"Three quarks for Muster Mark!
Sure he has not got much of a bark
And sure any he has it's all beside the mark."

from *Finnegans Wake* (1939) by James Joyce

"In 1963, when I assigned the name "quark" to the fundamental constituents of the nucleon, I had the sound first, without the spelling, which could have been "kwork". Then, in one of my occasional perusals of *Finnegans Wake*, by James Joyce, I came across the word "quark" in the phrase "Three quarks for Muster Mark". Since "quark" (meaning, for one thing, the cry of the gull) was clearly intended to rhyme with "Mark", as well as "bark" and other such words, I had to find an excuse to pronounce it as "kwork". … I argued, therefore, that perhaps one of the multiple sources of the cry "Three quarks for Muster Mark" might be "Three quarts for Mister Mark", in which case the pronunciation "kwork" would not be totally unjustified. In any case, the number three fitted perfectly the way quarks occur in nature."

from *The Quark and the Jaguar (1994)*,
Murray Gell-Mann, American physicist (1929-)

Current Assignments ...

For today

- Sects. 14.3-14.4, 15.1-15.4, Ch. 17

Office hours:
3-4 Tuesdays
& Thursdays

For Lecture 24

- Discussion of exam format
- Review of the course – no new material

Homework #5

- Posted March 21. Due 11:00 AM, Friday, April 5

Writing Assignment #2

- Posted Feb. 28. Due 11:00 AM, Thursday, April 4

Suggested Conceptual Exercises

- Chapter 15: 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23

Tutorial #11

- Homework #4 will be returned; post-class survey

Review of Lecture 22

Textbook, Sections 13.6-13.7

- Observing atomic spectra
- Models of the atom
- The quantum atom
- Energy transitions in atoms

Textbook, Sections 14.1-14.2

- The strong nuclear force
- Nuclear structure

Plan for Lecture 23

Textbook, Sections 14.3-14.4

- Radioactive decay
- Half-life
- Schroedinger's Cat

Textbook, Sections 15.1-15.4

- Nuclear fusion and fission
- The nuclear energy curve

Chapter 17 – *this material will NOT be covered on the exam*

- The idea of a quantized field
- Quantum electrodynamics and antimatter
- Electroweak unification and neutrinos
- Grand unification and quarks
- Quantum gravity and strings

Three Types of Nuclear Reactions

- Radioactive decay
  → Discovered by Henri Becquerel (uranium, 1896) and by Marie and Pierre Curie (radium, 1898), for which they shared 1903 Nobel Prize
- Fusion
- Fission

http://www.atomicarchive.com/Bios/CuriePhoto.shtml

We now know that every isotope whose atomic number is 84 or more is radioactive, as are some isotopes of lighter elements.

Radioactive Decay

- Some nuclei are unstable and spontaneously change their structure (decay).
- Such radioactive nuclei emit three types of radiation: alpha, beta, and gamma rays.

Beta rays (negatively charged)

Gamma rays

Alpha rays (positively charged)

Textbook Figure 14.4

Radioactive Decay

- **Alpha decay:** nucleus emits an alpha particle = ${}^{4}_{2}He$ nucleus = 2 protons + 2 neutrons.
- **Beta decay:** nucleus emits a beta particle = an electron (although no electrons in nucleus!)
- **Gamma decay:** nucleus emits a photon as it returns to its ground state; often follows alpha and beta decay.

Textbook Figure 14.7

Textbook Figure 14.8

Radioactive Decay

- Radioactive decay transforms the nucleus.
  - → Alpha decay decreases the atomic number by 2 and the mass number by 4.
  - → Beta decay increases the atomic number by 1 and does not change the mass number (loses a neutron and gains a proton).
- The energy transformation that takes place in radioactive decay is:

  nuclear energy → thermal energy (kinetic energy of alpha and beta particles) + radiant energy (of gamma photons)

${}^{90}_{38}Sr$ is a radioactive isotope that undergoes beta decay. Its daughter nucleus is

(A) ${}^{86}_{36}Kr$ Krypton

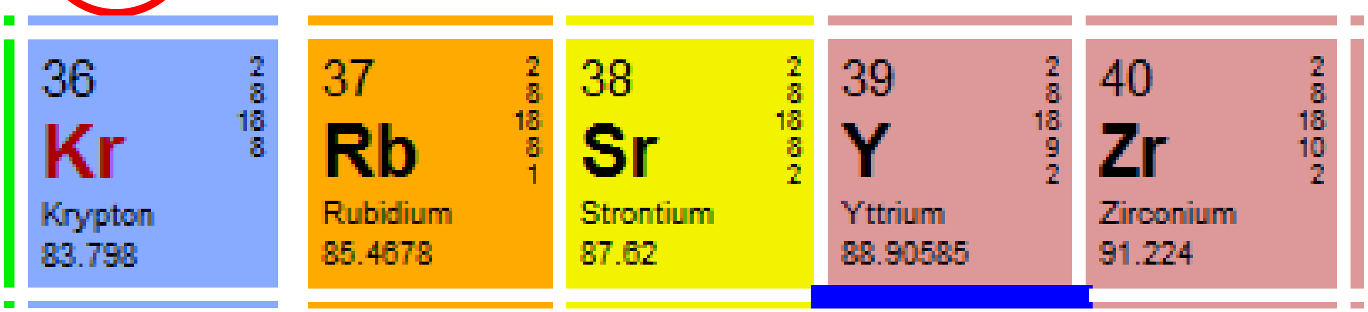
(B) ${}^{88}_{37}Rb$ Rubidium

(C) ${}^{89}_{37}Rb$ Rubidium

(D) ${}^{89}_{39}Y$ Yttrium

(E) ${}^{90}_{39}Y$ Yttrium

Beta decay increases the atomic number by 1 (38 to 39) and does not change the mass number (stays at 90).



Half-Life: When Does a Nucleus Decay?

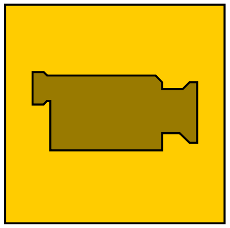
- As with other quantum processes, the time any nucleus will decay cannot be predicted.
- Nuclear decay rates are described by the half-life = the time it takes for half the remaining nuclei to decay.

Textbook
Table 14.1

Rate of Radioactive Decay

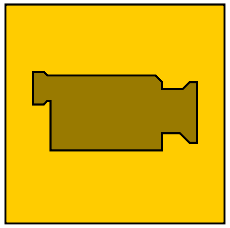
Decay of 500 radioactive atoms of "Balonium"

- http://www.upscale.utoronto.ca/PVB/Harrison/Flash/Nuclear/Decay/NuclearDecay.html



Decay of assorted isotopes

- http://www.colorado.edu/physics/2000/isotopes/radioactive_decay3.html

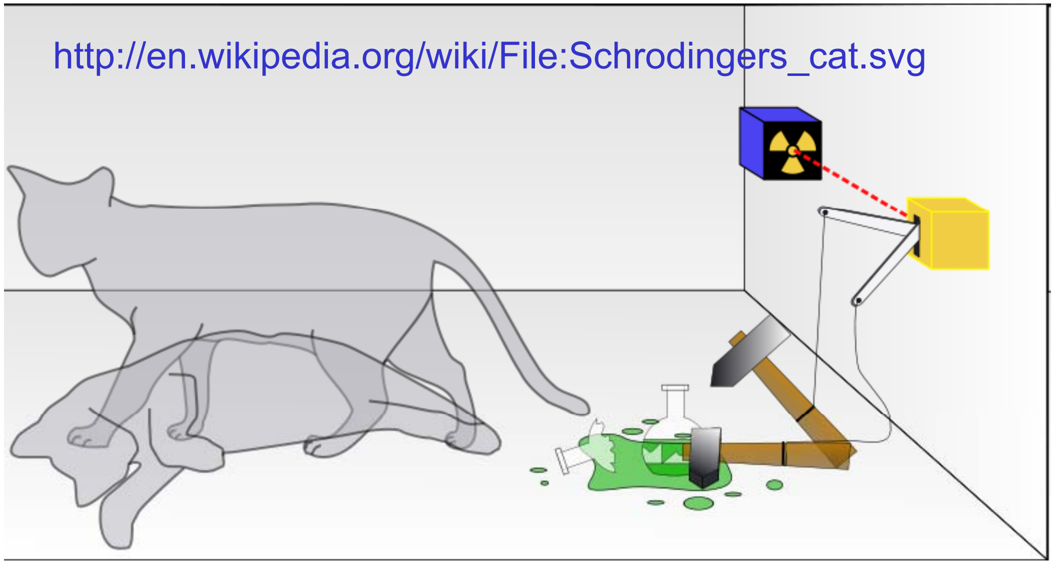


The Universal Decay Curve

It is labeled for ^{14}C, but works for any other isotope with a change of the horizontal scale.

Textbook Figure 14.10

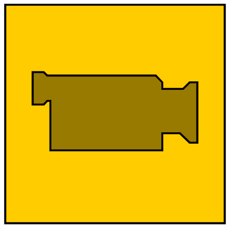
Schroedinger's Cat (1935)



- Imagine a device with one ^{13}N atom and a detector that responds when it decays.
- Connected to the detector is a hammer.
- When the atom decays, the hammer is released and falls on a glass vial containing poison gas.
- The entire apparatus is put in a box with a cat.
- What happens after 10 minutes (^{13}N half-life)?

Is the Cat Dead or Alive?

- After 10 minutes, there is a 50% chance that the atom has decayed.
- Quantum mechanics says that the cat is 50% dead and 50% alive. It has a quantum state in which the living cat and dead cat are mixed in equal proportions.
- But when the box is opened, the cat must be dead or alive. Opening the box collapses the quantum state.
  - → This is similar to the double slit experiment.



http://www.upscale.utoronto.ca/GeneralInterest/Harrison/SchrodCat/SchrodCat.html

Nuclear Fission and Fusion

Textbook Figure 15.1

- Nuclear fission is the splitting of a single nucleus to make two smaller nuclei.
  - → Example: ${}^{2}_{1}H$ (deuterium) + energy → n + p
  - → This requires lots of energy because they are held together by the strong nuclear force.
- Nuclear fusion is the uniting of two small nuclei to make a single larger nucleus.
  - → Example: n + p → ${}^{2}_{1}H$ (deuterium) + energy
  - → Nuclear energy is released.
  - → The energy transformation is Nuclear E → Thermal E + Radiation E

Concept Check 3

Which isotope is created by the fusion of ${}^{1}_{1}H$ with ${}^{2}_{1}H$?

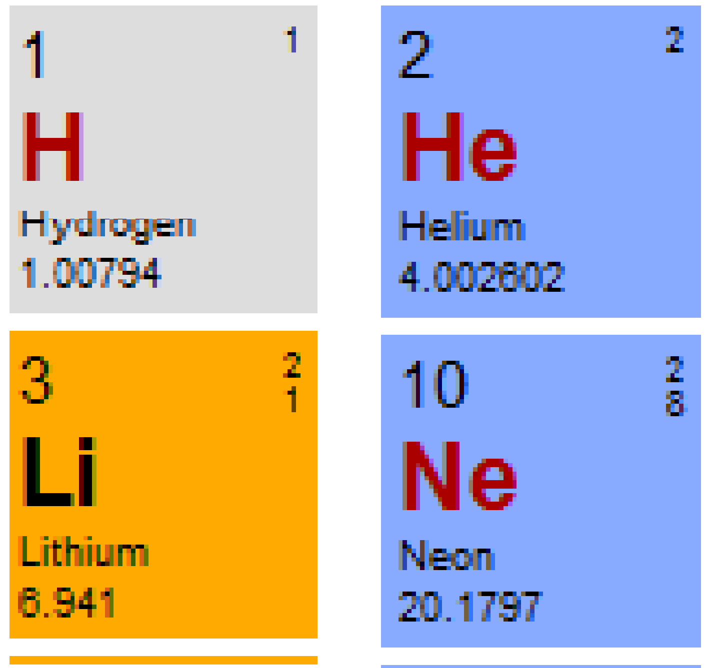
(A) ${}^{3}_{1}H$

(B) ${}^{3}_{2}H$

(C) ${}^{2}_{2}He$

(D) ${}^{3}_{1}He$

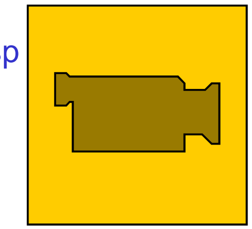
(E) ${}^{3}_{2}He$



The mass numbers add (1+2 = 3) and the atomic numbers add (1+1 = 2). The atomic number (2) defines the element - helium.

Hydrogen-Hydrogen Fusion

- Hydrogen-hydrogen fusion powers the sun and stars: http://www.sciencemuseum.org.uk/exhibitions/energy/site/EIZInfogr7.asp



$$^{1}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + \text{energy}$$

- But the two hydrogen nuclei are positively charged and so they repel each other.
- So this nuclear reaction can only take place at very high temperatures:

$$\text{Thermal } E_{in} + \text{Nuclear } E \rightarrow \text{Thermal } E_{out} + \text{Radiation } E$$

- This reaction can be self-sustaining at sufficiently high temperatures.
  - → This is called a "thermonuclear" reaction.

The Nuclear Energy Curve

Textbook Figure 15.4

Nuclear energy per nuclear particle for all nuclei

Iron is the most stable element

Mass number

Lighter elements can generate energy by fusion

Heavier elements can generate energy by fission

The Origin of the Elements

- The big bang created three elements – hydrogen, helium, and lithium.
- Where did the other elements come from?
- They come from stars. Stars can fuse elements up to iron in their cores; when a massive star collapses into a supernova many different, and heavier, elements are made. The explosion ejects these elements into interstellar space, where they can be part of the formation of new stars.
- You are truly made of star stuff!

The Discovery of Nuclear Fission

- 1933 - Irene Joliot-Curie created the first artificial radioactive isotope (Al + alpha)
- 1934 - Enrico Fermi created 40 new radio-active isotopes by bombarding with neutrons.
- Experiments on neutron bombardment of uranium (element 92) produced lanthanum (element 57) and barium (element 56).
- 1938 - Lise Meitner and Otto Frisch proposed that the addition of an energetic neutron to a uranium nucleus could cause it to oscillate and split into roughly equal fragments.
  - → The discovery of nuclear fission.

Nuclear Fission

Textbook
Figure 15.10

http://www.classzone.com/books/earth_science/terc/content/visualizations/es0702/es0702page01.cfm?chapter_no=visualization

- The nuclear energy curve shows that the final energy < initial energy, so nuclear energy is released.
- Detailed energy calculations confirmed this.
- The "nuclear age" began.

Chapter 17

- The following slides highlight some of the material in Chapter 17.

- None of the material in the following slides or from Chapter 17 will be included in the final exam.

- This is for your interest only!

Quantized Fields

- Core of quantum theory: the universe is made only of fields (EM, gravitational, matter).
- Recall: EM fields fill the universe and have quantized energies. The EM quantum is the photon.
- Matter field quanta are electrons, protons, neutrons, and so on.
- The fundamental ingredients of nature are fields. Both matter and radiation are quantized bundles of field energy.

The Quantum Theory of Fields

- The essential reality is a few fields, such as the EM field, that fill the universe and that are quantized and obey special relativity.
- Everything that happens in nature is a result of changes in these fields.
- Quantization requires that, whenever an interaction occurs, these fields must exhibit themselves as tiny bundles or quanta of field energy.
- All of nature's particles of radiation and matter are quanta of this sort.

Quantum Electrodynamics

- Quantum electrodynamics is the quantum theory of electricity and magnetism.
- Quantized electromagnetic fields interact with quantized matter fields.
- Instead of a continuous force between two electrons, the field theory exchanges a quantum of energy.
- This can be illustrated using "Feynmann diagrams".

Feynmann Diagrams

This diagram shows the interaction of two electrons exchanging a photon.

Textbook Figure 17.2

In this way, energy and momentum are transferred from one electron to the other.

More Feynmann Diagrams

If the electromagnetic force is small (particles far apart), the path looks almost Newtonian (left). If it is large, the path is decidedly non-Newtonian.

weakly interacting electrons

strongly interacting electrons

Textbook Figure 17.3

The Positron

- Quantum field theory predicted the existence of a positive electron - a <u>positron</u> (mass of electron, positive charge).
- Experimentally observed in 1932

→ detected in motion of cosmic rays through a strong magnetic field in a cloud chamber

Positron track

Lead plate

Textbook Figure 17.4

Antiparticles

- Positron - first antiparticle proposed/observed
- Relativity requires that quantum theory be symmetric under time reversal.
  - → This implies that every particle must have an antiparticle of the same mass. Other properties of antiparticles have the same magnitude but opposite sign.
- Antiparticles are created in pairs, and annihilate into photons.

Textbook Figure 17.5

Antimatter

- Antiparticles imply the existence of antimatter.
  - → Single atoms have been created in the lab.
  - → The lack of annihilation radiation (e.g., from colliding matter and antimatter galaxies) argues against large-scale existence of antimatter.
  - → The universe is thought to be mostly matter.
- Current theory holds that there was a tiny (1 part in 10^8) excess of matter over antimatter after the big bang.
  - → All the antimatter annihilated with most of the matter, leaving today's lopsided distribution.

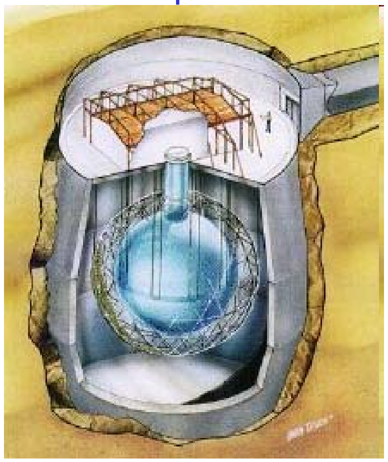
The Muon and Tau Particles

- Since the discovery of the electron and positron, two additional electron-like particles have been discovered:
  - → The muon has about 200 times the mass of the electron.
  - → The tau is about twice the mass of a proton (~3500 times electron mass).
- It is not known why they exist, although the theory that explains the excess of matter over antimatter in the early universe requires all three in order to work.

Neutrinos

- 1930: Wolfgang Pauli proposed that a new particle, a neutrino, was emitted in beta decay.
  - → Enrico Fermi showed that they implied the existence of a new force, the weak nuclear force.
  - → Weaker than EM force, and short range.
- Neutrinos have no electric charge and very little mass. They pass through matter, hardly interacting with it.
  - → Millions are passing through you now!
- Sudbury Neutrino Observatory
  - → Observed solar neutrinos (1999-2006)

http://www.sno.phy.queensu.ca/



The Electroweak Force

- In 1967, Abdus Salam and Steven Weinberg proposed the unification of the EM and weak forces into the electroweak force.
- EM and weak interactions of electrons, positrons, neutrinos, and antineutrinos happen by the exchange of other particles.
- There are four such exchange particles: the photon plus three new ones, the W+, W-, Z.
  - → They are like photons with mass (~100 times the proton mass).
  - → All three new particles have been observed.

The Electroweak Force

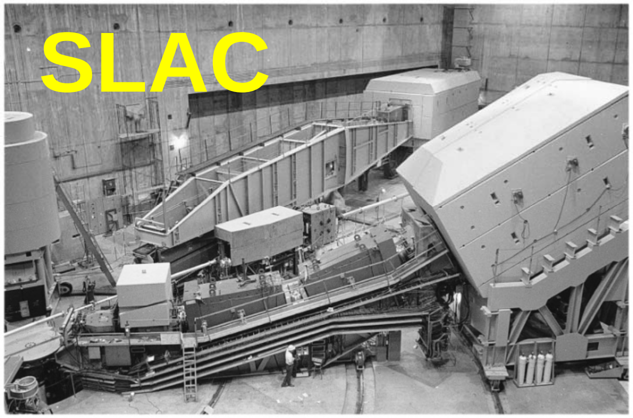
Textbook
Table 17.1

Unifications in Physics

Textbook Figure 17.10

This chart shows the unifications that have been accomplished in physics, as well as those that are yet to come.

Discovery of Quarks



- All electroweak particles are point particles, but protons and neutrons have a finite size.
- 1960s: Murray Gell-Mann proposed that protons and neutrons are made of quarks.
- 1968: Confirmed by experiments at the Stanford Linear Accelerator (SLAC).
  - → Studies of the proton and neutron showed that each contained three small scattering centers – corresponding perfectly to the proposed quarks.

Quarks and the Strong Force

- The force field that is quantized to produce quarks is the strong nuclear force field.
- Two different types of quarks, called up and down quarks, form the neutron and proton, with charges of +2/3e and -1/3e, respectively.
- The field quanta of the strong force are called gluons (because they are like glue).
  - → No mass or charge. Exert and feel strong force.
- There are also three generations of quarks.
  - → Each has heavier and unstable versions of the up and down quarks.

The Strong Force

Textbook
Table 17.2

u = up	c = charm	t = top
d = down	s = strange	b = bottom

Quarks Cannot Be Separated

If you try, you create quark-antiquark pairs.

Textbook Figure 17.15

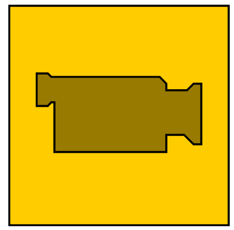
The Standard Model

- The combination of the electroweak theory and the theory of the strong force is called the Standard Model.
  - → It is our current theory of matter at the microscopic level.
  - → It has been thoroughly tested, and works well.
- But it is not complete.
  - → It doesn't include gravity.
  - → It suggests the existence of a new field, called the Higgs field, that gives masses to the elementary particles.

Large Hadron Collider (LHC)

- The world's largest and highest-energy particle accelerator.
  - → Lies in an underground tunnel 27 km in circumference, near Geneva, Switzerland.
- One of its goals - detection of the Higgs particle (mass of gold atom but very unstable)
- 10 Sept 2008 – operational
- 20 Nov 2009 – proton beams circulated
- 30 March 2010 – start of research program with first proton-proton collisions between 3.5 TeV beams, (the highest-energy man-made particle collisions)
- 4 July 2012 – discovery of a new particle “consistent with” the Higgs boson

The LHC Rap



- http://www.youtube.com/watch?gl=GB&hl=en-GB&v=j50ZssEojtM

What About Gravity?

- This drawing illustrates the fundamental conflict between gravity and quantum mechanics.
- General relativity describes a gently curved space.
- Quantum mechanics predicts that, at the smallest scales, space looks like the top pyramid – "quantum foam."

Textbook Figure 17.16

Quantum Gravity?

- A quantum theory of gravity predicts a highly variable curvature of space at the smallest scales (Uncertainty Principle).
  - → Unlike smooth curvature of general relativity.
- Much work has been done to unify gravity and quantum mechanics, but with little success.
  - →The quantum foam tends to yield infinite or negative quantities when calculating probabilities, whose values should be between 0 and 1.

Gravitons

- One fundamental component of any successful quantum theory of gravity is the force carrier, called the graviton.
  - → This is the quantum of the gravitational field.
- It should have zero mass and zero charge.
- The extreme weakness of gravitational interactions between subatomic particles means that gravitons may never be observed even if they do exist.

Fundamental Constants (Hobson)

- The fundamental constants that should appear in any quantum theory of gravity are the speed of light, Planck's constant, and the gravitational constant.
- It is possible to combine these constants in such a way that they yield a distance, called the Planck length, at which quantum gravitational effects become significant. This length is about 10^{-35} m; this is the approximate scale of the quantum foam.

Fundamental Constants (Hobson)

- These constants can also be combined to form a time during which these fluctuations take place; this Planck time is 10^{-43} seconds.
- Finally, the Planck mass, which is the typical energy of gravitational fluctuations, is about 10^{19} times the mass of the proton.
- The Planck mass, time, and length define the Planck scale of quantum-gravitational phenomena.

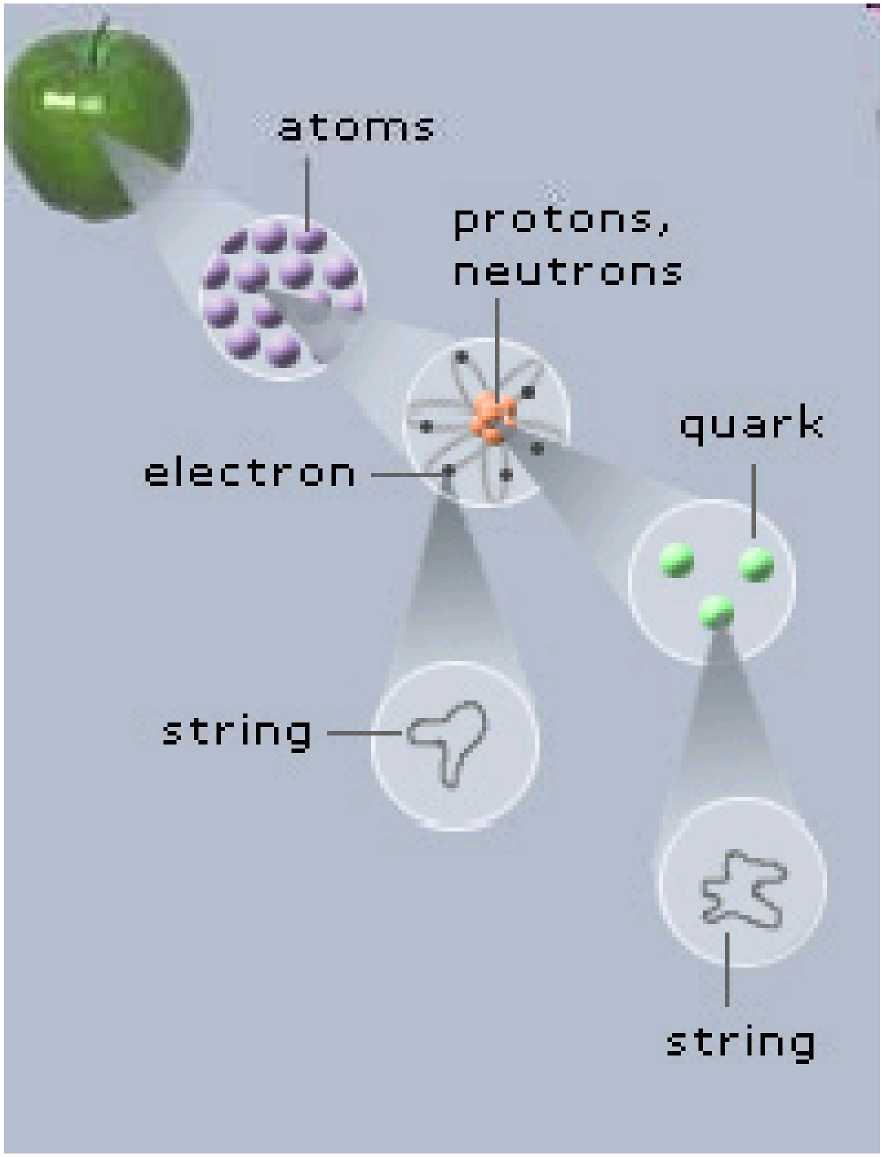
Nature at Planck Scale (Hobson)

- A sphere whose radius is the Planck length will, during time intervals of Planck time, have energy fluctuations as large as the Planck energy.
  - → This will cause spacetime to curve around on itself and split off, creating a small black hole – the weirdness of quantum gravity.
- At the Planck scale, all four forces (electromagnetic, weak, strong, and gravitational) are roughly equal in strength.
  - → Two particles having the Planck mass, separated by the Planck length, and carrying a unit charge will experience EM and gravitational forces that are approx. equal.

String Theory

- The string hypothesis (not yet tested) attempts to unify general relativity and quantum theory.
  - → Fundamental particles are not single points, but very tiny vibrating loops called strings.
- The theory only works if there are 10 spatial dimensions, not 3. Where are the other 7?
  - → String theory suggests that the 7 dimensions are very small, curved in on each other.
  - → These 7 dimensions give the strings enough ways to vibrate so they can successfully describe all the fundamental particles.

String Theory



String Theory in Two Minutes or Less

http://www.youtube.com/watch?v=fvBW_8Jw8Lo&list=PLEC19A1D29048CD71&index=2

http://www.pbs.org/wgbh/nova/elegant/everything.html