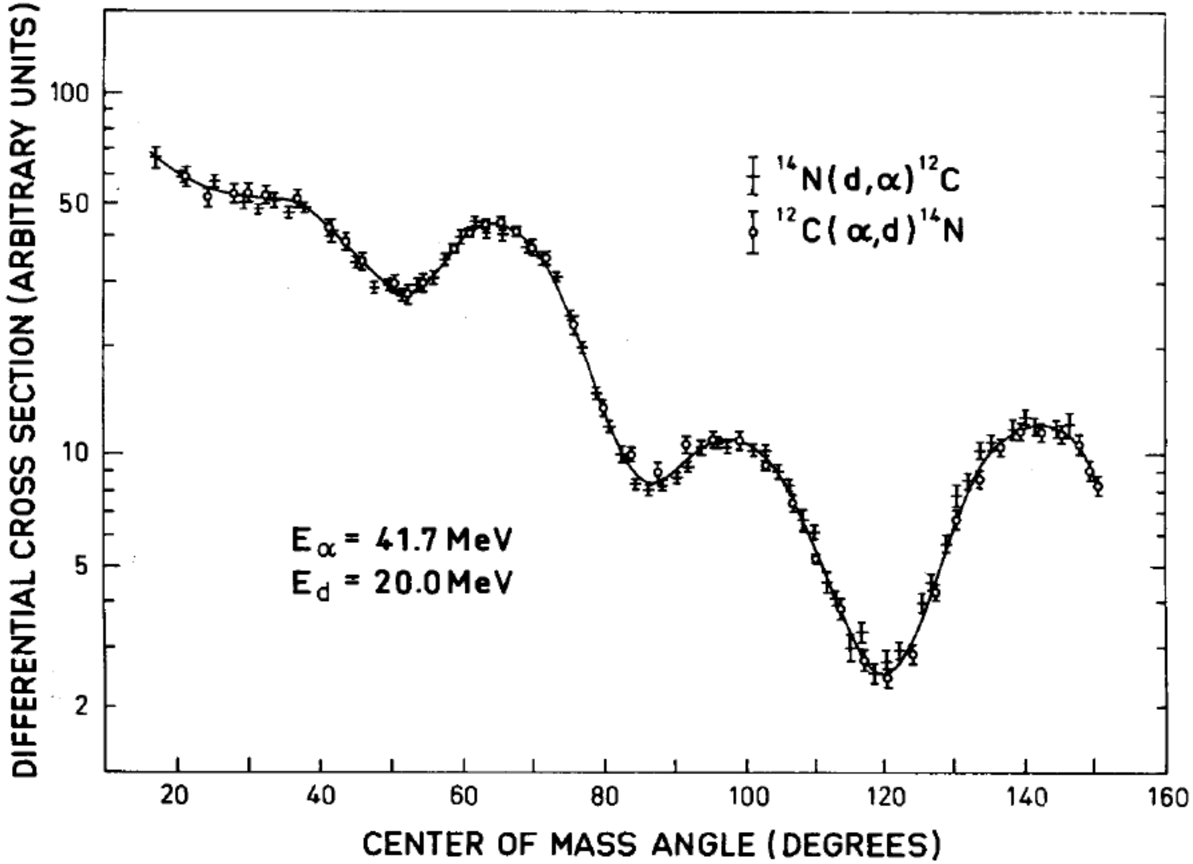
Time Reversal symmetry and nuclear reactions

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

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.

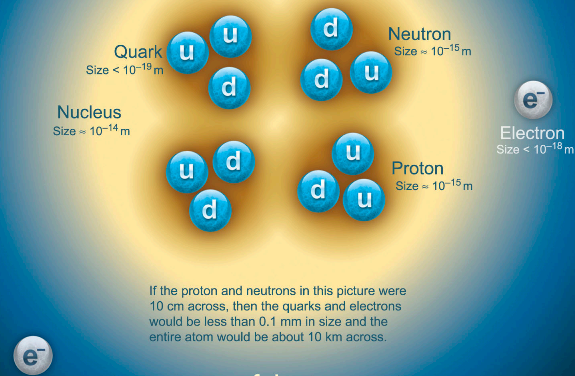
Neutrinos

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

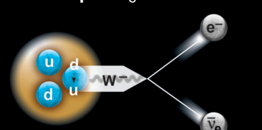
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

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

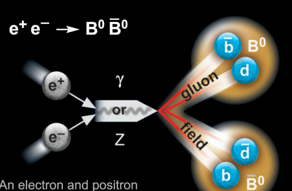
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

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



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.

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

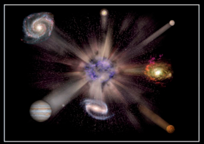


An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

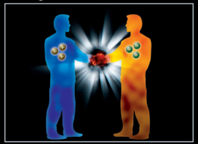
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

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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Intrinsic parity

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The Intrinsic Parity of Elementary Particles

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(Received June 16, 1952)

The limitations to the concept of parity of quantum-mechanical states and, in particular, of intrinsic parity of elementary particles are discussed. These limitations are shown to follow from "superselection rules," i.e., from restrictions on the nature and scope of possible measurements. The existence of such superselection rules is proved for the case of spinor fields; it is also conjectured that a superselection rule operates between states of different total charge.

- Parity is a multiplicative quantum number $\mathcal{P}_{12} = \mathcal{P}_1 \mathcal{P}_2 (-1)^{L_{12}}$
- Quarks have intrinsic parity +1
- The lighter baryons (qqq) have positive intrinsic parity. What about light antibaryons?
- What about mesons?

In 1954, Chinowsky and Steinberger demonstrated that the pion has negative parity (is a pseudoscalar particle)

Charge conjugation

$\mathcal{C}$ - interchanges particles & antiparticles

It reverses all the internal quantum numbers such as charge, lepton number, baryon number, and strangeness. It does not affect mass, energy, momentum or spin.

$$\mathcal{C}|\psi\rangle = |\bar{\psi}\rangle \qquad \mathcal{C}^2 = 1$$

What are the eigenstates of charge conjugation?

$$\mathcal{C}|\psi\rangle = \eta_C|\psi\rangle \Rightarrow \eta_C = \pm 1$$

C-parity or charge parity

$\Rightarrow$ photon, neutral pion…
What about positronium, neutrino?

- Maxwell equations are invariant under $\mathcal{C}$
- $\mathcal{C}$ reverses the electric field
- Photon has charge parity η_C=-1

$$\pi_0 \to \gamma + \gamma \Rightarrow \eta_C(\pi_0) = 1$$

- Is the following decay possible?

$$\pi_0 \to \gamma + \gamma + \gamma$$

http://pdg.lbl.gov/2016/tables/contents_tables.html

Other Symmetries

$\mathcal{CP}$ - violated in K^0 decay (1964 Cronin & Fitch experiment)

$$K_2^0 \to \pi^+ + \pi^-$$

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EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

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(Received 10 July 1964)

$\mathcal{CPT}$ - follows from relativistic invariance

The CPT theorem appeared for the first time in the work of Julian Schwinger in 1951 to prove the connection between spin and statistics. In 1954, Lüders and Pauli derived more explicit proofs. At about the same time, and independently, this theorem was also proved by John Stewart Bell. These proofs are based on the principle of Lorentz invariance and the principle of locality in the interaction of quantum fields.

Since $\mathcal{CP}$ is violated, $\mathcal{T}$ has to be violated as well!

HW3: Using information from PDG.lbl.gov and nndc.bnl.gov determine whether the following decays/reactions are allowed by fundamental symmetries:

a. $\pi^0 \longrightarrow \mu^- + e^+$
b. $e + \overline{e} \longrightarrow \gamma$
c. Gamma decay of excited state of ^{40}Ca at 3353keV
d. Decay of meson $\eta \longrightarrow \gamma + \pi^0$
e. Decay of meson $\eta \longrightarrow \pi^0 + \pi^0 + \pi^0$