Basic Properties of Nuclei

By

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Symbols for Nuclear Quantities

Symbol	**Name**	**Explanation**
A	Mass Number	the number of nucleons (protons and neutrons) in the nucleus
Z	Atomic Number	the number of protons in the nucleus
N	neutron Number	The number of neutrons in the nucleus

An Example:

A description of the nucleus

Mass Number(A)	Chemical Symbol

27	
	Al
13	
Atomic Number	
(Z)	

Here the symbol is for aluminum (aluminium for the rest of the world). A typical aluminum atom has a mass number of 27 and an atomic number of 13. Therefore it has 13 protons(atomic number) and 14 neutrons

(27 - 13 = 14).

So the relationship is:

A = Z + N

In fact this is how the neutron number is calculated. But what about atoms that have the same number of protons and different numbers of neutrons? The number of protons determines what the atom is, and some atoms have different numbers of neutrons. These called **isotopes.** For example, hydrogen has three isotopes:

1	2	3
H (Hydrogen)	H (Deuterium)	H (Tritium)
1	1	1

Density of the Nucleus:

The nucleus is about 2.3 x 10^{14} times as dense as water. So a cubic meter of nuclear material would have a mass of 2.3 x 10^{17} kg.

Physicists today speak of the mass of the nucleus in terms of its *rest energy*. Yes that is correct. Mass is energy! This concept is best demonstrated by Einstein's special theory of relativity. Rest energy is equal to the mass times the square of the speed of light.

Or E_0= m c^2. The Energy is expressed in MeV or million electron volts, this makes the mass units MeV/c^2, strange indeed.

Mass of proton, neutron and electron			
Particle	**kg**	**u**	**Mev/c^2**
proton	1.673 x 10^{-27}	1.007 276	938.3
neutron	1.675 x 10^{-27}	1.008 665	939.6
electron	9.109 x 10^{-31}	0.000 549	0.5110

Properties of nuclei

The density inside a large nucleus is approximately 1.4 E44 nucleons per cubic meter. The radius of a nucleus is proportional to the cubic root of the number of particles,

$$R = A^{1/3} \cdot 1.2 \times 10^{-15}\ m$$

From our studies of atomic physics, we saw that the radius of the innermost Bohr orbit around a nucleus of charge Z was (5.3 E-11 m)/Z. So for the heaviest nucleus the radius of the inner-most electronic orbit is 100 times larger than the radius of the nucleus.

Due to the Pauli-exclusion principle which discourages like particles from being in the same place, nuclei prefer configurations of roughly equal numbers of protons and neutrons. However, due to the Coulomb force, heavy nuclei prefer to have more neutrons than protons. For example ^{238}U has 146 neutrons and only 92 protons.

Structure of the nucleus

The constitution of the nucleus was poorly understood at the time because the only known particles were the electron and the proton. It had been established that nuclei are typically about twice as heavy as can be accounted for by protons alone. A consistent theory was impossible until English physicist James Chadwick discovered the neutron in 1932. He found that alpha particles reacted with beryllium nuclei to eject neutral particles with nearly the same mass as protons. Almost all nuclear phenomena can be understood in terms of a nucleus composed of neutrons and protons. Surprisingly, the neutrons and protons in the nucleus move to a large extent in orbitals as though their wave functions were independent of one another. Each neutron or proton orbital is described by a stationary wave pattern with peaks and nodes and angular momentum quantum numbers. The theory of the nucleus based on these orbitals is called the shell nuclear model. It was introduced independently in 1948 by Maria Goeppert Mayer of the United States and Johannes Hans Daniel Jensen of West Germany, and it developed in succeeding decades into a comprehensive theory of the nucleus.

The interactions of neutrons with nuclei had been studied during the mid-1930s by Italian-born American physicist Enrico Fermi and others. Nuclei readily capture neutrons, which, unlike protons or alpha particles, are not repelled from the nucleus by a positive charge. When a neutron is captured, the new nucleus has one higher unit of atomic mass. If a nearby isotope of that atomic mass is more stable, the new nucleus will be radioactive, convert the neutron to a proton, and assume the more-stable form.

Nuclear fission was discovered by German chemists Otto Hahn and Fritz Strassmann in 1938 during the course of experiments initiated and explained by Austrian physicist Lise Meitner. In fission a uranium nucleus captures a neutron and gains enough energy to trigger the inherent instability of the nucleus, which splits into two lighter nuclei of roughly equal size. The fission process releases more neutrons, which can be used to produce further fissions. The first nuclear reactor, a device designed to permit controlled fission chain reactions, was constructed at the University of Chicago under Fermi's direction, and the first self-sustaining chain reaction was achieved in this reactor in 1942. In 1945 American scientists produced the first fission bomb, also called an atomic bomb, which used uncontrolled fission reactions in either uranium or the artificial element plutonium. In 1952 American scientists used a fission explosion to ignite a fusion reaction in which isotopes of hydrogen combined thermally into heavier helium nuclei. This was the first thermonuclear bomb, also called an H-bomb, a weapon that can release hundreds or thousands of times more energy than a fission bomb.

Quantum field theory and the standard model

Dirac not only proposed the relativistic equation for the electron but also initiated the relativistic treatment of interactions between particles known as quantum field theory. The theory allows particles to be created and destroyed and requires only the presence of suitable interactions carrying sufficient energy. Quantum field theory also stipulates that the interactions can extend over a distance only if there is a particle, or field quantum, to carry the force. The electromagnetic force, which can operate over long distances, is carried by the photon, the quantum of light. Because the theory allows particles to interact with their own field quanta, mathematical difficulties arose in applying the theory.

The theoretical impasse was broken as a result of a measurement carried out in 1946 and 1947 by American physicist Willis Eugene Lamb, Jr. Using microwave techniques developed during World War II, he showed that the hydrogen spectrum is actually about one-tenth of one percent different from Dirac’s theoretical picture. Later, German-born American physicist Polykarp Kusch found a similar anomaly in the size of the magnetic moment of the electron. Lamb’s results were announced at a famous Shelter Island Conference held in the United States in 1947. German-born American physicist Hans Bethe and others realized that the so-called Lamb shift was probably caused by electrons and field quanta that may be created from the vacuum. The previous mathematical difficulties were overcome by Richard Feynman, Julian Schwinger, and Tomonaga Shin’ichirō, who shared the 1965 Nobel Prize for Physics, and Freeman Dyson, who showed that their various approaches were mathematically identical. The new theory, called quantum electrodynamics, was found to explain all the measurements to very high precision. Apparently, quantum electrodynamics provides a complete theory of how electrons behave under electromagnetism.