Into Innerspace

An overview of the femto-cosmos

The Search for Basic Constituents Traces Back to Greek Times

- Atomic Hypothesis from Democritus

- How many "basic" constituents should we expect?
  - Air
  - Fire
  - Earth
  - Water
  Say the Greeks

Atoms make up the everyday material world

- Crystalline arrays – solids
- Loose atoms rattling around – gases
- Sloppy arrangements of atoms – liquids
- We're going to skip over intermediate length scales (biology, materials science, chemistry, condensed matter physics...) and go straight to the atomic scale
- Used to be, we'd say you can't "see" atoms, but now we can! (Atomic Force Microscopy)
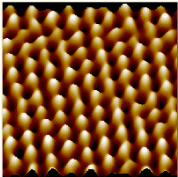

Atoms can now be "seen"

Image of individual atoms in Mica (from www.di.com, Digital Instruments)

see also http://stm2.nrl.navy.mil/how-afm/how-afm.html
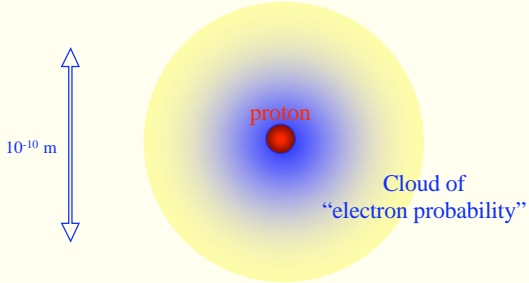

Atoms Are Composite Objects

- **Protons** (+ electric charge), **p**
- **Electrons** (– electric charge), **e**
- **Neutrons** (no charge), **n**
- **Proton** and **Neutron** have about the same mass
- **Electron** is about 2000 times less massive than **proton**
- <u>Electrical Forces</u> produce attraction between **electrons** and the **protons** in the nucleus (they are oppositely charged)

Chemical elements are defined by the number of protons in the atom's nucleus
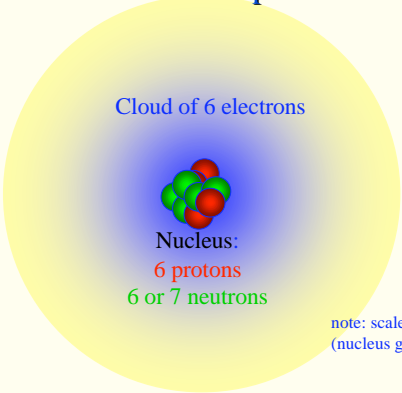
- **Hydrogen: 1 proton & 1 electron**

10^{-10} m

proton

Cloud of
"electron probability"

Carbon has 6 protons

Cloud of 6 electrons

Nucleus:
6 protons
6 or 7 neutrons

note: scale is wrong
(nucleus greatly exaggerated)

The physics of atoms and their nuclei is well understood

- **The breakthroughs were made in the 1920's – 1930's**
  - Quantum Mechanics – discrete energy levels
  - Relativity – things are different when you're really zipping!
- **Evidence for depth of understanding is all around you**
  - Lasers
  - Microwave ovens
  - X-ray imaging
  - Fluorescent lights
  - Nuclear power
- **Quantum Mechanics helps us understand the basic properties of atoms, and explains the grouping in the Periodic Table**

Periodic Table of the Elements

What about the constituents of atoms?

- Separate an electron from the atom for study...

Cloud of electrons

nucleus

Electrons Appear to be Fundamental

- **As far as we can tell, electrons have no ingredients**
- **The lack of substructure makes them useful probes for other particles**
  - Fling them really hard at nuclei to see if they "hit" anything
  - Electron microscopes
  - Particle accelerators

What about substructure in protons and neutrons?

- Can whack protons and neutrons with electrons and see what happens....

proton

Electron
Beam

"Deep Inelastic Scattering" experiments indicate the
electrons occasionally strike hard nuggets in the proton

Quarks!

The Elementary Particles are "Related"

- Electric charge of electron and proton are equal and opposite, to remarkable accuracy
- Neutron left alone for 15 minutes will "Beta-decay" into e, p , neutrino (very light, chargeless lepton)

proton

Poof!

neutron

electron

neutrino

But that's not all!

- Antimatter : Each elementary particle has an "antimatter" counterpart
  - Electron – Positron
  - Proton – Antiproton
  - Neutron – Antineutron
  - etc. – anti-etc.
- $E=mc^2$ says matter and energy are interchangeable
- If they find one another – major fireworks!

Particle-Antiparticle Dating Service: Particle Colliders

- Directing beams of particles and antiparticles at each other at ferocious energies can make new stuff
- It's like reproducing the Big Bang, but at lower energies

particle

Lots 'o stuff

antiparticle

Particle Accelerators are Big!

Short-Lived Matter

- A veritable zoo of particles (muon, tau, mesons, hadrons....)
- Confusion in the 1960's – things seemed to be getting worse!
  - hundreds of "new" particles observed
- Recognition in 1970's, 1980's that there was order to all this mess
  - Electron has two short-lived siblings (muon, tau), each has a neutrino cousin (lepton family)
  - Nuclear matter is made up of 6 quarks, arranged as three generations with 2 members each
  - Imagine all the combinations!

The Standard Model of Particle Physics

Basic Ingredients are quarks and the electron-like objects (leptons)

Fundamental forces are mediated by photon, gluons, W's and Z's (bosons)

(Fermilab)

Quark Soup

- Combinations of quarks make up all the exotic particles cataloged in the 1960s
  - 6 quarks, 6 anti-quarks, grouped in twos and threes
  - Many dozens of combinations, only 1 or 2 stable
  - Charges always come out in integer multiples
- Examples:
  - Up, charm, top quarks have +2/3 charge
  - Down, strange, bottom quarks have –1/3 charge
  - 2u + 1d (uud) → proton, with +1 charge
  - 2d + 1u (ddu) → neutron, with neutral charge

Is There Additional Substructure?

- Much current debate on this topic
- Could all the particles be different "states" of a more basic entity? String theory suggests so.
  - 11 dimensional Universe!?
  - Particles correspond to different string vibrational modes
  - *The Elegant Universe*, by Brian Greene, describes this view
- A difficulty: seems experimentally inaccessible!
  - "Planck Scale", 10^{-35} meters, requires solar-system sized accelerator!

What holds the nucleus together?

- Electrical charges interact, and like charges repel
  - Opposites attract, of course
- The closer they get, the more protons in the nucleus should be repelled from each other!
- Something must serve as the glue to hold the nucleus together
  - The "strong" nuclear force: overcomes the electrical "Coulomb" force at short distances
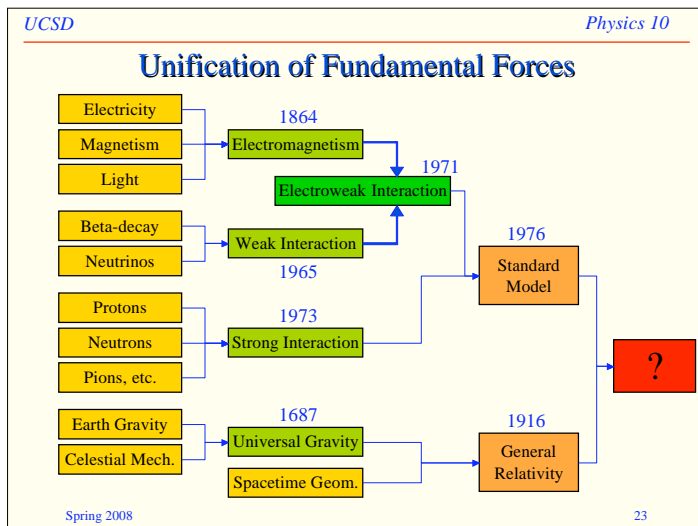 - Felt by quarks, not by electrons or their cousins (collectively called leptons)

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All Forces are Mediated by Exchange Particles

- Strong nuclear force – "gluons" (massive)
- Weak nuclear force – W, Z (massive)
- Electrical and Magnetic phenomena – photon (massless)
- Gravity – graviton (massless, although no one has yet seen one)

- The range (extent) of the force depends on the mass of the exchange particle
  - Which is why the strong and weak forces are remote from everyday experience, being mediated by massive particles
  - Gravity and electromagnetic forces extend infinitely far (though weaken with increased distance)

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Unification of Fundamental Forces

| Electricity |
| Magnetism | → Electromagnetism | 1864 |
| Light |

1971 → Electroweak Interaction

| Beta-decay |
| Neutrinos | → Weak Interaction | 1965 | 1976 → Standard Model |

| Protons |
| Neutrons | → Strong Interaction | 1973 |
| Pions, etc. |

?

| Earth Gravity |
| Celestial Mech. | → Universal Gravity | 1687 | 1916 → General Relativity |
| Spacetime Geom. |

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Assignments

- HW 1 due today (Now)
  - turn in at lecture, or into box outside SERF 336 by 3PM
- Submit Question/Observation TODAY (4/11) by midnight via WebCT
  - hard time cutoff: after this, late submission available for half credit
- HW 2: due Friday (4/18):
  - Hewitt 11.E.16, 11.E.20, 11.E.32, 11.P.5, 2.E.6, 2.E.11, 2.E.14, 2.E.36, 2.E.38, 3.E.4, 3.E.5, 3.E.6, 3.E.19
- Read Hewitt, Chap. 11, pp. 202–217
- Read Hewitt Chapters 2, 3, 4 for next week

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