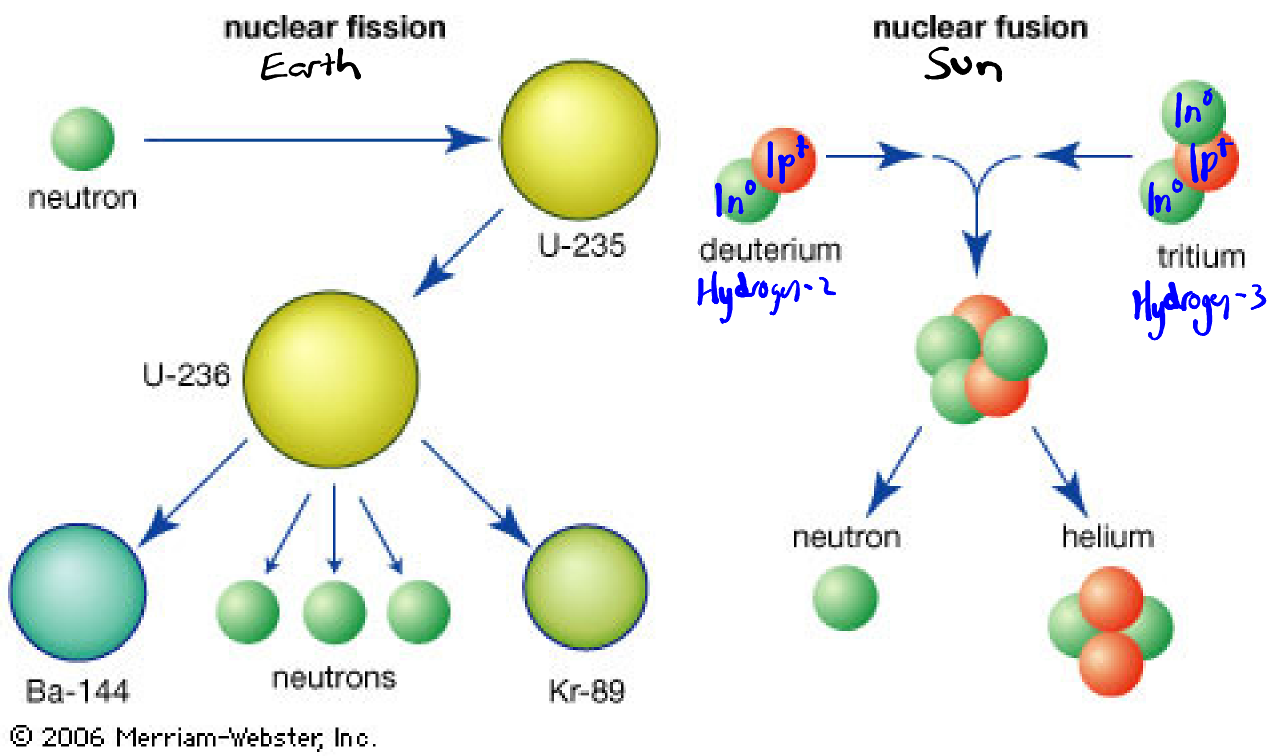
L10 - Fission and Fusion

Note: The *Physics 30 Textbook* and the *Physics 30 Data Sheet* use different constants for the speed of light and different conversions between atomic mass units and kilograms.

Textbook	*Data Sheet*
1 u = 1.66,539 x 10^{-27} kg	1 u = 1.66 x 10^{-27} kg
c = 2.997,925 x 10^{8} m/s	c = 3.00 x 10^{8} m/s
1 u = 931.494 MeV	

I have used the Physics 30 Data Sheet constants when keying all textbook questions. Because of this, my answers vary slightly when compared to the textbook answers.



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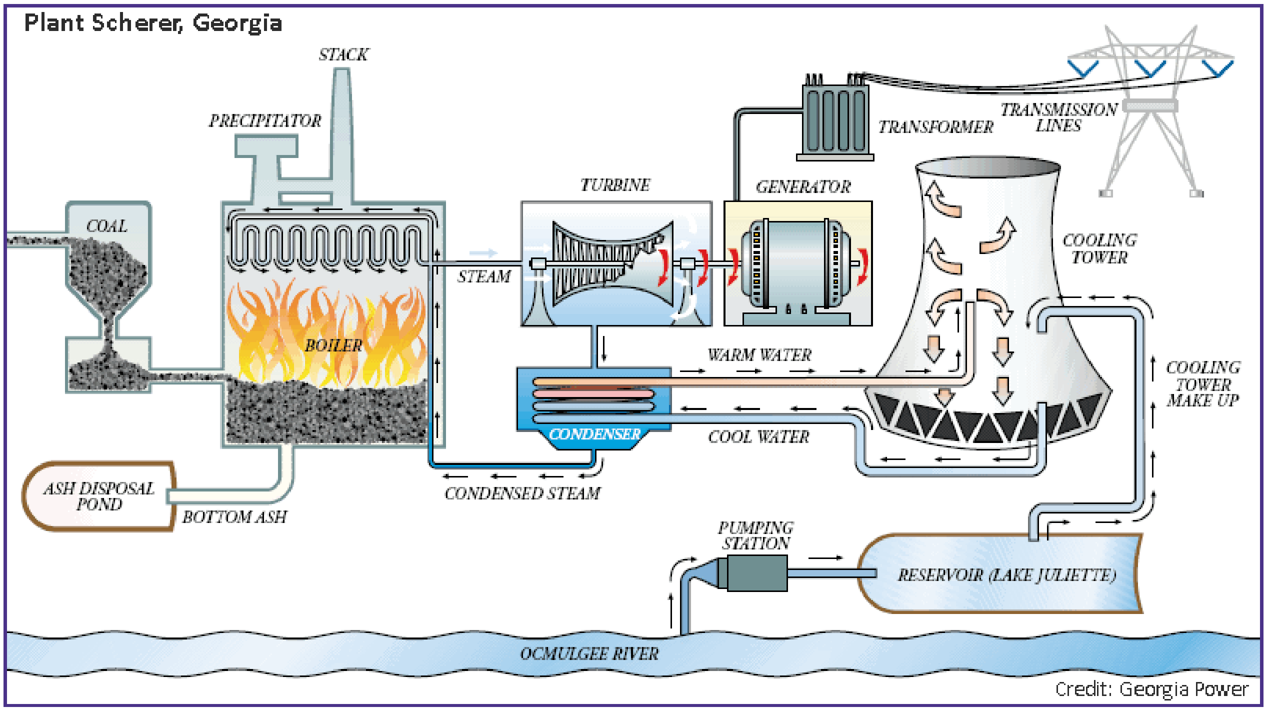
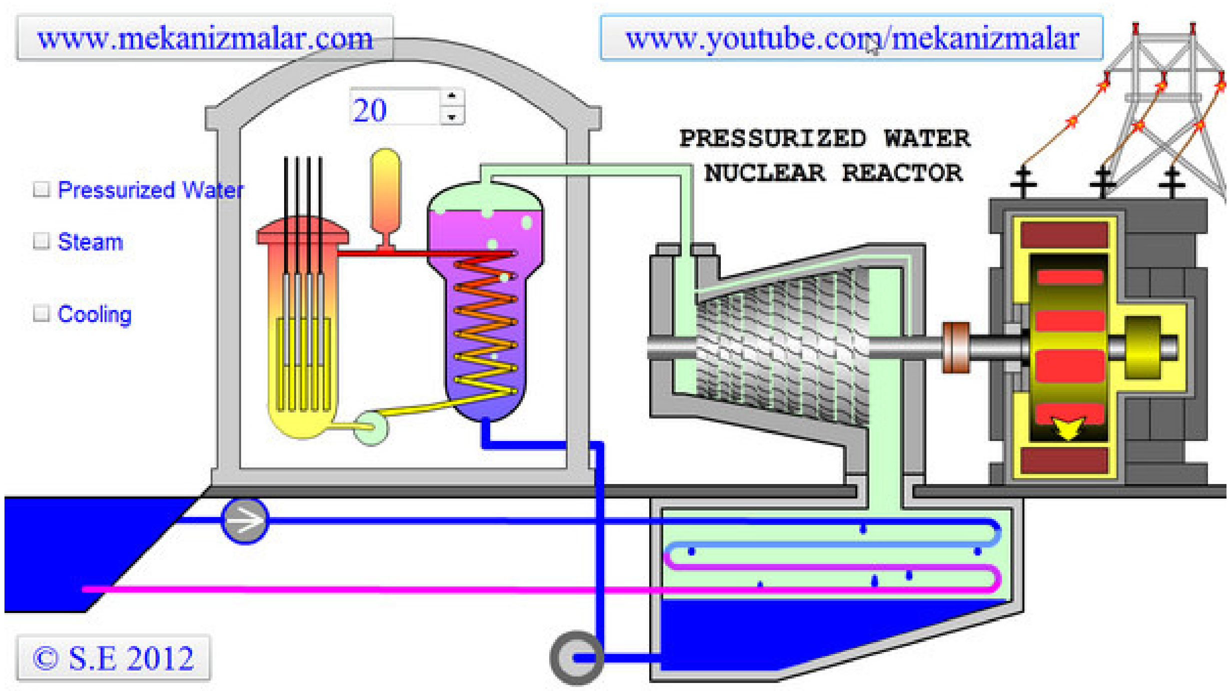
Alberta - Coal Power Plant



Springfield - Nuclear Power Plant



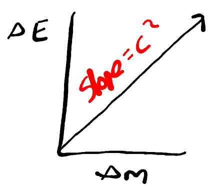
Atomic Mass Unit per Nucleon

Atomic Mass Unit .... $u = 1.66 \times 10^{-27}$ kg

$m_{proton} = 1.67 \times 10^{-27}$ kg $m_{neutron} = 1.67 \times 10^{-27}$ kg

Isotope	Atomic Mass Unit (from Periodic Table; average of all isotopes)	Atomic Mass Unit (accurate for this specific isotope)	Mass per Nucleon
Hydrogen-1	1.01 u	1.007825 u	1.007825 u
Carbon-12	12.01 u	12 u	1.000000 u
Iron-56	55.85 u	55.934938 u	0.998838 u
Uranium-238	238.03 u	238.050788 u	1.000213

BIG QUESTION: Why is the nucleon mass changing depending on where it is found on the periodic table?

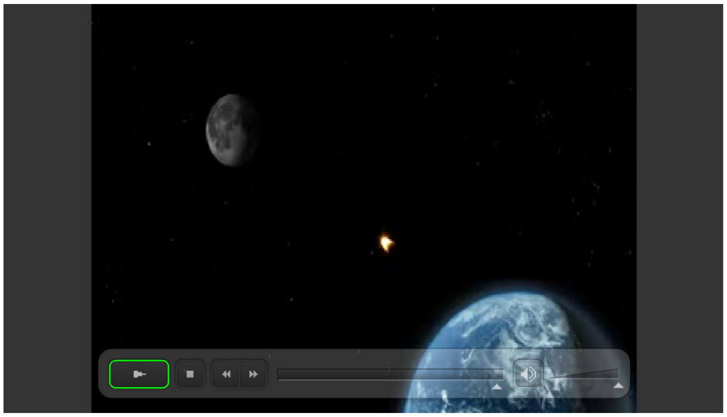


$\Delta E = \underset{\text{slope}}{\underline{\quad}}\, m$

or

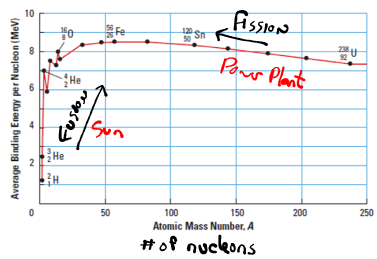
$\Delta E = \Delta m \underset{\text{slope}}{\underline{c^2}}$

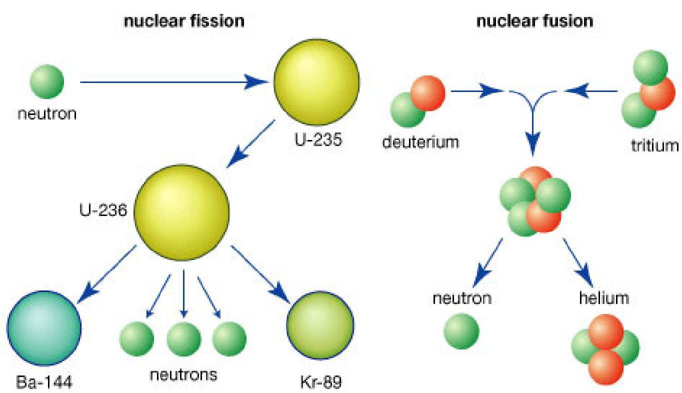
Fission and Fusion



Important Concepts:
- The reason Iron 56 is most strongly bound is because the diameter of an iron nucleus is about equal to the range of the nuclear force. At Iron 56, you have the largest nucleus in which every particle attracts every other particle.
- The diameter of the Iron 56 nucleus is the distance over which the attractive nuclear force is stronger than the repulsive electrostatic force.
- There are some bumps in the graph of nuclear binding energies, bumps representing details in the structure of the nuclear force. The most striking anomaly is the Helium 4 nucleus which is far more tightly bound than neighboring nuclei. This tight binding of Helium 4 is the reason that α particles rather than individual protons are emitted in radioactive decays.

Not important:
- Protons and neutrons are fermions, with different values of the strong isospin quantum number, so two protons and two neutrons can share the same space wave function since they are not identical quantum entities.
- This is why Iron, with approximately 56 nucleons, has a nucleus only 2.5 nucleons wide.



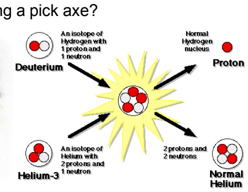


Q1: Which process provides more energy, Fission or Fusion?

Sun

Q2: Which reaction occurs in stars, Fission or Fusion?

Q3: Why is this person carrying a pick axe?

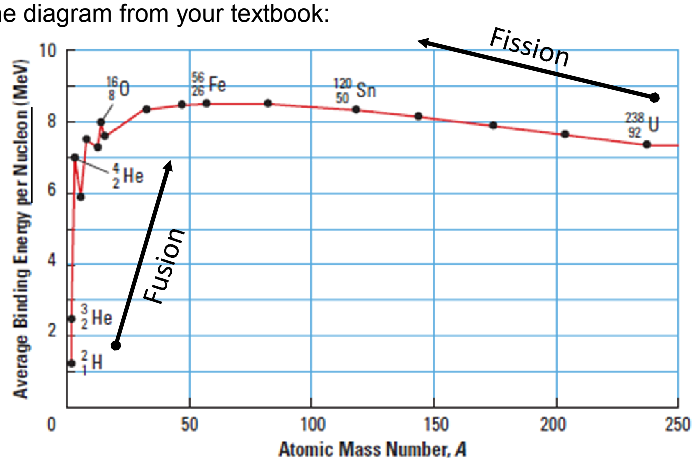


Atomic Mass Unit per Nucleon

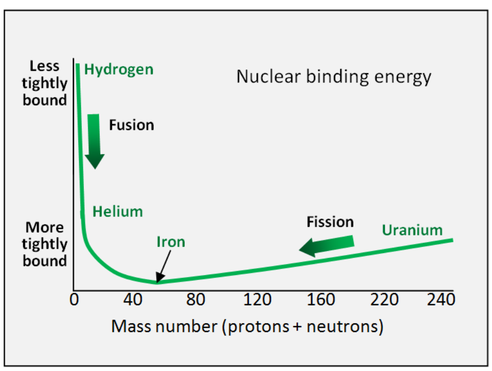
Binding Energy: The net energy required to liberate all of the protons and neutrons in a nucleus.

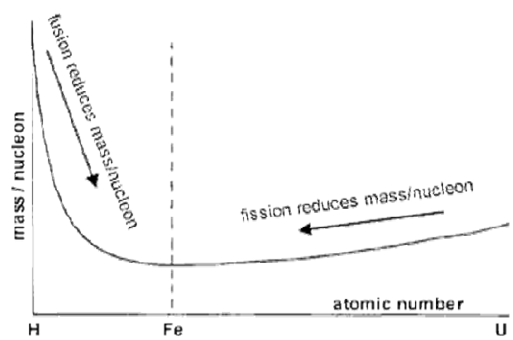
$$E_{nucleus} + E_{binding} \Rightarrow E_{nucleons}$$

The diagram from your textbook:



The diagrams I prefer:





BIG QUESTION: How does the energy stored in the nucleus relate to the mass per nucleon?

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Conservation of Mass-Energy

Physics Principles

0 Uniform motion ($\vec{F}_{net} = 0$)
1 Accelerated motion ($\vec{F}_{net} \neq 0$)
2 Uniform circular motion ($\vec{F}_{net}$ is radially inward)
3 Work-energy theorem
4 Conservation of momentum
5 Conservation of energy
6 ~~Conservation of mass-energy~~
7 Conservation of charge
8 Conservation of nucleons
9 Wave-particle duality

Notice that there is no *Conservation of Mass* physics principle?

In a nuclear reaction mass disappears, Einstein proposed that mass is energy and if the mass before is greater than the mass afterwards, in order for conservation of energy to be true, energy must be given off.

$$\Delta E = \Delta mc^2$$

Definitions

Mass Defect: The nucleus of each atom (aside from Hydrogen-1) has a mass lower than expected from adding the masses of its neutrons and protons. This is known as the mass defect.

Mass-Energy Equivalence: Mass and energy are related by the equation $\Delta E = \Delta mc^2$, where ΔE is the energy, Δm is the mass defect, and c is the speed of light.

Binding Energy: The energy holding the protons and neutrons together in an atomic nucleus. The mass defect is converted into energy by Einstein's equation, which also explains how a small mass can release a huge amount of energy.

Mass defect

Table 1: Atomic mass units.

	Mass (atomic mass unit)
Proton	1.00728 u
Neutron	1.00867 u
Helium nucleus	4.00151 u

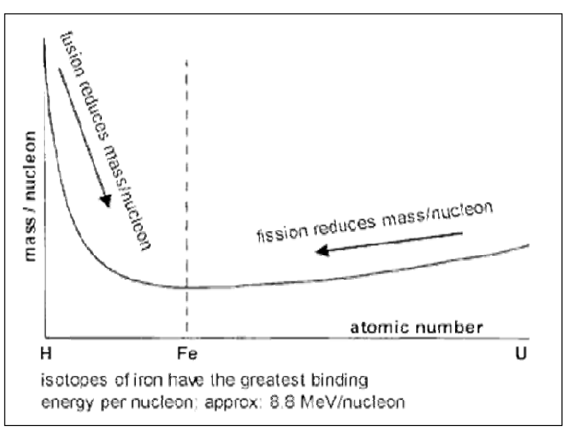
Example 1.
Using the data in table 1, calculate the mass defect for a helium nucleus in atomic mass units and in kilograms.

Mass of 2p + 2n = (2 x 1.00728 u) + (2 x 1.00867 u)
= 4.03190 u

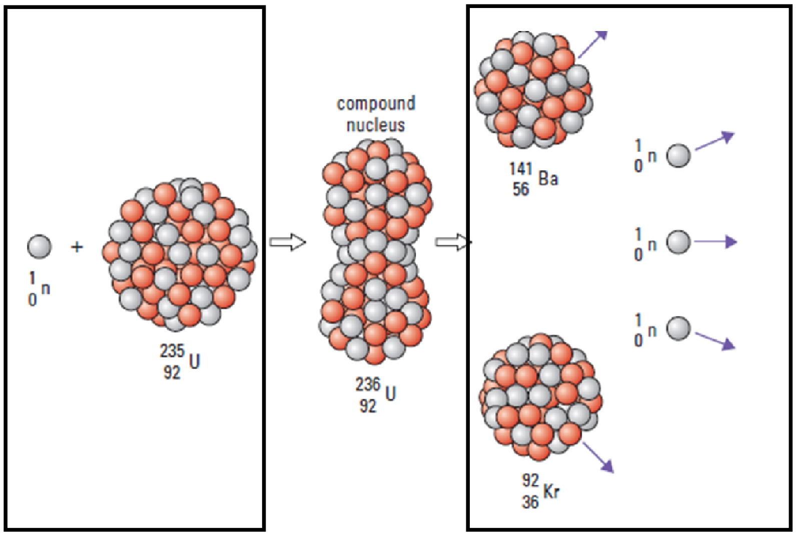
Mass defect = 4.03190 u – 4.00151 u = **0.03039 u**

$E=mc^2$ ← Mass defect in kg = 0.03039 x 1.6605 x 10^{-27} kg
= **5.046 x 10^{-29} kg**

Physics Principle #6 - Conservation of Mass-Energy:
For any closed system, the total of the energy and the energy equivalent of the mass in the system is constant.



Nuclear Fission



Initial	Final
$^{235}_{92}U$ = 235.043,930 u	$^{141}_{56}Ba$ = 140.914,412 u
$^{1}_{0}n$ = 1.008,665 u	$^{92}_{36}Kr$ = 91.926,156 u
	$^{1}_{0}n$ = 1.008,665 u
	$^{1}_{0}n$ = 1.008,665 u
	$^{1}_{0}n$ = 1.008,665 u
Initial Mass = 236.052,595 u	Final Mass = 235.866,563 u

Δm = 0.186,032 u

BIG QUESTION: Where did the missing mass go?

$$\Delta E = \Delta mc^2$$

What are our S.I. Units? Atomic Mass Unit .... $u = 1.66 \times 10^{-27}$ kg

$$\frac{0.186,032\,u}{1} \times \frac{1.66\times10^{-27}\,kg}{1\,u} = 3.0881312\times10^{-28}\,kg$$

$$\Delta E = \Delta mc^2$$
$$= (3.0881312\times10^{-28})(3.0\times10^{8})^2 = 2.77931808\times10^{-11}\,J$$

$$\frac{2.77931808\times10^{-11}\,J}{1} \times \frac{1\,eV}{1.60\times10^{-19}\,J} = 173,707,380\,eV$$

173.7 MeV

Q1: Calculate the energy released by the fission reaction:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\ ^{1}_{0}\mathrm{n}.$$

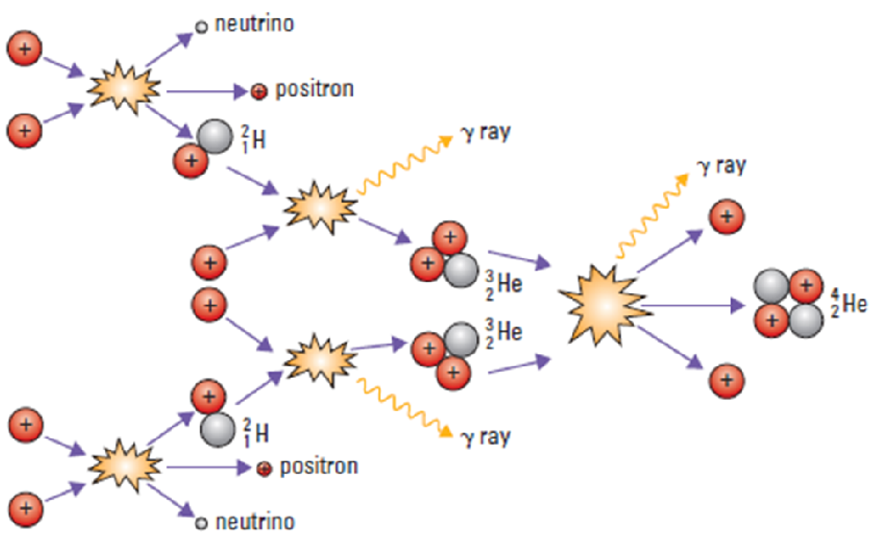
NOTE: See *Table 7.5 Atomic Masses of Selected Isotopes* on Pg. 881.

U-235 ⇒ 235.043,930 u
Ba-141 ⇒ 140.914,412 u
Kr-92 ⇒ 91.926,156 u
Neutron ⇒ 1.008,665 u

Nuclear Fusion

Positron

Step	Reaction	Energy Released
1	$2\ {}^{1}_{1}H \rightarrow {}^{2}_{1}H + {}^{0}_{1}\beta + \nu$ (twice)	0.42 MeV (twice)
2	${}^{1}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + \gamma$ (twice)	5.49 MeV (twice)
3	$2\ {}^{3}_{2}He \rightarrow {}^{4}_{2}He + 2\ {}^{1}_{1}H + \gamma$	12.85 MeV
4	${}^{0}_{1}\beta + {}^{0}_{-1}\beta \rightarrow 2\gamma$ (twice)	1.02 MeV (twice)
Total	$4\ {}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\ {}^{0}_{1}\beta + 2\nu + 7\gamma$	26.71 MeV



Q2: Write the reaction formula for the fusion of helium-4 with oxygen-16. How much energy does this reaction release? 4+16 → 20 "Cons. of Nucleons"

He-4 ⇒ 4.002,603 u
O-16 ⇒15.994,915 u
Ne-20 ⇒ 19.992,440 u

$^{4}_{2}He + {}^{16}_{8}O \Rightarrow {}^{20}_{10}Ne$

2+8 → 10 "Cons. of Charge"

Initial

4.002,603u
15.994,915u
19.997518u

$\Delta m = \frac{0.005078u}{1} \times \frac{1.66 \times 10^{-27}}{1u} = 8.42948 \times 10^{-30} kg$

$\Delta E = \Delta mc^2$
$= (8.42948 \times 10^{-30})(3 \times 10^8)^2$
$= 7.586532 \times 10^{-13} J$ → eV → MeV

Which Physics Principles were used to predict the product was Ne-20? 8, 7

Which Physics Principle was necessary to determine how much energy was released? 6

Physics Principles

0 Uniform motion ($\vec{F}_{net} = 0$)
1 Accelerated motion ($\vec{F}_{net} \neq 0$)
2 Uniform circular motion ($\vec{F}_{net}$ is radially inward)
3 Work-energy theorem
4 Conservation of momentum
5 Conservation of energy
6 Conservation of mass-energy
7 Conservation of charge
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