

NUCLEAR FORCES

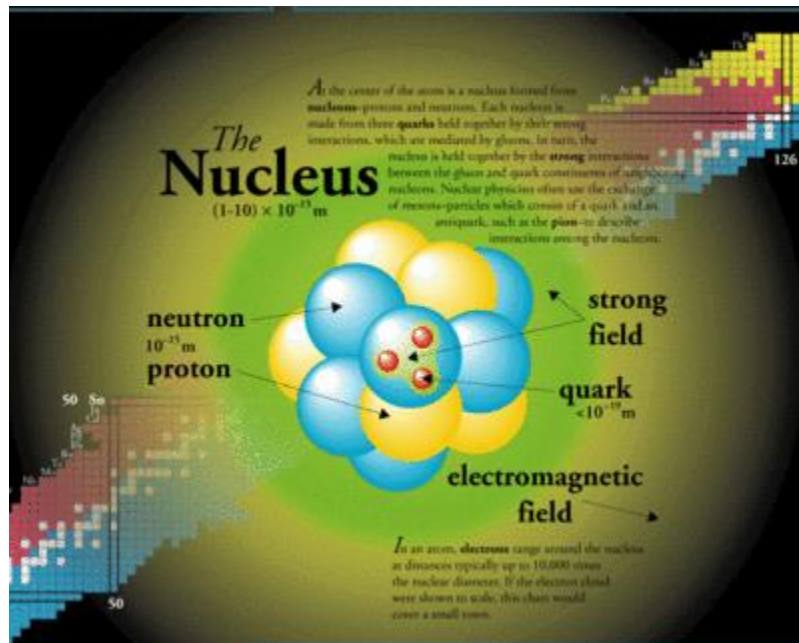


Figure 1: The atomic nucleus made up from protons (yellow) and neutrons (blue) and held together by nuclear forces.

Nuclear forces (also known as **nuclear interactions** or **strong forces**) are the forces that act between two or more nucleons. They bind protons and neutrons (“nucleons”) into atomic nuclei. The nuclear force is about 10 millions times stronger than the chemical binding that holds atoms together in molecules. This is the reason why nuclear reactors produce about a million times more energy per kilogram fuel as compared to chemical fuel like oil or coal. However, the range of the nuclear force is short, only a few femtometer ($1 \text{ fm} = 10^{-15} \text{ m}$), beyond which it decreases rapidly. That is why, in spite of its enormous strength, we do not feel anything of this force on the atomic scale or in everyday life. The development of a proper theory of nuclear forces has occupied the minds of some of the brightest physicists for seven decades and has been one of the main topics of physics research in the 20th century. The original idea was that the force is caused by the exchange of particles lighter than nucleons known as mesons, and this idea gave rise to the birth of a new sub-field of modern physics, namely, (elementary) particle physics. The modern perception of the nuclear force is that it is a residual interaction (similar to the van der Waals force between neutral atoms) of the even stronger force between quarks, which is mediated by the exchange of **gluons** and holds the quarks together inside a nucleon.

Historical perspective

After the discovery of the neutron by Chadwick in 1932 (Chadwick, 1932), it was clear that the atomic nucleus is made up from protons and neutrons. In such a system, electromagnetic forces cannot be the reason why the constituents of the nucleus are sticking together. Indeed, the repulsive electrical Coulomb force between the protons should blow the nucleus apart. Therefore, the concept of a new strong nuclear force was introduced. In 1935, the first theory for this new force was developed by the Japanese physicist Hideki Yukawa (Yukawa,1935), who suggested that the nucleons would exchange particles between each other and this mechanism would create the force. Yukawa constructed his theory in analogy to the theory of the electromagnetic interaction where the exchange of a (massless) photon is the cause of the force. However, in the case of the nuclear force, Yukawa assumed that the “force-makers” (which were eventually called “mesons”) carry a mass of a fraction of the nucleon mass. A massive particle limits the effect of the force to a finite range, since the uncertainty principle allows massive particles to travel only a finite distance. The meson predicted by Yukawa was finally found in 1947 in cosmic ray and in 1948 in the laboratory and called the pion. Yukawa was awarded the Nobel Prize in 1949. In the 1950s and 60s more mesons were found in accelerator experiments and the meson theory of nuclear forces was extended to include many mesons. These models became known as one-boson-exchange models, which is a reference to the fact that the different mesons are exchanged singly in this model. The one-boson-exchange model is very successful in explaining essentially all properties of the nucleon-nucleon interaction at low energies. Also, in the 1970s and 80s, meson models were developed that went beyond the simple single-particle exchange mechanism. These models included, in particular, the explicit exchange of two pions with all its complications. Well-known models of the latter kind are the Paris (Lacombe et al.,1980) and the Bonn potential (Machleidt et al., 1987).

Since these meson models were quantitatively very successful, it appeared that they were the solution of the nuclear force problem. However, with the discovery (in the 1970s) that the fundamental theory of strong interactions is quantum chromodynamics (QCD) and not meson theory, all “meson theories” had to be viewed as models, and the attempts to derive a proper theory of the nuclear force had to start all over again.

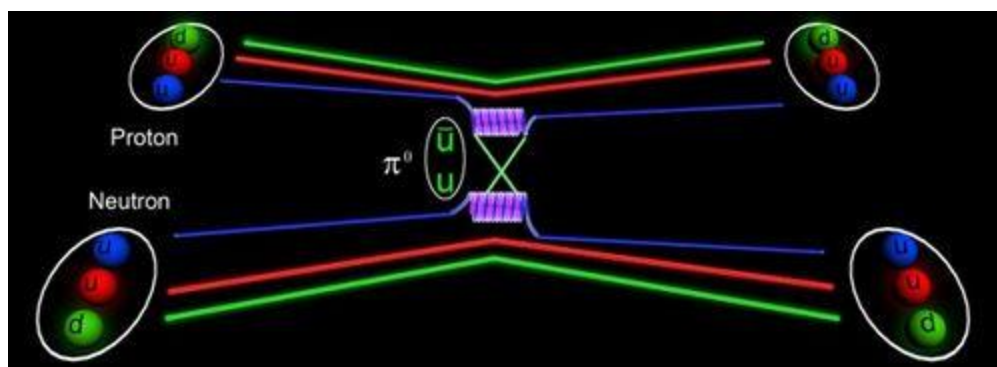


Figure 2: The exchange of a pion between two nucleons in the quark picture.

The problem with a derivation of nuclear forces from QCD is two-fold. First, each nucleon consists of three quarks such that the system of two nucleons is already a six-body problem. Second, the force between quarks, which is created by the exchange of gluons, has the feature of being very strong at the low energy scale that is characteristic of nuclear physics. This extraordinary strength makes it difficult to find “converging” mathematical solutions. Therefore, during the first round of new attempts, the models proposed were just “QCD-inspired”. The positive aspect of these models is that they try to explain nucleon structure (which consists of three quarks) and nucleon-nucleon interactions (six-quark systems) on an equal footing. Some of the gross features of the two-nucleon force, like the “hard core” (see below) are explained successfully in such models. However, from a critical point of view, it must be noted that these quark-based approaches are yet another set of models and not a theory. Alternatively, one may try to solve the six-quark problem with brute computing power, by putting the six-quark system on a four dimensional lattice of discrete points which represents the three dimensions of space and one dimension of time. This method has become known as lattice QCD and is making progress. However, such calculations are computationally very expensive and cannot be used as a standard nuclear physics tool.

Around 1990, a major breakthrough occurred when the Nobel laureate Steven Weinberg applied the concept of an Effective Field Theory (EFT) to low-energy QCD (Weinberg, 1979, 1991). He simply wrote down the most general theory that is consistent with all the properties of low-energy QCD, since that would make this theory identical to low-energy QCD. A particularly important property is the so-called chiral symmetry, which is “spontaneously” broken. Massless particles observe chiral symmetry, which means that their spin and momentum are either parallel (“right-handed”) or anti-parallel (“left-handed”) and remain so forever. Since the quarks, which nucleons are made of (“up” and “down” quarks), are almost massless, approximate chiral symmetry is a given. Naively, this symmetry should have the consequence that one finds in nature mesons of the same mass, but with positive and negative [parity](#). However, this is not the case and such failure is termed a “spontaneous” breaking of the symmetry. According to a theorem first proven by Jeffrey Goldstone, the spontaneous breaking of a symmetry creates a particle, which in this case is the pion. Thus, the pion becomes the main player in the creation of the nuclear force. The interaction of pions with nucleons is weak as compared to the interaction of gluons with quarks. Therefore, pion-nucleon processes can be calculated without problem. Moreover, this effective field theory can be expanded in terms of powers of momentum over “scale”, where scale denotes the “chiral [symmetry breaking](#) scale” which is about 1 GeV ($= 10^9$ eV). This scheme is also known as [Chiral Perturbation Theory](#) (ChPT) and allows to calculate the various terms that make up the nuclear force systematically power by power, or order by order. Another advantage of the chiral EFT approach is its ability to generate not only the force between two nucleons, but also many-nucleon forces, on the same footing. In modern theoretical nuclear physics, the chiral EFT approach is becoming increasingly popular and is applied with great success.

Properties of the nuclear force

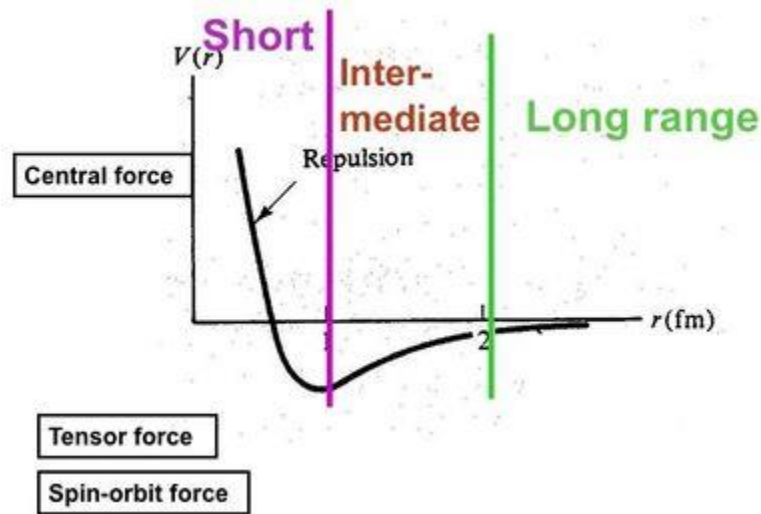


Figure 3: The major components of the nuclear force. The central force is best analyzed in terms of the three ranges indicated.

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.

Phenomenological approaches

Traditionally, research on the nuclear force has proceeded along two lines: phenomenology and theory. We start with phenomenology. At very low energy, nucleon-nucleon scattering can be described by the so-called effective range expansion which, in its simplest version, has only two parameters (Bethe, 1949), see Brown and Jackson (1976) for a text-book presentation. In modern times, this expansion has been recovered from an EFT which does not include the pion ('pionless EFT'), see, e.g., Bedaque and van Kolck (2002) for an introduction. At intermediate energies, the spin-dependence of the nuclear force becomes important. To produce a general expression for the NN potential (that includes spin and momentum dependences), Okuba and Marshak (1958) imposed the following symmetries,

- Translational invariance
- Galilean invariance
- Rotational invariance
- Space reflection invariance
- Time reversal invariance
- Invariance under the interchange of particle 1 and 2
- Isospin symmetry
- Hermiticity

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