Nuclear Forces

By

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Nuclear force is one of the four fundamental forces of nature, the others being gravitational and electromagnetic forces. In fact, being 10 million times stronger than the chemical binding forces, they are also known as the strong forces. In this section, we will discuss this force in detail. *We can define nuclear force as:*

The nuclear force is a force that acts between the protons and neutrons of atoms.

The nuclear force is the force that binds the protons and neutrons in a nucleus together. This force can exist between protons and protons, neutrons and protons or neutrons and neutrons. This force is what holds the nucleus together.

The charge of protons, which is +1*e*, tends to push them away from each other with a strong electric field repulsive force, following Coulomb's law. But nuclear force is strong enough to keep them together and to overcome that resistance at short range.

Properties of Nuclear Force

- It is attractive in nature but with a repulsive core. That is the reason that the nucleus is held together without collapsing in itself.

- The range of a nuclear force is very short. At 1 Fermi, the distance between particles in a nucleus is tiny. At this range, the nuclear force is much stronger than the repulsive Coulomb's force that pushes the particles away. However, if the distance is anything more than 2.5 Fermi, nuclear force is practically non-existent.

- The nuclear force is identical for all nucleons. It does not matter if it is a neutron or proton, once the Coulomb resistance is taken into consideration, nuclear force affects everything in the same way.

- At a distance of less than 0.7 Fermi, this force becomes repulsive. It is one of the most interesting properties of nuclear force, as this repulsive component of the force is what decides the size of the nucleus. The nucleons come closer to each other till the point that the force allows, after which they cannot come any closer because of the repulsive property of the force.

Properties of the nuclear force

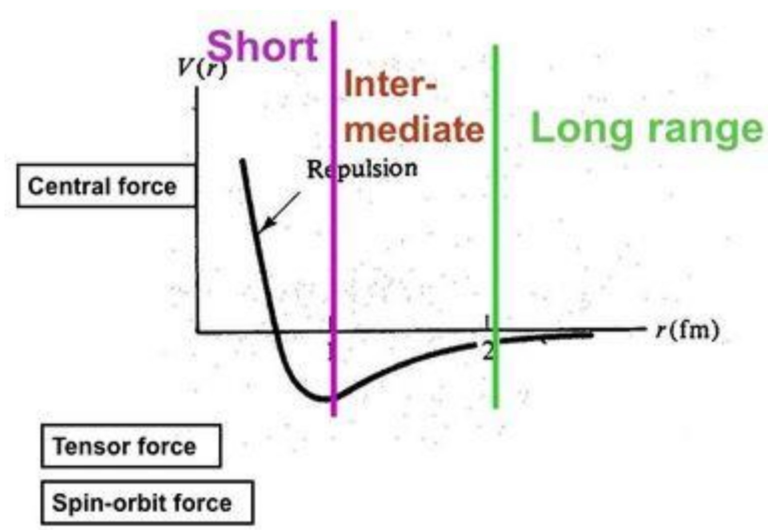


Figure : The major components of the nuclear force. The central force is best analyzed in terms of the three ranges indicated.

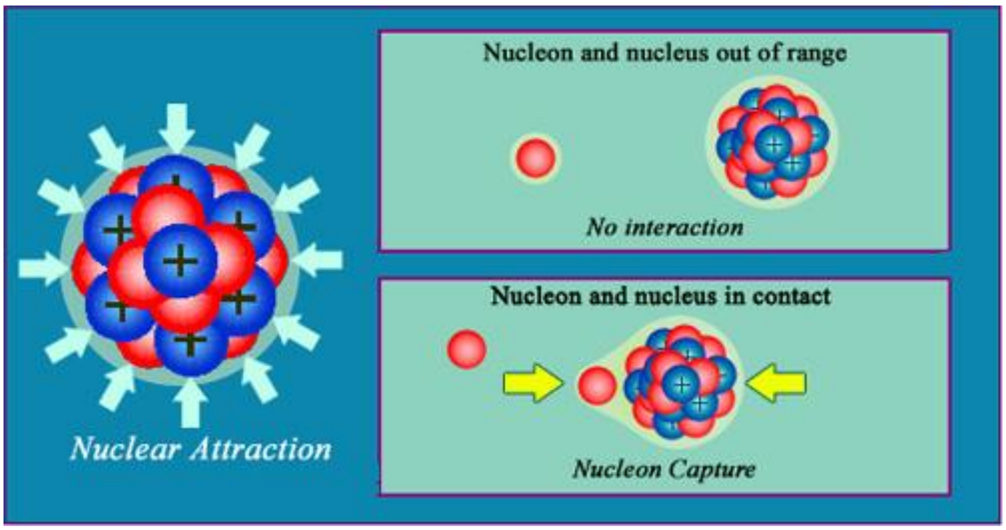
Some properties of nuclear interactions can be deduced from the properties of nuclei. Nuclei exhibit a phenomenon known as saturation: the volume of nuclei increases proportionally to the number of nucleons. This property suggests that the **nuclear (central) force** is of short range (a few fm) and strongly **attractive** at that range, which explains nuclear binding. But the nuclear force has also a very complex spin-dependence. Evidence of this property first came from the observation that the deuteron (the proton-neutron bound state, the smallest atomic nucleus) deviates slightly from a spherical shape: it has a non-vanishing quadrupole moment. This suggests a force that depends on the orientation of the spins of the nucleons with regard to the vector joining the two nucleons (a **tensor force**). In heavier nuclei, a shell structure has been observed which, according to a proposal by M. G. Mayer and J. H. D. Jensen, can be explained by a strong force between the spin of the nucleon and its orbital motion (the **spin-orbit force**). More clear-cut evidence for the spin-dependence is extracted from scattering experiments where one nucleon is scattered off another nucleon, with distinct spin orientations. In such experiments, the existence of the nuclear spin-orbit and tensor forces has clearly been established. Scattering experiments at higher energies (more than 200 MeV) provide evidence that the nucleon-nucleon interaction turns repulsive at short inter-nucleon distances (smaller than 0.5 fm, the **hard core**).

Besides the force between two nucleons (2NF), there are also three-nucleon forces (3NFs), four-nucleon forces (4NFs), and so on. However, the 2NF is much stronger than the 3NF, which in turn is much stronger than the 4NF, and so on. In exact calculations of the properties of light nuclei based upon the "elementary" nuclear forces, it has been shown that 3NFs are important. Their contribution is small, but crucial. The need for 4NFs for explaining nuclear properties has not (yet) been established.

Nuclear forces are approximately **charge-independent** meaning that the force between two protons, two neutrons, and a proton and a neutron are nearly the same (in the same quantum mechanical state) when electromagnetic forces are ignored.

Three nuclear forces and their hierarchy

Three types of force act alongside each other inside a nucleus. The dominant one is the nuclear or **'strong'** interaction which ensures the cohesion of the nucleus by pulling the various nucleons together, a force which is also responsible for the production of alpha radiation. Secondly, the **electromagnetic repulsion** among the like-charged protons, but is considerably less powerful than the strong force. The third of these nuclear interactions is the **'weak'** force ; neither attractive nor repulsive, it acts inside the individual nucleons and can occasionally lead to a neutron's transformation into a protonon (or vice versa), accompanied by a release of beta radiation. The interplay between these three forces dictates how stable or unstable a nucleus is.

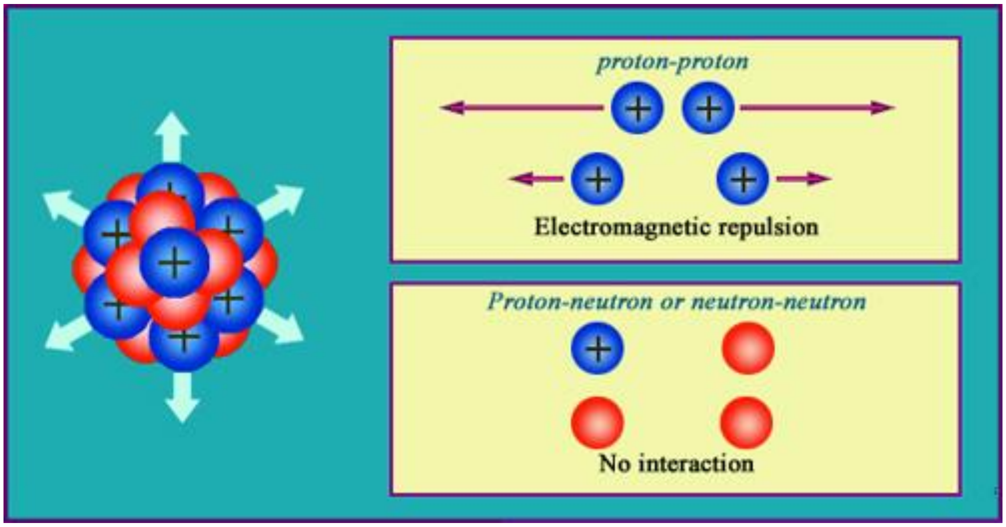


A very strong short range attraction

The cohesion of the nuclear structure is mainly due to the attractive strong force, which is capable of overcoming the electrical repulsion the protons exert on each other. This 'strong force' is only effective over short distances, as a nucleon passing very close to a nucleus will not feel its influence. The force only starts to apply when direct contact is made – to symbolise this 'nuclear glue', the nucleons and nuclei above have been drawn with a layer of glue surrounding them.

All nuclei are practically incompressible like the molecules of a liquid. This is caused by the direct contact that exists between the constituent neutrons and protons.

The nucleons are all held together by a contact force, called nuclear or strong, which is the dominant force inside the nucleus. Despite being remarkably powerful, this nuclear glue only acts over the shortest of distances. This explains why these forces went undetected for decades even after the discovery of radioactivity. These distances are so short, in fact, that neutrons can travel in the immediate vicinity of a nucleus without being affected by the force and eventually absorbed into the nucleus.

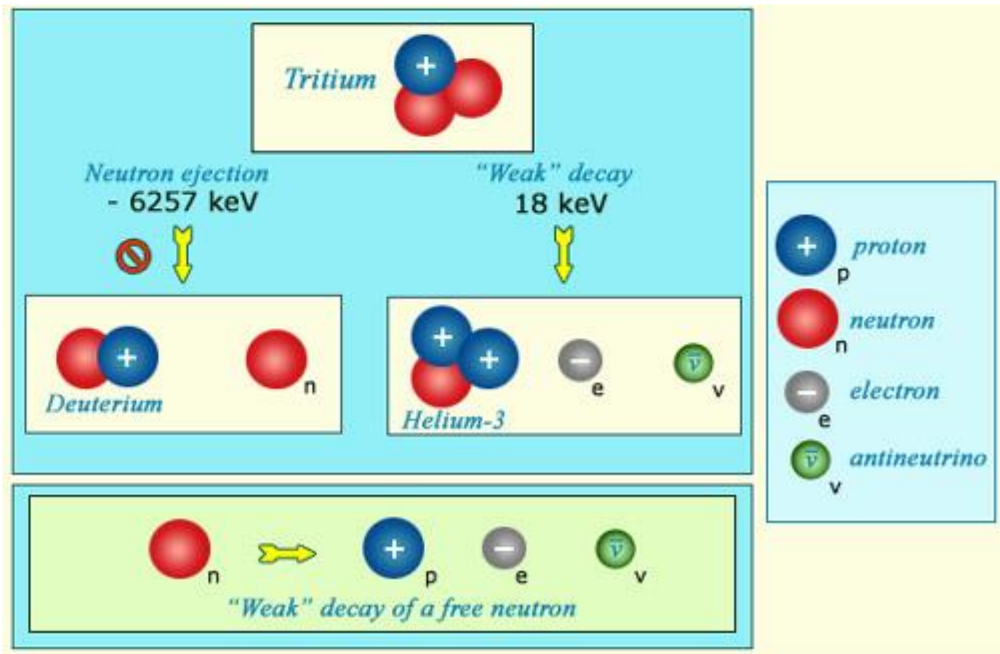


The electrical repulsion of protons

Two electrical charges of the same sign repel each other. This repulsion increases with the inverse of the square of the distance, as dictated by Coulomb's law. The protons (in blue) are affected by this repulsion inside the nucleus, as opposed to the red neutrons, whose absence of charge makes them immune. Without the strong nuclear forces capable of overcoming these repulsions, the nucleus would explode. The strong force needs to be very intense to hold the protons together in such a small volume.

The electromagnetic repulsion takes place within the nucleus between like electric charges. These charges are carried by the protons, whose close proximity to each other intensifies this repulsive force. The strong nuclear attraction must be immensely powerful to overcome the repulsion taking place in a sphere whose radius is only of a few millionths of a billionth of a metre.

The third nuclear force is a discreet one that nevertheless plays a fundamental role in the universe. Without the *'weak force'*, our Sun would stop shining due to the inability of hydrogen nuclei to fuse to form deuterium, the Sun's main energy-producing reaction.



The tritium "weak decay"

The example of tritium, the simplest of radioactive nuclei, shows how nature occasionally uses the 'weak forces' to change the proportions of protons and neutrons. One may suppose that tritium, given the fact that it contains one proton and two neutrons, could eject one of its two neutrons to reach stability. Such an expulsion, however, would require too much energy to occur, and so one of the neutrons is transformed into a proton, accompanied by the release of a beta electron and an antineutrino. This process releases enough energy to occur and make tritium radioactive; an instability that is caused by the weak force.

Without the weak force, there would be a great deal more than 287 'natural' nuclei in the world. In the absence of beta radioactivity, the only way for a nucleus to maintain the correct proton/neutron balance would be the expulsion of a proton or neutron. This requires energy and do not occur naturally. Without the weak force which allows neutrons to transform into protons (and vice versa) at a cheap price, several thousands of recorded unstable and radioactive nuclei would be stable.