Quadrant II – Notes

Programme: Bachelor of Science (Third Year)

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Paper Title: Nuclear Physics

Unit 2: Nuclear Forces

Module Name: Meson theory of nuclear forces, estimation of mass of meson using Heisenberg's Uncertainty Principle; Yukawa potential.

Module No: 06

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The Exchange Force Model

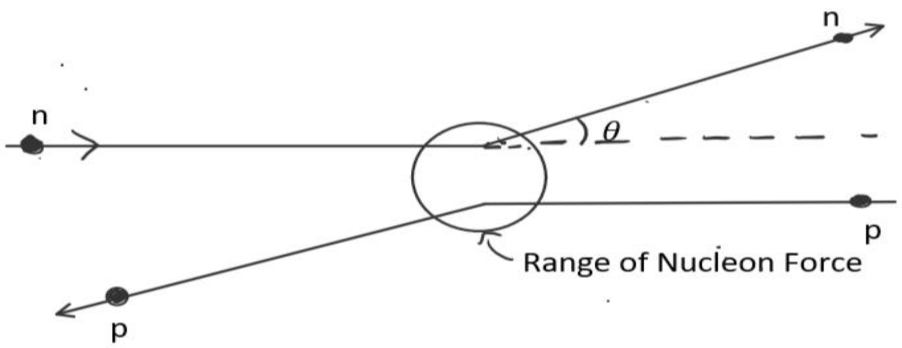
The exchange force denotes a force produced by the exchange of force carrier particles. Yukawa suggested that the nuclear forces were transmitted between the nucleons by other particles, as yet undiscovered, which have now to be known by the name of the mesons. Evidence in support of presence of exchange forces in nuclei can be seen in the study of np scattering at higher energies.

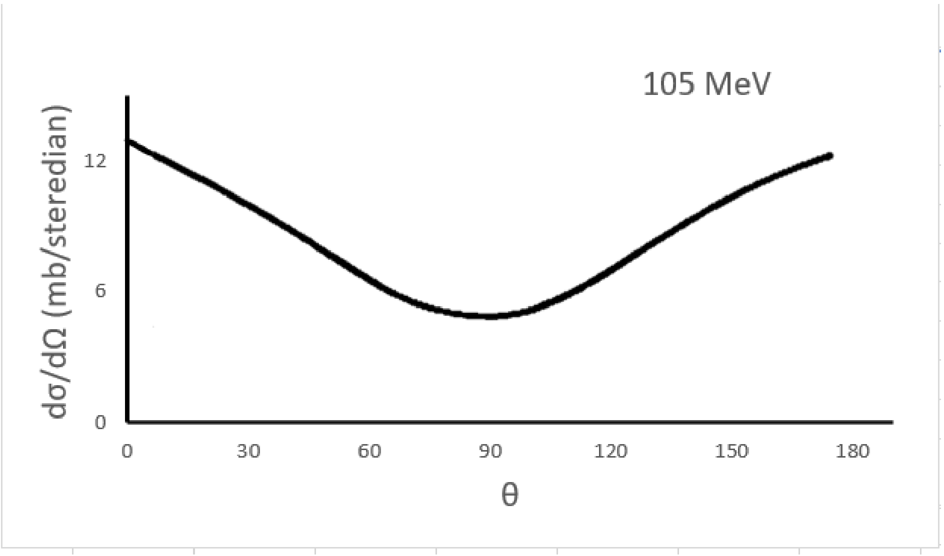
Study of np scattering at higher energies.

In the np scattering experiment, it was expected that the differential cross section for scattering, $d\sigma/d\Omega$ would generally increase for decreasing scattering angle. Hence, a strong peak in the cross section at forward angles near 0° was expected. For small scattering angle

$$\sin\theta \approx \theta = \frac{\Delta p}{p} = \frac{\mathrm{F}\Delta t}{p} = \frac{1}{p}\frac{V_0}{R}\frac{R}{v} = \frac{V_0}{pv} = \frac{V_o}{2T}$$

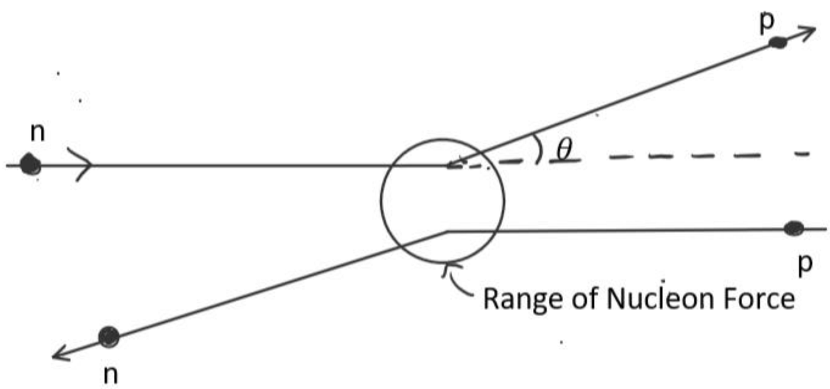
Here $p,\ m,\ v,$ and T stand for the projectile's momentum, mass, speed, and kinetic energy; F is the force exerted on it for time Δt as it passes through the nucleon potential of width R and depth V_0 . For the energies around 100-500 MeV the values of θ is in the range of 10° or smaller.





The neutron-proton differential cross-sections. The strong backward peak (near 180°) is evidence of the nuclear force.

The surprising observation made in the scattering experiments was the increase in yield at large angles and the symmetry of the scattering distribution around 90°. This observation can be explained using the exchange model. During the collision the neutron and proton exchange places. A forward-moving neutron becomes a proton and a backward moving proton (in the centre of mass frame) becomes a neutron. Strong backward peak in np scattering can be explained by exchange forces. Some particle is exchanged between the nucleons that changes their character.



A particle is exchanged during the neutron proton interaction which changes a neutron into proton and proton into neutron.

Meson theory of Nuclear Forces

In view of the preceding discussion, we can conclude that some particle (quanta of the nuclear field) is exchanged in the nucleon-nucleon interaction. As a spin ½ neutron turns into a spin ½ proton, the exchanged particle must have integral spin (0 or 1). As the exchange forces apply to nn, pp and np interactions, there must be an uncharged and charged variety of the exchanged particle. As the nuclear force has a finite range the exchange particle must have a non zero mass

Estimation of the mass of a Meson using Heisenberg's Uncertainty principle

Based on the observed range of the nuclear force, we can estimate the mass of the exchanged particle. Let us assume that a nucleon (which we denote by N, to include both neutrons and protons) emits a particle x. A second nucleon absorbs the particle x:

$$N_1 \rightarrow N_1 + x$$

$$x + N_2 \rightarrow N_2$$

The conservation of energy seems to be violated as nucleon emits a particle of mass energy $m_x c^2$ and still remain a nucleon. The conservation of energy is not violated if the emission and absorption of the particle, with a mass energy $m_x c^2$, takes place within a short time Δt, such that

$$\Delta E \Delta t \sim \hbar$$

where ΔE is the uncertainty in our knowledge of energy and Δt is the time interval characteristic of the rate of change of the system.

If the meson travels at about one half the speed of light, it can travel a distance

$$R = \frac{1}{2} c\Delta t = \frac{1}{2} c \frac{\hbar}{m_x c^2}$$

For the nuclear force with the range 1 Fermi the mass of the exchanged particle is

$$m_x = 270\, m_e$$

Where $m_e$is the mass of the electron.

More on Mesons

The exchanged particles that carry the nuclear force are called ***mesons.*** The meson-exchange theory of nuclear forces was first postulated by Hideki Yukawa in 1935. The π-mesons or pions are the exchange particles responsible for the longer range (1.0- 1.5 fm) part of the nucleon-nucleon potential. To satisfy all the varieties of the exchanges needed in the two-nucleon system, the pions must have spin 0 and there must be three variety of pions:

- $\pi^+$and π^- with mass 139.6 MeV and electric charge +1 and -1 respectively.
- π^0 with mass 135.0 MeV and electric charge 0.

At much shorter ranges (0.23 fm) the exchange of ω mesons (mass 783 MeV) may be responsible for the repulsive core.

The small violation of charge independence may be explained by the differing masses of the charged and neutral pion. The single pion that is exchanged between two identical nucleons must be a π^0:

$$n_1 \to n_1 + \pi^0 \qquad \pi^0 + n_2 \to n_2$$

$$p_1 \to p_1 + \pi^0 \qquad \pi^0 + p_2 \to p_2$$

for the charged pion will not work

$$n_1 \to p_1 + \pi^- \quad \text{but} \quad \pi^- + n_2 \to \ ?$$

$$p_1 \to n_1 + \pi^+ \quad \text{but} \quad \pi^+ + p_2 \to \ ?$$

For the neutron-proton interaction, the single pion that is exchanged between neutron and proton can be charged as well as neutral pions:

$$n_1 \to n_1 + \pi^0 \qquad \pi^0 + p_2 \to p_2$$

$$n_1 \to p_1 + \pi^- \qquad \pi^- + p_2 \to n_2$$

Yukawa Potential

Yukawa wrote an approximate expression of the potential energy of interaction between two nucleons

$$V = -g^2 \frac{e^{-r/R}}{r}$$

- g is the coupling constant
- r is the internucleon distance
- R is the range of the nuclear force related to the mass of the pion.
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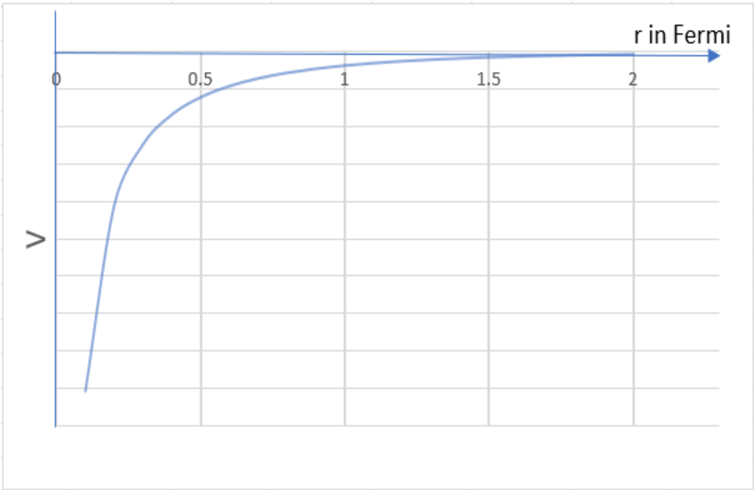

Yukawa Potential

$V(r) \propto \frac{e^{-r/R}}{r}$ decreases in magnitude with increasing r fairly gradually, but the decrease is much more rapid then that of the long range coulomb potential $V(r) \propto \frac{1}{r}$.