a place of mind

FACULTY OF EDUCATION

Department of
Curriculum and Pedagogy

Physics
Nuclear Physics:
Nuclear Reactions

Science and Mathematics
Education Research Group

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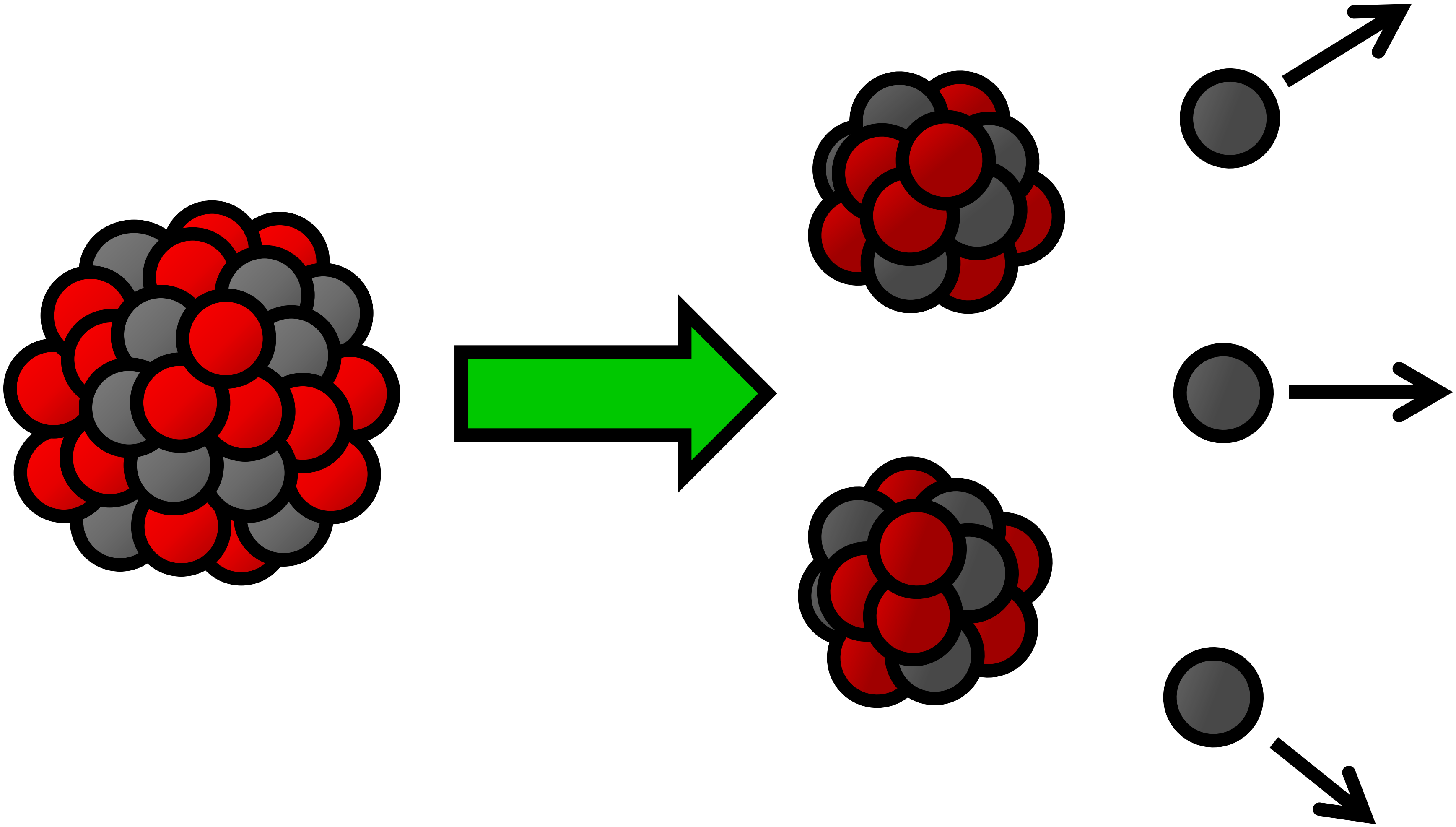
Fission and Fusion Reactions



Nuclear Reactions I

Nuclear fusion occurs when two or more lighter nuclei join together to form a new heavier nucleus.

Nuclear fission occurs when a heavy nucleus splits into lighter nuclei.

What type of reaction is shown below?

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{98}_{40}\mathrm{Zr} + {}^{135}_{52}\mathrm{Te} + 3\,{}^{1}_{0}\mathrm{n} $$

A. Nuclear fusion

B. Nuclear fission

C. Neither A or B

Solution

Answer: B

Justification: The nuclear reaction is a fission reaction.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{98}_{40}Zr + ^{135}_{52}Te + 3^{1}_{0}n$$

An uranium-235 nucleus splits into two lighter nuclei, zirconium-98 and tellurium-135. This fission reaction is *induced* because it relies on the presence of a neutron to form a highly unstable isotope.

The reaction can be more accurately described as a two-step process:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U \text{ (unstable)}$$

$$^{236}_{92}U \rightarrow ^{98}_{40}Zr + ^{135}_{52}Te + 3^{1}_{0}n$$

Nuclear Reactions II

Another common induced fission reaction of uranium-235 is shown below, where X is an unknown isotope.

What is the unknown isotope X?

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{144}_{56}\mathrm{Ba} + \mathrm{X} + 3\,{}^{1}_{0}\mathrm{n}$$

A. $^{89}_{36}\mathrm{Ac}$

B. $^{90}_{36}\mathrm{Th}$

C. $^{89}_{36}\mathrm{Kr}$

D. $^{90}_{36}\mathrm{Kr}$

E. $^{92}_{36}\mathrm{Kr}$

Hint: Isotopes are labelled $^{A}_{Z}\mathrm{E}$

A $\rightarrow$ mass number

Z $\rightarrow$ atomic number

E $\rightarrow$ element symbol

Press for hint

Solution

Answer: C $\quad {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3{}^{1}_{0}\mathrm{n}$

Justification: The number of protons and neutrons in the nuclear reaction must be conserved.

There are 92 protons (the atomic number of uranium) on the left side of the equation, so isotope X must contain $92 - 56 = 36$ protons. This corresponds to the element krypton (Kr).

We can use the mass numbers of the reactants and products to determine the mass number of X. This will ensure that the neutrons are conserved: $235 + 1 = 144 + x + 3(1)$

$$x = 89$$

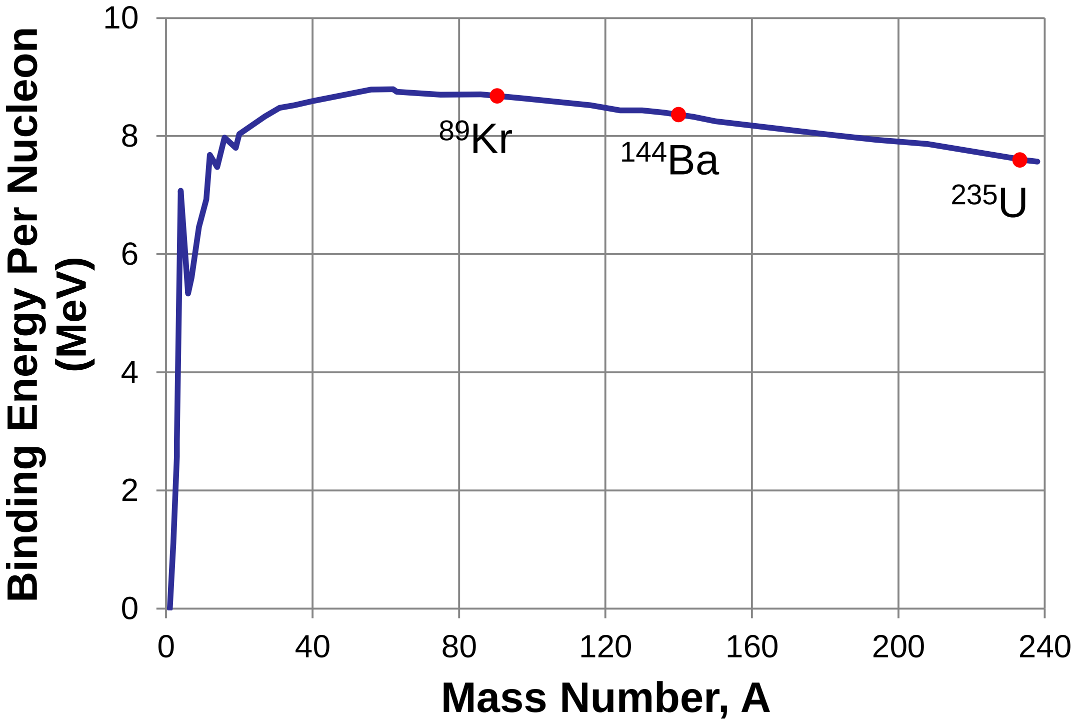
The isotope is therefore ${}^{89}_{36}\mathrm{Kr}$. ${}^{89}\mathrm{Kr}$ contains 36 protons and therefore 53 neutrons, for a total of 89 nucleons.

Nuclear Reactions III

Consider the following nuclear fission reaction:

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{144}_{56}\text{Ba} + {}^{89}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n}$$

Which side of the reaction will have more mass?



A. Left side

B. Right side

C. Both sides have the same mass

Solution

Answer: A

Justification: From the binding energy curve, we can find that both ^{144}Ba and ^{89}Kr have a higher binding energy per nucleon than ^{235}U. The lower binding energy per nucleon of ^{235}U means that it has less mass defect per nucleon compared to ^{144}Ba and ^{89}Kr.

$$E_{binding} = m_{defect} c^2$$

Since the number of nucleons is conserved in the reaction, ^{235}U should be heavier than the products.

Likewise, ^{144}Ba and ^{89}Kr have more binding energy per nucleon and therefore have larger mass defect per nucleon. We can expect ^{144}Ba and ^{89}Kr to have less mass (due to more mass defect) than ^{235}U.

Answer continues on the next slide

Solution Continued

Answer: A

Justification: We can find the atomic mass of each isotope in data tables and calculate the mass of each side of the reaction:

$$m_U + m_n = 235.0439\,\text{u} + 1.0087\,\text{u} = 236.0526\,\text{u}$$

$$m_{Ba} + m_{Kr} + 3m_n = 143.9229\,\text{u} + 88.9176\,\text{u} + 3\cdot 1.0087\,\text{u} = 235.8666$$

As predicted, the original uranium has more mass than its fission products by 0.1860 u.

Nuclear Reactions IV

Consider the following nuclear fission reaction:

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$$

Is the reaction endothermic or exothermic?

Recall that the left side of the equation has more mass than the right side.

A. Exothermic

B. Endothermic

C. Energy is not involved in the reaction

Solution

Answer: A

Justification: The reaction is exothermic, which means that energy is released as a product in the reaction.

Mass and energy must be conserved in the nuclear reaction. Since the left side of the reaction has more mass, mass must have been converted into energy. When the large uranium atom splits into smaller nuclei of less mass, energy is released. Most of this energy is in the form of kinetic energy of the particles.

You may recall that the amount of energy released is equal to:

$$E = m_d c^2$$

where m_d is the mass defect of the reaction, and c is the speed of light.

Nuclear Reactions V

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{144}_{56}\mathrm{Ba} + ^{89}_{36}\mathrm{Kr} + 3^{1}_{0}\mathrm{n}$$

We found that the difference in mass between the products and reactants is 0.1860 u (or 3.0885×10^{-28} kg). How much energy is released when a single uranium nucleus splits?

A. $4.447 \cdot 10^{-36}$ MeV

B. $2.776 \cdot 10^{-11}$ MeV

C. $5.780 \cdot 10^{-7}$ MeV

D. 173.5 MeV

E. $1.733 \cdot 10^{8}$ MeV

$$E = mc^2$$

$$c = 2.9979 \cdot 10^8 \text{ m/s}$$

$$1\,\mathrm{u} = 931.5\,\mathrm{MeV}$$

Press for hint

Solution

Answer: D

Justification: If we apply the formula $E = mc^2$, mass must be given in terms of kg so that the formula returns the units joules.

$$\begin{aligned} E &= mc^2 \\ &= (3.0885 \cdot 10^{-28}\ \mathrm{kg})(2.9979 \cdot 10^{8}\ \mathrm{m/s})^2 \\ &= 2.7758 \cdot 10^{-11}\ \mathrm{J} \end{aligned}$$

It is common to convert this into units of megaelectron volts (MeV) using the following conversions:

$$2.7758 \cdot 10^{-11}\ \mathrm{J} \times \frac{1\,\mathrm{eV}}{1.602 \cdot 10^{-19}\ \mathrm{J}} \times \frac{1\,\mathrm{eV}}{10^{6}\ \mathrm{eV}} = 173.3\,\mathrm{MeV}$$

For a single reaction, this is a lot of energy.

Alternative Solution

Answer: D

Justification: Some students may recall that $1\ \mathrm{u}$ is equivalent to $931.5\ \mathrm{MeV}$. This can be found by repeating the steps in the previous slide, except finding the energy equivalent of $1\ \mathrm{u} = 1.6605 \times 10^{-27}\ \mathrm{kg}$. Using this conversion, we can quickly find the answer we obtained previously:

$$0.1860\,\mathrm{u} \times \frac{931.5\,\mathrm{MeV}}{1\,\mathrm{u}} = 173.3\,\mathrm{MeV}$$

Nuclear Reactions VI

Nuclear fusion occurs when two or more lighter nuclei join together to form a new heavier nucleus.

Nuclear fission occurs when a heavy nucleus splits into lighter nuclei.

What type of reaction is shown below?

$${}^{2}_{1}\mathrm{D} + {}^{3}_{1}\mathrm{T} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$$

A. Nuclear fusion

B. Nuclear fission

C. Neither A or B

Note:

${}^{2}_{1}\mathrm{D}$ is equivalent to ${}^{2}_{1}\mathrm{H}$.

${}^{3}_{1}\mathrm{T}$ is equivalent to ${}^{3}_{1}\mathrm{H}$.

Solution

Answer: A

Justification: The nuclear reaction is a fusion reaction.

$$^{2}_{1}\mathrm{D} + {}^{3}_{1}\mathrm{T} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$$

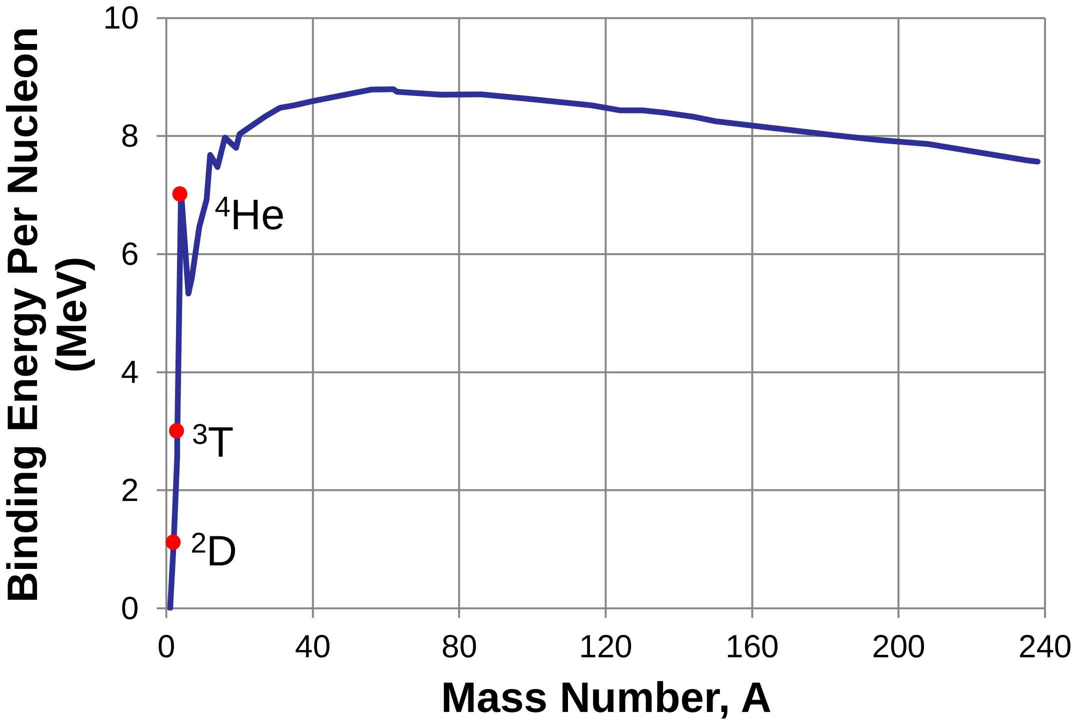
In this reaction, deuterium (hydrogen with 1 neutron) and tritium (hydrogen with 2 neutrons) fuse together to form a heavier helium nucleus along with a neutron.

Nuclear Reactions VII

Which side of the reaction will have less mass?

$$^{2}_{1}\text{D} + {}^{3}_{1}\text{T} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n}$$

Review question 3 if needed.



A. Left side

B. Right side

C. Both sides have the same mass

Solution

Answer: B

Justification: From the binding energy curve, we can conclude that ^{4}He has a much larger binding energy per nucleon than both deuterium and tritium. Since nucleons are conserved in reactions, ^{4}He must also have more mass defect per nucleon than deuterium and tritium, so we should expect ^{4}He to have less mass.

$$m_D + m_T = 2.014102\text{u} + 3.016049\text{u} = 5.030151\text{u}$$

$$m_{He} + m_n = 4.002603\text{u} + 1.0087\text{u} = 5.011303\text{u}$$

Notice how in both fusion and fission reactions, the reaction products have less mass and so the reactions release energy. Multiplying the mass defect by $931.5\ \text{MeV}/\text{u}$ shows that this reaction releases about $17.6\ \text{MeV}$ of energy.

Nuclear Reactions VIII

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

In order for deuterium and tritium to fuse together, the two nuclei must be brought close together. This does not often occur naturally due to electrostatic forces keeping the nuclei apart.

Under what conditions might deuterium and tritium undergo nuclear fusion?

A. Many free neutrons to trigger a reaction

B. At high pressures

C. At high temperatures

D. Both B and C

E. All of A, B, and C

Solution

Answer: D

Justification: High temperatures (several million kelvin) are needed so that the deuterium and tritium nuclei have enough kinetic energy to overcome electrostatic repulsion.

High pressures ensure that many nuclei are found in close proximity of each other, increasing the likelihood of collisions between deuterium and tritium. A place where with high enough temperature and pressure where fusion reactions can occur naturally is in the Sun.

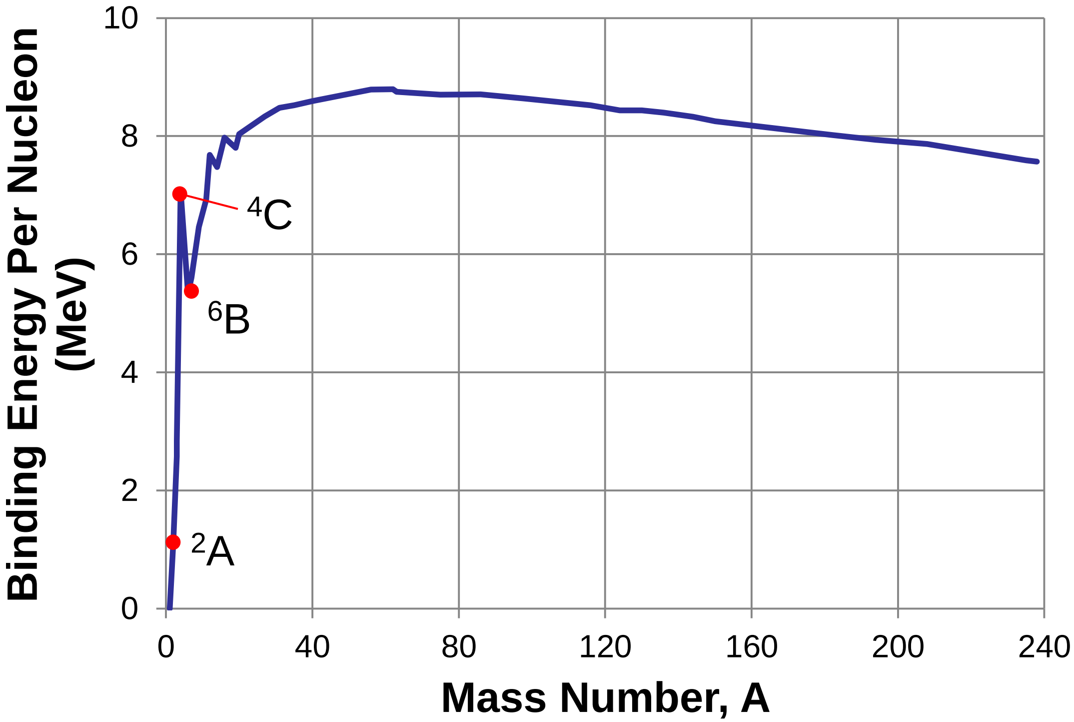
Unlike the fission reaction we saw earlier, no neutrons are needed to start a reaction.

Nuclear Reactions IX

Suppose a reaction occurs between the following unknown elements.

$$^{2}A + {}^{6}B \rightarrow {}^{4}C + {}^{4}C$$

Do you expect the reaction to be endothermic or exothermic?



A. Endothermic

B. Exothermic

C. Both sides have the same mass

Solution

Answer: B

Justification: This is similar to the fusion reaction seen in question 7. The isotopes A and B have less binding energy per nucleon than isotope C. Since C has more mass defect per nucleon, we can expect that the two C isotopes will have less mass than A and B. In order to make up for the "missing mass" on the side of the products, energy must be produced.

$$^{2}A + {}^{6}B \rightarrow {}^{4}C + {}^{4}C + \text{energy}$$

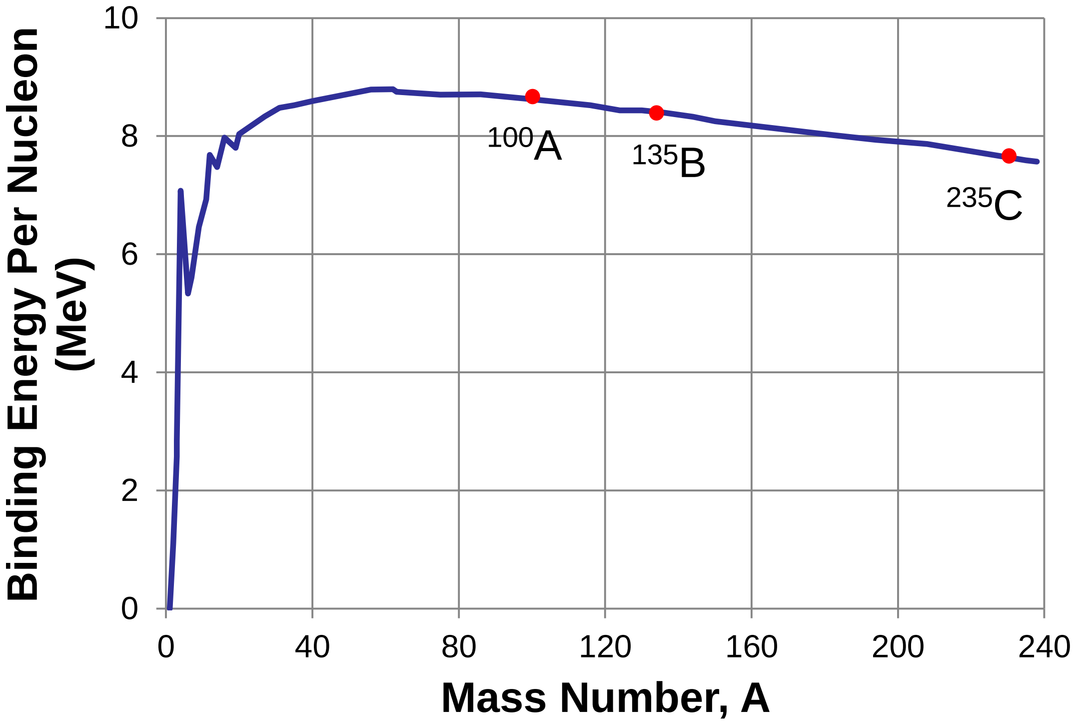
Reactants	Products
8 total nucleons	8 total nucleons
Less binding energy per nucleon	More binding energy per nucleon
Less mass defect per nucleon	More mass defect per nucleon
More total mass	Less total mass

Nuclear Reactions X

Suppose a reaction occurs between the following unknown elements.

$$^{100}A + {}^{135}B \rightarrow {}^{235}C$$

Do you expect the reaction to be endothermic or exothermic?



A. Endothermic

B. Exothermic

C. Both sides have the same mass

Solution

Answer: A

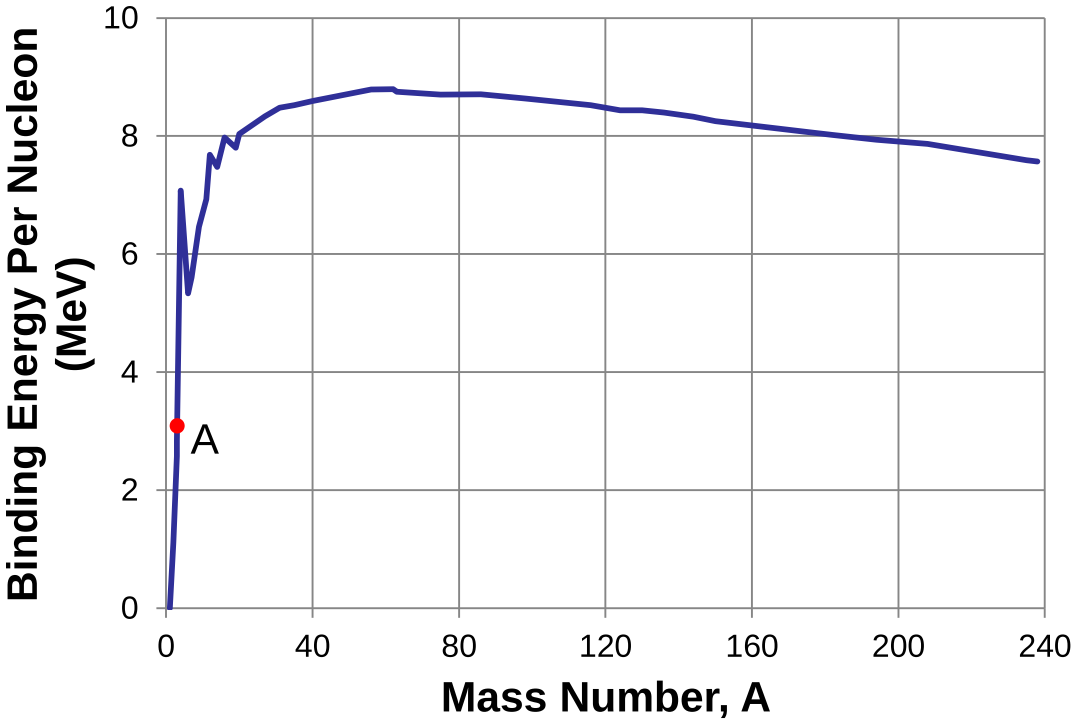
Justification: Energy is required to make this reaction occur. It neither a fission or fusion reaction. The isotopes A and B have more binding energy per nucleon than C. Therefore, A and B have more mass defect per nucleon and less total mass than C. If the products have more total mass, then the reactants must have more total energy so that mass-energy is conserved.

$$^{100}A + {}^{135}B + \text{energy} \rightarrow {}^{235}C$$

Reactants	Products
235 total nucleons	235 total nucleons
More binding energy per nucleon	Less binding energy per nucleon
More mass defect per nucleon	Less mass defect per nucleon
Less total mass (more energy)	More total mass (less energy)

Nuclear Reactions XI

Consider the unknown element A shown in the binding energy per nucleon curve. Should we look for a nuclear fusion or nuclear fission reaction involving as a reactant A if we want to produce energy?



A. Nuclear fusion

B. Nuclear fission

C. Neither type will produce energy

Solution

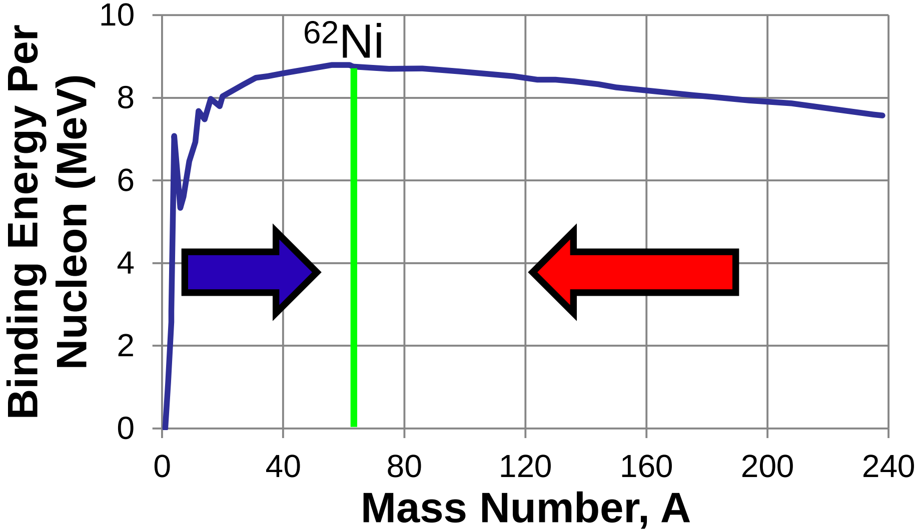
Answer: A

Justification: The element A is to the left of ^{62}Ni (the maximum of the binding energy curve). In order for the reaction to release energy, we want the products of the reaction to have more binding energy per nucleon. This occurs when A fuses with another light nuclei to form a heavier element.

An example of this was seen in question 7. Recall that the fusion reaction in question 7 released energy.

If A splits into smaller nuclei, the products will have less binding energy per nucleon than A. This reaction will not produce energy.

Extend Your Learning: Nickel-62

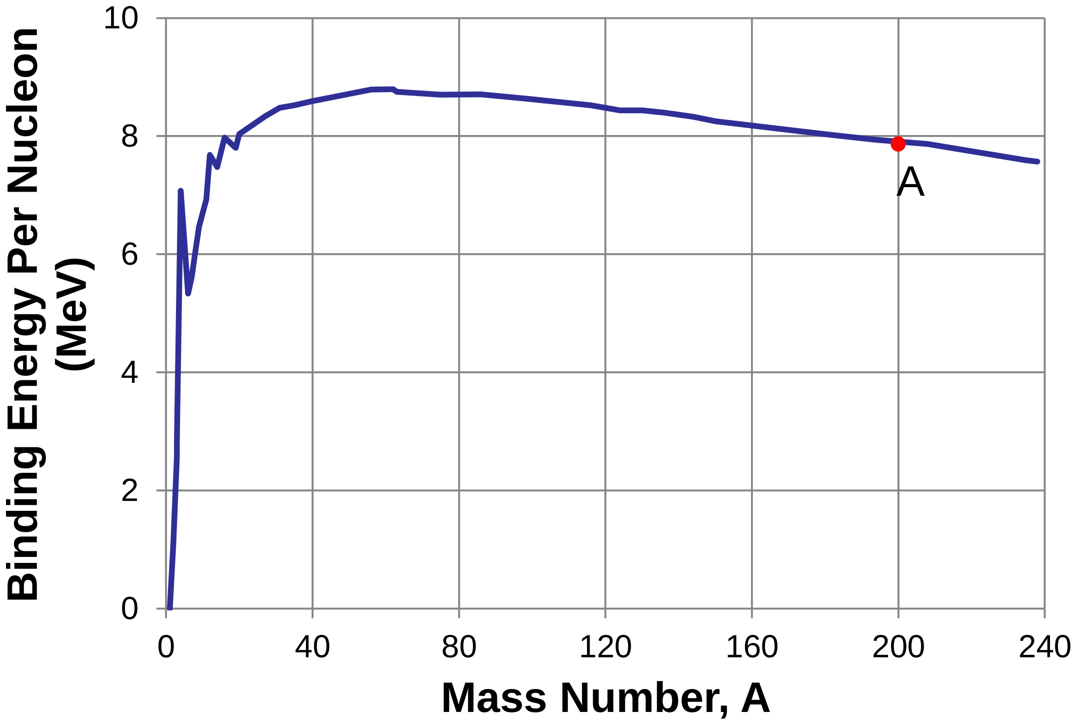


The maximum of the binding energy curve occurs at nickel-62. This means that its nucleus is held together with the most energy for its size, making it very stable.

The stability of nickel-62 makes it very unlikely to be used as a reactant in nuclear reactions. Instead, nickel-62 tends to be the final product of many reactions. Smaller nuclei fuse to become closer to nickel, while heavier nuclei divide to become closer to nickel. This is one reason why nickel is one of the most abundant elements.

Nuclear Reactions XII

Consider the unknown element A shown in the binding energy per nucleon curve. Should we look for a nuclear fusion or nuclear fission reaction involving A as a reactant if we want to produce energy?



A. Nuclear fusion

B. Nuclear fission

C. Neither type will produce energy

Solution

Answer: B

Justification: The element A is to the right of ^{62}Ni (the maximum of the binding energy curve). In order for the reaction to release energy, we want the products of the reaction to have more binding energy per nucleon. This occurs when A splits into two smaller nuclei, each with larger binding energies per nucleon.

An example of this was seen in question 3. Recall that the fission reaction in question 3 released energy.

If A fuses with another element to form a heavier nucleus, the product will have lower binding energy per nucleon. This reaction will not produce energy.

Summary

Elements to the left of ^{62}Ni undergo nuclear fusion to produce energy and become more stable.

Elements to the right of ^{62}Ni undergo nuclear fission to release energy and become more stable.