Meson theory of nuclear force (Yukawa Potential):→

Yukawa in 1935, proposed that nuclear forces are due to an exchange of particles of intermediate mass, known as mesotrons or mesons (Yukawa particle). In the nuclear field particle has finite rest mass because, the nuclear force is short range. The rest mass M_π of the field particle may be computed as follows:-

When one nucleon exerts force on the other, mesons is created and the creation of meson violates the conservation of energy by the amount ΔE corresponding to meson rest mass, i.e.

$$\Delta E = M_\pi c^2 \quad \text{——— (1)}$$

The duration of excursion of meason, Δt is given by uncertainty principle,

$$\Delta t \approx \frac{\hbar}{\Delta E}$$

In this time meson can cover a distance r_0, given by

$$r_0 = c\Delta t = \frac{c\hbar}{\Delta E},$$

$$r_0 = \frac{c\hbar}{M_\pi c^2} = \frac{\hbar}{M_\pi c} \quad \text{——— (3)}$$

r_0 is the range of nuclear force and if we put $r_0 = 1.4 f$, then

$$M_\pi = \frac{\hbar}{r_0 c} = \frac{.045\times10^{-34}}{1.4\times10^{-15}\times3.0\times10^{8}} \quad \left(6.6\times10^{-34}\right)$$

$$= 0.25\times10^{-27}\,kg$$

Or

$$M_\pi = \frac{0.25\times10^{-27}}{9.01\times10^{-31}}$$

$$M_\pi = 270\, M_0$$

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M_0 being the rest mass of e^-. In 1947, Powell et.al, discovered π-meson in cosmic radiations and has a mass $273 M_0$. This particle, π-meson (pion), is exact Yukawa particle. The pions are of three kinds; positive (π^+) negative (π^-) and neutral (π^0), all with intrinsic spin $s=0$. Their rest masses are 139·6 MeV, 139·6 MeV and 135·0 MeV, respectively. The force field betn two protons or two neutrons is carried by a neutral pion while betn a neutron and proton by a charged pion. ⊛- - - ⊛

(Yukawa Potential) → According to Yukawa's hypothesis, nucleon is regarded as source of field quanta and hence of the meson field. A nucleon is thought to be surrounded by virtual pions. The meson field possesses a static type of interaction which can be represented by a potential function. Now, an expression for the potential func. will be derived.

The relativistic form of energy E of particle of rest mass M_π and momentum p is given by

$$E^2 = p^2c^2 + M_\pi^2 c^4 \quad \text{——— (4)}$$

Where, c is the velocity of light. In quantum Mechanics

$$E \to i\hbar\frac{\partial}{\partial t} \text{ and } p = -i\hbar\nabla \quad \text{——— (5)}$$

Putting in eqn (4)

$$-\hbar^2\frac{\partial^2}{\partial t} = \hbar^2c^2\nabla^2 + M_\pi^2 c^4 \quad \text{——— (6)}$$

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If ϕ is pion wave func. then wave eq^n for pion takes the form

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \frac{M_\pi^2 c^2}{\hbar^2}\right)\phi = 0 \quad \text{—— (7)}$$

This is Klein Gordan eq^n for a free particle of spin 0. If $M_\pi = 0$, we get

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\phi = 0 \quad \text{—— (8)}$$

This is wave eq^n for EM field. Thus, eq^n (4) may be thought as derived from eq^n(5). Now the simplest type of EM field is electrostatic field. The corresponding eq^n is obtained by putting $\frac{\partial \phi}{\partial t} = 0$, i.e,

$$\nabla^2 \phi = 0 \text{ ; Laplace eq}^n$$

The identical eq^n for the meson field is

$$\left(\nabla^2 - \frac{M_\pi^2 c^2}{\hbar^2}\right)\phi = 0 \quad \text{—— (9)}$$

This is in absence of any source of mesons, but in the presence of source, the eq^n should resemble with Poisson's eq^n, i.e, it should have the form.

$$(\nabla^2 - \mu^2)\phi = 4\pi g\, \delta(r) \quad \text{—— (10)}$$

Where, $\mu = \frac{M_\pi c}{\hbar} = \frac{1}{r_0}$. The factor 'g' plays the same role as the charge 'e' plays in the case of electrostatic field, and is a measure of nuclear field and known as mesic charge. $\delta(r)$ is Dirac delta func. $\{\delta(r) = 1$ at $r = 0$, $\delta(r) = 0$, at finite $r\}$. The solution of eq^n(9) comes out to be

$$\phi = g\,\frac{e^{-\mu r}}{r} \quad \text{—— (11)}$$

$$V(r) = g\phi = g^2\,\frac{e^{-\mu r}}{r} \quad \text{—— (12)}$$

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The shape of the potential is shown is fig. 1.

Meson theory provides a natural explanation for the exchange forces. The meson theory helps in predicting

(a) the existence of pions

(b) their mass within 10%

(c) pion's spin and parity.

(d) no. of different pion species and their electric charges

(e) Isotropic spin of pions

(f) large pion-nucleon scattering cross-section

(g) The existence of pion based reaction in nucleon-nucleon collisions and in the absorption of γ-quanta with energies in excess of 150 MeV by nucleons.

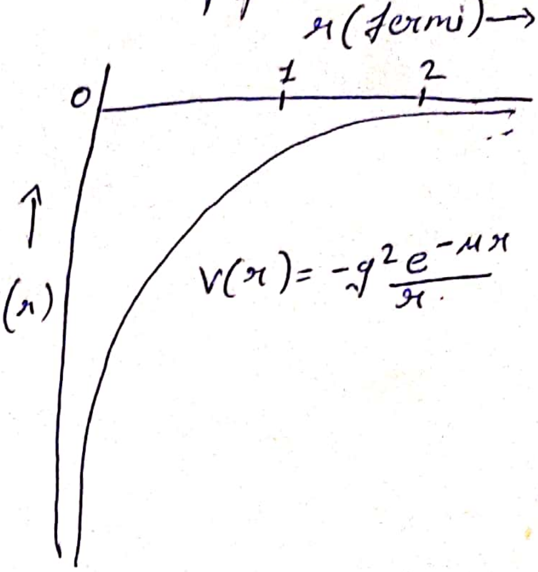

Fig 1. Yukawa Potential: eqn (12)

The meson theory provides correct description of the nature of nuclear forces upto energies of the order of several hundred MeV.

(*) Acco. to uncertainty principle, if a nucleon stands alone, the pion must be reabsorbed by the same nucleon from which it was emerged. But, if two are close together, a pion could be emitted by one and absorbed by the other. The net result is that a pion has jumped across from one nucleon to another, and in process, the nucleon, change their roles. Yukawa realised that this kind of pion exchange could produce a strong attracting force betn two nucleons, called an exchange force. The range of the force can be calculated from uncertainty principle as $\hbar/m_0 c \approx 1.4f$. (*)

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