angular momentum conservation postulated the existence of a light uncharged particle of spin $\hbar/2$ and called it the ***neutrino.*** The existence of neutrinos was proven much later in the 1950's by *Reines and Cowan* in experiments using intense antineutrino fluxes from reactors.

In *1933 Fermi* put forward his theory of $\beta$-decay and introduced a new type of force, the *weak interaction*, which creates an electron and an antineutrino in the transformation of a neutron into a proton. It should be pointed out that *Dirac* had predicted the existence of anti-particles specifically that of a positive electron. The positive electron or ***positron*** was discovered by *Anderson* in *1932*. We now believe that all particles have their counterpart anti-particles.

Some people (Heisenberg, Yukawa) had toyed with the idea that nuclear electrons may be responsible for nuclear binding. With the expulsion of the electron from the nucleus it was soon realised that the forces that hold a nucleus together could not be ordinary electrostatic forces since electrically neutral neutrons are bound in the nucleus.

The crucial steps in the exploration of nuclear forces were made by *Wigner (1933)*. He showed that *this force must have a very short range of action but must be very strong within this range*. *Heisenberg (1932) and Majorana (1933)* showed that the *nuclear forces must be "saturated"* i.e. not all pairs of nucleons within a nucleus can exert attractive forces upon each other.

In the mid-30's Fermi and co-workers showed that neutrons could be slowed down to thermal energies and that at low velocities they were particularly effective in disintegrating other nuclei. This discovery was followed by the *fission of uranium by Hahn and Strassmann (1938)*. In such a reaction the neutron splits the uranium nucleus into two large fragments with the emission of several additional neutrons. This opened the way to the liberation of nuclear energy on a large scale *(Fermi 1942)* and to other well-known destructive applications.

In *1935 Yukawa* published his theory of nuclear forces in which he postulated the existence of a particle with a mass intermediate between the electron and proton masses and thus christened a ***meson.*** Furthermore he argued that it should interact strongly with matter and have a lifetime of the order of 1/10 to 1/100 of a microsecond. In 1937 cosmic ray studies led to the discovery of mesons now known as ***$\mu$−mesons (muons).*** Unfortunately muons did not quite have the properties expected of Yukawa mesons. *To this day the reason for the existence of muons is not known*.

In *1947 Lattes et.al.* found events in photographic emulsion demonstrating the existence of ***$\pi$-mesons (pions)*** decaying at rest into a mono-energetic muon and a neutral particle later proved to be a neutrino i.e. $\pi^+ \rightarrow \mu^+ \nu$ .

## 1.3 Nucleons have structure - discovery of quarks.

The energy of the charged particle accelerators has been increasing since their invention in 1920's and 1930's. This has enabled a study of matter in finer and finer detail. For example the present CERN Large Hadron Collider can probe matter down to $10^{-20}$ m.

Experiments at these accelerators led to the discovery of many new particles and showed that the neutrons and protons were just the lightest particles in a spectrum of fermion states called ***baryons*** nearing 100 at the latest count. An equally numerous sequence of boson states called ***mesons*** has also been discovered, the pion being the lightest.

## Appendix 1.1 Practical Units and Definitions

The conventional system of units (mks) employed in physics is not suited to the problems of nuclear and particle physics.

Einstein's relation linking energy, mass, and momentum is given by

$$E^2 = p^2c^2 + m^2c^4.$$

Hence, if energy $E$ is measured in electron volts (eV), then momentum $p$ is measured in eV/$c$ and mass $m$ in eV/$c^2$.

An electron volt is the amount of energy gained by an electron when traversing a potential difference of 1 V. One GeV is 1,000,000,000 (i.e. $10^9$) eV.

| | | |
|---|---|---|
| • **<u>Energy</u>** <u>in electron-volts</u> | **eV** | 1 eV = 1.6022 $10^{-19}$ J |
| Typical atomic energies | tens of eV | |
| Typical nuclear energies | few MeV | 1 MeV = $10^6$ eV ($m_e c^2$ = 0.5 MeV ) |
| Typical sub-nuclear energies | few GeV | 1 GeV = $10^9$ eV ($m_p c^2 \approx$ 1 GeV ) |

• **<u>Mass and Momentum</u>**

| | | |
|---|---|---|
| Special Relativity: | $E^2 = p^2c^2 + m^2c^4$ | |
| If we measure E in MeV | then momentum can be measured in | MeV/c |
| | and mass can be measured in | MeV/$c^2$ |

1 MeV/$c^2$ = 1.7827 $10^{-30}$ kg.

| | | |
|---|---|---|
| • **<u>Length</u>** | m | |
| Wavelengths in nm | 1 nm = $10^{-9}$ m, or 10 Å | |
| Nuclear dimension | few fm | 1 fm = $10^{-15}$ m. ( fermi or femtometre ) |
| | | Nucleon dimension ~ 1 fermi. |

A much used quantity is **ħ c = 197 MeV . fm** (~ 200 MeV.fm)

• **<u>Some Definitions</u>**

| | | |
|---|---|---|
| Nucleon | a neutron or a proton | |
| Atomic number (or number of protons) | Z | *isotope* - nucleus with same Z |
| Number of neutrons | N | *isotone* - nucleus with same N |
| Mass number (or number or nucleons) | A | *isobar* - nucleus with same A |

# 2. The Nuclear Force

**The nuclear force is responsible for the binding of nucleons (neutrons and protons) into nuclei**. It is **not** considered to be **one of the fundamental forces of Nature** as are gravitational, weak, electromagnetic or strong forces. It appears that the nuclear force is a remnant of the strong force and **it's understanding is largely empirical**. A useful analogy can be drawn between the molecular force and the nuclear force. *The nucleon-nucleon interaction is to the strong interaction what the molecular interaction is to the electromagnetic interaction*. Molecular interaction is not fundamental but is a remnant of the fundamental electromagnetic interaction.

The nuclear forces arising between nucleons are now seen to be analogous to the forces in chemistry between neutral atoms called van der Waals forces. Such forces between atoms are much weaker than the electrical forces that hold the atoms themselves together, and their range is shorter, because they arise from spontaneous separation of charges inside the atom.

**Information on forces can be gathered by examining:**

- **i) the spectra of the simplest system bound by that force (static properties),**
- **ii) the scattering of two particles that are affected by the force in question.**

The success of the atomic theory can be measured in terms of its ability to describe exactly the energies of the observed excited states in atoms. A wealth of data exists on these excited states. Theories are generally first applied to the simplest systems imaginable. It is no surprise that deep understanding of atomic physics is obtained from a very detailed study of the simplest atom, the hydrogen atom.

We can ask whether there exists a "hydrogen atom" bound by the nuclear force. Indeed a two nucleon bound system, the deuteron (deuterium), exists consisting of a proton and a neutron. Unfortunately it has no excited states and thus the information about the nuclear force that can be obtained is somewhat limited. However another method of studying the nuclear force is to study the scattering of one nucleon against another. In this chapter we shall use both methods to obtain a consistent description of nuclear forces.



## 2.1 Nuclei exist as bound systems.

We start by making a trivial observation that nuclei exist as bound systems and that they consist of $N$ neutrons and $Z$ protons collectively known as nucleons. The number of nucleons in a nucleus is A = N + Z.

The binding force is obviously attractive but cannot be the electromagnetic force since the only charged particles inside are protons that repel each other. But it must be much stronger than the electromagnetic force over inter-nucleon distances. However, beyond inter-atomic distances it must be very weak. Also certain particles like electrons do not "feel" the nuclear force.

### *2.2.1 Mirror Nuclei and charge symmetry.*

Consider pairs of so-called **mirror nuclei** e.g. ${}^{3}_{1}H$ and ${}^{3}_{2}He$ or ${}^{11}_{5}B$ and ${}^{11}_{6}C$. Each member of any such pair can be transformed into the another by replacing all the neutrons by protons or vice a versa. When allowance is made for the difference in Coulomb energy between the two members of any pair, the two nuclei are found to have essentially identical properties both with respect to the ground state and to all excited states.

This is illustrated by Fig. 2.2. The energy levels are almost identical. Note that the spin-parity of the levels is identical. A more thorough discussion of the pattern of energy levels of nuclei will be presented in Chapter 5. From this one can conclude that to a high degree of precision that *n-n interaction is identical to p-p interaction, it being understood that the Coulomb interaction is switched off in the latter*. This general property of nucleon-nucleon interaction is known as **charge symmetry**.

## 2.3 Nuclear Radii (Handout: HO_Ch. 2)

The definition of a nuclear radius is somewhat arbitrary since the value depends on the phenomenon used to measure it. However all results agree qualitatively and to a certain extent quantitatively. Attributing a radius, R, to nucleus does not imply a sharp edge.

The scattering methods use as projectiles

| | |
|---|---|
| $\alpha$, n, p | dominant interaction is nuclear |
| electrons | interaction is electromagnetic (so only probes the proton distribution) |



To "see" an object one requires projectiles (radiation) with a Compton wavelength < size of the object. Hence for an object of a size of 5 fm

alphas(non-relativistic) $T = \frac{p^2}{2M_\alpha} = \frac{h^2}{2M_\alpha\lambda^2} \approx \frac{4\pi^2(\hbar c)^2}{2M_\alpha\lambda^2c^2} = \frac{4\pi^2 \times 200^2}{2 \times 4000 \times 5^2}\frac{(MeV \times fm)^2}{MeV \times fm^2} \approx 8 \text{ MeV}$

electrons (have to be relativistic) $p \approx \frac{h}{\lambda} \approx \frac{2\pi\hbar c}{\lambda c} = \frac{2\pi \times 200}{5}\frac{MeV \times fm}{fm \times c} \approx 240 \frac{\text{MeV}}{\text{c}}$

### ***2.3.1 Electron scattering***

Electron scattering measurements give the most detailed information at present obtainable on the nuclear charge distribution. The form of the proton distribution is given by the so-called "Woods Saxon" formula (Fig. 2.3).

$$\rho(r) = \frac{\rho(0)}{1 + e^{(r-R)/a}} \qquad \textbf{Eqn. 2.2}$$

with $R = r_o A^{1/3}$ **Eqn. 2.3**

where $r_o = 1.1\text{–}1.2$ fm and $a \sim 0.5$ fm

for all nuclei with $A > 4$.

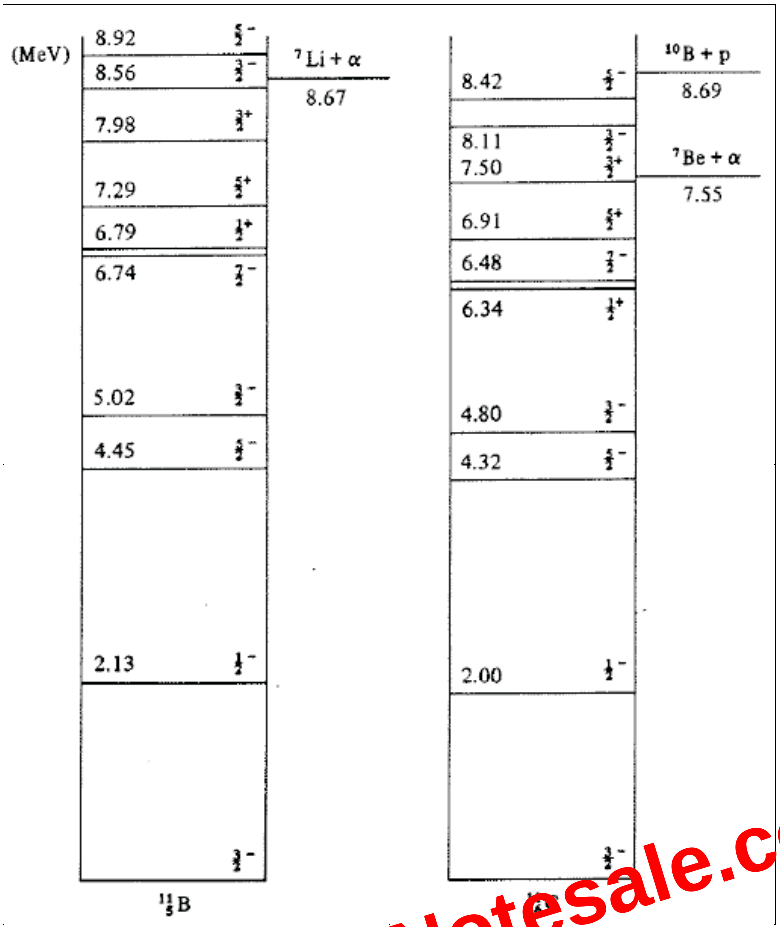


Fig. 2.2: Energy level diagram for mirror nuclei $^{11}{}_5$B and $^{11}{}_6$C. The spins and parities are also given. Note the proton separation energy form $^{11}{}_6$C at 8.69 MeV and the α-particle separation energies.



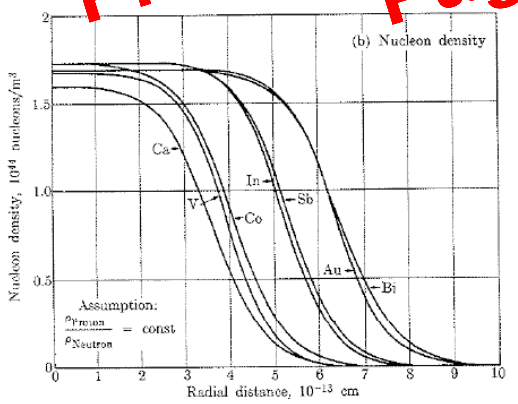


Fig. 2.3: Nucleon density as determined by high-energy electron scattering (Woods–Saxon form).

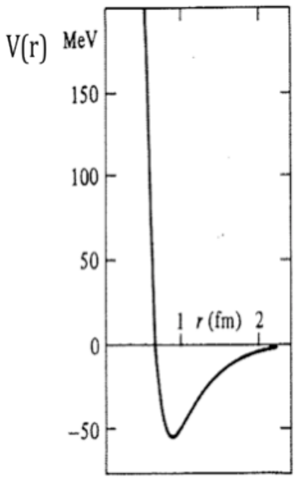


Fig. 2.4: One of the components of the nuclear potential. An important feature is the repulsive core which stops nuclei collapsing