PHYS 3446 – Lecture #9

Thursday, Feb 19, 2015
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- Nuclear potential
- Nuclear Range
- Early Nuclear models

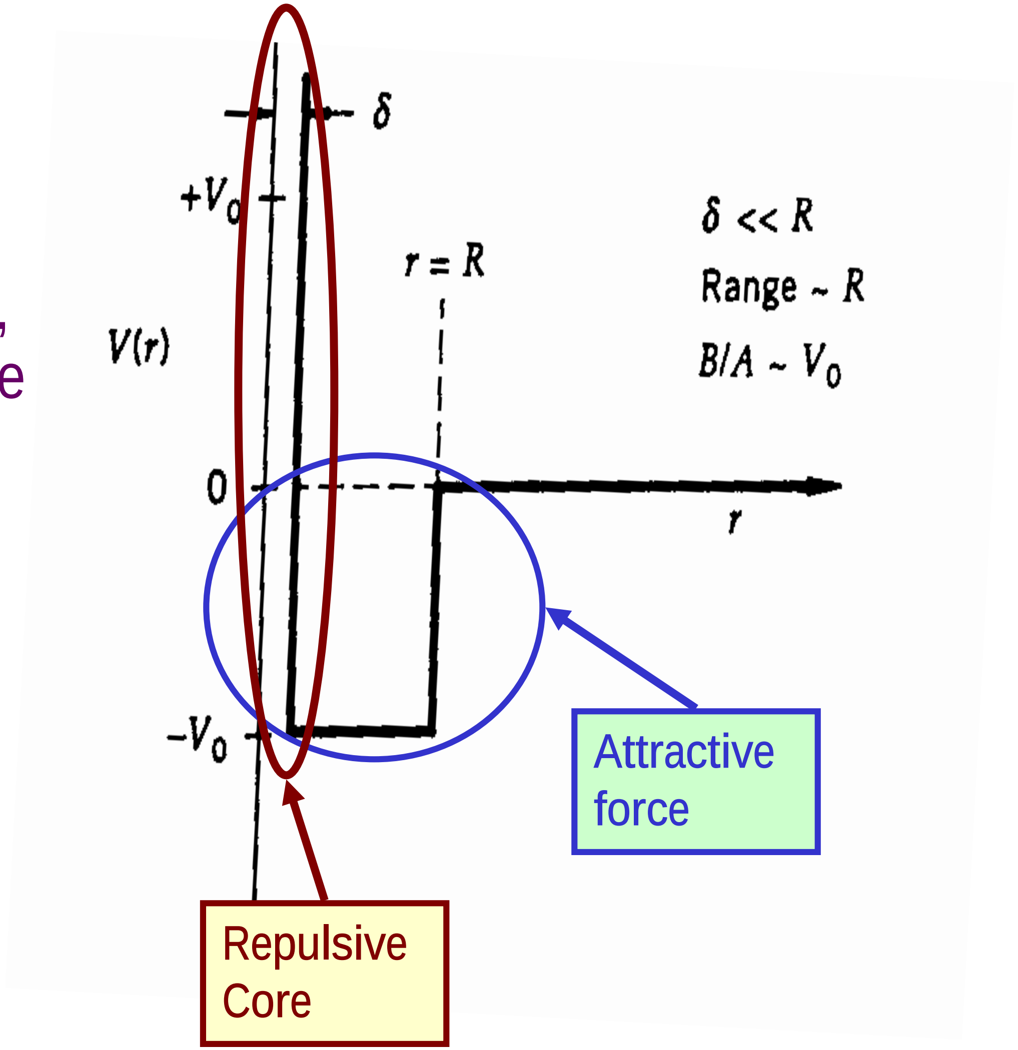
Shape of the Nuclear Potential

- Nuclear force keeps the nucleons within the nucleus.
  - What does this tell you about the nature of the nuclear force?

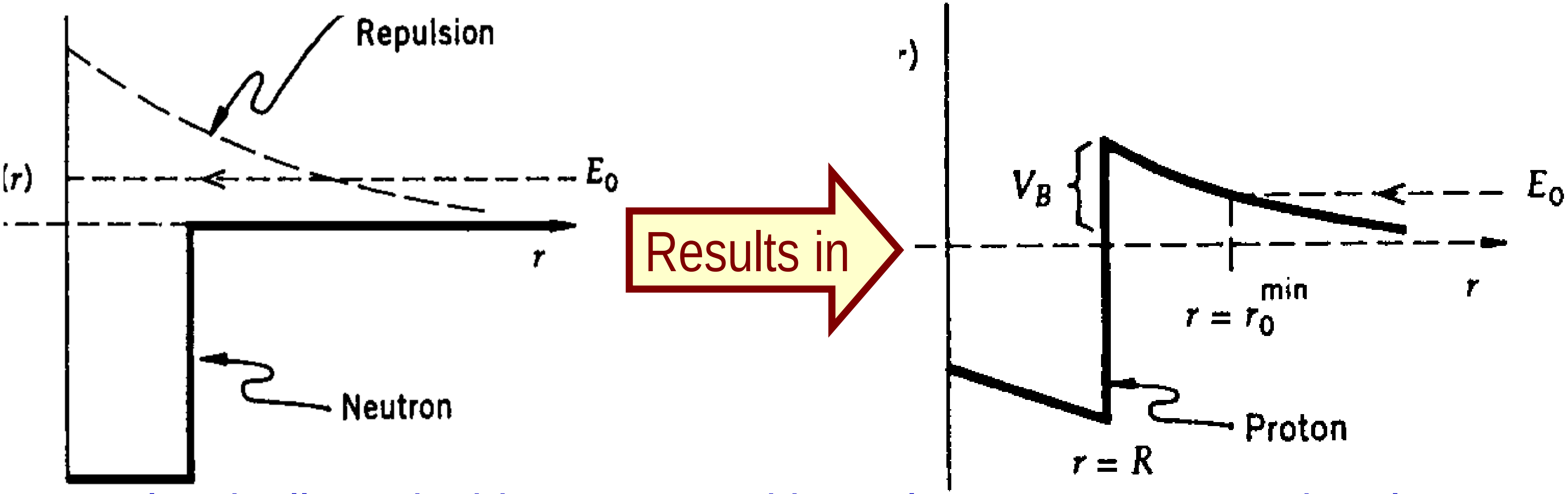
  $\Rightarrow$It must be attractive!!
- However, scattering experiments with high energy revealed a repulsive core!!
  - Below a certain length scale, the nuclear force changes from attractive to repulsive.
  - What does this tell you?
    - Nucleons have substructure….
- This repulsive feature is good, why?
  - If the nuclear force were attractive at all distances, the nucleus would collapse in on itself.

Shape of the Nuclear Potential

- We can express this behavior in terms of a square-well potential
  - For low energy particles, the repulsive core can be ignored, why?
    - they don't reach the core
- This model is too simplistic, since there are too many abrupt changes in potential.
  - Also ignores Coulomb effects



Nuclear Potential w/ Coulomb Corrections



- Classically an incident proton with total energy E_0 cannot be closer than $r=r_0$. Why?
  - For $R<r<r_0$, $V(r) >E_0$ and KE<0 ➔ Physically impossible
- What about a neutron?
  - Could penetrate into the nuclear center.
- Low energy scattering experiments did not provide the exact shape of the potential but did give info on the range and height of the potential
- The square-well shape provides a good phenomenological description of the nuclear force.

Nuclear Potential

- A square well nuclear potential → provides the basis of quantum theory with discrete energy levels and corresponding bound state just like in atoms
  - Presence of nuclear quantum states have been confirmed through
    - Scattering experiments
    - Studies of the energies emitted in nuclear radiation
- Studies of mirror nuclei and the scatterings of protons and neutrons demonstrate
  - Aside from the Coulomb effects, the forces between two neutrons, two protons or a proton and a neutron are the same
    - Nuclear force has nothing to do with electrical charge
    - Protons and neutrons behave the same under the nuclear force
  - Referred to as <u>charge independence</u> of nuclear force.

Nuclear Potential – Iso-spin symmetry

- Strong nuclear force is independent of the electric charge carried by nucleons
  - Concept of strong isotopic-spin symmetry.
    - proton and neutron could be viewed as two different iso-spin state of the same particle called nucleon
  - In other words,
    - If Coulomb effect were turned off, protons and neutrons would be indistinguishable in their nuclear interactions
    - Can you give another case just like this???
  - This is analogous to the indistinguishability of spin up and down states in the absence of a magnetic field!!
- This is called Iso-spin symmetry (predates quark model, no longer really used except in Nuclear classes!)

Range of the Nuclear Force

- EM force can be understood as a result of a photon exchange
  - Photon propagation is described by the Maxwell's equation
  - Photons propagate at the speed of light.
  - What does this tell you about the mass of the photon?
    - Massless
- Coulomb potential is $$V(r) \propto \frac{1}{r}$$

Massless particle exchange

- What does this tell you about the range of the Coulomb force?
  - Long range.

Yukawa Potential

- For massive particle exchanges, the potential takes the form

$$V(r) \propto \frac{e^{-\frac{mc}{\hbar}r}}{r}$$

  - What is the mass, m, in this expression?
    - Mass of the particle exchanged in the interaction
      - The mass of the mediator of the force
- This form of potential is called Yukawa Potential
  - Formulated by Hideki Yukawa in 1934
- What does Yukawa potential turn to in the limit m →0?
  - Coulomb potential

Ranges in Yukawa Potential

- From the form of the Yukawa potential

$$V(r) \propto \frac{e^{-\frac{mc}{\hbar}r}}{r} = \frac{e^{-r/ƛ}}{r}$$

- The range of the interaction is given by some characteristic value of r. What is this?
  - Compton wavelength of the mediator with mass, m: $ƛ = \frac{\hbar}{mc}$
- What does this mean?
  - Once the mass of the mediator is known, range can be predicted
  - Once the range is known, the mass can be predicted

Ranges in Yukawa Potential

- Let's put Yukawa potential to work
- What is the range of the nuclear force?
  - About the same as the typical size of a nucleus
    - 1.2×10^{-13}cm
  - thus the mediator mass is

$$mc^2 = \frac{\hbar c}{\lambda} \approx \frac{197\,MeV - fm}{1.2\,fm} \approx 164\,MeV$$

- This is close to the mass of a well known π meson (pion)

$$m_{\pi^+} = m_{\pi^-} = 139.6\,MeV/c^2; \quad m_{\pi^0} = 135\,MeV/c^2$$

- Thus, it was thought for a while that π are the mediators of the nuclear force

Nuclear Models

- Experiments showed that the nuclear forces have different characteristics than other forces
- Quantifying the nuclear forces and understanding the structure of the nucleus were not straightforward
- Several phenomenological models (not theories) developed that describe subsets of the experimental observations
- Most of the models assume a central potential, like the Coulomb potential

Nuclear Models: Liquid Droplet Model

- This was the earliest phenomenological model and had success in describing the binding energy of a nucleus
- Nucleus is essentially spherical with radius proportional to $A^{1/3}$.
  - Densities are independent of the number of nucleons
- Led to a model that envisions the nucleus as an incompressible liquid droplet
  - In this model, nucleons are equivalent to molecules
- Quantum properties of individual nucleons are ignored

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- An early attempt to incorporate quantum effects
- Assumes nucleus as a gas of free protons and neutrons confined to the nuclear volume