# Lecture 19
# Nuclear Rockets and Nuclear Power

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# Nuclear Rockets

| Type | Energy $\left[\frac{joules}{kgm}\right]$ |
|---|---|
| Heat of Fusion - Water | $334{,}000 \approx 93\ Wh/kgm$ |
| Batteries, Fuel Cells | $10^5 - 10^6$ |
| Melted matter, $LiOH, LiH, LiF$ | $> 10^6$ |
| Combustion – oxidation chemistry | $> 10^7$ |
| Binding energy (dissociation - recombination | $> 10^8$ |
| Fission | $8 \times 10^{13}$ |
| Fusion | $4 \times 10^{14}$ |
| Antimatter annihilation $E/m = c^2$ | $9 \times 10^{16}$ |

$10 - 100\ Wh/kgm$ for batteries

$30{,}000\ Wh/kgm$ for $H_2$

Chemical

Nuclear binding energy

# Nuclear Rockets

| Type | $I_{sp}\ (sec)$ | $U\left(\frac{\mathbf{km}}{\mathbf{sec}}\right)$ |
|---|---|---|
| Fission – Solid Core | 800 - 1000 | 8 - 10 |
| Fission – Gaseous Core | 2000 - 7000 | 20 - 70 |
| Fission – Pulsed (ORION) | 2500 – 150,000 | 25 - 1500 |
| Fission – Fission Fragments | 1,000,000 | 10,000 |
| Fusion | 20,000 – 1,000,000 | 200 – 10,000 |
| Antimatter/Matter Annihilation | 10,000,000 | 100,000 |

The speed of light is ~ 300,000 km/s!

# Radioisotopes for Nuclear Power

Radioisotopes decay naturally and give off heat as they decay!

| Element | Name | Atomic Mass |
|---|---|---|
| Pu | Plutonium | 238 |
| Cu | Curium | 244 |
| Po | Polonium | 210 |
| Ra | Radium | 226 |
| Pm | Promethium | 147 |
| Sr | Strontium | 90 |
| Cm | Curium | 247 |
| Rn | Radon | 222 |
| Xe | Xenon | 144 |

$$_{88}Ra^{226} \rightarrow {}_{2}He^{4} + {}_{86}Rn^{222}$$

Obeys certain laws:

1. Conservation of electric charge
2. Conservation of momentum
3. Combined conservation of mass and energy

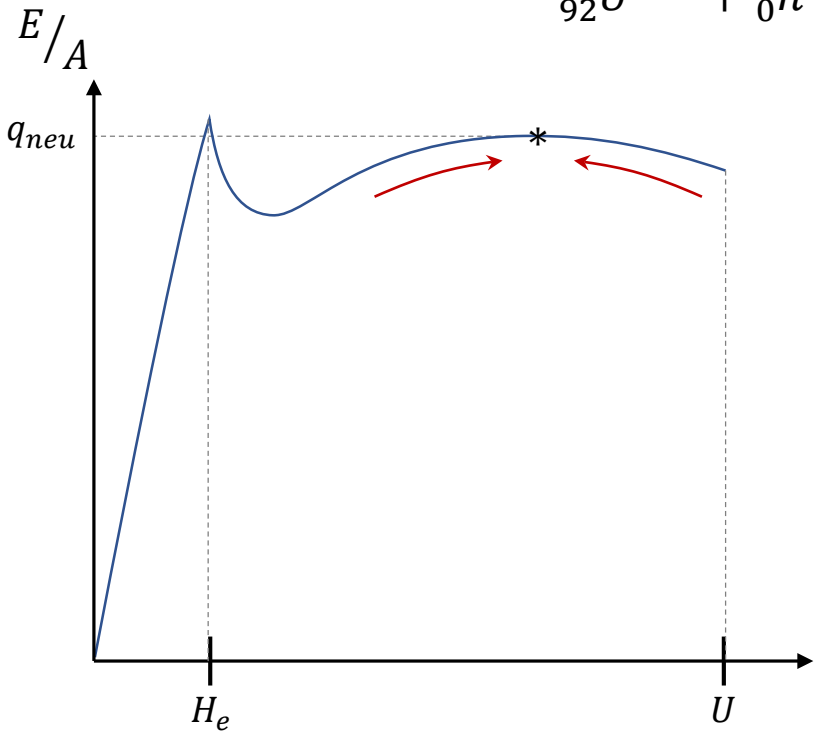
$$E = mc^2$$

# Nuclear Power

$$M_{atom} = NM_n + ZM_p - \frac{|E|}{C^2}$$

$A = N + Z =$ number of neutrons plus number of protons

$$_{92}U^{235} + _{0}n^{1} \rightarrow _{38}Sr^{90} + _{54}Xe^{144} + _{0}n^{1} + _{0}n^{1} + E$$




$E/A =$ Binding energy per number of particles in nucleus

In order to get useful energy from binding, we must go towards center of chart in a change!

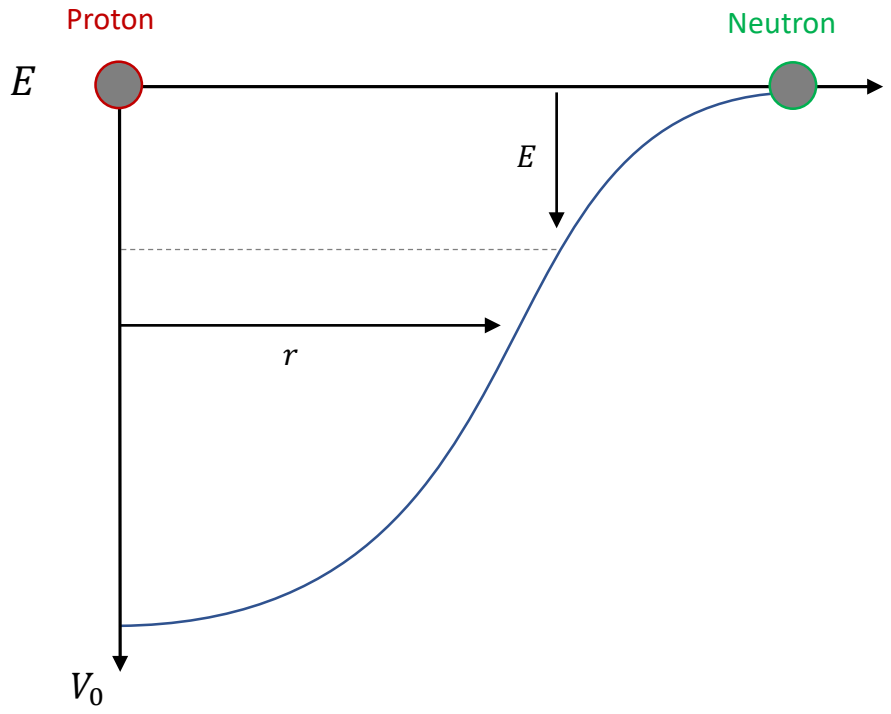
The universe is slowly changing to iron *Fe*. However, we can relax because worse things will happen sooner.

# Radioisotopes

The nucleus is also quantized but is not as well organized as electronic quantization.

Look at the Nuclear force. This is much greater than the Gravitational force. It does not affect particles outside the nucleus. Interaction is only between nucleons in the same nucleus. These nucleons have great kinetic energy.

Determine order of magnitude of the Nuclear force:



# Nuclear Powerplants

Radium { Atomic Number: 88; Mass Number: 226 }

Radium continually emits $\alpha$-particles

$$_{88}Ra^{226} \rightarrow {}_{2}He^{4} + {}_{86}Rn^{222}$$

Combine { 2. Conservation of Mass; 3. Conservation of Energy }

1. Conservation of Electric Charge
2. Conservation of Mass
3. Conservation of Energy
4. Conservation of Momentum (including any momentum)

Angular momentum is more important than translational momentum!

Boron goes to Carbon

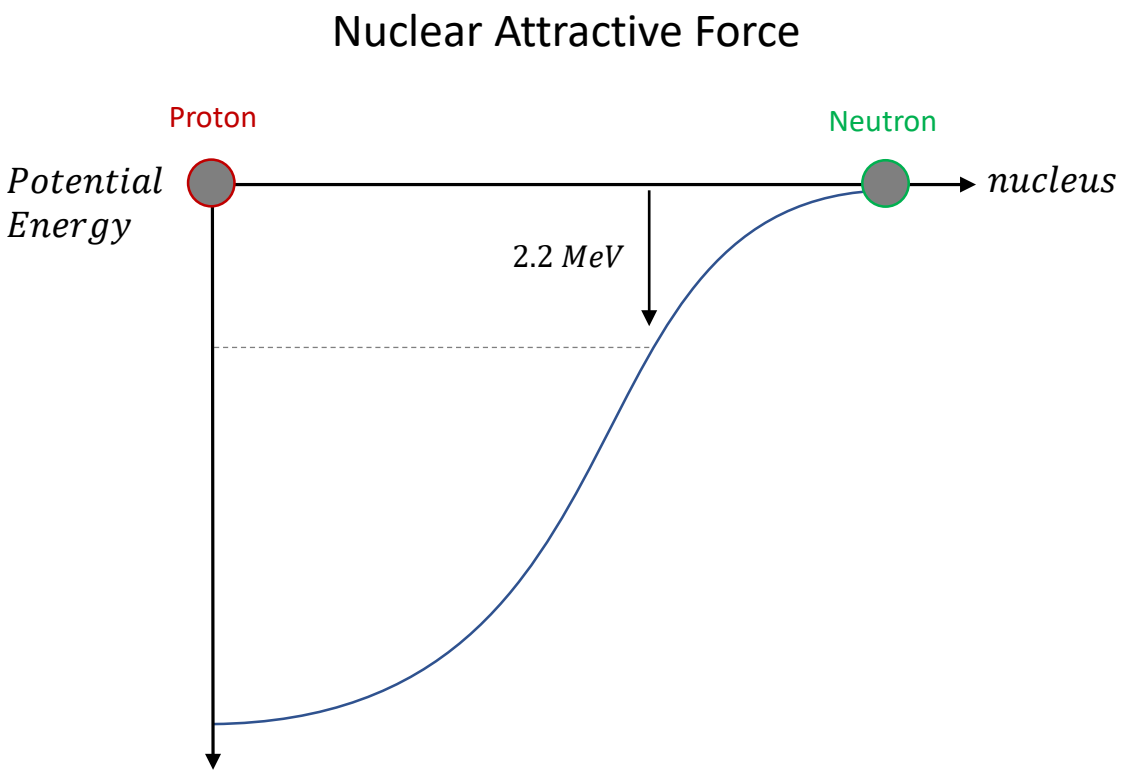
$$_{5}B^{12} \rightarrow {}_{6}C^{12} + {}_{-1}e^{0}$$

Positrons have a short lifetime due to annihilation

The Neutrino was recently discovered and explains conservation of momentum!

Neutrino has “no” mass, no charge, but only momentum!

# Nuclear Powerplants




$2.2\ MeV$ is a quantized energy which is radiated away (photons). Now the system is stable and the neutron and proton will not fly apart unless $2.2\ MeV$ is added. This is the binding energy analogous to chemical heat of formation in chemical reactions.

$$1\ amu = \frac{1}{16}\ mass\ O\ atom$$

$$1\ amu = 930\ MeV$$

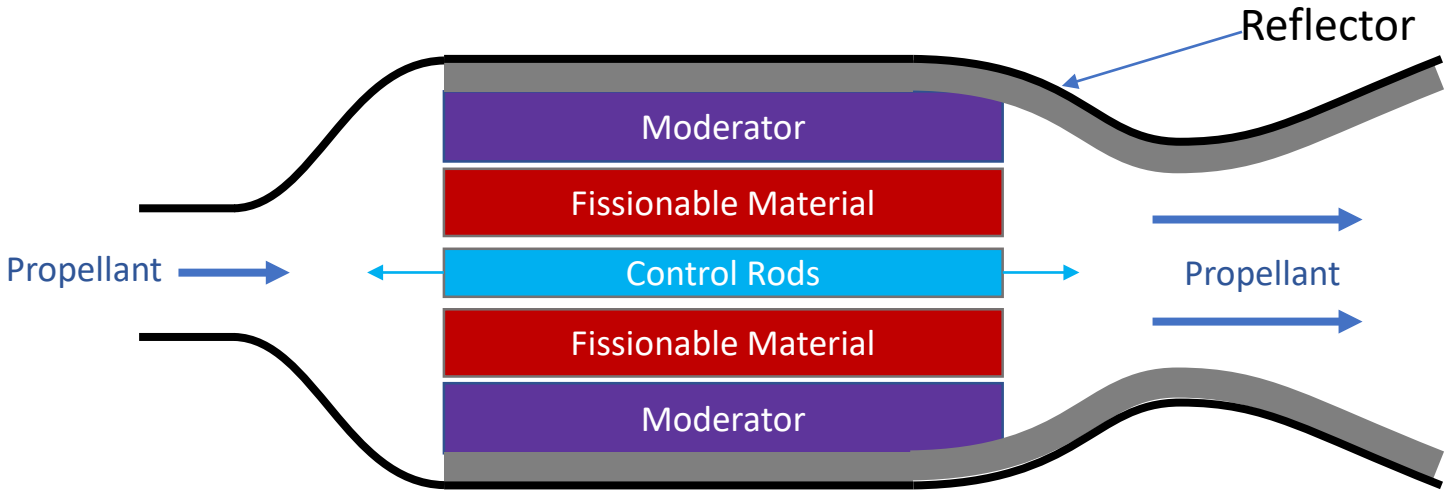
$$10^{12}\ eV = 10^{6}\ MeV = 1\ erg\ = 10^{-7}\ \text{joules}$$

# Nuclear Rockets

In the solid-core and gaseous-core rockets,
the fissionable material passes energy to the propellant.

Fissionable fragments and ORION concepts
use the fissionable material as propellants.

***Solid-core nuclear rocket design***




***Reflector*** – keeps neutrons from escaping
***Control Rod*** – absorbs neutrons at sufficient rate to control reaction and prevent explosion
***Moderator*** – absorbs energy from neutrons and heats up. The transfers heat to the propellant flow

Graphite is a good moderator

1. Sublimes at high temperature $3620\ K$
2. Doesn't crack under thermal shock
3. Low molecular weight so it takes more energy in collision with neutrons

Hydrogen is a good propellant because of low molecular weight

Uranium carbide is a typical fissionable material

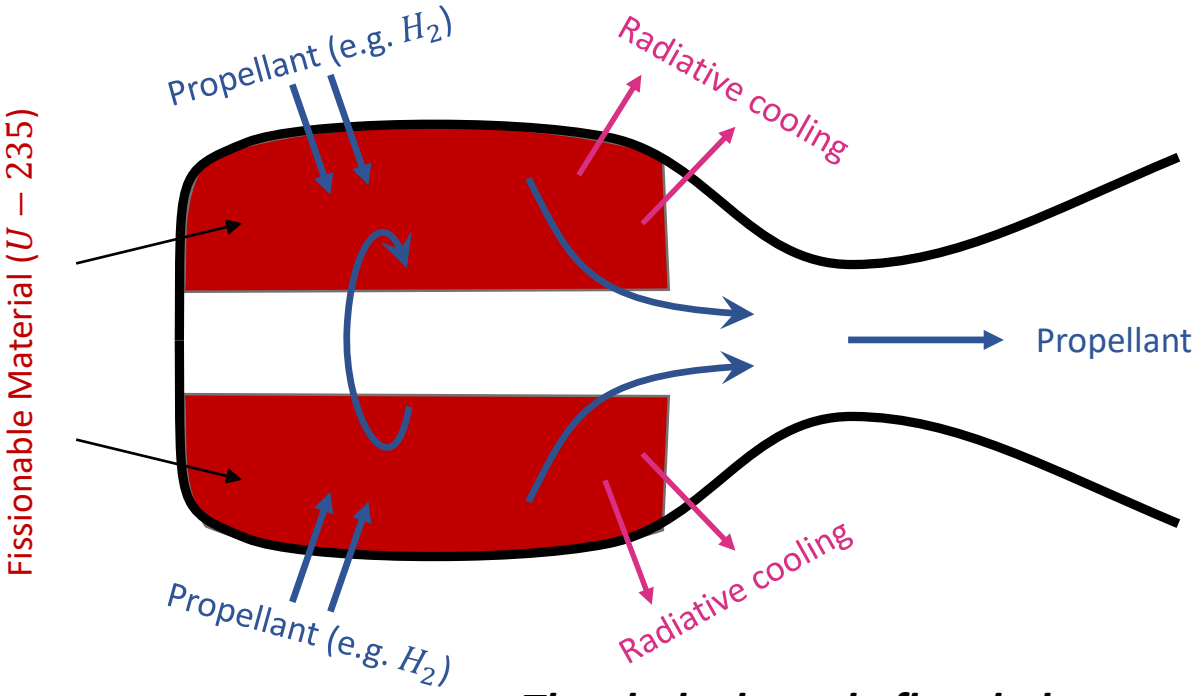
The boiling point of the moderator is the limitation!

***The choked nozzle flow behaves exactly the same as a chemical-rocket nozzle flow!***

# Nuclear Rockets

***Gaseous-core rockets (In the Future)***

Fissionable material is placed in the gas phase where temperatures can be much greater than wall temperature. Therefore, material problems become a less significant limit on temperature. Small passages into larger chamber prevent critical mass.




Fissionable material radiates heat to the propellant

The walls are cooled by radiative loss to the environment

($H_2$) Propellant is introduced with a tangential velocity component causing swirl and a centrifugal effect to hold heavy fissionable material. Light propellant moves towards the center and out of the nozzle!

***The choked nozzle flow behaves exactly the same as a chemical-rocket nozzle flow!***