8.701

Introduction to Nuclear and Particle Physics

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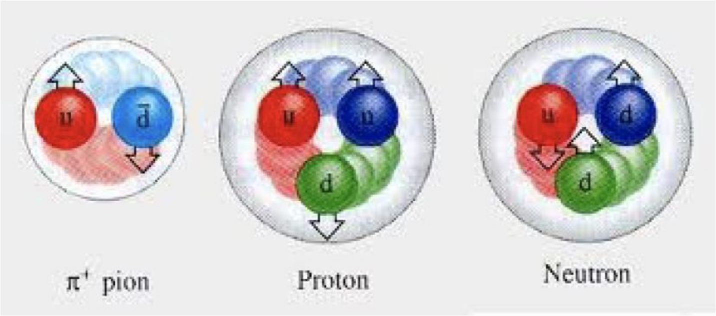
9. Nuclear Physics

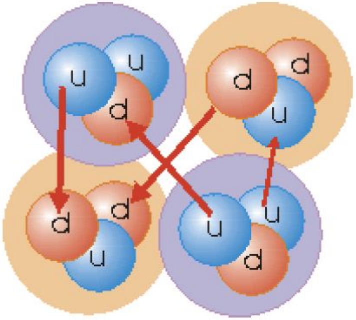
9.4 Nuclear Force

Strong vs Nuclear Force

Strong force acts between quarks in hadrons



The nuclear force is the residual interaction between quarks localized in different hadrons.



Experimental Studies

Our understanding of nuclear force is based on three types of experimental information:

1. results of nucleon-nucleon (proton-proton, neutron-neutron, and proton-neutron) scattering experiments. Some of these experiments are conducted with spin-polarized projectiles/targets.
2. Nuclear binding energies and masses, especially for light nuclei.
3. Nuclear structure information, such as energies, spins, parities, magnetic and quadrupole moments, especially for light nuclei.

Nuclear force: radial part

Experimental results indicate that nuclear force depends on

1. the distance between interacting nucleons (the radial part),
2. spins and angular momenta of interacting nucleons (spin-orbit and tensor part).

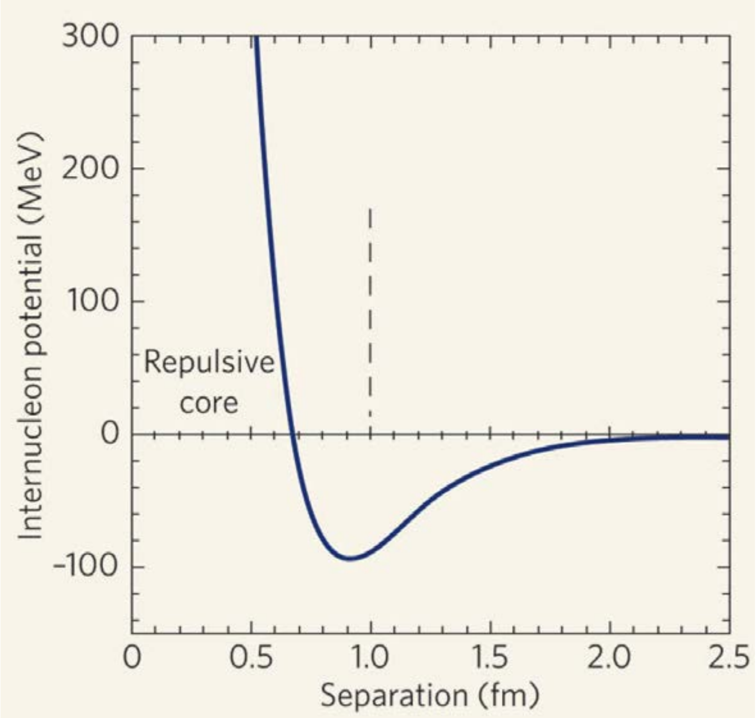
Experimental results indicate that nuclear force does not depend on the type of interacting nucleons.

Nuclear force: radial part

The nuclear force is short range, which implies it vanishes for distances longer than ~ 2 fm.

The nuclear force is strongly attractive at distances of ~ 1 fm.

The nuclear force is strongly repulsive on for distances shorter than ~ 0.5 fm (the hard core of nuclear potential).



Nuclear force: radial part

The argument for the short range of nuclear forces are

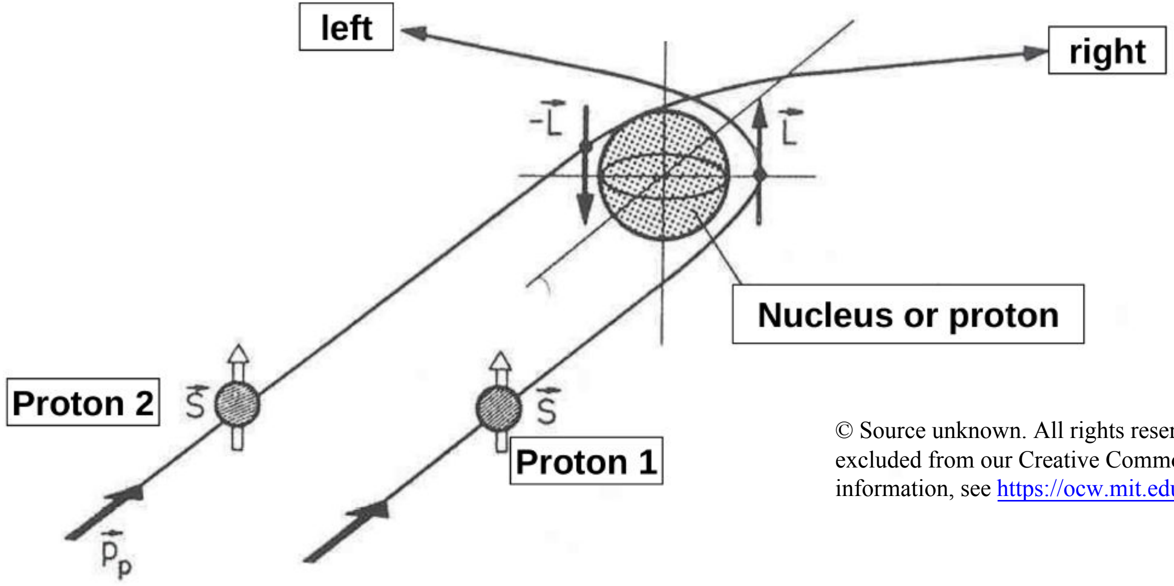
1. Binding energies per nucleon which are roughly constant indicating that nucleons in nuclei interact only with their immediate neighbours.
2. Measurements of distances between nuclei at which nuclear reactions start to occur, these are $\sim$1-2 [fm] larger than corresponding nuclear radii.
3. Nuclear densities which are only slightly smaller than nucleon density indicating very dense packing of nucleons in a nucleus.

Arguments for the attractive nuclear force is the fact that nuclei are bound.

Arguments for the repulsive nuclear force at short distances come from high-energy nucleon-nucleon scattering experiments.

Spin-orbit force

Scattering of spin-polarized nucleons indicates that nuclear force has a component which depends on the spin and angular momentum of the interacting nucleon



Charge independence of nuclear force

Nucleon-nucleon scattering experiments indicate that the nuclear force is independent of electric charge.

If you think about it, why should it? Nuclear force comes from the residual strong force, while the charge plays a role in electromagnetic interactions.

Charge-independence of the nuclear force implies that if electromagnetic effects are eliminated the scattering of protons on protons, protons on neutrons and neutrons on neutrons yields (nearly) the same results.

Electromagnetic effects to be eliminated need to be calculated and subtracted from the data (there is no other way to "turn off" the electromagnetic force).

In fine details the charge independence is broken, for example by the small mass difference between the proton and neutron mass.

Mirror nuclei

Charge independence of nuclear force is manifested in properties of mirror nuclei.

Mirror nuclei are these which have numbers of protons and neutrons exchanged one with respect to the other like

$$^{A}_{Z}X_{N} \text{ is a mirror nucleus of } ^{A}_{N}Y_{Z}$$

Examples of mirror nuclei are ^{3}He and ^{3}H, ^{7}Li and ^{7}Be, etc.

Due to the charge independence of the nuclear force the masses, binding energies and excitation spectra, when corrected for the electromagnetic (Coulomb) terms are very similar in light mirror nuclei.

In heavy mirror nuclei the effect breaking charge independence of nuclear force are strong, and the similarity does not hold.

Binding and excitation energies in mirror nuclei

A	Nucleus	Total Binding Energy (MeV)	Coulomb Energy (MeV)	Net Nuclear Binding Energy (MeV)
3	^{3}H	−8.486	0	−8.486
	^{3}He	−7.723	0.829	−8.552
13	^{13}C	−97.10	7.631	−104.734
	^{13}N	−94.10	10.683	−104.770
23	^{23}Na	−186.54	23.13	−209.67
	^{23}Na	−181.67	27.75	−209.42
41	^{41}Ca	−350.53	65.91	−416.44
	^{41}Sc	−343.79	72.84	−416.63