Physics in the Universe: Unit 4

Nuclear Processes

Background for Teachers and Instructional Suggestions

Energy related to changes in the nuclei of atoms drives about 20% of California's electricity generation (California Energy Commission Energy Almanac 2015) (from fission in nuclear power plants), half the heat flowing upwards from Earth's interior (from the radioactive decay of unstable elements) (Gando et al. 2011), all of the energy we receive from the Sun (from nuclear fusion in its core). In this instructional segment, students will develop **models** for these processes. Students will need to apply an understanding of the internal ***structure*** of atoms and be able to read the periodic table, topics introduced in the high school chemistry class and no longer addressed at the middle grade level. If students have not yet taken high school chemistry, teachers can use nuclear processes to introduce these topics.

Changes in the nucleus occur at a length ***scale*** too small to observe directly, but students can detect **evidence** of these processes by looking at energy and matter that radiate out of the nucleus as a result of these changes. One can think of these emissions as an ***effect*** and **develop a model** that **explains** the ***cause***. Students begin the instructional segment by making observations of a cloud chamber[1] (as a video clip or classroom demonstration). Strange streaks whiz through the cloud chamber. Students can measure background radiation using a Geiger counter or even a smartphone app[2]. With these observations, students now **obtain information** about the discovery of radioactivity and how scientists in the late 1800's like Becquerel and the Curies determined that the particles they see had mass, were often charged, and emanated in high concentrations from different types of natural materials. Over time,

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[1] MIT Video, Cloud Chamber: http://video.mit.edu/watch/cloud-chamber-4058/

[2] Australian Nuclear Science and Technology Organization, Smart phone radiation detector 'app' tests positive: http://www.ansto.gov.au/AboutANSTO/MediaCentre/News/ACS049898

this understanding has led to the modern **models** of radioactivity and the modern tools for measuring its effects. These concepts can generally not be explored in direct experimentation in the classroom, so access to and **analysis of data** from external sources and use of simulations will play an important role in engaging students in three-dimensional learning.

Scientists know of only four fundamental interactions, also known as fundamental forces: gravitational, electromagnetic, strong nuclear and weak nuclear. All interactions between matter in the Universe involve one of these forces. Students studied the first two during instructional segment 2, and the focus in this instructional segment is on the effects of the remaining two. The strong force ensures the ***stability*** of ordinary matter by binding the atomic nucleus together, while the weak mediates radioactive decay. Although the strong and weak nuclear forces are essential for matter, as we know it, to exist, they are difficult to conceptualize and relate to because they operate at distances ***scales*** too small to be seen. As the nucleus gets larger, forces holding nuclei together are overcome by electrostatic repulsion, which is why the largest atoms on the periodic table are unstable. It is this instability that result in the nucleus changing in one or more ways.

The Earth receives more ***energy*** from the Sun in an hour and a half than all of humanity uses in a year, but this energy does not come from nothing. Nuclear reactions, too, must obey ***conservation*** laws, but now students must apply the principle of mass-energy equivalence ($E=mc^2$) to revise the view that matter is conserved as atoms, to a more accurate view that the number of nucleons (sum of protons and neutrons) is conserved. Neither mass, nor the number of atoms of each type are conserved in nuclear processes, and although such mass conservation “laws” are applicable to gravitational and electromagnetic processes they must be revised and refined as we examine nuclear processes, This revision and refinement process should be stressed as an essential part of the nature of science.

Nuclear ***changes*** all release large amounts of ***energy***, but they do so by different mechanisms. Scientists have recognized several classes of nuclear processes, including combining small nuclei to make larger ones (fusion) and larger nuclei emitting smaller pieces (fission, alpha decay, and beta decay). Students develop **models** to illustrate the ***changes*** in the composition of the nucleus of the atom and the ***energy*** released during each of these processes (*HS-PS1-8*). Such models could be in the form of equations or diagrams (Figure 7). Although it is not necessary to include quantitative calculations, the models should communicate the conservation of the combined mass-energy system.

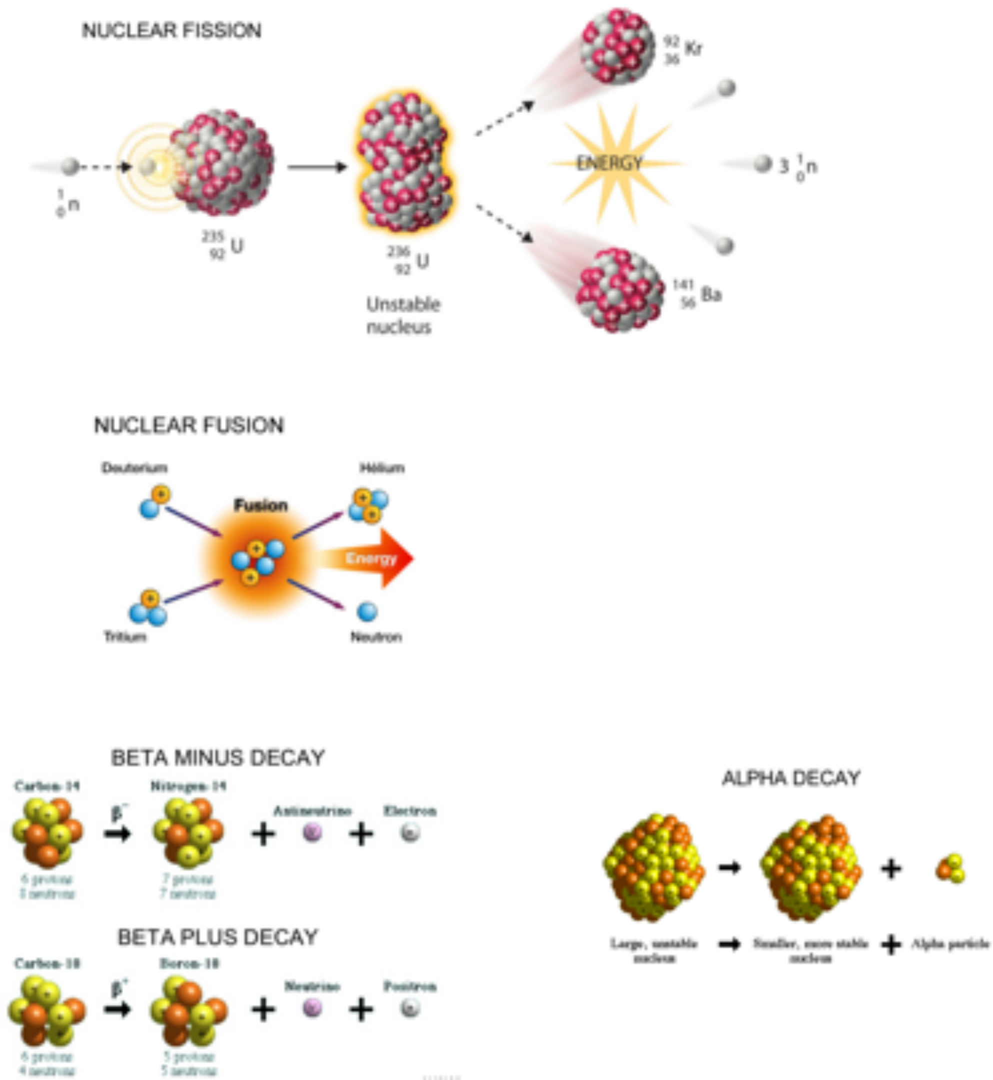

Figure 7 Students should be able to develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of

fission, fusion, and radioactive decay. (Pares Space Warp Research 2015; Thomas Jefferson National Accelerator Facility – Office of Science Education 2015)

In fusion, small nuclei combine together to form larger ones. Since all nuclei have positive charges (made only of positive protons and neutral neutrons), electrostatic forces will tend to repel nuclei apart from one another. The closer nuclei get to one another, the stronger the electrostatic repulsion. Nuclei can get very close to one another if they collide when they are moving very fast. If they manage to get close enough to one another, another interaction becomes important: the strong nuclear force which is what holds nuclei together in the first place. Like creating a new chemical bond, creating new strong force interactions releases ***energy***. Students will revisit fusion and apply their qualitative model of it to stars in instructional segment 6, since stellar cores are the only place where fusion naturally occurs. Efforts have been made to use fusion to make energy on Earth, but the engineering task is challenging. If scientists and engineers can get it to work, fusion would be cleaner and safer than just about any other known energy source and is therefore a worthwhile area of research. Even though fusion can be recreated in laboratories, a large amount of energy needs to be utilized to speed nuclei up fast enough to achieve fusion. Unless the fusion device is extremely efficient, it ends up taking more energy to start the fusion than the fusion actually releases. California hosts the most advanced fusion experiment in the world at the Lawrence Livermore National Laboratory where scientists and engineers are working daily to make breakthroughs. Students could explore an interactive computer simulation of the experiment where they adjust the speed at which atoms are accelerated until fusion is achieved, making measurements about the amount of energy used in the device and the amount of energy released by fusion.

Weak interaction processes (beta decay) should be introduced as ***changes*** in which neutrons transform into protons or protons transform to neutrons. Beta decay allows atoms to move closer to the optimal ratio of protons and neutrons, and is key to understanding why all stable nuclei have roughly equal numbers of protons and neutrons, with a few more neutrons as nuclei gets bigger. Protons have an electric charge while neutrons are neutral and have a slightly larger mass. Conservation laws dictate that the charge and extra mass cannot just appear or disappear but must come from somewhere. Applying the reasoning from conservation laws, students recognize that other subatomic particles like positrons and neutrinos must exist along with protons, neutrons, and electrons.

While beta decay involves small ***changes*** to nuclei, sometimes the competition between different forces within the nucleus cause it to spontaneously split apart to form two or more smaller nuclei. One of these smaller products is often a helium nucleus composed of two protons and two neutrons. This particle is often called an alpha particle, so this type of fission is referred to as alpha decay. The smaller nuclei require less total binding energy, so some of that energy is converted into kinetic energy causing the smaller nuclei to rapidly fly away from one another. These nuclei are also usually unstable because smaller nuclei require a different ratio of protons to neutrons in order to be stable than the original larger nucleus. These smaller nuclei will often release even more energy either undergoing beta decay or by releasing energy by gamma radiation when their component protons and neutrons rearrange to a lower (more stable) energy configuration.

Nuclear power plants rely on the release of ***energy*** from nuclear ***changes*** in uranium (and sometimes plutonium). Nuclei of these atoms are unstable and naturally decay primarily by alpha, beta, and gamma decay, but this process is very slow. Reactors extract most of their energy by inducing fission. This is accomplished primarily by separating out uranium-235 (a nucleus with 92 protons and 143 neutrons) from other forms of uranium with different numbers of neutrons. These other forms of uranium absorb neutrons, which prevents the fission process from speeding up. When fission occurs in one atom of this purer uranium, neutrons that are given off are likely to collide with other uranium atoms and induce them to fission. As a result, energy release can maintained at a rate far above the typical background level for naturally occurring concentrations of uranium. This energy is used to heat water just like other thermoelectric power plants. Students can use an online simulator to model the fission process and can be given the challenge to adjust the simulator settings to find the minimum concentration of uranium-235 required to maintain a certain energy output from fission.[3]

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[3] PhET, Nuclear Fission: https://phet.colorado.edu/en/simulation/nuclear-fission

Using Radioactive Decay to Understand Earth Processes

How old is the Earth? How long ago did human civilizations arrive in California? How long has this boulder been exposed at the Earth's surface? Practically any time scientists want to know about the age of events older than the written historical record, they turn to radioactive decay to help them find out. This section shows how students can apply their **model** of microscopic radioactive decay to answer such real-world questions. None of the PE's related to radiometric dating require that students can perform calculations of decay rates. The emphasis is instead on a qualitative model of the radiometric dating process and, more importantly, on the **analysis** of results from radiometric dating to identify ***patterns*** that provide **evidence** of processes shaping Earth's surface.

When an atom has an unstable nucleus, it will undergo decay at a random time. Different elements behave differently as the number protons and neutrons in a nucleus affects the probability that an atom will decay in a certain time period, but it is not possible to predict when any given nucleus will decay. Science usually strives to find ***cause and effect*** relationships to predict when future events will occur, but having decay being largely based on fixed probabilities means that it is not sensitive to external triggers (at least under most natural conditions). Scientists have learned to calibrate radiometric clocks by measuring the proportion of radioactively unstable atoms (often called 'parent products') to stable products that are produced following decay (so-called 'daughter products'). In a simple system of pure uranium-235 (a nucleus with 92 protons and 143 neutrons), about 50% of the atoms will have decayed after 700 million years (defined as its 'half-life'). This probability has been calculated from much shorter observations of radioactive decay in laboratories. By contrast, pure carbon-14 (a nucleus with 6 protons and 8 neutrons) decays at a much faster rate with 50% of the atoms decaying into nitrogen-14 within just 5,730 years. Students can visualize what is meant by half-life using a computer simulation[4] or classroom activity with pennies representing individual atoms that 'decay' as they flip from heads to tails[5].

Real materials on earth rarely involve pure chunks of Uranium-235, Carbon-14, or any other radioactive parent product. There are initial amounts of other types of atoms, including daughter products. Additionally, the system may not be closed and a portion of the daughter product may escape. Having 'extra' or 'missing' daughter products would affect the calculated age, if not properly recognized. Scientists have developed sophisticated tests involving comparisons of multiple parent-daughter systems to account for these issues and ensure accurate date measurements.

Scientists use these radiometric clocks to calculate the age of natural materials and learn about the past. For example, scientists have dated meteorites that have crashed into Earth's surface. These objects have compositions similar to what we expect the core of the Earth to look like, and are therefore interpreted to be pieces of other planetary objects that formed around the same time as our core. Many of these meteorites have similar ages of around 4.5-4.6 billion years and none have been found with ages older than that. Ages on the Moon are also similar, though a bit younger (4.4-4.5 billion years old). Students can use all this information as **evidence** for making a claim about the age of Earth itself and use information about the age of the Moon to construct an account of the timing and possible mechanism by which it formed (*HS-ESS1-6*). A detailed assessment task for this PE was written by the authors of NGSS as a model of how the 3-dimensional learning appears in the classroom[6].

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[4] PhET, Radioactive Dating Game: https://phet.colorado.edu/en/simulation/radioactive-dating-game

[5] Center for Nuclear Science and Technology Information of the American Nuclear Society, Half-Life : Paper, M&M's, Pennies, or Puzzle Pieces: http://www.nuclearconnect.org/in-the-classroom/for-teachers/half-life-of-paper-mms-pennies-or-puzzle-pieces

[6] Achieve, Unraveling Earth's Early History — High School Sample Classroom Task: http://www.nextgenscience.org/sites/ngss/files/HS-ESS_EarlyEarth_version2.pdf

Since Earth formed, its surface has been constantly reshaped. We know this, in part, due to evidence from radiometric dating. Plate tectonics is one process that actively moves and deforms rocks, and students **analyzed a range of data types** supporting this theory at the middle grade level (MS-ESS2-3). Now, students evaluate the theory to see if it is consistent with evidence from rock ages calculated using radiometric dating.

The oldest individual minerals in some of Earth's oldest rocks are about 4.4 billion years old, though these rocks form only a tiny fraction of the planet's surface. Few rock formations are older than even 3 billion years, and those rocks are only found on the continents. The spatial distribution of the ages of rocks on continents has complicated ***patterns***. For example, some of the oldest rocks in California are located just outside the Los Angeles area in the San Gabriel Mountains. They formed 1.8 billion years ago, they are literally touching rocks just 85 million years old, and with rocks with a range of ages in between are all located within the same mountain range. This jumble of ages is evidence of California's complicated geologic history where faults slice up rock formations and move them across the state. Some might be surprised to find that the rest of the US does not appear that much different (Figure 8). In fact, all continents show evidence of very complicated geologic histories where rocks of very different ages are mixed as continents are built up by the collision of smaller pieces and then broken back apart by later episodes of motion in a different direction.

Measurements of the seafloor age, however, are much younger (no rock being older than 280 million) years and show a clear pattern. We know that there must have been oceans older than 280 million years ago because we have found fossil marine creatures in rocks currently attached to continents that date back much older than that. So what happened to the rest of the old seafloor? A clue comes from the fact that ages typically progress in a logical order in a symmetric pattern from the middle of the ocean outwards.

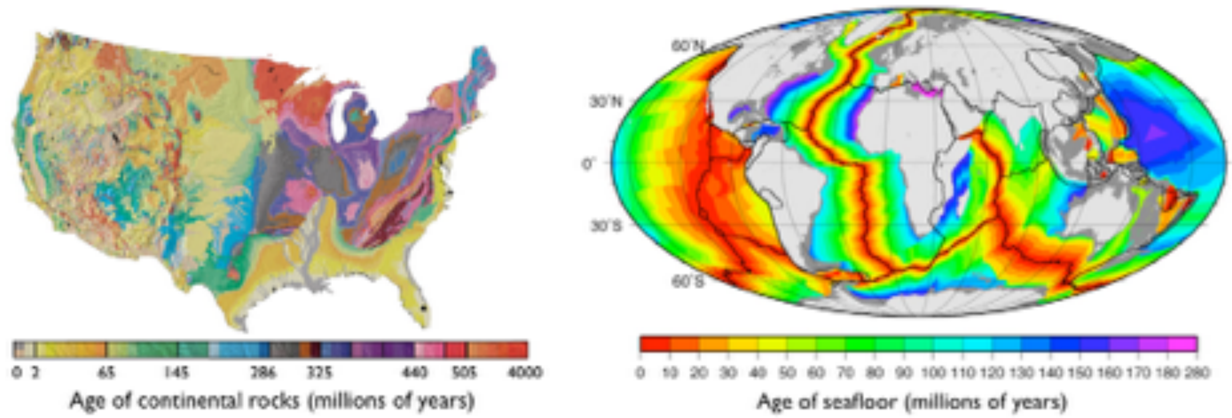

Figure 8. Map of rock ages in the continental US (left) and seafloor (right). Continental rocks are as old as 4 billion years and are a jumbled mix of ages. Seafloor rocks show a consistent pattern and are never older than 280 million years. (National Oceanic and Atmospheric Administration, National Centers for Environmental Information 2015)

Running along the center of the ocean is a band of rock with zero age. This means that there is no accumulated daughter product from radioactive decay (above the background level). How can this be when the unstable parent isotopes are present and therefore constantly decaying into the daughter products? When rock is hot, atoms can move around relatively easily and daughter products for radioactive decay can therefore escape or equilibrate with the background concentration of that element. As a rock cools, atoms are locked into their positions in crystal lattices; this is the moment when the geologic clock starts ticking. The new crust in the center of the ocean was therefore very hot in the recent past, which is evidence that it rose up from Earth's interior. As new crust is progressively forming, it also must move constantly away from middle of the ocean. Students can calculate the rate of this motion using the radiometric age dates. At the same time, older crust must therefore be sinking down (which would be expected as the crust becomes denser as it cools over time, and explains why there are no older seafloor ages).