Galilean (Lorentz) Invariance

In atomic nucleus $v^2/c^2<0.1$, i.e., kinematics is nonrelativistic

$$\vec{r}_k\,' = \vec{r}_k$$

$$\vec{v}_k\,' = \vec{v}_k - \vec{u}, \qquad \vec{p}_k\,' = \vec{p}_k - m_k\vec{u}$$

$$\vec{s}_k\,' = \vec{s}_k$$

$$U(\vec{u}) = \exp\left\{\frac{i}{\hbar}\vec{u}M\vec{R}_{c.m.}\right\}$$

$$M = \sum_k m_k, \qquad \vec{R}_{c.m.} = \frac{1}{M}\sum_k m_k r_k,$$

$$H = H_{\text{int}} + \frac{\vec{P}^2}{2M}$$

Such a separation can be done for Galilean-invariant interactions

Depends only on relative coordinates and velocities!

$$\frac{i}{\hbar}[H,\vec{R}_{c.m.}]=\frac{1}{M}\vec{P}$$

no new conservation laws and quantum numbers!

Relativistic generalization

$$H=\left(H_{\mathrm{int}r}^{2}+c^{2}\vec{P}^{2}\right)^{1/2}$$

- Center-of-mass coordinate cannot be introduced in a relativistically covariant manner
- All powers of c.m. momentum are present
- Unitary transformation contains gradient terms and spin-dependent terms!

Space Reflection (Parity)

$$\vec{r}_k\,' = -\vec{r}_k = P\,\vec{r}_k P^{-1}$$

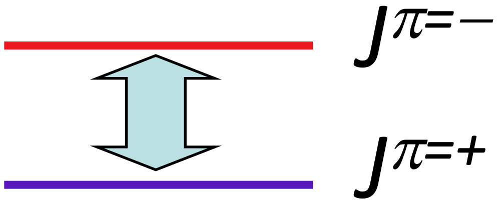
$$\vec{p}_k\,' = -\vec{p}_k, \quad \vec{s}_k\,' = \vec{s}_k$$

$$PU(\vec{a}) = U(-\vec{a})P, \quad PR(\vec{\chi}) = R(\vec{\chi})P$$

$$P|\Psi\rangle = \pi|\Psi\rangle, \quad P^2 = 1 \Rightarrow \pi = \pm 1$$

Which quantities/operators are invariant with respect to space reflection:
(a) Kinetic energy; (b) Projection of particle's spin on its momentum; (c) Electric charge

Weak interaction produces a very small parity mixing


$J^{\pi=-}$

$J^{\pi=+}$

Parity-violating matrix elements are of the order of 0.1 eV. This leads to the mixing amplitude of the order of 10^{-7}

Experimental test of parity violation
(Lee and Yang, 1956; Wu et al., 1957)

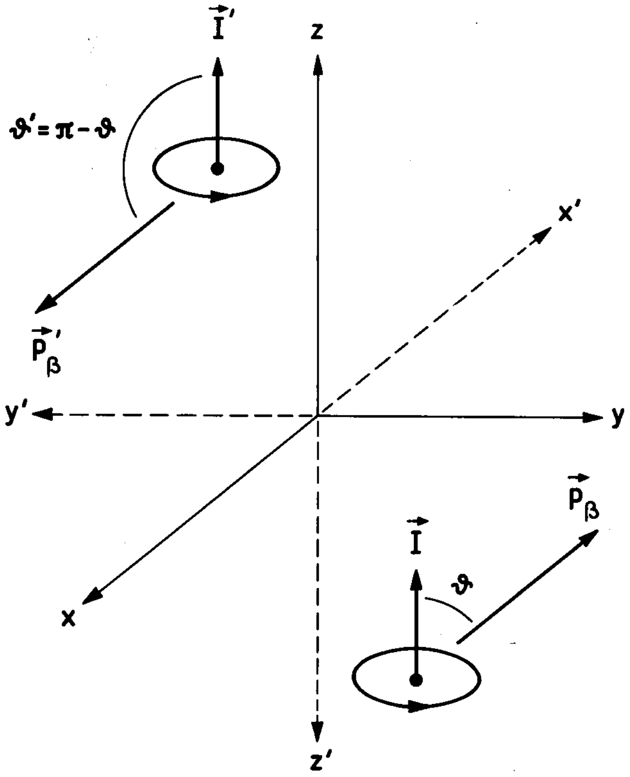
$T_{1/2}$=5.2713(8) y, produced in nuclear reactors

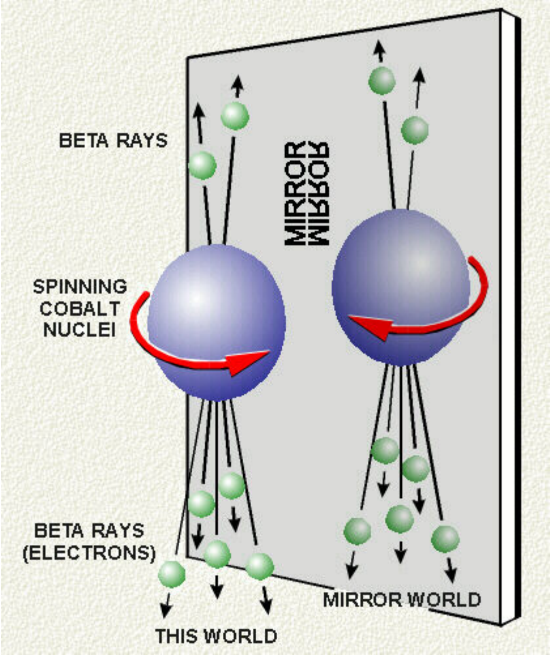
$$^{60}\mathrm{Co} \rightarrow ^{60}\mathrm{Ni} + e^- + \bar{\nu}_e + 2\gamma$$

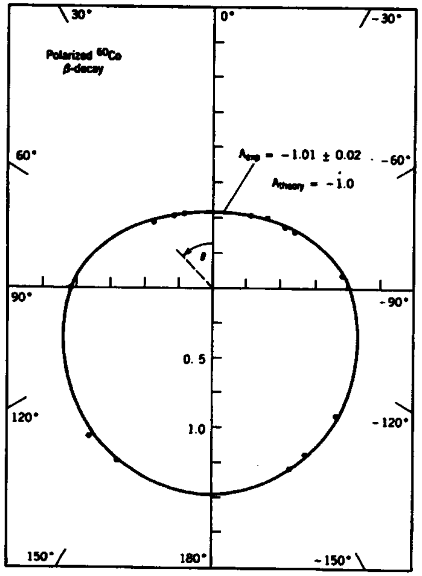
$$\boxed{\left\langle \vec{p}_\beta \vec{I}_i \right\rangle \neq 0!}$$

pseudoscalar

Parity violation in a beta decay of polarized ^{60}Co ($J^\pi=5^+$): the emission of beta particles is greater in the direction opposite to that of the nuclear spin.







Time Reversal

$$\vec{r}_k\,' = \vec{r}_k = T\,\vec{r}_k\,T^{-1}$$

$$\vec{p}_k\,' = -\vec{p}_k\,, \qquad \vec{s}_k\,' = -\vec{s}_k$$

$\mathcal{T}$ cannot be represented by an unitary operator. Unitary operations preserve algebraic relations between operators, while $\mathcal{T}$ changes the sign of commutation relations.

$$\left[p_x, x\right] = -i\hbar \longrightarrow \left[p_x\,', x\,'\right] = i\hbar$$

$$\left[s_x, s_y\right] = i s_z \longrightarrow \left[s_x\,', s_y\,'\right] = -i s_z\,'$$

In order to save the commutation relations, on has to introduce:

$$T = UK$$

antiunitary

unitary

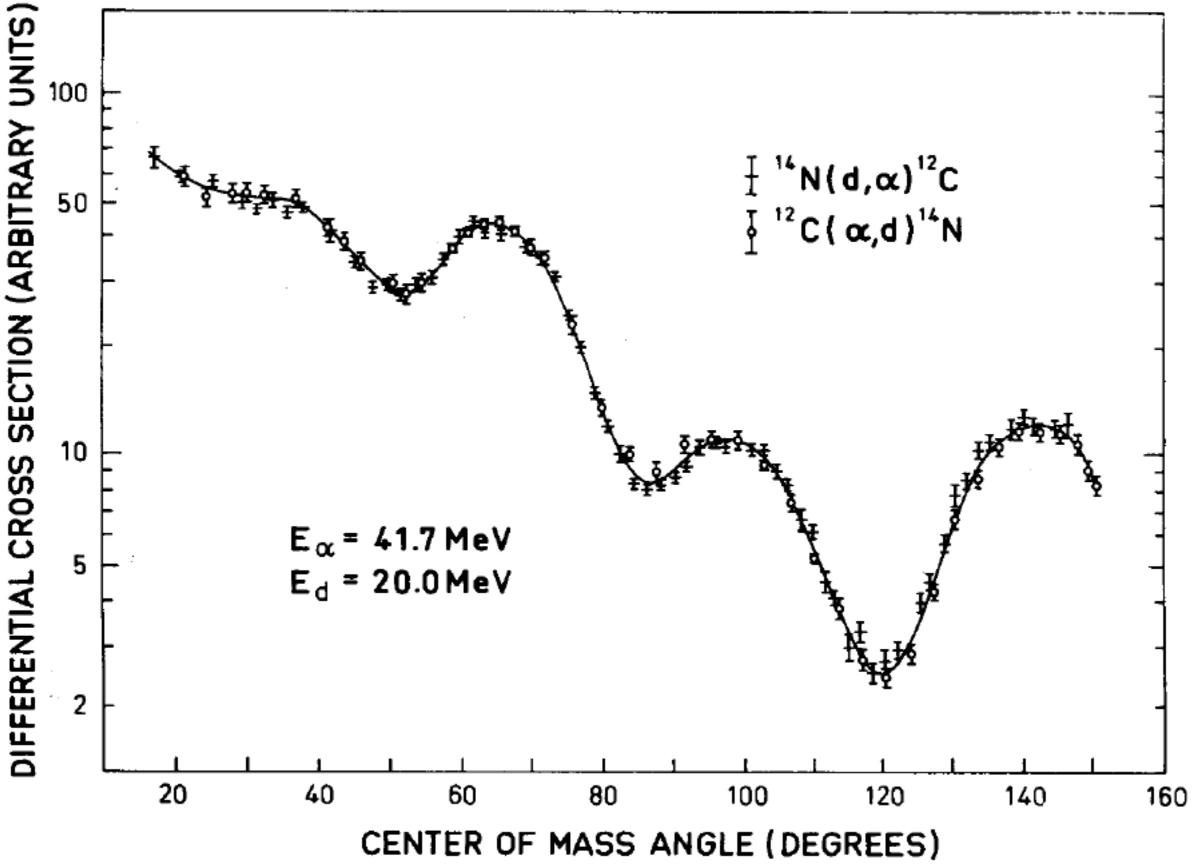
takes complex conjugate of all *c* numbers

$$\langle B | A \rangle = \langle B' | A' \rangle^{*}$$

Time Reversal symmetry and nuclear reactions

$$a_1 + a_2 \Leftrightarrow b_1 + b_2$$

normal and inverse
kinematics!



THE STANDARD MODEL OF
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV $= 10^9$ eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.

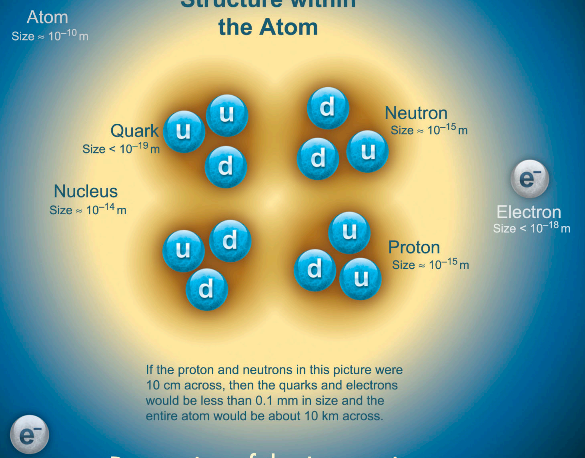
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

$(q\bar{q}), (qqq)$

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at **ParticleAdventure.org**

Properties of the Interactions

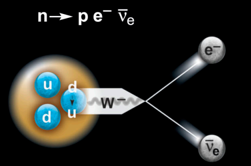
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Particle Processes

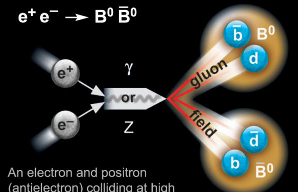
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

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



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+ e^- \rightarrow B^0 \bar{B}^0$

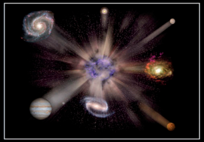


An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

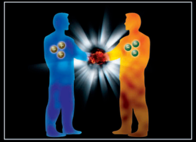
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?



The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?



Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).

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