Announcements

- HW6 due, Mon, 5 pm
- Review, 235 ISB, Wed, 10-12 am
- Final, 235 ISB, Fri, noon-3 pm
- Bring calculator and book, open-book and open-notes

Lecture 20 Topics

Elementary particle physics

- Forces
- Particles
- Conservation rules in particle decay
- Low energy symmetry breaking in weak force

Underlying ideas in physics

- Scale: temporal and spatial
- Energy
- Conservation and Symmetry

Forces

TABLE 12.1 Fundamental forces and particles

Force	Gravitation	Electroweak			Strong	Residual
Property	Mass/energy	Charge/weak charge			Color charge	
Strength	$\sim 10^{-39}$	$\sim 10^{-2}$	$\sim 10^{-6}$		1	
Range	$1/r^2$	$1/r^2$	10^{-3} fm		short	1 fm
Mediating Bosons	Graviton?	Photon, γ	W^+, W^-	Z^0	Gluon	$\pi^{\pm}, \pi^0$
Spin	2?	1	1	1	1	0
Mass	0?	$< 6 \times 10^{-22}$	80.4×10^3	91.2×10^3	< 10	140, 135
Charge	—	0	+1, −1	0	0	$\pm 1, 0$
Color charge	—	—	—	—	r, g, or b + $\bar{r}$, $\bar{g}$, or $\bar{b}$	Neutral

$$\Delta x \approx c\Delta t \approx \frac{\hbar}{c}\frac{1}{m}$$

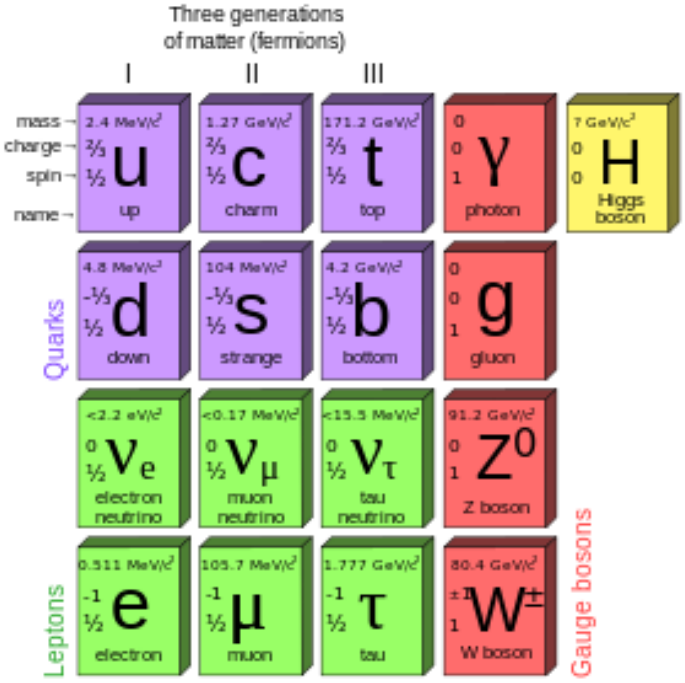
- When the mediating particle has mass
- When it doesn't

Elementary particles

Three classes of particles:

- Six quarks → strong force
- Six leptons → electroweak force
- Four mediating particles (bosons) called field quanta
  - → Graviton: gravitational force
  - → Photon: electromagnetic force
  - → W^+, W^-, Z^0: weak force
  - → Gluon: strong force between quark
  - → Pion: residual strong force betwee

- Particles experiencing forces (fermions
  - Mass/energy for gravitational force
  - Charge/weak charge for electrowea
  - Color charge for strong force



Quarks for Strong force

- Particles that experience strong force are Quarks
- Six types
  - Spin ½
  - Have different mass
  - Have different charge
  - Have all three color charge
  - Have antiparticles
  - Not separable

Quarks
Participants in gravitation, electroweak, and strong

	Spin	Mass	Charge	Color charge
Up, u	$\frac{1}{2}$	~5	$+\frac{2}{3}$	r, g, b
Down, d	$\frac{1}{2}$	~10	$-\frac{1}{3}$	r, g, b
Strange, s	$\frac{1}{2}$	~100	$-\frac{1}{3}$	r, g, b
Charm, c	$\frac{1}{2}$	$\sim 1.3 \times 10^3$	$+\frac{2}{3}$	r, g, b
Bottom, b	$\frac{1}{2}$	$\sim 4.5 \times 10^3$	$-\frac{1}{3}$	r, g, b
Top, t	$\frac{1}{2}$	$\sim 180 \times 10^3$	$+\frac{2}{3}$	r, g, b

- Proton (uud), Neutron (udd)

Hadrons

TABLE 12.2 Commonly produced hadrons

Baryons	Mass (MeV/c^2)	Spin	Strangeness	I, I_3	Lifetime, τ (or width $\hbar/\tau$)
p (uud)	938	$\frac{1}{2}$	0	$\frac{1}{2}, +\frac{1}{2}$	$>10^{32}$ yr
n (udd)	940	$\frac{1}{2}$	0	$\frac{1}{2}, -\frac{1}{2}$	889 s
Σ^+ (uus)	1189	$\frac{1}{2}$	−1	1, +1	8.0×10^{-11} s
Σ^0 (uds)	1193	$\frac{1}{2}$	−1	1, 0	7.4×10^{-20} s
Λ^0 (uds)	1116	$\frac{1}{2}$	−1	0, 0	2.6×10^{-10} s
Σ^- (dds)	1197	$\frac{1}{2}$	−1	1, −1	1.5×10^{-10} s
Ξ^0 (uss)	1315	$\frac{1}{2}$	−2	$\frac{1}{2}, -\frac{1}{2}$	2.9×10^{-10} s
Ξ^- (dss)	1321	$\frac{1}{2}$	−2	$\frac{1}{2}, -\frac{1}{2}$	1.6×10^{-10} s
Δ^{++} (uuu)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, +\frac{3}{2}$	120 MeV
Δ^+ (uud)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, +\frac{1}{2}$	120 MeV
Δ^0 (udd)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, -\frac{1}{2}$	120 MeV
Δ^- (ddd)	1232	$\frac{3}{2}$	0	$\frac{3}{2}, -\frac{3}{2}$	120 MeV
Σ^{*+} (uus)	1383	$\frac{3}{2}$	−1	1, +1	~40 MeV
Σ^{*0} (uds)	1384	$\frac{3}{2}$	−1	1, 0	~40 MeV
Σ^{*-} (dds)	1387	$\frac{3}{2}$	−1	1, −1	~40 MeV
Ξ^{*0} (uss)	1532	$\frac{3}{2}$	−2	$\frac{1}{2}, +\frac{1}{2}$	~10 MeV
Ξ^{*-} (dss)	1535	$\frac{3}{2}$	−2	$\frac{1}{2}, -\frac{1}{2}$	~10 MeV
Ω^- (sss)	1672	$\frac{3}{2}$	−3	0, 0	8.2×10^{-11} s

Mesons	Mass (MeV/c^2)	Spin	Strangeness	I, I_3	Lifetime, τ (or width $\hbar/\tau$)
$\pi^+(u\bar{d})$	140	0	0	1, +1	2.6×10^{-8} s
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$\pi^-(d\bar{u})$	140	0	0	1, −1	2.6×10^{-8} s
$K^+(u\bar{s})$	494	0	+1	$\frac{1}{2}, +\frac{1}{2}$	1.2×10^{-8} s
$K^0_S(d\bar{s}, s\bar{d})$	498	0	mix	$\frac{1}{2}$, mix	8.9×10^{-11} s
$K^0_L(d\bar{s}, s\bar{d})$	498	0	mix	$\frac{1}{2}$, mix	5.2×10^{-8} s
$K^-(s\bar{u})$	494	0	−1	$\frac{1}{2}, -\frac{1}{2}$	1.2×10^{-8} s
$\rho^+(u\bar{d})$	769	1	0	1, +1	151 MeV
$\rho^0(u\bar{u} + d\bar{d})$	769	1	0	1, 0	151 MeV
$\rho^-(d\bar{u})$	769	1	0	1, −1	151 MeV
$K^{*+}(u\bar{s})$	892	1	+1	$\frac{1}{2}, +\frac{1}{2}$	50 MeV
$K^{*0}(d\bar{s})$	896	1	+1	$\frac{1}{2}, -\frac{1}{2}$	51 MeV
$\overline{K^{*0}}(s\bar{d})$	896	1	−1	$\frac{1}{2}, +\frac{1}{2}$	51 MeV
$K^{*-}(s\bar{u})$	892	1	−1	$\frac{1}{2}, -\frac{1}{2}$	50 MeV
Heavy mesons—containing quarks beyond the strange					
$J/\psi\ (c\bar{c})$	3100	1	0	0, 0	87 keV
$\Upsilon\ (b\bar{b})$	9460	1	0	0, 0	~50 keV

50 MeV corresponds to a lifetime of 10^{-23} second

Hadrons: Intrinsic properties

- Spin:
  - Three quarks → ½ or 3/2
  - Two quarks → 0 or 1
- Isospin(I):
  - Up and down quarks' Isospin = ½
  - Strange quark's Isospin = 0
- Strangeness (S):
  - The number of strange quarks
  - When having one strange quark, S=-1, two S=-2
  - When having one antistrange quark, S=+1

Leptons

-Leptons do not have color charge
-Electron, muon, and tauon have charge and are very much alike except their mass.
-Leptons have spin 1/2 .
-Leptons have antiparticles.

Leptons
Participants in gravitation and electroweak

	Spin	Mass	Charge
Electron, e	$\frac{1}{2}$	0.511	−1
e-neutrino, ν_e	$\frac{1}{2}$	$< 10^{-5}$	0
Muon, μ	$\frac{1}{2}$	106	−1
μ-neutrino, ν_μ	$\frac{1}{2}$	< 0.2	0
Tauon, τ	$\frac{1}{2}$	1.78×10^3	−1
τ-neutrino, ν_τ	$\frac{1}{2}$	< 20	0

Conservation rules

TABLE 12.4 Some conservation rules

Conserved? / Interaction	Momentum, Energy, Angular Momentum, Charge, Color	Baryon Number (B)	Lepton Numbers* (L_e, L_μ, L_τ)	Strangeness	Parity (P)	Charge Conjugation (C)	Time Reversal (T)
Strong	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Electromagnetic	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak	Yes	Yes	Yes	No	No	No	No

* Recent evidence indicates some exceptions.

Energy: decay products' energy cannot be higher than initial particle's energy
Spin
Charge
Strangeness: +1 for one antistrange quark, -1 for one strange quark
Baryon Number: +1 for a baryon, -1 for an antibaryon, 0 for nonbaryons.
Lepton Number: Separately done for electron, muon, and tauon. 1 for each electron and electron neutrino and -1 for each corresponding antiparticle

Quarks
Participants in gravitation, electroweak, and strong

	Spin	Mass	Charge	Color charge
Up, u	$\frac{1}{2}$	~5	$+\frac{2}{3}$	
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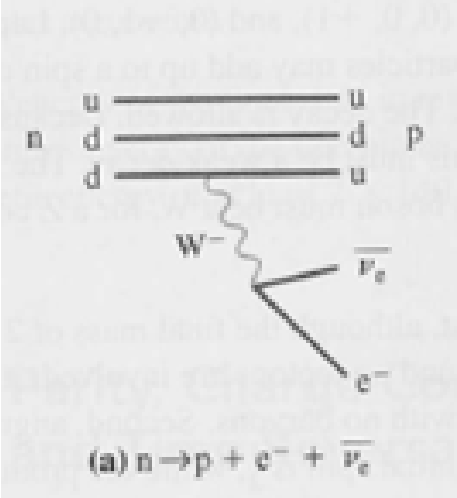
Decay Possible?

Mass=940
Charge = 0
Spin=1/2
Strangeness=0
Baryon number=1
Lepton number (e)=0



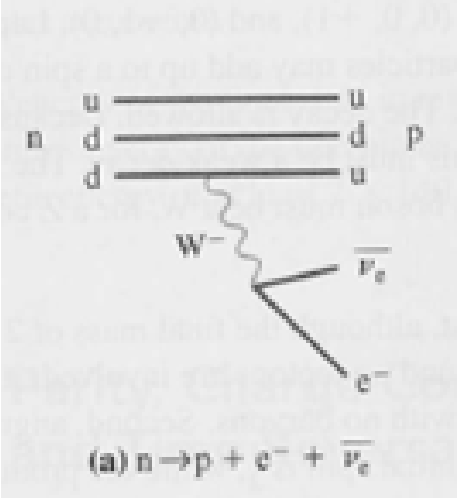
Mass=938
Spin=1/2
Charge = +1
Strangeness=0
Baryon number=1
Lepton number=0

Mass=0
Spin=1/2
Charge = -1
Strangeness=0
Baryon number=0
Lepton number=-1

Mass=0.51
Spin=1/2
Charge = 0
Strangeness=0
Baryon number=0
Lepton number=1

Decay Possible?

Mass=940
Charge = 0
Spin=1/2
Strangeness=0
Baryon number=1
Lepton number (e)=0



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Lepton number=0

Mass=0
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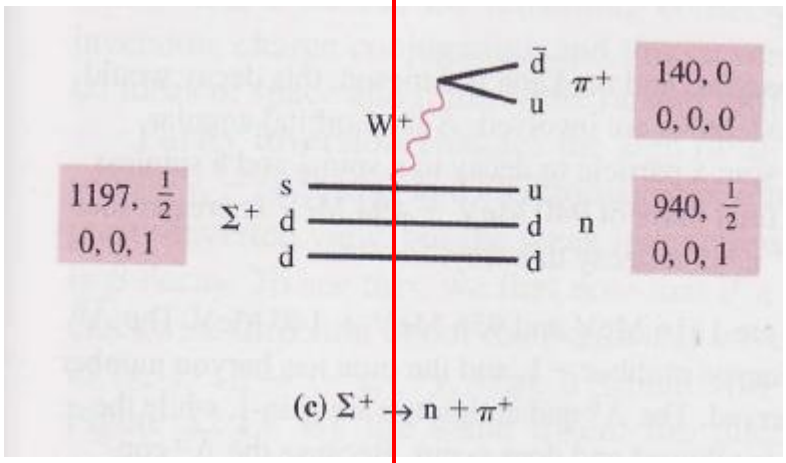
Charge = -1
Strangeness=0
Baryon number=0
Lepton number=-1

Strangeness not conserved in weak decay
Some flexibility in angular momentum

Mass=0.51
Spin=1/2
Charge = 0
Strangeness=0
Baryon number=0
Lepton number=1

Mass, S, charge
L(e), L(μ), B



Strangeness = -1

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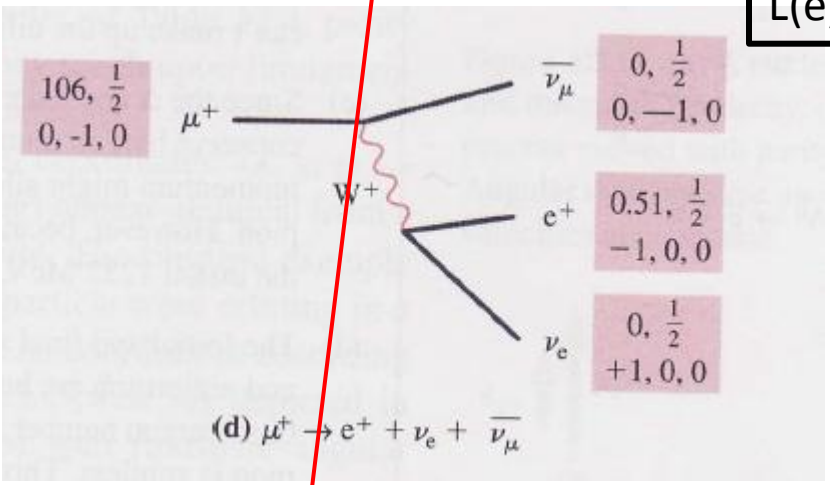

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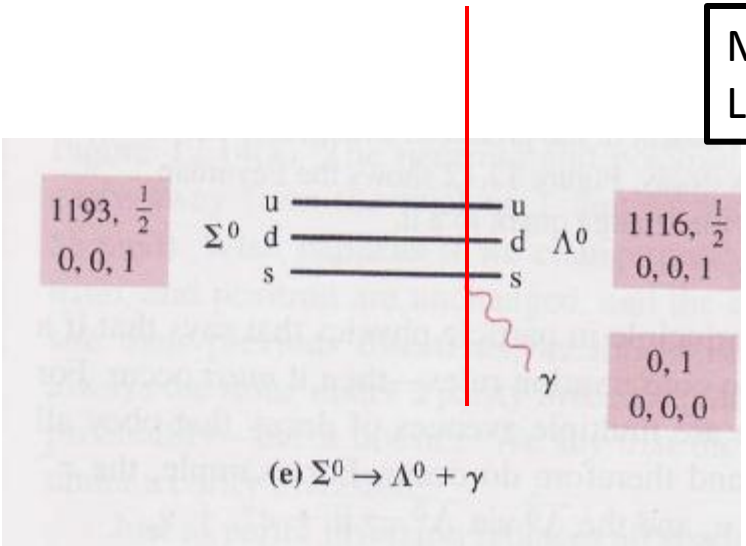

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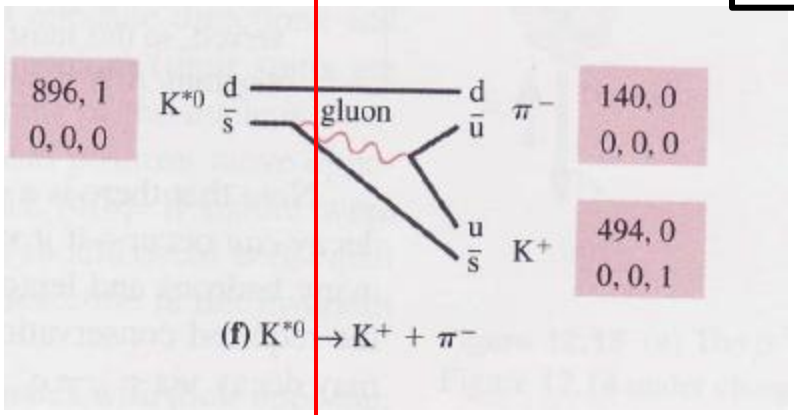

Strangeness = +1

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Mass, S, charge
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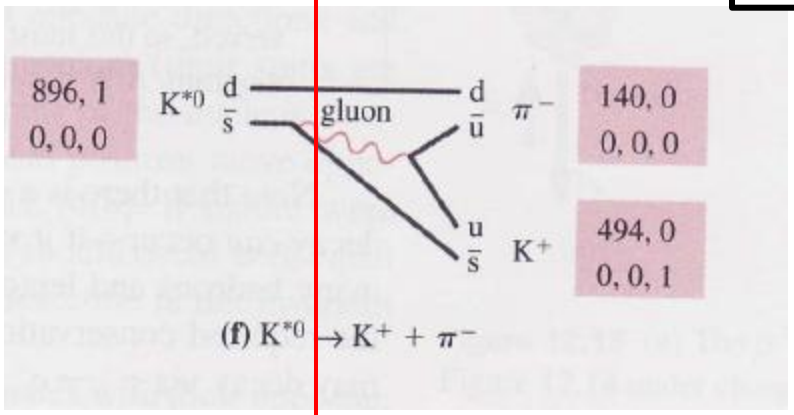

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Spin?

Conservation rules

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Lepton Number: Separately done for electron, muon, and tauon. 1 for each electron and electron neutrino and -1 for each corresponding antiparticle

Symmetry breaking in weak interactions

Three symmetry operations:

-P: Parity inversion (x, y, z) → (-x, -y, -z)

-C: Charge conjugation particles → anti-particles

-T: Time reversal t → - t

CPT theorem: under combined operations, all interactions are invariant

Symmetry breaking in weak interactions

Three symmetry operations:

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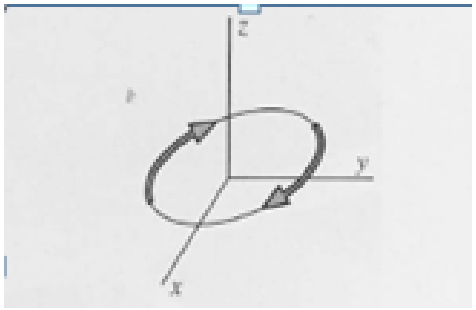
CPT theorem: under combined operations, all interactions are invariant

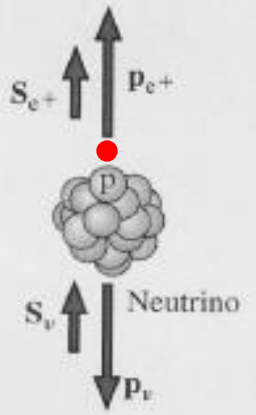
Parity inversion does not change spin direction



Symmetry breaking in weak interactions

$${}^{A}_{Z}X(parent) \rightarrow {}^{A}_{Z-1}Y(daughter) + {}^{0}_{+1}\beta^{+} + \nu$$

Figure 12.14 (a) A nucleus losing 1 unit of spin in β^+ decay. (b) The process viewed with parity reversed. Angular momenta are unchanged, but velocities are opposite.



(a)

Apply Parity Inversion

Symmetry breaking in weak interactions

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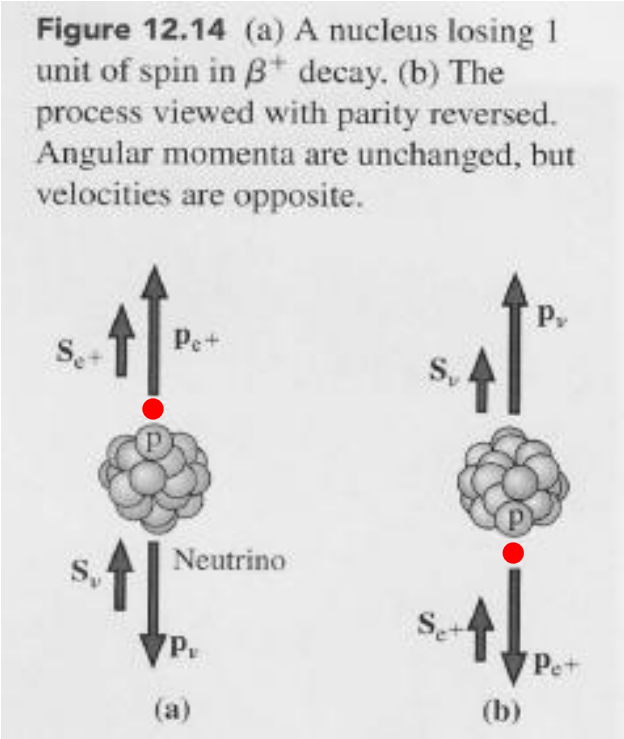

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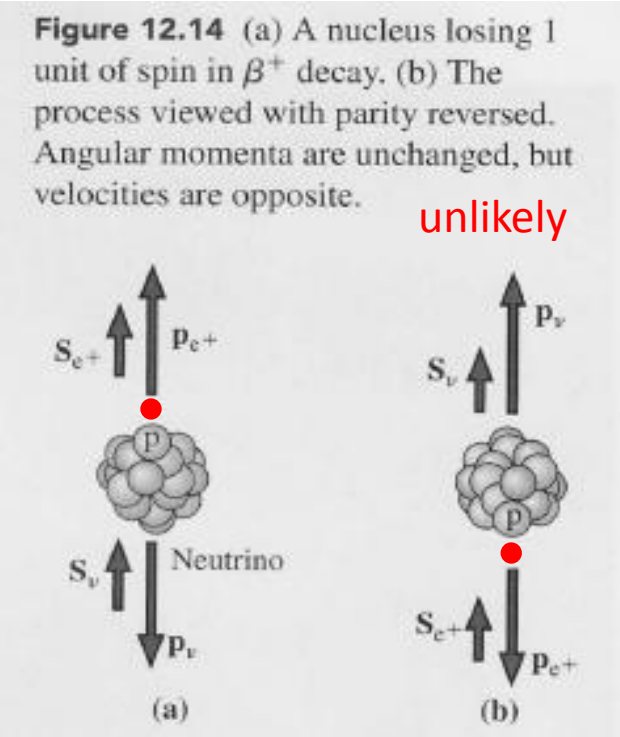
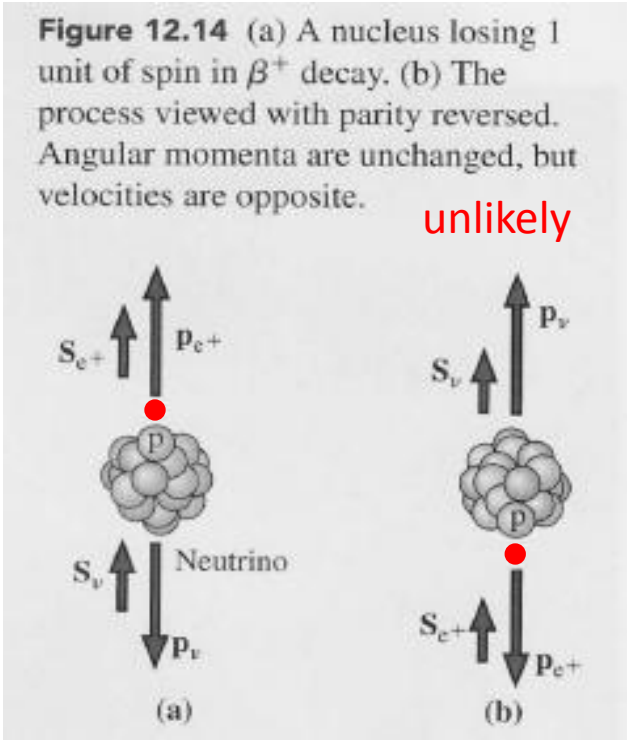


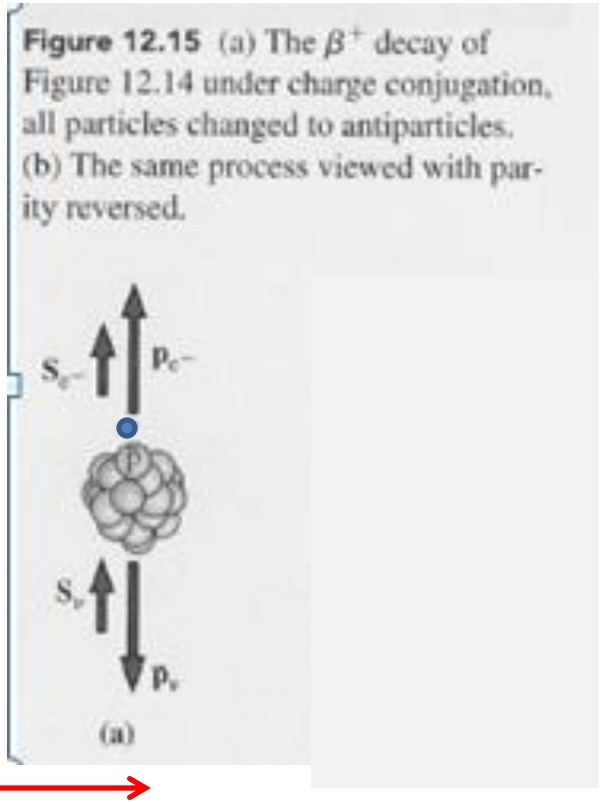
Examine: Spin and momentum alignment

In nature, both cases do not occur with equal probability

Symmetry breaking in weak interactions

$${}^{A}_{Z}X(parent) \rightarrow {}^{A}_{Z-1}Y(daughter) + {}^{0}_{+1}\beta^{+} + \nu$$





Apply Charge Conjugation

Symmetry breaking in weak interactions

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Figure 12.14 (a) A nucleus losing 1 unit of spin in β^+ decay. (b) The process viewed with parity reversed. Angular momenta are unchanged, but velocities are opposite.

unlikely

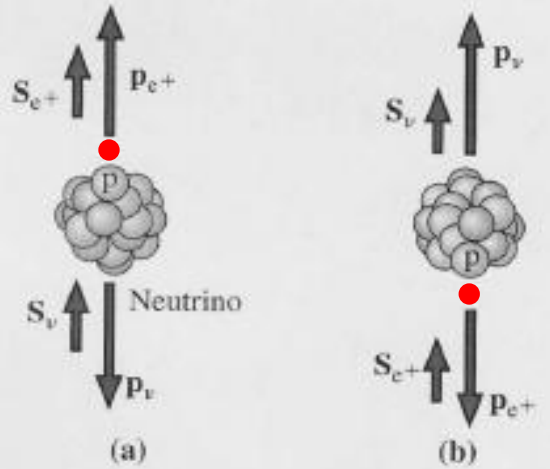
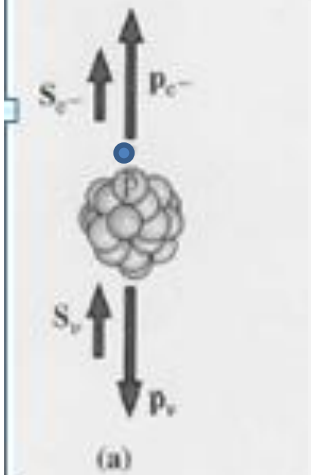


Figure 12.15 (a) The β^+ decay of Figure 12.14 under charge conjugation, all particles changed to antiparticles. (b) The same process viewed with parity reversed.



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Symmetry breaking in weak interactions

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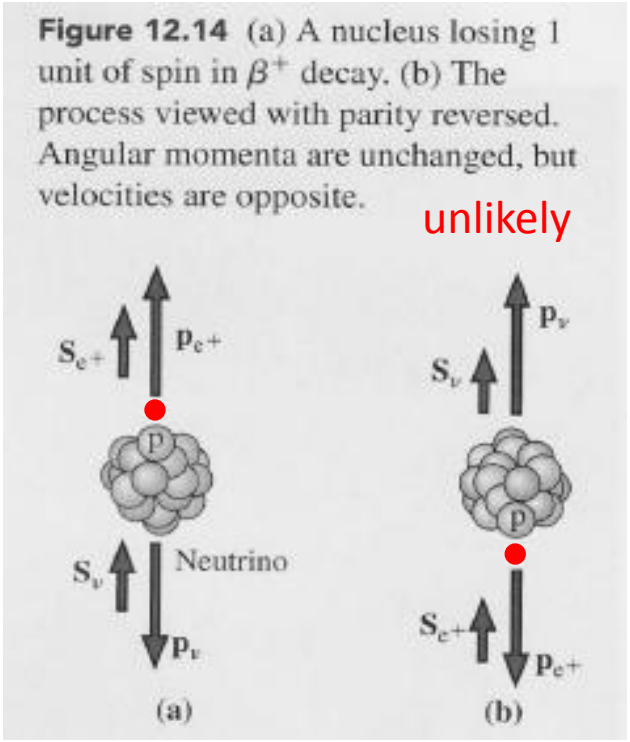


Figure 12.14 (a) A nucleus losing 1 unit of spin in β^+ decay. (b) The process viewed with parity reversed. Angular momenta are unchanged, but velocities are opposite.

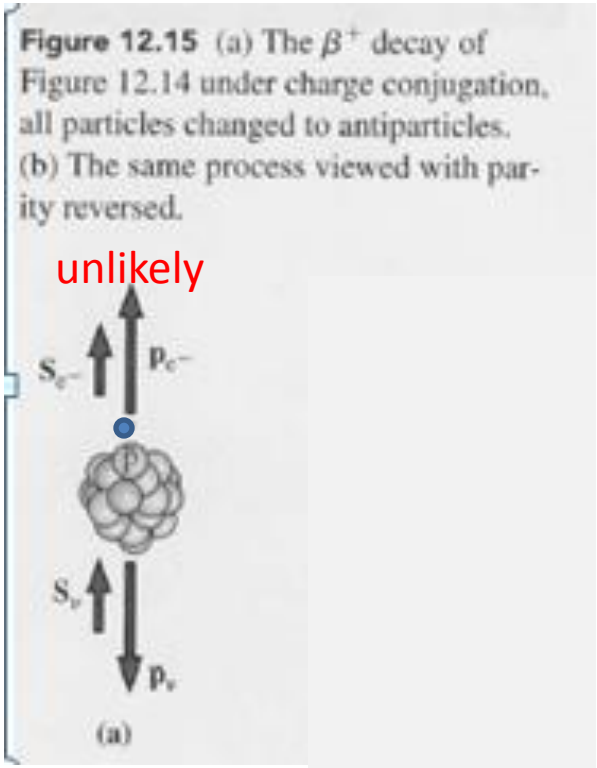
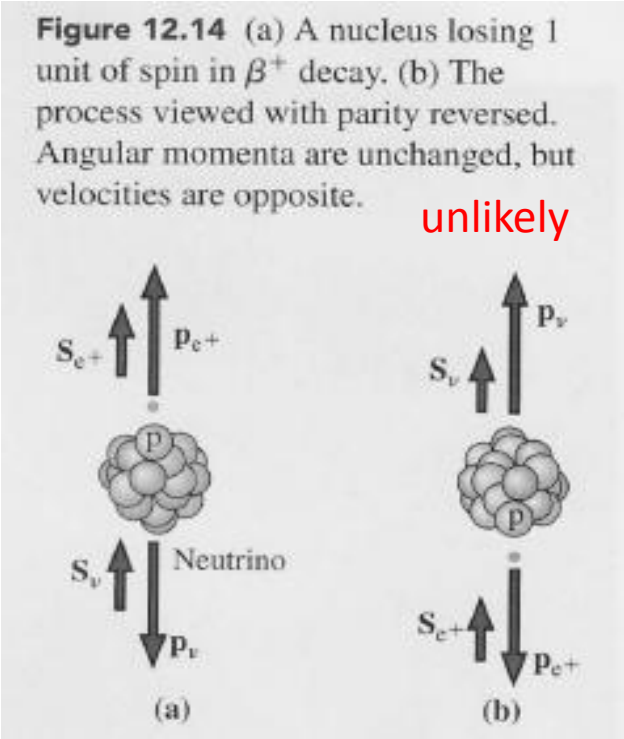


Figure 12.15 (a) The β^+ decay of Figure 12.14 under charge conjugation, all particles changed to antiparticles. (b) The same process viewed with parity reversed.

Apply Charge Conjugation

Symmetry breaking in weak interactions

$${}^{A}_{Z}X(parent) \rightarrow {}^{A}_{Z-1}Y(daughter) + {}^{0}_{+1}\beta^{+} + \nu$$



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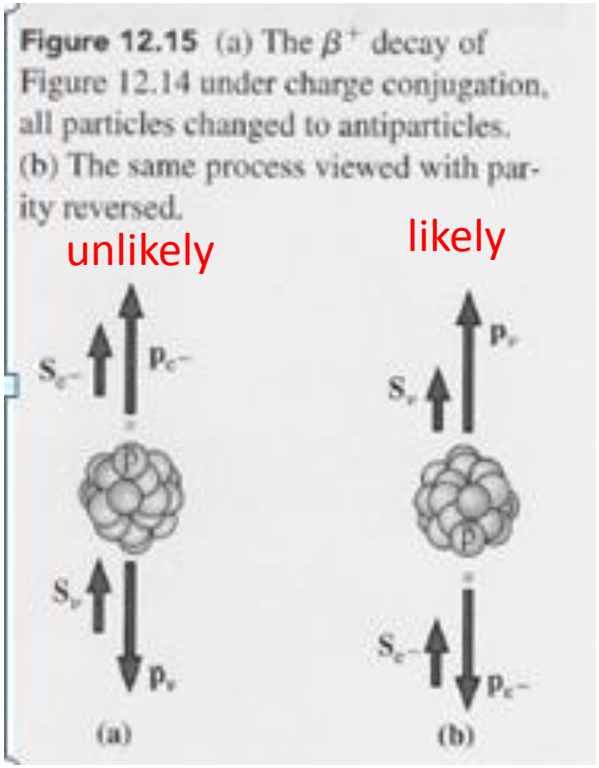
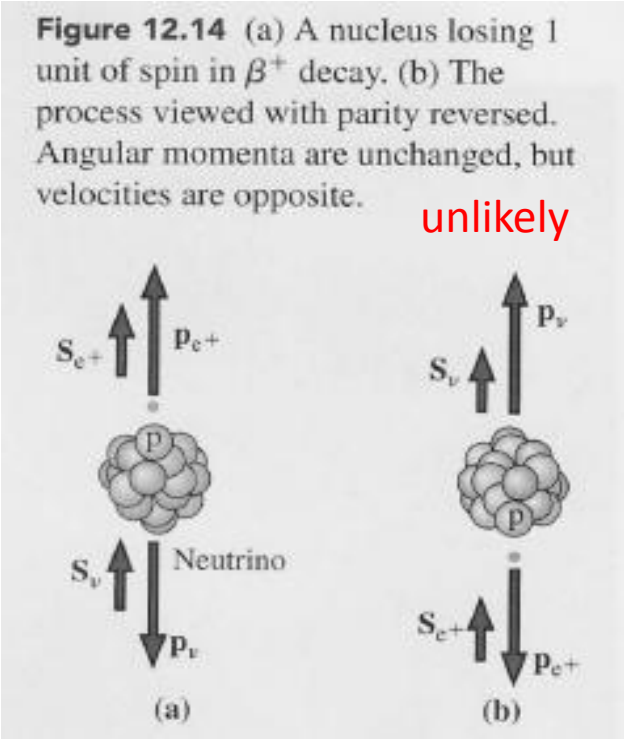


Figure 12.15 (a) The β^+ decay of Figure 12.14 under charge conjugation, all particles changed to antiparticles. (b) The same process viewed with parity reversed.

But, there are some exceptions → imbalance in matter and antimatter

Symmetry breaking in weak interactions

$${}^{A}_{Z}X(parent) \rightarrow {}^{A}_{Z-1}Y(daughter) + {}^{0}_{+1}\beta^{+} + \nu$$



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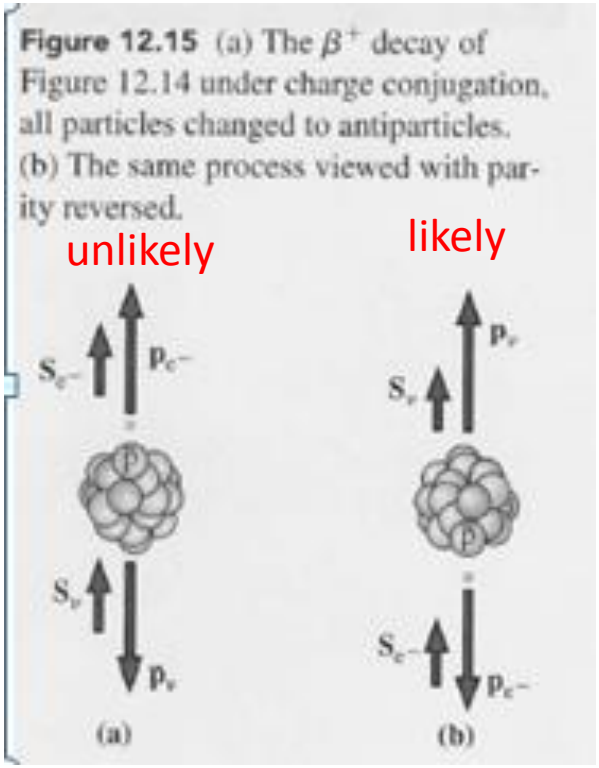


Figure 12.15 (a) The β^+ decay of Figure 12.14 under charge conjugation, all particles changed to antiparticles. (b) The same process viewed with parity reversed.

P or C operation does not preserve symmetry, but CP does.

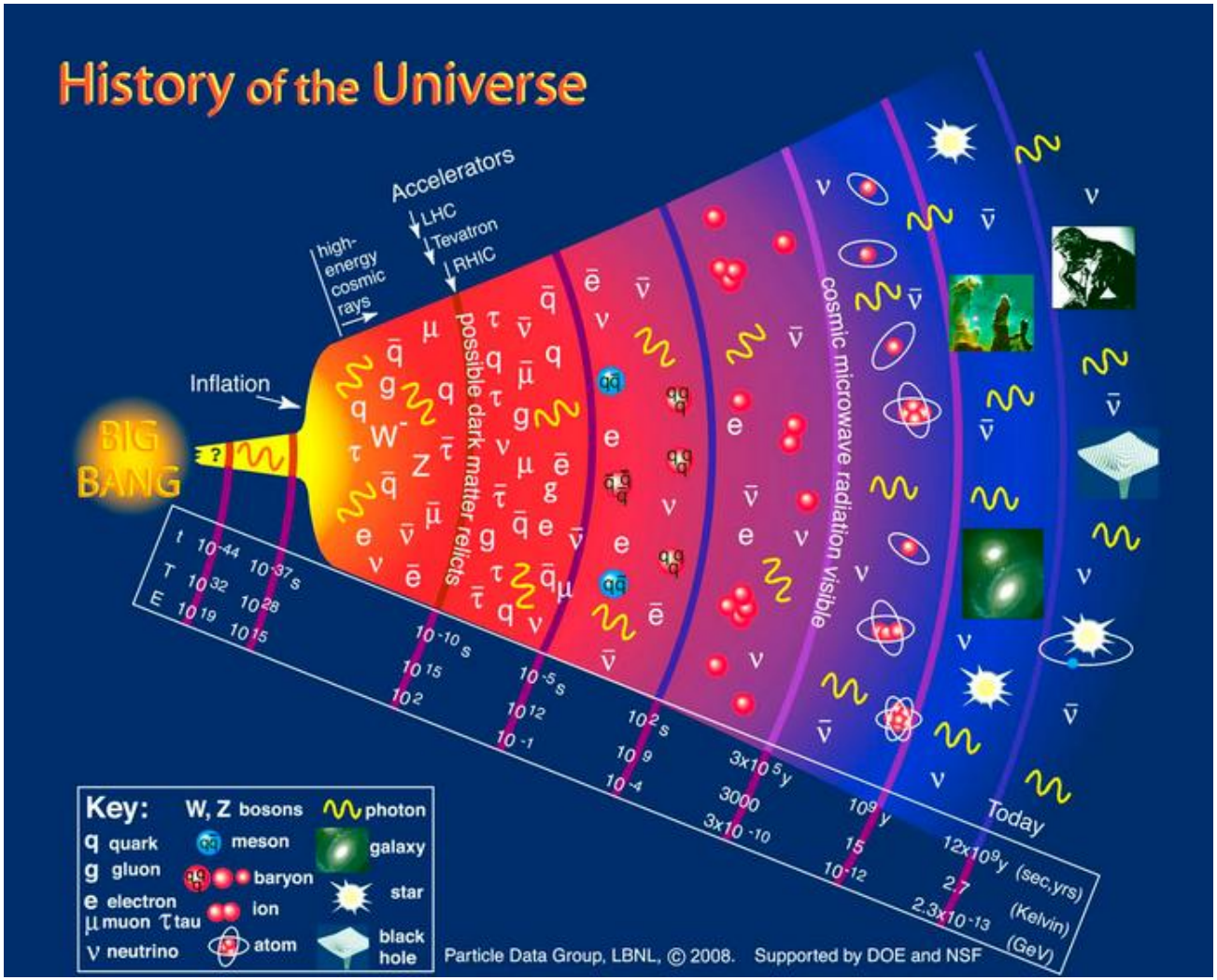
But, there are some exceptions → imbalance in matter and antimatter

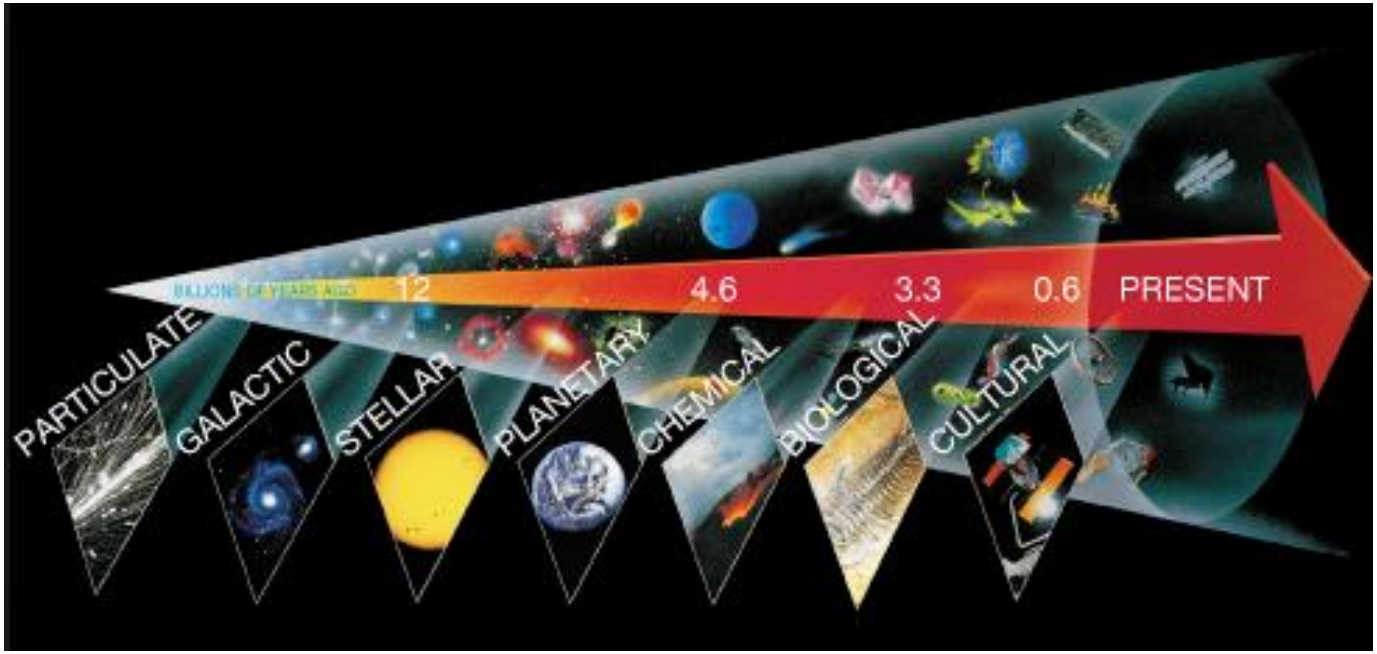
Symmetry-Conservation

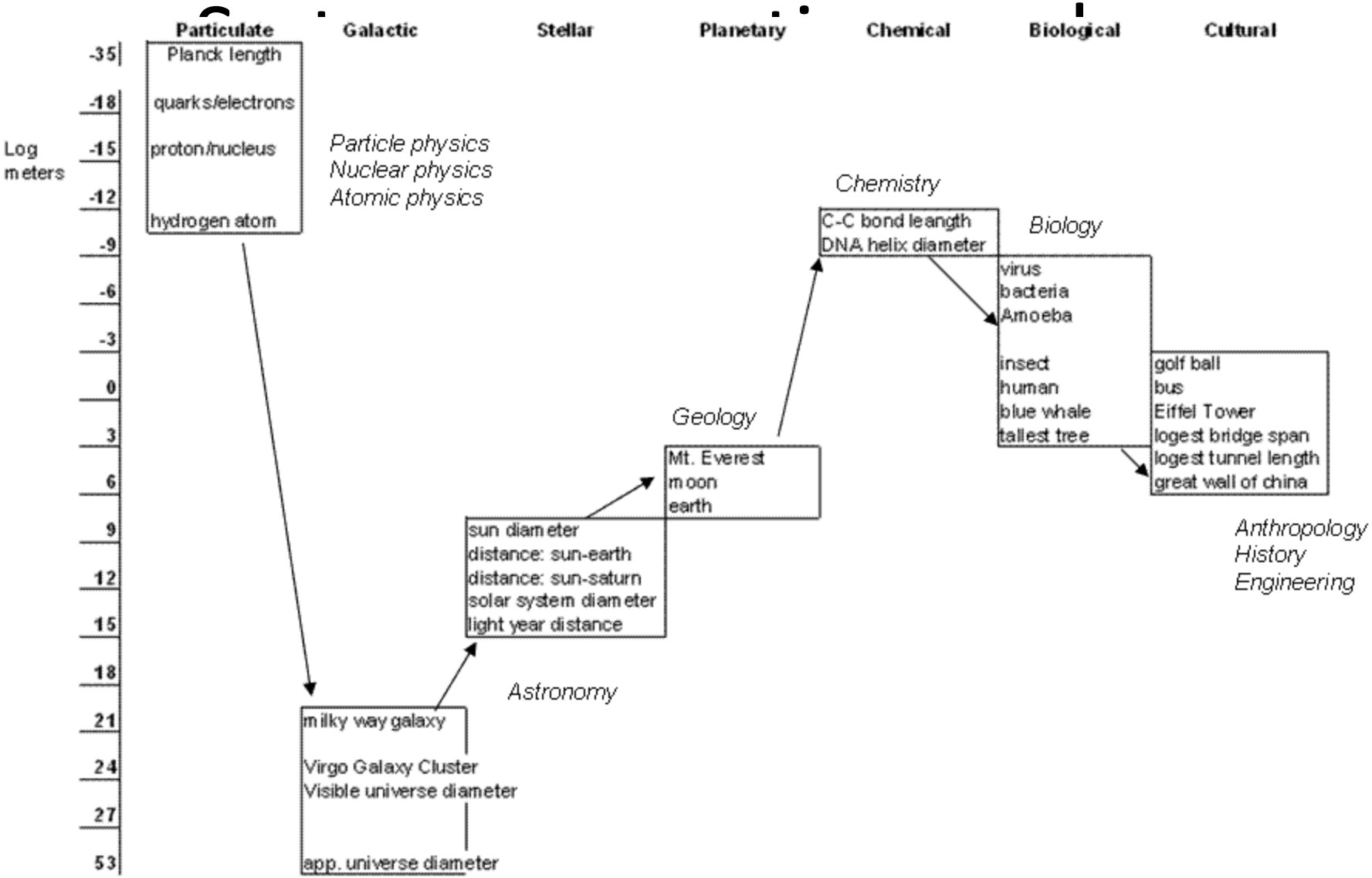
Symmetry operation	*Conserved quantity*
All interactions are independent of:	
Translation in space	Linear momentum **p**
Translation in time	Energy E
Rotation in space	Angular momentum **L**
Electromagnetic gauge transformation	Electric charge q
Lorentz transformation	Velocity of center of mass **V**
Interchange of identical particles	Type of statistical behavior
Inversion of space, time, and charge	Product of charge parity, space parity, and time parity CPT
?	Baryon number B
?	Lepton number L
?	Lepton number M
The strong and electromagnetic interactions only are independent of:	
Inversion of space	Parity P
Reflection of charge	Charge parity C, isotopic spin component I_3, and strangeness S
The strong interaction only is independent of:	
Charge	Isotopic spin I

Spatial scale

- 10 ^ -16 meter to 10 ^ 24 meter (visible universe)


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
atom
black hole
ν neutrino
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF


BILLIONS OF YEARS AGO
12
4.6
3.3
0.6
PRESENT
PARTICULATE
GALACTIC
STELLAR
PLANETARY
CHEMICAL
BIOLOGICAL
CULTURAL


Particulate
Galactic
Stellar
Planetary
Chemical
Biological
Cultural
Log meters
-35
-18
-15
-12
-9
-6
-3
0
3
6
9
12
15
18
21
24
27
53
Planck length
quarks/electrons
proton/nucleus
hydrogen atom
Particle physics
Nuclear physics
Atomic physics
milky way galaxy
Virgo Galaxy Cluster
Visible universe diameter
app. universe diameter
Astronomy
sun diameter
distance: sun-earth
distance: sun-saturn
solar system diameter
light year distance
Geology
Mt. Everest
moon
earth
Chemistry
C-C bond leangth
DNA helix diameter
Biology
virus
bacteria
Amoeba
insect
human
blue whale
tallest tree
golf ball
bus
Eiffel Tower
logest bridge span
logest tunnel length
great wall of china
Anthropology
History
Engineering