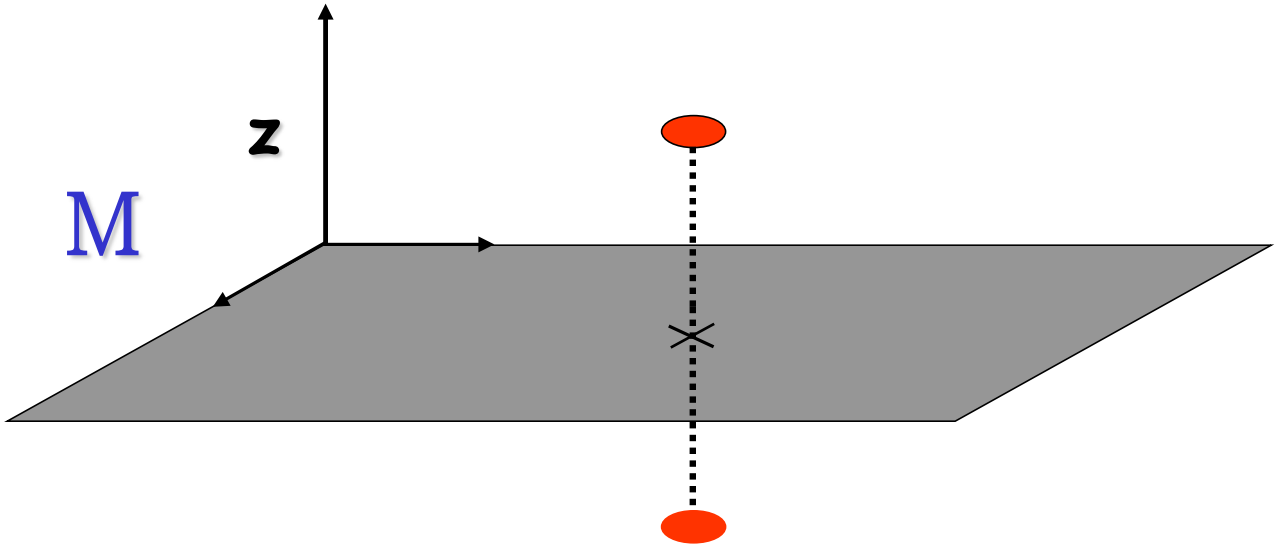


Parity

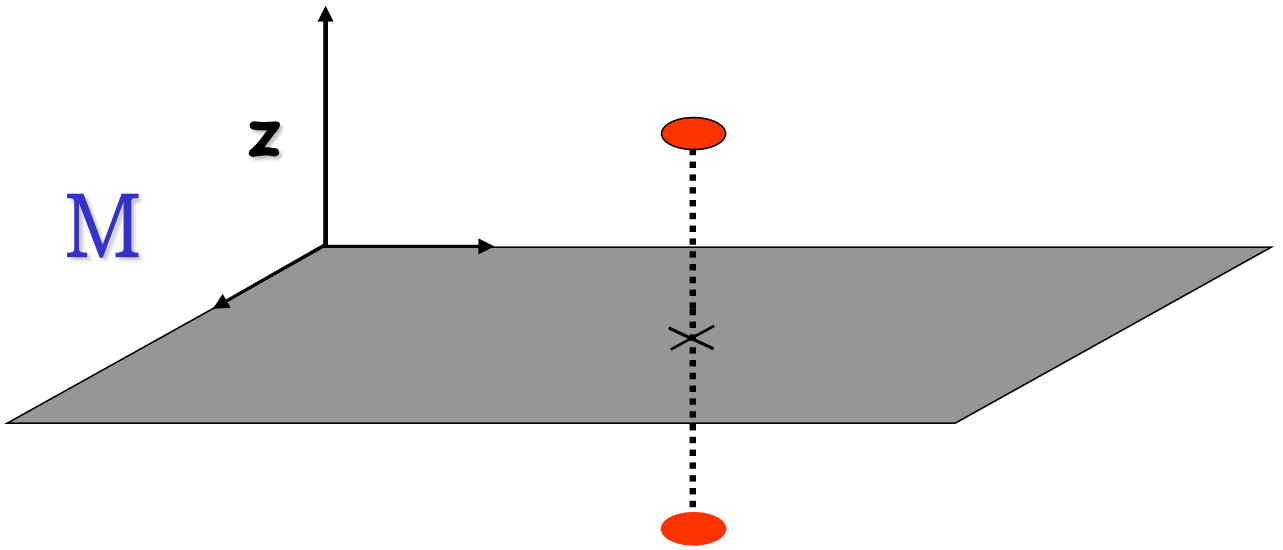


(pseudovecteurs)

Mirror operation with respect to a plane ("mirror")



Mirror operation with respect to a plane ("mirror")



The parity operator can be defined as the product of the symmetry operator with respect to a plane and a rotation of an angle π around the axis (Oz)

$$P = e^{-i\pi J_z/\hbar} \cdot M$$

As systems are generally rotation invariant, the operations P and M are equivalent

The rules for intrinsic parity

data

$\eta_\pi = -1 \qquad \eta_\gamma = -1$

$\eta_p = +1 \qquad \eta_n = +1$

arbitrarily set values

The rules for intrinsic parity

data

$\eta_\pi = -1 \quad \eta_\gamma = -1$

$\eta_K = -1$, ...

$\eta_p = +1 \quad \eta_n = +1$

arbitrarily set values

$\eta_\Lambda = +1$, ...

$\eta_q = +1$

$\eta_{\bar{x}} = -\eta_x$

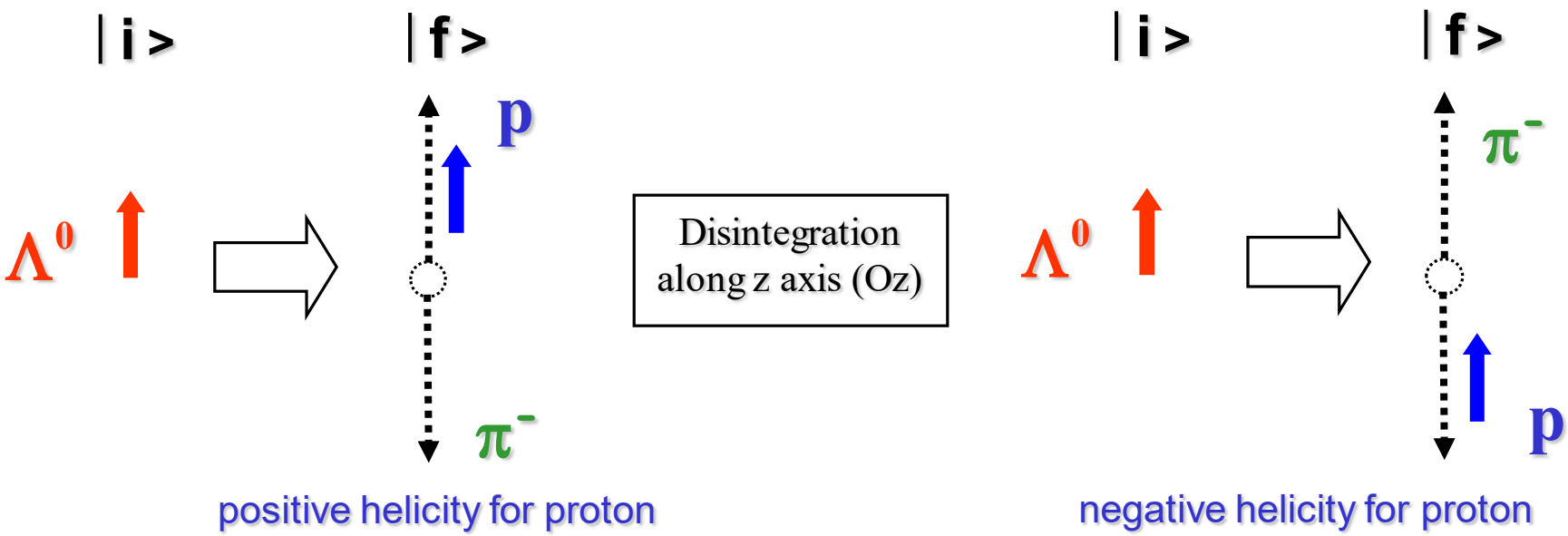
Spin half integer (fermions)

$\eta_{\bar{x}} = \eta_x$

Spin integer (bosons)

Symmetry breaking in weak interactions

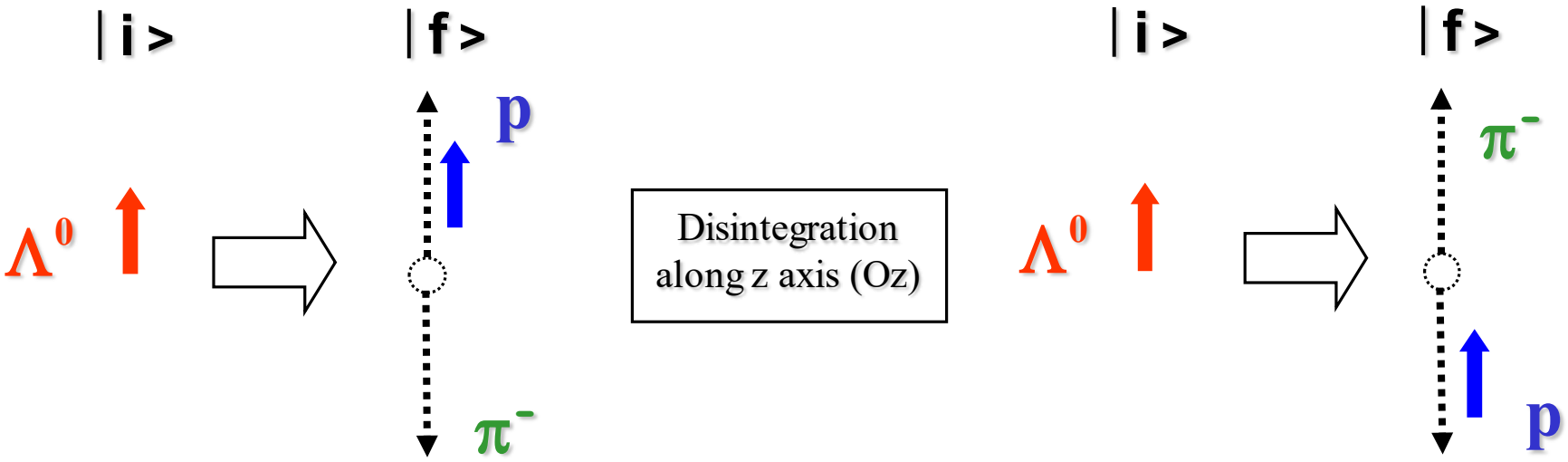
$\Lambda^0 \rightarrow p + \pi^-$



positive helicity for proton

negative helicity for proton

$\Lambda^0 \rightarrow \quad p + \pi^-$



positive helicity for proton

negative helicity for proton

Transition amplitude

$a = \langle f | i \rangle \rightarrow$ proba. $= |a|^2$

Transition amplitude

$b = \langle f | i \rangle \rightarrow$ proba. $= |b|^2$

$\Lambda^0 \rightarrow \quad p + \pi^-$

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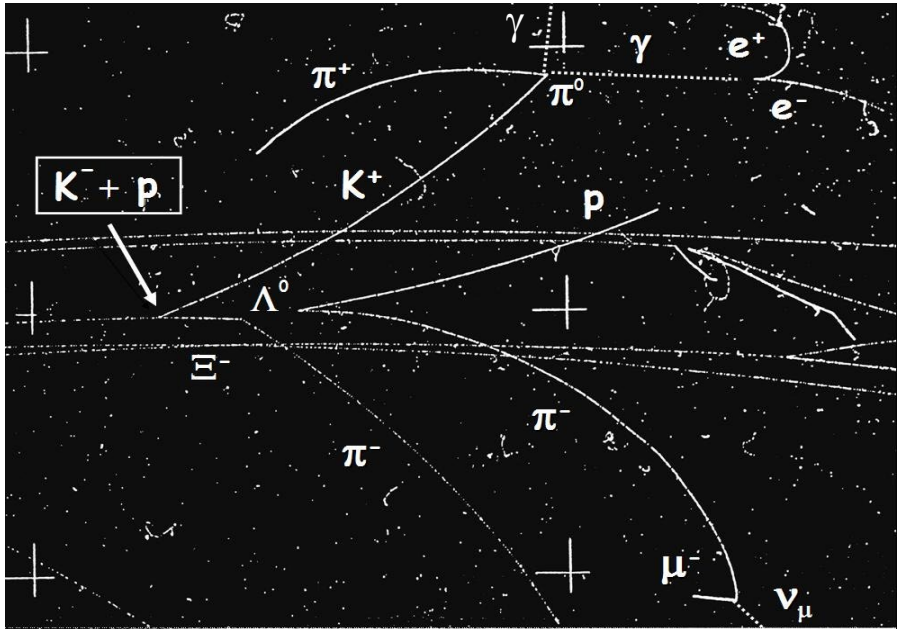
Transition amplitude

$b = \langle f | i \rangle \rightarrow$ proba. $= |b|^2$

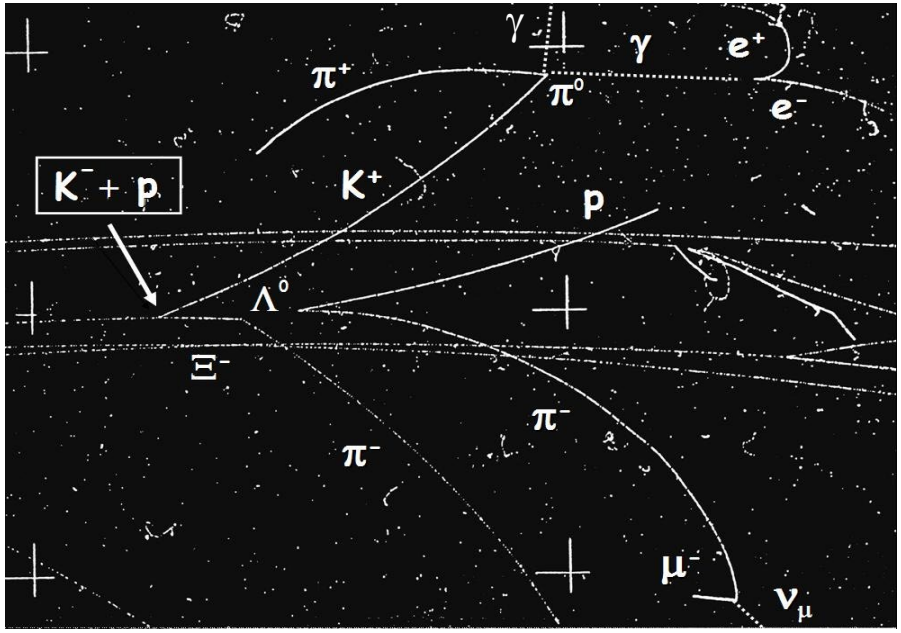
Parity conservation $[H_{weak}, P] = 0 \rightarrow |a|^2 = |b|^2$



Probability of finding the proton at θ

$$W(\theta) = |a|^2 \cos^2(\theta/2) + |b|^2 \sin^2(\theta/2)$$

$$W(\theta) = \frac{[|a|^2 + |b|^2]}{2} + \frac{[|a|^2 - |b|^2]}{2} \cos(\theta)$$



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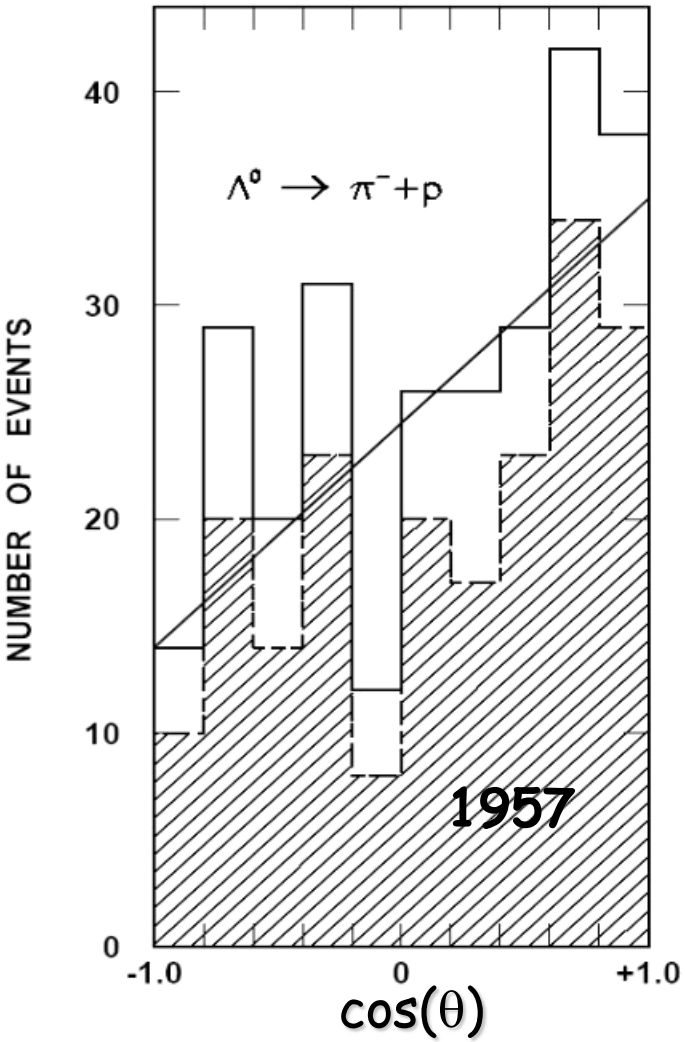
Parity Conservation → $W = [|a|^2 + |b|^2]$

No angular dependency !

Parity Conservation ?

$\Lambda^0 \rightarrow p + \pi^-$

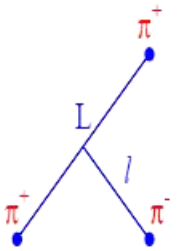


Weak interactions do not conserve parity

A little bit of history …

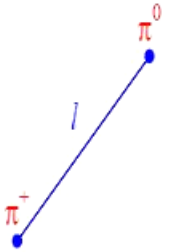
Puzzle τ–θ (T.D. Lee, C.N. Yang 1956)

$\tau^+ \to \pi^+\pi^+\pi^-$



$\eta = \eta_\pi^3(-1)^{l+L}$

$\theta^+ \to \pi^+\pi^0$



$\eta = \eta_\pi^2(-1)^l$

π spin=0 parity= -1

τ, θ spin=0, same mass, same lifetime

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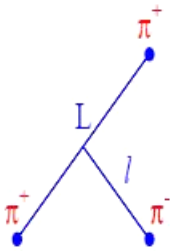

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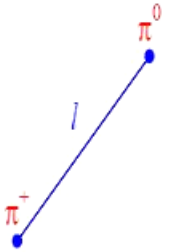


$$\eta = \eta_\pi^2(-1)^{l}$$

π spin=0 parity= -1

τ, θ spin=0, same mass, same lifetime

Lee and Yang hypothesis

$$\tau = \theta \quad (K^+)$$

parité non conservée

Proposed verification

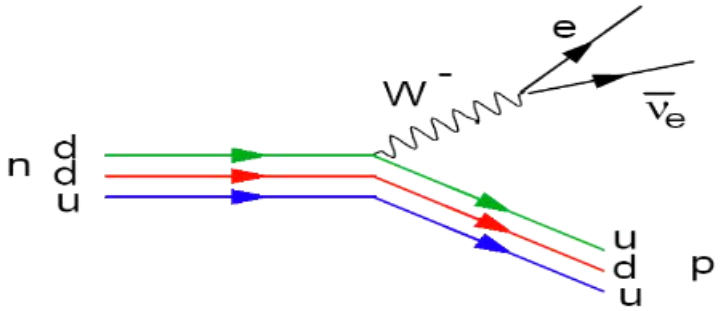
$$^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e^- + \bar{\nu}$$

$$\pi^- \to \mu^- + \nu_\mu$$
$$\mu^- \to \mathrm{e}^- + \bar{\nu}_\mathrm{e} + \nu_\mu$$

$$\Lambda \to \mathrm{p} + \pi^-$$

Hypothesis juin 1956

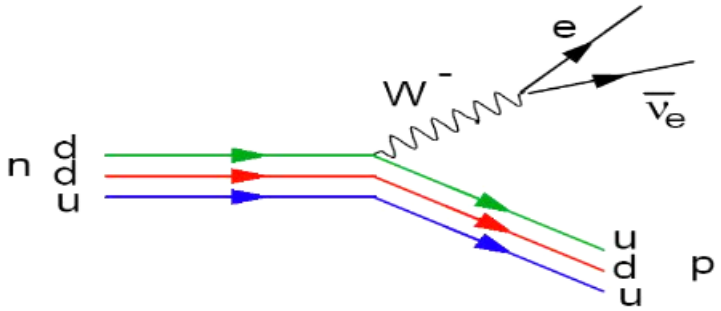
Verifications
- ^{60}Co janvier 1957
- $\pi \to \mu \to$ e janvier 1957
- $\Lambda \to \mathrm{p} + \pi^-$ octobre 1957



1957

$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu}$$

Spin



1957

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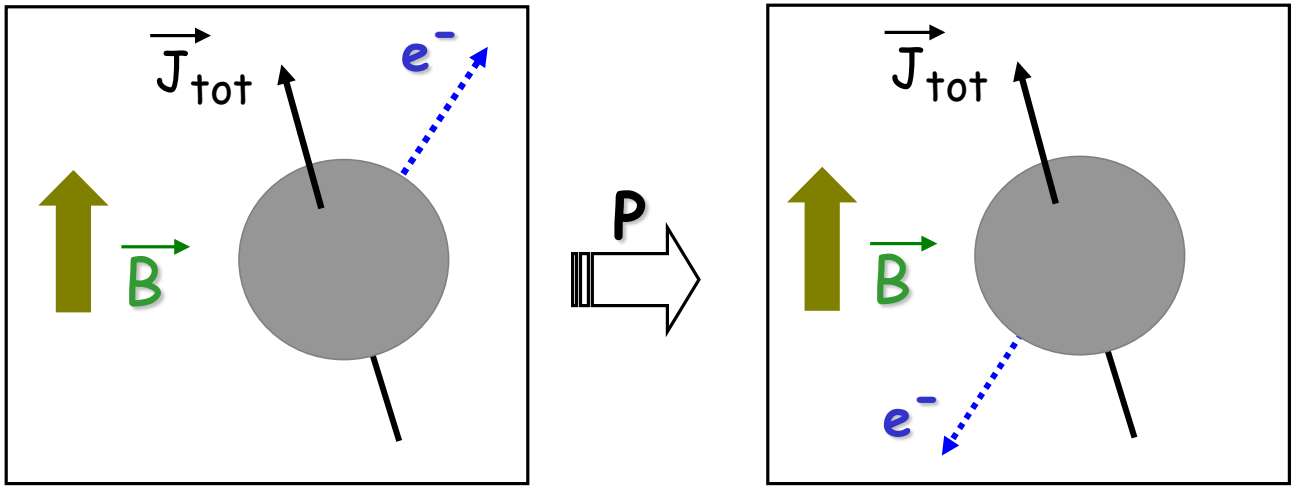

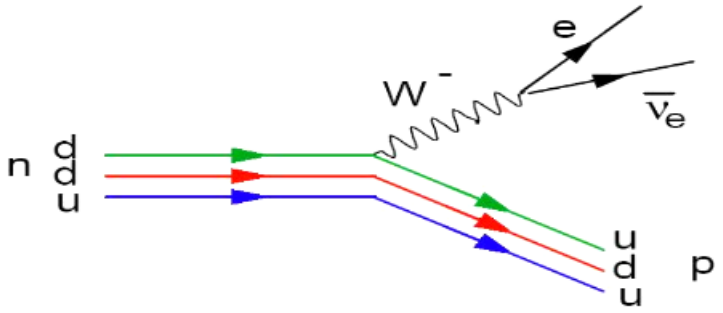

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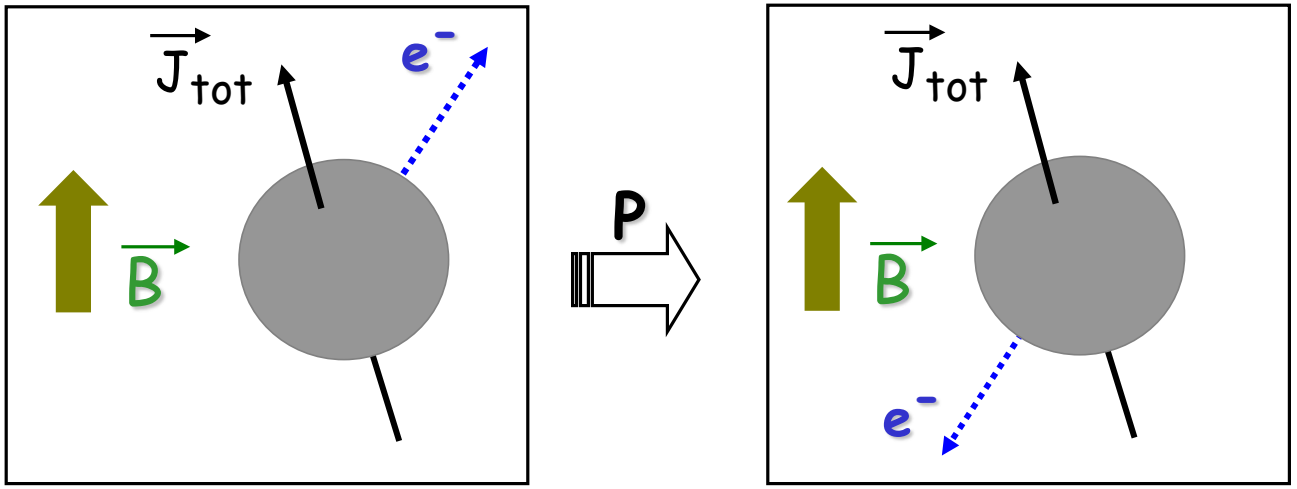
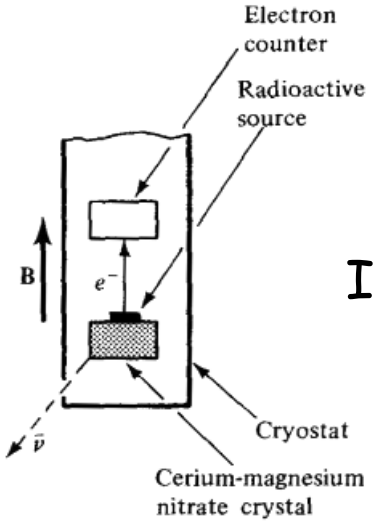
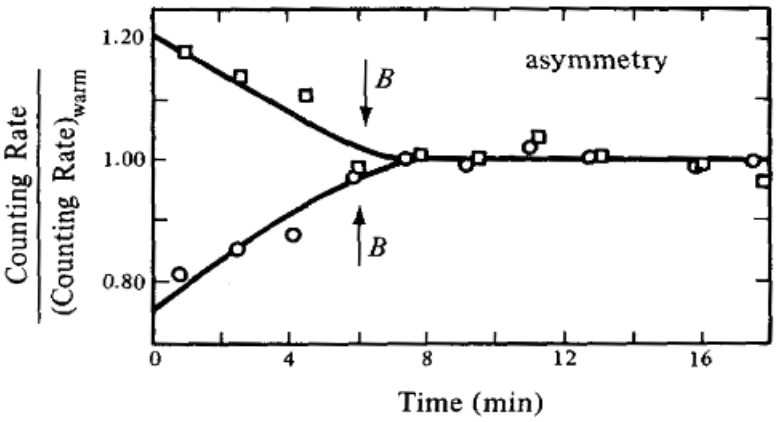




$$I(\theta) = 1 - \beta\cos(\theta)$$



Conservation Laws

Conserved quantities	Strong	Electro.	Weak
Energy-Momentum	✓	✓	✓
Angular momentum	✓	✓	✓
Electrical charge	✓	✓	✓
Leptonic number (L_e, L_μ, L_τ)	✓	✓	✓
Baryonic number B	✓	✓	✓
Flavor	✓	✓	✗
Charge Conjugation	✓	✓	✗
Parity	✓	✓	✗

Electoweak theory in the standard model

First interaction

quantas : W^+, W^-, W^0

100% of non conservation of parity

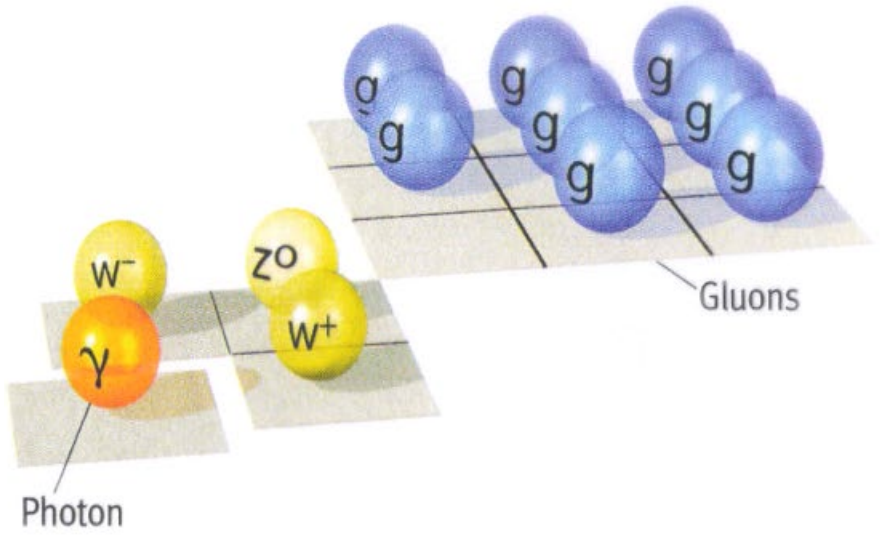
Second interaction

quantum : B^0

some non conservation of parity

Interaction mixing

$$|\gamma\rangle = \sin\theta_W|W^0\rangle + \cos\theta_W|B^0\rangle$$
$$|Z^0\rangle = \cos\theta_W|W^0\rangle - \sin\theta_W|B^0\rangle$$



Results

Electromagnetism	γ	Parity conservation
Weak	$W^{\pm}$	100% parity violation
Weak	Z^0	Parity violation

Quanta forces

Measurement of neutrino helicity

$$Eu + e^- \rightarrow Sm^* + \nu$$
$$Sm^* \rightarrow Sm + \gamma$$

$$\lambda_\nu = -\frac{1}{2}\hbar$$

1958

Eu, Europium Z=63 (isotope)
Sm, Samarium Z =62

Measurement of neutrino helicity

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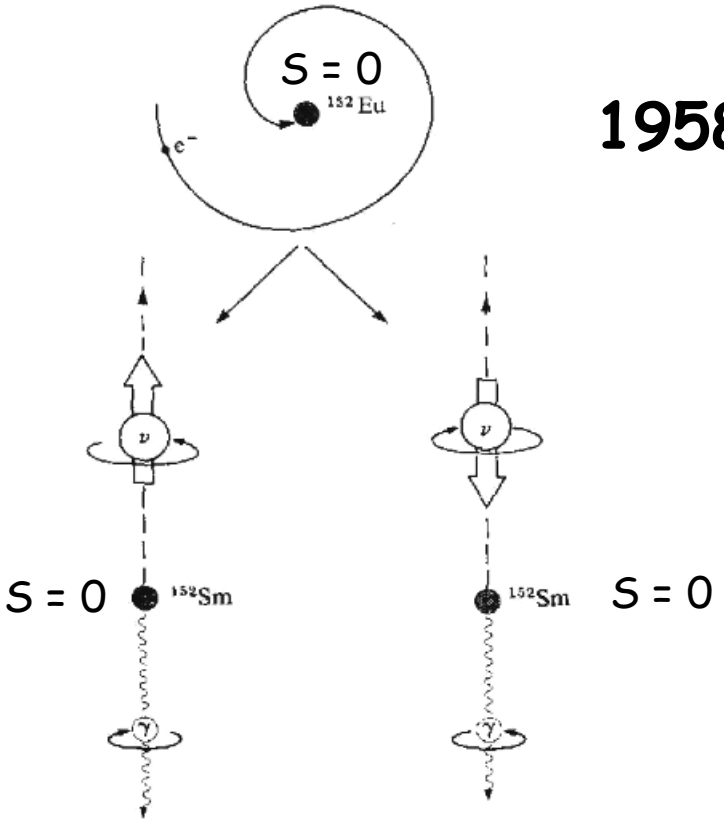
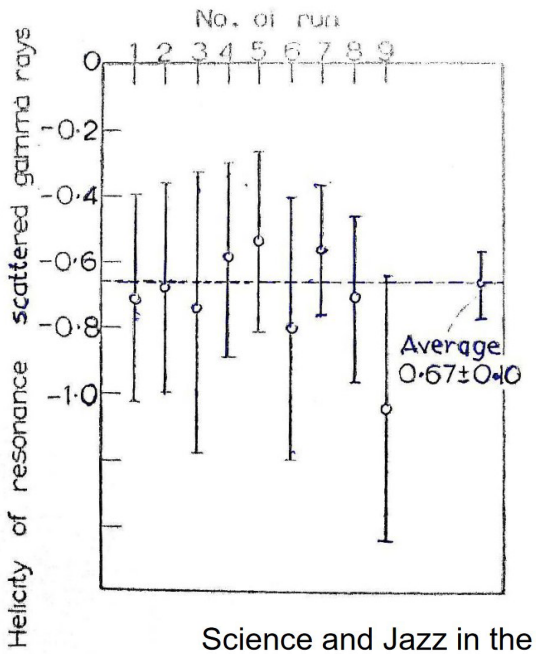


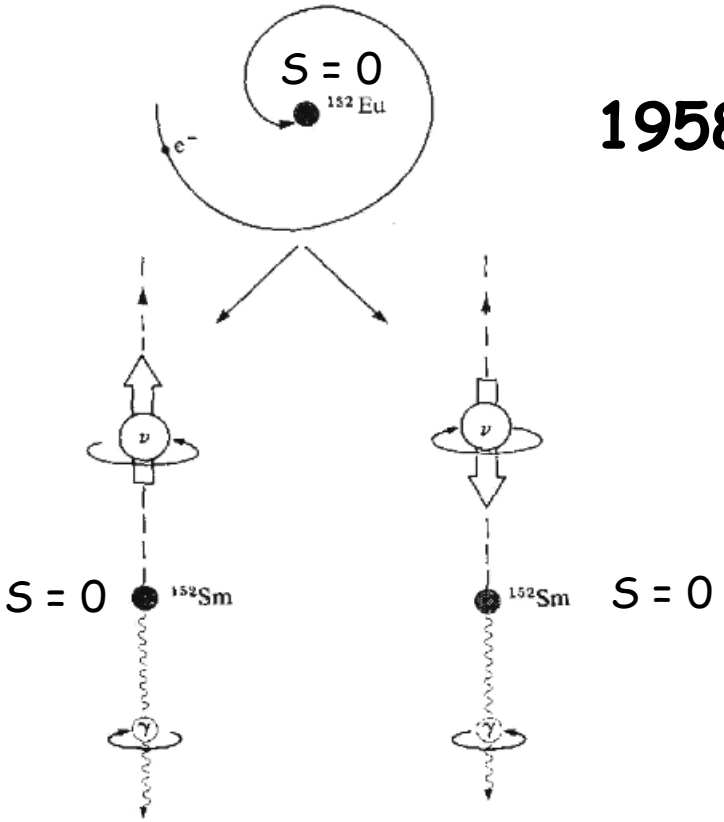
1958

Measurement of neutrino helicity

The Helicity of the 963 γ-ray is Negative



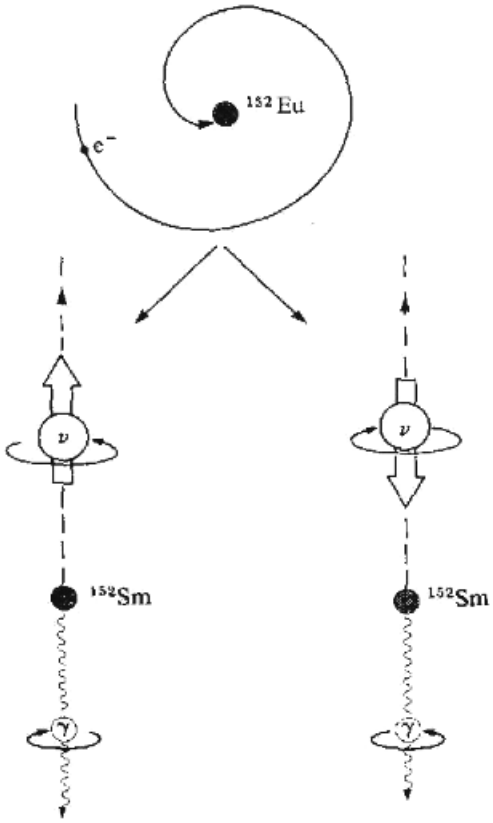
Science and Jazz in the NY Daily News
Sunday September 21, 1958



1958

Measurement of neutrino helicity

?



1958

Never observed **Observed**

always negative !

Lesson 7

Conservation Laws

Conserved quantities	Strong	Electro.	Weak
Energy-Momentum	✓	✓	✓
Angular momentum	✓	✓	✓
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