Fundamental Forces

&

Elementary Particles

Forces of Nature

Four forces responsible for all phenomena

- **Gravitational force (10^{-45})**
  - interaction between masses (all particles)
  - most familiar to us
- **Weak force (10^{-8})**
  - responsible for some nuclear decays and reactions in stellar interiors
- **Electromagnetic force (10^{-2})**
  - restricted to electrically charged particles
  - holds atoms/molecules together
- **Strong (nuclear) force (1)**
  - holds nuclei together

How does a force “work”?

- **Issue:** How is a force transmitted between particles not in direct physical contact with each other?
- **In classical physics use concept of “field” (resulting in action at a distance) :**
  - A particle, by virtue of its presence somewhere, modifies the space around it, i.e. it “creates a field”
  - A second particle, a distance **r** away, is embedded in this field
  - The field “acts” on this second particle
  - Result: The second particle experiences the force acted on it by the first particle
- **In 20th century physics (quantum mechanics) use concept of “exchange force”:**
  - Two particles interact with each other by exchanging a (virtual) particle between them

“Virtual” Exchange Particle

- An exchange particle (“field quantum”) is:
  - created (and emitted) by one of the interacting particles, is absorbed by the other. This process produces the interaction
  - specific to an interaction (different for different interactions)
- How can energy be conserved during this creation?
  - QM: Energy measured in Δt is uncertain by ΔE
  - **Heisenberg Uncertainty Principle $\Delta E \Delta t \geq h / 2\pi$**
- No extra energy needed to create it! May exist for short enough Δt between creation and absorption for its energy ΔE to obey HUP and thus not violate energy conservation
  - is called a **“virtual”** particle (we never see it)
- This exchange leads to a change in the momentum and energy of the interacting particles (force)

Example: Yakawa (strong) Force

- Prediction of exchange particle for nuclear (strong) force
- Use range of nuclear force: 1.5 fm = 1.5 x 10^{-15} m
- The longest time Δt a particle could exist, if moving with speed of light c, and the corresponding ΔE, using the H.U. P., would be:

$$\Delta t = \frac{\Delta x}{c} = \frac{1.5x10^{-15}}{3x10^{8}} = 5x10^{-24}s$$

$$\Delta E = \frac{\hbar}{\Delta t} = \frac{1.05x10^{-34}J \cdot s}{5x10^{-24}s}\frac{1}{1.6x10^{-13}J/MeV} = 131MeV$$

- Predicted (1935) new particle of 131 MeV rest energy
- Discovered pion (1947) and measured rest energy

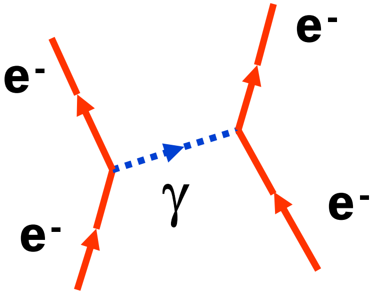
E_o = 140 MeV! (Rest mass m_o: 140 MeV/c^2)

Exchange Particle Mass vs Range of Interaction

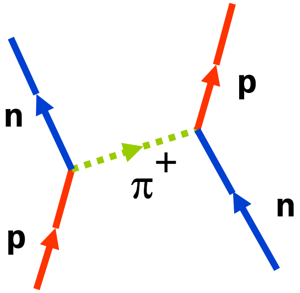
- Field quantum may have zero or non zero mass
- The greater the mass the more energy needed for its creation ∴ the shorter time it can exist (to not violate E-conservation, and be within HUP limits)

  ∴ the shorter the range of the corresponding force
- For zero mass, the range is infinite

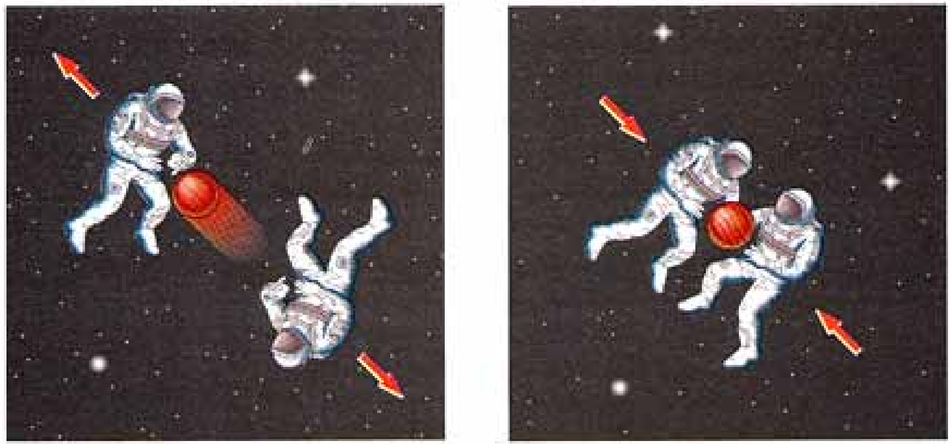
  CONCLUSION: The range of the force associated with the exchange of an virtual particle is inversely proportional to the mass of this particle



Feynman Diagrams



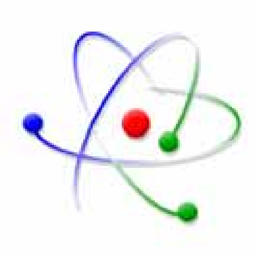
The Field Quanta



FORCE	STRENGTH	QUANTUM	MASS (GeV/c^2)	RANGE (m)
Gravitational	10^{-45}	Graviton?	Zero	Infinite $\propto 1/r^2$
Weak	10^{-8}	$W^{\pm}$, Z^0	80, 91	$<2 \times 10^{-18}$
Electromagnetic	10^{-2}	Photon	Zero	Infinite $\propto 1/r^2$
Strong (nuclear)	1	(π meson) Gluon	(0.14) Zero	(10^{-15}) Infinite

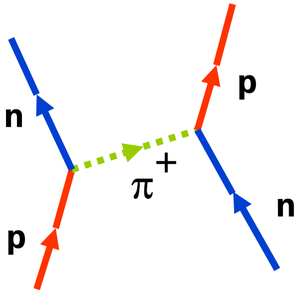
Structure of Matter (Up to the late ‘60s)

- Atoms consist of nuclei surrounded by electrons bound to the nucleus through the electromagnetic force

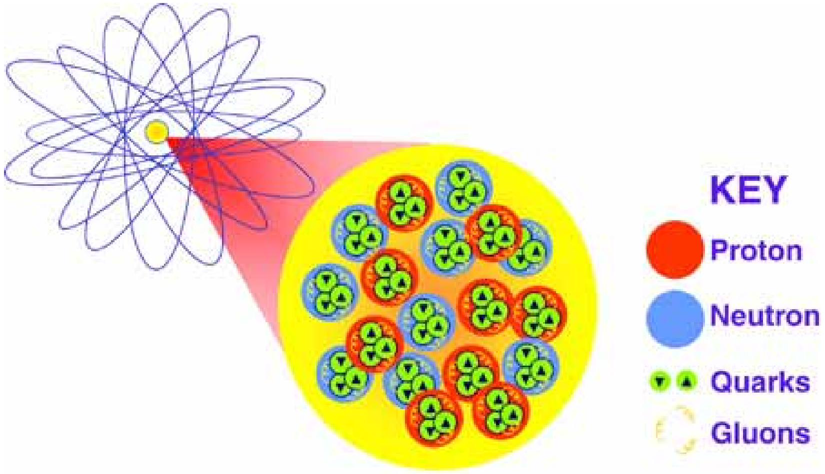


- Nuclei consist of protons and neutrons bound together by the nuclear force

- The nuclear force is understood in terms of an exchange of mesons
  - Basis of successful models of nuclear structure



Current Understanding of Structure of Matter



- Protons, neutrons and mesons are not elementary particles
  - They are composites of quarks
- The most fundamental constituents of matter are quarks, leptons
- Quarks interact through the exchange of gluons
- Individual quarks do not exist in isolation
  - Always bound together to form nucleons and mesons
- Theory for nuclear force: Quantum Chromodynamics (QCD)

Particle “Spin”

- Each nuclear particle has a property called “spin”
  - Intrinsic angular momentum (“rotation” about their own axis)
  - One specific, fixed (not arbitrary) value for each particle
  - Comes in units of $\hbar = h/2\pi$ ($h = 6.626\text{x}10^{-34}$ J.s)
  - It can only be either an integer or half-integer multiple of h-bar (0, 1, 2… or 1/2, 3/2, 5/2…)
- Spin may serve as a criterion for classifying particles
- Different statistics for each type of spin value
  - Half-integer spin particles are called **Fermions**
    - Obey Fermi-Dirac Statistics
    - No two-particles in exactly the same state (Pauli Exclusion Principle)
    - Examples: e, p, n, quarks
  - Integer spin particles are called **Bosons**
    - Obey Bose-Einstein Statistics
    - Examples: photon, gluons

Particle Classification - Particle Zoo

- Many particles are known (100s) - most are not elementary
- Detecting patterns in data very useful - remember periodic table?

  May classify nuclear particles **by their interaction:**
- **(1) Hadrons:** They may experience **all four** forces. **Are NOT elementary** particles, have structure and size. Two categories:
  - **Baryons** - heavy particles (p, n, Λ, Σ, Ω, antiparticles)
    - All have half-integer spin (fermions)
    - Some are stable (do not decay)
  - **Mesons** - less heavy (π, η, ρ, K, antiparticles)
    - All have integer spin (bosons)
    - All are unstable

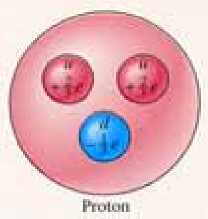
Particle Classification - Particle Zoo

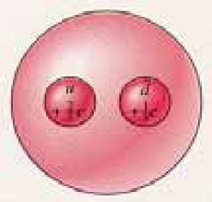
- **(2) Leptons:** Do **NOT** experience the **strong** force but experience all other three forces
  - **Are elementary** particles, no internal structure, zero size (<10^{-16} cm)
  - All have spin 1/2 (units of $h/2\pi$) - they are “fermions”
  - Generally light (but not always)
  - There are only 6 (plus 6 antiparticles): e, μ, τ, ν_e, ν_μ, ν_τ

Particle Classification - Particle Zoo

- **(3) Quarks:** Experience **all** four forces
  - Are **elementary particles**, no internal structure, zero size
  - Are the **constituents of hadrons (baryons and mesons)**
  - Come in 6 types (**flavors**): u (up), d (down), s (strange), c (charmed), t (top), b (bottom), plus a set of antiquarks
  - Have **fractional** electric charge (+ 2/3 e, -1/3 e)
  - Have "color charge" ("red", "blue", "green")
    - Needed to satisfy Pauli Exclusion Principle (Ω^-, sss, $3/2\hbar$)
    - Same colors repel, opposites (color-anticolor) attract

      Different colors attract (less so)
  - All have spin 1/2 (fermions)
  - Are **not found isolated** in the laboratory
    - Strong force increases with distance between quarks
  - Baryons are made of 3 quarks, mesons of 2 (qq-bar pair)
    - 3 colors make up white = colorless





Particle Classification - Particle Zoo

- **(4) Field Quanta (or Gauge Bosons):**
  - γ **Electromagnetic interaction**
  - **W^+, W^-, Z^o Weak Interaction**
    - Carry “weak charge”
  - **8 gluons Strong (color) Interaction**
    - 6 carry “color”
    - 2 colorless
  - **graviton? Gravitational Interaction**
    - Not observed yet
  - They are the force carriers
  - All have spin 1 (graviton 2) - (bosons)
  - All are elementary, no internal structure, no size

Some Particle History

- The plethora of hadrons led to the search for a more fundamental set of particles out of which baryons and mesons would be built.
- 1963 - Gell-Mann and Zweig proposed such a model, where baryons and mesons are composites of elementary constituents, labeled quarks. Baryons: 3 quarks. Mesons: one quark, one anti-quark.
  - For each quark there is a corresponding antiparticle, all properties the same except for opposite electric charge.
- 1963 quarks proposed : **up**, **down**, **strange**. Discovered early '70s
- 1967 **charmed** quark proposed - discovered in 1974
  - cc-bar in J/psi SLAC/BNL).
- 1975 - **Tau lepton** (SLAC) discovered
  - Led to proposal of 2 more quarks top, bottom.
- 1977 - **Bottom** quark discovered (bb-bar in Y-, Fermi Lab)
- 1995 - **Top** quark discovered (Fermi Lab)

Some Particle Properties

CATEGORY	PARTICLE	MASS	SPIN	LIFETIME (s)
Hadrons	Proton (p)	938.3	½	Stable
	Neutron(n)	939.6	½	889
	Omega (Ω^-)	2285	3/2	$0.82\text{x}10^{-10}$
	Pion (π^+,π^-)	139.6	0	$2.6\text{x}10^{-8}$
	Kaon (K^+,K^-)	494	0	$1.2\text{x}10^{-8}$
Leptons	Electron (e^-,e^+)	0.511	½	Stable
	Muon (μ^-,μ^+)	105.7	½	$2.2\text{x}10^{-6}$
	Tau (τ^-,τ^+)	1784	½	$3.0\text{x}10^{-13}$
	Neutrino (ν)	small	½	Stable
Field Quanta	Photon (γ)	0	1	Stable
	Z°	91117	1	$\sim 10^{-25}$

Elementary Particles

(Summary)

QUARK	CHARGE (e)	SPIN (h/2π)	MASS (MeV/c^2)
Up (u)	+2/3	½	2-8
Down (d)	-1/3	½	5-15
Strange (s)	-1/3	½	100-300
Charmed (c)	+2/3	½	1000-1600
Top (t)	+2/3	½	$1.8 \mathrm{x} 10^5$
Bottom (b)	-1/3	½	4100-4500

LEPTONS	CHARGE (e)	SPIN (h/2π)	MASS (MeV/c^2)
Electron (e^-)	-1	½	0.511
Muon (μ^-)	-1	½	106
Tau (τ^-)	-1	½	1784
Electron Neutrino (ν_e)	0	½	<7.3 eV
Muon Neutrino (ν_μ)	0	½	<270 keV
Tau Neutrino (ν_τ)	0	½	<35 MeV

GAUGE BOSONS (Field Particles)	ELECTRIC CHARGE	SPIN (h/2π)	MASS (GeV/c^2)
Graviton	0	2	0
W±, Z°	±1, 0	1	80.41, 91.12
Photon (γ)	0	1	0
Gluon (g) – 8 varietie	0	1	0
Higgs Boson (H°)???	0	1	40-1000???

More Hadron Properties

- For Baryon properties:
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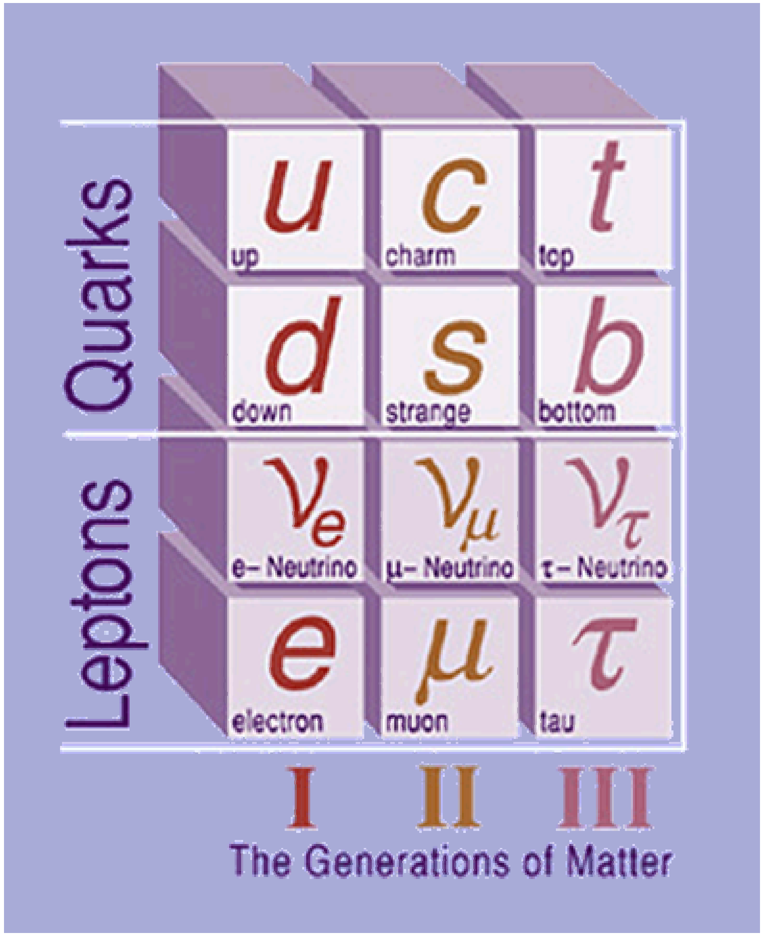
- For Meson properties:
- C:\Documents and Settings\Dimitri\Desktop\meson.html

Elementary Particle Generations



- **12 Elementary Particles**
  - Plus 4 field quanta
  - Plus antiparticles
- **3 Generations**
- Masses of (II) > (I)
- Masses of (III) > (II)
- (I) is for ordinary matter
- Q: Only three generations?
  - Only three ν observed (1991, CERN)
  - Therefore expect only three generations

Understanding Elementary Particles and their Interactions

- (1) The Standard Model - **It includes:**
  - Theory of the **Electroweak Interaction**
    - combines Electromagnetic and Weak Interactions
    - two aspects of a single unified “electroweak” interaction
    - same strength at very high energies (10^{-10} s after Big Bang)
    - “symmetry breaking” at low energies ($m_{W,Z} \neq 0$, $m_{\gamma} = 0$)
    - Spectacular successes (e.g. discovery of $W^{\pm}$, Z°)
    - Predicts the Higgs boson (undetected at present)
  - Quantum Electrodynamics **(QED)**
  - Theory of **Strong (color) Interaction**
    - Force between quarks and gluons
      - Nuclear force is “remnant” of this force
    - Quantum Chromodynamics **(QCD)** - very complicated math

Understanding Elementary Particles and their Interactions

- **(2) Einstein’s Theory of General Relativity**
  - Theory of **Gravitational Interaction**
  - Not a quantum theory, expected to fail at small distances…

Standard Model
Many Remaining Questions...

- Are the current elementary particles really elementary?
- Why do quarks and leptons have the mass they do?
- Why are there only 3 generations of elementary particles?
- Why does the electron and the proton have exactly the same charge? They are different in almost every other way.
- Why is the neutron heavier than the proton? The opposite would be easier to understand - proton has electric charge
- Why does the photon have zero mass but W,Z have mass? They mediate one single force (electroweak force)
- Why does the W and Z have the mass they have?
- Does the Higgs boson exist? It would explain these masses and symmetry breaking. Has not been seen yet (need TeV)

Further Unification of Forces?

- **Electroweak unification** - First successful step
- **Grand Unification Theories (GUTs)** - Next step
  - Would merge the Electroweak and Color Force
  - Current Predictions:
    - Proton Decay (10^{31} years) - Not seen yet
    - Neutrinos have mass - Observed 1998
  - Hopeful signs for ultimate success
- **Ultimate goal:** Include Gravity in Unification
  - Superstring Theory (“theory of everything”)
  - Particles: string-like structures; $\sim 10^{-35}$ m
  - Needs 10-dimensional space-time
  - Extremely complicated math
  - The jury is still out...

Evolution of Forces in Nature

From the Big Bang to the Present