Fundamental Particles and Forces

A Look at the Standard Model and Interesting Theories

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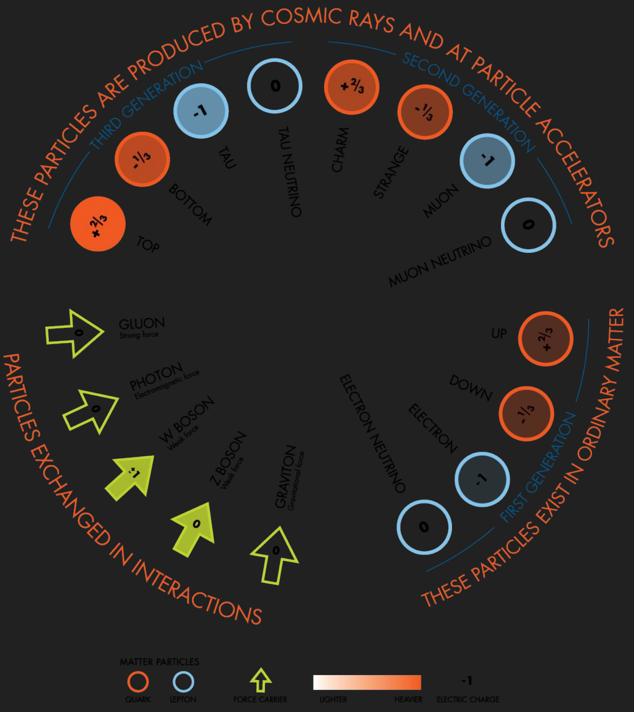
Overview

- Introduction to Fundamental Particles and Forces
- Brief History of Discovery
- The Standard Model
- Problems with the Standard Model
- Other Interesting Theories
- Future Discoveries

Introduction to Fundamental Particles and Forces

- What are the fundamental forces?
  - Weak force
  - Strong force
  - E-M force
  - Gravity
- What is a fundamental particle?
  - Fermions
    - Leptons
    - Quarks
  - Bosons

Force	Description	Strength	Range (m)	Particle
Strong	Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1
Weak	neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2



Brief History of Discovery

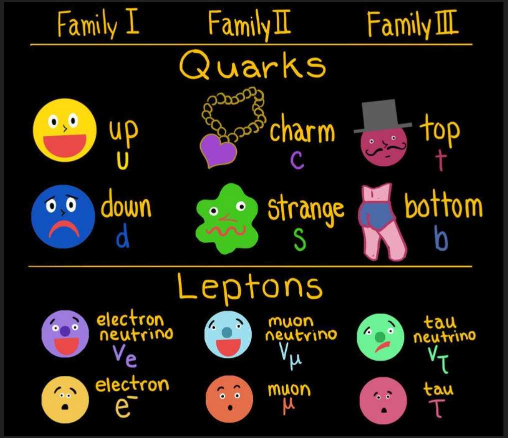
- Particle physics began as high-energy nuclear physics
- 1897 - J.J. Thompson discovered the electron, first elementary particle
- 1911 - Ernest Rutherford and co. found data suggesting an atomic nucleus
- 1919-1932: proton, neutron, and positron discovered
- Almost all new particle discoveries up to 1955 were made using cosmic radiation
  - Muon, pion, kaon, etc.
- After 1955, particle accelerators began taking over

Brief History of Discovery

- 1962 - electron and muon found to be associated with distinct neutrinos
- 1964 - Gell-Mann and Zweig independently proposed hadrons could be made up of three elementary fermions
    - Quarks (or “aces”)
- 1964 - Yang-Mills theory (no massless gauge bosons found)
    - Evaded this problem with the Higgs mechanism
    - Introduced a spin-0 boson called the Higgs boson
- 1965 - Yoichiro Nambu proposed “color” charge in quarks
    - Grew interest in color theory, or quantum chromodynamics (QCD)
- 1967 - electroweak theory proposed using the Higgs mechanism
- 1974 - discovery of the charm quark
- 1977 - discovery of bottom quark at Fermilab (followed by top quark evidence as well)
- 1979 - Birth of the Standard Model through Yang-Mills gauge theories and electroweak theory

The Standard Model

- Fermions
  - Composed of leptons and quarks, separated into three "families" by mass
  - Constrained by the Pauli Exclusion Principle
  - Half-integer spin
  - Held together with gluons to form hadrons, such as nucleons
    - Hadrons with three bound quarks are baryons
    - All baryons are fermions (due to spin)
  - Up and down quarks make up ordinary matter
    - Proton is uud, neutron is udd
  - The other quarks are only created in high-energy interactions
  - All leptons are partnered with a neutral lepton, the neutrino
    - Neutrinos only interact with the weak force



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

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

The Standard Model

- Bosons
  - Integer spin
  - Convey force
  - Do not follow Pauli Exclusion Principle
  - Hadrons composed of two bound quarks (mesons)
    - All mesons are bosons (due to spin)
  - Composite mesons exist as well as the gauge bosons shown in the table
    - Muons, pions, kaons
  - 12 gauge bosons in the Standard Model:
    - Photon, 3 weak bosons, and 8 gluons

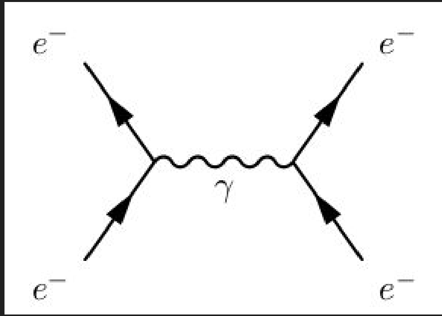
BOSONS force carriers spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

The Standard Model

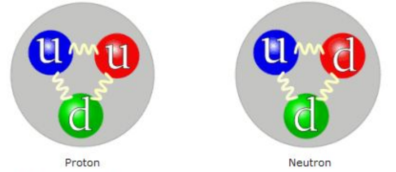
- Quantum Electrodynamics (QED)
  - Quantitative description of the electromagnetic interactions
  - Sinitiro Tomonaga, Julian Schwinger, and Richard Feynman shared the Nobel Prize for Physics for this discovery in 1965
  - the force between two charged particles is characterized by the exchange of a field quantum, the photon
    - Electric charge is conserved in all interactions
    - Feynman Diagrams
      - Aid in calculating cross-sections and decay rates
  - Precisely calculated the electron's magnetic moment



The Standard Model

- Unified Electroweak Theory (Yang-Mills Theory)
    - Yang-Mills - Generalized principle of gauge invariance
    - Requires three massless gauge bosons: one with positive electric charge, one with negative electric charge, and one electrically neutral.
    - Groundwork laid by Yang-Mills led to theoretical breakthroughs
        - 1961 - Sheldon Glashow linked weak interaction with QED by formulating a gauge field theory with three massless vector bosons in addition to the photon
            - Problem solved of no massless vector bosons with the Higgs mechanism, giving the bosons mass
    - **Ultimately became "Self-consistent unified electroweak theory that predicted one massless particle (the photon) and three new massive particles: the W^-, W^+, and Z bosons."**
        - W bosons possess the unique ability to change the flavor of the fermions with which it interacts

The Standard Model



Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

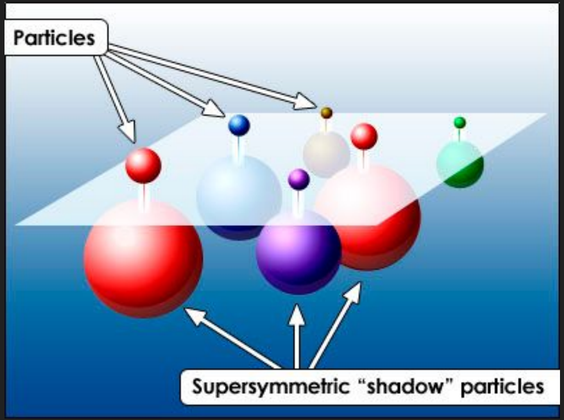
- Quantum Chromodynamics (QCD)
    - “Quantum gauge theory that describes the strongest of the four fundamental interactions”
    - Massless gluons mediate the strong interaction, carrying a “color” charge
    - Difference from QED: gluons themselves carry the color charge and interact among themselves.
        - In QED, photons couple only to electrically charged particles,
    - Quarks experience color confinement, meaning they must always bind with other quarks and antiquarks to create colorless bound states
    - Color charge also solves the problem of the Δ^{++} baryon, which is composed of uuu
        - This quark binding should not be possible due to Pauli Exclusion Principle
            - Only possible through different color quantum states of each quark

Problems with the Standard Model

- Standard Model doesn't include:
  - Gravity
  - Dark Matter and dark energy
  - Neutrino Mass
- Hierarchy problem
  - Masses introduced to Standard Model through Higgs Field mechanism
  - Higgs gets quantum corrections due to heavy virtual particles
  - In turn, the Higgs bare mass gets some number tweaking to balance out the corrections

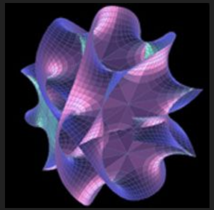
Other Interesting Theories

- Grand Unification Theory - theory that attempts to describe all interactions as one unified model
- Supersymmetry
  - Automatic cancellation of large corrections in hierarchy problem
  - Relates virtual fermions and bosons, ensuring this cancellation
  - Predicts existence of supersymmetric particles (sparticles)
  - May also allow for gravity unification
  - Regular symmetry relates particles of the same spin
  - Includes the graviton and Einstein's theory of gravity
  - All particles assigned to a single irreducible gauge group
    - Restrictive theory so only eight viable models exist



Other Interesting Theories

- String Theory - models all particles as tiny, vibrating, supersymmetric strings
  - To make this math consistent, need to have 10 dimensions
  - How a string vibrates in certain dimensions determines its properties or how we view it
- M-theory - unified theory of the five top superstring theories into one Theory of Everything
  - Added 1 dimension to the existing superstring theories, bringing total to 11
  - The five theories are related by mapping (dualities), implying they are reflections of the same underlying theory
  - No experimental evidence and not even a completed theory
  - Mathematically elegant and relatively simplistic
  - Supported by notables Stephen Hawking and Michio Kaku



Conclusion

- Future Discoveries
  - Three main ways we hope to test for grand unification
    - Predictions for the particle structure and the fundamental couplings
    - Look for rare effects such as proton decay, neutrino mass, etc. which do not occur in the Standard Model
    - Trace the cosmological constraints and interplay between cosmology and particle physics
      - Match evolution and decay of all the particles in the GUT from the Big Bang with current observations
  - The Search for Supersymmetry
  - Attempt to find the graviton

Conclusion

- Fermions and Bosons and the Standard Model
- Problems with the Standard Model
- Grand Unified Theories and looking forward to understanding our reality

References

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Appendix

- Standard Model has three gauge symmetries corresponding to the fundamental interactions [symmetry group U(1)×SU(2)×SU(3)]:
    - color SU(3) (strong interaction)
    - weak isospin SU(2) (electroweak interaction)
    - Hypercharge U(1) (strong interaction)

Gauge fields examples: E-M field, gravitational field

Quantizing the gauge fields gives us the gauge bosons

Transformation between gauges form a Lie group (symmetry group)

The transformations of the field do not change the quantized gauge, thus gauge invariance

Non-Abelian = non-commutative symmetry group