Name: ______________________________________ Date: ________________________

Guided Learning: Radioactivity and the Weak Force

Learning goals
After completing this activity, you will be able to …

- Explain how radioactivity was discovered.
- Describe two common types of nuclear decay: alpha decay and beta decay.
- Calculate the mass number and atomic number of a daughter atom after alpha decay or beta decay.
- Relate alpha decay to the balance of the strong force and electromagnetism.
- Relate beta decay to the weak force.

Vocabulary: alpha decay, beta decay, electromagnetism, gamma decay, gamma ray, nuclear decay, nucleon, phosphorescent, positron, quantum tunneling, quark, radioactive, strong nuclear force, uncertainty principle, weak force

Warm-up question
Some atomic nuclei are unstable and have a tendency to emit particles and/or energy. Why do you think some atoms are unstable while others are stable?

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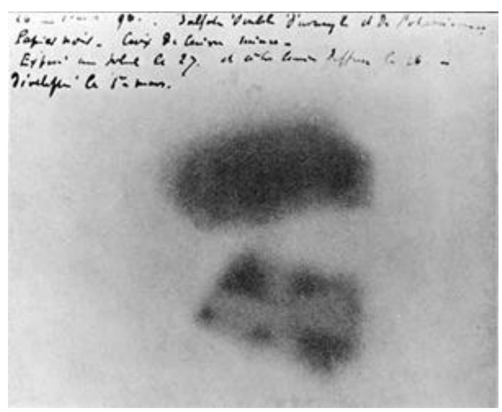
Activity A: Radioactivity
In 1896, a French physicist named Henri Becquerel conducted a series of experiments with **phosphorescent** substances, or substances that will glow in the dark after heating or exposure to sunlight. To study the phosphorescence of uranium salts, Becquerel prepared a photographic plate, wrapped the plate in opaque paper, placed uranium salts on top of the paper, and exposed it to sunlight for several hours. When he developed the plate, Becquerel discovered a blurry image of the salts on the plate. Becquerel concluded that the uranium salts must emit some sort of energy or particle that could penetrate paper and fog the plate.



The discovery of radiation: ghostly images on a photographic plate produced by uranium salts

Becquerel’s discovery led to a new field of physics, the study of **radioactive** substances. Subsequent research by such pioneers as Ernest Rutherford, Paul Villard, and Pierre and Marie Curie established other characteristics of radiation:

- Radiation is the release of particles and/or energy from unstable atomic nuclei.
- Several naturally-occurring elements are radioactive or have radioactive isotopes. These include uranium, thorium, potassium, carbon, radium, and radon.
- Nuclei emit particles and/or energy in a process called **nuclear decay**. There are several forms of nuclear decay:
    - In **alpha decay**, the nucleus emits an *alpha particle*, which consists of two protons and two neutrons.
    - In **beta decay**, the nucleus emits a *beta particle*, a high-energy electron or **positron**. (A positron is the antimatter equivalent of an electron.)
    - In **gamma decay**, the nucleus emits a **gamma ray**. Gamma rays are a type of high-frequency, high-energy electromagnetic radiation. Gamma rays have no mass and therefore do not change the composition of the nucleus. Gamma decay usually accompanies other forms of nuclear decay.
- Nuclear decay can change atoms of one element to another.
    - Alpha decay reduces the atomic number by two (because two protons are emitted) and reduces the mass number by four (two protons and two neutrons are emitted).
    - When an electron is emitted in beta decay, a neutron is transformed into a proton. This increases the atomic number by one (a proton is added) while leaving the mass number unchanged.
    - When a positron is emitted in beta decay, a proton is transformed into a neutron. This reduces the atomic number by one (a proton becomes a neutron) while leaving the mass number unchanged.

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1. What evidence did Becquerel find that uranium salts were emitting some sort of unusual particles and/or energy? ____

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2. How do alpha, beta, and gamma decay affect the composition of the nucleus?

   Alpha decay: ____

   Beta decay (electron-emitting): ______________________________

   Gamma decay: ____

3. How does gamma decay differ from alpha and beta decay? ___________________________

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4. Uranium-238 has an atomic number of 92 and a mass number of 238. It decays in several steps of alpha and beta decay before it eventually becomes stable lead-206.

   What is the atomic number and mass number a U-238 atom after one alpha decay and two electron-emitting beta decays? To solve this problem, go through the steps below.

   A. After the alpha decay: Mass number: _____ Atomic number: _____

   B. After the first beta decay: Mass number: _____ Atomic number: _____

   C. After the second beta decay: Mass number: _____ Atomic number: _____

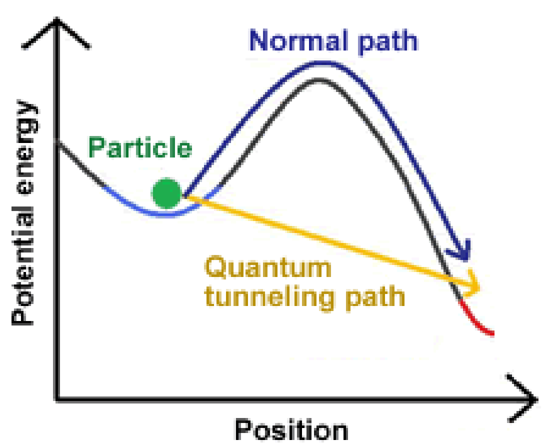
Activity B: Alpha decay

Within the nucleus of an atom, two opposing forces act on protons and neutrons: the **strong nuclear force** and **electromagnetism**. The strong nuclear force is an attractive force between protons and neutrons that bind them together inside the nucleus. As its name implies, the strong force is very powerful. However, it only operates at short distances. Electromagnetism is an attractive force between opposite charges and a repulsive force between similar charges.

Inside the nucleus, the positively-charged protons are repelled from one another by electromagnetism but held in place by the strong force, which at that distance is more powerful than electromagnetism. For most atoms, this results in a stable nucleus. However, in some cases, the geometry of the nucleus and relative numbers of protons and neutrons cause a difference between the strength of electromagnetism and the strong nuclear force. In this case, the atom may have the potential for alpha decay.

The actual occurrence of alpha decay depends on a bizarre process called **quantum tunneling**. To escape from the nucleus, the alpha particle must move far enough from the nucleus to escape the grasp of the strong nuclear force. This requires more energy than the particle has, so such an escape would seem to be impossible.

However, the **uncertainty principle** of quantum mechanics states that there is a limit to how well we can know the position and energy of any particle at any one time. Thus, even though it *seems* impossible for the alpha particle to have enough energy to escape the nucleus, there is a tiny possibility that at some point it will escape from the nucleus.



Quantum tunneling: An object tunnels through a potential energy barrier to achieve a more stable (lower energy) state.

Alpha particles are very massive compared to beta particles but do not penetrate materials very easily: they can be blocked by a layer of clothing or even a layer of dead skin cells. Alpha radiation is usually only harmful if radioactive materials, such as radon gas, are inhaled and become lodged in the lungs.

1. How does the electromagnetic force cause nuclear particles to repel one another?

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2. Why must an alpha particle move certain distance away from the nucleus before it can be emitted? ____

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Activity C: Beta decay

The second common type of nuclear decay is beta decay. Beta decay occurs if there are too many neutrons or too many protons in the nucleus. If there are too many neutrons, a neutron will transform into a proton. If there are too many protons, a proton will change into a neutron.

Quick Check:

1. In any nuclear reaction, the total charge must be conserved. That means that the total charge before the decay event is the same as the total charge after the decay event. If this is true, what type of particle must be emitted from the nucleus when a neutron turns into a proton? Explain your answer.

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2. What type of particle must be emitted from the nucleus when a proton turns into a neutron?

   Explain: ____

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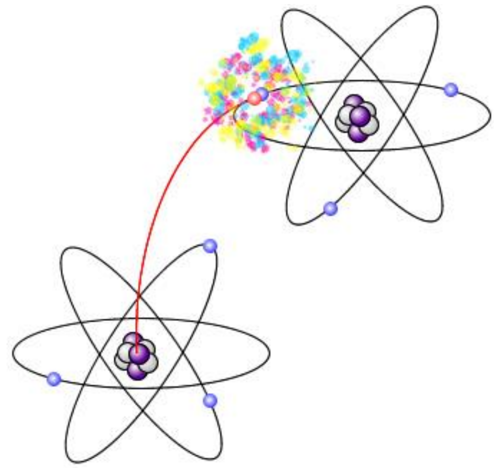
To conserve the total charge in the system during beta decay, a charged beta particle is emitted from the nucleus. When a neutron transforms into a proton, the total quantity of positive charge increases. To compensate, a negatively charged electron is emitted from the nucleus. This process is called *beta minus decay*.

If a proton transforms into a neutron, the amount of positive charge decreases. To compensate, a positively-charged particle called a positron is emitted in a process called *beta plus decay*.

Positrons are the antimatter equivalents of electrons. Like electrons, positrons have almost no mass. When a positron meets an electron, the particles annihilate one another in a burst of energy.

Beta particles (electrons and positrons) are much smaller and lighter than alpha particles. Individual beta particles have less energy than alpha particles, but are also able to travel farther and can penetrate thin materials such as clothing or skin.

Beta decay occurs because of the **weak force**, one of the four fundamental forces in nature (the others are the strong nuclear force, electromagnetism, and gravity). You will learn about the weak force in greater detail in the next section.



Annihilation occurs when a positron collides with an electron.

1. How are the processes of beta minus decay and beta plus decay related? _______________

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2. Why is beta radiation considered more dangerous than alpha radiation? _________________

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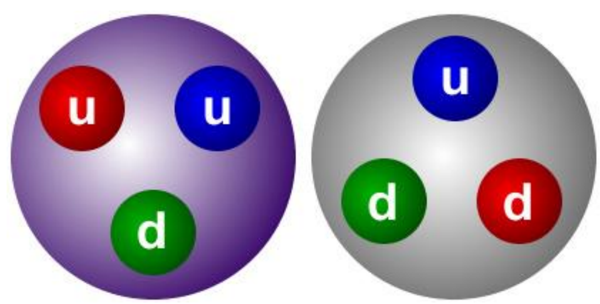
Activity D: The weak force

To understand how protons and neutrons turn into one another, it helps to know the structure of these particles. Each **nucleon**, or nuclear particle, is composed of three smaller particles called **quarks**. There are six types, or "flavors," of quarks: up, down, charm, strange, top, and bottom. Protons and neutrons are made of up and down quarks: Protons consist of two up quarks and one down quark. Neutrons consist of two down quarks and one up quark.



Protons (left) and a neutrons (right) are made of quarks (colored balls).

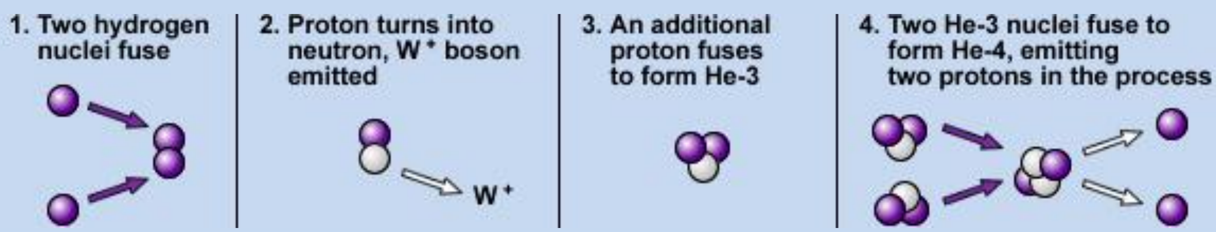
Quarks have fractional charges. The charge of an up quark is +⅔, and the charge of a down quark is –⅓. This gives protons a charge of 1^+ and neutrons no charge at all.
For a neutron to turn into a proton, a down quark must turn into an up quark. The down quark does this by emitting a particle called a W^- boson. The W^- boson is an odd particle. It is very heavy, about 80 times more massive than a proton, but only exists for a tiny period of time. After about a 3×10^{-25} seconds, the W^- boson decays into a high-energy electron and an *electron antineutrino*. The electron antineutrino is a neutral particle that has about the same mass as an electron. This event is caused by the weak force, which is also known as the *weak interaction*.

A similar, but much rarer, event occurs when a proton turns into a neutron. An “up” quark emits a W^+ boson, which then decays into a positron and an *electron neutrino*.

The existence of W^- and W^+ bosons was predicted in 1968 by Sheldon Glashow, Abdus Salam, and Steven Weinberg. They were discovered at the 1983 at CERN, the world’s most powerful particle accelerator at the time. This discovery was a major triumph for particle physics and has encouraged scientists to explore how each of the fundamental forces is related to one another. In 2008 an even larger particle accelerator, the Large Hadron Collider (LHC) opened at CERN. The main goal of the LHC is to discover the *Higgs boson*, a particle that will confirm that the electromagnetic force and the weak force are the same force at extremely high energies.

Astronomy connection

Although the weak force is the least known of all of the fundamental forces, it plays a vital role in the universe. Inside a star, hydrogen atoms are fused into helium atoms, producing vast quantities of energy. This process is called nuclear fusion. The formation of helium occurs over several steps; summarized below:



Notice that step two requires a proton to transform into a neutron, releasing a W^+ boson. This transformation occurs because of the weak force. Without this step, helium could not be produced from hydrogen and significant energy could not be produced. The humble weak force allows stars to shine and thus is a key to life on Earth as well.

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1. What must happen for a neutron to turn into a proton? ______________________________

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2. How is a W^- boson involved in beta decay? ______________________________________

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3. What natural event provides evidence that the weak force exists? ______________________

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4. How does the weak force relate to beta decay? ____________________________________

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5. How does the weak force help stars to shine? _____________________________________

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6. **Discussion question:** Why is it significant that the existence of the W bosons was predicted long before they were actually discovered?

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