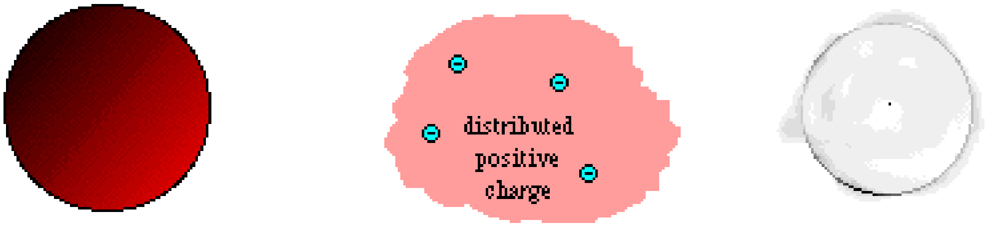
Chapter 2 The Atomic Nucleus

Searching for the ultimate building blocks of the physical world has always been a central theme in the history of scientific research. Many acclaimed ancient philosophers from very different cultures have pondered the consequences of subdividing regular, tangible objects into their smaller and smaller, invisible constituents. Many of them believed that eventually there would exist a final, inseparable fundamental entity of matter, as emphasized by the use of the ancient Greek word, ατομοσ (*atom*), which means "not divisible." Were these atoms really the long sought-after, indivisible, structureless building blocks of the physical world?

The Atom

By the early 20th century, there was rather compelling evidence that matter could be described by an atomic theory. That is, matter is composed of relatively few building blocks that we refer to as atoms. This theory provided a consistent and unified picture for all known chemical processes at that time. However, some mysteries could not be explained by this atomic theory. In 1896, A.H. Becquerel discovered penetrating radiation. In 1897, J.J. Thomson showed that electrons have negative electric charge and come from ordinary matter. For matter to be electrically neutral, there must also be positive charges lurking somewhere. Where are and what carries these positive charges?

A monumental breakthrough came in 1911 when Ernest Rutherford and his coworkers conducted an experiment intended to determine the angles through which a beam of alpha particles (helium nuclei) would scatter after passing through a thin foil of gold.



Indivisible Atom (hard sphere)

'Plum-pudding' Atom

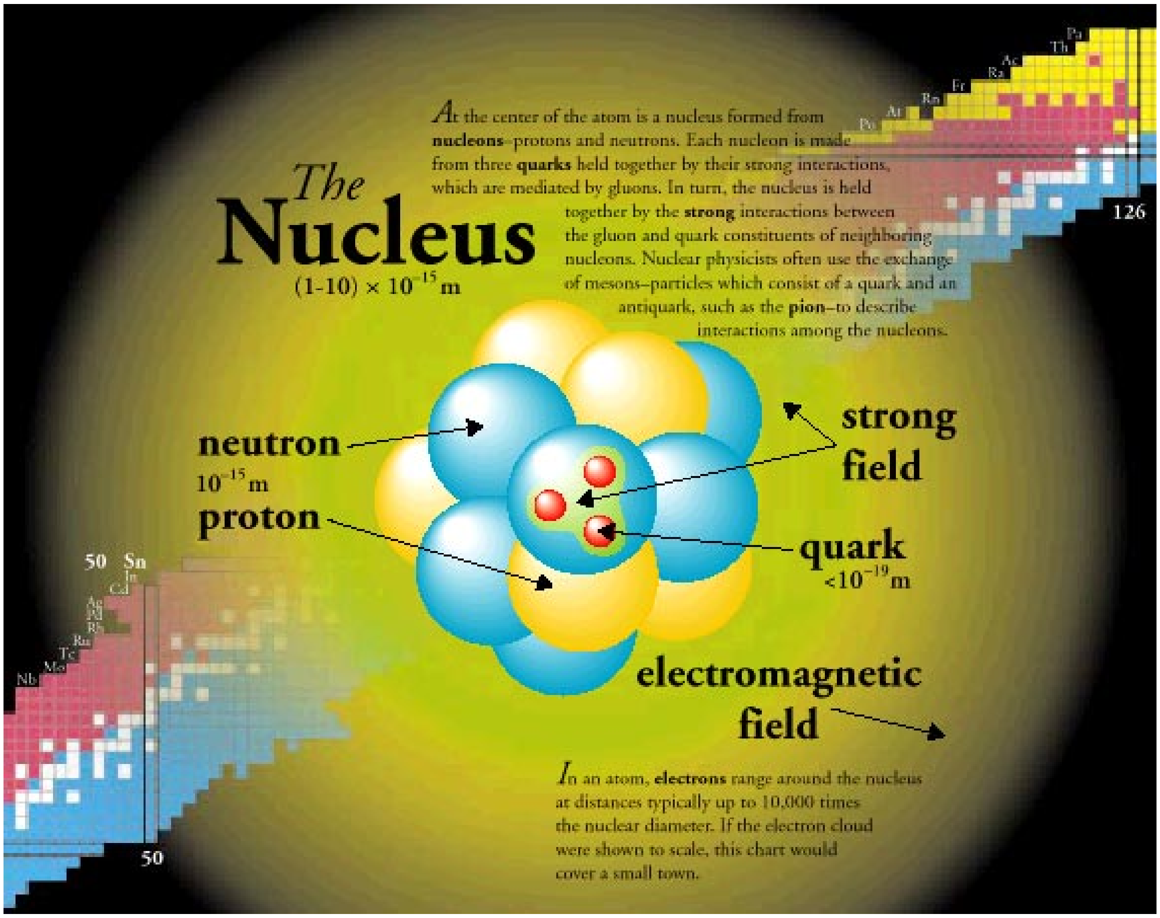
Rutherford Atom

Fig. 2-1. Models of the atom. The dot at the center of the Rutherford atom is the nucleus. The size of the dot is enlarged so that it can be seen in the figure (see Fig. 2-2).

What results would be expected for such an experiment? It depends on how the atom is organized. A prevailing model of the atom at the time (the Thomson, or "plum-pudding," atom) proposed that the negatively charged electrons (the plums) were mixed with smeared-out positive charges (the pudding). This model explained the neutrality of bulk material, yet still allowed the description of the flow of electric charges. In this model, it would be very unlikely for an alpha particle to scatter through an angle greater than a small fraction of a degree, and the vast majority should undergo almost no scattering at all.

The results from Rutherford's experiment were astounding. The vast majority of alpha particles behaved as expected, and hardly scattered at all. But there were alpha particles that scattered through angles greater than 90 degrees, incredible in light of expectations for a "plum-pudding" atom. It was largely the evidence from this type of experiment that led to the model of the atom as having a nucleus. The only model of the atom consistent with this Rutherford experiment is that a small central core (the nucleus) houses the positive charge and most of the mass of the atom, while the majority of the atom's volume contains discrete electrons orbiting about the central nucleus.

Under classical electromagnetic theory, a charge that is moving in a circular path, loses energy. In Rutherford's model, the electrons orbit the nucleus similar to the orbit of planets about the sun. However, under this model, there is nothing to prevent the electrons from losing energy and falling into the nucleus under the influence of its Coulomb attraction. This stability problem was solved by Niels Bohr in 1913 with a new model in which there are particular orbits in which the electrons do not lose energy and therefore do not spiral into the nucleus. This model was the beginning of *quantum mechanics*, which successfully explains many properties of atoms. Bohr's model of the atom is still a convenient description of the energy levels of the hydrogen atom.



At the center of the atom is a nucleus formed from **nucleons**–protons and neutrons. Each nucleon is made from three **quarks** held together by their strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the **strong** interactions between the gluon and quark constituents of neighboring nucleons. Nuclear physicists often use the exchange of mesons–particles which consist of a quark and an antiquark, such as the **pion**–to describe interactions among the nucleons.

In an atom, **electrons** range around the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were shown to scale, this chart would cover a small town.

Fig. 2-2. The nucleus.

The Nucleus

The nucleus depicted in Fig. 2-2 is now understood to be a quantum system composed of protons and neutrons, particles of nearly equal mass and the same intrinsic angular momentum (spin) of 1/2. The proton carries one unit of positive electric charge while the neutron has no electric charge. The term *nucleon* is used for either a proton or a neutron. The simplest nucleus is that of hydrogen, which is just a single proton, while the largest nucleus studied has nearly 300 nucleons. A nucleus is identified as in the example of Fig. 2-3 by its *atomic number Z* (*i.e.*, the number of protons), the *neutron number*, N, and the *mass number*, A, where $A = Z + N$.

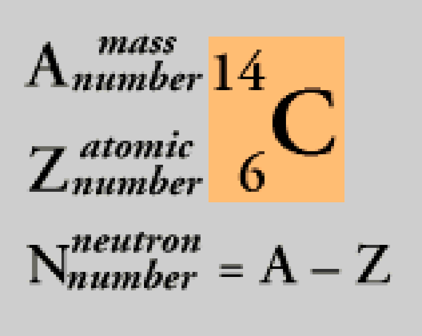


Fig. 2-3. The convention for designating nuclei is by atomic number, Z, and mass number, A, as well as its chemical symbol. The neutron number is given by $N = A - Z$.

What else do we know about the nucleus? In addition to its atomic number and mass number, a nucleus is also characterized by its size, shape, binding energy, angular momentum, and (if it is unstable) *half-life*. One of the best ways to determine the size of a nucleus is to scatter high-energy electrons from it. The angular distribution of the scattered electrons depends on the proton distribution. The proton distribution can be characterized by an average radius. It is found that nuclear radii range from $1\text{-}10 \times 10^{-15}$ m. This radius is much smaller than that of the atom, which is typically 10^{-10} m. Thus, the nucleus occupies an extremely small volume inside the atom. The nuclei of some atoms are spherical, while others are stretched or flattened into deformed shapes.

The binding energy of a nucleus is the energy holding a nucleus together. As shown in Fig. 2-4, this energy varies from nucleus to nucleus and increases as A increases. Because of variations in binding energy, some nuclei are unstable and decay into other ones. The rate of decay is related to the mean lifetime of the decaying nucleus. The time required for half of a population of unstable nuclei to decay is called the half-life. Half-lives vary from tiny fractions of a second to billions of years.

The Isotopes of Hydrogen

It is often useful to study the simplest system. Therefore, hydrogen, the simplest nucleus, has been studied extensively. The *isotopes* of hydrogen show many of the effects found in more complicated nuclei. (The word *isotope* refers to a nucleus with the same Z but different A).

There are three isotopes of the element hydrogen: hydrogen, deuterium, and tritium. How do we distinguish between them? They each have one single proton ($Z = 1$), but differ in the number of their neutrons. Hydrogen has no neutron, deuterium has one, and tritium has two neutrons. The isotopes of hydrogen have, respectively, mass numbers of one, two, and three. Their nuclear symbols are therefore ^{1}H, ^{2}H, and ^{3}H. The atoms of these isotopes have one electron to balance the charge of the one proton. Since chemistry depends on the interactions of protons with electrons, the chemical properties of the isotopes are nearly the same.

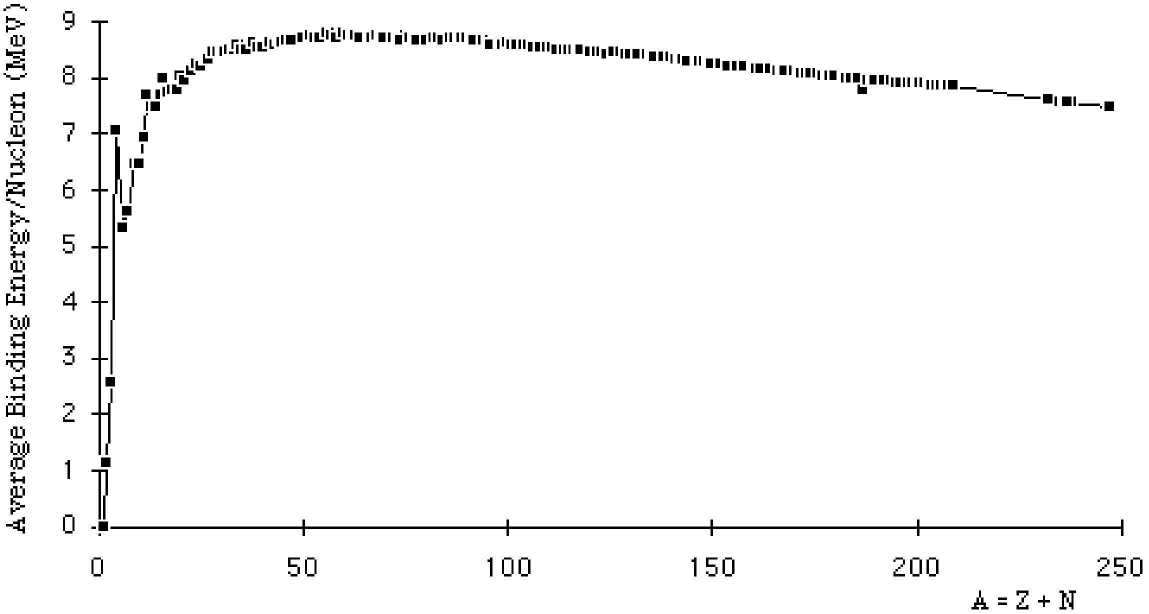


Fig. 2-4. The curve of the average binding energy per nucleon.

Energy may be released as a packet of electromagnetic radiation, a *photon*. Photons created in nuclear processes are labeled *gamma rays* (denoted by the Greek letter gamma, γ). For example, when a proton and neutron combine to form deuterium, the reaction can be written $^1\text{n} + {}^1\text{H} \rightarrow {}^2\text{H} + \gamma$. Energy must balance in this equation. Mass can be written in *atomic mass units* (u) or in the equivalent energy units of million electron-volts divided by the square of the speed of light (MeV)/c^2. (From Einstein's mass-energy equivalence equation, $E = mc^2$, u = 931.5 MeV/c^2.) The mass of the deuterium nucleus (2.01355 u) is less than the sum of the masses of the proton (1.00728 u) and the neutron (1.00866 u), which is 2.01594 u. Where has the missing mass (0.00239 u) gone? The answer is that the attractive nuclear force between the nucleons has created a negative nuclear potential energy—the binding energy E_B—that is related to the missing mass, Δm (the difference between the two masses). The photon released in forming deuterium has an energy of 2.225 MeV, equivalent to the 0.00239 u required to separate the proton and neutron back into unbound particles. The nuclear decay photons are, in general, higher in energy than photons created in atomic processes.

When tritium is formed by adding a neutron to deuterium, $^1\text{n} + {}^2\text{H} \rightarrow {}^3\text{H} + \gamma$, a larger amount of energy is released—6.2504 MeV. The greater binding energy of tritium compared to deuterium shows that the nuclear potential energy does not grow in a simple way with the addition of nucleons (the total binding energy is roughly proportional to A). The binding energy per nucleon continues to grow as protons and neutrons are added to construct more massive nuclei until a maximum of about 8 MeV per nucleon is reached around A = 60, past which the average binding energy per nucleon slowly decreases up to the most massive nuclei, for which it is about 7 MeV.

How does a nucleus, which can have up to approximately 100 protons, hold itself together? Why does the electrical repulsion among all those positive charges not cause the nucleus to break up? There must be an attractive force strong enough to be capable of overcoming the repulsive Coulomb forces between protons. Experiment and theory have come to recognize an attractive nuclear interaction that acts between nucleons when they are close enough together (when the range is short enough). The balance between electromagnetic and nuclear forces sets the limit on how large a nucleus can grow.

Theoretical Models

A goal of nuclear physics is to account for the properties of nuclei in terms of mathematical models of their structure and internal motion. Three important nuclear models are the Liquid Drop Model, the Shell Model (developed by Maria Goeppert-Mayer and Hans Jensen), which emphasizes the orbits of individual nucleons in the nucleus, and the *Collective Model* (developed by Aage Bohr and Ben Mottleson), which complements the shell model by including motions of the whole nucleus such as rotations and vibrations.

The Liquid Drop Model treats the nucleus as a liquid. Nuclear properties, such as the binding energy, are described in terms of volume energy, surface energy, compressibility, etc.—parameters that are usually associated with a liquid. This model has been successful in describing how a nucleus can deform and undergo fission.

The Nuclear Shell Model is similar to the atomic model where electrons arrange themselves into shells around the nucleus. The least-tightly-bound electrons (in the incomplete shells) are known as valence electrons because they can participate in exchange or rearrangement, that is, chemical reactions. The shell structure is due to the quantum nature of electrons and the fact that electrons are *fermions*—particles of half-integer spin. Particles with integer spin are *bosons*. A group of bosons all tend to occupy the same state (usually the state with the lowest energy), whereas fermions with the same quantum numbers do just the opposite: they avoid each other. Consequently the fermions in a bound system will gradually fill up the available states: the lowest one first, then the next higher unoccupied state, and so on up to the valence shell. In atoms, for example, the electrons obey the *Pauli Exclusion Principle*, which is responsible for the observed number of electrons in each possible state (at most 2) characterized by quantum numbers n, l, and m. It is the Pauli Principle (based on the fermionic nature of electrons) that gives the periodic structure to both atomic and nuclear properties.

Since protons and neutrons are also fermions, the energy states the nucleons occupy are filled from the lowest to the highest as nucleons are added to the nucleus. In the shell model the nucleons fill each energy state with nucleons in orbitals with definite angular momentum. There are separate energy levels for protons and neutrons. The ground state of a nucleus has each of its protons and neutrons in the lowest possible energy level. Excited states of the nucleus are then described as promotions of nucleons to higher energy levels. This model has been very successful in explaining the basic nuclear properties. As is the case with atoms, many nuclear properties (angular momentum, magnetic moment, shape, etc.) are dominated by the last filled or unfilled valence level.

The Collective Model emphasizes the coherent behavior of all of the nucleons. Among the kinds of collective motion that can occur in nuclei are rotations or vibrations that involve the entire nucleus. In this respect, the nuclear properties can be analyzed using the same description that is used to analyze the properties of a charged drop of liquid suspended in space. The Collective Model can thus be viewed as an extension of the Liquid Drop Model; like the Liquid Drop Model, the Collective Model provides a good starting point for understanding fission.

In addition to fission, the Collective Model has been very successful in describing a variety of nuclear properties, especially energy levels in nuclei with an even number of protons and neutrons. These even nuclei can often be treated as having no valence particles so that the Shell Model does not apply. These energy levels show the characteristics of rotating or vibrating systems expected from the laws of quantum mechanics. Commonly measured properties of these nuclei, including broad systematics of excited state energies, angular momentum, magnetic moments, and nuclear shapes, can be understood using the Collective Model.

The Shell Model and the Collective Model represent the two extremes of the behavior of nucleons in the nucleus. More realistic models, known as unified models, attempt to include both shell and collective behaviors.

Sub-nucleonic Structure and the Modern Picture of a Nucleus

Do protons and neutrons have internal structure? The answer is yes. With the development of higher and higher energy particle accelerators, physicists have found experimentally that the nucleons are complex objects with their own interesting internal structures.

One of the most significant developments in modern physics is the emergence of the *Standard Model* of Fundamental Interactions (Fig. 2-5). This model states that the material world is made up of two categories of particles, *quarks* and *leptons*, together with their antiparticle counterparts. The leptons are either neutral (such as the neutrino) or carry one unit of charge, *e* (such as the electron, muon, and tau). The quarks are pointlike objects with charge 1/3*e* or 2/3 *e*. Quarks are spin-1/2 particles, and therefore are fermions, just as electrons are.

The quarks and leptons can be arranged into three families. The up- and down-quarks with the electron and the electron neutrino form the family that makes up ordinary matter. The other two families produce particles that are very short-lived and do not significantly affect the nucleus. It is a significant fact in the evolution of the universe that only three such families are found in nature—more families would have lead to a quite different world.

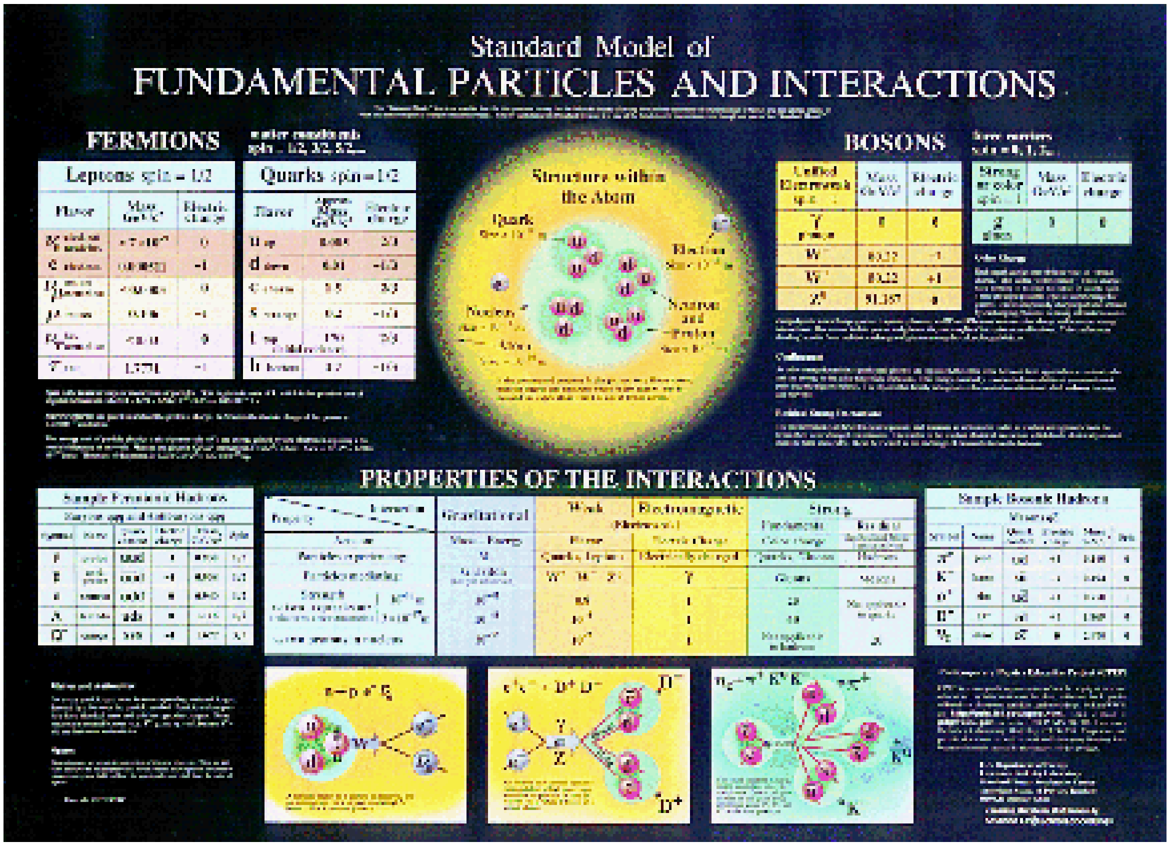


Fig. 2-5. The Standard Model of Particles and Interactions

One could imagine, then, trying to understand the structure of protons and neutrons in terms of the fundamental particles described in the Standard Model. Because the protons and neutrons of ordinary matter are affected by the strong interaction (i.e., the interaction that binds quarks and that ultimately holds nuclei together), they fall into the category of composite particles known as hadrons. Hadrons that fall into the subcategory known as baryons are made of three quarks. Protons, which consist of two up and one down quark, and neutrons (two down and one up quark) are baryons. There are also hadrons called mesons, which are made of quark-antiquark pairs, an example of which is the pion.

Because baryons and mesons have internal quark structure, they can be put into excited states, just as atoms and nuclei can. This requires that energy be deposited in them. One example is the first excited state of the proton, usually referred to as the Delta-1232 (where 1232 MeV/c^2 is the mass of the particle). In the Delta, it is thought that one of the quarks gains energy by flipping its spin with respect to the other two. In an atom, the energy needed to excite an electron to a higher state is on the order of a few to a thousand electron volts. In comparison, in a nucleus, a single nucleon excitation typically costs an MeV (10^6 eV). In a proton, it takes about 300 MeV to flip the spin of a quark. This kind of additional energy is generally only available by bombarding the proton with energetic particles from an accelerator.

Finding a proper theoretical description of the excited states of baryons and mesons is an active area of research in nuclear and particle physics. Because the excited states are generally very short-lived; they are often hard to identify. Research tools at the newly commissioned Jefferson Lab accelerator have been specially designed to look at the spectrum of mesons and baryons. Such research is also being actively pursued at Brookhaven National Laboratory and at many other laboratories. To study the Standard Model, accelerators that produce much higher energy beams are often needed. Such facilities include Fermilab, near Chicago, SLAC at Stanford, and CERN in Geneva. Accelerators for nuclear physics are described in more detail in Chapter 11.

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Web Sites:

The Particle Adventure - http://pdg.lbl.gov/cpep/adventure.html. Developed by CPEP to go along with their popular Standard Model Chart (Fig. 2-5). This web site has won numerous awards.