Radioactive Decay

Unit: Atomic, Particle, and Nuclear Physics

NGSS Standards/MA Curriculum Frameworks (2016): HS-PS1-8

AP® Physics 2 Learning Objectives/Essential Knowledge (2024): 7.C.3.1

Mastery Objective(s): (Students will be able to…)

- Explain the causes of nuclear instability.
- Explain the processes of α, $\beta-$, and $\beta+$ decay and electron capture.

Success Criteria:

- Descriptions & explanations are accurate and account for observed behavior.

Language Objectives:

- Explain what happens in each of the four types of radioactive decay.

Tier 2 Vocabulary: decay, capture

Labs, Activities & Demonstrations:

- (old) smoke detector & Geiger counter

Notes:

nuclear instability: When something is unstable, it is likely to change. If the nucleus of an atom is unstable, changes can occur that affect the number of protons and neutrons in the atom.

Note that when this happens, the nucleus ends up with a different number of protons. This causes the atom to literally turn into an atom of a different element. When this happens, the physical and chemical properties instantaneously change into the properties of the new element!

radioactive decay: the process by which the nucleus of an atom changes, transforming the element into a different element or isotope.

nuclear equation: an equation describing (through chemical symbols) what happens to an atom as it undergoes radioactive decay.

Causes of Nuclear Instability

Two of the causes of nuclear instability are:

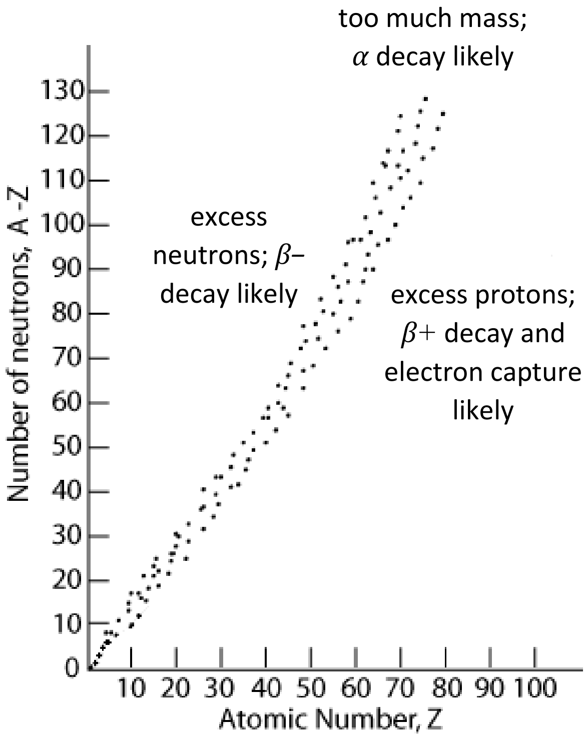
Size

Because the strong force acts over a limited distance, when nuclei get too large (more than 82 protons), it is no longer possible for the strong force to keep the nucleus together indefinitely. The form of decay that results from an atom exceeding its stable size is called alpha (α) decay.

The Weak Nuclear Force

The weak force is caused by the exchange (absorption and/or emission) of W and Z bosons. This causes a down quark to change to an up quark or vice-versa. The change of quark flavor has the effect of changing a proton to a neutron, or a neutron to a proton. (Note that the action of the weak force is the only known way of changing the flavor of a quark.) The form of decay that results from the action of the weak force is called beta (β) decay.

band of stability: isotopes with a ratio of protons to neutrons that results in a stable nucleus (one that does not spontaneously undergo radioactive decay). This observation suggests that the ratio of up to down quarks within the nucleus is somehow involved in preventing the weak force from causing quarks to change flavor.



<u>alpha (α) decay</u>: a type of radioactive decay in which the nucleus loses two protons and two neutrons (an alpha particle). An alpha particle is a ${}^{4}_{2}He^{2+}$ ion (the nucleus of a helium-4 atom), with two protons, a mass of 4 amu, and a charge of +2. For example:

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

Atoms are most likely to undergo alpha decay if they have an otherwise stable proton/neutron ratio but a large atomic number.

Alpha decay has never been observed in atoms with an atomic number less than 52 (tellurium), and is rare in elements with an atomic number less than 73 (tantalum).

<u>Net effects of α decay:</u>

- Atom loses 2 protons and 2 neutrons (atomic number goes down by 2 and mass number goes down by 4)
- An α particle (a ${}^{4}_{2}He^{+2}$ ion) is ejected from the nucleus at high speed.

<u>beta minus ($\beta-$) decay</u>: a type of radioactive decay in which a neutron is converted to a proton and the nucleus ejects a high speed electron (${}^{0}_{-1}e$).

Note that a neutron consists of one up quark and two down quarks (udd), and a proton consists of two up quarks and one down quark (uud). When $\beta-$ decay occurs, the weak force causes one of the quarks changes its flavor from down to up, which causes the neutron (uud) to change into a proton (udd). Because a proton was gained, the atomic number increases by one. However, because the proton used to be a neutron, the mass number does not change. For example:

$$ {}^{32}_{15}P \rightarrow {}^{32}_{16}S + {}^{0}_{-1}e $$

Atoms are likely to undergo $\beta-$ decay if they have too many neutrons and not enough protons to achieve a stable neutron/proton ratio. Almost all isotopes that are heavier than isotopes of the same element within the band of stability (because of the "extra" neutrons) undergo $\beta-$ decay.

<u>Net effects of $\beta-$ decay:</u>

- Atom loses 1 neutron and gains 1 proton (atomic number goes up by 1; mass number does not change)
- A $\beta-$ particle (an electron) is ejected from the nucleus at high speed.

Note that a $\beta-$ particle is assigned an atomic number of −1. *This does not mean an electron is some sort of "anti-proton".* The −1 is just used to make the equation for the number of protons work out in the nuclear equation.

<u>beta plus (β+) decay</u>: a type of radioactive decay in which a proton is converted to a neutron and the nucleus ejects a high speed antielectron (positron, ${}^{0}_{+1}e$).

With respect to the quarks, β+ decay is the opposite of β− decay When β+ decay occurs, one of the quarks changes its flavor from up to down, which changes the proton (uud) into a neutron (udd). Because a proton was lost, the atomic number decreases by one. However, because the neutron used to be a proton, the mass number does not change. For example:

$${}^{23}_{12}\text{Mg} \rightarrow {}^{23}_{11}\text{Na} + {}^{0}_{+1}e$$

Atoms are likely to undergo β+ decay if they have too many protons and not enough neutrons to achieve a stable neutron/proton ratio. Almost all isotopes that are lighter than the isotopes of the same element that fall within the band of stability ("not enough neutrons") undergo β+ decay.

<u>Net effects of β+ decay:</u>

- Atom loses 1 proton and gains 1 neutron (atomic number goes down by 1; mass number does not change)
- A β+ particle (an antielectron or positron) is ejected from the nucleus at high speed.

<u>electron capture</u> (sometimes called "K-capture"): when the nucleus of the atom "captures" an electron from the innermost shell (the K-shell) and incorporates it into the nucleus. This process is exactly the reverse of β− decay; during electron capture, a quark changes flavor from up to down, which changes a proton (uud) into a neutron (udd):

$${}^{23}_{12}\text{Mg} + {}^{0}_{-1}e \rightarrow {}^{23}_{11}\text{Na}$$

Note that β+ decay and electron capture produce the same products. Electron capture can sometimes (but not often) occur without β+ decay. However, β+ decay is <u>*always*</u> accompanied by electron capture.

Atoms are likely to undergo electron capture (and usually also β+ decay) if they have too many protons and not enough neutrons to achieve a stable neutron/proton ratio. Almost all isotopes that are lighter than the isotopes of the same element that fall within the band of stability undergo electron capture, and usually also β+ decay.

<u>Net effects of electron capture:</u>

- An electron is absorbed by the nucleus.
- Atom loses 1 proton and gains 1 neutron (atomic number goes down by 1; mass number does not change)

gamma (γ) rays: most radioactive decay produces energy. Some of that energy is emitted in the form of gamma rays, which are very high energy photons of electromagnetic radiation. (Radio waves, visible light, and X-rays are other types of electromagnetic radiation.) Because gamma rays are waves (which have no mass), they can penetrate far into substances and can do a lot of damage. Because gamma rays are not particles, emission of gamma rays does not change the composition of the nucleus.

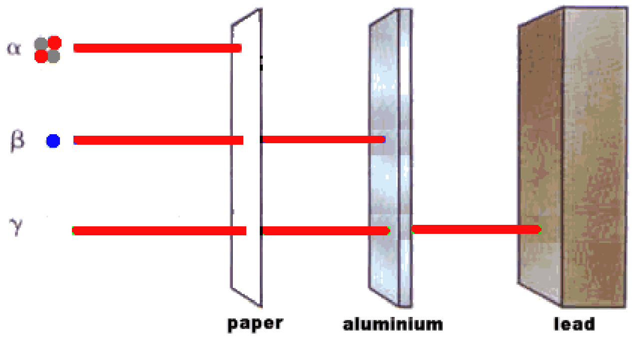
All of the types of radioactive decay mentioned in these notes also produce γ rays. This means to be complete, we would add gamma radiation to each of the radioactive decay equations described above:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He} + {}^{0}_{0}\gamma \qquad {}^{32}_{15}\text{P} \rightarrow {}^{32}_{16}\text{S} + {}^{0}_{-1}e + {}^{0}_{0}\gamma$$

$$^{23}_{12}\text{Mg} \rightarrow {}^{23}_{11}\text{Na} + {}^{0}_{+1}e + {}^{0}_{0}\gamma \qquad {}^{23}_{12}\text{Mg} + {}^{0}_{-1}e \rightarrow {}^{23}_{11}\text{Na} + {}^{0}_{0}\gamma$$

penetrating power: the distance that radioactive particles can penetrate into/through another substance is directly related to the velocity of the emission (faster = more penetrating) and inversely related to the mass of the emission (heaver = less penetrating):

gamma rays	**beta particles**	**alpha particles**
lightest	⟷	heaviest
fastest	⟷	slowest
most penetrating power	⟷	least penetrating power



Note also that denser substances (such as lead) do a better job of blocking and absorbing radioactive emissions. This is why lead is commonly used as shielding for experiments involving radioactive substances.