6. Glenn Seaborg: Venturing Beyond Uranium

CHAPTER 1: The Germans Split the Uranium Atom

Alignment with the NRC's National Science Education Standards
B: Physical Science
Structure of Atoms

- The nuclear forces that hold the nucleus of an atom together, at nuclear distances, are usually stronger than the electric forces that would make it fly apart. Nuclear reactions convert a fraction of the mass of interacting particles into energy, and they can release much greater amounts of energy than atomic interactions. Fission is the splitting of a large nucleus into smaller pieces.

F: Science and Technology in Local, National, and Global Challenges

- Understanding basic concepts and principles of science and technology should precede active debate about the economics, policies, politics, and ethics of various science- and technology-related challenges. However, understanding science alone will not resolve local, national, or global challenges.

Alignment with the Next Generation Science Standards
Science and Engineering Practices
8. Obtaining, Evaluating, and Communicating Information

- Gather, read, and evaluate scientific and/or technical information from multiple authoritative sources, assessing the evidence and usefulness of each source.

Disciplinary Core Ideas

- Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process.

On a panel in the host scene, the Periodic Table fills in with all the elements Moseley predicted.

CONCEPT IN BRIEF: element

HOST

In the decades after Harry Moseley's death, chemists found all the missing elements he had left room for. By 1945, every space was filled, from the lightest element, hydrogen, to the heaviest, uranium. The Periodic Table was complete.

Except it wasn't. By this time, the next generation of element hunters had already begun a whole new chapter. They had figured how to *create new elements* – elements that didn't exist anywhere on earth.

Host steps forward to reveal photo of young Glenn Seaborg on a panel.

CONCEPT IN BRIEF: fission

EXAMPLE OF SCIENCE PRACTICE: obtaining, evaluating, and communicating information

HOST

The central character in these events was a young American chemist named Glenn Seaborg. He set out with a simple desire to make one of these new elements.

Host steps forward again. A mushroom cloud appears on a second panel.

HOST

But he would end up changing the world forever, unleashing a force of unimaginable destructive power.

Cut to barbershop scene: A young man leafs through the January 31, 1939, issue of the San Francisco Chronicle while getting his hair cut.

NARR: The story begins in late January 1939, when a young physicist in Berkeley, California, learned of a startling discovery in an unusual way.

ERIC SEABORG, partly in VO

One of my father's colleagues, Luis Alvarez, was sitting in the barber shop getting his hair cut when he read about this in the paper.

Alvarez leaps from the chair, rips off the barber's bib and runs out of the shop.

PHYSICIST LUIS ALVAREZ, partly in VO

Buried on an inside page of the *San Francisco Chronicle* was a story from Washington. German chemists had split the uranium atom by bombarding it with neutrons. I stopped the barber, mid-snip, and ran all the way to the Radiation Laboratory to spread the word.

Photo of the Rad Lab exterior

LUIS ALVAREZ VO

The first person I saw was my graduate student, Phil Abelson.

Abelson sits at the control panel of the cyclotron. We hear the sound of running footsteps.

PHIL ABELSON, partly in VO

I was at the control console operating the cyclotron. About 9:30 a.m., I heard the sound of running footsteps outside.

Alvarez bursts into the cyclotron room and blurts out the news.

LUIS ALVAREZ

Phil, the Germans have split the uranium atom! Hahn and Strassman have done it. Uranium split in two!

PHIL ABELSON

When I heard what he had read, I was stunned.

STOP AND THINK 1: What was significant about the news that chemists had split the atom?

Possible Student Answers: Students may know that this was the first time that people had caused a change to the nucleus of an atom, which is called a nuclear reaction.

EVERYDAY APPLICATION 1: Splitting the uranium atom led to the atomic bomb, nuclear power plants, and radioactive isotopes used for medical and safety applications.

Photo of Sather Gate at UC Berkeley in the 1930s

NARR: Word spread quickly across the University of California campus.

Photo of young Glenn Seaborg at Sather Gate

NARR: One of the first to hear the news was Glenn Seaborg, then a 26-year-old chemistry instructor.

ERIC SEABORG

He was just stunned, and he spent hours walking the streets of Berkeley thinking about it.

GLENN SEABORG

I was exhilarated at the discovery, but at the same time I felt stupid for having overlooked this possibility. I'd missed the chance for an astounding discovery.

CHAPTER 2: A Nobel Prize-Winning Mistake

Alignment with the NRC's National Science Education Standards

B: Physical Science

Structure of Atoms

- Matter is made of minute particles called atoms, and atoms are composed of even smaller components. These components have measurable properties, such as mass and electrical charge. Each atom has a positively charged nucleus surrounded by negatively charged electrons. The electric force between the nucleus and electrons holds the atom together.
- The atom's nucleus is composed of protons and neutrons, which are much more massive than electrons. When an element has atoms that differ in the number of neutrons, these atoms are called different isotopes of the element.
- The nuclear forces that hold the nucleus of an atom together, at nuclear distances, are usually stronger than the electric forces that would make it fly apart. Nuclear reactions convert a fraction of the mass of interacting particles into energy, and they can release much greater amounts of energy than atomic interactions. Fission is the splitting of a large nucleus into smaller pieces.

G: History and Nature of Science

Science as a Human Endeavor

- Individuals and teams have contributed and will continue to contribute to the scientific enterprise. Doing science or engineering can be as simple as an individual conducting field studies or as complex as hundreds of people working on a major scientific question or technological problem. Pursuing science as a career or as a hobby can be both fascinating and intellectually rewarding.

Nature of Scientific Knowledge

- Because all scientific ideas depend on experimental and observational confirmation, all scientific knowledge is, in principle, subject to change as new evidence becomes available. … In situations where information is still fragmentary, it is normal for scientific ideas to be incomplete, but this is also where the opportunity for making advances may be greatest.

Historical Perspectives

- Usually, changes in science occur as small modifications in extant knowledge. The daily work of science and engineering results in incremental advances in our understanding of the world and our ability to meet human needs and aspirations. Much can be learned about the internal workings of science and the nature of science from study of individual scientists, their daily work, and their efforts to advance scientific knowledge in their area of study.

Alignment with the Next Generation Science Standards

Science and Engineering Practices

1. Asking Questions and Defining Problems

- Ask questions to clarify and refine a model, an explanation, or an engineering problem.

2. Developing and Using Models
- Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.

3. Planning and Carrying Out Investigations
- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
- Select appropriate tools to collect, record, analyze, and evaluate data.

4. Analyzing and Interpreting Data
- Evaluate the impact of new data on a working explanation and/or model of a proposed process or system.

Constructing Explanations and Designing Solutions
- Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena.

8. Obtaining, Evaluating, and Communicating Information
- Construct, use, and/or present an oral and written argument or counter-arguments based on data and evidence.

Disciplinary Core Ideas
- Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects.
- Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons.
- Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process.

Crosscutting Concepts
- In nuclear processes, atoms are not conserved, but the total number of protons plus neutrons is conserved.

Host enters studio. Suspended in mid-air to his left is an animation of the atom showing only red protons in the nucleus.

CONCEPT IN BRIEF: atom

HOST

Many other had missed it too. In fact, the splitting of the atom – nuclear fission – was so unexpected that it forced scientists to rethink what they knew about the atom.

Camera pulls back to reveal a panel on which there is a photo of Rutherford's lab group. James Chadwick is highlighted when he's mentioned. The neutron appears in the nucleus.

HOST

To understand why, we need to step back a few years to 1932, when another of "Rutherford's Boys," James Chadwick, discovered the final piece of the atom: the neutron.

CU of the protons and neutrons together in the nucleus.

HOST

The neutron has almost the same mass as the proton, and they both occupy the nucleus. But the neutron is electrically neutral – hence its name.

Host reaches out and grabs a neutron from the nucleus. He throws it across the screen, and it enters a uranium nucleus.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

HOST

Right away, scientists realized this made the neutron the perfect projectile for firing at the atom. Unlike those positive alpha particles that Rutherford and his students had been using, it would not be repelled as it approached the nucleus. It could go right in.

EXAMPLE OF SCIENCE PRACTICE: developing and using models

PHYSICIST JIM GATES

You didn't have to fight the electrical repulsion to get this object to go inside the nucleus and probe the structure there.

Photo of Enrico Fermi and his colleagues at the University of Rome in the mid-1930s

CONCEPT IN BRIEF: contributions of individuals and teams to the scientific enterprise

NARR: One of the first to use the neutron in this way was an Italian physicist named Enrico Fermi.

Animation illustrating Fermi's approach: A beam of neutrons fired at a sample of uranium results in a shower of fragments.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

NARR: In 1934, Fermi began firing neutrons at uranium atoms, creating a shower of fragments he would then analyze.

In the animation, we now zoom in to the see the interaction of a single neutron with one uranium nucleus. The neutron chips off a piece of the nucleus, and we see that the nucleus has lost two protons and two neutrons, resulting in a new element. It lands in the box for element 90, thorium, in the Periodic Table below it.

CONCEPT IN BRIEF: atomic number

NARR: He found that a neutron sometimes chipped off a piece of the uranium nucleus, lowering its atomic number and turning it into a different element, a few spots lower in the Periodic Table.

Another fragment tries to land in the boxes from 82 (lead) to 91 (protactinium) but is rejected by all.

NARR: But some of Fermi's fragments didn't match any of the elements just below uranium. What could they be?

STOP AND THINK 2: How might the process of changing atomic nuclei result in new elements?

Possible Student Answers: Students may consider the fact that the number of protons in the nucleus defines an element and, so, in changing atomic nuclei, scientists might discover very rare elements or even make elements not found in nature.

Photo of Fermi, then animation showing neutron absorption as he imagined it. The white neutron turns into a red proton.

EXAMPLE OF SCIENCE PRACTICE: constructing explanations and designing solutions

NARR: Fermi concluded that sometimes an incoming neutron is *absorbed* by the uranium nucleus … and then spontaneously changes.

PHYSICIST JIM GATES

The neutron becomes a shape-shifter and changes itself into a proton!

EXAMPLE OF SCIENCE PRACTICE: obtaining, evaluating, and communicating information

In the animation, we again see one of the neutrons change into a proton. The number of protons in the nucleus ticks up to 93, forming a new element.

PHYSICIST JIM GATES VO

But when you change the number of protons in the atom, you change the chemistry. You have changed the identity of the atom.

Elements 93 and 94 (Ausonium – Ao – and Hesperium – Es) are added to the Periodic Table.

PHYSICIST DAVID KAISER, partly in VO
They eventually concluded, they published a paper saying they had found "transuranic elements" – elements that were even heavier than uranium. They figured they had pushed beyond the end of the Periodic Table.

Footage of Fermi accepting the Nobel Prize

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

NARR: For this remarkable achievement, Fermi won the Nobel Prize in December 1938. But even as he was shaking the hand of the King of Sweden, German scientists were making the discovery that would prove Fermi wrong.

Photo of grim Fermi. Push in to blackboard to reveal tiny neutron approaching huge uranium nucleus 238 times its size.

NARR: Like almost everyone else at the time, Fermi had underestimated the neutron.

PHYSICIST DAVID KAISER VO
It was very much smaller than the nucleus it was being fired at. It had no electric charge. It couldn't shove things around by electric repulsion.

Push in to part of Periodic Table Fermi hadn't checked

NARR: So Fermi's team hadn't checked to see if the neutron had broken the uranium nucleus in half, into much lighter elements.

PHYSICIST DAVID KAISER
They figured there's no way this tiny, little wimpy thing could bust apart something as huge, as massive, as an entire uranium nucleus.

GLENN SEABORG
Breaking a nucleus in two with a neutron would be like breaking a boulder in half by tossing a pebble at it. We all knew it was impossible for uranium atoms to break apart in that way.

Photo montage of Hahn, Strassman, Meitner and Frisch

NARR: But when the Germans repeated Fermi's experiments, they found that's exactly what happened.

Animation of the Hahn and Strassman discovery: Uranium nucleus splits in two like a water drop, the two fragments landing in the barium and krypton boxes of the Periodic Table.

PHYSICIST DAVID KAISER, partly in VO

They did not find things that looked heavier than uranium. They found well-known elements that were about half as heavy – much, much lower on the Periodic Table. The uranium nucleus had been split in two, in a way that no one had imagined possible or even worth looking for.

EXAMPLE OF SCIENCE PRACTICE: analyzing and interpreting data

Notes from the Field:

My students like to see examples like this, where scientists think they have everything figured out, only to make new discoveries.

CHAPTER 3: The Berkeley Cyclotron

Alignment with the NRC's National Science Education Standards

B: Physical Science

Structure of Atoms

- Matter is made of minute particles called atoms, and atoms are composed of even smaller components. These components have measurable properties, such as mass and electrical charge. Each atom has a positively charged nucleus surrounded by negatively charged electrons. The electric force between the nucleus and electrons holds the atom together.
- The atom's nucleus is composed of protons and neutrons, which are much more massive than electrons. When an element has atoms that differ in the number of neutrons, these atoms are called different isotopes of the element.
- The nuclear forces that hold the nucleus of an atom together, at nuclear distances, are usually stronger than the electric forces that would make it fly apart. Nuclear reactions convert a fraction of the mass of interacting particles into energy, and they can release much greater amounts of energy than atomic interactions. Fission is the splitting of a large nucleus into smaller pieces.

F: Science in Personal and Social Perspectives

Science and Technology in Local, National, and Global Challenges

- Science and technology are essential social enterprises, but alone they can only indicate what can happen, not what should happen. The latter involves human decisions about the use of knowledge.

G: History and Nature of Science
Nature of Scientific Knowledge

- Because all scientific ideas depend on experimental and observational confirmation, all scientific knowledge is, in principle, subject to change as new evidence becomes available. … In situations where information is still fragmentary, it is normal for scientific ideas to be incomplete, but this is also where the opportunity for making advances may be greatest.

Historical Perspectives

- Usually, changes in science occur as small modifications in extant knowledge. The daily work of science and engineering results in incremental advances in our understanding of the world and our ability to meet human needs and aspirations. Much can be learned about the internal workings of science and the nature of science from study of individual scientists, their daily work, and their efforts to advance scientific knowledge in their area of study.

Alignment with the Next Generation Science Standards
Science and Engineering Practices
1. Asking Questions and Defining Problems

- Ask questions that arise from careful observation of phenomena, or unexpected results, to clarify and/or seek additional information.

Disciplinary Core Ideas

- Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons.
- Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process.

Crosscutting Concepts

- In nuclear processes, atoms are not conserved, but the total number of protons plus neutrons is conserved.

New York Times headline: VAST ENERGY FROM URANIUM ATOM.

CONCEPT IN BRIEF: Influence of society and culture on science

NARR: The tremendous energy released when the atom split had profound implications for a world at the brink of war.

PHYSICIST DAVID KAISER, partly in VO
Across the world, physicists came to remarkably similar conclusions right away. Could the energy trapped in that nucleus be used to make an explosive unthinkably more powerful than conventional, chemical explosives?

Photo of young Seaborg in trench coat

ERIC SEABORG, partly in VO

A lot of people were thinking about the possibility of the atomic bomb. But my father, he was mostly thinking about the scientific implications.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

NARR: For Seaborg, the discovery of fission presented an unexpected opportunity – a second chance to be the first to discover elements beyond uranium.

In the Periodic Table, elements 93 and 94 disappear.

ERIC SEABORG, partly in VO

Fermi had said he had discovered all these transuranium elements. Those findings just went out the window. So if there were transuranium elements to be found, well, they were still there to be discovered.

Photo of the Berkeley campus in the 1930s

CONCEPT IN BRIEF: importance of scientific tools

NARR: And Berkeley was the perfect place to do it.

Notes from the Field:

I like to connect what was done in the 1930s to the work that continues to be done today in this field.

Photos of Lawrence and his 27-inch cyclotron

NARR: Under the leadership of Ernest Lawrence, Cal's Radiation Laboratory had led the world in the development of the cyclotron, a device for flinging subatomic particles at ever-greater speeds.

Animation of cyclotron

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

PHYSICIST JIM GATES, partly in VO

What Lawrence did was figure out that you could take a proton, or some particle that you are accelerating, and put it in a circular path, using magnetic fields to make it go in a circle.

NARR: By rapidly switching the electrical charge of the two "dees," Lawrence kept the proton chasing the ever-moving negative plate, boosting its speed on each pass.

PHYSICIST JIM GATES, partly in VO

You hit it once. When it comes around again, you hit it again, you hit it again, you hit it again. And then suddenly, you've got this really energetic tiny particle that you can then aim to your target and use it to study what's going on.

EVERYDAY APPLICATION 2: Although originally created for physics research, cyclotrons are now most often used for medical applications and are found in hospitals. Cyclotrons accelerate subatomic particles to create a beam. The beams can treat cancer directly and can also create radioisotopes that are used diagnostically in medicine. The radioisotopes are used in a technique called "positron emission tomography" (PET). A radioisotope is injected into a specific part of the body, and how much of the radioisotope accumulates is related to how well that part of the body is functioning. The radioisotope emits gamma rays, which are measured. The amount of gamma rays will show if the right amount—too much or too little of the radioisotope—has accumulated. PET is used for cancer detection, heart imaging, and brain imaging.

CHAPTER 4: The First Transuranic Element: Neptunium

Alignment with the NRC's National Science Education Standards

B: Physical Science

Structure of Atoms

- Matter is made of minute particles called atoms, and atoms are composed of even smaller components. These components have measurable properties, such as mass and electrical charge. Each atom has a positively charged nucleus surrounded by negatively charged electrons. The electric force between the nucleus and electrons holds the atom together.
- The atom's nucleus is composed of protons and neutrons, which are much more massive than electrons. When an element has atoms that differ in the number of neutrons, these atoms are called different isotopes of the element.
- The nuclear forces that hold the nucleus of an atom together, at nuclear distances, are usually stronger than the electric forces that would make it fly apart. Nuclear reactions convert a fraction of the mass of interacting particles into energy, and they can release much greater amounts of energy than atomic interactions. Fission is the splitting of a large nucleus into smaller pieces.

Structure and Properties of Matter

- An element is composed of a single type of atom. When elements are listed in order according to the number of protons (called the atomic number), repeating patterns of physical and chemical properties identify families of elements with similar properties. This "Periodic Table" is a consequence of the repeating pattern of outermost electrons and their permitted energies.

G: History and Nature of Science

Science as a Human Endeavor

- Individuals and teams have contributed and will continue to contribute to the scientific enterprise. Doing science or engineering can be as simple as an individual conducting field studies or as complex as hundreds of people working on a major scientific question or technological problem. Pursuing science as a career or as a hobby can be both fascinating and intellectually rewarding.

Nature of Scientific Knowledge

- Science distinguishes itself from other ways of knowing and from other bodies of knowledge through the use of empirical standards, logical arguments, and skepticism, as scientists strive for the best possible explanations about the natural world.
- Scientific explanations must meet certain criteria. First and foremost, they must be consistent with experimental and observational evidence about nature, and must make accurate predictions, when appropriate, about systems being studied. They should also be logical, respect the rules of evidence, be open to criticism, report methods and procedures, and make knowledge public.
- Because all scientific ideas depend on experimental and observational confirmation, all scientific knowledge is, in principle, subject to change as new evidence becomes available. … In situations where information is still fragmentary, it is normal for scientific ideas to be incomplete, but this is also where the opportunity for making advances may be greatest.

Alignment with the Next Generation Science Standards

Science and Engineering Practices

3. Planning and Carrying Out Investigations

- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
- Select appropriate tools to collect, record, analyze, and evaluate data.

6. Constructing Explanations and Designing Solutions

- Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena.
- Apply scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion.

Disciplinary Core Ideas

- Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons.
- Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process.

Crosscutting Concepts

- In nuclear processes, atoms are not conserved, but the total number of protons plus neutrons is conserved.

Photo of young Edwin McMillan

CONCEPT IN DETAIL: fission

NARR: Just weeks after the news of fission broke, a young Berkeley physicist named Ed McMillan …

McMillan enters the cyclotron room and places his sample in front of the neutron window.

NARR: … set out to study this new phenomenon. He would repeat the Germans' experiments by bombarding uranium atoms with neutrons from the cyclotron.

Back in the lab, McMillan brushes a yellow slurry onto a small piece of white filter paper and sets it aside to dry.

NARR: To prepare his target, he applied a thin layer of uranium oxide to a piece of filter paper. His goal was to split the uranium atoms and track how far the resulting fragments flew.

PHIL ABELSON

Ed started by capturing the fission products in a stack of thin foils.

McMillan makes a stack of cigarette papers.

PHIL ABELSON VO

But eventually he found that cigarette papers worked just as well.

He puts the cigarette papers on top of the now-dry filter paper target, then places them all in a small frame. We freeze it for animation. In the animation, a beam of neutrons strikes the target, sending fragments flying.

NARR: He stacked the cigarette papers behind the uranium-coated filter paper. When this target was struck with neutrons from the cyclotron, atomic fragments would scatter in all directions.

The animation now rotates to reveal the stack of papers. We separate them to show how the fragments are caught in different layers.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

NARR: Some would burrow into the stack of cigarette papers, penetrating to different depths.

McMillan loosens the frame and peels off the cigarette papers one at a time, starting with the one farthest from the filter paper. He tests each one with a Geiger counter and finds they are mildly radioactive – no surprise.

NARR: McMillan then checked the papers one at a time to see how far the radioactive fragments had traveled. As expected, he found different levels of radioactivity on each paper.

After the last cigarette paper, McMillan tests the filter paper with the Geiger counter too. To his surprise, it is much "hotter" than the cigarette papers.

NARR: The surprise came when he measured the target itself. It was much more radioactive than expected, suggesting that one product of the reaction hadn't moved at all but remained on the filter paper.

GLENN SEABORG
This lack of mobility implied that it might not be a fission product at all.

CONCEPT IN BRIEF: Scientific knowledge evolves by using new evidence to build on earlier knowledge

McMillan thinks about what his finding might mean.

NARR: As the possibilities raced through McMillan's mind, he quickly arrived at an explanation: This fragment had stayed put because it was much heavier than the others.

EXAMPLE OF SCIENCE PRACTICE: constructing explanations and designing solutions

Reprise of the Fermi animation showing an incoming neutron being absorbed into the nucleus and changing into a proton.

NARR: Instead of splitting into smaller pieces, a uranium atom had *absorbed* an incoming neutron, and then that neutron had spontaneously changed into a proton, in just the way Fermi had proposed.

ERIC SEABORG
What McMillan was seeing was what Fermi thought he was seeing.

In the animation, uranium's atomic number increases by 1, becoming element 93.

NARR: If so, this would be a brand new form of matter – the *real* element 93.

STOP AND THINK 4: Why does adding a proton to a nucleus result in a new element?

Possible Student Answers: Students should recall the fact that the number of protons in the nucleus—the atomic number—defines an element.

Abelson and McMillan at work on chemistry experiment

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

NARR: But to prove it, he would need to show that its chemistry was unlike any other element … a precaution Fermi hadn't taken. For help on this, McMillan turned to an old friend – Phil Abelson, who was back in Berkeley on a short vacation.

STOP AND THINK 5: Why did the team test the chemical properties of the sample?

Possible Student Answers: Students should recall that every substance, including elements, has unique chemical and physical properties. These properties are, therefore, used to identify substances.

CONCEPT IN BRIEF: Periodic Table

With McMillan watching over his shoulder, Abelson performs chemical tests on McMillan's activity. A white precipitate begins to fall in the tube. Abelson and McMillan shake hands in celebration.

ERIC SEABORG VO

Phil Abelson was really taken by this activity McMillan had found. And he decided he was going to follow up on it. It was certainly a very productive vacation, because it didn't take him long – really a few days – to rule out that it was any of the other elements, 92 and down.

PHIL ABELSON

We had discovered element 93.

Animation: In close-up, neptunium takes its spot in the 1940 Periodic Table, one box to the right of uranium.

NARR: They named it neptunium, because it was beyond uranium, just as the planet Neptune is beyond Uranus.

The Periodic Table turns, and we look down the bottom row of elements as new boxes are added with question marks.

NARR: With this discovery, the search for elements had entered a whole new realm. Up to now, it had been a matter of *finding* elements that already existed in nature. But from this point on, element hunters would be *creating new elements*. There was no telling how far the Periodic Table might extend.

STOP AND THINK 6: Edwin McMillan observed that when a uranium nucleus split into smaller nuclei after neutron bombardment, the nuclei shot off. However, there was little movement when a uranium nucleus absorbed a neutron and formed the nucleus of the element neptunium. What can you infer about the energy changes that take place during nuclear splitting and during nuclear absorption of a neutron?

Possible Student Answers: Students might infer that energy is released when nuclei split and is not released when nuclei add neutrons.

CHAPTER 5: War Intervenes

Alignment with the NRC's National Science Education Standards

F: Science in Personal and Social Perspectives

Science and Technology in Local, National, and Global Challenges

- Science and technology are essential social enterprises, but alone they can only indicate what can happen, not what should happen. The latter involves human decisions about the use of knowledge.
- Understanding basic concepts and principles of science and technology should precede active debate about the economics, policies, politics, and ethics of various science- and technology-related challenges. However, understanding science alone will not resolve local, national, or global challenges.
- Individuals and society must decide on proposals involving new research and the introduction of new technologies into society. Decisions involve assessment of alternatives, risks, costs, and benefits and consideration of who benefits and who suffers, who pays and gains, and what the risks are and who bears them. Students should understand the appropriateness and value of basic questions—"What can happen?"—"What are the odds?"—and ''How do scientists and engineers know what will happen?"

G: History and Nature of Science

Science as a Human Endeavor

- Scientists are influenced by societal, cultural, and personal beliefs and ways of viewing the world. Science is not separate from society but rather science is a part of society.

Photo of McMillan at blackboard

NARR: McMillan immediately set out to create element 94.

Photo of the Berkeley Faculty Club

GLENN SEABORG, partly in VO
While Ed was doing this research he lived at the Faculty Club, just down the hall from me. I kept track of his progress at breakfast, in the hallway, even in the shower.

Photo of McMillan

ERIC SEABORG VO
My father was fascinated by McMillan's search for 94, and he knew that McMillan was closing in on it. And then suddenly McMillan disappeared.

Photos of the MIT radar lab, scientists at work there

NARR: Like many other American scientists, McMillan had been called to help the country prepare for war. He had moved to the Massachusetts Institute of Technology to join the team developing radar.

ERIC SEABORG
So my father wrote to him and asked him if he could continue with this project, looking for 94 as a collaborator. And Ed McMillan very graciously said, "Yes. I would be delighted if you would do so."

GLENN SEABORG
If Ed had left for MIT just a few months later, he certainly would have been the one to find element 94. As it was, I was in the right place at the right time. It would be the discovery that changed everything for me.

Seaborg plasters yellow uranium powder onto a piece of copper plating the same size as McMillan's cigarette papers.

NARR: As a chemist, Seaborg was thrilled at the chance to create a new element. But he conducted his research with one eye on the changes that were sweeping the world.

CONCEPT IN BRIEF: contributions of individuals and teams to the scientific enterprise

CONCEPT IN BRIEF: serendipity

Notes from the Field:

I point out to my students the role that chance can play in how scientific discoveries are made and by whom.

Headlines and war footage

CONCEPT IN DETAIL: Influence of society and culture on science

NARR: In the past year, Germany had invaded Poland. France and Great Britain had declared war. Italy had sided with Germany. Fighting now raged across much of Europe and North Africa.

Photo of Einstein ca 1939

NARR: Albert Einstein, alarmed at these events and aware of Germany's head start in nuclear research …

Copy of Einstein's August 1939 letter to FDR, with key phrases highlighted

NARR: … had written to President Roosevelt, urging him to launch an American effort to create an atomic bomb powered by the fission of uranium.

CHAPTER 6: Plutonium

Alignment with the NRC's National Science Education Standards

B: Physical Science

Structure of Atoms

- Matter is made of minute particles called atoms, and atoms are composed of even smaller components. These components have measurable properties, such as mass and electrical charge. Each atom has a positively charged nucleus surrounded by negatively charged electrons. The electric force between the nucleus and electrons holds the atom together.
- The atom's nucleus is composed of protons and neutrons, which are much more massive than electrons. When an element has atoms that differ in the number of neutrons, these atoms are called different isotopes of the element.
- The nuclear forces that hold the nucleus of an atom together, at nuclear distances, are usually stronger than the electric forces that would make it fly apart. Nuclear reactions convert a fraction of the mass of interacting particles into energy, and they can release much greater amounts of energy than atomic interactions. Fission is the splitting of a large nucleus into smaller pieces.
- Radioactive isotopes are unstable and undergo spontaneous nuclear reactions, emitting particles and/or wavelike radiation. The decay of any one nucleus cannot be predicted, but a large group of identical nuclei decay at a predictable rate. This predictability can be used to estimate the age of materials that contain radioactive isotopes.

G: History and Nature of Science

Science as a Human Endeavor

- Individuals and teams have contributed and will continue to contribute to the scientific enterprise. Doing science or engineering can be as simple as an individual conducting field studies or as complex as hundreds of people working on a major scientific question or technological problem. Pursuing science as a career or as a hobby can be both fascinating and intellectually rewarding.
- Scientists are influenced by societal, cultural, and personal beliefs and ways of viewing the world. Science is not separate from society but rather science is a part of society.

Nature of Scientific Knowledge

- Because all scientific ideas depend on experimental and observational confirmation, all scientific knowledge is, in principle, subject to change as new evidence becomes available. In situations where information is still fragmentary, it is normal for scientific ideas to be incomplete, but this is also where the opportunity for making advances may be greatest.

Historical Perspectives

- Usually, changes in science occur as small modifications in extant knowledge. The daily work of science and engineering results in incremental advances in our understanding of the world and our ability to meet human needs and aspirations. Much can be learned about the internal workings of science and the nature of science from study of individual scientists, their daily work, and their efforts to advance scientific knowledge in their area of study.

Alignment with the Next Generation Science Standards

Science and Engineering Practices

1. Asking Questions and Defining Problems

- Ask questions that arise from careful observation of phenomena, or unexpected results, to clarify and/or seek additional information.

3. Planning and Carrying Out Investigations

- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
- Select appropriate tools to collect, record, analyze, and evaluate data.

6. Constructing Explanations and Designing Solutions

- Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena.

Disciplinary Core Ideas

- Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons.
- Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process.

Crosscutting Concepts

- In nuclear processes, atoms are not conserved, but the total number of protons plus neutrons is conserved.

Animation shows uranium dividing into two kinds – U-238 and U-235.

CONCEPT IN DETAIL: isotope

NARR: By now it was clear there are two very different kinds of uranium. Only one of them was easy to split.

PHYSICIST DAVID KAISER VO

The one that would do that most readily was a very unusual kind of uranium that had fewer neutrons in the nucleus, this very fissionable, potentially explosive kind of U-235.

ERIC SEABORG

But that is only about one percent of all the uranium. The much more common element is the uranium-238, but it doesn't fission.

Photo of Seaborg

CONCEPT IN BRIEF: risks associated with scientific discovery

NARR: But Seaborg realized he might be able to turn this inactive uranium into a new element that *was* capable of splitting.

CONCEPT IN DETAIL: impact of scientific and technologic progress on society

GLENN SEABORG

We knew early on that element 94 could be a big prize. If we could transform U-238 into a fissionable material, we would increase a hundredfold the amount of material usable for a bomb.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

Seaborg loads the now-dry copper plate into the same metal frame McMillan had used for his cigarette papers, then exits with it.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

NARR: With this goal in mind, Seaborg picked up where McMillan had left off.

Animation shows that U-238 absorbs a neutron, becoming Uranium 92-239, then decays to Neptunium 93-239. Next we see the further change Seaborg contemplates: 93-239 decays to 94-239 as a neutron becomes a proton.

NARR: He knew from McMillan's work that uranium bombarded with neutrons sometimes changed into neptunium. But neptunium itself was radioactive – spontaneously changing form. Could it be "shape-shifting" into element 94?

Joined by Arthur Wahl, Seaborg places the copper plate uranium sample in front of the cyclotron neutron window. They talk briefly.

CONCEPT IN BRIEF: contributions of individuals and teams to the scientific enterprise

NARR: To find out, Seaborg and graduate student Arthur Wahl used the Berkeley cyclotron to create a sample of neptunium, in the same way McMillan had.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

GLENN SEABORG (TO WAHL)

Now Arthur, what we want here is the sample directly in line. You see?

Seaborg and Wahl depart.

NARR: They would then watch for signs that neutrons inside it were changing into protons, forming element 94.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

As Seaborg watches, Wahl places a copper plate with a thin layer of dried yellow slurry atop a special detector with a toggle switch. Seaborg flips the switch, and the counter immediately begins crackling, indicating that element 93 is giving off beta particles (electrons) as neutrons in its nucleus turn into protons. Wahl moves the copper plate to a dish atop the lab shelf.

NARR: Sure enough, a special radiation detector showed that's exactly what was happening. But to be sure they had a new element, they'd need to create enough of it to test its chemistry.

Zoom to copper plate on dish. In animation, atoms decay into 94.

NARR: For that they'd have to wait for neptunium to break down, atom by atom, into what they hoped was element 94.

Seaborg and Wahl perform chemical tests in the lab late at night. Superimposed on the scene is a Periodic Table in which, one by one, all the known elements are eliminated.

NARR: After a month, Seaborg and Wahl had enough material to test. Mindful of Fermi's mistake, they painstakingly checked to make sure the product of their experiment was not an element that had already been discovered.

ERIC SEABORG VO

And it took them weeks to actually separate it from every other known element, but they were eventually successful in doing that.

As Seaborg adds drops to the liquid, it turns purple. This is what they are looking for. It shows that this substance behaves like no other known element.

NARR: The last possibility was finally eliminated late one night in February 1941.

CONCEPT IN BRIEF: use of empirical standards, logical arguments, and skepticism to form scientific explanations

In the Periodic Table graphic, the last elements to be ruled out are actinium, the 15 rare earths, and finally thorium, leaving only one possibility: Element 94. Pu takes its place alongside Neptunium.

EXAMPLE OF SCIENCE PRACTICE: constructing explanations and designing solutions

NARR: There was then no doubt. They had discovered element 94: plutonium.

Footage of Seaborg and Wahl after their discovery

GLENN SEABORG, partly in VO

We felt like shouting our discovery from the rooftops. Under normal circumstances, we would have rushed to publish our claim to the discovery of a new element.

ERIC SEABORG

But they realized that if this was a fissionable element, it was of military importance, and there was a war going on. And so they actually had to keep it secret.

CONCEPT IN DETAIL: Influence of society and culture on science

Notes from the Field:

My students were interested to hear that Seaborg's discovery had to be kept secret. This sparked an interesting conversation about how the war affected science.

Seaborg and Wahl work in the lab.

PHYSICIST DAVID KAISER, partly in VO

Maybe for the first time ever in this history of the race to find and create new elements, Seaborg was not able to just tell anyone he knew about this very exciting, new discovery. What had changed was the condition of the world.

CHAPTER 7: Could it be Used in a Bomb?

Alignment with the NRC's National Science Education Standards

B: Physical Science

Structure of Atoms

- The nuclear forces that hold the nucleus of an atom together, at nuclear distances, are usually stronger than the electric forces that would make it fly apart. Nuclear reactions convert a fraction of the mass of interacting particles into energy, and they can release much greater amounts of energy than atomic interactions. Fission is the splitting of a large nucleus into smaller pieces.
- Radioactive isotopes are unstable and undergo spontaneous nuclear reactions, emitting particles and/or wavelike radiation. The decay of any one nucleus cannot be predicted, but a large group of identical nuclei decay at a predictable rate. This predictability can be used to estimate the age of materials that contain radioactive isotopes.

F: Science in Personal and Social Perspectives

Science and Technology in Local, National, and Global Challenges

- Science and technology are essential social enterprises, but alone they can only indicate what can happen, not what should happen. The latter involves human decisions about the use of knowledge.
- Understanding basic concepts and principles of science and technology should precede active debate about the economics, policies, politics, and ethics of various science- and technology-related challenges. However, understanding science alone will not resolve local, national, or global challenges.
- Individuals and society must decide on proposals involving new research and the introduction of new technologies into society. Decisions involve assessment of alternatives, risks, costs, and benefits and consideration of who benefits and who suffers, who pays and gains, and what the risks are and who bears them. Students should understand the appropriateness and value of basic questions—"What can happen?"—"What are the odds?"—and ''How do scientists and engineers know what will happen?"

G: History and Nature of Science

Science as a Human Endeavor

- Scientists are influenced by societal, cultural, and personal beliefs and ways of viewing the world. Science is not separate from society but rather science is a part of society.

Alignment with the Next Generation Science Standards

Science and Engineering Practices

3. Planning and Carrying Out Investigations

- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
- Select appropriate tools to collect, record, analyze, and evaluate data.

4. Analyzing and Interpreting Data
- Evaluate the impact of new data on a working explanation and/or model of a proposed process or system.

Disciplinary Core Ideas
- Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons.
- Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process.

Crosscutting Concepts
- In nuclear processes, atoms are not conserved, but the total number of protons plus neutrons is conserved.

Bombing of London footage, Japanese aggression in Asia, Hitler

NARR: By now, German planes were regularly bombing English cities … Japan had entered the war … and there were reports that Adolf Hitler had launched an effort to create an atomic bomb.

CONCEPT IN BRIEF: Influence of society and culture on science

Roosevelt's response to Einstein, footage of Lyman Briggs at the blackboard at a meeting of the Uranium Committee

NARR: In response to Einstein's plea, President Roosevelt had authorized a modest research program into the possibility of a weapon fueled by the fission of uranium-235.

PHYSICIST DAVID KAISER, partly in VO

And Seaborg had realized, here is a type of material he'd made from scratch in the laboratory that might be an even more efficient fuel for that kind of weapon.

Plutonium swirls in the flask.

CONCEPT IN BRIEF: contributions of individuals and teams to the scientific enterprise

NARR: But was it? *Discovering* plutonium was just the first step.

Seaborg and Segre prepare uranium tubes for bombardment by the cyclotron. Photo of Segrè.

NARR: Seaborg would need to create much more of it to find out if this new element was capable of fission. Joining Seaborg to answer this critical question was Emilio Segrè, a Jewish physicist who had fled Italy amidst rising anti-Semitism.

Segre closes the box and places it in front of the cyclotron's neutron window. They exit.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

NARR: They placed a two-and-a-half-pound sample of uranium next to the cyclotron and bombarded it with neutrons.

Seaborg and Segrè, wearing lead-impregnated gloves and goggles, leave the chemistry lab carrying a long pole from which a lead bucket is suspended.

CONCEPT IN BRIEF: risks associated with scientific discovery

ERIC SEABORG, partly in VO

During the early work of the discovery of plutonium, they were working with very small amounts, so they were not concerned about radioactivity. But to test for the fissile nature, they had to use much larger quantities. And that meant that they had to worry about radiation exposure. They were not really set up to do that kind of work, but they had to just improvise. So they would have goggles. They would have lead-lined gloves, and they ended up using buckets on poles. On looking back on it, my father said, "Gee, you know, it really seemed primitive," although they managed to do it.

Seaborg and Segrè stand behind a concrete wall with a small hole that allows them to peer through. They use a long pole with a "gripper" on the end to pour liquid from an Erlenmeyer flask into a beaker filled with yellow powder (the "irradiated uranium" that was in the tubes exposed to the cyclotron.) Later, Seaborg cranks a centrifuge.

NARR: Seaborg and Segrè separated element 93 from the rest of the reaction products … spun it to further purify the sample … and then did it all over again.

Reprise images to suggest repeating the process

CONCEPT IN DETAIL: fission

GLENN SEABORG, partly in VO

We called it a night at 10 p.m., but we were back first thing in the morning to repeat the process – six cycles over the next three days. It was tedious work, but the hours flew by, because we knew we were on the verge of a discovery.

Seaborg holds up a centrifuge tube with a small amount of white material in the bottom.

NARR: The work was finally completed in March 1941.

Seaborg places the sediment from the centrifuge tube in a platinum dish the size of a dime. He spreads it smoothly over the dish, and Segrè squeezes a dab of Duco cement from a tube onto the sample. Seaborg labels it "A."

ERIC SEABORG, partly in VO

The results of all these separations was a very small amount of plutonium that they put on a small dish. And they actually covered it with Duco Cement so that it wouldn't go anywhere.

NARR: They labeled it Sample A.

The team enters the cyclotron room and places Sample A in front of the cyclotron.

GLENN SEABORG VO

Then came the moment of truth: Was this new element fissile? Was it a potential source of immense power?

Joe Kennedy arranges the detection device. Seaborg, Segre and Wahl gather around to listen. Seaborg says: "Okay, Joe." Joe flicks the switch. We hear the sound of fission.

GLENN SEABORG VO

We placed Sample A in the path of the cyclotron's neutrons … and had our answer almost immediately. The counter registered the unmistakable kicks of fission.

The men's faces show that this is a sobering moment.

EXAMPLE OF SCIENCE PRACTICE: analyzing and interpreting data

ERIC SEABORG, partly in VO

They knew immediately what the implications were. There was a large portion of uranium that could not be used in a bomb. What plutonium offered was a chance to turn all of that uranium 238 into a fissionable material.

PHYSICIST JIM GATES, partly in VO

Seaborg figured out how to take this uranium 238 and turn it into a new element, plutonium, which readily fissions.

CONCEPT IN BRIEF: impact of scientific and technologic progress on society

ERIC SEABORG

And that meant there could be much more material made for bombs or for use in nuclear power.

CHAPTER 8: The Atomic Bomb

Alignment with the NRC's National Science Education Standards

B: Physical Science

Structure of Atoms

- The nuclear forces that hold the nucleus of an atom together, at nuclear distances, are usually stronger than the electric forces that would make it fly apart. Nuclear reactions convert a fraction of the mass of interacting particles into energy, and they can release much greater amounts of energy than atomic interactions. Fission is the splitting of a large nucleus into smaller pieces.
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- Science and technology are essential social enterprises, but alone they can only indicate what can happen, not what should happen. The latter involves human decisions about the use of knowledge.
- Understanding basic concepts and principles of science and technology should precede active debate about the economics, policies, politics, and ethics of various science- and technology-related challenges. However, understanding science alone will not resolve local, national, or global challenges.
- Individuals and society must decide on proposals involving new research and the introduction of new technologies into society. Decisions involve assessment of alternatives, risks, costs, and benefits and consideration of who benefits and who suffers, who pays and gains, and what the risks are and who bears them. Students should understand the appropriateness and value of basic questions—"What can happen?"—"What are the odds?"—and ''How do scientists and engineers know what will happen?"

G: History and Nature of Science

Science as a Human Endeavor

- Scientists are influenced by societal, cultural, and personal beliefs and ways of viewing the world. Science is not separate from society but rather science is a part of society.

Alignment with the Next Generation Science Standards

Science and Engineering Practices

1. Asking Questions and Defining Problems

- Ask questions to clarify and refine a model, an explanation, or an engineering problem.

3. Planning and Carrying Out Investigations
- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
- Select appropriate tools to collect, record, analyze, and evaluate data.

6. Constructing Explanations and Designing Solutions
- Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena.

Disciplinary Core Ideas
- Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons.
- Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process.

Crosscutting Concepts
- In nuclear processes, atoms are not conserved, but the total number of protons plus neutrons is conserved.

Archival footage of car arriving, man entering building

CONCEPT IN BRIEF: Influence of society and culture on science

NARR: Seaborg's discovery soon came to the attention of the leaders of the nascent American effort to create an atomic bomb …

Photo of Compton, Conant and Bush together

NARR: … including physicist Arthur Compton … and Harvard president James Bryant Conant … who met in late 1941 met to discuss Seaborg's findings.

ERIC SEABORG

That lunch where they discussed the possibility of creating a bomb was on December 6, 1941.

Photo of the Faculty Club, sound of football game on the radio

ERIC SEABORG VO

The next day, my father was home at the Faculty Club, listening to a football game on the radio, when the announcer broke in.

Footage of Pearl Harbor attack and sound of radio bulletin

RADIO ANNOUNCER

We interrupt this program to bring you a special news bulletin. The Japanese have attacked Pearl Harbor, Hawaii, by air, President Roosevelt has just announced ...

GLENN SEABORG, partly in VO

Our team had already been working hard in anticipation of war. In an instant, "the day that shall live in infamy" made work on anything else seem irrelevant.

FDR declares war before Congress, to thunderous applause.

PRESIDENT ROOSEVELT

The American people, in their righteous might, will win through to absolute victory!

War headline

NARR: With America now in the war, the atom bomb effort took on a new urgency.

Photo of Compton and Vannevar Bush in deep discussion

NARR: The leaders of the effort asked Seaborg …

Footage of University of Chicago during the war

NARR: … to report to the University of Chicago, where he would spend the next four years working on the Manhattan Project.

Photo of young Seaborg and his wife

NARR: Newly married and just 30 years old, he was put in charge of a team responsible for separating plutonium from other fission products.

Fermi highlighted in group shot of Chicago scientists

NARR: The responsibility for *creating* the plutonium fell to Enrico Fermi, who had fled fascist Italy after winning the Nobel Prize.

Notes from the Field:

Seaborg’s own words about what he and other scientists felt during the war are very important. It is difficult to understand why someone would want to use science to create weapons like the atomic bomb, but this helps put it in perspective a bit more.

CONCEPT IN DETAIL: importance of scientific tools

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

Footage of Fermi at work in Chicago, paintings of the Chicago Pile 1 experiment

NARR: In an abandoned squash court under the university football stands, Fermi's team built a nuclear reactor out of wood, graphite and uranium. In a historic experiment in December 1942, "Chicago Pile 1" went critical, spitting out energy and neutrons at an ever-rising rate.

PHYSICIST DAVID KAISER

Their first-ever nuclear reactor was actually creating a self-sustaining nuclear reaction.

Animation shows how the chain reaction worked.

EXAMPLE OF SCIENCE PRACTICE: constructing explanations and designing solutions

PHYSICIST DAVID KAISER VO

Certain nuclei would split in two. That would release some neutrons as well as energy.

PHYSICIST JIM GATES, partly in VO

Those neutrons then collide with other atoms. And then you get a cascade, which we call a chain reaction.

End of animation shows the creation of plutonium.

NARR: Fermi's chain reaction not only showed an atomic bomb was possible but also provided a more efficient way to turn uranium-238 into plutonium.

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

Archival footage of Fermi

NARR: From Fermi's experiment emerged two distinct strategies for making an atomic bomb.

Archival photos of the Manhattan Project

NARR: One would seek to concentrate the tiny amount of natural uranium that could be split. The other would focus on making plutonium.

GLENN SEABORG

***Our* challenge was to find a way to separate relatively small amounts of plutonium from tons of material so intensely radioactive that no one could come near it.**

STOP AND THINK 7: What difficulties might occur when a separation process involving radioactive substance is scaled up?

Possible Student Answers: Students might suggest difficulties such as danger from radioactivity, large amounts of waste products generated, or the need to design and build new equipment to do the same process on a larger scale.

Composite image of Met Lab chemists

NARR: As the magnitude of the challenge became clear, Seaborg would recruit more than a hundred chemists to join him in the effort.

CONCEPT IN DETAIL: contributions of individuals and teams to the scientific enterprise

GLENN SEABORG

"No matter what you do with the rest of your life," I said, "nothing will be as important as your work on this project. It will change the world."

CONCEPT IN BRIEF: risks associated with scientific discovery

Photos/footage of the huge extraction plants at Hanford

CONCEPT IN BRIEF: science in personal and community health

NARR: In 1943, banking on the process Seaborg's team had developed, the U.S. government began building a huge separation plant in Hanford, Washington. Here, in buildings as long as three football fields, plutonium would be made by remote control.

CONCEPT IN DETAIL: impact of scientific and technologic progress on society

More Hanford images showing the size of the place

ERIC SEABORG, partly in VO

When my father got out there, he was just awestruck. And he couldn't believe that this element that he had discovered would result in these huge plants being built.

Archival footage of Los Alamos scientists preparing the test bomb known as "the gadget"

NARR: From Hanford came the pounds of plutonium that were needed for a bomb.

Alamogordo map with drawing of tower

NARR: On July 16, 1945, at a desert site near Alamogordo, New Mexico …

Archival footage: Bomb is hoisted into tower.

NARR: … scientists from nearby Los Alamos conducted the first test of an atomic bomb … with a weapon made from plutonium.

Footage of Trinity explosion

NARR: A blinding flash of light and a deafening explosion signaled the beginning of the nuclear age.

Continuing footage of the Alamogordo explosion, Hiroshima aftermath images

NARR: Just three weeks later, an American bomber dropped a uranium bomb on the city of Hiroshima, killing 100,000 Japanese.

Nagasaki aftermath images

NARR: Three days after that, a plutonium bomb destroyed the city of Nagasaki, finally bringing the war to an end.

STOP AND THINK 8: Some scientists supported the use of the atomic bomb and some did not. What is your opinion on the use of the atomic bomb to help end the Second World War?

Possible Student Answers: Answers will vary.

EVERYDAY APPLICATION 4: The United States is the only country to have used atomic bombs in warfare. However, it is believed that eight countries have successfully built and detonated atomic bombs and that 19,000 atomic bombs exist worldwide. To set standards relating to atomic bombs, the international community has drafted a Treaty on the Non-Proliferation of Nuclear Weapons. This treaty endeavors to both oversee and curtail further development and manufacture of atomic bombs, and to set a goal for total disarmament in the future.

CHAPTER 9: The Search for More Elements

Alignment with the NRC's National Science Education Standards

B: Physical Science

Structure of Atoms

- Matter is made of minute particles called atoms, and atoms are composed of even smaller components. These components have measurable properties, such as mass and electrical charge. Each atom has a positively charged nucleus surrounded by negatively charged electrons. The electric force between the nucleus and electrons holds the atom together.

Structure and Properties of Matter

- Atoms interact with one another by transferring or sharing electrons that are furthest from the nucleus. These outer electrons govern the chemical properties of the element.
- An element is composed of a single type of atom. When elements are listed in order according to the number of protons (called the atomic number), repeating patterns of physical and chemical properties identify families of elements with similar properties. This "Periodic Table" is a consequence of the repeating pattern of outermost electrons and their permitted energies.

G: History and Nature of Science

Nature of Scientific Knowledge

- Science distinguishes itself from other ways of knowing and from other bodies of knowledge through the use of empirical standards, logical arguments, and skepticism, as scientists strive for the best possible explanations about the natural world.
- Scientific explanations must meet certain criteria. First and foremost, they must be consistent with experimental and observational evidence about nature, and must make accurate predictions, when appropriate, about systems being studied. They should also be logical, respect the rules of evidence, be open to criticism, report methods and procedures, and make knowledge public.

Alignment with the Next Generation Science Standards

Science and Engineering Practices

1. Asking Questions and Defining Problems

- Ask questions that arise from careful observation of phenomena, or unexpected results, to clarify and/or seek additional information.

3. Planning and Carrying Out Investigations

- Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
- Select appropriate tools to collect, record, analyze, and evaluate data.

8. Obtaining, Evaluating, and Communicating Information

- Construct, use, and/or present an oral and written argument or counter-arguments based on data and evidence.

Disciplinary Core Ideas

- Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons.
- Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process.

Crosscutting Concepts

- In nuclear processes, atoms are not conserved, but the total number of protons plus neutrons is conserved.

VJ Day photo, Physical Review paper on the discovery of plutonium, finally published in 1946. CU shows names of Seaborg, McMillan, Kennedy and Wahl.

CONCEPT IN DETAIL: contributions of individuals and teams to the scientific enterprise

NARR: Only then could Seaborg reveal the discovery that had made this bomb possible.

Photo of McMillan. Photo of Seaborg accepting the Nobel Prize.

NARR: For their discovery of the first two elements beyond uranium, Ed McMillan and Glenn Seaborg won the Nobel Prize in Chemistry. But Seaborg wasn't content to rest on his laurels.

PHYSICIST DAVID KAISER

Seaborg had the ambition to create more new elements, to go beyond element 94, beyond plutonium.

Bottom-lit photo of Seaborg and other scientist over a vat

NARR: So even before the war ended, he and his Chicago team had resumed the hunt for new elements.

Sound up from the Nov. 11, 1945, edition of the radio show the Quiz Kids, including applause. Photo of Seaborg with the host and a little girl.

EXAMPLE OF SCIENCE PRACTICE: obtaining, evaluating, and communicating information

RADIO ANNOUNCER

Thank you, Bob Murphy, and good evening everyone. Well, children ...

ERIC SEABORG VO

Late in 1945 my father was on a radio program called the "Quiz Kids."

RADIO ANNOUNCER
... a most distinguished scientist, Dr. Glenn T. Seaborg.

ERIC SEABORG, partly in VO
And one of the kids asked him, as kids do, "Have you found any new elements lately?"

Photos of people listening to radio

GLENN SEABORG (ON THE RADIO)
Well yes, Dick. Recently there have been two new elements discovered – elements with atomic number 95 and 96.

ERIC SEABORG
And that's how the world came to know about americium and curium.

Photo of Albert Ghiorso with Seaborg

NARR: Back at Berkeley after the war, Seaborg and his team continued their quest …

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

Animation: An alpha particle is fired at an americium atom. It fuses to form berkelium.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

NARR: … bombarding heavy elements with smaller ones in hopes they would fuse to form a brand new type of matter.

Photo of Seaborg at blackboard with list of elements ending in berkelium and californium

CONCEPT IN DETAIL: Periodic Table

NARR: They created five new elements in the next ten years, including berkelium and californium …

Animation: The elements from 89 to 92 move to a new position below the lanthanides at the bottom of the table.

NARR: … and rearranged the Periodic Table in the process.

Photo of Seaborg and McMillan. The transuranic elements are highlighted in the modern Periodic Table.

NARR: Since Seaborg and McMillan first ventured beyond uranium, more than 25 new entries have been added to the table …

Pictures of these pioneers appear in the table in their element boxes.

NARR: … including elements named for Lawrence … Mendeleev … Fermi … Einstein … Curie … Rutherford …

Photo of Seaborg pointing to his element 106, seaborgium

NARR: … and Seaborg himself.

CHAPTER 10: The Search Continues

Alignment with the NRC's National Science Education Standards

B: Physical Science

Structure of Atoms

- Matter is made of minute particles called atoms, and atoms are composed of even smaller components. These components have measurable properties, such as mass and electrical charge. Each atom has a positively charged nucleus surrounded by negatively charged electrons. The electric force between the nucleus and electrons holds the atom together.

Structure and Properties of Matter

- Atoms interact with one another by transferring or sharing electrons that are furthest from the nucleus. These outer electrons govern the chemical properties of the element.
- An element is composed of a single type of atom. When elements are listed in order according to the number of protons (called the atomic number), repeating patterns of physical and chemical properties identify families of elements with similar properties. This "Periodic Table" is a consequence of the repeating pattern of outermost electrons and their permitted energies.

G: History and Nature of Science

Nature of Scientific Knowledge

- Science distinguishes itself from other ways of knowing and from other bodies of knowledge through the use of empirical standards, logical arguments, and skepticism, as scientists strive for the best possible explanations about the natural world.
- Scientific explanations must meet certain criteria. First and foremost, they must be consistent with experimental and observational evidence about nature, and must make accurate predictions, when appropriate, about systems being studied. They should also be logical, respect the rules of evidence, be open to criticism, report methods and procedures, and make knowledge public.

Alignment with the Next Generation Science Standards
Science and Engineering Practices
1. Asking Questions and Defining Problems
   - Ask questions that arise from careful observation of phenomena, or unexpected results, to clarify and/or seek additional information.

2. Developing and Using Models
   - Develop, revise, and/or use a model based on evidence to illustrate and/or predict the relationships between systems or between components of a system.

3. Planning and Carrying Out Investigations
   - Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, cost, risk, time), and refine the design accordingly.
   - Select appropriate tools to collect, record, analyze, and evaluate data.

Disciplinary Core Ideas
- The periodic table orders elements horizontally by the number of protons in the atom's nucleus and places those with similar chemical properties in columns. The repeating patterns of this table reflect patterns of outer electron states.
- Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons.

Photo montage of modern element hunters

CONCEPT IN BRIEF: Scientific knowledge evolves by using new evidence to build on earlier knowledge

NARR: Around the world today, others continue to hunt for new elements, using techniques like those Seaborg pioneered.

EXAMPLE OF SCIENCE PRACTICE: planning and carrying out investigations

Wide shot of the Periodic Table. From their boxes, four elements emerge to fill four circles: potassium explodes/oxygen burns brightly/phosphorus glows in its vessel/radium glows in the dark.

NARR: So far there are 118 known elements, each with its own distinct personality. And yet all these elements – and any new ones we might find – are made up of just a few things in combination.

CONCEPT IN DETAIL: Element

The Greek element animation fills the four circles, then dissolves to reveal the structure of the atom.

CONCEPT IN DETAIL: atom

NARR: Not air, water, earth and fire, as the ancient Greeks believed ... but protons, neutrons and electrons.

EXAMPLE OF SCIENCE PRACTICE: developing

The three particles appear in front of the host.

and using models

HOST

Amazingly, all of matter – planets and stars, plants and animals, you and me – it's all made of just these three basic parts – protons, neutrons and electrons – mixed in different ratios.

Reprise images from the series, featuring the seven major characters

EXAMPLE OF SCIENCE PRACTICE: asking questions and defining problems

NARR: We know all of this because of a long chain of people who've struggled to answer the simple question: What is the world made of?

CHEMIST GREG PETSKO, partly in VO

We're surrounded by matter. It's everything that we see and interact with. And yet, at the time this quest began, nobody understood what it was made of. Nobody understood anything about it.

HISTORIAN LARRY PRINCIPE, partly in VO

Just making one tiny step in the understanding of the natural world sometimes takes generations. There's no guide book to tell us how to do this. We have to figure it out.

AUTHOR RICHARD HOLMES, partly in VO

Nature is wonderful and mysterious, and it's hidden. But if you apply the tools of science, you can make it reveal its secrets.

Photos of the seven main characters are arrayed on panels behind the host as he walks.

HOST

It's taken centuries just to identify the elements, with each generation of scientists building on the work of those who came before. But this is just the first step.

Still to be answered are myriad questions about how these building blocks fit together to make the infinite variety of substances in nature – and how *we* can combine them in novel ways to make fantastic new materials nature never imagined. Answering those questions will take the efforts of many more scientific detectives like the ones we've met. As much as we've learned in the search for the elements, we've only begun to solve the mystery of matter.

ANNOUNCER: Major funding for *The Mystery of Matter: Search for the Elements* was provided by the National Science Foundation, where discoveries begin. Additional funding provided by the Arthur Vining Davis Foundations – dedicated to strengthening America's future through education. And by the following.

Production Credits/Web tag/DVD offer

ANNOUNCER: To learn more about the search for the elements and watch bonus videos on the featured scientists, visit pbs.org/mystery of matter. *The Mystery of Matter: Search for the Elements* is available on DVD. To order, visit ShopPBS.org or call 1-800-PLAY-PBS.

Banner: More from The Mystery of Matter

Photos of Seaborg and his colleagues, ending with Seaborg pointing to element 106 in the Periodic Table.

ERIC SEABORG, partly in VO

The team that discovered element 106 was trying to decide what to name this element. And they went through a long list of names until one day Al Ghiorso walked into my father's office and said, "What would you think of naming it seaborgium?" And my father was just dumbfounded and thrilled. And he said this would be the greatest honor he'd ever received, because it would be forever. As long as there were Periodic Tables, there would be seaborgium.

ACTIVITY IDEAS

Neutrons in Radioactive Isotopes

Isotopes with an odd number of neutrons are often more unstable and are, therefore, radioactive. The following table contains a list of all the known radioisotopes—radioactive isotopes—with their atomic number and mass number. Have students work in groups to calculate the number of neutrons in each radioisotope by subtracting the atomic number from the mass number. What do the results show? What patterns do students see that are related to the number of neutrons?

Table: Radioactive Isotopes

Element	Atomic #	Mass #	Element	Atomic #	Mass #	Element	Atomic #	Mass #
Hydrogen (H)	1	3	Niobium (Nb)	41	95	Polonium (Po)	84	210
Beryllium (Be)	4	7	Molybdenum (Mo)	42	93	Radon (Rn)	86	220
Beryllium (Be)	4	8	Technetium (Tc)	43	99	Radon (Rn)	86	222
Beryllium (Be)	4	10	Ruthenium (Ru)	44	103	Radium (Ra)	88	224
Carbon (C)	6	14	Ruthenium (Ru)	44	106	Radium (Ra)	88	225
Calcium (Ca)	20	41	Palladium (Pd)	46	107	Radium (Ra)	88	226
Calcium (Ca)	20	46	Silver (Ag)	47	111	Thorium (Th)	90	228
Calcium (Ca)	20	48	Tin (Sn)	50	126	Thorium (Th)	90	229
Iron (Fe)	26	54	Antimony (Sb)	51	125	Thorium (Th)	90	230
Iron (Fe)	26	55	Tellurium (Te)	52	127	Thorium (Th)	90	232
Iron (Fe)	26	59	Tellurium (Te)	52	129	Thorium (Th)	90	234
Iron (Fe)	26	60	Iodine (I)	53	123	Proactinium (Pa)	91	234
Cobalt (Co)	27	56	Iodine (I)	53	129	Uranium (U)	92	233
Cobalt (Co)	27	57	Iodine (I)	53	131	Uranium (U)	92	234
Cobalt (Co)	27	58	Xenon (Xe)	54	125	Uranium (U)	92	235
Cobalt (Co)	27	60	Xenon (Xe)	54	127	Uranium (U)	92	236
Nickel (Ni)	28	59	Xenon (Xe)	54	133	Uranium (U)	92	238
Nickel (Ni)	28	63	Cesium (Cs)	55	134	Neptunium (Np)	93	237
Zinc (Zn)	30	65	Cesium (Cs)	55	135	Plutonium (Pu)	94	238
Zinc (Zn)	30	72	Cesium (Cs)	55	137	Plutonium (Pu)	94	239
Selenium (Se)	34	79	Cerium (Ce)	58	144	Plutonium (Pu)	94	240
Selenium (Se)	34	82	Promethium (Pm)	61	147	Plutonium (Pu)	94	241
Krypton (Kr)	36	85	Europium (Eu)	63	154	Plutonium (Pu)	94	242
Rubidium (Rb)	37	87	Europium (Eu)	63	155	Plutonium (Pu)	94	244
Strontium (Sr)	38	89	Iridium (Ir)	77	188	Americium (Am)	95	241
Strontium (Sr)	38	90	Iridium (Ir)	77	189	Americium (Am)	95	242
Yttrium (Y)	39	90	Iridium (Ir)	77	190	Americium (Am)	95	243
Yttrium (Y)	39	91	Iridium (Ir)	77	192	Curium (Cm)	96	242
Zirconium (Zr)	40	93	Iridium (Ir)	77	193	Curium (Cm)	96	243
Zirconium (Zr)	40	94	Iridium (Ir)	77	194	Curium (Cm)	96	244
Zirconium (Zr)	40	96	Lead (Pb)	82	210	Curium (Cm)	96	247
Niobium (Nb)	41	93	Bismuth (Bi)	83	210			

Source: http://www.buzzle.com/articles/list-of-radioactive-elements.html

Radioactive Decay Series

When a radioisotope decays, very often the new element is also a radioisotope, which in turns decays into a third radioisotope, and so on. This sequence of decay events is called a radioactive decay series. The ending point of the series is an isotope that is not radioactive. Explain radioactive decay series to students, and present one of the decay series presented in a fact sheet from the Argonne National Laboratory, *Natural Decay Series: Uranium, Radium, and Thorium*. Then review how to write nuclear reactions with students and have them write nuclear reactions about some or all of the steps in a decay series.

Download fact sheet at http://www.ead.anl.gov/pub/doc/natural-decay-series.pdf.http://gonuke.org/ComprehensiveTeachingToolkits/Radiation%20Protection/ChSCC_RP/Columbia%20Basin%20RPT-111/Supplementary%20materials/natural-decay-series.pdf

TEACHER NOTES

IN-DEPTH INVESTIGATION: NUCLEAR POWER

Context

The work done by Seaborg and others in splitting the atom allowed people to harness the energy that holds large atoms together. Initially, energy produced by fission was used as a weapon of war. Currently, nuclear power plants harness the energy produced by fission to generate electricity. Because of the deadly nature of uncontrolled fission, the use of nuclear power plants is controversial.

Overview

Students read about nuclear power plants and their pros and cons. Students then participate in a Take-A-Stand activity in which they share their own points of view about whether people should continue or end the use of nuclear power plants.

Next Generation Science Standards Alignment

Science and Engineering Practices

7. Engaging in Argument from Evidence

- Compare and evaluate competing arguments in light of currently accepted explanations and new evidence.

Disciplinary Core Ideas

- All forms of energy production and other resource extraction have associated economic, social, environmental, and geopolitical costs and risks as well as benefits. New technologies and social regulations can change the balance of these factors.
- When evaluating solutions, it is important to take into account a range of constraints, including cost, safety, reliability, and aesthetics, and to consider social, cultural, and environmental impacts.
- Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process.

Performance Expectations

- HS-ESS3-2: Evaluate competing design solutions for developing energy resources based on cost-benefit ratios.

Understanding Goals

Students should understand:

- Isotopes are atoms of an element that have differing numbers of neutrons.
- Nuclear reactions are reactions in which the nuclei of atoms are changed.
- Fission is a type of nuclear reaction in which a nucleus splits to form smaller nuclei.
- The nuclear force is much stronger than the electric force and, therefore, huge amounts of energy are released when an unstable nucleus undergoes fission.
- A nuclear fuel is a radioactive isotope that will split—undergo fission—when bombarded by neutrons.
- Nuclear power plants use the energy released by the fission of a nuclear fuel to heat water into steam, which turns a turbine and generates electricity.
- A nuclear chain reaction is fission of a nuclear fuel that can continue on its own after initial bombardment of the fuel by neutrons. The reaction continues because the initial fission of atoms of the nuclear fuel releases additional neutrons that bombard neighboring atoms.

- Under normal operating conditions, nuclear power plants release very little radiation and no harmful gases (e.g., greenhouse gases and gases that lead to acid rain). The plant does generate nuclear waste, which is stored in tightly sealed containers.
- When a nuclear power plant or stored nuclear waste containers malfunction or are damaged in a natural disaster, the nuclear power plant or waste containers may release very high levels of radiation, which can result in death, radiation sickness, cancers, and genetic damage.
- Sources of energy that do not release carbon dioxide are being reexamined due to the evidence that global warming is caused by the release of carbon dioxide from the burning of fossil fuels.
- Understanding basic concepts and principles of science and technology should precede active debate about the economics, policies, politics, and ethics of various science- and technology-related challenges.
- Individuals and society must decide on the introduction of technologies into society. Decisions involve assessment of alternatives, risks, and costs and benefits, and consideration of who benefits and who suffers, who pays and gains, and what the risks are and who bears them.
- To solve the world's energy problems, people must improve on and create new energy technologies.

Student Materials

You will find on the following pages a reading and an activity for students.

Activity Facilitation

- Decide if you want students to work on their evaluation of pros and cons individually or in groups.
- Review the pros and cons.
- After students have finished their reports but before they participate in the Take-A-Stand, have students share their decisions and reasoning verbally or in a poster.

Activity Rubric

Criteria	Not evident	Limited	Developing	Competent	Accomplished
Decisions about the use of nuclear power plants should relate to risks, benefits, and costs	Did not make a decision	Made a decision but did not evaluate risks, benefits, and costs	Made a decision and evaluated risks, benefits, and costs, but explanation of how decision related to risks, benefits, and costs was not clear	Made a decision and evaluated risks, benefits, and costs, and explanation of how decision related to risks, benefits, and costs was somewhat clear	Made a decision and evaluated risks, benefits, and costs, and explanation of how decision related to risks, benefits, and costs was completely clear
Productively participated in Take-a-Stand discussion	Did not participate in discussion	Participated in discussion but did not present an argument	Participated in discussion and presented an argument, but the argument was not persuasive	Participated in discussion and presented an argument, and the argument was somewhat persuasive	Participated in discussion and presented an argument, and the argument was very persuasive

IN-DEPTH INVESTIGATION: NUCLEAR POWER

READING: Electricity from the Atom?

The work done by Seaborg and others in splitting the atom allowed people to harness the energy that holds large atoms together. Nuclear power plants use this energy to generate electricity. Currently, nuclear power plants provide 13.5% of the world's electricity.

The Operation of Nuclear Power Plants

The structure that provides energy in a nuclear power plant is a nuclear reactor**.** This structure controls a nuclear reaction, which are reactions in which the nuclei of atoms are changed. The splitting of an atom—called fission—is an example of a nuclear reaction. Nuclear power plants use the energy released by fission to heat water into steam, which turns a turbine and generates electricity.

Nuclear reactors use a nuclear fuel. A nuclear fuel is a specific isotope of an element whose nucleus will split when bombarded with neutrons. (Recall that isotopes are atoms of an element that have differing numbers of neutrons.) There are only a few isotopes that can be used as nuclear fuel. All nuclear fuels are actinides—these are metallic elements with atomic numbers 89 through 103. Additionally, most nuclear fuels are isotopes that have an even number of protons and an odd number of neutrons.

The most common nuclear fuel is uranium-235. The number 235 is the mass number of a specific isotope of uranium. Uranium-235 is relatively rare when compared to the most common isotope of uranium, uranium-238.

The nuclear fuel is placed inside the reactor vessel and is bombarded with neutrons. If the fuel used is uranium-235, the neutrons cause fission of some of the uranium-235 atoms. A large amount of energy in the form of heat and additional neutrons is released by the fission nuclear reaction. Because the additional neutrons cause more fission of some of the uranium-235 atoms, this kind of reaction is called a chain reaction. The nuclear reactor contains rods that absorb some of the neutrons to ensure that the reaction does not proceed too quickly.

The main components of a nuclear power plant are:

- the core, which contains the nuclear reactor
- the coolant, which transfers the heat from the nuclear reaction to the turbine
- the turbine, which generates electric energy
- the containment structure, which keeps the reactor separate from the environment

The Science Behind Nuclear Power Plants

The energy used in nuclear power plants is the energy released by the fission of a (relatively) small number of atoms. Where does this energy come from? The answer relates to the forces involved. The forces that hold the nuclei of atoms together are immense—much, much greater than gravitational, electric, and magnetic forces. Therefore, nuclei have huge amounts of nuclear potential energy associated with them.

Typically, large nuclei are less stable than smaller nuclei and require more energy to hold them together. When an unstable nucleus undergoes fission to form two smaller, more stable nuclei, the difference in energy between the large nucleus and the smaller nuclei is released. Nuclear fuels are isotopes with large nuclei.

An analogy to the nuclear potential energy associated with large nuclei is the chemical potential energy associated with large molecules. When large molecules break down into smaller, more stable molecules, some chemical potential energy is released. In a similar fashion, when large nuclei break down into smaller, more stable nuclei, some nuclear potential energy is released.

Another Look at Nuclear Power Plants

People need energy to power their homes and their vehicles. Most of the world's energy comes from the burning of fossil fuels such as gas, coal, and oil. However, this burning releases carbon dioxide and other gases that have been linked to global warming and the acidification of the environment. In addition, the world's supply of fossil fuels is dwindling. In other words, there is a looming energy crisis.

To solve the world's energy crisis, people must employ energy technologies that do not use fossil fuels. For this reason, many people are taking another look at nuclear power plants.

Because of the deadly nature of uncontrolled fission that can occur during malfunctions or natural disasters, the use of nuclear power plants is controversial. There have been three serious nuclear accidents—at Chernobyl, Three Mile Island, and Fukushima. The explosion that occurred at Chernobyl, located in the Ukraine, was the most devastating nuclear accident in history. More than 30 people died immediately, and there were thousands of cancer cases that occurred after the explosion. Hundreds of thousands of people had to move away from the area around the plant.

However, people are now weighing the risks of nuclear accidents against the risks of global warming, which include catastrophic events such as widespread flooding and loss of cropland. Are there ways that the safety of nuclear power can be improved? Can alternative energy sources, such as the sun, wind, tides, and falling water, provide enough energy without the use of fossil fuels or nuclear power?

The Risks, Benefits, and Costs of Nuclear Power Plants

It is important for everyone to consider the use of technologies that can have a large impact on people or on the environment, such as the use of nuclear power plants. When considering the use of nuclear power plants, it is not enough that you understand their operation and the science that makes them work. You should also assess their risks, benefits, and costs. To begin to do this, review the pros and cons of nuclear power plants that follow. You will use this information to develop your own opinion about the use of nuclear power plants.

Pros

- Nuclear power plants have inexpensive day-to-day operating costs.
- Nuclear power plants can produce large amounts of electricity on demand for industries and cities.
- There are relatively large reserves of nuclear fuel.
- The technology is reliable and ~~well-developed~~well developed. It is generally a reliable process that can be counted on to produce electricity for many years (average availability over three years is about 80%).
- The amount of waste products is very small, and can be stored in fire-, water-, and earthquake-proof capsules to ensure safety.

Cons

- Nuclear power plants have very expensive start-up costs and costs of recycling and disposing of nuclear waste.
- A problem in the operation of a nuclear power plant will result in an immediate and sustained loss of electricity.

- Under normal operating conditions, nuclear power plants generate nuclear waste. How to safely store nuclear waste over long periods of time is a problem that has not been fully solved.
- When a nuclear power plant or stored nuclear waste containers malfunction or are damaged in a natural disaster, they may release very high levels of radiation, which can result in death, radiation sickness, cancers, and genetic damage.
- Terrorists can use nuclear waste to create “dirty bombs.”

ACTIVITY: Take-A-Stand

Using what you have learned about nuclear power plants, decide whether you support their use. Write a short report that describes your decision and your reasons for your decision.

To complete this activity, you will “take a stand” to show your decision. To do this, you will stand along a curve in the classroom. One end of the curve represents the opinion that people should continue the use of nuclear power plants. The other end of the curve represents the opinion that people should immediately end the use of nuclear power plants. Points along the curve represent opinions that are between the opinions at each end, such as an opinion that people should limit the use of nuclear power plants. You should stand along the line at the point that best represents your opinion.

During the activity, you and your classmates will share the reasons for your opinions in a persuasive manner. Only one person should talk at a time and everyone should listen closely. At the end of the activity, you may change your position along the curve if certain arguments have persuaded you to change your opinion.

TEACHER NOTES

IN-DEPTH INVESTIGATION: MODELING THE NUCLEUS

Context

The cause of radioactivity is unstable nuclei. The transformation of an unstable nucleus into a more stable nucleus is an example of radioactive decay. Just as chemical reactivity is correlated with electron arrangements and the electrical forces among electrons and nuclei, nuclear reactivity is correlated with particles in the nucleus and the electrical and nuclear forces among those particles.

Overview

Students read about factors that affect the stability of the nucleus and the two types of radioactive decay processes. Students graph the ratio of neutrons to protons for stable and unstable isotopes and develop a model that predicts which isotopes will be radioactive and the type of radioactive decay they will undergo.

Next Generation Science Standards Alignment

Science and Engineering Practices

2. Developing and Using Models
    - Develop a model based on evidence to predict the relationships between systems or between components of a system.
5. Using Mathematics and Computational Thinking
    - Use mathematical representations of phenomena to describe and support explanations.
6. Constructing Explanations and Designing Solutions:
    - Apply scientific reasoning and models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion.
7. Engaging in Argument from Evidence:
    - Evaluate the evidence and reasoning behind currently accepted explanations to determine the merits of arguments.

Disciplinary Core Ideas

- Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve release or absorption of energy. The total number of neutrons plus protons does not change in any nuclear process.

Crosscutting Concepts

- In nuclear processes, atoms are not conserved, but the total number of protons plus neutrons is conserved.

Performance Expectations

- Structure and Properties of Matter HS-PS1-8: 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.

Understanding Goals

Students should understand:

- Isotopes are atoms of an element that have differing numbers of neutrons.
- Unstable isotopes are radioactive and they undergo nuclear reactions called radioactive decay processes in which the unstable isotopes are transformed into more-stable isotopes.
- There are two main kinds of radioactive decay processes. In alpha decay, an alpha particle is ejected and the nucleus loses two protons and two neutrons. In beta decay, a beta particle is ejected and a neutron is converted to a proton or a proton is converted to a neutron. There are three different kinds of beta decay:

  - Beta-minus decay: A neutron is converted into a proton.
  - Beta-plus decay: A proton is converted into a neutron.
  - Electron capture: A proton is converted into a neutron (the process is slightly different than beta-plus decay)
- The ratio of neutrons to protons affects isotope stability.
- Isotopes with an even number of protons or of neutrons, or both, are more stable.
- All isotopes of elements greater than atomic number 82 are radioactive.

Student Materials

You will find on the following pages a reading and an activity for students.

Activity Facilitation

- Assign each group to examine one of the four tables of isotope data.
- Ensure that students have a method for graphing. If using paper, give students colored pencils or markers.
- Circulate to students when they work on the activity.
- When students examine the table and graph, they should note the following:
  - There is a narrow range of ratios of neutrons of protons that results in more stable isotopes.
  - Isotopes that have a lower ratio of neutrons of protons have too many neutrons and undergo electron capture to convert a proton to a neutron.
  - Isotopes that have a higher ratio of neutrons of protons have too many neutrons and undergo beta-minus decay to convert a neutron to a proton.
- Have each group share their observations and conclusions with the class.

Activity Rubric

Criteria	Not evident	Limited	Developing	Competent	Accomplished
Develop criteria to predict if an isotope is radioactive and how it will decay	No criteria developed	Criteria did not reference information from reading and data analysis	Criteria referenced some of the information from reading and data analysis	Criteria referenced most of the information from reading and data analysis	Criteria referenced all of the information from reading and data analysis
Explain if your data analysis supports the claims made by scientists	No explanation	Explanation did not refer to data analysis	Explanation referred to data analysis, but the reasoning that linked claim and data analysis was not convincing	Explanation referred to data analysis, and the reasoning that linked claim and data analysis was somewhat convincing	Explanation referred to data analysis, and the reasoning that linked claim and data analysis was completely convincing

IN-DEPTH INVESTIGATION: MODELING THE NUCLEUS

READING: Stable and Unstable Isotopes

At the end of the 1800s, scientists discovered radioactivity. This phenomenon was the emission of energetic particles and waves from unstable isotopes. (Isotopes are atoms of an element that have differing numbers of neutrons.) By releasing these particles and waves, an unstable nucleus undergoes radioactive decay and becomes more stable.

The type of decay an isotope undergoes, and the kind of radiation it emits, depends on why that isotope is unstable. There are two main types of decay processes, alpha decay and beta decay. However, beta decay is subdivided into three different kinds. The four decay processes follow.

- Alpha decay: The nucleus ejects an alpha particle, which contains two protons and two neutrons.
- Beta-minus decay: A neutron is converted into a proton.
- Electron capture: A proton is converted into a neutron.
- Beta-plus decay: A proton is converted into a neutron.

Just as electron arrangements and forces are correlated with chemical reactivity, the number and ratio of protons and neutrons and forces in the nucleus are correlated with isotope stability.

Particles in the nucleus exert two kinds of forces on each other, electric and nuclear. The electric force is destabilizing because the positively charged protons repel each other. In contrast, the nuclear force is a stabilizing force. This force is found only in the nucleus and it causes protons to attract protons, neutrons to attract neutrons, and protons to attract neutrons.

When protons are close to each other, the nuclear force between them is a thousand times stronger than the electric force. However, the strength of the nuclear force decreases rapidly with distance. When protons are far apart in a large nucleus, the electric force between them is stronger than the nuclear force. This destabilizes the nucleus and causes it to break apart. In fact, all isotopes of elements greater than atomic number 82 are radioactive and typically undergo alpha decay.

ACTIVITY: Which isotopes are unstable?

Which isotopes are unstable? In this activity, you will work with a group to examine isotope data.

1. Your teacher will assign you one of four tables found on the following pages. Examine the isotope data and look for factors that relate to radioactivity. Consider the ratio of neutrons to protons, whether numbers of protons are odd or even, and whether numbers of neutrons are odd or even.
2. Graph number of neutrons vs. number of protons for each isotope in your table. When marking the points on your graph, use three colors or shapes to differentiate the following isotopes:
   - stable isotopes,
   - radioactive isotopes that undergo electron capture
   - radioactive isotopes that undergo beta-minus decay

   Note: You may want to split up this work—but be sure to use the same scale divisions on each graph.
3. Review the reading, the data, and the graph you made. Develop criteria to predict if a particular isotope is radioactive, and if so, the type of radioactive decay process it will undergo.
4. Scientists think that isotopes with an even number of protons or neutrons (or both) are more stable. Does the data in your table support this claim? Explain using examples.
5. Scientists think that the ratio of neutrons to protons is related to isotope stability. Does the data in your table and graph support this claim? Explain using examples.

Table 1: *Isotopes for Atomic Numbers 1-22. Decay processes are shown for radioactive isotopes.*

Isotope	Protons	Neutrons	Decay Process	Isotope	Protons	Neutrons	Decay Process
^{1}H	1	0		^{32}S	16	16	
^{2}H	1	1		^{33}S	16	17	
^{3}H	1	2	Beta-minus decay	^{34}S	16	18	
^{3}He	2	1		^{35}S	16	19	Beta-minus decay
^{4}He	2	2		^{36}S	16	20	
^{6}Li	3	3		^{38}S	16	22	Beta-minus decay
^{7}Li	3	4		^{35}Cl	17	18	
^{7}Be	4	5	Electron capture	^{36}Cl	17	19	Beta-minus decay
^{8}Be	4	4	Alpha decay	^{37}Cl	17	20	
^{9}Be	4	5		^{36}Ar	18	18	
^{10}Be	4	6	Beta-minus decay	^{37}Ar	18	19	Electron capture
^{10}B	5	5		^{38}Ar	18	20	
^{11}B	5	6		^{39}Ar	18	21	Beta-minus decay
^{12}C	6	6		^{40}Ar	18	22	
^{13}C	6	7		^{42}Ar	18	24	Beta-minus decay
^{14}C	6	7	Beta-minus decay	^{39}K	19	20	
^{14}N	7	7		^{40}K	19	21	Electron capture
^{15}N	7	8		^{41}K	19	22	
^{16}O	8	8		^{42}K	19	23	Beta-minus decay
^{17}O	8	9		^{43}K	19	24	Beta-minus decay
^{18}O	8	10		^{40}Ca	20	20	
^{19}F	9	10		^{41}Ca	20	21	Electron capture
^{20}Ne	10	10		^{42}Ca	20	22	
^{21}Ne	10	11		^{43}Ca	20	23	
^{22}Ne	10	12		^{44}Ca	20	24	
^{22}Na	11	11	Electron capture	^{45}Ca	20	25	Beta-minus decay
^{23}Na	11	12		^{46}Ca	20	26	
^{24}Na	11	13	Beta-minus decay	^{47}Ca	20	27	Beta-minus decay
^{24}Mg	12	12		^{48}Ca	20	28	
^{25}Mg	12	13		^{43}Sc	21	23	Electron capture
^{26}Mg	12	14		^{44}Sc	21	24	Electron capture
^{28}Mg	12	16	Beta-minus decay	^{46}Sc	21	25	
^{26}Al	13	13	Electron capture	^{47}Sc	21	26	Beta-minus decay
^{27}Al	13	14		^{48}Sc	21	27	Beta-minus decay
^{28}Si	14	14		^{44}Ti	22	22	Electron capture
^{29}Si	14	15		^{45}Ti	22	23	Electron capture
^{30}Si	14	16		^{46}Ti	22	24	
^{31}Si	14	17	Beta-minus decay	^{47}Ti	22	25	
^{32}Si	14	18	Beta-minus decay	^{48}Ti	22	26	
^{31}P	15	16		^{49}Ti	22	27	
^{32}P	15	17	Beta-minus decay	^{50}Ti	22	28	
^{33}P	15	18	Beta-minus decay				

Table 2: *Isotopes for Atomic Numbers 23-34. Decay processes are shown for radioactive isotopes.*

Isotope	Protons	Neutrons	Radioactive	Isotope	Protons	Neutrons	Decay Process
^{48}V	23	25	Electron capture	^{62}Zn	30	32	Electron capture
^{49}V	23	26	Electron capture	^{64}Zn	30	34	
^{50}V	23	27	Beta-plus decay	^{65}Zn	30	35	Electron capture
^{51}V	23	28		^{66}Zn	30	36	
^{48}Cr	24	24	Electron capture	^{67}Zn	30	37	
^{50}Cr	24	26		^{68}Zn	30	38	
^{51}Cr	24	27	Electron capture	^{70}Zn	30	40	
^{52}Cr	24	28		^{72}Zn	30	42	Beta-minus decay
^{53}Cr	24	29		^{66}Ga	31	35	Electron capture
^{54}Cr	24	30		^{67}Ga	31	36	Electron capture
^{52}Mn	25	27	Electron capture	^{69}Ga	31	38	
^{53}Mn	25	28	Electron capture	^{71}Ga	31	40	
^{54}Mn	25	29	Electron capture	^{72}Ga	31	41	Beta-minus decay
^{55}Mn	25	30		^{73}Ga	31	42	Beta-minus decay
^{56}Mn	25	31	Beta-minus decay	^{66}Ge	32	34	Electron capture
^{52}Fe	26	26	Electron capture	^{68}Ge	32	36	Electron capture
^{54}Fe	26	28		^{69}Ge	32	37	Electron capture
^{55}Fe	26	29	Electron capture	^{70}Ge	32	38	
^{56}Fe	26	30		^{71}Ge	32	39	Electron capture
^{57}Fe	26	31		^{72}Ge	32	40	
^{58}Fe	26	32		^{73}Ge	32	41	
^{59}Fe	26	33	Beta-minus decay	^{74}Ge	32	42	
^{60}Fe	26	34	Beta-minus decay	^{76}Ge	32	44	
^{55}Co	27	32	Electron capture	^{77}Ge	32	45	Beta-minus decay
^{56}Co	27	29	Electron capture	^{71}As	33	38	Electron capture
^{57}Co	27	30	Electron capture	^{72}As	33	39	Electron capture
^{58}Co	27	31	Electron capture	^{73}As	33	40	Electron capture
^{59}Co	27	32		^{74}As	33	41	Beta-minus decay
^{60}Co	27	33	Beta-minus decay	^{75}As	33	42	
^{56}Ni	28	28	Electron capture	^{76}As	33	43	Beta-minus decay
^{57}Ni	28	29	Electron capture	^{77}As	33	44	Beta-minus decay
^{58}Ni	28	30		^{72}Se	34	38	Electron capture
^{59}Ni	28	31	Electron capture	^{73}Se	34	39	Electron capture
^{60}Ni	28	32		^{74}Se	34	40	
^{61}Ni	28	33		^{75}Se	34	41	Electron capture
^{62}Ni	28	34		^{76}Se	34	42	
^{63}Ni	28	35	Beta-minus decay	^{77}Se	34	43	
^{64}Ni	28	36		^{78}Se	34	44	
^{66}Ni	28	38	Beta-minus decay	^{79}Se	34	45	Beta-minus decay
^{61}Cu	29	32	Electron capture	^{80}Se	34	46	
^{63}Cu	29	34		^{82}Se	34	48	
^{64}Cu	29	35	Electron capture				
^{65}Cu	29	36					
^{67}Cu	29	38	Beta-minus decay				

Table 3: *Isotopes for Atomic Numbers 35-44. Decay processes are shown for radioactive isotopes.*

Isotope	Protons	Neutrons	Decay Process
^{76}Br	35	41	Electron capture
^{77}Br	35	42	Electron capture
^{79}Br	35	44	
^{81}Br	35	46	
^{82}Br	35	47	Beta-minus decay
^{83}Br	35	48	Beta-minus decay
^{76}Kr	36	40	Electron capture
^{78}Kr	36	42	
^{79}Kr	36	43	Electron capture
^{80}Kr	36	44	
^{81}Kr	36	45	Electron capture
^{82}Kr	36	46	
^{83}Kr	36	47	
^{84}Kr	36	48	
^{85}Kr	36	49	Beta-minus decay
^{86}Kr	36	50	
^{88}Kr	36	52	Beta-minus decay
^{81}Rb	37	44	Electron capture
^{83}Rb	37	46	Electron capture
^{84}Rb	37	47	Electron capture
^{85}Rb	37	48	
^{86}Rb	37	49	Electron capture
^{87}Rb	37	50	Beta-minus decay
^{82}Sr	38	44	Electron capture
^{83}Sr	38	45	Electron capture
^{84}Sr	38	46	
^{85}Sr	38	47	Electron capture
^{86}Sr	38	48	
^{87}Sr	38	49	
^{88}Sr	38	50	
^{89}Sr	38	51	Beta-minus decay
^{90}Sr	38	52	Beta-minus decay
^{91}Sr	38	53	Beta-minus decay
^{85}Y	39	46	Electron capture
^{86}Y	39	47	Electron capture
^{87}Y	39	48	Electron capture
^{88}Y	39	49	Electron capture
^{89}Y	39	50	
^{90}Y	39	51	Beta-minus decay
^{91}Y	39	52	Beta-minus decay
^{92}Y	39	53	Beta-minus decay
^{93}Y	39	54	Beta-minus decay
^{86}Zr	40	46	Electron capture
^{88}Zr	40	48	Electron capture
^{89}Zr	40	49	Electron capture
^{90}Zr	40	50	
^{91}Zr	40	51	
^{92}Zr	40	52	
^{93}Zr	40	53	Beta-minus decay
^{94}Zr	40	54	
^{95}Zr	40	55	Beta-minus decay
^{96}Zr	40	56	Beta-minus decay
^{90}Nb	41	49	Electron capture
^{91}Nb	41	50	Electron capture
^{92}Nb	41	51	Electron capture
^{93}Nb	41	52	
^{94}Nb	41	53	Beta-minus decay
^{95}Nb	41	54	Beta-minus decay
^{90}Mo	42	48	Electron capture
^{92}Mo	42	50	
^{93}Mo	42	51	Electron capture
^{94}Mo	42	52	
^{95}Mo	42	53	
^{96}Mo	42	54	
^{97}Mo	42	55	
^{98}Mo	42	56	
^{99}Mo	42	57	Beta-minus decay
^{100}Mo	42	58	
^{93}Tc	43	50	Electron capture
^{94}Tc	43	51	Electron capture
^{95}Tc	43	52	Electron capture
^{96}Tc	43	53	Electron capture
^{97}Tc	43	54	Electron capture
^{98}Tc	43	55	Beta-minus decay
^{99}Tc	43	56	Beta-minus decay
^{96}Ru	44	52	
^{97}Ru	44	53	Electron capture
^{98}Ru	44	54	
^{99}Ru	44	55	
^{100}Ru	44	56	
^{101}Ru	44	57	
^{102}Ru	44	58	
^{103}Ru	44	59	Beta-minus decay
^{104}Ru	44	60	
^{105}Ru	44	61	Beta-minus decay
^{106}Ru	44	62	Beta-minus decay

Table 4: *Isotopes for Atomic Numbers 45-52. Decay processes are shown for radioactive isotopes.*

Isotope	Protons	Neutrons	Decay Process	Isotope	Protons	Neutrons	Decay Process
^{99}Rh	45	54	Electron capture	^{110}Sn	50	60	Electron capture
^{100}Rh	45	55	Electron capture	^{112}Sn	50	62	
^{101}Rh	45	56	Electron capture	^{113}Sn	50	63	Electron capture
^{102}Rh	45	58	Electron capture	^{114}Sn	50	64	
^{103}Rh	45	58		^{115}Sn	50	65	
^{105}Rh	45	58	Beta-minus decay	^{116}Sn	50	66	
^{100}Pd	46	54	Electron capture	^{117}Sn	50	67	
^{101}Pd	46	54	Electron capture	^{118}Sn	50	68	
^{102}Pd	46	56		^{119}Sn	50	69	
^{103}Pd	46	57	Electron capture	^{120}Sn	50	70	
^{104}Pd	46	58		^{121}Sn	50	71	Beta-minus decay
^{105}Pd	46	59		^{122}Sn	50	72	
^{106}Pd	46	60		^{123}Sn	50	73	Beta-minus decay
^{107}Pd	46	61	Beta-minus decay	^{124}Sn	50	74	
^{108}Pd	46	62		^{125}Sn	50	75	Beta-minus decay
^{109}Pd	46	63	Beta-minus decay	^{126}Sn	50	76	Beta-minus decay
^{110}Pd	46	64		^{127}Sn	50	77	Beta-minus decay
^{112}Pd	46	66	Beta-minus decay	^{117}Sb	51	66	Electron capture
^{105}Ag	47	58	Electron capture	^{119}Sb	51	68	Electron capture
^{106}Ag	47	59	Electron capture	^{120}Sb	51	69	Electron capture
^{107}Ag	47	60		^{121}Sb	51	70	
^{109}Ag	47	62		^{122}Sb	51	71	Electron capture
^{111}Ag	47	64	Beta-minus decay	^{123}Sb	51	72	
^{112}Ag	47	65	Beta-minus decay	^{124}Sb	51	73	Beta-minus decay
^{113}Ag	47	66	Beta-minus decay	^{125}Sb	51	74	Beta-minus decay
^{106}Cd	48	58		^{126}Sb	51	75	Beta-minus decay
^{107}Cd	48	59	Electron capture	^{127}Sb	51	76	Beta-minus decay
^{108}Cd	48	60		^{128}Sb	51	77	Beta-minus decay
^{109}Cd	48	61	Electron capture	^{129}Sb	51	78	Beta-minus decay
^{110}Cd	48	62		^{116}Te	52	64	Electron capture
^{111}Cd	48	63		^{118}Te	52	66	Electron capture
^{112}Cd	48	64		^{119}Te	52	67	Electron capture
^{113}Cd	48	65	Beta-minus decay	^{120}Te	52	68	
^{114}Cd	48	66		^{121}Te	52	69	Electron capture
^{115}Cd	48	67	Beta-minus decay	^{122}Te	52	70	
^{116}Cd	48	68		^{123}Te	52	71	
^{117}Cd	48	69	Beta-minus decay	^{124}Te	52	72	
^{109}In	49	60	Electron capture	^{125}Te	52	73	
^{111}In	49	62	Electron capture	^{126}Te	52	74	
^{113}In	49	64		^{127}Te	52	75	Beta-minus decay
^{115}In	49	66	Beta-minus decay	^{128}Te	52	76	
				^{129}Te	52	77	Beta-minus decay
				^{130}Te	52	78	

WEB RESOURCES

PhET Interactive Simulations of Fission, Alpha Decay, and Beta Decay
http://phet.colorado.edu/en/simulation/nuclear-fission
http://phet.colorado.edu/en/simulation/alpha-decay
http://phet.colorado.edu/en/simulation/beta-decay
It can be difficult to visualize the dynamic nuclear processes of fission, alpha decay, and beta decay from diagrams alone. These three PhET simulations help students gain a better understanding of these processes. The simulations offer intuitive controls, measurement instruments, and multiple linked representations.

Diagram of Radioactive Alpha Decay
http://www.sciencephoto.com/media/1122/view
This site has a drawing and explanation for the sequential alpha decay of element 112 (copernicium) to element 110 (darmstadtium) to hassium to seaborgium.

Reflections on the Legacy of a Legend
http://www.fas.org/sgp/othergov/doe/lanl/pubs/00818011.pdf
This article from Los Alamos Science describes Glenn Seaborg's work.

Glenn T. Seaborg, Citizen-Scholar
http://www.nmu.edu/seaborg/node/9
An engaging short biography of Glenn Seaborg that emphasizes his "Yooper" roots in the Upper Peninsula of Michigan. Site maintained by the Seaborg Mathematics and Science Center of Northern Michigan University.

Glenn Seaborg: His Life and Contributions
http://www.lbl.gov/Publications/Seaborg/
This comprehensive multi-page site includes Seaborg's biography, works, and influence. There are many descriptions of important events in Seaborg's life in his own words. Site maintained by the Lawrence Berkeley Laboratory.

1979: Glenn T. Seaborg (1912–1999)
http://pubs.acs.org/cen/priestley/recipients/1979seaborg.html
This article is in a special issue of *Chemical & Engineering News* and commemorates Seaborg's life. It contains links that describe the American Chemical Society's prestigious Priestley Medal, which Seaborg was awarded in 1979.

The Plutonium Story
http://www.osti.gov/scitech/servlets/purl/5808140
This document is Seaborg's typed summary of how he synthesized and identified the first synthetic transuranic element, plutonium.

Glenn Theodore Seaborg
http://www.chemheritage.org/discover/online-resources/chemistry-in-history/themes/atomic-and-nuclear-structure/seaborg.aspx
This short biography succinctly describes Glenn Seaborg's work.

Federation of America Scientists: Excerpt from the Congressional Record, September 26, 1997, and a Reprint of "Secrecy Runs Amok" by Glenn Seaborg

http://www.gpo.gov/fdsys/pkg/CREC-1997-09-26/pdf/CREC-1997-09-26-senate.pdf

S. 1231 (pages S10065 through S10065) of this reproduction of the Congressional Record describes the effort by Glenn Seaborg to declassify the journal that he kept when he was chair of the Atomic Energy Commission from 1961 to 1971, via a bill introduced into Congress. The Congressional Record includes an article written by Seaborg, in which he discusses the balance between the "right of the public to know" and the "right of the nation to protect itself."