RECALL: HEISENBERG'S UNCERTAINTY PRINCIPLE

\[ \Delta x \Delta p \sim h \]

Can you say where it is precisely? Can you measure \( \lambda \) precisely?

NO

NO

YES

YES

WAVE A:

WAVE B:

\( \lambda = \frac{h}{mv} \)

\( (\lambda \downarrow \Rightarrow v \uparrow) \)

\( \Delta x \Delta \omega \sim \frac{h}{m} \)

\( \Delta E \sim \hbar \)

IS AT THE CORE OF Q.M. → IMPLICATIONS IN:

QUANTUM COMPUTING, RADIOACTIVE DECAY, BIG-BANG, LARGE SCALE STRUCTURE, PARTICLE PRODUCTION → VACUUM IS NOT VOID!
**OUR JOURNEY SO FAR:**

<table>
<thead>
<tr>
<th>mL</th>
<th>US (chunks, things)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-5}$ m</td>
<td>hair width/dust</td>
</tr>
<tr>
<td>$10^{-10}$ m</td>
<td>molecules</td>
</tr>
<tr>
<td>$10^{-14}$ m</td>
<td>atomic radius</td>
</tr>
<tr>
<td>$10^{-14}$ m</td>
<td>nucleus</td>
</tr>
</tbody>
</table>

**THE ATOM**

- **Chemistry**
  - $e^-$

- **Atomic Phys.**
  - NUCLEAR PHYS.

<table>
<thead>
<tr>
<th>ATOM</th>
<th>Z</th>
<th>A (rounded)</th>
<th>Neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>He</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Li</td>
<td>3</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Be</td>
<td>4</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>N</td>
<td>7</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>U</td>
<td>92</td>
<td>238</td>
<td>146</td>
</tr>
</tbody>
</table>

- **2 protons (+ charge)**
- **A - 2 neutrons (0 charge)**

**HYDROGEN**

**HEL I U M**

*WEIRD! NUCLEUS SHOULD BLOW APART WITH ALL THE + CHARGE CRAMMED IN A TINY VOLUME*
What's in the nucleus? What holds it together?

Proton (Rutherford 1918)

α → N

α + N → O + p

He was disintegrating N into O and a proton

A: 4 14 17 1

Centuries old dream: transmutation of elements

\[ \text{Mass} \sim 938 \text{ MeV/c}^2 = 1 \text{ AMU (atomic mass unit)} \]

Charge = +1, Spin = \( \frac{1}{2} \) (Fermion)

 MASS OF ELECTRON \( \sim 0.511 \text{ MeV/c}^2 \) \times 2000 = HEAVIER

Neutron (Bothe, Becker (1930), Chadwick (1932))

\[ \text{Mass} \sim 940 \text{ MeV/c}^2 \]

Charge = 0

Spin = \( \frac{1}{2} \) (Fermion)

\[ \text{Very penetrating radiation: neutral, non-ionizing} \]
WHY DON'T NUCLEI EXPLODE?

Electric Force: $\rightarrow \bigstar$ $\bigstar \rightarrow$ No Good

Gravity: $F_g/F_e \sim 10^{-46}$ No Way!

NEW FORCE (ATTRACTIVE): "STRONG NUCLEAR" FORCE

Imagine that two protons approach each other

$p \rightarrow \bigstar \leftarrow \bigstar$ COULOMB REPULSION UNTIL $10^{-15}$ m APART

Then the strong force kicks in and they stick together.

Properties:

- STRONGER THAN E. M. FORCE
- LIMITED IN RANGE TO NO MORE THAN $\sim 10^{-15}$ m
Solve Schrödinger Eq. for p and n in nucleus.

→ Discrete Available Energy Levels (just like e⁻)

\[ \epsilon_3 \rightarrow \gamma \]

Atom ionization: \( E \sim 10 \text{ eV} \)

(to remove one e⁻ from atom)

\[ \epsilon_2 \rightarrow 10^6 \text{ eV} \]

Nucleus: \( E \sim 10^6 \text{ eV} \)

(to remove one p or n)

Huge difference between atomic (chemical) and nuclear energy!!
NUCLEAR DECAYS: NUCLEUS CAN BE UNSTABLE → TENDS TO DECAY TO LOWER ENERGY (MORE STABLE) STATE

1. θ RADIATION (photon)

   \[ ^{A}_{Z}X \rightarrow ^{A}_{Z}X + \gamma \]

   EXCITED STATE \rightarrow GROUND STATE (EM RADIATION)

2. β DECAY

   \[ ^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y + e^- \]

   FOURTH FORCE "WEAK FORCE"

   \[ n \rightarrow p + e^- \quad (p^+ \rightarrow n + e^+) \]

   A STAYS THE SAME, Z CHANGES

3. α DECAY: NUCLEUS OF THE

   \[ ^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + \alpha \]

   NUCLEUS BECOMES MORE STABLE AFTER DECAY

   A is REDUCED BY 4 UNITS (AMU), Z is REDUCED BY 2 UNITS