THE NUCLEUS

Nuclear Energy Levels

A nucleus consists of two types of particles, referred to collectively as nucleons. The positive charge and roughly half the mass of the nucleus are contributed by protons. Each proton possesses a positive charge of $+1.6 \times 10^{-19}$ coulombs, equal in magnitude but opposite in sign to the charge of an electron. The number of protons (or positive charges) in the nucleus is the atomic number of the atom. The mass of a proton is 1.6734×10^{-27} kg. Neutrons, the second type of nucleon, are uncharged particles with a mass of 1.6747×10^{-27} kg. Outside the nucleus, neutrons are unstable and divide into protons, electrons, and antineutrinos (see Chapter 3). The half-life of this transition is 12.8 minutes. Neutrons are usually stable inside nuclei. The number of neutrons in a nucleus is the neutron number N for the nucleus. The mass number A of the nucleus is the number of nucleons (neutrons and protons) in the nucleus. The mass number $A = Z + N$.

The standard form used to denote the composition of a specific nucleus is

$$^{A}_{Z}\mathrm{X}$$

where X is the chemical symbol (e.g., H, He, Li) and A and Z are as defined above. There is some redundancy in this symbolism. The atomic number, Z, is uniquely associated with the chemical symbol, X. For example, when $Z = 6$, the chemical symbol is always C, for the element carbon.

Expressing the mass of atomic particles in kilograms is unwieldy because it would be a very small number requiring scientific notation. The atomic mass unit (amu) is a more convenient unit for the mass of atomic particles. 1 amu is defined as 1/12 the mass of the carbon atom, which has six protons, six neutrons, and six electrons. Also,

$$1 \text{ amu} = 1.6605 \times 10^{-27} \text{ kg}$$

The shell model of the nucleus was introduced to explain the existence of discrete nuclear energy states. In this model, nucleons are arranged in shells similar to those available to electrons in the extranuclear structure of an atom. Nuclei are extraordinarily stable if they contain 2, 8, 14, 20, 28, 50, 82, or 126 protons or similar numbers of neutrons. These numbers are termed magic numbers and may reflect full occupancy of nuclear shells. Nuclei with odd numbers of neutrons or protons tend to be less stable than nuclei with even numbers of neutrons and protons. The pairing of similar nucleons increases the stability of the nucleus. Data tabulated below support this hypothesis.

Number of Protons	Number of Neutrons	Number of Stable Nuclei
Even	Even	165
Even	Odd	57
Odd	Even	53
Odd	Odd	6

Nuclear Forces and Stability

Protons have "like" charges (each has the same positive charge) and repel each other by the electrostatic force of repulsion. One may then ask the question, How does a nucleus stay together? The answer is that when protons are very close together, an attractive force comes into play. This force, called the "strong nuclear force," is 100 times greater than the electrostatic force of repulsion. However, it acts only over distances of the order of magnitude of the diameter of the nucleus. Therefore, protons can stay together in the nucleus once they are there. Assembling a nucleus by forcing protons together requires the expenditure of energy to overcome the electrostatic repulsion. Neutrons, having no electrostatic charge, do not experience the electrostatic force. Therefore, adding neutrons to a nucleus requires much less energy. Neutrons are, however,

Superconductors have zero resistance to the flow of electricity. They also exhibit another interesting property called the Meisner Effect: If a superconductor is placed in a magnetic field, the magnetic field lines flow around it. That is, the superconductor excludes the magnetic field. This can be used to create a form of magnetic levitation.

As of this writing, magnetic resonance imagers are the only devices using the principles of superconductivity that a typical layperson might encounter. Other applications of superconductivity are found chiefly in research laboratories.

The word "atom" comes from the Greek "atomos" which means "uncuttable."

The half-life for decay of the neutron is 12.8 minutes. This means that in a collection of a large number of neutrons, half would be expected to undergo the transition in 12.8 minutes. Every 12.8 minutes, half the remaining number would be expected to decay. After 7 half-lives (3.7 days), fewer than 1% would be expected to remain as neutrons.

Masses of atomic particles are as follows:

$$\text{Electron} = 0.00055 \text{ amu}$$

$$\text{Proton} = 1.00727 \text{ amu}$$

$$\text{Neutron} = 1.00866 \text{ amu}$$

Note that the proton and neutron have a mass of approximately 1 amu and that the neutron is slightly heavier than the proton.

Quantum Electrodynamics (QED)
Modern quantum mechanics explains a force in terms of the exchange of "messenger particles." These particles pass between (are emitted and then absorbed by) the particles that are affected by the force.
The messenger particles are as follows:

Force	Messenger
Strong nuclear	Gluon
Electromagnetic	Photon
Weak nuclear	"W" and "Z"
Gravity	Graviton

affected by a different "weak nuclear force." The weak nuclear force causes neutrons to change spontaneously into protons plus almost massless virtually noninteracting particles called neutrinos. The opposite transition, protons turning into neutrons plus neutrinos, also occurs. These processes, called beta decay, are described in greater detail in Chapter 3. The fourth of the traditional four "fundamental forces" of nature, gravity, is extremely overshadowed by the other forces within an atom, and thus it plays essentially no role in nuclear stability or instability. The relative strengths of the "four forces" are as follows:

Type of Force	Relative Strength
Nuclear	1
Electrostatic	10^{-2}
Weak	10^{-13}
Gravitational	10^{-39}

Of these forces, the first three have been shown to be manifestations of the same underlying force in a series of "Unification Theories" over recent decades. The addition of the fourth, gravity, would yield what physicists term a "Grand Unified Theory," or GUT.

Nuclear Binding Energy

The mass of an atom is less than the sum of the masses of its neutrons, protons, and electrons. This seeming paradox exists because the binding energy of the nucleus is so significant compared with the masses of the constituent particles of an atom, as expressed through the equivalence of mass and energy described by Einstein's famous equation.[29]

$$E = mc^2$$

The mass difference between the sum of the masses of the atomic constituents and the mass of the assembled atom is termed the *mass defect*. When the nucleons are separate, they have their own individual masses. When they are combined in a nucleus, some of their mass is converted into energy. In Einstein's equation, an energy E is equivalent to mass m multiplied by the speed of light in a vacuum, c (2.998×10^8 m/sec) squared. Because of the large "proportionality constant" c^2 in this equation, one kilogram of mass is equal to a large amount of energy, 9×10^{16} joules, roughly equivalent to the energy released during detonation of 30 megatons of TNT. The energy equivalent of 1 amu is

$$\frac{(1\text{ amu})(1.660 \times 10^{-27}\text{ kg/amu})(2.998 \times 10^{8}\text{ m/sec})^2}{(1.602 \times 10^{-13}\text{ J/Mev})} = 931\text{ MeV}$$

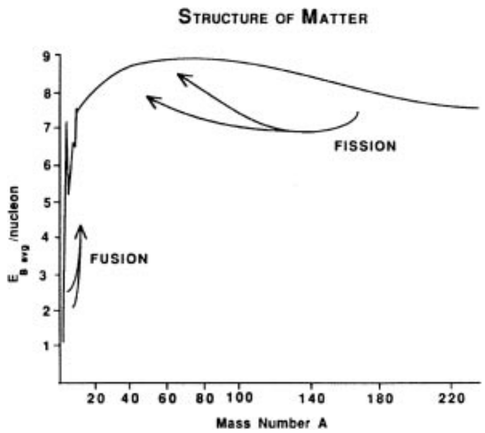
The binding energy (mass defect) of the carbon atom with six protons and six neutrons (denoted as $^{12}_{6}C$) is calculated in Example 2-2.

Example 2-2

$$\begin{aligned}
\text{Mass of 6 protons} &= 6(1.00727\text{ amu}) = 6.04362\text{ amu}\\
\text{Mass of 6 neutrons} &= 6(1.00866\text{ amu}) = 6.05196\text{ amu}\\
\text{Mass of 6 electrons} &= 6(0.00055\text{ amu}) = 0.00330\text{ amu}\\
\text{Mass of components of } ^{12}_{6}\text{C} &= 12.09888\text{ amu}\\
\text{Mass of } ^{12}_{6}\text{C atom} &= 12.00000\text{ amu}\\
\text{Mass defect} &= 0.09888\text{ amu}\\
\text{Binding energy of } ^{12}_{6}\text{C atom} &= (0.09888\text{ amu})(931\text{ MeV/amu})\\
&= 92.0\text{ MeV}
\end{aligned}$$

Almost all of this binding energy is associated with the ${}^{12}_{6}C$ nucleus. The average binding energy per nucleon of ${}^{12}_{6}C$ is 92.0 MeV per 12 nucleons, or 7.67 MeV per nucleon.

In Margin Figure 2-8 the average binding energy per nucleon is plotted as a function of the mass number A.



MARGIN FIGURE 2-8
Average binding energy per nucleon versus mass number.

NUCLEAR FISSION AND FUSION

Energy is released if a nucleus with a high mass number separates or fissions into two parts, each with an average binding energy per nucleon greater than that of the original nucleus. The energy release occurs because such a split produces low-Z products with a higher average binding energy per nucleon than the original high-Z nucleus (Margin Figure 2-8). A transition from a state of lower "binding energy per nucleon" to a state of higher "binding energy per nucleon" results in the release of energy. This is reminiscent of the previous discussion of energy release that accompanies an L to K electron transition. However, the energy available from a transition between nuclear energy levels is orders of magnitude greater than the energy released during electron transitions.

"The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from the transformation of these atoms is talking moonshine."
E. Rutherford, 1933.

The critical mass of ${}^{235}U$ is as little as 820 g if in aqueous solution or as much as 48.6 kg if a bare metallic sphere.[30]

Certain high-A nuclei (e.g., ${}^{235}U$, ${}^{239}Pu$, ${}^{233}U$,) fission spontaneously after absorbing a slowly moving neutron. For ${}^{235}U$, a typical fission reaction is

$${}^{235}_{92}U + \text{neutron} \rightarrow {}^{236}_{92}U \rightarrow {}^{92}_{36}Kr + {}^{141}_{56}Ba + 3\ \text{neutrons} + Q$$

The energy released is designated as Q and averages more than 200 MeV per fission. The energy is liberated primarily as γ radiation, kinetic energy of fission products and neutrons, and heat and light. Products such as ${}^{92}_{36}Kr$ and ${}^{141}_{56}Ba$ are termed fission by-products and are radioactive. Many different by-products are produced during fission. Neutrons released during fission may interact with other ${}^{235}U$ nuclei and create the possibility of a chain reaction, provided that sufficient mass of fissionable material (a critical mass) is contained within a small volume. The rate at which a material fissions may be regulated by controlling the number of neutrons available each instant to interact with fissionable nuclei. Fission reactions within a nuclear reactor are controlled in this way. Uncontrolled nuclear fission results in an "atomic explosion."

Nuclear fission was observed first in 1934 during an experiment conducted by Enrico Fermi.[31, 32] However, the process was not described correctly until publication in 1939 of analyses by Hahn and Strassmann[33] and Meitner and Frisch.[34] The first controlled chain reaction was achieved in 1942 at the University of Chicago. The first atomic bomb was exploded in 1945 at Alamogordo, New Mexico.[35]

Certain low-mass nuclei may be combined to produce a nucleus with an average binding energy per nucleon greater than that for either of the original nuclei. This process is termed nuclear fusion (Margin Figure 2-8) and is accompanied by the release of large amounts of energy. A typical reaction is

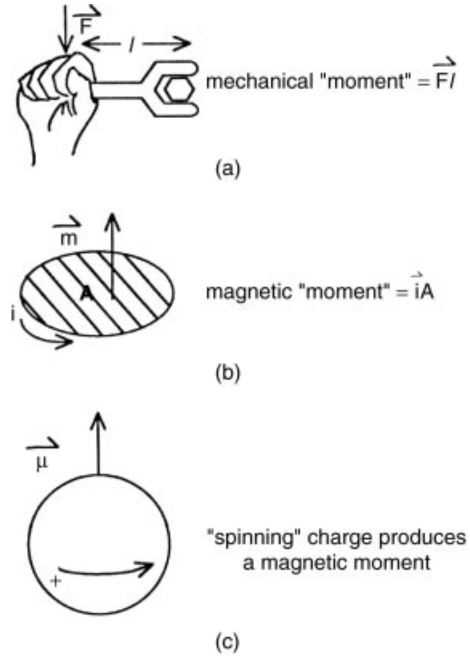
$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + \text{neutron} + Q$$

In this particular reaction, $Q = 18$ MeV.

To form products with higher average binding energy per nucleon, nuclei must be brought sufficiently near one another that the nuclear force can initiate fusion. In the process, the strong electrostatic force of repulsion must be overcome as the two nuclei approach each other. Nuclei moving at very high velocities possess enough momentum to overcome this repulsive force. Adequate velocities may be attained by heating a sample containing low-Z nuclei to a temperature greater than 12×10^{6} °K, roughly equivalent to the temperature in the inner region of the sun. Temperatures this high may be attained in the center of a fission explosion. Consequently, a fusion (hydrogen) bomb is "triggered" with a fission bomb. Controlled nuclear fusion has not

The only nuclear weapons used in warfare were dropped on Japan in 1945. The Hiroshima bomb used fissionable uranium, and the Nagasaki bomb used plutonium. Both destroyed most of the city on which they fell, killing more than 100,000 people. They each released energy equivalent to about 20,000 tons of TNT. Large fusion weapons (H-bombs) release up to 1000-fold more energy.

yet been achieved on a macroscopic scale, although much effort has been expended in the attempt.



MARGIN FIGURE 2-9
The concept of a "moment" in physics. **A**: A mechanical moment is defined by force **F** and length l. **B**: A magnetic moment is defined by current i and the area A enclosed by the current. **C**: The magnetic moment produced by a spinning charged object.

NUCLEAR SPIN AND NUCLEAR MAGNETIC MOMENTS

Protons and neutrons behave like tiny magnets and are said to have an associated magnetic moment. The term *moment* has a strict meaning in physics. When a force is applied on a wrench to turn a bolt (Margin Figure 2-9A), for example, the mechanical moment is the product of force and length. The mechanical moment can be increased by increasing the length of the wrench, applying more force to the wrench, or a combination of the two. A magnetic moment (Margin Figure 2-9B) is the product of the current in a circuit (a path followed by electrical charges) and the area encompassed by the circuit. The magnetic moment is increased by increasing the current, the area, or a combination of the two. The magnetic moment is a vector, a quantity having both magnitude and direction.

Like electrons, protons have a characteristic called "spin," which can be explained by treating the proton as a small object spinning on its axis. In this model, the spinning charge of the proton produces a magnetic moment (Margin Figure 2-9C).

The "spinning charge" model of the proton has some limitations. First, the mathematical prediction for the value of the magnetic moment is not equal to what has been measured experimentally. From the model, a proton would have a fundamental magnetic moment known as the nuclear magneton, u_n:

$$u_n = \frac{e\hbar}{2m_p} = 3.1525 \times 10^{-12} \text{ eV/gauss}$$

where e is the charge of the proton in coulombs, $\hbar$ is Planck's constant divided by 2π, and m_p is the mass of the proton. The magnetic moment magneton, u_p of the proton, however, is

$$u_p = \text{magnetic moment of the proton} = 2.79u_n$$

The unit of the nuclear magneton, energy (electron volt) per unit magnetic field strength (gauss), expresses the fact that a magnetic moment has a certain (potential) energy in a magnetic field. This observation will be used later to describe the fundamental concepts of magnetic resonance imaging (MRI).

The second difficulty of the spinning proton model is that the neutron, an uncharged particle, also has a magnetic moment. The magnetic moment of the neutron equals $1.91u_n$. The explanation for the "anomalous" magnetic moment of the neutron, as well as the unexplained value of the proton's magnetic moment, is that neutrons and protons are not "fundamental" particles. Instead, they are each composed of three particles called quarks[39] that have fractional charges that add up to a unit charge. Quarks do not exist on their own but are always bound into neutrons, protons, or other particles. The presence of a nonuniform distribution of spinning charges attributable to quarks within the neutron and proton explains the observed magnetic moments.

The magnetic moment of the proton was first observed by Stern and colleagues in 1933.[36, 37] The magnetic moment of the neutron was measured by Alvarez and Bloch in 1940.[38] Bloch went on to write the fundamental equations for the "relaxation" of nuclear spins in a material in a static magnetic field that has been perturbed by radiofrequency energy. These equations are the basis of magnetic resonance imaging.

When magnetic moments exist near each other, as in the nucleus, they tend to form pairs with the vectors of the moments pointed in opposite directions. In nuclei with even numbers of neutrons and protons (i.e., even Z, even N), this pairing cancels out the magnetic properties of the nucleus as a whole. Thus an atom such as $^{12}_{6}C$ with 6 protons and 6 neutrons has no net magnetic moment because the neutrons and protons are "paired up."

An atom with an odd number of either neutrons or protons will have a net magnetic moment. For example, $^{13}_{6}C$ with 6 protons and 7 neutrons has a net magnetic moment because it contains an unpaired neutron. Also, $^{14}_{7}N$ with 7 protons and 7 neutrons has a small net magnetic moment because both proton and neutron numbers are odd and the "leftover" neutron and proton do not exactly cancel each other's moments. Table 2-3 lists a number of nuclides with net magnetic moments. The

TABLE 2-3 Nuclides with a Net Magnetic Moment[a]

Nuclide	*Number of Protons*	*Number of Neutrons*	*Magnetic Moment (Multiple of u_n)*
^{1}H	1	0	2.79
^{2}H	1	1	0.86
^{13}C	6	7	0.70
^{14}N	7	7	0.40
^{17}O	8	9	−1.89
^{19}F	9	10	2.63
^{23}Na	11	12	2.22
^{31}P	15	16	1.13
^{39}K	19	20	0.39

[a] Data from Heath, R. L. Table of the Isotopes, in Weast, R. C., et al.(eds.), *Handbook of Chemistry and Physics*, 52nd edition. Cleveland, Chemical Rubber Co., 1972, pp. 245–256.

"Virtual particles" such as quark–antiquark pairs, or "messenger particles" that carry forces between particles, can appear and disappear during a time interval Δt so long as $\Delta t < h/\Delta E$. ΔE is the change in mass/energy of the system that accounts for the appearance of the particles, and h is Planck's constant. This formula is one version of Heisenberg's Uncertainty Principle. In the nucleus, the time interval is the order of magnitude of the time required for a beam of light to cross the diameter of a single proton.

presence of a net magnetic moment for the nucleus is essential to magnetic resonance imaging (MRI). Only nuclides with net magnetic moments are able to interact with the intense magnetic field of a MRI unit to provide a signal to form an image of the body.

NUCLEAR NOMENCLATURE

Isotopes of a particular element are atoms that possess the same number of protons but a varying number of neutrons. For example, ^{1}H (protium), ^{2}H (deuterium), and ^{3}H (tritium) are isotopes of the element hydrogen, and $^{9}_{6}$C, $^{10}_{6}$C, $^{11}_{6}$C, $^{12}_{6}$C, $^{13}_{6}$C, $^{14}_{6}$C, $^{15}_{6}$C, and $^{16}_{6}$C are isotopes of carbon. An isotope is specified by its chemical symbol together with its mass number as a left superscript. The atomic number is sometimes added as a left subscript.

Isotones are atoms that possess the same number of neutrons but a different number of protons. For example, $^{5}_{2}$He, $^{6}_{3}$Li, $^{7}_{4}$Be, $^{8}_{5}$B, and $^{9}_{6}$C are isotones because each isotope contains three neutrons. *Isobars* are atoms with the same number of nucleons but a different number of protons and a different number of neutrons. For example, $^{6}_{2}$He, $^{6}_{3}$Li, and $^{6}_{4}$Be are isobars ($A = 6$). *Isomers* represent different energy states for nuclei with the same number of neutrons and protons. Differences between isotopes, isotones, isobars, and isomers are illustrated below:

The general term for any atomic nucleus, regardless of A, Z, or N, is "nuclide."

	Atomic No. Z	**Neutron No. N**	**Mass No. A**
Isotopes	Same	Different	Different
Isotones	Different	Same	Different
Isobars	Different	Different	Same
Isomers	Same	Same	Same (different nuclear energy states)

The full explanation of nuclear spin requires a description of the three main types of quark (up, down, and strange) along with the messenger particles that carry the strong nuclear force between them (gluons) together with the short-lived "virtual" quarks and antiquarks that pop in and out of existence over very short time periods within the nucleus.[39]