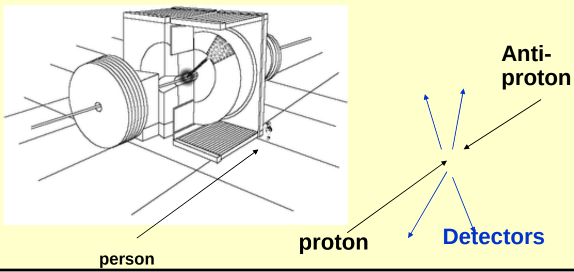
Lecture 24: The fundamental building blocks of matter

"Elementary" Particles: The Ultimate Building Blocks of Matter

- Experiments on very small particles using very large accelerators as "microscopes"
- Fermilab at Batavia, Illinois and CERN at Geneva are the largest physics experiments in the world



Announcements

- Schedule:
  - Today: Current Physics - Elementary Particles of Matter March (Ch 19 +)
  - Next Time: Current Physics - The Universe March (Ch 12 and 20)
  - Dec. 10: Summary of Course
- Homework
  - Report/Essay due Monday Dec. 8
- Final Exam

  Friday, Dec. 19, 7-10 PM
  Room 151 Loomis
  - CONLFICTS????

More Information

- Web Sites
  - Contemporary Physics Education Project provides "The Particle Adventure: An Interactive Tour of the Inner Workings of the Atom and Tools for Discovery"

    http://pdg.lbl.gov/cpep/adventure.html
  - Fermilab WWW site

    http://www.fnal.gov/
  - CERN WWW site

    http://www.cern.ch/

  Very Good

  - Many images in this presentation are from FermiLab WWW pages and the Physics Education Project above

Video: Nova on PBS Oct. 28, Nov 4, 2003 with Brian Greene

Overview

- Where are we?
  - By 1930, we have arrived at a new space-time description of physical events (relativity) and a new description of the interactions in nature (quantum mechanics).
  - Next step: combine the results of these two 20th century revolutions into a single theory which describes the interactions of the fundamental building blocks of nature.
- Today's focus:
  - A snapshot of the developments from 1930 to today.
  - Our focus will be on the search for the ultimate particles.
  - The "Standard Model" that describes know particles today
  - Questions that may lead to future discoveries
- Next Time:
  - The Universe as we see it: Galaxies, Stars, Black Holes, ….
  - Evidence for the "Big Bang"
  - The quantum soup in the first moments of the Universe
  - Will the Universe keep expanding? Will it collapse to a point?

Our Current Theory of Matter

- Quantum Mechanics: The fundamental theory
- Quantum Mechanics leads to the fundamental distinction of two types of particles:
- Fermions: Particles (like electrons) that can be created or destroyed only in combination with its antiparticle
- Bosons: Particles (like photons) that can be created or destroyed in arbitrary numbers
- The Fundamental Forces in Nature act between the particles (Fermions) and are carried by Bosons
- Current Theoretical understanding: The "Standard Model"

The Fundamental Forces

- What are the fundamental forces?
  - Gravity: Holds stars together. The weakest force between fundamental entities. Example: calculate the ratio of the gravitational force to the electrical force between two electrons. Answer $\sim 10^{-42}$!
  - Electromagnetic: Holds atoms together. Much stronger than gravity (and the weak force below) Example: atoms, molecules, solids, …..
  - Strong: Holds the nucleus together. The strongest force at small distances. Example: mesons formed from quarks hold together protons in nucleus – recently "top quark" produced at Fermilab!
  - Weak: Allows for transmutation of elements. Stronger than gravitational force at very short distances. Example: nuclear beta decay
- What does the "Standard Model" have to say about these forces?
  - It gives the form of the weak, electromagnetic and strong forces in terms of the fundamental entities (quarks & leptons) mediated by various bosons.

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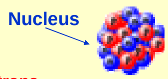
Constituents of the Atom

- Atoms as understood in 1930:
  - electrons, negatively charged "particles" described in terms of quantum states (solutions to Schrodinger's equation).
  - protons, the heavy positive nucleus of the hydrogen atom
  - nuclei, positively charged (must be composed of something more fundamental from which are made the many nuclei observed)
    - 1932: Chadwick observes a penetrating neutral radiation produced in the collision of alpha particles with berylium, the neutron, whose mass is close to that of the proton.
- Great success & simple picture:



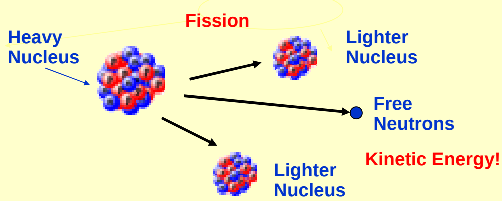
  - All elements are composed of three constituents, electrons, protons and neutrons.
    One other fundamental entity, the photon (the quantum of electromagnetic radiation) is produced when electrons change states in the atom.
  - A given element is defined in terms of how many electrons (which equals the number of protons) it has. Different isotopes correspond to different numbers of neutrons in the nucleus.

1930's

- Hitler comes to power in 1933
- German Science in Turmoil - "Jewish Science" forbidden, . . .
- Einstein happens to be on a visit to Princeton --- which becomes his home for the rest of his life
- Scientists flee - Fermi, Szilard, Teller, . . .
- America becomes the center of science research in the world
- Great progress in areas of quantum mechanics, but not the revolutionary advances of the 1920's

Nuclear Energy

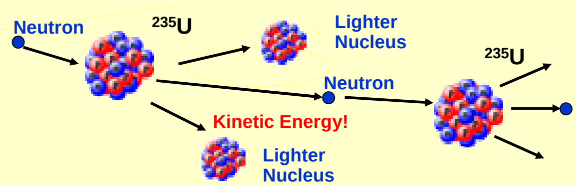
- The Discovery of the Neutron (1932) in England paved the way for the release of nuclear energy
  - Nuclei are neutrons and protons bound by nuclear forces
  - Adding particles to make heavier nuclei increases stability up to a point
  - For nuclei heavier than iron (Fe) stability decreases
  - Very heavy nuclei may decay to nuclei like Fe and release energy



The Chain Reaction and the Release of Nuclear Energy

- Discovered in Berlin in 1938

neutron + ^{235}U → Lighter nuclei + neutrons + energy



- December 2, 1942, First Controlled Chain Reaction
  - Beneath Stagg Field, University of Chicago
    Team led by Enrico Fermi
  - Led to the Manhattan Project

Anything Else?

- Anti-matter
  - Paul Dirac (1927) made the first successful combination of relativity & quantum mechanics. Predicted that for every particle there is an an anti-particle
  - In 1933, Anderson used a cloud chamber to study the naturally occurring cosmic rays. Discovered the "positron", the anti-particle of the electron.
  - Now other antiparticles are known: anti-protons, ….
- More
  - In 1937, Anderson & Neddermeyer discovered another new kind of particle in cosmic rays. This particle, now called the muon, like an electron, but heavier.
  - Then the pion, which decayed into a muon plus another particle (neutrino) assumed to exist to conserve energy. Neutrino interactions were not seen until 1962.

And still more!

- Many new particles were discovered with the advent of particle accelerators in the 1950's (e.g., the Cosmotron at Brookhaven, the Bevatron at Berkeley).
  - Baryons: particles with lifetimes ~ 10^{-10} seconds, ultimately decaying to protons. Anti-particles also seen (anti-proton in 1955)
    - Λ^0, Σ^+, Σ^-, Σ^0, Ξ^-, Ξ^0
  - Mesons: particles with lifetimes ~ 10^{-8} seconds, typically lighter than the proton and never decaying into protons.
    - K^+, K^- , K^0
  - Resonances: Extremely short-lived (~10^{-25} sec). Not seen directly but existence inferred.
    - Baryons: Total = 53 (N, Δ, Λ, Σ, Ξ, Ω)
    - Mesons: Total = 25 (ρ, ω, ϕ, η, K*...)
- Too many particles to all be "elementary" - must be some underlying pattern!

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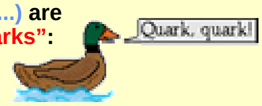
Quarks: Charge +/- 1/3, 2/3 e

•Proposed by Gellman and Zweig, 1963

•Hadrons (protons, neutrons, ...) are made of combinations of "quarks": u(up), d(down) & s(strange)



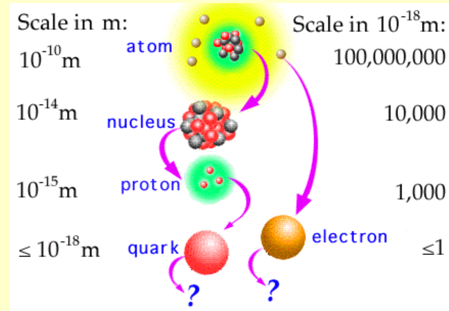
• Mesons: quark-antiquark eg $\pi^+ = u\bar{d}$, $K^+ = u\bar{s}$
• Baryons: quark-quark-quark eg $p = uud$, $\Omega^- = sss$

•Neutron: (u d d) charge = 2/3 - 1/3 - 1/3 = 0

•Proton: (u u d) charge = 2/3 + 2/3 - 1/3 = 1

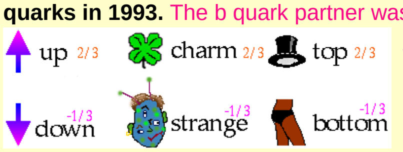
Great success! Particles grouped in families made of quarks. No extra particles!

Scale of Sizes



More Quarks?

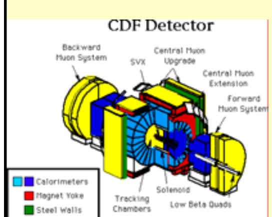
- November, 1974: J/Ψ particle discovered which doesn't fit!
  - Interpretation: evidence for new quark: c (charm). $J/\Psi = c\bar{c}$
- Similar case in 1977: ϒ(Upsilon) particle discovered.
  - Interpretation: evidence for new quark: b (bottom). $\Upsilon = b\bar{b}$
- Five quarks in 1993. The b quark partner was missing!

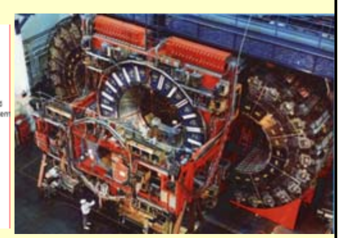


•Search for the top quark. Discovery in 1995 by CDF experiment at Fermilab. UIUC important collaborator.

The CDF Experiment

- CDF detects what is produced when high energy (900 GeV) protons and anti-protons collide.
  - Momenta of charged particles determined by curvature in a magnetic field.
  - Energies of particles determined by energy deposition in calorimeter (measures heat).
  - All particles detected except neutrinos.

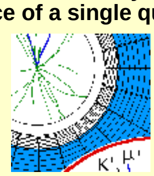




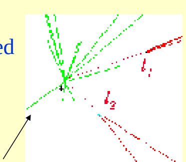
The Top Quark Discovery

- Observe the "Jets" of particles that are decay products of the fleeting existence of a single quark

CDF event display showing fully reconstructed decay of a B meson to a J/psi and a K*.



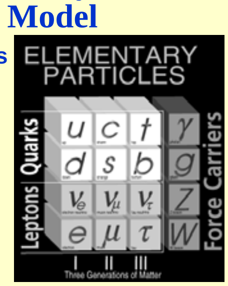
Detailed view of reconstructed charged tracks near the event vertex of a top quark decay in CDF.



Quark

Our Current Theory: The Standard Model

- Fermions: Quarks, Leptons (e.g. electrons)
- Bosons: Force Carriers (e.g. photons)
- Only the quarks feel the effects of the strong nuclear force. Quarks and leptons feel the weak nuclear force. All particles that have electric charge feel the electromagnetic force.



- Baryons (including protons, neutrons, and mesons) are made up of quarks bound together by gluons
- Quarks and Leptons come in pairs (e.g., an electron and its neutrino ν_e)

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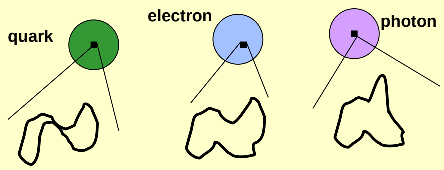
Search for the Ultimate Theory

- The "Theory of everything"
  - Combine quantum theory
    Quarks, Leptons (electrons), photons,

    with Gravity
    (Einstein's theory of space-time)
  - String theory!
    Everything is made of strings
    "Curled up" dimensions

Video: Nova on PBS Oct. 28, Nov 4, 2003 with Brian Greene



Comments & Questions

- The Standard Model gives a unified description of the strong, weak & electromagnetic interactions and the fundamental fermions (quarks & leptons)
  - All known forces are included except gravity
- What more can we want to know?
  - Are there more generations of particles to come?
  - Why is out universe made mainly of matter and not antimatter?
  - Why do some of the fundamental particles have mass?
  - Do neutrinos have mass? A current question bearing on the universe! (Nobel Prize in 2002)
  - Unified "theory of everything"? String theory?
- Connections with cosmology.
  - If the universe started from a Big Bang, then the first second on the life of the universe were a hot quantum soup of these particles! More about this next time.

Summary

- Fundamental Forces
  - Gravity, Electromagnetic, Strong, Weak
- Fundamental Particles
  - Fermions: Quarks, Leptons
  - Bosons: Force Carriers like the photon, gluon
- Electrons are leptons; Neutrons, Protons are made of quarks
- Forces transmitted by exchange of quanta of the force carriers
- The "Standard Model" is the present unified theory of all forces except gravity
- Attempts to make the "Theory of Everything" lead to strange "strings" far beyond the reach of current experiments
- Future??