

# Essential Elements of Nuclear Physics

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## Abstract

This one hour lecture was devised early in my career (1964-1985) as a teacher of physics at the Illinois Institute of Technology in Chicago.

The proton, or hydrogen atom nucleus, has been known since Rutherford's scattering experiments of 1911. The neutron was discovered much later, in 1923, by Chadwick. All nuclei in our world of matter are believed to be built out of neutrons and protons, although there may somewhere exist a world of antimatter in which all atoms would be constructed out of antiprotons (of negative charge) and antineutrons (particles distinct from neutrons).

The forces which bind neutrons and protons together to form complex nuclei are not electromagnetic forces. Instead the attraction between two nucleons, the generic name for neutrons and protons, is an intense force when it is acting, but it only acts when the nucleons are touching. Because of this resemblance of nucleons to sticky impenetrable spheres, the volume of all nuclei is approximately proportional to the total number of nucleons involved; i.e., the atomic weight  $A$ . This agrees with the experimental observation that the radius of a nucleus is given by  $R = r_0 A^{1/3}$ .

If one discounts the Coulomb repulsion between two protons, the scattering experiments reveal that the nuclear force between two nucleons is the same, irregardless of whether the nucleons are protons or neutrons. In fact, it is possible to consider the neutron and the proton as two different states of the same particle. The slightly higher mass of the neutron might be accounted for because of the differing electromagnetic interactions of the two particles.

It is known that both the neutron and the proton have spin  $1/2\hbar$ . Furthermore, there is a process called *beta decay*, under which a neutron can change into a proton, emitting an electron and a neutrino in the process. This process is attributable to nonnuclear, nonelectromagnetic interactions called *weak interactions*. Because of the weakness of the interaction, a free neutron has an average lifetime of 11 minutes before it decays into a proton, electron and neutrino. Within a nucleus, able to supply energy, conversion of a proton into a neutron, positron and neutrino is also possible, although the isolated proton is absolutely stable. When a nucleus undergoes  $\beta^-$  decay,  $A$  remains unchanged, but  $Z$  increases by one unit. In  $\beta^+$  decay,  $A$  remains unchanged, but  $Z$  decreases by one unit. The light particles come off with such high energy that they escape from the atom, even though an electron could in principle be bound if it had lower energy. Neutrinos have virtually no interactions with anything, and they can pass readily through all matter.

If there were no weak interactions, certain types of radioactive decay would still be possible. For example, a certain nucleus may, because of collisions, find itself in an excited state, much as an atom may find itself in an excited state. The excited nucleus may drop down to its ground state by emitting photons of extremely high energy, gamma rays.

If there were no electromagnetic interactions and no weak interactions, alpha decay of nuclei would still be possible. It is found that the nucleus of the helium atom, the so-called *alpha particle*, is an extremely tightly bound system. It consists of two protons and two neutrons. Often it requires less energy to remove four nucleons (in the form of an alpha particle) from a nucleus than it requires to remove one nucleon. For example,  $C^{12}$  can be regarded as three alpha particles.

In a scattering experiment one of these alpha particles can be removed quite easily. Some nuclei hold onto an alpha particle constituent so weakly that in the course of time the alpha particle will escape from the nucleus by the process of alpha decay. This is really a tunneling process, in which a particle is trapped in a well surrounded by a wall of finite thickness. Quantum mechanically the particle can gradually leak through the barrier. When a nucleus undergoes alpha decay the value of  $A$  changes by 4 units, while  $Z$  changes by 2 units.

There are whole series of radioactive decays, which usually terminate at the stable isotope of lead. It is ironic that the alchemists dreamed of transmuting lead into gold, whereas we find that today that most elements which are radioactive transmute into lead.

The electromagnetic properties of nucleons are interesting in their own right. Since a charged particle has an electromagnetic field with which is associated a certain energy, one might expect a charged particle to be more massive than its uncharged relative, by Einstein's  $E = Mc^2$  formula. However, it is the neutron which is more massive. One should not, however, overlook the fact that both the neutron and the proton are like little magnets. Like the electron they have spin  $1/2\hbar$ , which can be demonstrated in Stern-Gerlach type experiments. When passed through an inhomogeneous magnetic field, a beam of neutrons or protons will split up into precisely two beams, which is a characteristic of a spin  $1/2\hbar$  particle. The angle of separation of the two beams is a measure of the magnetic moment of the particles. In spite of the fact that neutrons are neutral, they do split up into two beams, so one knows they have a nonzero magnetic moment.

Recall that the magnetic moment of an electron is twice what one would expect classically for a particle of spin  $1/2\hbar$ . It is in fact given by the Bohr magneton,  $-e\hbar/2m$ . One might expect that the proton would have a magnetic moment of one nuclear magneton,  $e\hbar/2M$ , and that the neutron would have no magnetic moment. However, experiments reveal that the proton magnetic moment is about +2.79 nuclear magnetons, and that the neutron magnetic moment is about -1.9 nuclear magnetons. These odd values are associated with peculiarities of nuclear forces (strong interactions). In fact, it is possible to regard the nucleons themselves as complex structures, quite far removed from point particles such as the electron. After all, in energetic collisions nucleons are readily changed into a host of exotic particles, all of which are subject to the strong interactions.

In a magnetic field, the spin of a proton may be found either to be along the direction of the field, or opposite to it. If it is one way the energy of the proton is higher than if it is the other way. In thermal equilibrium one would anticipate that the lower energy state would be slightly more likely to be filled. If a rapidly fluctuating perpendicular magnetic field is superimposed upon the strong magnetic field, and if the frequency is adjusted just right, energy will be absorbed. Protons in the lower energy state will have their spins flipped, and they will end up in the higher energy state. By measuring the frequency at which this happens, one can determine the proton magnetic moment. [View experiment in graduate physics lab.]