DEVIL PHYSICS
THE BADDEST CLASS ON CAMPUS
IB PHYSICS

TSOKOS LESSON 7-2
NUCLEAR REACTIONS

Review Videos-Radioactivity2

Review Videos - Strong and Weak Nuclear Forces

Essential Idea:

- Energy can be released in nuclear decays and reactions as a result of the relationship between mass and energy.

Nature Of Science:

- Patterns, trends and discrepancies: Graphs of binding energy per nucleon and of neutron number versus proton number reveal unmistakable patterns.
- This allows scientists to make predictions of isotope characteristics based on these graphs.

Theory Of Knowledge:

- The acceptance that mass and energy are equivalent was a major paradigm shift in physics.
- How have other paradigm shifts changed the direction of science?
- Have there been similar paradigm shifts in other areas of knowledge?

Understandings:

- The unified atomic mass unit
- Mass defect and nuclear binding energy
- Nuclear fission and nuclear fusion

Applications And Skills:

- Solving problems involving mass defect and binding energy
- Solving problems involving the energy released in radioactive decay, nuclear fission and nuclear fusion

Applications And Skills:

- Sketching and interpreting the general shape of the curve of average binding energy per nucleon against nucleon number

Guidance:

- Students must be able to calculate changes in terms of mass or binding energy
- Binding energy may be defined in terms of energy required to completely separate the nucleons or the energy released when a nucleus is formed from its nucleons

Data Booklet Reference:

$$\Delta E = \Delta m * c^2$$

Utilization:

- Our understanding of the energetics of the nucleus has led to ways to produce electricity from nuclei but also to the development of very destructive weapons
- The chemistry of nuclear reactions (see Chemistry option sub-topics C.3 and C.7)

Aims:

- Aim 5: some of the issues raised by the use of nuclear power transcend national boundaries and require the collaboration of scientists from many different nations

Aims:

- Aim 8: the development of nuclear power and nuclear weapons raises very serious moral and ethical questions:
  - who should be allowed to possess nuclear power and nuclear weapons?
  - who should make these decisions?
- There also serious environmental issues associated with the nuclear waste of nuclear power plants.

Define the ***unified mass unit*** *(u)*

- Equal to 1/12 of the mass of a Carbon-12 atom
  - Mass of a mole of Carbon-12 is 12g
  - Avogadro's number gives atoms per mole
  - Therefore the mass of a Carbon-12 atom is

$$M = \frac{12}{6.02x10^{23}} x10^{-3} kg$$

$$M = 1.99x10^{-26} kg$$

Define the *unified mass unit (u)*

- Equal to 1/12 of the mass of a Carbon-12 atom
  - So 1 atomic mass unit is:

$$1u = \frac{1}{12} x 1.99 x 10^{-26} kg = 1.66 x 10^{-27} kg$$

$$1u = 1.6605402 x 10^{-27} kg$$

Define the ***unified mass unit (u)***

- Find the mass of an electron, proton and neutron in amu's

Unified mass unit	**$1.6605402 \times 10^{-27}$ kg**
Electron	$9.1093897 \times 10^{-31}$ kg
Proton	$1.6726231 \times 10^{-27}$ kg
Neutron	$1.6749286 \times 10^{-27}$ kg

Table 3.1.

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Proton	$1.6726231 \times 10^{-27}$ kg
Neutron	$1.6749286 \times 10^{-27}$ kg

Table 3.1.

Electron: 0.0005486 u

Proton: 1.007276 u

Neutron: 1.008665 u

State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- The mass of the ***nucleus*** is equal to the atomic mass minus the mass of the electrons:

$$M_{nucleus} = M_{atom} - Zm_{electron}$$

- The atomic mass is given by the periodic table and the electron mass is given in the previous table

State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- The mass of a helium nucleus would thus be:

$$M_{nucleus} = 4.0026 - 2x0.0005486$$

$$M_{nucleus} = 4.00156u$$

- However, if we add the masses of the individual nucleons we get:

$$2m_p + 2m_n = 4.0320u$$

- **What's up with that?**

State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- The mass of the protons plus the mass of the neutrons is ***larger*** than the atomic mass
- The difference between the two is called the ***mass defect***

$$\delta = Zm_p + (A - Z)m_n - M_{nucleus}$$

State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- Find the mass defect of a gold nucleus in amu's if the atomic mass given on the periodic table is 196.967 u

$$^{197}_{79}Au$$

Unified mass unit	$1.6605402 \times 10^{-27}$ kg
Electron	$9.1093897 \times 10^{-31}$ kg
Proton	$1.6726231 \times 10^{-27}$ kg
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$$^{197}_{79}Au$$

$$\delta = Zm_p + (A-Z)m_n - M_{nucleus}$$

$$Zm_p = (79)(1.6726231x10^{-27} \div 1.6605402x10^{-27})$$

$$(A-Z)m_n = (197-79)(1.6749286x10^{-27} \div 1.6605402x10^{-27})$$

$$M_{nucleus} = 196.967u - (79)(9.1093897^{-31} \div 1.6605402x10^{-27})$$

State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- Find the mass defect of a gold nucleus in amu's if the atomic mass given on the periodic table is 196.967 u

$${}^{197}_{79}Au$$

$$\delta = Zm_p + (A-Z)m_n - M_{nucleus}$$

$$Zm_p = 79.5748u$$

$$(A-Z)m_n = 119.022u$$

$$M_{nucleus} = 196.924u$$

$$\delta = (79.5748u) + (119.022u) - (196.924u) = 1.6728u$$

State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- Find the mass defect of a gold nucleus if the atomic mass given on the periodic table is 196.967 u $^{197}_{79}Au$
- **Answer: 1.67 u which is the equivalent of 1.7 neutrons**

State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- Einstein's mass-energy formula
  - What happened to the missing mass?
  - Einstein said, "No worries, it's all relative."

$$E = mc^2$$

  - His theory of special relativity states that mass and energy are equivalent and can be converted into each other.
  - Throw a match into a bucket of gasoline and note the conversion of mass into energy BUT, *this reaction is not reversible!*

State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- Einstein's mass-energy formula
  - Conversion of energy into mass is not as common, but explains why photons have momentum
  - The mass defect of the nucleus has been converted into energy – ***binding energy (E_b)*** – and is stored in the nucleus

$$E_b = \delta c^2$$

State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- Binding Energy

$$E_b = \delta c^2$$

  - The binding energy of a nucleus is the work (energy) required to completely separate the nucleons of a nucleus
  - The work required to remove one nucleon from the nucleus is ***very roughly*** the binding energy divided by the number of nucleons
  - More importantly, the binding energy of a nucleus is a measure of how stable it is – higher the binding energy, the more stable the nucleus is

Segre Plots

- At low Z numbers, stable nuclides have N = Z
- At higher Z numbers, N > Z

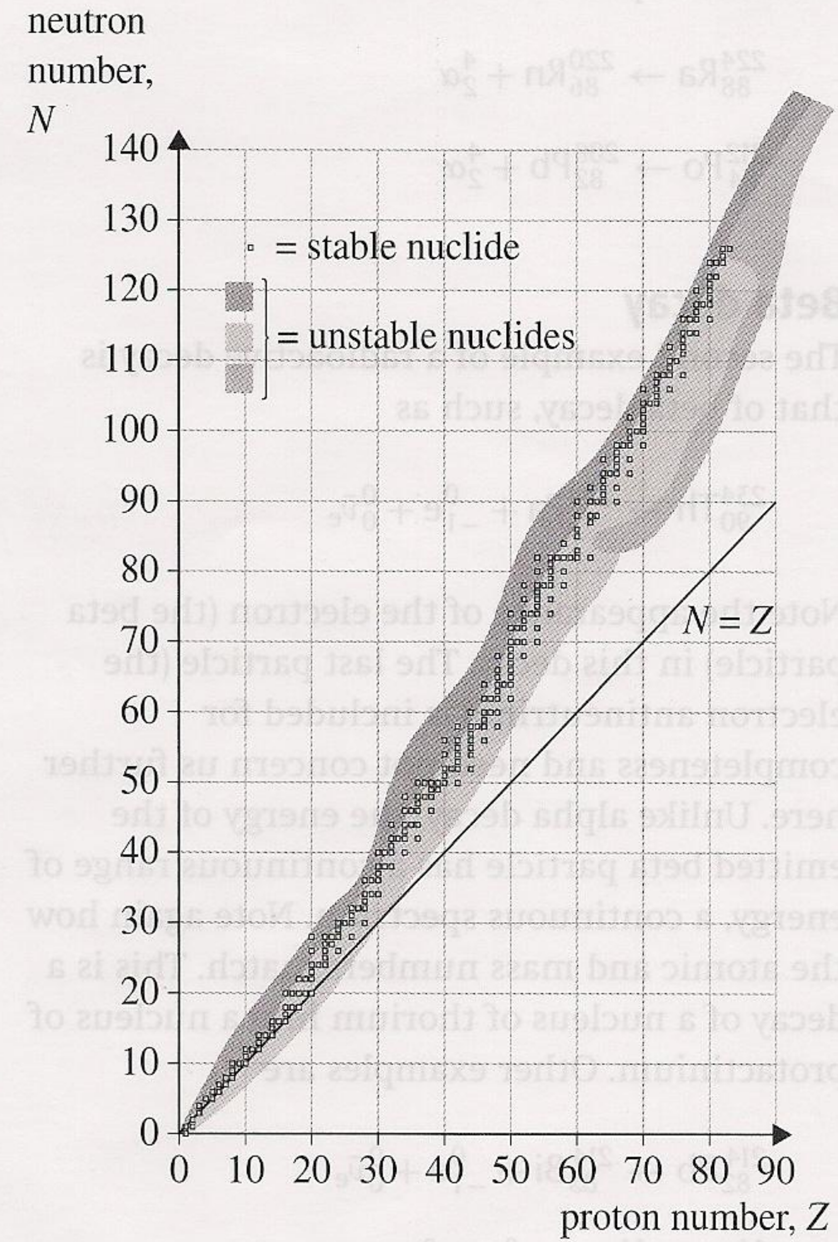
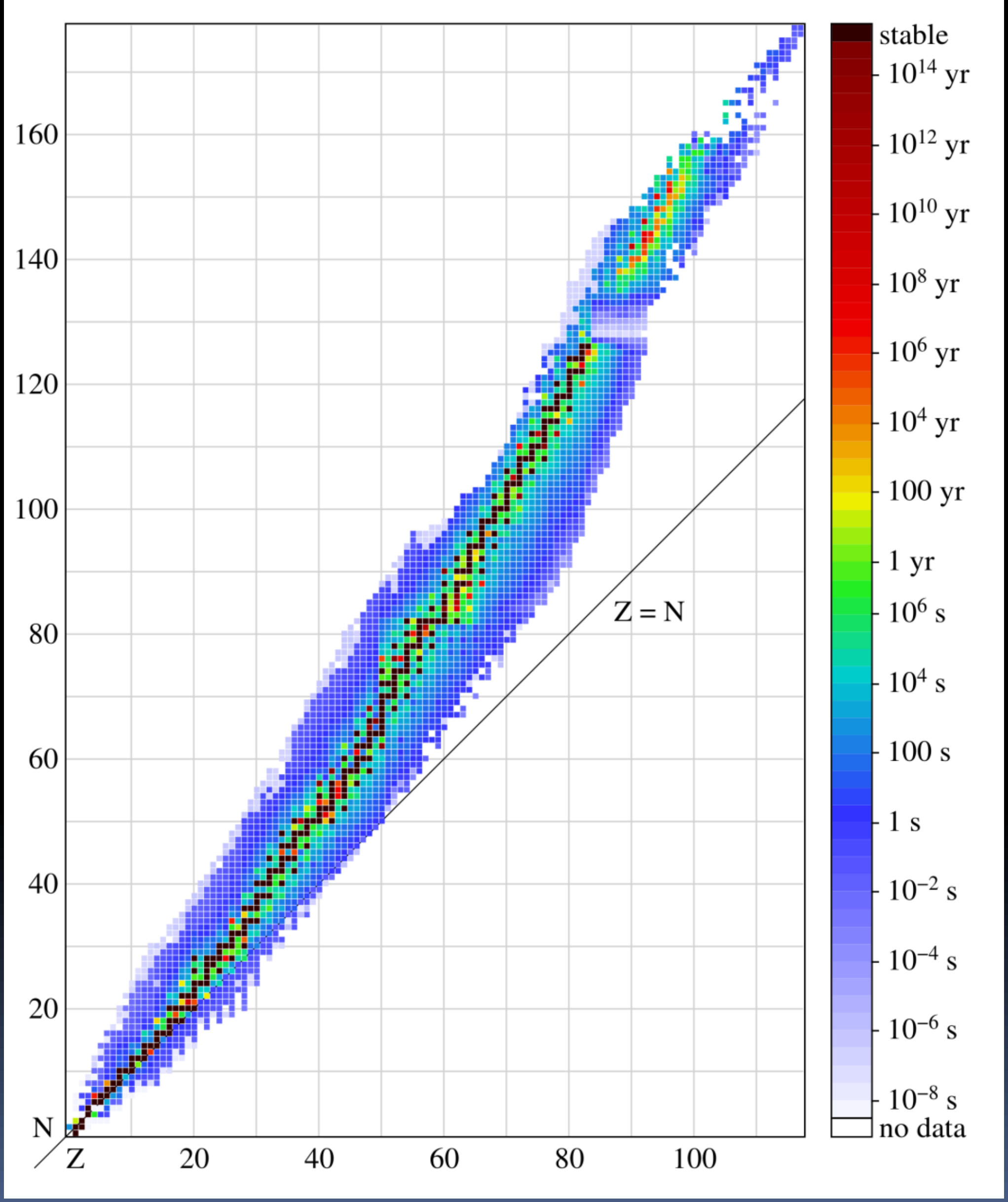


Figure 2.4 A Segre plot of stable nuclides.

Segre Plots

- Most nuclides are unstable
- Unstable nuclides emit particles that carry energy away from the nucleus
- This is called radioactivity



State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- How much binding energy is there in 1u of mass defect?

$$E_b = \delta c^2$$

$$1u = \frac{1}{12} x 1.99 x 10^{-26} kg = 1.66 x 10^{-27} kg$$

State the meaning of the terms *mass defect* and *binding energy* and solve related problems

- How much binding energy is there in 1u of mass defect?

$$E_b = \delta c^2$$

$$E_b = m_\delta c^2$$

$$E_b = \left(1.66x10^{-27} kg\right)\left(3.00x10^{8} m/s\right)^2$$

$$E_b = 1.49x10^{-10} J$$

State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- How much binding energy is there in 1u of mass defect?

$$E_b = 1.49x10^{-10}\,J$$

  - Converting this to electronvolts:

$$E_b = \left(1.49x10^{-10}\,J\right)\left(\frac{1eV}{1.60x10^{-19}\,J}\right)$$

$$E_b = 931.5x10^{6}\,eV = 931.5MeV$$

State the meaning of the terms *mass defect* and *binding energy* and solve related problems

- This gives us an important relationship – the binding energy per unit of mass defect

$$E_b / u\delta = 931.5 MeV$$

- What is the binding energy of a helium nucleus?

State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- What is the binding energy of a helium nucleus?
  - Recall that the mass defect of helium is 0.0304*u*

$$E_b/u\delta = 931.5MeV$$

$$(0.0304)x(931.5MeV) = 28.32MeV$$

  - This is extremely high and explains why alpha particles are emitted when unstable nuclei decay

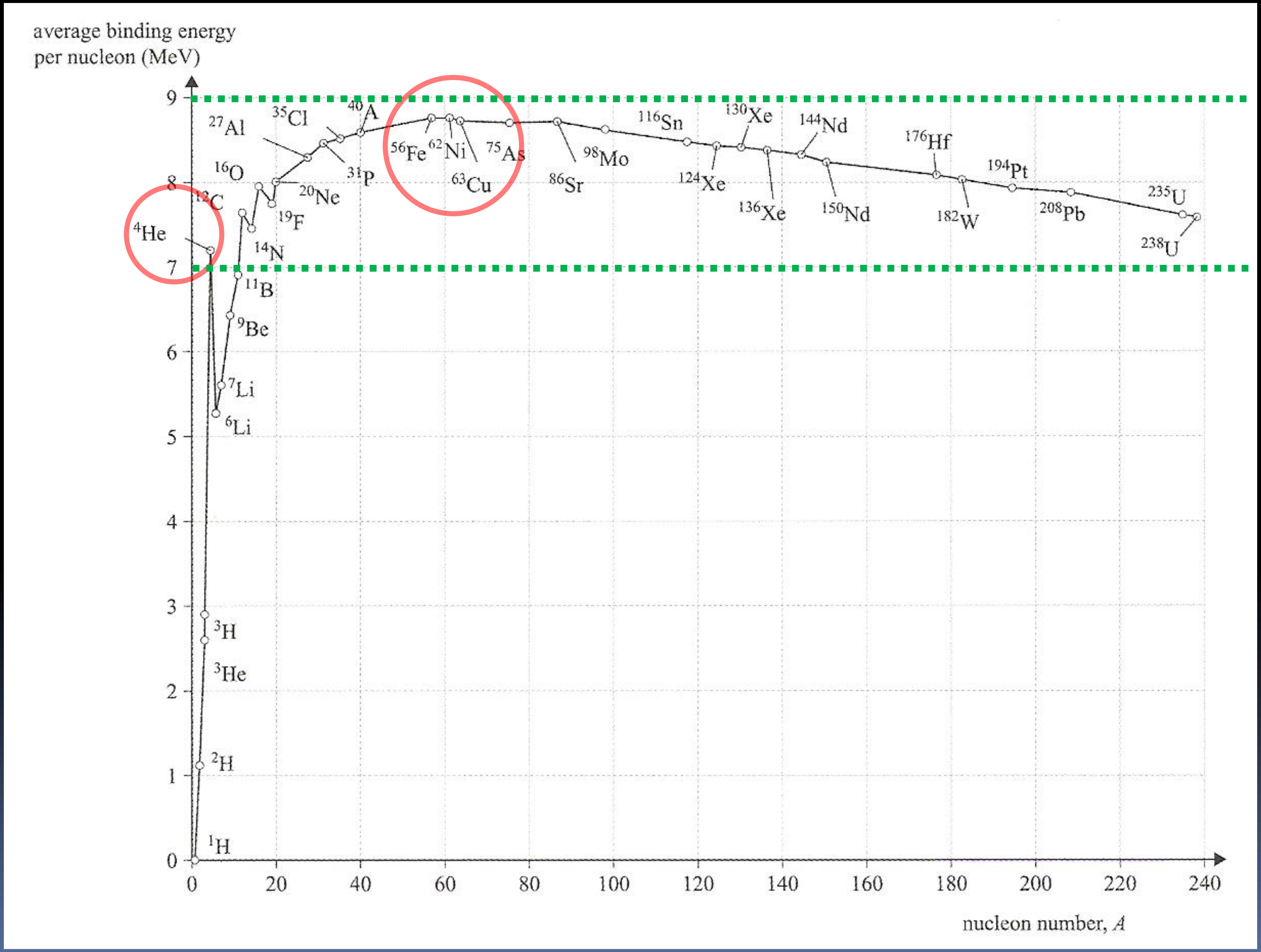
State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems

- What is the binding energy ***per nucleon*** of a helium nucleus?

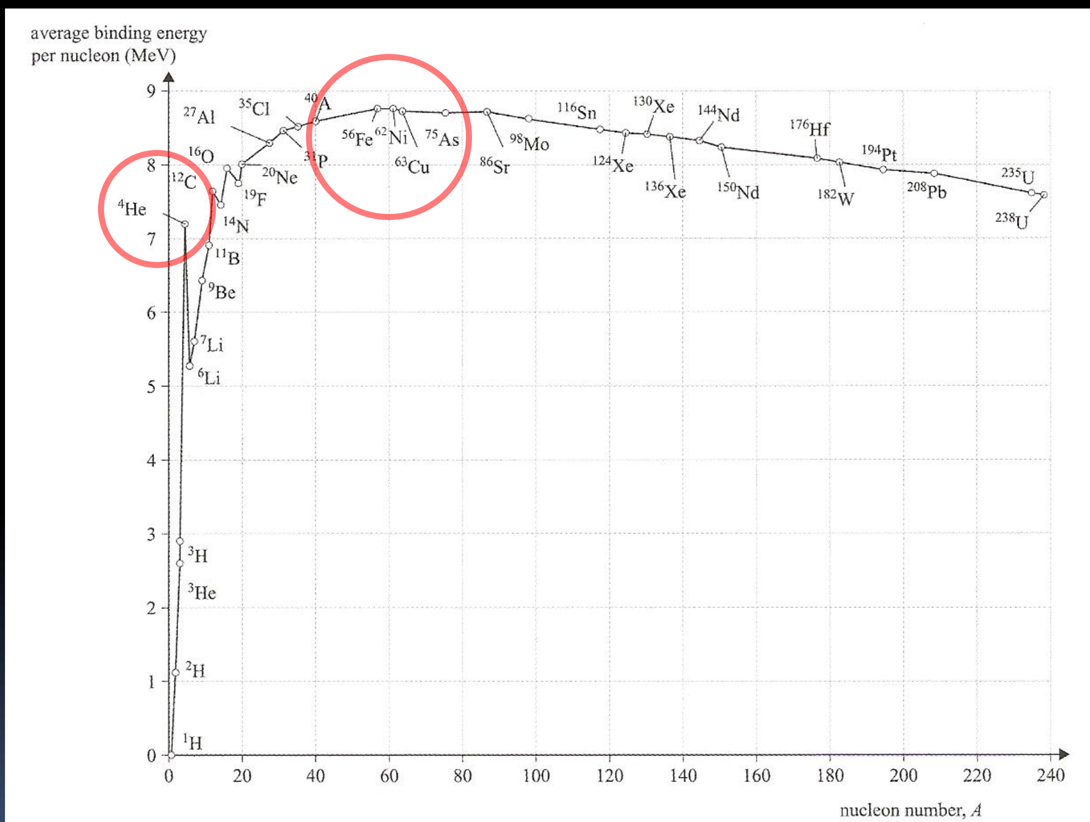
$$E_b = 28.32MeV \div 4 = 7.1MeV$$

  - Most nuclei have a binding energy per nucleon of approximately 7-9 MeV
  - The following chart shows binding energy per nucleon vs. number of nucleons

Understand the meaning of the graph of ***binding energy per nucleon*** versus ***mass number***



Understand the meaning of the graph of ***binding energy per nucleon*** versus ***mass number***



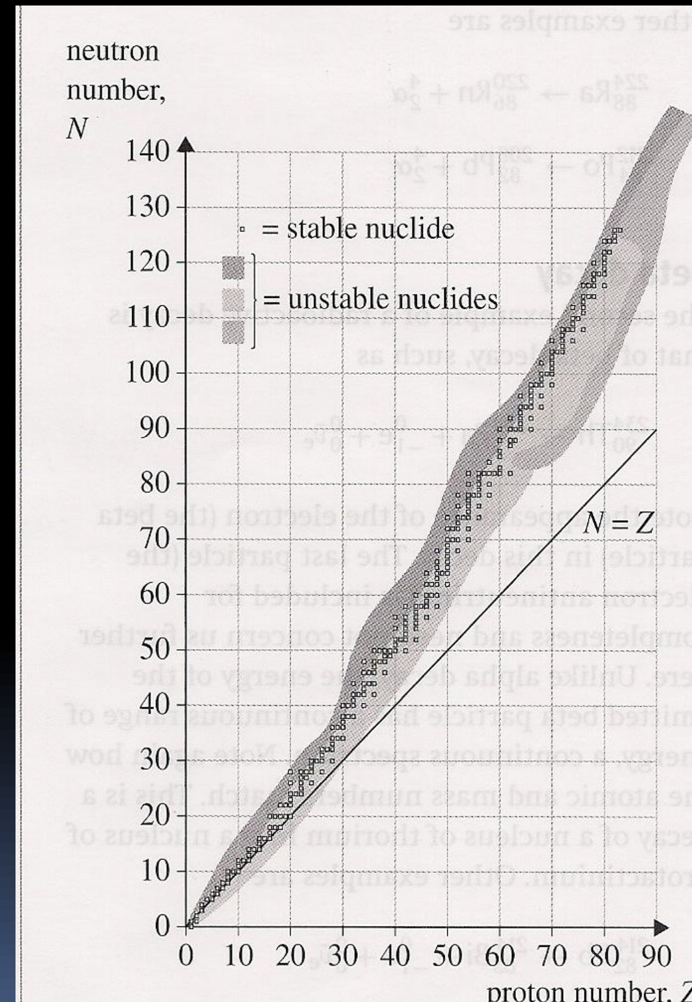
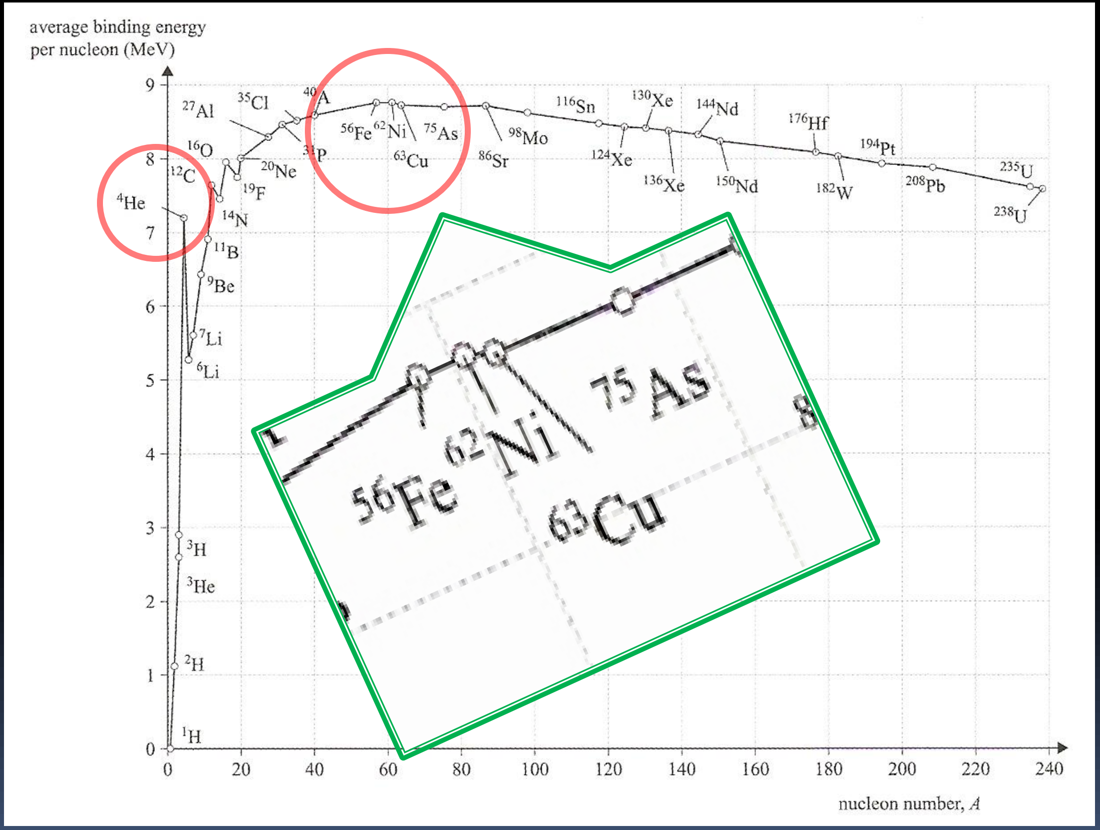


Figure 2.4 A Segre plot of stable nuclides.

Understand the meaning of the graph of ***binding energy per nucleon*** versus ***mass number***



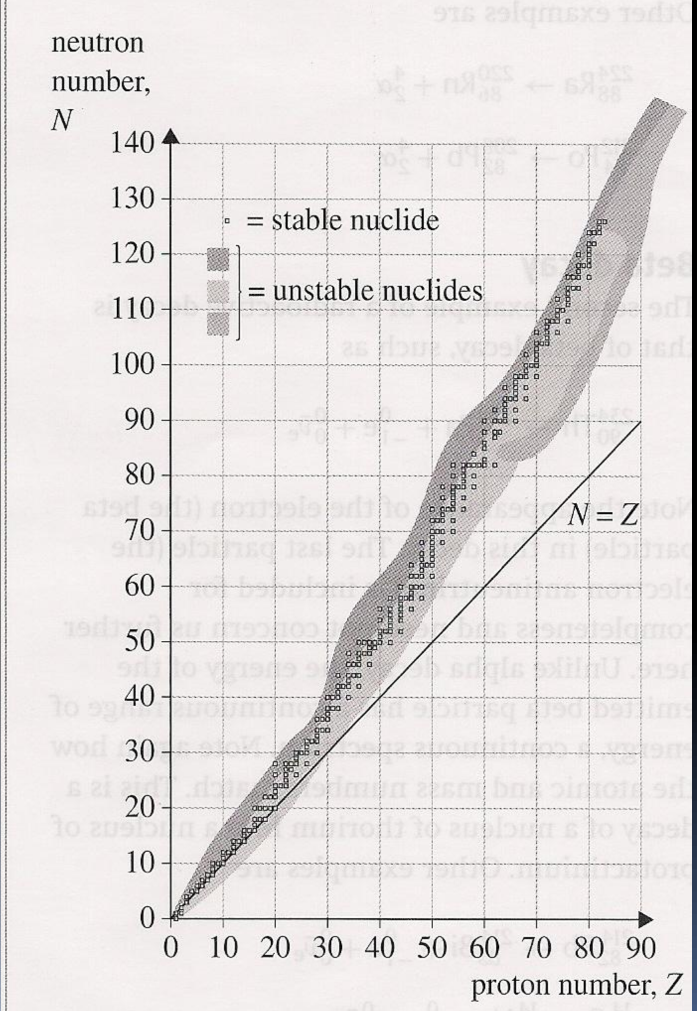


Figure 2.4 A Segre plot of stable nuclides.

Energy released in a decay

- Consider this decay of radium into radon plus an alpha particle:

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

  - The mass/energy to the left of the arrow must equal the mass/energy to the right of the arrow – including kinetic energy

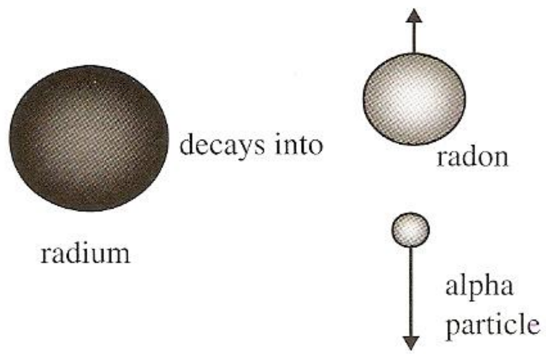


Figure 3.2 The energy released in a nuclear reaction is in the form of kinetic energy of the products.

Energy released in a decay

- Consider this decay of radium into radon plus an alpha particle:

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

  - Energy is based on nuclear mass, not atomic mass, but since the atomic number is conserved here (no loss of electrons) and since we are only interested in mass differences, we can use atomic mass
    - *i.e. electron mass will cancel out and not affect the mass difference*

Energy released in a decay

- Consider this decay of radium into radon plus an alpha particle:

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

  - If energy is to be released in this reaction, the mass of the radium atom must be greater than the mass of the radon atom plus the mass of the alpha particle
  - Difference in masses provides kinetic energy
  - Assume the radium atom is at rest

Energy released in a decay

- Consider this decay of radium into radon plus an alpha particle:

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

  - Mass of radium = 226.0254 u
  - Mass of radon = 222.0176 u
  - + Mass of helium = 4.0026 u
  - Sum = 226.0202 u
  - Mass difference = 0.0052 u

Energy released in a decay

- Consider this decay of radium into radon plus an alpha particle:

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

  - Mass difference = 0.0052 u
  - The energy released in this decay is

$$(0.0052)x(931.5MeV) = 4.84MeV$$

Energy released in a decay

- Consider this decay of radium into radon plus an alpha particle:

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

  - The energy released in one decay is 4.84 MeV
  - What is the energy release by 50-g of radium?

$$(50g)x\left(\frac{1mol}{226g}\right)x\left(\frac{6x10^{23}atoms}{mol}\right) = 1.3x10^{23}atoms$$

$$(1.3x10^{23}atoms)x(4.84MeV) = 6.3x10^{23}MeV$$

$$6.3x10^{23}MeVx(1.6x10^{-19}J/eV) \approx 1x10^{11}J$$

Energy released in a decay

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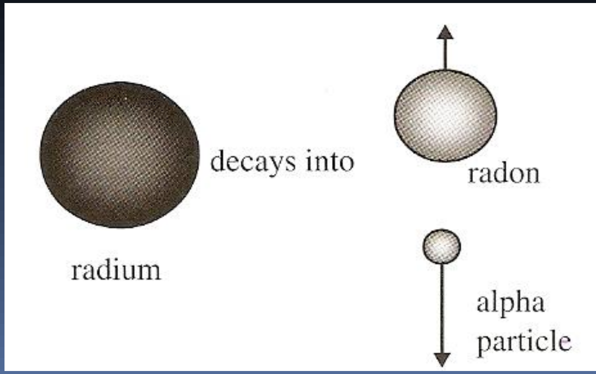
$$6.3x10^{23}MeVx(1.6x10^{-19}\ J/eV) \approx 1x10^{11}J$$

Energy released in a decay

- Consider this decay of radium into radon plus an alpha particle:

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

What happens to the energy released by 50-g of radium? Use conservation of momentum and assume they go in opposite directions.



$$m_{radon}v_{radon} = m_{alpha}v_{alpha}$$

$$\frac{m_{radon}}{m_{alpha}}v_{radon} = v_{alpha}$$

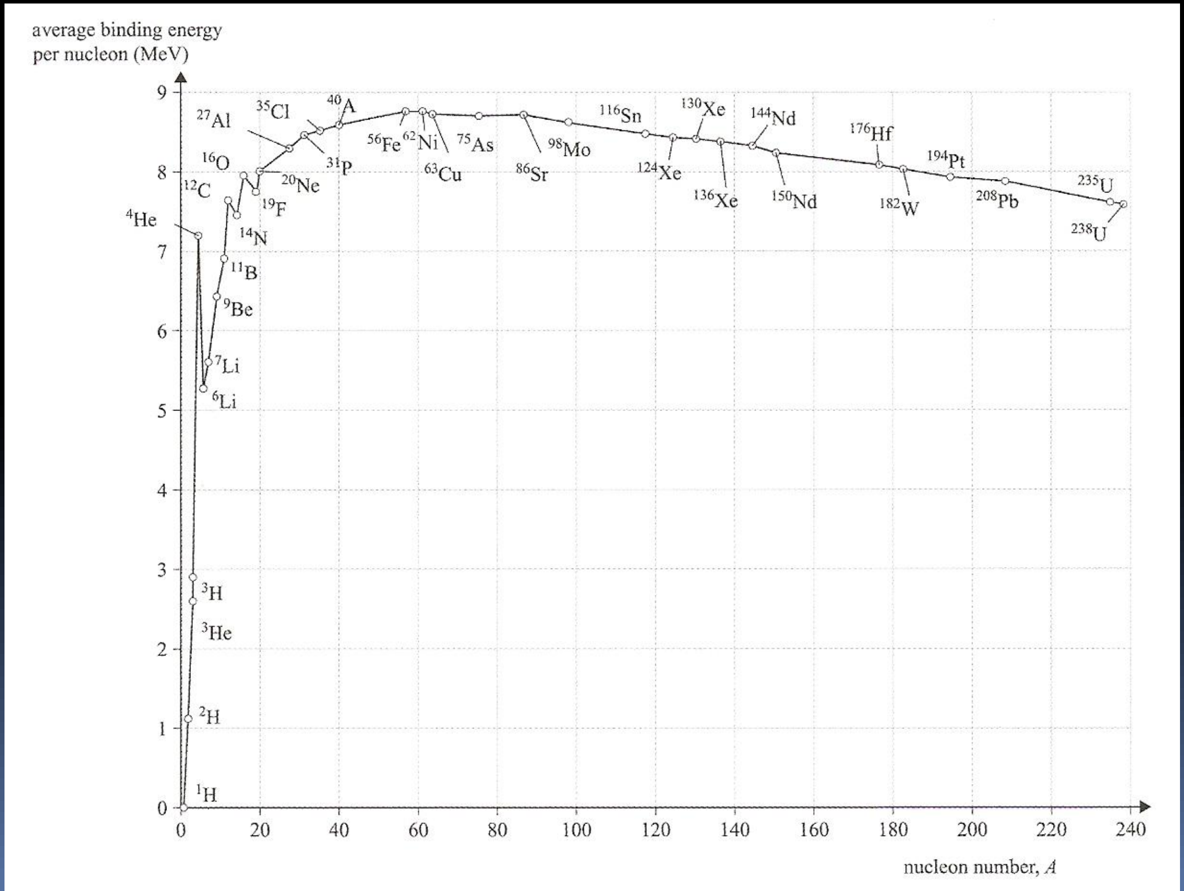
$$\frac{222}{4}v_{radon} = v_{alpha}$$

$$55v_{radon} = v_{alpha}$$

Energy released in a decay

- Consider this decay of radium into radon plus an alpha particle:

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



Write ***nuclear reaction equations*** and balance the atomic and mass numbers

- Consider a reaction in which the mass on the left side is less than the mass on the right side. Can this occur?

Write ***nuclear reaction equations*** and balance the atomic and mass numbers

- Consider a reaction in which the mass on the left side is less than the mass on the right side. Can this occur?
  - Yes. Consider:

$$^{14}_{7}N + ^{4}_{2}\alpha \rightarrow ^{17}_{8}O + ^{1}_{1}p$$

  - While the atomic numbers and mass numbers are balanced, the masses are not.
  - The sum of the nucleon masses on the left is 18.0057 while the sum on the right is 18.0070

Write ***nuclear reaction equations*** and balance the atomic and mass numbers

- Consider a reaction in which the mass on the left side is less than the mass on the right side.

$$^{14}_{7}N + ^{4}_{2}\alpha \rightarrow ^{17}_{8}O + ^{1}_{1}p$$

  - The mass on the left is 18.0057u
  - The mass on the right is 18.0070u
  - The reaction can only occur if the alpha particle has enough kinetic energy to overcome the mass difference and the kinetic energy that will result from the reaction.

Write ***nuclear reaction equations*** and balance the atomic and mass numbers

- Reaction of 4 particles

$$A + B \rightarrow C + D$$

- Energy release/requirements given by the mass difference:

$$\Delta m \rightarrow \left(m_A + m_B\right) - \left(m_C + m_D\right)$$

- Energy will be released if Δm is positive
- Energy is required if Δm is negative

Write ***nuclear reaction equations*** and balance the atomic and mass numbers

- The amount of energy released is given by:

$$\Delta E = (\Delta m)c^2$$

Summary – Part A

- Define the ***unified mass unit***
- State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems
- Understand the meaning of the graph of ***binding energy per nucleon*** versus ***mass number***
- Write ***nuclear reaction equations*** and balance the atomic and mass numbers

Summary – Part B

- State the meaning of and difference between ***fission*** and ***fusion***
- Understand that nuclear fusion takes place in the ***core of the stars***
- Solve problems of ***fission*** and ***fusion reactions***

State the meaning of and difference between ***fission* and *fusion***

State the meaning of and difference between ***fission*** and ***fusion***

- Nuclear fission is the process in which a heavy nucleus splits into lighter nuclei
- A typical reaction occurs when the nucleus of U-235 absorbs an extra neutron to become U-236
- This "triggers" the reaction by making the U-235 more unstable

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U $$

State the meaning of and difference between ***fission*** and ***fusion***

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{236}_{92}U$$

- This occurs only momentarily as the atom then splits into lighter nuclei
- One of several possibilities is,

$$^{236}_{92}U \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3^{1}_{0}n$$

State the meaning of and difference between ***fission*** and ***fusion***

$$^{236}_{92}U \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3^{1}_{0}n$$

- Note that in this reaction, three neutrons are released

$$3^{1}_{0}n \longrightarrow \; ^{1}_{0}n + ^{235}_{92}U \rightarrow ^{236}_{92}U$$

- These three neutrons have enough energy to start three more reactions
- Those three start another three each and the result is a ***chain reaction***

State the meaning of and difference between ***fission*** and ***fusion***

$$^{236}_{92}U \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3^{1}_{0}n$$

- A minimum mass is required to start a chain reaction
- This is known as the ***critical mass***

State the meaning of and difference between ***fission*** and ***fusion***

$$^{236}_{92}U \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3^{1}_{0}n$$

- The energy released in this fission reaction is given below

mass of uranium plus neutron	= 236.0526 u
mass of products	
= 143.92292 u + 88.91781 u	
+ 3 × 1.008665 u	= 235.8667250 u
mass difference	= 0.185875 u
energy released	= 0.185875 × 931.5 MeV
	= 173.14 MeV

State the meaning of and difference between ***fission*** and ***fusion***

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+ 3 × 1.008665 u	= 235.8667250 u
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energy released	= 0.185875 × 931.5 MeV
	= 173.14 MeV

- This excess energy is translated into kinetic energy
- Conservation of momentum and energy equations are used to determine particle velocities

State the meaning of and difference between ***fission*** and ***fusion***

mass of uranium plus neutron	= 236.0526 u
mass of products = 143.92292 u + 88.91781 u + 3 × 1.008665 u	= 235.8667250 u
mass difference	= 0.185875 u
energy released	= 0.185875 × 931.5 MeV = 173.14 MeV

- **What is a natural by-product of increased kinetic energy of atoms?**

State the meaning of and difference between ***fission*** and ***fusion***

State the meaning of and difference between ***fission*** and ***fusion***

- **Energy released in 1kg of U-235**

mass of uranium plus neutron	= 236.0526 u
mass of products = 143.92292 u + 88.91781 u + 3 × 1.008665 u	= 235.8667250 u
mass difference	= 0.185875 u
energy released	= 0.185875 × 931.5 MeV = 173.14 MeV

$$(1kg)x\left(\frac{1000g}{kg}\right)x\left(\frac{mol}{235g}\right)x\left(\frac{6x10^{23}nuclei}{mol}\right)$$

$$\left(2.55x10^{23}nuclei\right)\left(173.14MeV\right)\left(\frac{1.602177x10^{-13}J}{1MeV}\right)$$

$$7.1x10^{13}J$$

State the meaning of and difference between ***fission*** and ***fusion***

- **Energy released in 1kg of U-235**
  - **7.1×10^{13} J**
- **Energy released in 1kg of nitroglycerin**
  - **6.7×10^{6} J**
- **U-235 fission is roughly 10 million times more powerful than nitroglycerine**

State the meaning of and difference between ***fission*** and ***fusion***

- **The rate of reaction in nuclear reactors must be controlled in order to prevent an explosion**
  - **This is done mainly by control rods that absorb some of the neutrons given off in the reactions**
  - **Also by the water surrounding the fuel rods that slow down the released neutrons**

State the meaning of and difference between ***fission*** and ***fusion***

- **Fusion is the joining of two lighter nuclei into one heavier one**
- **An example reaction is,**

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n$$

- **Two deuterium nuclei produce helium-3 and a neutron**

State the meaning of and difference between ***fission*** and ***fusion***

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n $$

- **The energy given off by this reaction is,**

2 × mass of deuterium	= 4.0282 u
mass of helium + neutron	= 4.0247 u
mass difference	= 0.0035 u
energy released	= 0.0035 × 931.5 MeV
	= 3.26 MeV

State the meaning of and difference between ***fission*** and ***fusion***

$$ {}_{1}^{2}H + {}_{1}^{2}H \rightarrow {}_{2}^{3}He + {}_{0}^{1}n $$

- **The energy given off by one kilogram of deuterium is roughly 1×10^{13} J**
- **This is seven times less than the fission reaction, but when you're talking about a 10^{13} order of magnitude, who's gonna notice?**

State the meaning of and difference between ***fission*** and ***fusion***

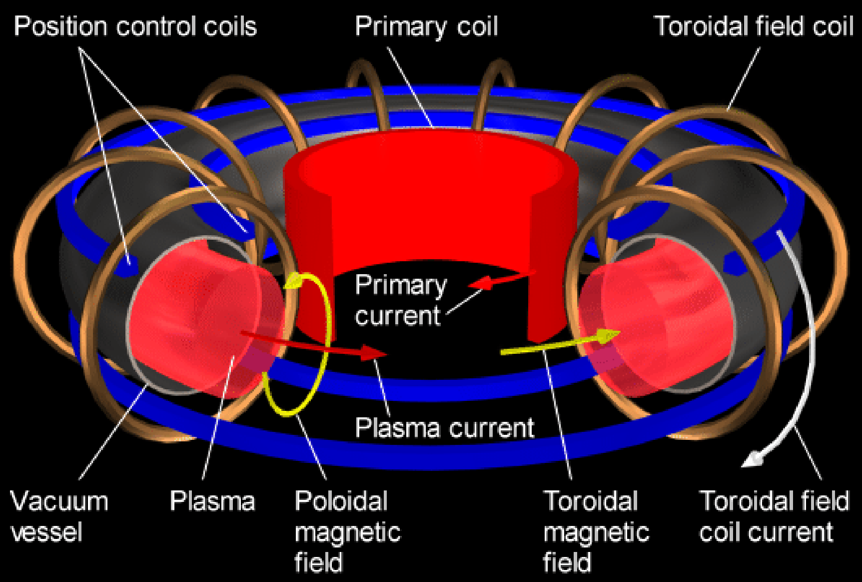
- **Fusion requires extremely high temperatures to overcome electrostatic repulsion**
- **High temperature means high kinetic energy of atoms**
- **High kinetic energy allows them to get close enough for the strong nuclear force to take over**

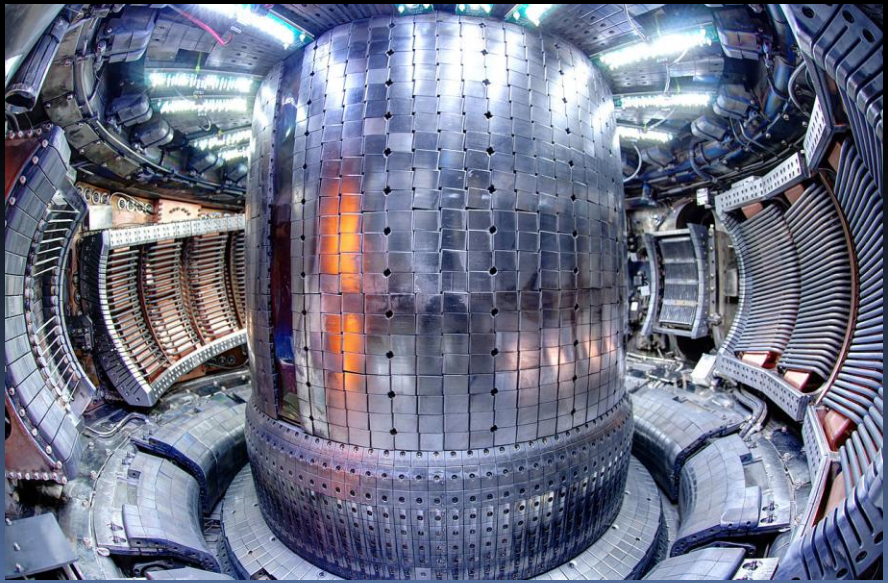
State the meaning of and difference between ***fission*** and ***fusion***

- **Temperatures required (10^9 K) turn everything into plasma**
  - **In stars, only 10^6 K required due to the tremendous pressure created by gravitational attraction**
- **How do you contain the reactants?**

State the meaning of and difference between *fission* and *fusion*

- Temperatures required turn everything into plasma
- How do you contain the reactants?
- Electromagnetic fields in machines called Tokamaks
- This is why fusion energy has not become commercially feasible in spite of all the environmental benefits



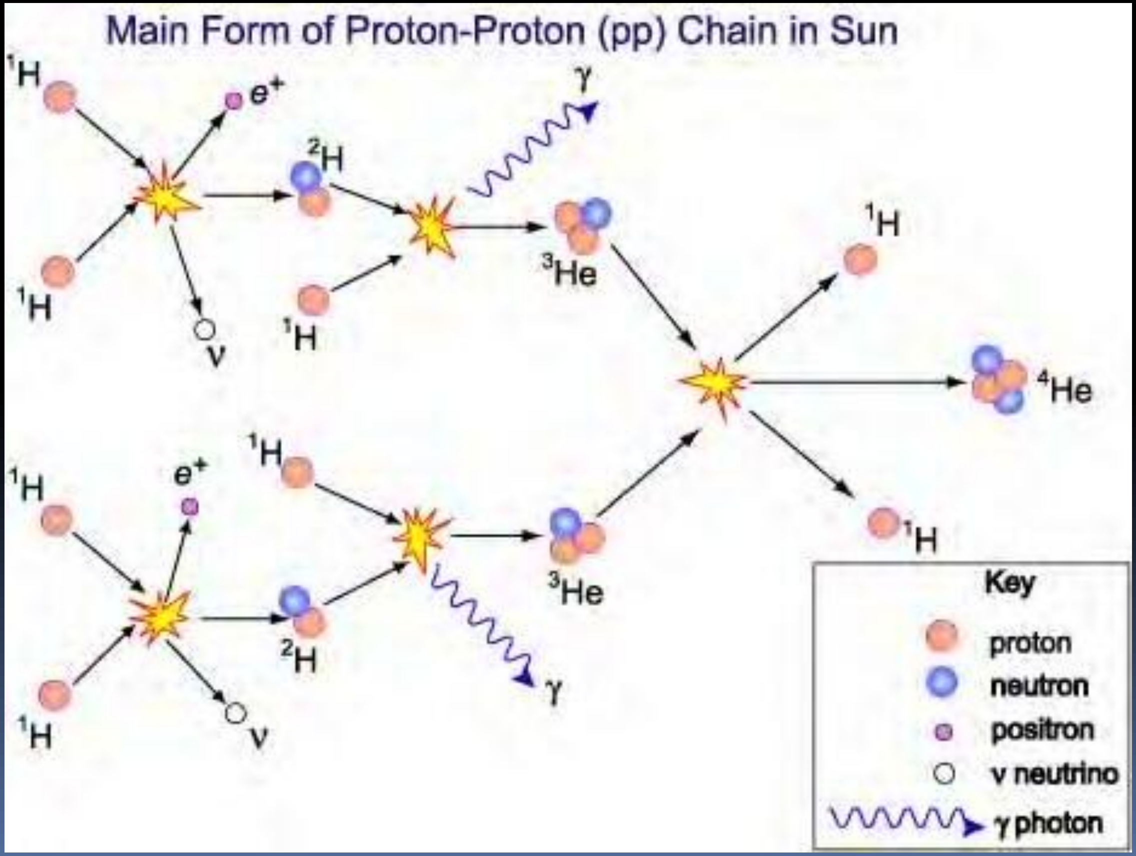


Understand that nuclear fusion takes place in the ***core of the stars***

- Typical reaction:

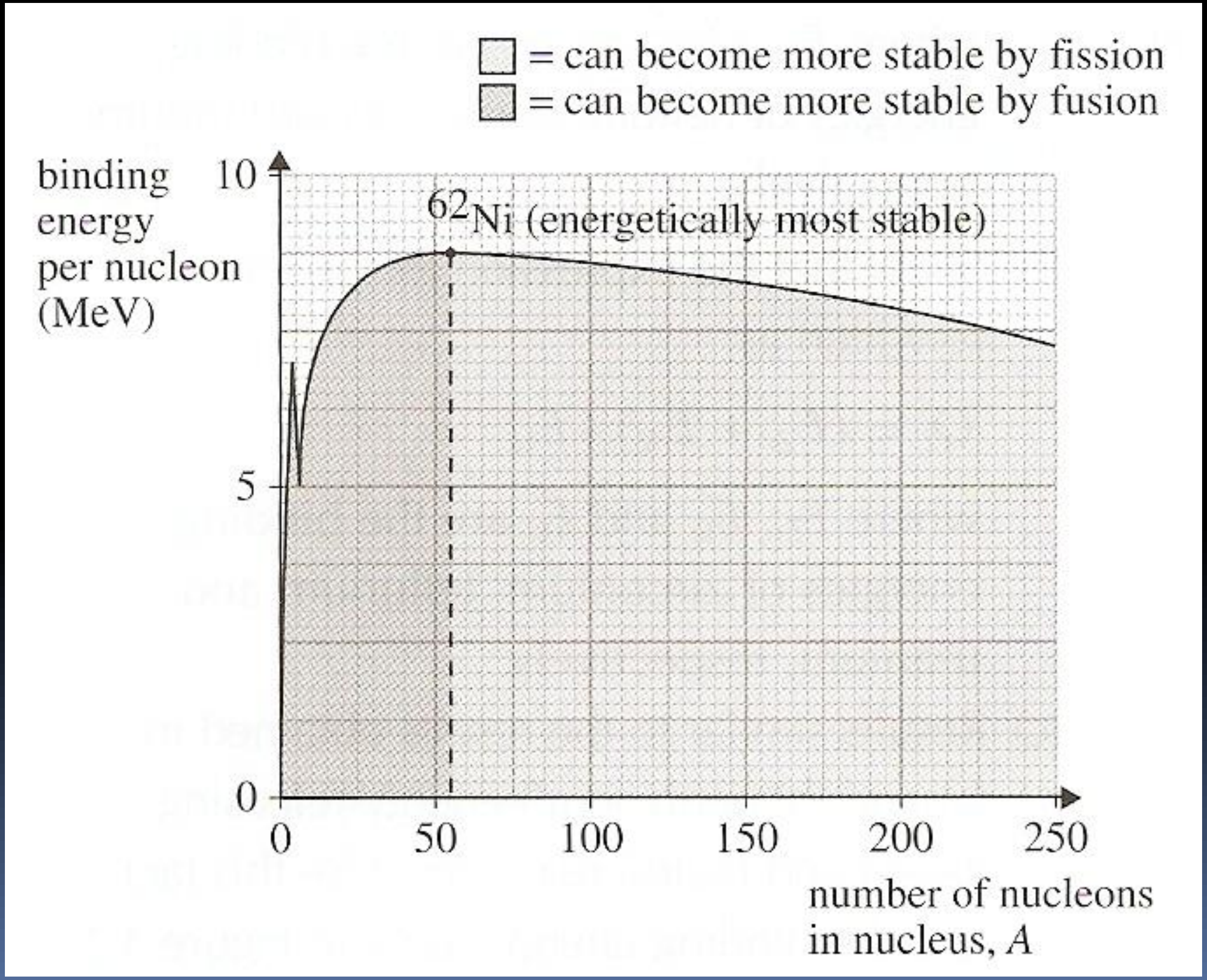
$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{1}e + 2\nu_{e} + {}^{0}_{0}\gamma$$

- Fusion is the energy engine for stars
- Stars exist in a plasma state
  - Extremely high temperatures
  - Extremely high pressures



Fission OR *Fusion*???

- Recall the binding energy per nucleon plot:



Understand that nuclear fusion takes place in the ***core of the stars***

- Stars are also element factories producing all of the elements contained in our bodies
- More on this in astrophysics (optional)

Summary – Part A

- Define the ***unified mass unit***
- State the meaning of the terms ***mass defect*** and ***binding energy*** and solve related problems
- Understand the meaning of the graph of ***binding energy per nucleon*** versus ***mass number***
- Write ***nuclear reaction equations*** and balance the atomic and mass numbers

Summary – Part B

- State the meaning of and difference between ***fission*** and ***fusion***
- Understand that nuclear fusion takes place in the ***core of the stars***
- Solve problems of ***fission*** and ***fusion reactions***

Understandings:

- The unified atomic mass unit
- Mass defect and nuclear binding energy
- Nuclear fission and nuclear fusion

Applications And Skills:

- Solving problems involving mass defect and binding energy
- Solving problems involving the energy released in radioactive decay, nuclear fission and nuclear fusion

Applications And Skills:

- Sketching and interpreting the general shape of the curve of average binding energy per nucleon against nucleon number

Guidance:

- Students must be able to calculate changes in terms of mass or binding energy
- Binding energy may be defined in terms of energy required to completely separate the nucleons or the energy released when a nucleus is formed from its nucleons

Data Booklet Reference:

$$\Delta E = \Delta m * c^2$$

Essential Idea:

- Energy can be released in nuclear decays and reactions as a result of the relationship between mass and energy.

QUESTIONS?

Homework

#16-