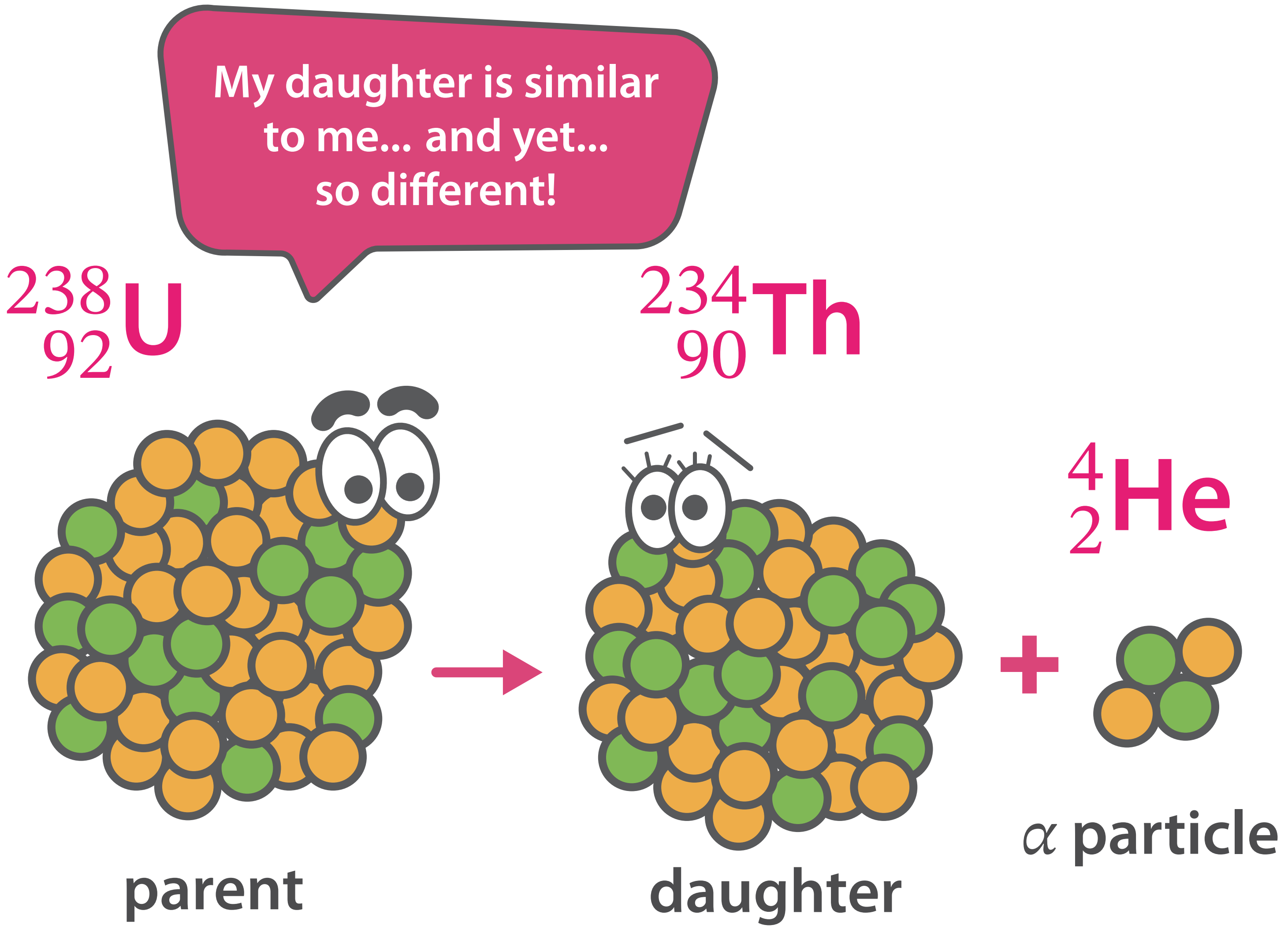
Nuclear Reactions



Lesson Objectives

You will be able to

- explain the concept of nuclear stability,
- identify positron emission and electron capture,
- compare nuclear and chemical reactions,
- give examples of transmutation reactions,
- define transuranium elements.

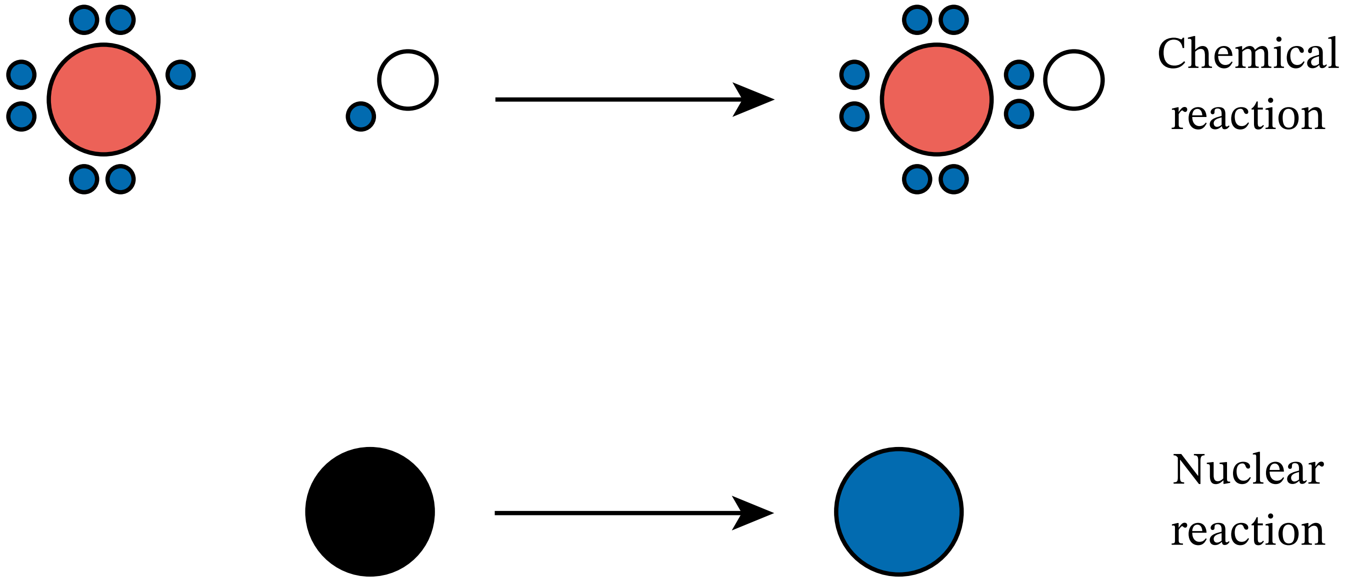
What Are Nuclear Reactions?

In nuclear reactions, atomic nuclei change from one state to another.

Nuclear reactions are responsible for making almost all of the large atoms in the universe and making solar energy in the Sun's hot and high-pressure interior.

Nuclear reactions can even be used to make electricity in nuclear power plants and diagnose diseases in hospital settings.

The change that occurs during a nuclear reaction is different from the change that occurs during a chemical reaction.

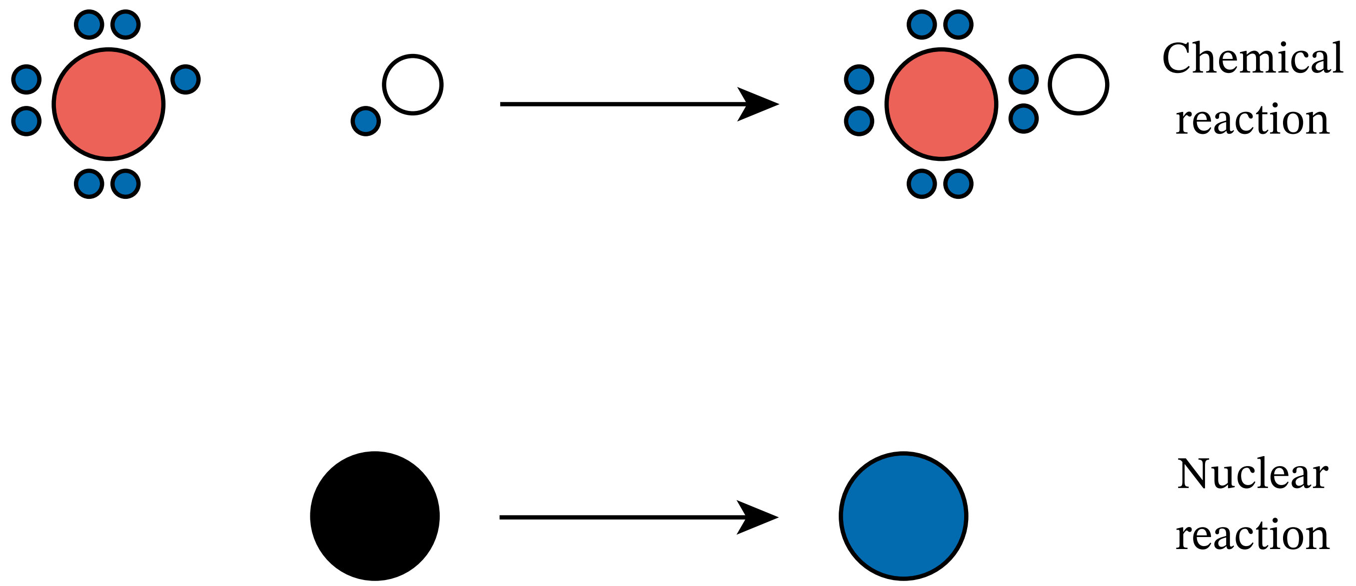


What Are Nuclear Reactions? (Continued)

Chemical reactions happen when electrons are exchanged between at least two interacting atoms.

Even though chemical reactions produce different chemical compounds, the identity of the atoms remains the same.

This means there are the same numbers and types of atoms in the reactants and products; they are just combined in different ways that we can see in the diagram below.



Definition: Nuclear Reaction

It is a process involving a change to the nuclei of atoms, typically resulting in the transformation of atoms of one element into atoms of another element.

What Are Nuclear Reactions? (Continued)

During a nuclear reaction, neutrons and protons can change, and the entire nuclei can combine or break apart.

These changes often result in an atom of one element transforming into an atom of a completely different element.

The transformation processes are usually accompanied by extremely large changes in energy that can be up to a million times greater than the amount of energy released during conventional chemical reactions.

Isotopes have similar chemical reactions because they have the same number of electrons, but they will have different nuclear reactions because they have different numbers of neutrons.

One isotope can contain more nucleons than another isotope, and this will make it more or less likely to undergo a nuclear reaction.

For example, carbon-14 is used for determining the age of carbon-based archeological samples because it slowly transforms into nitrogen-14, but carbon-12 will not, making it useless for determining the age of anything that is discovered by archeologists.

What Are Nuclear Reactions? (Continued)

These differences between chemical reactions and nuclear reactions can be summarized in the following table.

Chemical Reactions	Nuclear Reactions
They take place between the electrons of the atom's outermost shells.	They take place between the nuclei of atoms.
They do not cause an element to transform into another.	They can cause a transformation in an element's isotope or can cause an element to transform into another element entirely.
They give the same products of the reaction even with different isotopes of the same elements.	They give different products with different isotopes of the same element.
They produce small amounts of energy.	They produce large amounts of energy.

What Are Nuclear Reactions? (Continued)

Nuclear reactions can be represented in a reaction equation style.

To represent particles participating in the reaction, we will use nuclide notation ${}^{A}_{Z}\mathrm{X}$, where X is the symbol for the particle (such as the atomic symbol), A is the mass number (sum of neutrons and protons), and Z is the charge of the particle (number of protons in the nuclei).

For example, the reaction that is used in carbon dating is shown below. In this reaction, carbon-14 transforms into nitrogen-14 and emits an electron:

$$ {}^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e} $$

For a nuclear reaction to be balanced, the total A and the total Z must be the same on both sides of the reaction arrow. This is shown below:

$$ {}^{\text{total } A}_{\text{total } Z}\text{reactants} = {}^{\text{total } A}_{\text{total } Z}\text{products}. $$

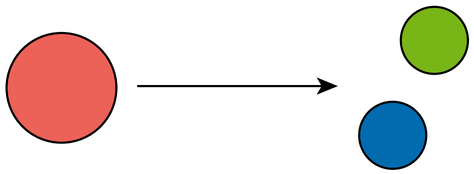
In the above reaction, the total A on both sides of the equation is 14 and the total Z on both sides of the equation is 6, meaning that the reaction is correctly balanced.

Types of Nuclear Reactions

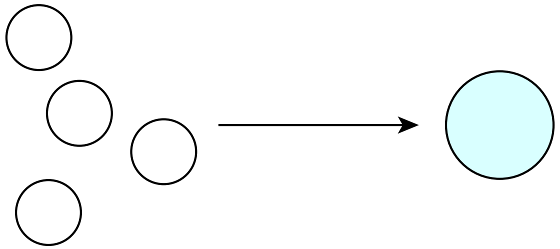
There are three different types of nuclear reactions: fission, fusion, and transmutation.

Fission occurs when a heavy nucleus is split into two or more smaller nuclei.

Fission produces a lot of energy that is used to generate electricity inside nuclear power plants.



Fusion is when two or more lighter nuclei combine to form a heavier nucleus. The reaction that occurs in the Sun and other stars is a fusion reaction that begins with hydrogen nuclei fusing to create helium.



Transmutation involves the transformation of an atom of one element into an atom of a different element. There are two subtypes of transmutation: radioactive decay and bombardment.

Definition: Transmutation

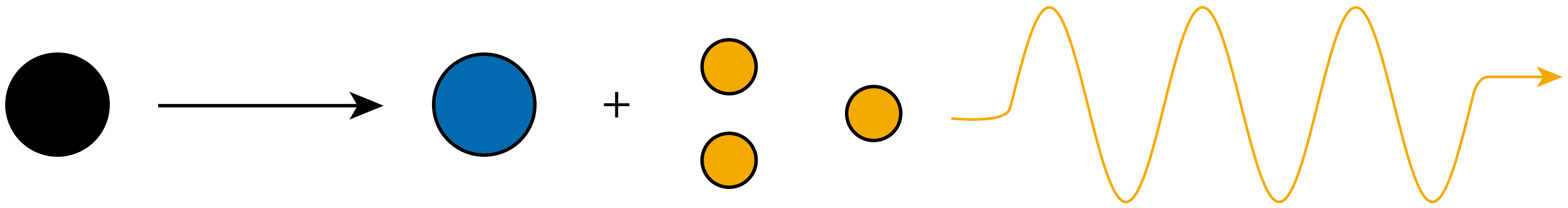
It is a type of nuclear reaction where atoms of one element transform into atoms of another element.

Types of Nuclear Reactions (Continued)

Transmutation by radioactive decay is a process that happens in nature to isotopes that are unstable.

An unstable or radioactive isotope will spontaneously emit particles or energy, called radiation, causing the isotope to transform into one that is more stable.

There are several kinds of radioactive decay that will be discussed in more detail later.



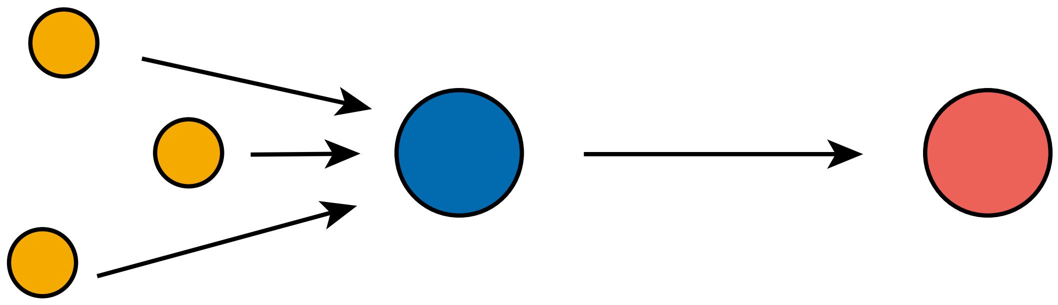
Definition: Radioactive Decay

It is the process by which unstable atoms spontaneously transform by the emission of charged particles, energy, or a combination of both.

Types of Nuclear Reactions (Continued)

Transmutation by bombardment also results in atoms of an element transforming into atoms of a different element.

Bombardment is a nonspontaneous process where an atom is bombarded with smaller particles, such as neutrons or alpha particles, that combine with the atom to form a different, larger nucleus.



Definition: Bombardment

It is a nonspontaneous process where an atom is bombarded with smaller particles, which combine to form a different, larger nucleus.

Types of Nuclear Reactions (Continued)

The first example of transmutation by bombardment occurred in 1919 when the scientist Ernest Rutherford bombarded atoms of nitrogen-14 with alpha particles.

However, back then, apart from observing that protons were emitted, he did not know what the other product of the reaction was.

A few years later, in 1925, fellow scientist Patrick Blackett was able to identify the residual nuclide as being oxygen-17. This process also emits protons as follows:

$$^{14}_{7}\text{N} + ^{4}_{2}\text{He} \longrightarrow ^{17}_{8}\text{O} + ^{1}_{1}\text{p}$$

Elements that have an atomic number greater than 92, which are called the transuranium elements, are created by bombardment.

Most of these elements do not exist in nature, and they are all radioactive.

Definition: Transuranium Element

They are elements with atomic numbers greater than 92. These elements are usually not found in nature but instead are artificially created by the process of transmutation by bombardment.

Example 1: Identifying the Radiation Involved in a Reaction Equation

Using the equation that follows, which type of ionizing radiation, x, was used to bombard beryllium-9 and aid James Chadwick in the discovery of the neutron in 1932?

$$x + {}^{9}_{4}\text{Be} \longrightarrow {}^{12}_{6}\text{C} + {}^{1}_{0}\text{n}$$

A. Positrons
B. γ rays
C. β particles
D. α particles

Answer

Atoms can be bombarded with particles to cause a nuclear reaction to occur.

In the equation above, atoms of beryllium-9 are bombarded with an unknown particle, causing them to transform into atoms of carbon-12 and emit neutrons.

Example 1 (Continued)

For nuclear reactions,

$$^{\text{total } A}_{\text{total } Z}\text{reactants} = {}^{\text{total } A}_{\text{total } Z}\text{products}$$

So, we will be able to work out the identity of the unknown particle by determining the value of A and Z for it.

On the products side of the equation, the total $A = 13$ and the total $Z = 6$.

The reactants side must have the same totals.

The value of A for the unknown particle must be the total A minus the value of A for beryllium $(13 - 9)$, which gives us 4.

Similarly, the value of Z for the unknown particle must be the total Z minus the value of Z for beryllium $(6 - 4)$, which is 2.

So, the unknown particle has $A = 4$ and $Z = 2$. This corresponds to a nucleus composed of four particles: two protons and two neutrons. This is an alpha (α) particle or the He^{2+} ion.

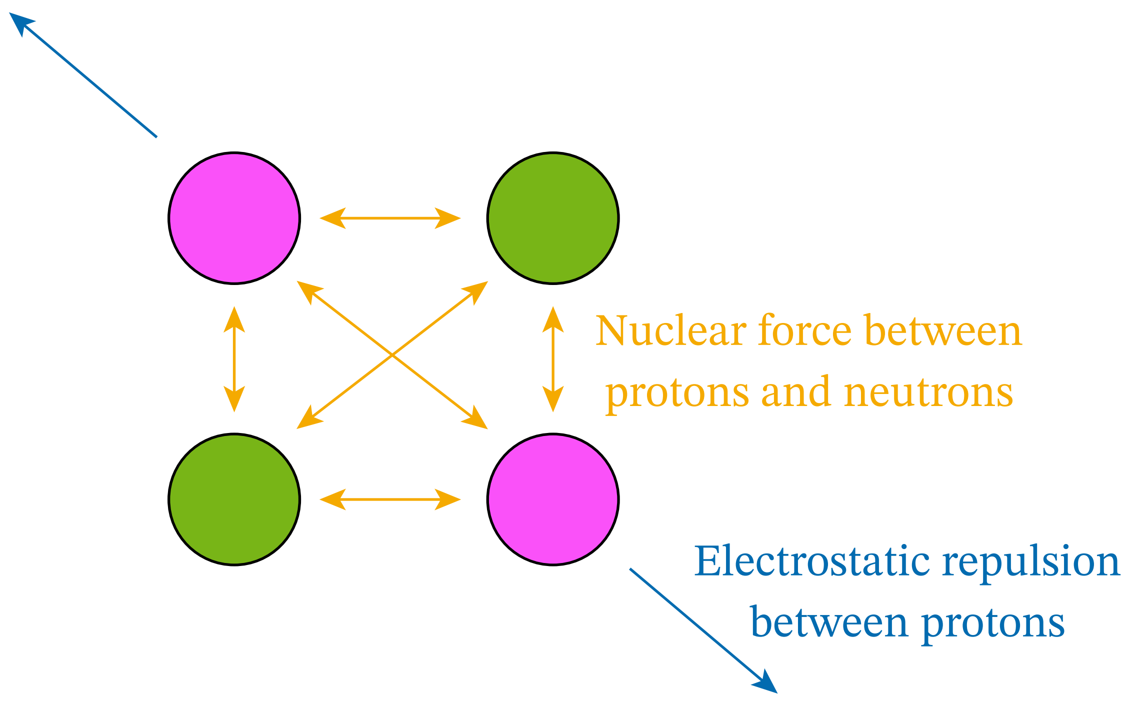
Nuclear Stability

We now know what nuclear reactions are, how they differ from chemical reactions, and the different types of nuclear reactions that can occur.

However, there is one important topic we largely have not discussed yet.

If carbon-14 is unstable and undergoes radioactive decay to nitrogen-14, then why is carbon-12 stable and does not decay?

The only difference between these isotopes is the number of neutrons: carbon-12 has six neutrons, while carbon-14 has eight; therefore, the answer must have something to do with the number of neutrons an atom has.

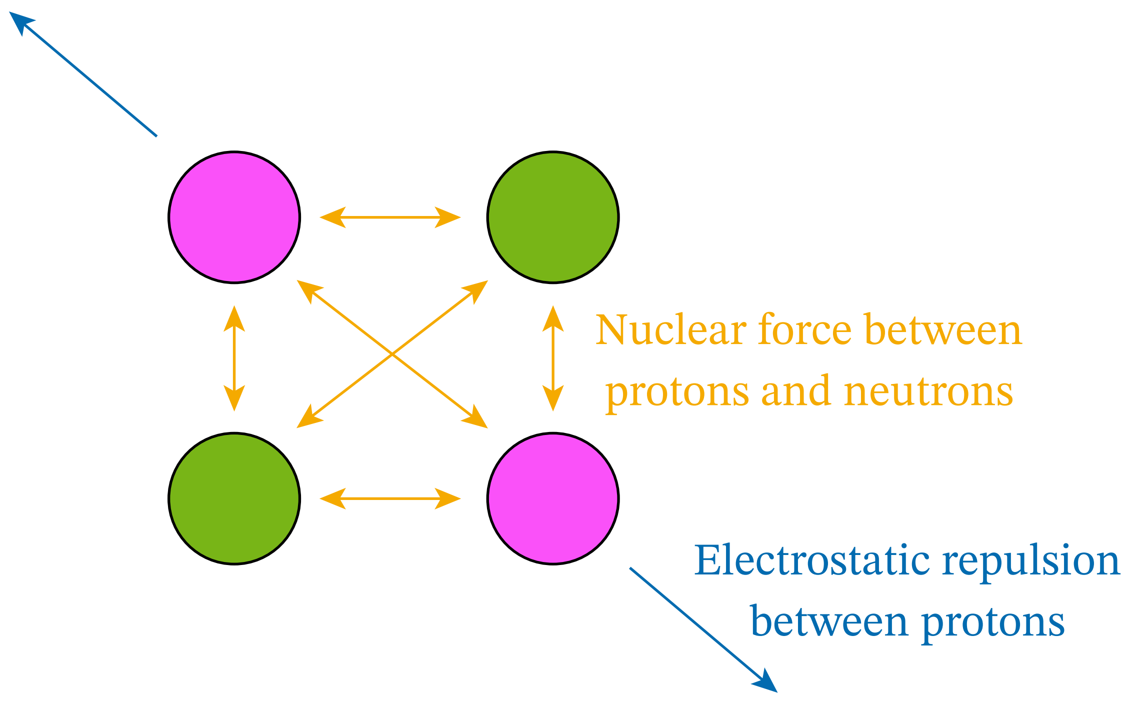


Nuclear Stability (Continued)

Nuclei are held together by the nuclear force, an extremely strong attractive force between protons and neutrons in the nucleus.

The strong attraction of the nuclear force is why the positively charged protons in the nucleus do not repel each other.

Neutrons are important for nuclear stability because they provide more of the attractive nuclear force in the nucleus to overcome the electrostatic repulsion between protons.



Nuclear Stability (Continued)

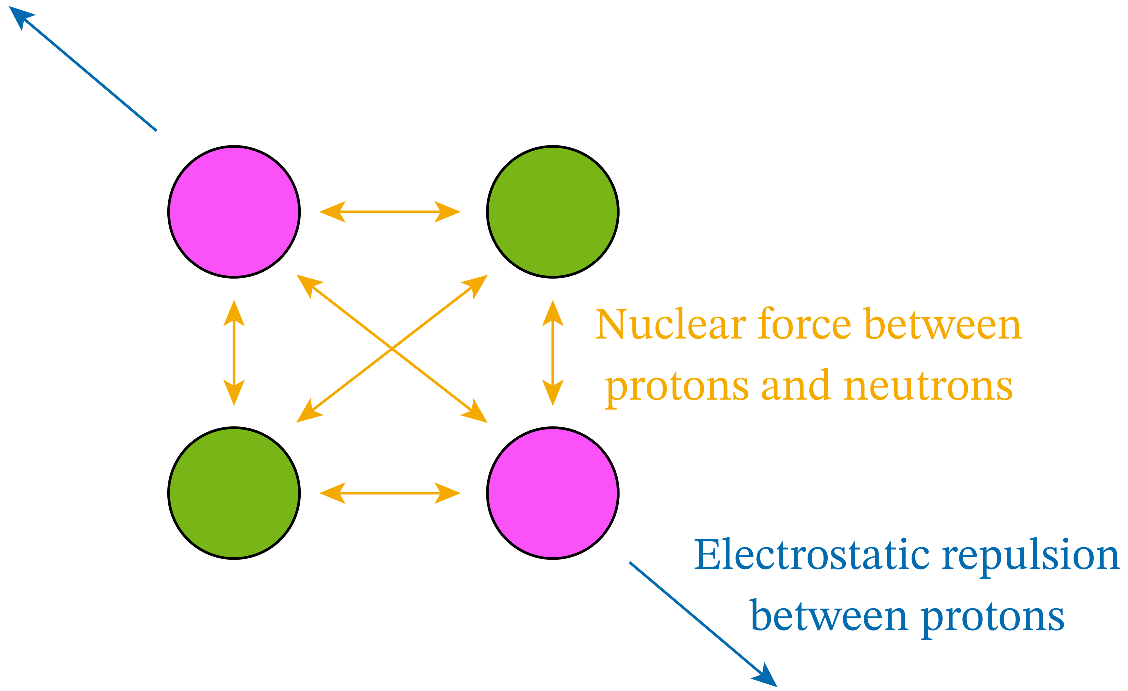
With the right number of neutrons, the nucleus will be held together by the nuclear force and the atom will be stable.

If there are too many or too few neutrons in the nucleus, the atom will be unstable.

The ratio of neutrons to protons in the nucleus can be used to predict nuclear stability since atoms of an element with a specific neutron-to-proton ratio will be stable.

This stable neutron-to-proton ratio can be visualized on a graph, shown in the next slide, that is commonly referred to as the "band of stability."

Each dot on the graph represents a stable isotope.



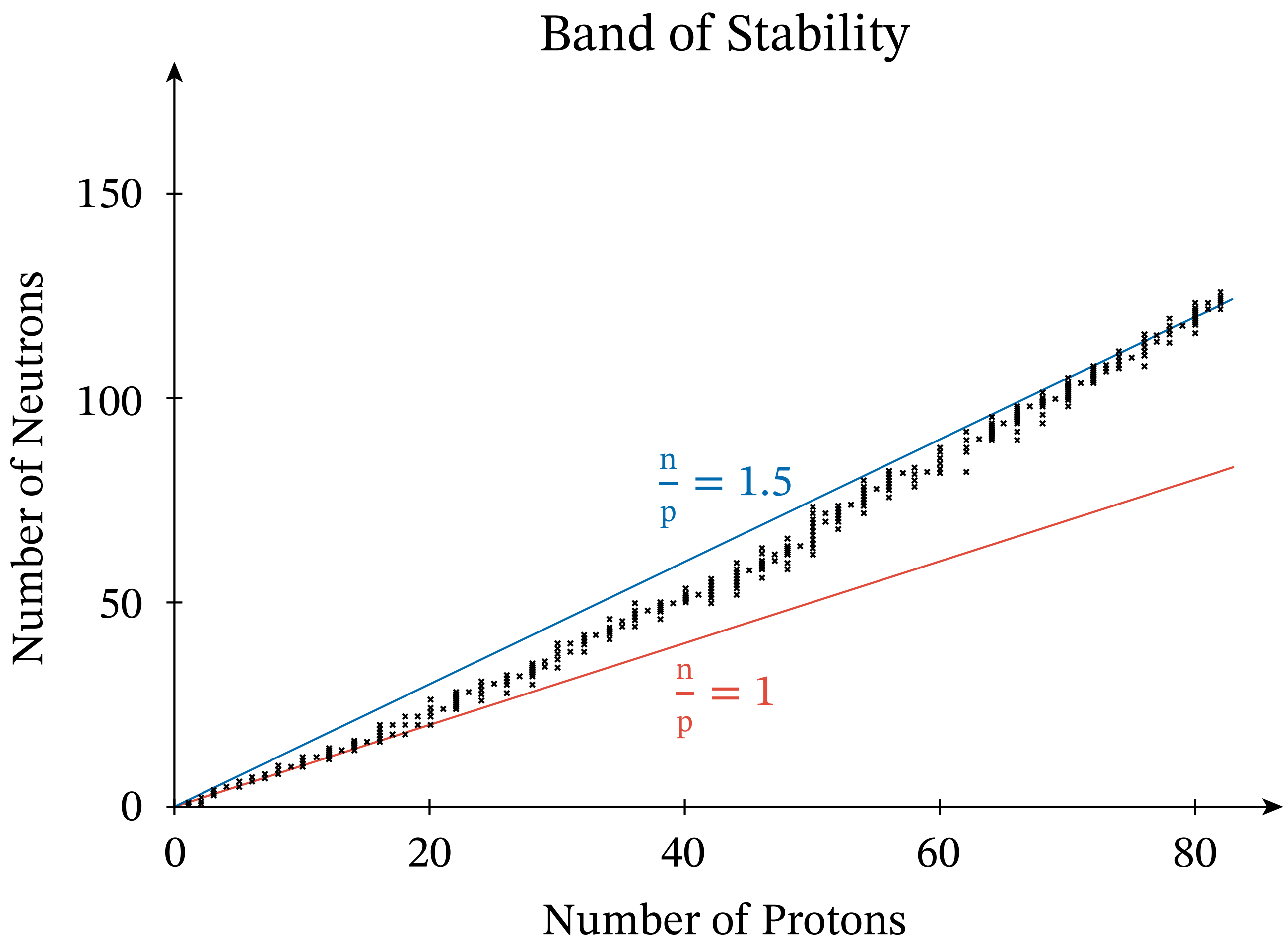
Nuclear Stability (Continued)

The most abundant stable isotopes of lighter elements, with atomic numbers of about 20 or less, have a neutron-to-proton ratio of about 1 : 1.

However, the more protons there are in the nucleus, the more neutrons are needed for the nucleus to be stable.

This is reflected by the neutron-to-proton ratio gradually increasing and approaching a ratio of 1.5 : 1 for heavier elements.

Any isotope not on the band of stability will be radioactive and will decay into an isotope that is on the band of stability over time.



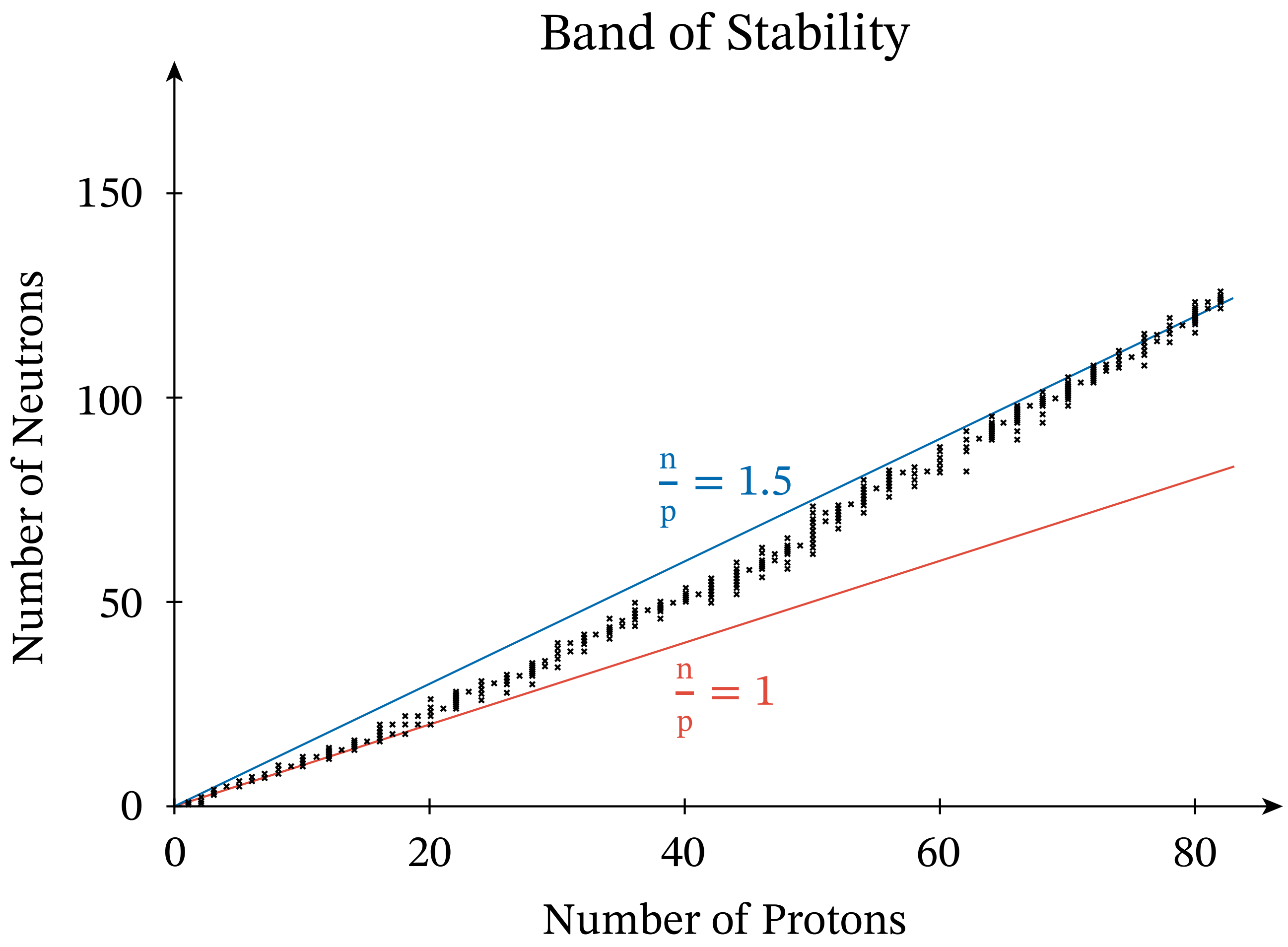
Nuclear Stability (Continued)

There are different types of radioactive decay that isotopes can undergo to become stable.

We will discuss several kinds of decay in detail: alpha decay, beta decay, positron emission, electron capture, and gamma emission.

In each type of decay, radiation is emitted from the nucleus.

This radiation can be a type of particle, energy, or a combination of the two.



Definition: Nuclear Force

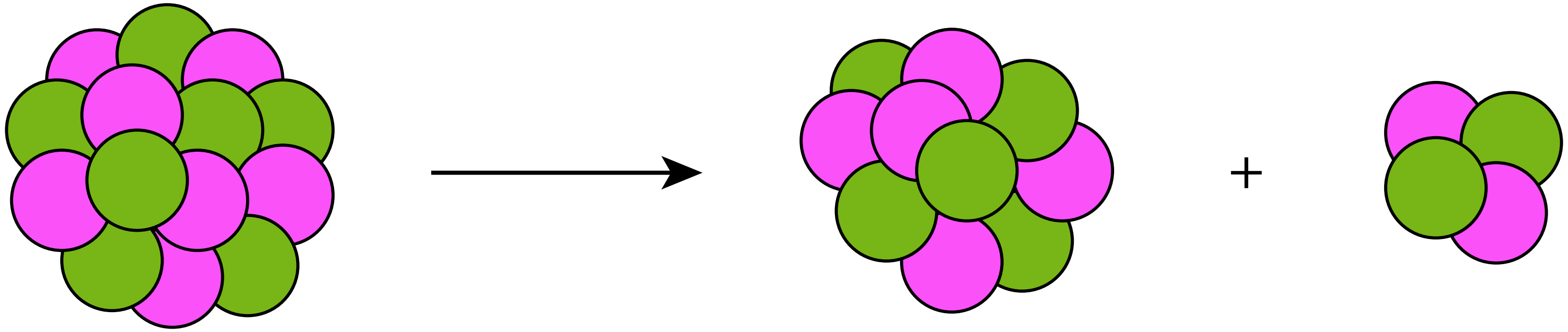
It is the strong, short-range, attractive force between protons and neutrons in the nuclei of atoms.

Radioactive Decay: Alpha Decay

When a nucleus undergoes alpha decay, an alpha particle is emitted.

Alpha particles are nuclei with two protons and two neutrons or the He^{2+} ion.

Emitting an alpha particle results in the nucleus losing two protons and two neutrons, decreasing A by 4 and Z by 2.



The general reaction that occurs during the alpha decay of an atom can be shown as follows:

$$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}X' + {}^{4}_{2}He$$

Reaction: Alpha Decay of an Atom

This is shown as follows:

$$^{A}_{Z}\mathrm{X} \longrightarrow {}^{A-4}_{Z-2}\mathrm{X}' + {}^{4}_{2}\mathrm{He}$$

Example 2: Identifying the Equation That Represents Alpha Decay

Which of the following equations represents the α decay of radium-226?

A. ${}^{226}_{88}\text{Ra} + {}^{4}_{2}\text{He} \longrightarrow {}^{230}_{90}\text{Th}$
B. ${}^{226}_{88}\text{Ra} \longrightarrow {}^{230}_{90}\text{Th} + {}^{4}_{2}\text{He}$
C. ${}^{226}_{88}\text{Ra} + {}^{4}_{2}\text{He} \longrightarrow {}^{222}_{86}\text{Rn}$
D. ${}^{230}_{90}\text{Th} \longrightarrow {}^{226}_{88}\text{Ra} + {}^{4}_{2}\text{He}$
E. ${}^{226}_{88}\text{Ra} \longrightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$

Answer

Alpha (α) decay is a type of radioactive decay where an alpha particle is ejected from the nucleus of an atom.

An alpha particle is a nucleus with two protons and two neutrons or a He^{2+} ion.

We want to identify the equation that represents the alpha decay of radium-226, so radium-226 will be the reactant and an alpha particle will be one of the products in this nuclear reaction.

Example 2 (Continued)

We can create a reaction equation for this nuclear reaction by representing both of these species using the notation ${}^{A}_{Z}\mathrm{X}$ in the question, where X is the symbol for the species, A is the mass number (sum of protons and neutrons), and Z is the charge (number of protons in the nuclei).

Using this notation, we have the equation

$$^{226}_{88}\mathrm{Ra} \longrightarrow \ ? + {}^{4}_{2}\mathrm{He}$$

We can identify the unknown product by balancing the equation, since, for nuclear reactions,

$$^{\text{total } A}_{\text{total } Z}\text{reactants} = {}^{\text{total } A}_{\text{total } Z}\text{products}$$

The total A on the reactants side is 226. The value of A for the unknown particle must be the total A minus the value of A for the alpha particle $(226 - 4)$, or 222.

Example 2 (Continued)

The total Z on the reactants side is 88. The value of Z for the unknown product is the total Z minus the Z for the alpha particle $(88 - 2)$, which gives us 86.

This gives us

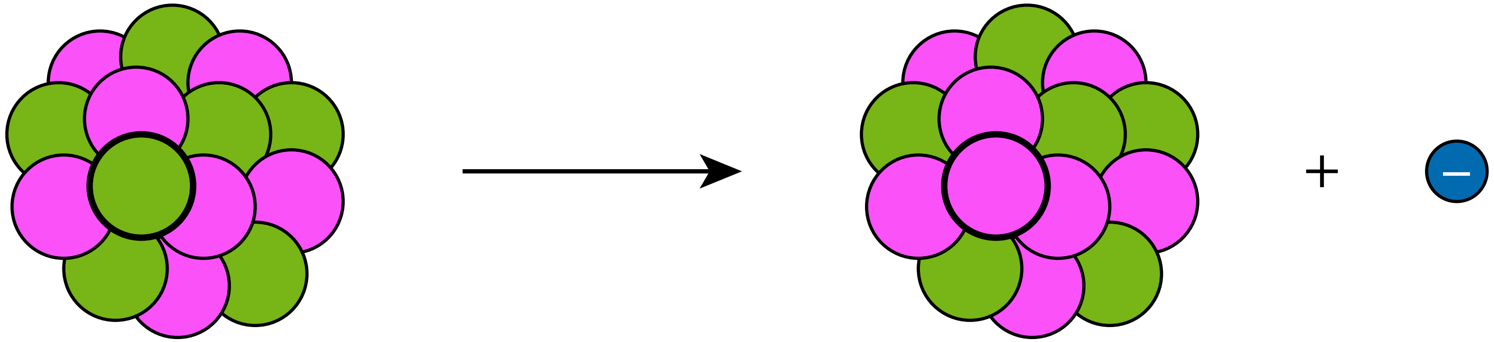
$$^{226}_{88}\text{Ra} \longrightarrow {}^{222}_{86}? + {}^{4}_{2}\text{He}$$

Radioactive Decay: Beta Decay

In β^- decay, an electron (or beta particle) is emitted from the nucleus.

This accompanies a neutron in the nucleus changing into a proton, increasing the number of protons in the nucleus (Z) by one.

β^- decay results in A remaining unchanged because the total number of protons and neutrons stays the same.



The general reaction that occurs during the beta (β^-) decay of an atom can be shown as follows:

$$^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z+1}\mathrm{X}' + {}^{0}_{-1}\mathrm{e}$$

Reaction: Beta (β^{-}) Decay of an Atom

$$^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z+1}\mathrm{X}' + {}^{0}_{-1}\mathrm{e}$$

Example 3: Determining Which Equation Corresponds to an Example of decay

Which of the following equations is correct for atomic transmutation via β^- decay?

$$ {}^{a}_{b}\text{X} \longrightarrow {}^{c}_{d}\text{Y} + \beta^- $$

A. $d = b - 1$

B. $a - c = d$

C. $b = d$

D. $c = a - 1$

E. $a = c$

Answer

β^- decay is a type of radioactive decay where an electron (${}^{0}_{-1}\text{e}$) is emitted from the nucleus.

The emission of an electron is accompanied by atoms of the reactant (X in the above equation) that are transformed into atoms of a different element (Y in the above equation) because a neutron in the nucleus is transformed into a proton.

Example 3 (Continued)

Let's determine the effect this transformation will have on the mass number and the charge of the nucleus.

If a neutron is transformed into a proton, the mass number will stay the same because the total number of protons and neutrons stays the same.

However, the charge will increase by one because the nucleus now contains an additional proton. Summarizing this in reaction equation form, we get the following:

$$^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z+1}\mathrm{X}' + {}^{0}_{-1}\mathrm{e}$$

If we compare this equation to the equation given in the question, we can see that $a = c$ (since the mass number is constant) and $d = b + 1$ (since the charge increased by one).

Therefore, option E is the only correct answer.

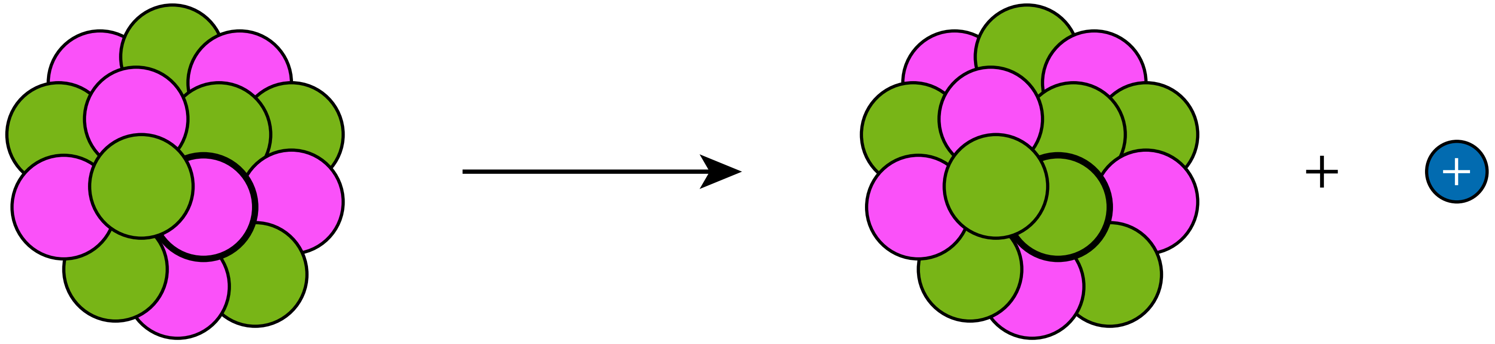
Radioactive Decay: Positron Emission

In positron emission, a positron is emitted from the nucleus.

A positron is a particle with the same mass as an electron but with an opposite charge (+1).

During this process, a proton in the nucleus is converted into a neutron.

Since the number of protons in the nucleus decreases by one, Z decreases by one, but A is unchanged.



The general reaction that occurs when an atom undergoes positron emission can be shown as follows:

$$^{A}_{Z}\mathrm{X} \longrightarrow \, ^{A}_{Z-1}\mathrm{X}' + \, ^{0}_{+1}\mathrm{e}$$

Reaction: Positron Emission

$$^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z-1}\mathrm{X}' + {}^{0}_{+1}\mathrm{e}$$

Example 4: Identifying the Decay Process Represented by a Reaction Equation

Which decay process is represented by the following equation?

$$^{8}_{5}\text{B} \longrightarrow {}^{8}_{4}\text{Be} + {}^{0}_{+1}\text{e}$$

A. Positron emission

B. Beta emission

C. Alpha emission

D. Gamma emission

E. Electron capture

Example 4 (Continued)

Answer

The equation above shows a nuclear reaction where atoms of boron-8 are transformed into atoms of beryllium-8.

This is an example of radioactive decay, the spontaneous transformation of unstable atoms.

Each decay process emits a characteristic form of radiation in the form of particles or energy.

This means we can identify the kind of decay represented in the equation above by identifying the particle or energy that is emitted.

During this process, a particle that has a mass number of zero and a charge of 1+ that corresponds to a positron is emitted.

A positron is a particle with the same mass as the electron but with an opposite charge (1+).

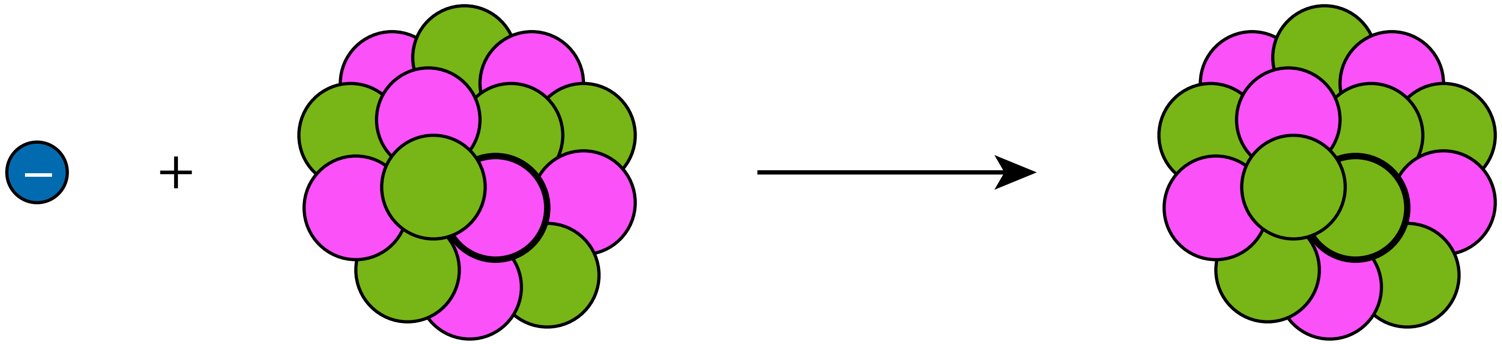
This means that the process represented in the equation is positron emission; the answer is option A.

Radioactive Decay: Electron Capture

In electron capture, a low-energy electron in the atom is absorbed by the nucleus.

This process converts a proton to a neutron and typically is accompanied by the emission of X-rays.

Electron capture has the same overall effect as positron emission: Z decreases by one and A is unchanged.



The general reaction that occurs during electron capture can be shown as follows:

$$ {}^{0}_{-1}\mathrm{e} + {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z-1}\mathrm{X}' $$

Reaction: Electron Capture

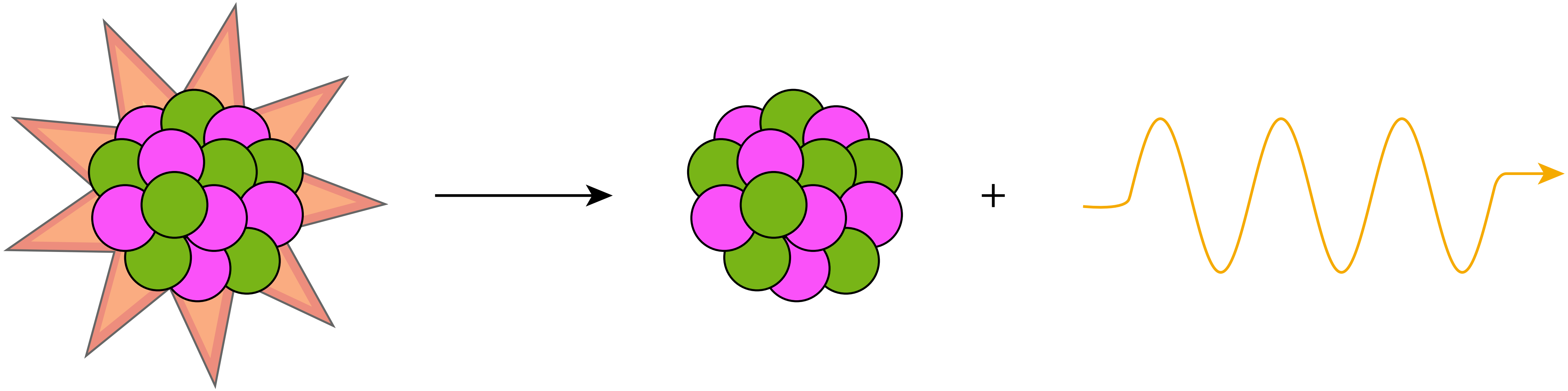
$$^{0}_{-1}\mathrm{e} + {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z-1}\mathrm{X}'$$

Radioactive Decay: Gamma Decay

In gamma decay, only gamma rays (γ) or high-energy photons are emitted.

During gamma decay, a nucleus that is in an excited state lowers its energy by emitting photons.

Since photons do not have any mass or charge, this kind of decay does not change A or Z.



The general reaction for gamma decay is as follows:

$$^{A}_{Z}X' \longrightarrow {}^{A}_{Z}X + {}^{0}_{0}\gamma$$

Reaction: Gamma Decay of an Atom

$$^{A}_{Z}\mathrm{X}' \longrightarrow {}^{A}_{Z}\mathrm{X} + {}^{0}_{0}\gamma$$

Example 5: Determining the Identity of an Emitted Particle from a Reaction Equation

Which subatomic particle (A) is emitted when the following unstable isotope of fluorine decomposes?

$$^{18}_{9}F \longrightarrow ^{17}_{8}O + A$$

A. Neutron

B. Quark

C. Electron

D. Positron

E. Proton

Example 5 (Continued)

Answer

To identify the type of particle emitted in the above reaction equation, we will have to determine the value of the mass number of the particle (A) and the charge of the particle (Z).

We will be able to figure out these out because, for nuclear reactions,

$$^{\text{total } A}_{\text{total } Z}\text{reactants} = ^{\text{total } A}_{\text{total } Z}\text{products}$$

On the reactants side of the equation, $A = 18$ for fluorine and $Z = 9$. This means the sum of $A = 18$ and the sum of $Z = 9$ for oxygen and the unknown particle on the products side.

$A = 17$ and $Z = 8$ for oxygen; both values are one less than the total value of A and Z on the reactants side. So, for the unknown particle, $A = 1$ and $Z = 1$, meaning it is a particle with a charge of 1+ and a mass number of 1.

This must be a proton; the correct answer is option E.

Radioactive Decay: Other Types

Though this is the correct form of decay for this question, it is not common for fluorine-18 to emit protons when it decays.

Instead, it usually emits positrons (particles with the same mass as an electron but opposite charge).

There are other types of radioactive decay, such as proton emission, neutron emission, and the emission of particles heavier than alpha particles, but they are far less common.

So, we will not discuss them in detail here.

Comparison between the Common Types of Radioactive Decay

The following table summarizes the common types of radioactive decay.

Type of Decay	Reaction	Change in A	Change in Z
Alpha	${}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A-4}_{Z-2}\mathrm{X}' + {}^{4}_{2}\mathrm{He}$	−4	−2
β^{-} decay	${}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z+1}\mathrm{X}' + {}^{0}_{-1}\mathrm{e}$	0	+1
Positron (β^{+}) emission	${}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z-1}\mathrm{X}' + {}^{0}_{+1}\mathrm{e}$	0	−1
Electron capture	${}^{0}_{-1}\mathrm{e} + {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z-1}\mathrm{X}'$	0	−1
Gamma	${}^{A}_{Z}\mathrm{X}' \longrightarrow {}^{A}_{Z}\mathrm{X} + {}^{0}_{0}\gamma$	0	0

The Relationship between Band of Stability and Types of Radioactive Decay

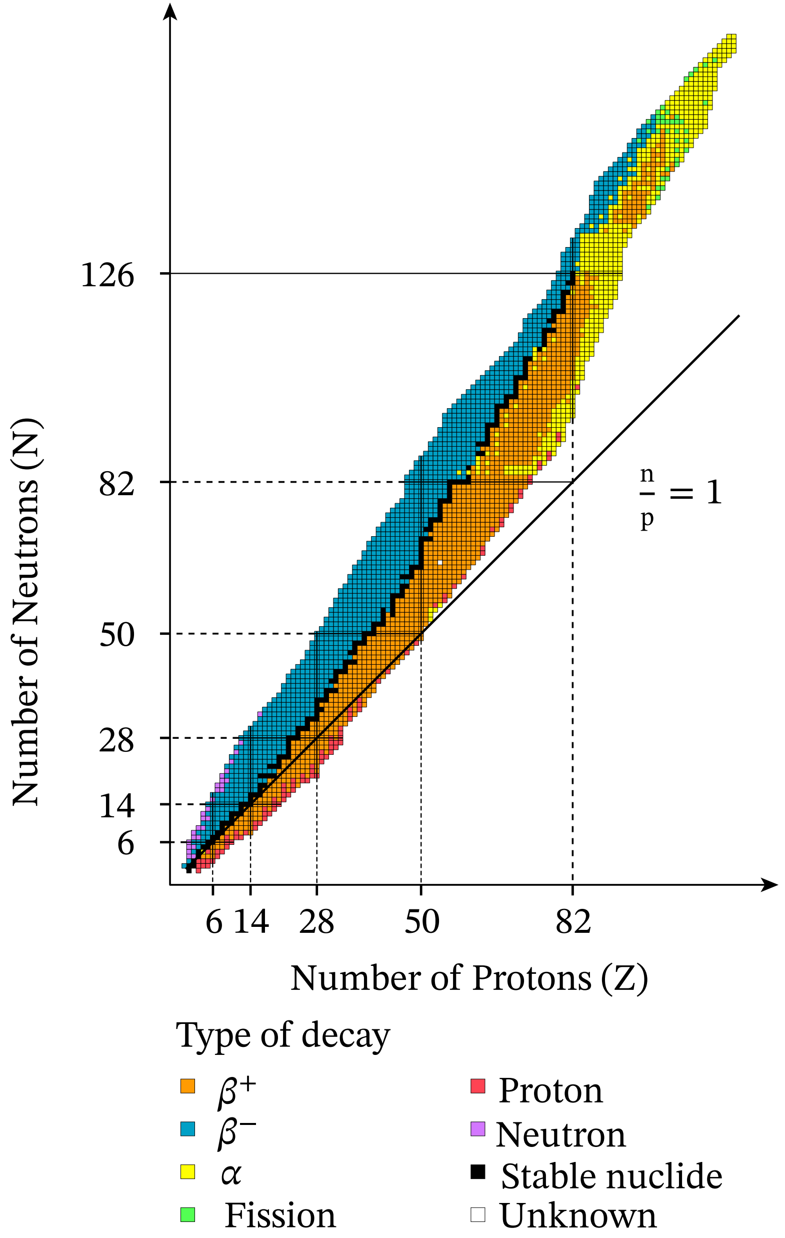
Now that we know the different types of radioactive decay, we need to determine which isotopes will undergo which kind of decay.

We can determine this with the neutron-to-proton ratio.

This information is summarized in the opposite graph.

Each region surrounding the belt of stability is color coded according to the type of decay atoms with that neutron-to-proton ratio will undergo to become stable.

If the neutron-to-proton ratio is too high, placing the isotope above the belt of stability, the atom will have too many neutrons to be stable.



The Relationship between Band of Stability and Types of Radioactive Decay (Continued)

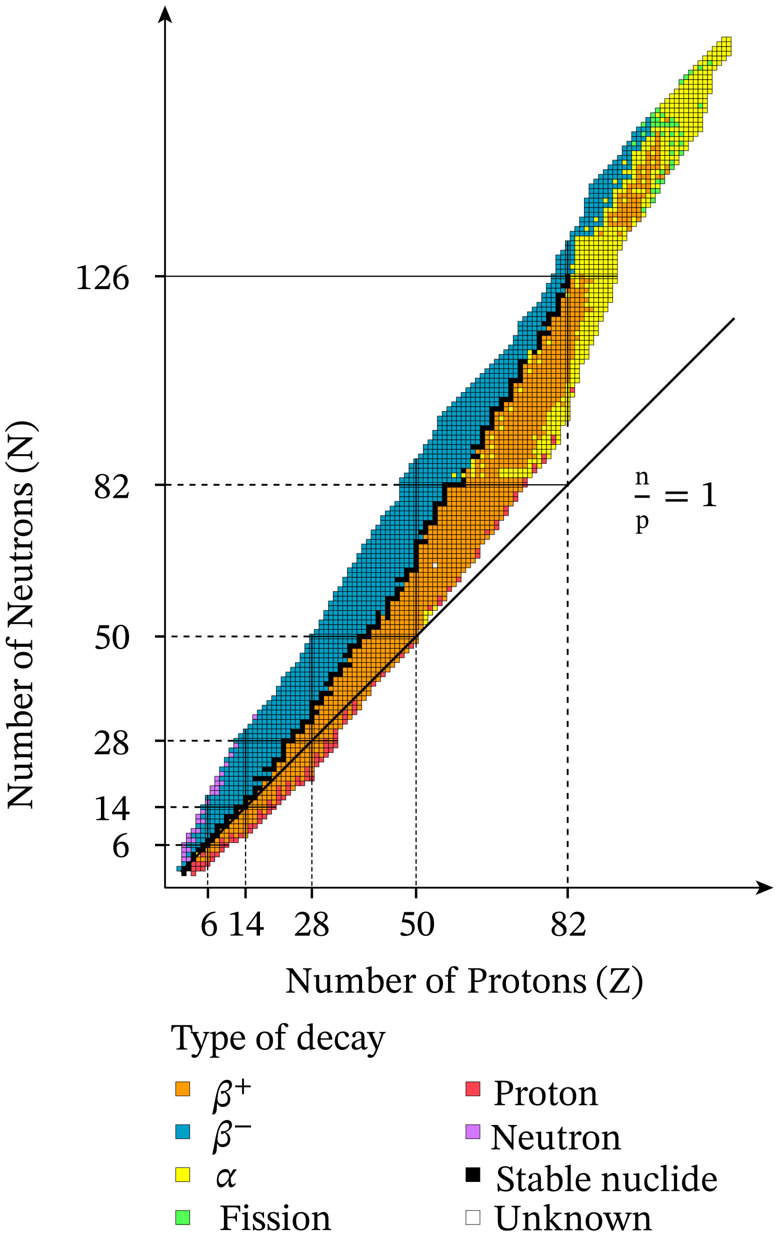
Atoms with too many neutrons to be stable will undergo β^{+} decay because β^{-} decay converts a neutron into a proton, reducing the neutron-to-proton ratio.

An example of this is carbon-14, which has a neutron-to-proton ratio of about 1 : 3.

This neutron-to-proton ratio is too low because atoms as light as carbon-14 should have a neutron-to-proton ratio closer to 1.

When carbon-14 decays by beta emission (β^{-}), it transforms into nitrogen-14, and its neutron-to-proton ratio is increased to 1:

$$^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e}$$



The Relationship between Band of Stability and Types of Radioactive Decay (Continued)

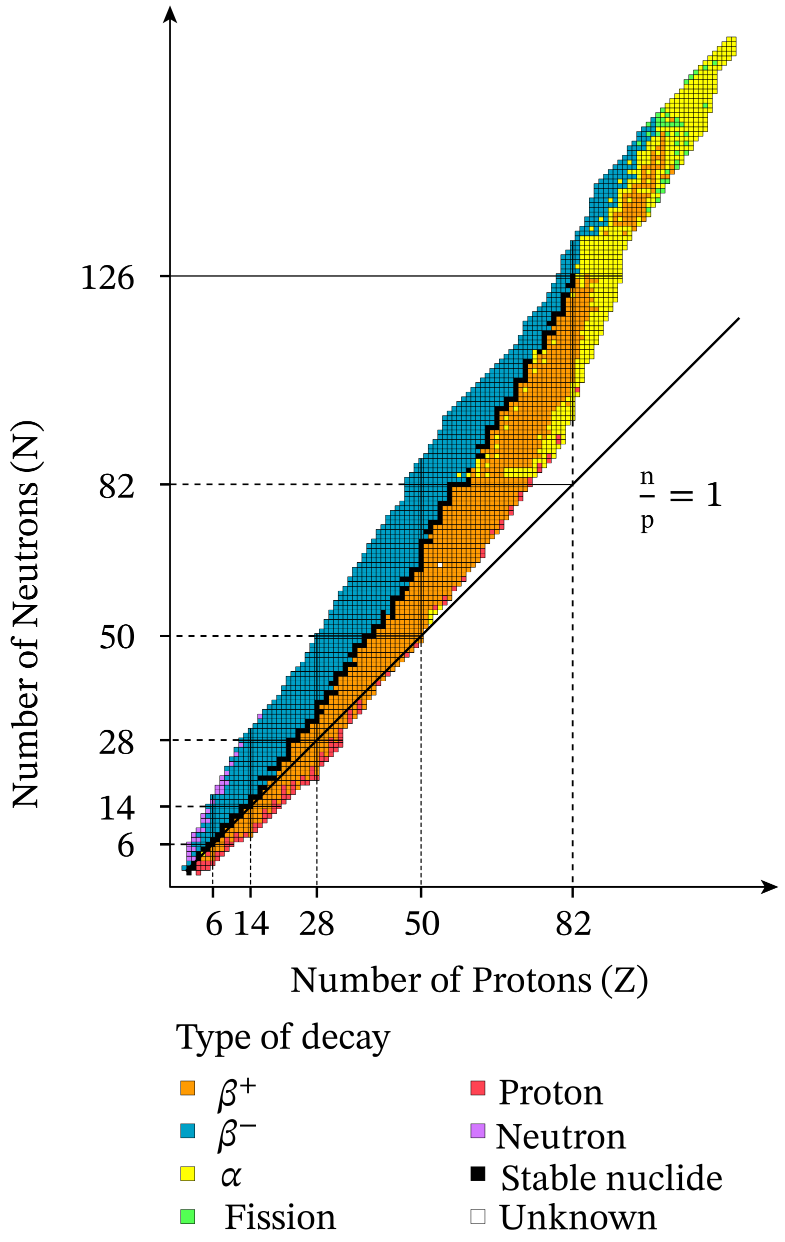
If the neutron-to-proton ratio is too low, placing the isotope below the belt of stability, the isotope will become stable through either positron (β^{-}) emission or electron capture.

This will increase the neutron-to-proton ratio since both processes convert a proton into a neutron.

Positron (β^{+}) emission is more common in lighter elements, while electron capture is more common in heavier elements.

Carbon-11 has a neutron-to-proton ratio of 0.83, which is below the belt of stability. It undergoes positron emission, converting it into boron-11 and increasing its neutron-to-proton ratio:

$$^{11}_{6}C \longrightarrow {}^{11}_{5}B + {}^{0}_{+1}e$$



The Relationship between Band of Stability and Types of Radioactive Decay (Continued)

Alpha decay typically occurs for heavier elements that have a mass number greater than about 200.

Uranium-238 is the most common isotope of uranium in nature.

This heavy nuclide undergoes alpha decay, converting it into thorium-234:

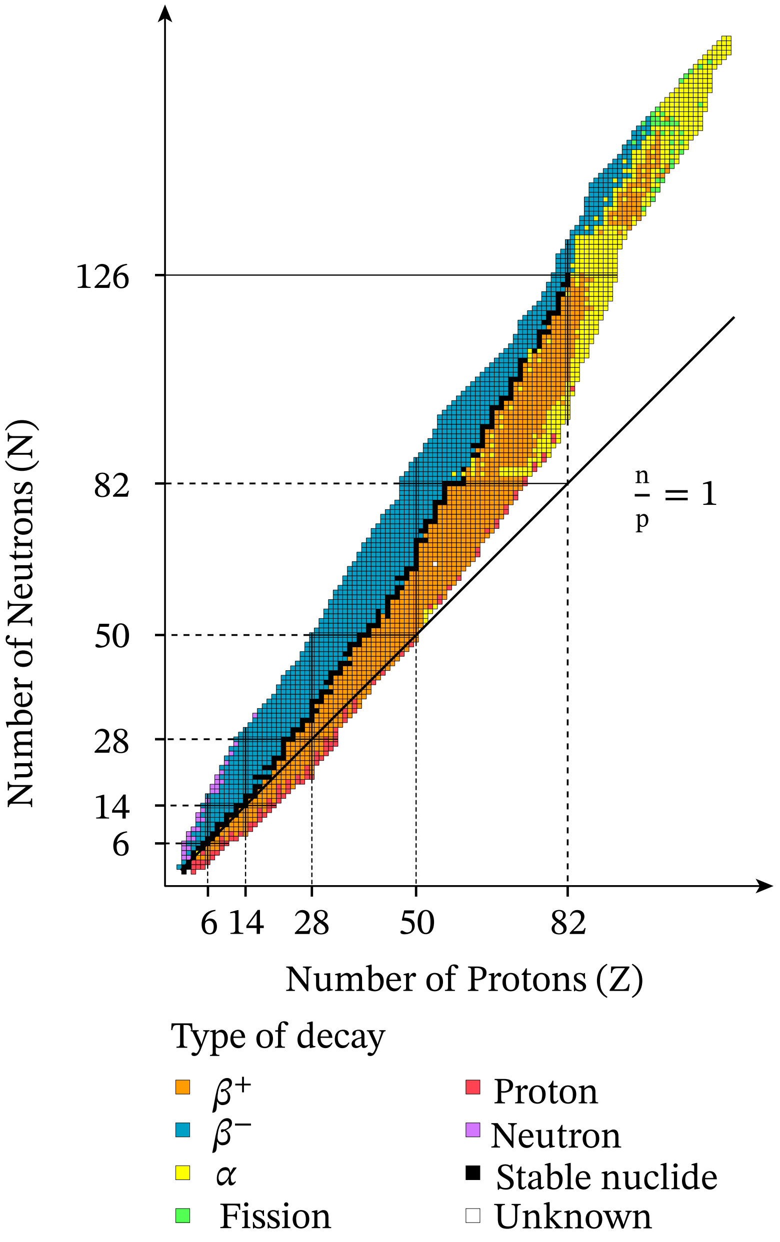
$$^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

Notice that gamma emission is not on the graph.

Gamma decay typically does not occur by itself.

Instead, it typically accompanies other kinds of radioactive decay, particularly beta decay.

Other high-energy photons, like X-rays, can be emitted during nuclear reactions as well.



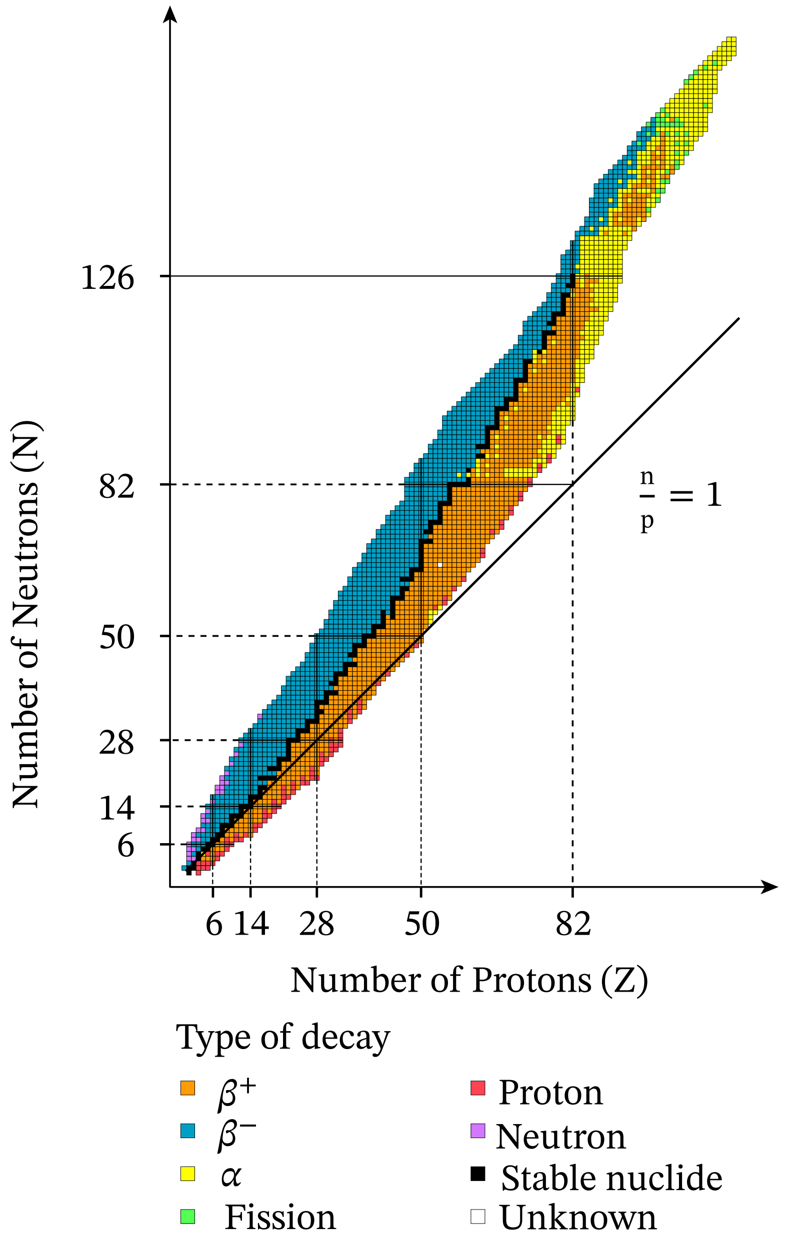
The Relationship between Band of Stability and Types of Radioactive Decay (Continued)

Energy is often emitted during nuclear reactions because the mass during a nuclear reaction is not quite constant.

There are actually tiny changes to the mass of the nuclides involved in the reaction.

As Einstein's famous equation $E = mc^2$ tells us, changes in mass, like the changes in mass during a nuclear reaction, are accompanied by a proportional change in energy.

This change in energy is emitted during a nuclear reaction as gamma rays or other photons.



Key Points

- Nuclear reactions involve changes to the nuclei of atoms and are distinct from chemical reactions.
- There are three types of nuclear reactions: fission, fusion, and transmutation.
- The total charge (Z) and the total mass (A) must be the same on each side of a nuclear reaction.
- Transmutation by radioactive decay is the spontaneous process where unstable isotopes transform into an isotope that is more stable.
- The neutron to proton ratio of isotopes can help us determine if it is unstable and which kind of decay (α, β^-, β^+, or electron capture) it will undergo to become stable.
- Transmutation by bombardment occurs when an atom is bombarded with smaller particles that combine to form a different, larger nucleus.