Nuclear Physics

- Nuclear Physics: Principles and Applications
  J.S. Lilley

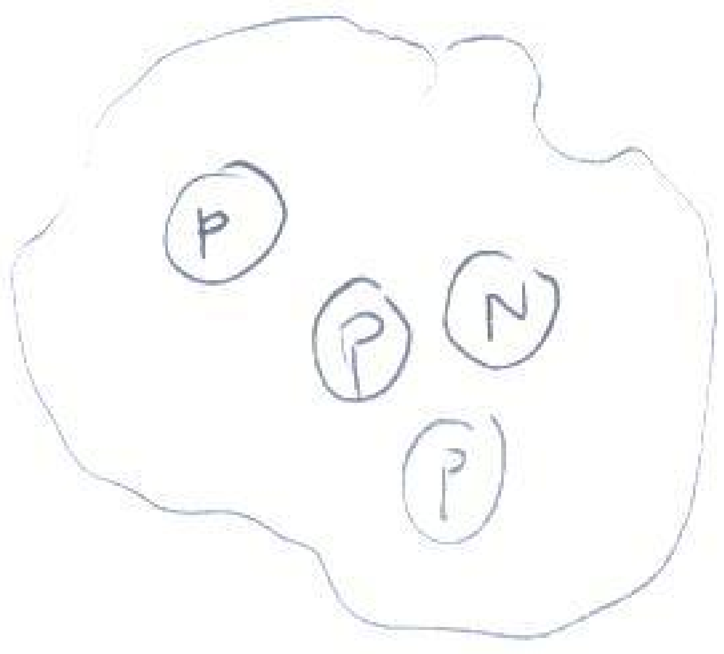
- Phys 4403, 11:00 am – 12:15 pm, LSE 205

  http://chemistryandphysics.astate.edu/teaney

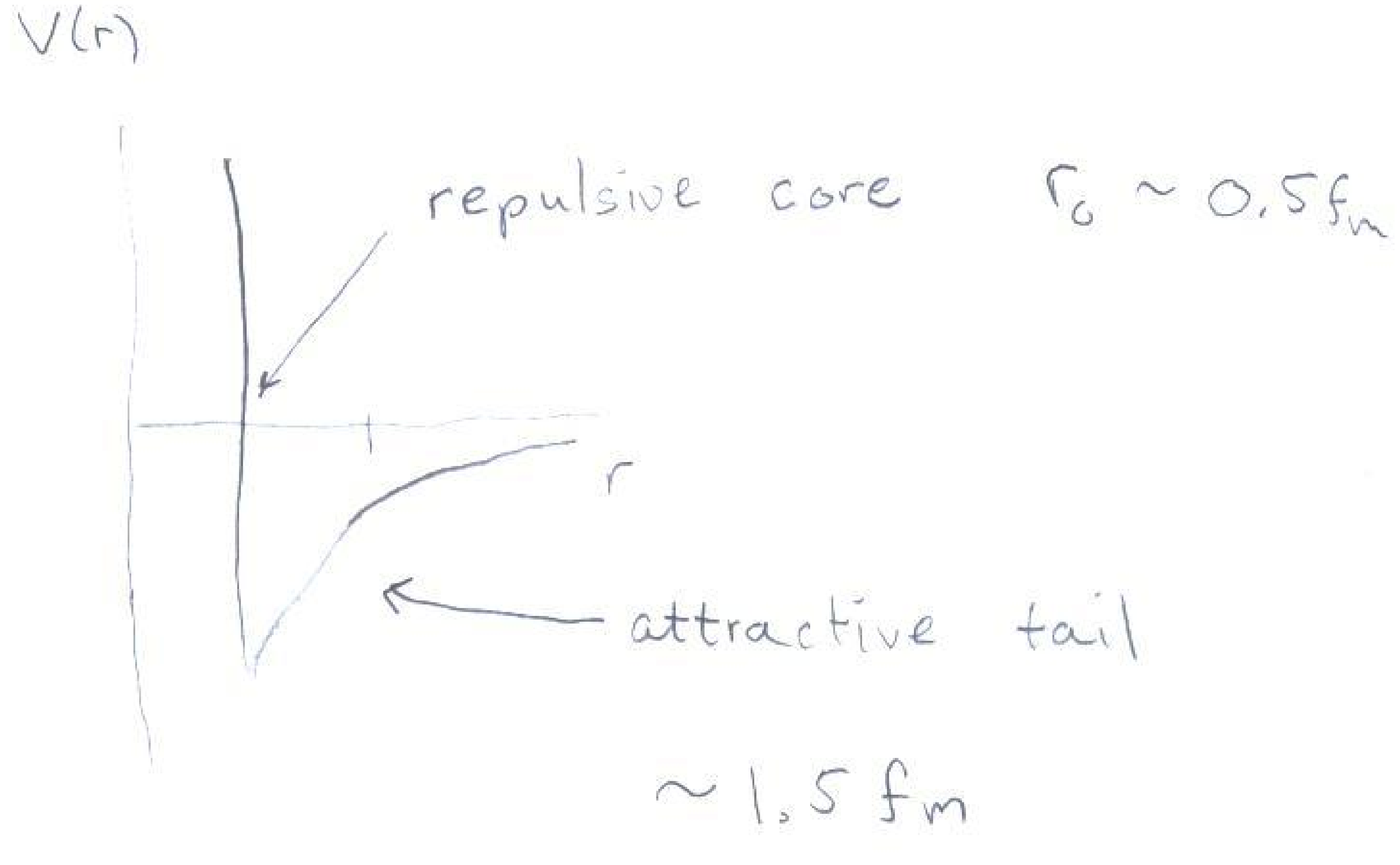
- This course will have a lot of homework

Basic Facts

- Why doesn't the nucleus blow up?



– There must be an attractive "relatively short" range force



Where does this scale come from?

$\hbar c \simeq 200$ MeV fm

$\hbar$, c , masses

$\hbar c \approx 200$ eV nm

→ enough to form all other dimensionfull quantities

Examples $\Delta x \Delta p \sim \hbar$ $\Delta t \Delta E \sim \hbar$

$$\frac{1}{\Delta x} \sim \frac{p}{\hbar} \sim \frac{mc}{\hbar}$$

$$\frac{1}{t} \sim \frac{E}{h} \sim \frac{mc^2}{\hbar}$$

So

$$\Delta x \sim \frac{\hbar}{m_\pi c}$$ substitute /

$$\Delta x \sim \frac{\hbar c}{m_\pi c^2} \Rightarrow m_\pi c^2 \sim \frac{\hbar c}{\Delta x} \sim \frac{200 \text{ MeV fm}}{1.5 \text{ fm}}$$

Yukawa ~1930 →

$c^2 m_\pi \sim 1.33$ MeV guess

$m_\pi^0 c^2 = 140$ MeV actual

Short range

$0.5\ \text{fm} \sim \frac{\hbar c}{m_\rho c^2}$

$m_\rho c^2 \sim \frac{200\ \text{MeV fm}}{0.5\ \text{fm}}$

$m_\rho c^2 \sim 400\ \text{MeV}$ ← guess

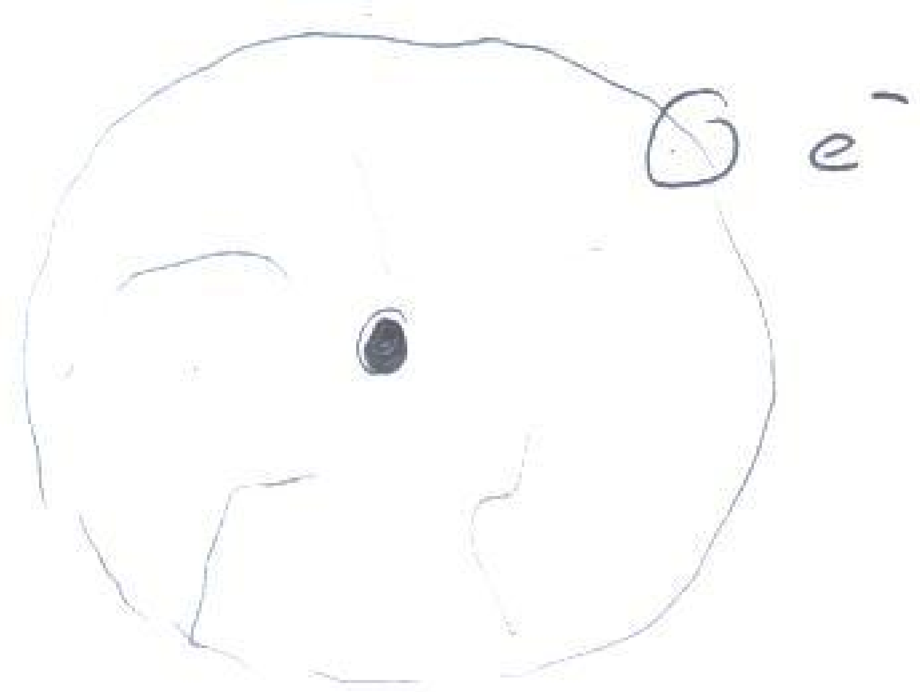
$m_\rho c^2 \sim 770\ \text{MeV}$ ← actual

Lots of other particles, $\rho, \sigma, \omega, \eta, \ldots$

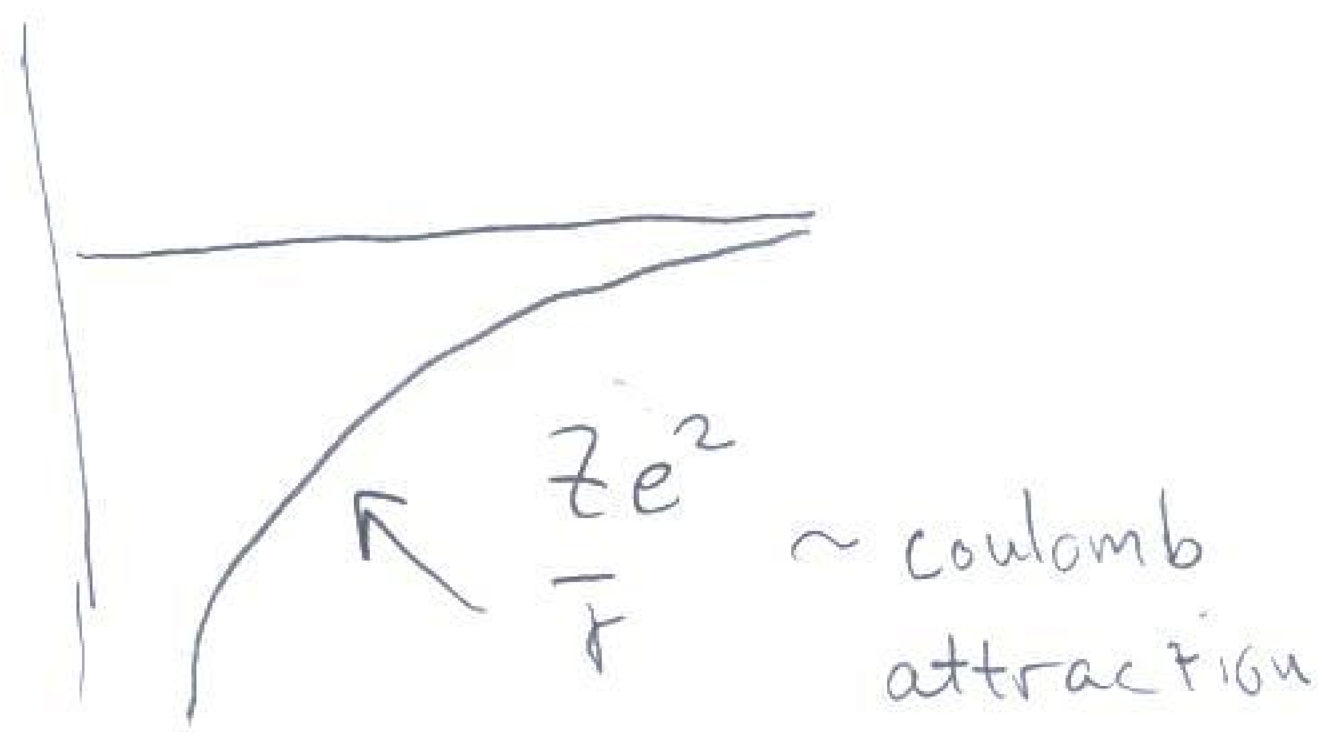
All of these add up to the repulsive core

The sizes of nuclei

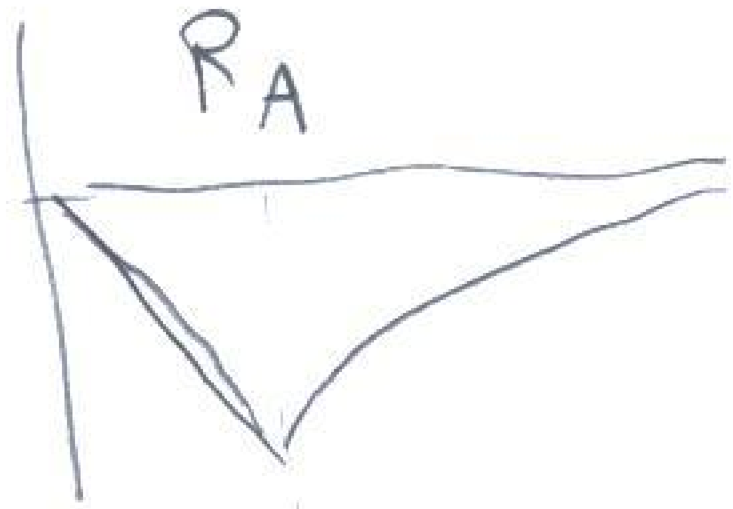
- Atom



- Normally treat nucleus as a point



- Actually ~ more like a sphere



$R_{Au} \sim 5\ \text{fm}$

<u>Estimate:</u>

$$|\psi|^2 \sim \frac{1}{a_0^3} \qquad \left[\int d^3r\, |\psi|^2 = 1 \right]$$

So

$$\langle \Delta V \rangle \sim \int^{R_A} d^3r\, |\psi|^2 \frac{Ze^2}{R_A} \sim R_A^3 \frac{1}{a_0^3} \frac{Ze^2}{R_A}$$

$$\langle \Delta V \rangle \sim \frac{R_A^2}{a_0^2} \; Z \underbrace{\frac{e^2}{a_0}}_{\sim 13.6\,\text{eV}}$$

$$\langle \Delta V \rangle \approx \frac{R_A^2}{a_0^2} \cdot Z \cdot (13.6\,\text{eV})$$

$$\langle \Delta V \rangle \sim \left(\frac{5 \times 10^{-15}\,\text{m}}{0.5 \times 10^{-10}\,\text{m}} \right)^2 \times Z \times 13.6\,\text{eV}$$

$$\Delta V \sim Z \times 13.6\,eV \times 10^{-8}$$

$$\frac{\Delta V}{\hbar} \sim \frac{\Delta V}{\hbar c} \times c = \frac{Z \times 13.6\,eV \times 10^{-8}}{200\,eV\,nm} \cdot 3 \times 10^{8}\,m/s$$

$$\sim Z \times 200\,MHz$$ ← Not that small

$$\Delta\omega \sim \left(\frac{Z}{40}\right)\left(\frac{R_A}{5\,fm}\right)^2 \cdot 8\,GHz$$

- Measure hyperfine structure for Lots of atoms!
- Measure for different Z, etc

Summary

$$R_A \propto A^{1/3}$$

- Important

$$\frac{A}{\frac{4}{3}\pi R_A^3} = \rho_0 = \text{constant} = \underbrace{\frac{1}{6}}_{0.16} \frac{\text{nucleons}}{\text{fm}^3}$$

ρ_0 ← nuclear density

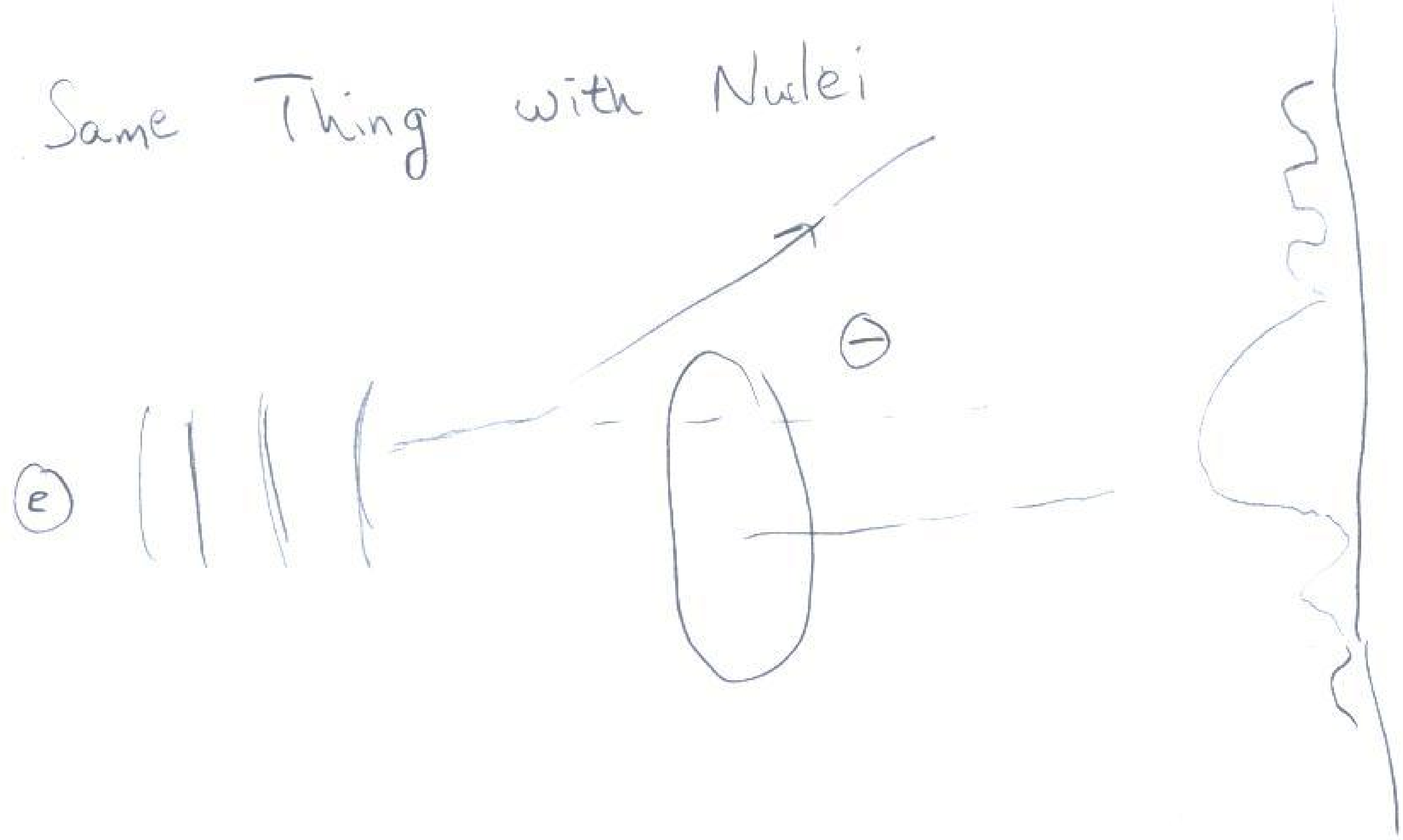
The nuclear density is constant!

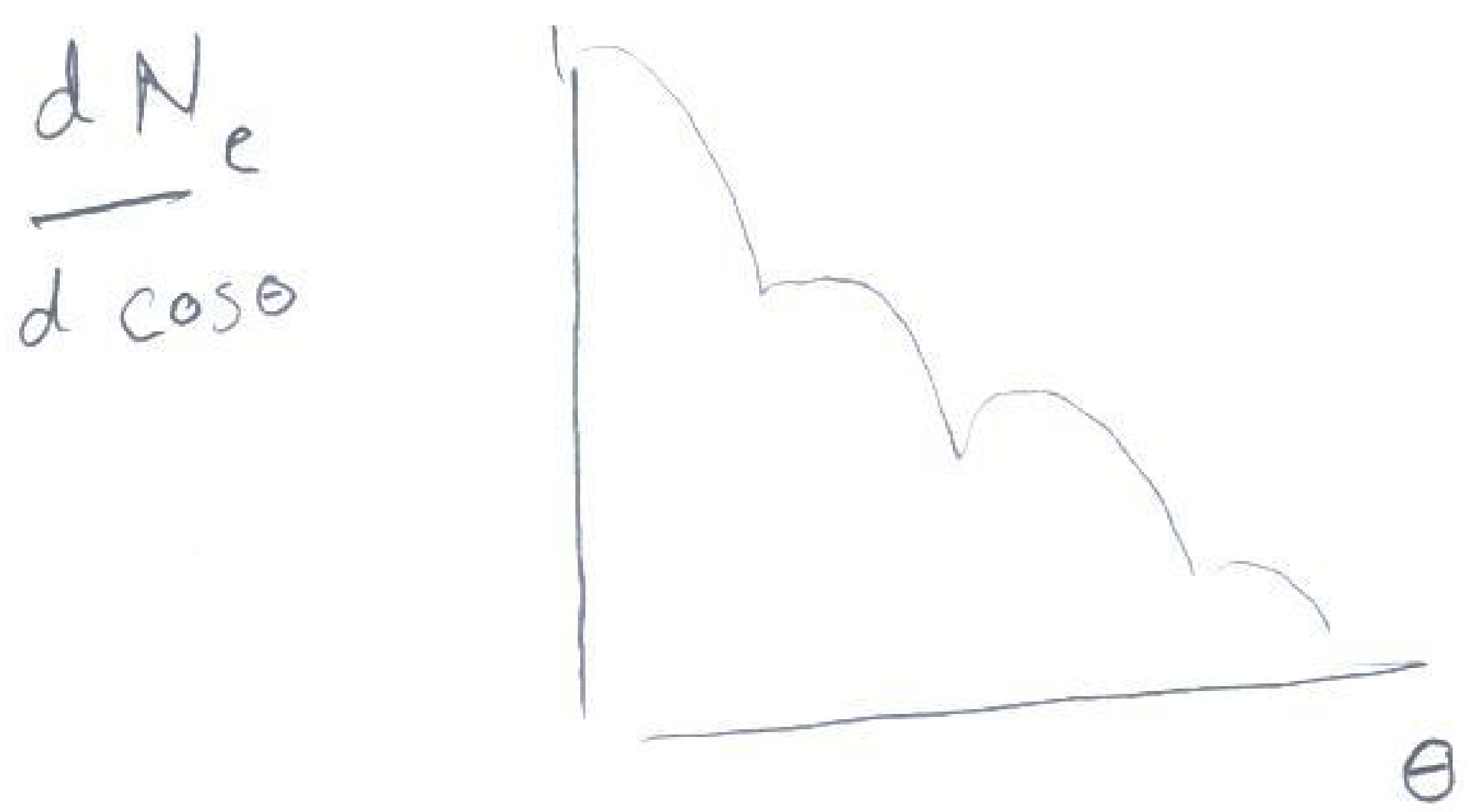
Direct Measurements ~ 60's

→ electron scattering

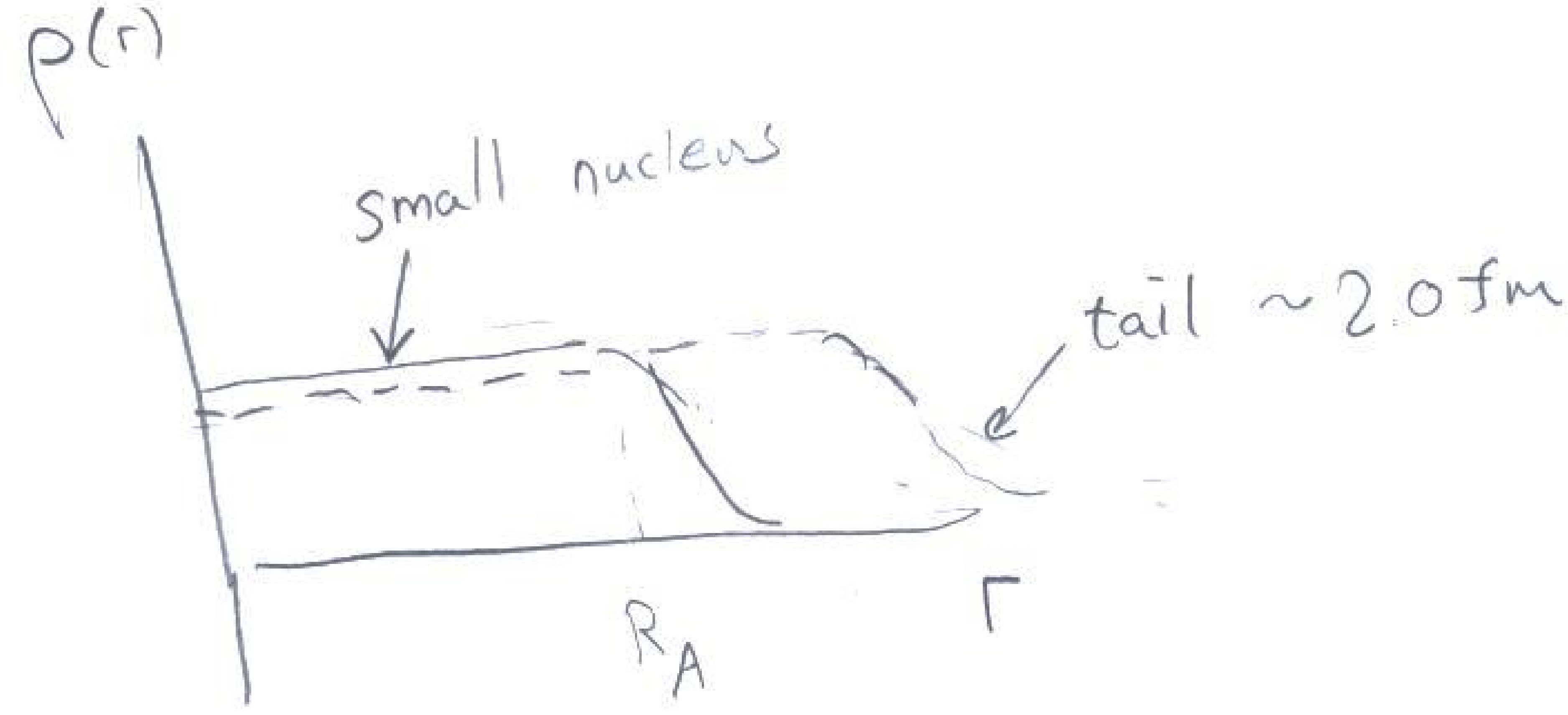
$$\sin\theta \simeq \frac{\lambda}{d}$$

Same Thing with Nuclei



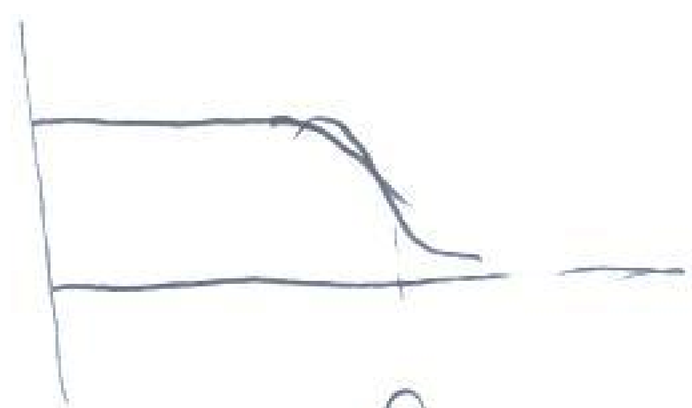


Summary



Often take a woods-saxon form

$$\rho = \frac{Const}{\left(1 + e^{(r-R_A)/\delta}\right)}$$



$\delta \simeq 0.55\,fm$

$R_A \propto A^{1/3}$, $R = r_0 A^{1/3}$

$r_0 = 1.07\,fm$

→ For $r \ll R_A$ $e^{(r-R_A)/\delta} \rightarrow$ tiny

$$\rho \rightarrow \frac{Const}{1 + tiny} \rightarrow Const$$

→ For $r \gg R_A$

$e^{(r-R_A)/\delta} \rightarrow$ huge

$$\rho \rightarrow \frac{const}{1 + huge} \rightarrow 0$$

Binding Energies

$$M_A = ZM_p + ZM_e + NM_N - BE$$ ← Binding Energy

$$= Z\underbrace{(M_p + M_e)}_{M_H} + NM_N - BE$$

(N ← number of nucleons)

$$\frac{BE}{(Z+N)} = \text{Binding Energy per Nucleon}$$

$$\frac{BE}{A} \simeq 8.5 \text{ MeV per nuleon}$$

- Interpretation

  (1) Each nucleon interacts with a small # of neighbors

  — Compare, in atoms $BE/_{\text{election}} \sim Z$

Consequences

- Non-relativistic is justified!

$$BE \sim \frac{1}{2} m_p v^2$$

$$\frac{2BE}{m_p c^2} \sim \left(\frac{v}{c}\right)^2$$

$$\frac{2 \cdot 8.5\ \text{MeV}}{938\ \text{MeV}} = \left(\frac{v}{c}\right)^2 \implies \frac{v}{c} = 0.13$$

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