405 - D4

ADVENTURES INSIDE THE ATOM

ALL ENERGY HAS ALWAYS COME FROM "OUT OF THIS WORLD!" THE FAR-OFF SUN HAS GIVEN US INDIRECTLY THE **STORED** ENERGY OF COAL AND OIL...THE **LIVING** ENERGY OF PLANTS AND ANIMALS (AND OF HUMANS, TOO).

TODAY, SCIENTISTS HAVE FOUND THE SOURCE OF THE SUN'S STRANGE AND WONDERFUL ENERGY LOCKED IN THE HEART OF THE ATOM... ARE RELEASING THAT **ATOMIC** ENERGY TO SERVE US ALL IN THE FUTURE AS A SOURCE OF ALMOST UNLIMITED POWER.

HERE IS THE THRILLING STORY OF MAN'S GREATEST ADVENTURE INTO THE UNKNOWN... AND HIS DISCOVERY OF NATURE'S GREATEST SECRET!

ADVENTURE SERIES
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THE STORY OF NUCLEAR ENERGY

16. Nuclear Reactions

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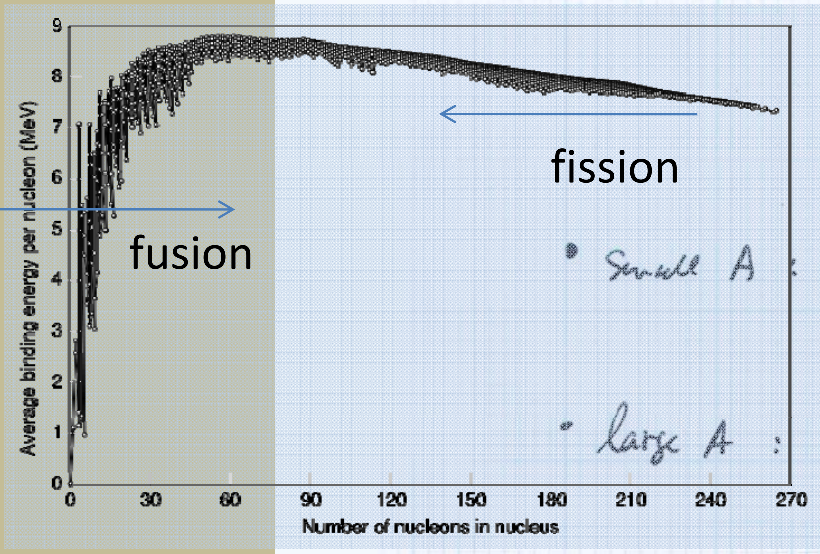
Fission and Fusion

our lives depend on this

we may be using this in the future

The Curve of Binding Energy



- Small A : binding energy increases for fusion (⟶)
- large A : binding energy increases for fission (⟵)

A system seeks the state of lowest potential energy

Unstable; precariously balanced; a slight perturbation — it will convert potential energy into kinetic energy.

Similarly, exothermic reactions and decays.

Nuclear Reactions

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$$\underbrace{a + b}_{\substack{\bullet\ \text{initial state;} \\ \bullet\ \text{reactants}}} \rightarrow \underbrace{c + d + \ldots}_{\substack{\bullet\ \text{final state;} \\ \bullet\ \text{products}}}$$

The reaction will occur spontaneously, with some rate $\leftarrow \boxed{\text{cross section}}$ (either fast or slow) if it is energetically possible:

- $E_{initial} = E_{final}$ because energy is conserved
- $M_i c^2 > M_f c^2$ mass energy is converted into kinetic energy; "exothermic"
- $M_i \cdot c^2 < M_f c^2$ kinetic energy is converted into mass energy; "endothermic" ← the initial $K_a + K_b$ must be large enough.

Fission and fusion reactions are exothermic. Mass energy decreases, $\underbrace{\text{kinetic energy increases}}_{\text{"heat"}}$, total energy is constant

In terms of binding energy

$$B(a) + B(b) < B(c) + B(d) + \cdots$$

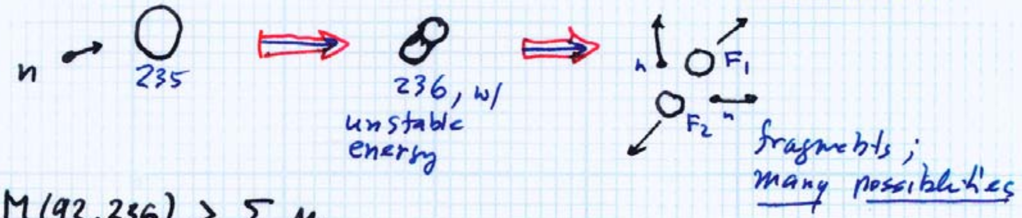
is exothermic ; the products (c, d, ...) have stronger binding than the reactants (a, b).

FISSION

- atom bombs ; U-235 or Pu-239
  (1945, Manhattan Project)
- nuclear power reactors ; U-235 mainly
  (1950's – 1970's ;
  maybe more in the future)

The fission reaction

$$n + U\text{-}235 \Rightarrow U\text{-}236 \Rightarrow \text{(2) large fragments} + \text{neutrons}$$



$$M(92,236) > \sum_k M_k$$
$$B(92,236) < \sum_k B_k$$

Baryon number is conserved so $\sum_k A_k = 236$

Charge is conserved so $\sum_k Z_k = 92$

Example

in a highly excited state

$$n + {}^{235}_{92}U \rightarrow {}^{236*}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3n$$

$T_{1/2} = 11.5$ sec $\quad T_{1/2} = 3.15$ min

$$236 = 144 + 89 + 3$$

$$92 = 56 + 36$$

Masses

	236.045568	U-236
	143.922953	Ba-144
	88.917630	Kr-89
	1.008664915	n

$$\Delta M = M_{236} - M_{144} - M_{89} - 3m_n$$

$$= 0.17899\ u \quad \times \frac{931.5\ \text{MeV}}{(1u)\times c^2}$$

$$= 166.75\ \text{MeV}/c^2$$

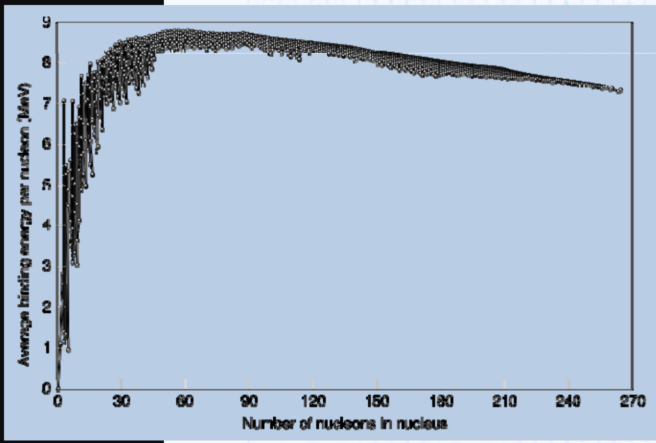
Mass energy released = 166.73 MeV

This is a typical number for fission of U-235.

$^{236}_{92}U \longrightarrow F_1 + F_2 +$ neutrons

- many fragments are possible
- most fission fragments are radioactive
  ($T_{1/2}$ ranges from ms to ky)
- energy released $= (M_i - M_f)c^2 \sim 150$ MeV.

Back of the envelope calculation



The curve of binding energy

$$\text{Slope} \simeq \frac{1 \text{ MeV}}{240-60}$$

$$= \frac{1}{180} \text{ MeV}$$

$$Q = B(F_1) + B(F_2) - B(236)$$

$$\underset{A\sim 60}{\uparrow} \qquad \underset{A\sim 180}{\uparrow} \qquad \underset{A\sim 240}{\uparrow}$$

$$Q \approx 9\text{MeV} \times 60 + \left(9 - \tfrac{2}{3}\times 1\right)\text{MeV} \times 180 - 8\text{MeV} \times 240$$

$$= 120 \text{ MeV}.$$

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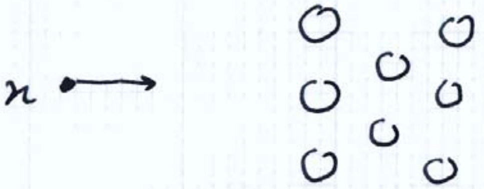
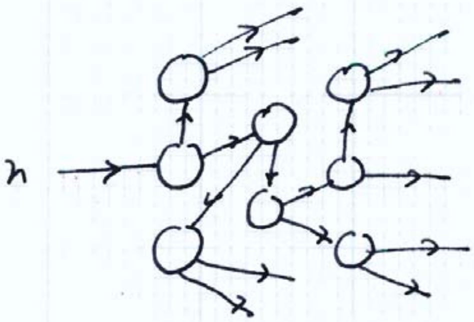
Chain Reactions





The number of neutrons grows rapidly (although not every neutron induces a fission)

The atom bomb – a fast chain reaction

Nuclear reactors – a slow and <u>controlled</u> chain reaction

- fuel rods (U-235)
- moderator (slows down the fast neutrons)
- control rods (absorb neutrons)