SECTION 6

The Strong Force: Inside the Nucleus

Section Overview

Students calculate the ratio of the proton mass to the electron mass and determine that most of the mass of the atom is in the nucleus. They analyze the structure of the carbon atom to account for the mass in the nucleus and find that the net charge of the atom, which is zero, cannot be explained by the presence of 12 protons, as there are only six electrons orbiting the nucleus. This dilemma is resolved with an introduction of the discovery of the neutron by James Chadwick, and students draw a sketch of what an atom would look like with neutrons as well as protons in the nucleus. They calculate the number of protons, neutrons, and electrons in the atom from the atomic mass and number and learn how to calculate the repulsive force between two protons using Coulomb's law. Subsequently, they recognize the need for nuclear forces to counter the effect of a Coulomb force. They learn that these nuclear forces of attraction, called the strong force, act only between nuclear particles—neutrons and protons—which are collectively baryons. The electrostatic and strong nuclear forces are further described as an exchange of virtual particles, and students draw Feynman diagrams to understand how these forces are transmitted.

Background Information

Because the atom is composed of electrons and protons, it was first thought that a nucleus had protons and electrons. The protons accounted for the mass of the nucleus but the embedded electrons could help account for its positive charge. For instance, carbon-12 has a mass of 12 but only has a + 6 charge in the nucleus. With Chadwick's discovery of the nucleus in 1932, an alternative explanation was presented. The carbon nucleus had a mass of 12 (6 protons + 6 neutrons) but only had a charge of +6 (6 protons). In this model, the electrons all reside outside the nucleus, as explained by quantum mechanics. By the Heisenberg uncertainty principle, if the position (and wavelength) of the electron were confined to the size of the nucleus, it would have enormous momentum and could not reside in the nucleus. Throughout the discussion of forces of nature, you have always been content to describe the forces. Newton in describing the force of gravitation stated, "I feign no hypothesis." He was not describing why the force exists or how it was transmitted, but rather he described the force in terms of mass and distance. The force at a distance (the Sun attracts Earth) has always seemed a bit of a mystery. How is the force transmitted?

The Feynman model (a part of quantum electrodynamics) seeks to explain the transmission of force as an exchange of virtual particles. The diagrams pictorially represent these exchanges but can also be used to calculate the strength of forces. Feynman shared the Nobel Prize with Schwinger and Tomonaga for these insights. The theory of quantum electrodynamics (QED) is probably the most precise theory there is in physics.

Crucial Physics

- The nucleus of an atom is composed of protons and neutrons. The protons carry the positive charge. Neutrons have approximately the same mass as protons and are uncharged.
- The combined number of protons and the number of neutrons in the nucleus is equal to the atomic mass number of the atom. The number of protons in the nucleus determines the atomic number of the atom and its chemical characteristics.
- Atoms with the same number of protons and different numbers of neutrons are known as isotopes.
- In a neutral atom, the number of electrons is equal to the number of protons.
- The nucleus of an atom is held together against the Coulomb force of repulsion by the strong force, which is very strong but short range.
- Forces may be described using Feynmann diagrams, which postulate the passing of particles between subatomic units.

Learning Outcomes	Location in the Section	Evidence of Understanding
Calculate the number of protons, electrons, and neutrons in a neutral atom, given the atomic number and atomic mass.	***Investigate*** Steps 5 and 6	Students calculate the number of protons, electrons, and neutrons in atoms of chlorine, gold, and potassium through their atomic numbers and mass.
Calculate the Coulomb force of repulsion between protons in a nucleus.	***Physics to Go*** Questions 4 and 9	Students calculate the Coulomb force of repulsion between two protons in a nucleus by solving problems in which the distance of separation between the protons is given.
Recognize that the nucleus cannot be held together against the force of Coulomb repulsion unless there is another force, the strong force, that holds the particles together.	***Investigate*** Step 7	Students recognize that a small separation distance between protons would make the repulsive Coulomb force very strong, so there must be another force holding both the protons and neutrons in the nucleus together. This force is called the strong force, which counters the force of repulsion between protons and acts between protons, neutrons, and protons and neutrons.

Section 6 Materials, Preparation, and Safety

Plan A

Materials and Equipment

- No materials or equipment are needed for this section.

Time Requirement

- Allow one and one half class periods or 60 minutes for the students to do the *Investigate* portion of this section.

Teacher Preparation

- No particular teacher preparation is required for this section, although you may choose to prepare transparencies to illustrate certain parts of the *Investigate*.

Safety Requirements

- There are no particular safety concerns for this *Investigate*.

Plan B

Materials and Equipment

- No materials or equipment are needed for this section.

Time Requirement

- Allow one class period or 45 minutes to do the *Investigate* portion of this section as a teacher-led discussion, as well as the *Physics Talk* and other parts of the section in the *Pacing Guide*.

Teacher Preparation

- No particular teacher preparation is required for this section, although you may choose to prepare transparencies to illustrate certain parts of the *Investigate*.

Safety Requirements

- There are no particular safety concerns for this *Investigate*.

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Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Understanding the development of the atomic model	***Investigate*** Step 3	**Augmentation** • Students should add the discovery of the neutron to the discovery chart they began making in *Section 3*. At this point, it may help visual learners and learners who struggle with reading if a column is added to the chart that includes a diagram of the atomic model as it developed.
Understanding the differences between the Coulomb force and the strong force	***Investigate*** Steps 7 and 8 ***Physics Talk***	**Augmentation** • Ask students to create a chart that lists the properties of the Coulomb force on the left side and the properties of the strong force on the right side. Students can continue to add to the list as they progress through the section. Tell students to underline any similarities they notice between the two forces. **Accommodation** • Provide a chart that lists the properties of both forces. Ask students to read the list and highlight or underline any similarities. If students struggle with comprehension, encourage them to write down questions they need answered in order to understand the properties.
Drawing Feynman diagrams	***Investigate*** Steps 10–12	**Augmentation** • Drawing a conceptual graph (Feynman diagram) to represent the forces between two particles that emit a virtual particle will be challenging for students who need to see and touch things to be able to make sense of them. For these students, it will help if they can see some examples of Feynman diagrams before they are asked to draw their own. If possible, a three-dimensional model that could be paired with a diagram would be the best way to help students understand the diagrams. • Encourage students to use different colors for each of the particles. Perhaps the class could create a chart of particles and an agreed-upon color for each particle. A color paired with a symbol makes it easier for students to remember the symbol and the word. **Accommodations** • For students who are having a difficult time drawing Feynman diagrams, it may help to give them some simple completed diagrams and description choices for what is represented in the diagrams. Then students can pair the descriptions with the correct diagram. • If there are students who are still struggling to understand the role of and interactions between protons, neutrons, and electrons, it may be beneficial to skip *Investigate, Steps 11* and *12* at this point because charged pions will only exacerbate their confusion.
Remembering the charge and mass of a proton and an electron	***Physics to Go*** Questions 4, 5, and 9	**Augmentation** • Students may look at these problems and not know how to solve them because only one number is given. Remind students to check their notes, the investigation, or *Physics Talk* to find the mass and charge of protons and electrons because they are constants that will usually not be given in a problem.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Vocabulary comprehension	***Investigate***	Some people think only of nuclear weapons when they encounter the word "atomic." Be sure students understand that "atomic" simply means "related to the atom."
Higher order thinking	***Investigate*** Step 2	Discuss the terms "atomic mass" and "atomic mass unit" with the class. Ask: "What is atomic mass? What information do you use to determine atomic mass? Is there any information you do not use? Explain."
Vocabulary comprehension	***Investigate*** Steps 7, 9	Model the correct pronunciation of baryons, mesons, and pions. Give students ample opportunities to use the terms, both orally and in writing. Using the terms will help students differentiate among them, which in turn will help students understand the interactions among atomic particles. Clarify for students the meaning of the term "virtual." It might help to discuss why photons are considered virtual particles when everything we see is the result of photons striking our retinas. Clarify that the photon itself is not seen; we do not see photons streaking across a room, so although they are closely related to light and to vision, we consider photons themselves to be invisible, and only detectable by their indirect effects.
Higher order thinking	***Investigate*** Step 8	Hold a class brainstorming session on what is meant by "the heaviest nucleus that is stable for geologic time scales." Don't reveal the explanation here; half-life is not covered until the next section. Instead, create a list of ideas and revisit it once the class has learned about half-life in *Section 7.*
Higher order thinking	***Physics Essential Questions*** Why do you believe?	Discuss the last sentence, focusing on the words "It was preferable to invent a new force." Ask: "Did scientists really invent a force? If not, what did they do? Was the scientists' decision a good one? Explain."

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SECTION 6

Teaching Suggestions and Sample Answers

What Do You See?

This illustration conveys its purpose with dramatic images. The labels convey the names of physics concepts that students are bound to point out. Using an overhead of this section, initiate a discussion on what's happening in the boxing rink. Consider drawing students' attention to the big sign that indicates that fundamental forces are at play. You might want to ask students how these forces are affecting the outcome of the sport and why has the artist chosen to depict people of such varying sizes. Encourage students to think in terms of a model and how the title might provide a link to what's happening in this illustration.

This *What Do You See?* is full of powerful images that are meant to make students curious and instantly capture their attention.

What Do You Think?

The opening sentence in this section almost makes it seem like the alchemist's dream is possible. You may want to discuss the possibility of lead turning into gold to prompt students into thinking about what makes one element different from the other. As students present their answers, ask them whether they can find any connection between these questions and the *What Do You See?* section. Remind them to record their answers in their *Active Physics* logs. Reaffirm that they will not be evaluated at this stage for the correctness of their response; however, students must know that if they make an earnest attempt to answers these questions to the best of their ability they will address their present conceptions more effectively due by actively engaging in an inquiry-based response.

What Do You Think?

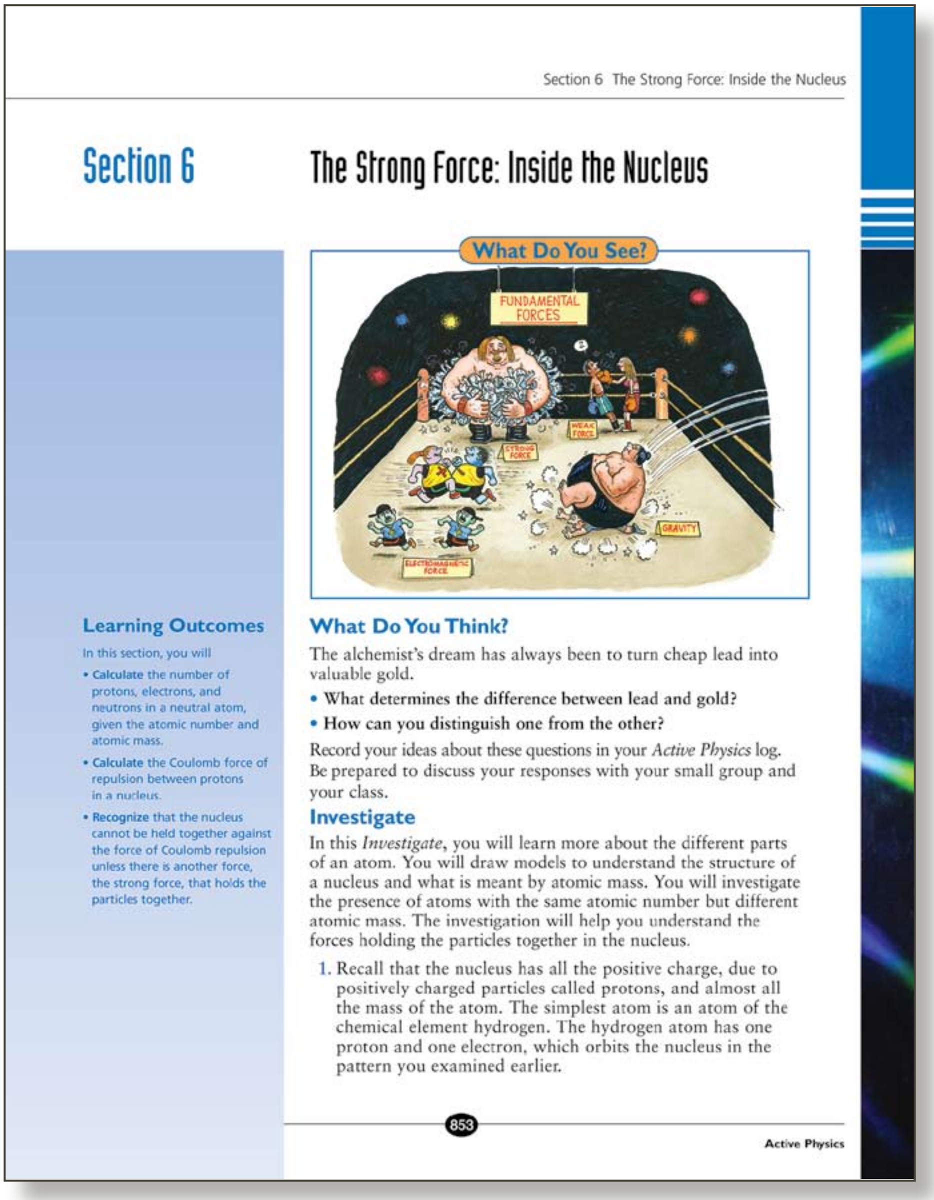
A Physicist's Response

Lead and gold have different numbers of protons, neutrons, and electrons. They are also different in their atomic weights and their availability on Earth. They have different physical and chemical properties, and you are able to distinguish between them on both the microscopic and macroscopic levels. Macroscopically, they have different densities, hardness, luster, and melting points. Microscopically, they differ in the numbers of electrons, protons, and neutrons.

Students' Prior Conceptions

The application of Coulomb's law to determine the repulsive force among the protons within the nucleus and subsequent calculations of the magnitude of this force develops students' understanding of one of the fundamental forces in nature, the strong force. Students are amazed that scientists classify all known forces into four fundamental forces, gravitational, electromagnetic, strong, and weak.

1. **Students hold the belief that the gravitational force is the strongest of the four fundamental forces and not the weakest.** You have another opportunity to evaluate student thinking and to address this misconception during teacher-student interactions in this section. Because the gravitational force is long-ranged, acting over huge cosmological distances, and is an attractive force between any two masses in the universe, students have difficulty accepting it as the "weakest" of the four fundamental forces. You may focus on the range of the strong force and the gravitational force and their relative magnitudes to unseat this prior student conception.



Investigate

1.a)

The ratio of the proton mass to the electron mass =

$$\left(1.7\times10^{-27}\ \text{kg}\right)/\left(9.1\times10^{-31}\ \text{kg}\right)=$$

1868.

1.b)

Yes, it does, because the proton with a mass 1868 times as large as the electron shows that most of the mass is in the nucleus.

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2.a)

12 protons equals a mass of 12 AMU, and the 6 electrons in the nucleus plus the 6 orbiting electrons add almost zero additional mass since collectively the 12 electron masses add up to approximately 0.007 AMU.

2.b)

Charge of 12 protons is equal to +12, charge of 6 electrons in the nucleus is equal to –6. Total charge within the nucleus is equal to +6. The 6 orbiting electrons would then add an additional 6 charges to make the atom neutral.

3.a)

6 protons + 6 neutrons = 12 mass units;
6 electrons ≈ 0 mass units (6/1868)

3.b)

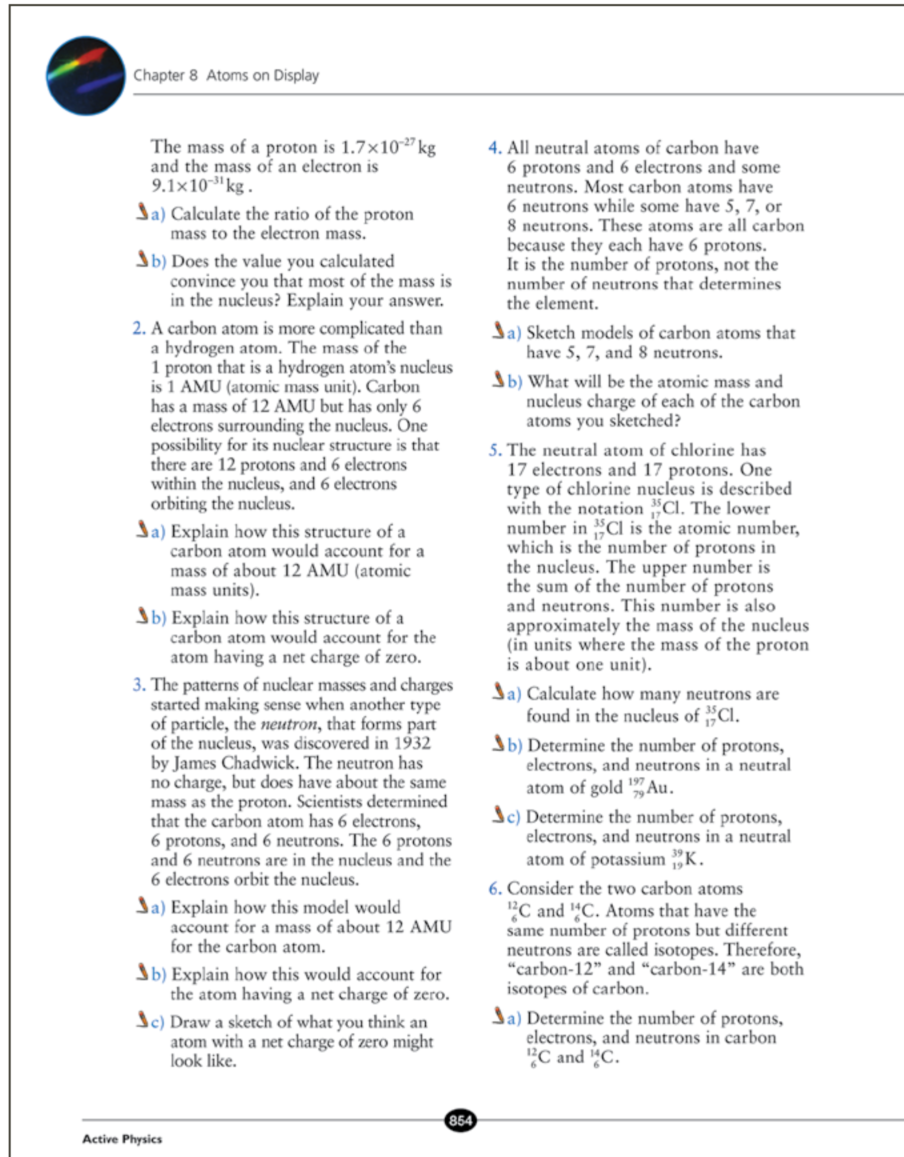
6 protons + 6 electrons = 0 charge

3.c)

Students' sketches of the atom will vary. Most students will probably opt for the solar-system model of the atom with the nucleus in the center and the electrons orbiting outside that they will have seen many times. All sketches should show 6 protons, 6 neutrons, and 6 electrons.

4.a)

Students' drawings should be very similar to what they drew for *Step 3.c)*, except that they have a different number of neutrons indicated.



Chapter 8 Atoms on Display

The mass of a proton is 1.7×10^{-27} kg and the mass of an electron is 9.1×10^{-31} kg.

a) Calculate the ratio of the proton mass to the electron mass.

b) Does the value you calculated convince you that most of the mass is in the nucleus? Explain your answer.

2. A carbon atom is more complicated than a hydrogen atom. The mass of the 1 proton that is a hydrogen atom's nucleus is 1 AMU (atomic mass unit). Carbon has a mass of 12 AMU but has only 6 electrons surrounding the nucleus. One possibility for its nuclear structure is that there are 12 protons and 6 electrons within the nucleus, and 6 electrons orbiting the nucleus.

a) Explain how this structure of a carbon atom would account for a mass of about 12 AMU (atomic mass units).

b) Explain how this structure of a carbon atom would account for the atom having a net charge of zero.

3. The patterns of nuclear masses and charges started making sense when another type of particle, the *neutron*, that forms part of the nucleus, was discovered in 1932 by James Chadwick. The neutron has no charge, but does have about the same mass as the proton. Scientists determined that the carbon atom has 6 electrons, 6 protons, and 6 neutrons. The 6 protons and 6 neutrons are in the nucleus and the 6 electrons orbit the nucleus.

a) Explain how this model would account for a mass of about 12 AMU for the carbon atom.

b) Explain how this would account for the atom having a net charge of zero.

c) Draw a sketch of what you think an atom with a net charge of zero might look like.

4. All neutral atoms of carbon have 6 protons and 6 electrons and some neutrons. Most carbon atoms have 6 neutrons while some have 5, 7, or 8 neutrons. These atoms are all carbon because they each have 6 protons. It is the number of protons, not the number of neutrons that determines the element.

a) Sketch models of carbon atoms that have 5, 7, and 8 neutrons.

b) What will be the atomic mass and nucleus charge of each of the carbon atoms you sketched?

5. The neutral atom of chlorine has 17 electrons and 17 protons. One type of chlorine nucleus is described with the notation ${}^{35}_{17}Cl$. The lower number in ${}^{35}_{17}Cl$ is the atomic number, which is the number of protons in the nucleus. The upper number is the sum of the number of protons and neutrons. This number is also approximately the mass of the nucleus (in units where the mass of the proton is about one unit).

a) Calculate how many neutrons are found in the nucleus of ${}^{35}_{17}Cl$.

b) Determine the number of protons, electrons, and neutrons in a neutral atom of gold ${}^{197}_{79}Au$.

c) Determine the number of protons, electrons, and neutrons in a neutral atom of potassium ${}^{39}_{19}K$.

6. Consider the two carbon atoms ${}^{12}_{6}C$ and ${}^{14}_{6}C$. Atoms that have the same number of protons but different neutrons are called isotopes. Therefore, "carbon-12" and "carbon-14" are both isotopes of carbon.

a) Determine the number of protons, electrons, and neutrons in carbon ${}^{12}_{6}C$ and ${}^{14}_{6}C$.

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4.b)

The atomic charge of all the atoms of carbon the students draw should be zero (+6 for six protons and –6 for six electrons = 0). The atomic mass for the atom with 5 neutrons should be 1 AMU, for 7 neutrons 13 AMU, and for 8 neutrons 14 AMU.

5.a)

35 – 17 = 18 neutrons

5.b)

79 protons, 79 electrons, 118 neutrons

5.c)

19 protons, 19 electrons, 20 neutrons

6.a)

Carbon-12 has 6 protons, 6 neutrons and 6 electrons. Carbon-14 has 6 protons, 8 neutrons and 6 electrons.

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b) Hydrogen nuclei have 1 proton and come in 3 isotopes: no neutrons, 1 neutron, and 2 neutrons. Write the symbols for these isotopes of hydrogen, H, using the appropriate subscripts and superscripts. Incidentally, the no-neutron isotope of H is by far the most abundant; the 1-neutron isotope is rare, and the 2-neutron isotope is rarer still.

7. You have learned that protons repel other protons. The repulsive force between two protons can be calculated using Coulomb's law:

$$F = k\frac{q_1 q_2}{d^2}$$

The nucleus is very tiny and the protons must be extremely close. Such a small separation distance would make the repulsive force between the protons extraordinarily strong. This strong repulsive force should push the protons apart. If no other force acts between protons, besides the Coulomb force, then no nucleus other than hydrogen (a single proton) could exist! There must be another kind of force holding the nucleus together, that helps cancel out the Coulomb force. This nuclear force is called the *strong force* and has the following properties:

- The strong force acts equally between proton-to-proton, proton-to-neutron, and neutron-to-neutron. Electrons do not "feel" it at all.
- The protons or neutrons have to essentially touch or overlap one another before the strong force overcomes the repulsive Coulomb force. At these extremely small distances the attractive strong force is much stronger than the force of repulsion between adjacent protons.
- When protons or neutrons do not touch, then the strong force between them is zero.

a) Why is it important that the strong force be strong at short distances and weak at long distances? In other words, what would happen if the nuclear force were equally strong between protons or neutrons on opposite sides of the nucleus and between protons or neutrons that touch each other?

b) What would happen if the strong nuclear force extended beyond the nucleus to the next atom?

c) In your *Active Physics* log, sketch two circles of equal size to represent two protons. Let each circle or proton have radius *R*, the "radius of the proton." Let the center-to-center distance between your protons be called *d*. Draw a graph showing how the strength of the strong force depends on *d*.

d) What happens in the region where *d* is less than 2*R*? What happens where *d* is greater than 2*R*?

8. Neutrons and protons collectively are called *baryons*. The strong force acts between baryons.

a) Are electrons baryons?

b) The Coulomb force in the nucleus acts only between protons. Why do you suppose that there is no Coulomb force between neutrons?

You can describe the forces within the nucleus in the following way:

- The nucleus is a "contest" between two forces: the long-range repulsive Coulomb force between protons and the short-range strong force between the touching baryons (protons and neutrons). The Coulomb force tries to push apart the nucleus, while the strong force tries to hold the nucleus together.

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6.b)

^1_1H, ^2_1H, ^3_1H

7.

The force between two protons, calculated using Coulomb's law, would be

$$F = \frac{kq_1q_2}{d^2} = \frac{(9\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)(1.6\times10^{-19}\ \text{C})^2}{(1\times10^{-15}\ \text{m})^2}$$

$= 230$ N !

where 1.6×10^{-19} C is the charge on each proton, and 1×10^{-15} m is the distance between two protons in a nucleus.

7.a)

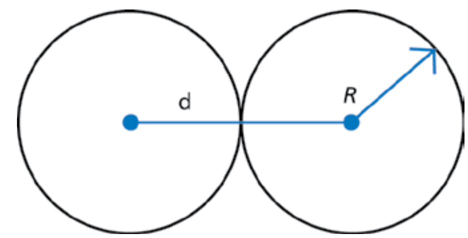
The force should be very strong at short distances to hold the protons within the nucleus. The force must be weak at long distances so that neighboring nuclei in different atoms should not be pulled together.

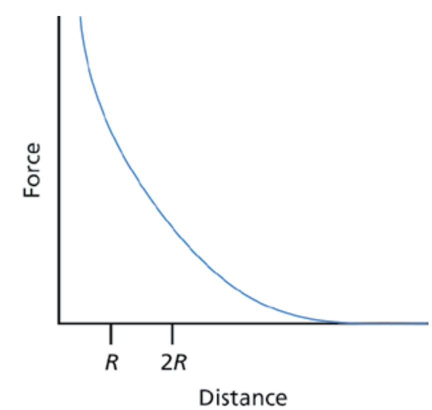
7.b)

If the strong force were extended out to atomic sizes, all the nearby atoms would be pulled together forming one giant nucleus.

7.c)

Student sketches should look like the first one below and the graph should look like the second one below.





7.d)

At a distance less than 2*R* the force is very strong. At a distance greater than 2*R*, the force rapidly goes to zero.

8.a)

No, electrons are a different class of particles called leptons.

8.b)

The coulomb force is a force between charges. There is no coulomb force for neutrons because they carry no charge.

CHAPTER 8

9.a)

The direction of the force of gravity on the penny tells it which way is down.

9.b)

Students will most likely have no idea about this. Current scientific theory postulates that particles called gravitons are passed between massive objects to exert the gravitational force.

9.c)

The direction of the force on the styrene-foam ball gives it the direction to move. Gravity is different from the electrostatic force because gravity acts on masses, while the electrostatic force acts on charges. In addition, gravity can only attract, while the electrostatic force may attract or repel.

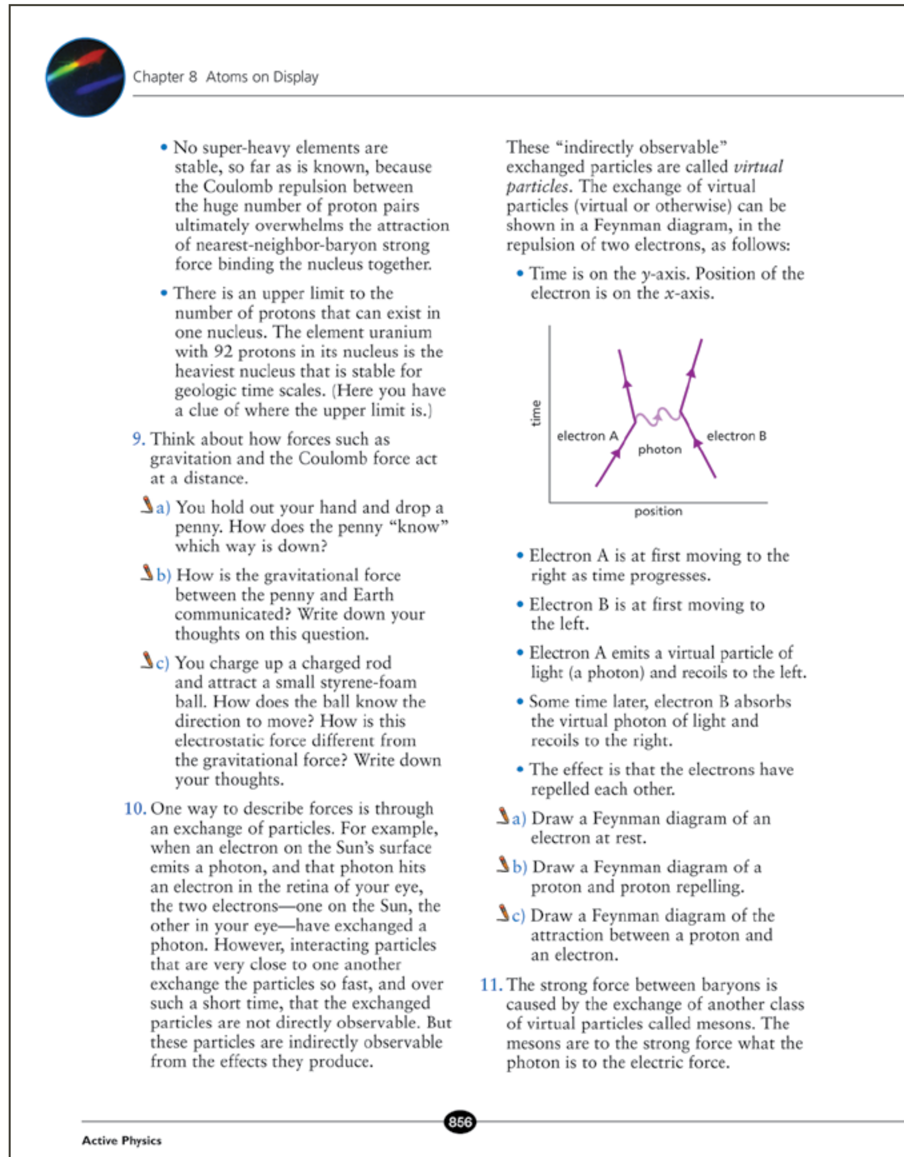
8-6a Blackline Master

10.a)

An electron at rest is a vertical line on the Feynman diagram.

10.b)

The Feynman diagram will be identical to that of the electrons in the student text except the particles will be protons.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- No super-heavy elements are stable, so far as is known, because the Coulomb repulsion between the huge number of proton pairs ultimately overwhelms the attraction of nearest-neighbor-baryon strong force binding the nucleus together.
- There is an upper limit to the number of protons that can exist in one nucleus. The element uranium with 92 protons in its nucleus is the heaviest nucleus that is stable for geologic time scales. (Here you have a clue of where the upper limit is.)

9. Think about how forces such as gravitation and the Coulomb force act at a distance.

a) You hold out your hand and drop a penny. How does the penny "know" which way is down?

b) How is the gravitational force between the penny and Earth communicated? Write down your thoughts on this question.

c) You charge up a charged rod and attract a small styrene-foam ball. How does the ball know the direction to move? How is this electrostatic force different from the gravitational force? Write down your thoughts.

10. One way to describe forces is through an exchange of particles. For example, when an electron on the Sun's surface emits a photon, and that photon hits an electron in the retina of your eye, the two electrons—one on the Sun, the other in your eye—have exchanged a photon. However, interacting particles that are very close to one another exchange the particles so fast, and over such a short time, that the exchanged particles are not directly observable. But these particles are indirectly observable from the effects they produce.

These "indirectly observable" exchanged particles are called *virtual particles*. The exchange of virtual particles (virtual or otherwise) can be shown in a Feynman diagram, in the repulsion of two electrons, as follows:

- Time is on the *y*-axis. Position of the electron is on the *x*-axis.

- Electron A is at first moving to the right as time progresses.
- Electron B is at first moving to the left.
- Electron A emits a virtual particle of light (a photon) and recoils to the left.
- Some time later, electron B absorbs the virtual photon of light and recoils to the right.
- The effect is that the electrons have repelled each other.

a) Draw a Feynman diagram of an electron at rest.

b) Draw a Feynman diagram of a proton and proton repelling.

c) Draw a Feynman diagram of the attraction between a proton and an electron.

11. The strong force between baryons is caused by the exchange of another class of virtual particles called mesons. The mesons are to the strong force what the photon is to the electric force.

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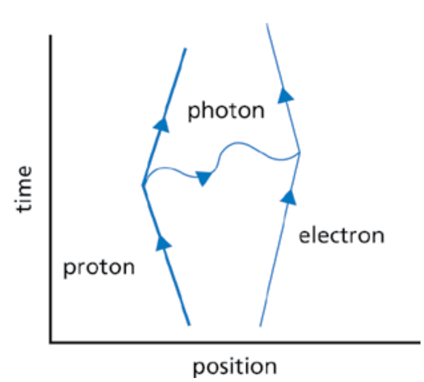
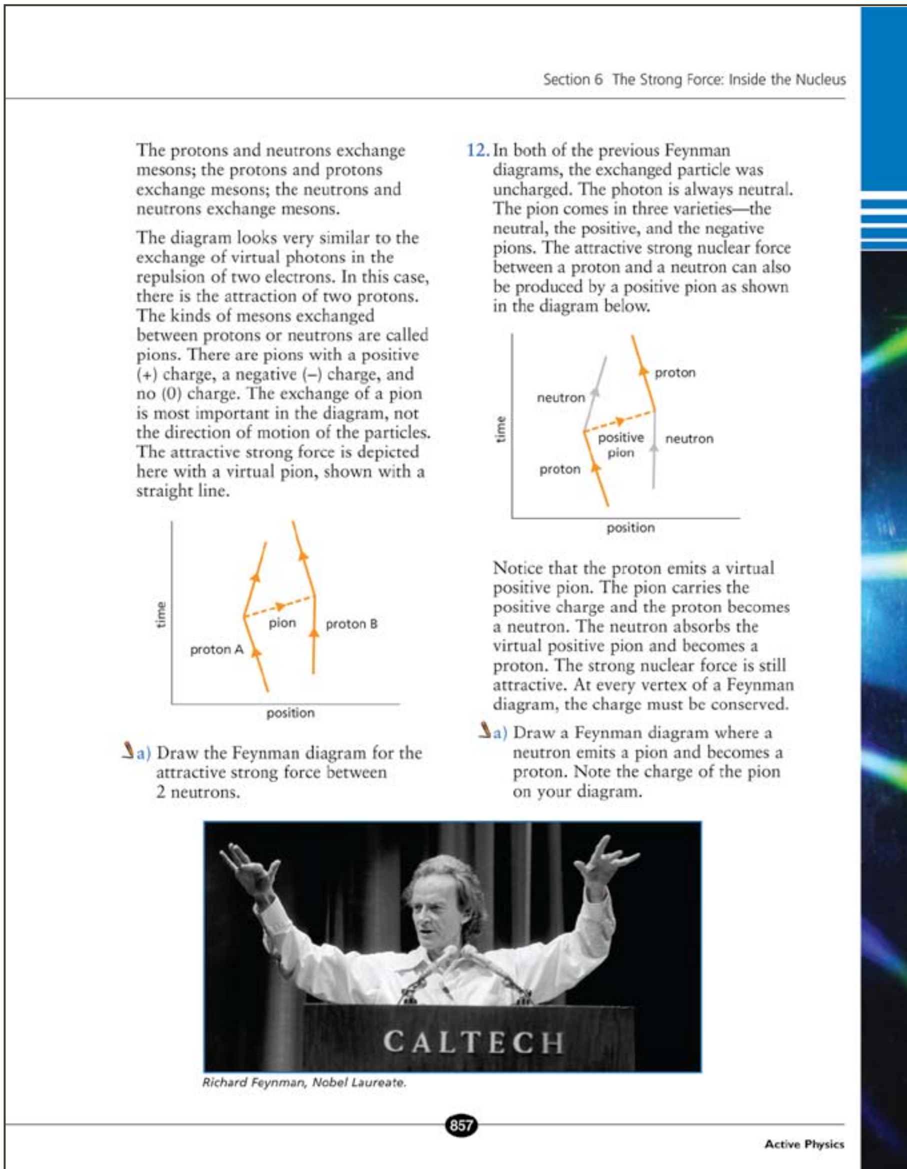
10.c)

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The protons and neutrons exchange mesons; the protons and protons exchange mesons; the neutrons and neutrons exchange mesons.

The diagram looks very similar to the exchange of virtual photons in the repulsion of two electrons. In this case, there is the attraction of two protons. The kinds of mesons exchanged between protons or neutrons are called pions. There are pions with a positive (+) charge, a negative (–) charge, and no (0) charge. The exchange of a pion is most important in the diagram, not the direction of motion of the particles. The attractive strong force is depicted here with a virtual pion, shown with a straight line.

time
pion
proton A
proton B
position

a) Draw the Feynman diagram for the attractive strong force between 2 neutrons.

12. In both of the previous Feynman diagrams, the exchanged particle was uncharged. The photon is always neutral. The pion comes in three varieties—the neutral, the positive, and the negative pions. The attractive strong nuclear force between a proton and a neutron can also be produced by a positive pion as shown in the diagram below.

time
proton
neutron
positive pion
neutron
proton
position

Notice that the proton emits a virtual positive pion. The pion carries the positive charge and the proton becomes a neutron. The neutron absorbs the virtual positive pion and becomes a proton. The strong nuclear force is still attractive. At every vertex of a Feynman diagram, the charge must be conserved.

a) Draw a Feynman diagram where a neutron emits a pion and becomes a proton. Note the charge of the pion on your diagram.

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Richard Feynman, Nobel Laureate.

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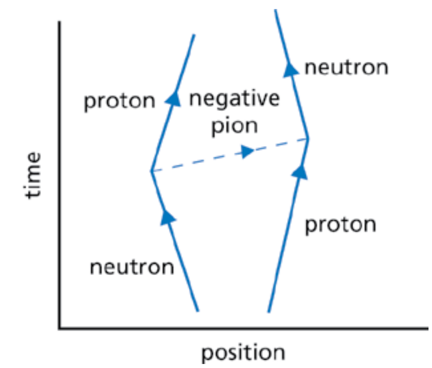
11.a)

The diagram will be identical to the Feynman diagram for the attraction of protons in the student textbook, except the protons will be labeled neutrons.

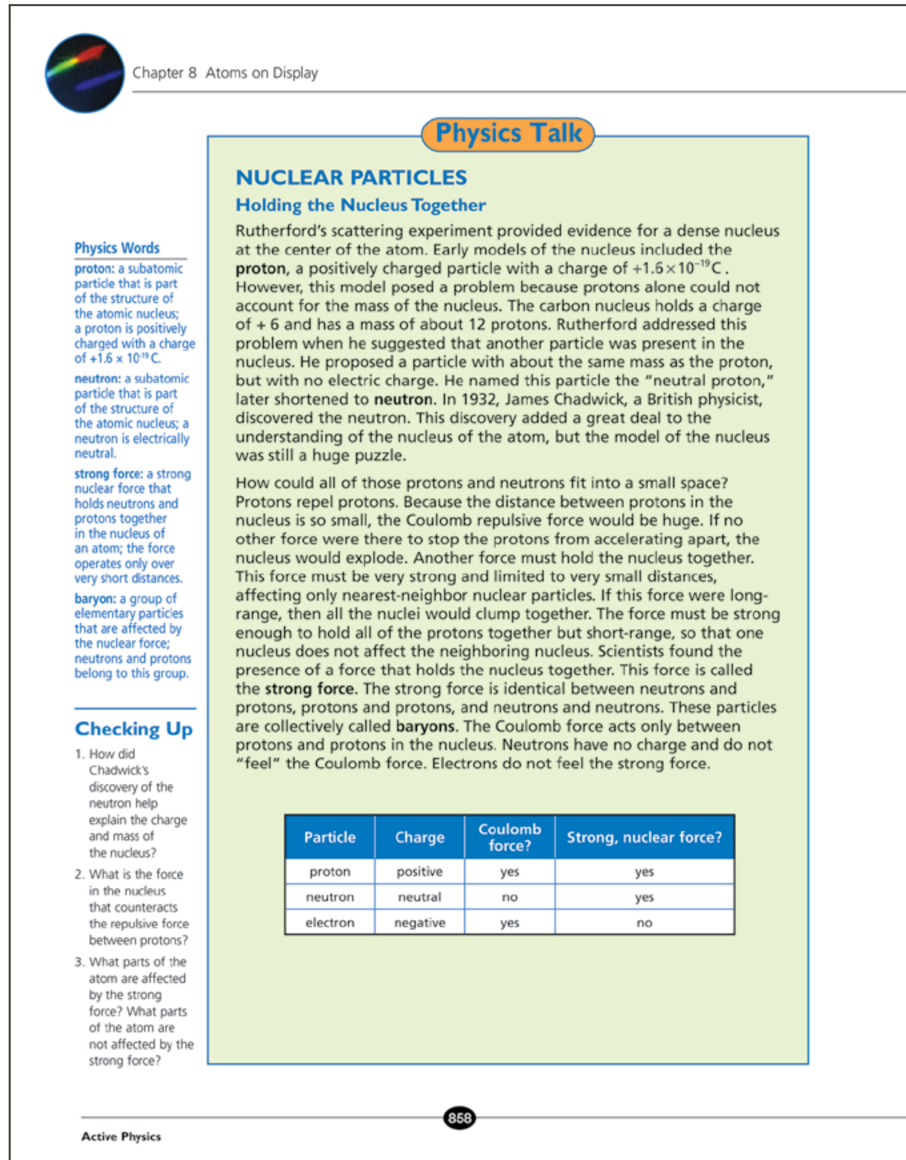
12.a)



Physics Talk

Students read about the evidence provided for the presence of nuclear particles and the forces that hold them together. The *Physics Talk* gives a brief history of how neutrons were discovered and explains how the forces acting between protons and protons, protons and neutrons, and neutrons and neutrons hold these particles together. The concept of strong force emerges gradually and students are given a succinct picture of why the nuclear particles do not clump together and do not escape away from each other.

For students to distinguish between different nuclear forces, have them study the table provided at the end of this section in the student text. Determine if students understand why the repulsive Coulomb force between protons cannot act alone. Ask them to describe strong force and how its presence explains why the nucleus does not explode. Emphasize that neutrons have no charge, which is why they do not feel the Coulomb force, but only experience the strong force in the nucleus. Encourage students to write the definitions of new physics terms that are introduced in this section.



Physics Talk

NUCLEAR PARTICLES

Holding the Nucleus Together

Rutherford's scattering experiment provided evidence for a dense nucleus at the center of the atom. Early models of the nucleus included the **proton**, a positively charged particle with a charge of $+1.6 \times 10^{-19}$ C. However, this model posed a problem because protons alone could not account for the mass of the nucleus. The carbon nucleus holds a charge of + 6 and has a mass of about 12 protons. Rutherford addressed this problem when he suggested that another particle was present in the nucleus. He proposed a particle with about the same mass as the proton, but with no electric charge. He named this particle the "neutral proton," later shortened to **neutron**. In 1932, James Chadwick, a British physicist, discovered the neutron. This discovery added a great deal to the understanding of the nucleus of the atom, but the model of the nucleus was still a huge puzzle.

How could all of those protons and neutrons fit into a small space? Protons repel protons. Because the distance between protons in the nucleus is so small, the Coulomb repulsive force would be huge. If no other force were there to stop the protons from accelerating apart, the nucleus would explode. Another force must hold the nucleus together. This force must be very strong and limited to very small distances, affecting only nearest-neighbor nuclear particles. If this force were long-range, then all the nuclei would clump together. The force must be strong enough to hold all of the protons together but short-range, so that one nucleus does not affect the neighboring nucleus. Scientists found the presence of a force that holds the nucleus together. This force is called the **strong force**. The strong force is identical between neutrons and protons, protons and protons, and neutrons and neutrons. These particles are collectively called **baryons**. The Coulomb force acts only between protons and protons in the nucleus. Neutrons have no charge and do not "feel" the Coulomb force. Electrons do not feel the strong force.

Particle	Charge	Coulomb force?	Strong, nuclear force?
proton	positive	yes	yes
neutron	neutral	no	yes
electron	negative	yes	no

Physics Words

proton: a subatomic particle that is part of the structure of the atomic nucleus; a proton is positively charged with a charge of $+1.6 \times 10^{-19}$ C.

neutron: a subatomic particle that is part of the structure of the atomic nucleus; a neutron is electrically neutral.

strong force: a strong nuclear force that holds neutrons and protons together in the nucleus of an atom; the force operates only over very short distances.

baryon: a group of elementary particles that are affected by the nuclear force; neutrons and protons belong to this group.

Checking Up

1. How did Chadwick's discovery of the neutron help explain the charge and mass of the nucleus?
2. What is the force in the nucleus that counteracts the repulsive force between protons?
3. What parts of the atom are affected by the strong force? What parts of the atom are not affected by the strong force?

Checking Up

1.

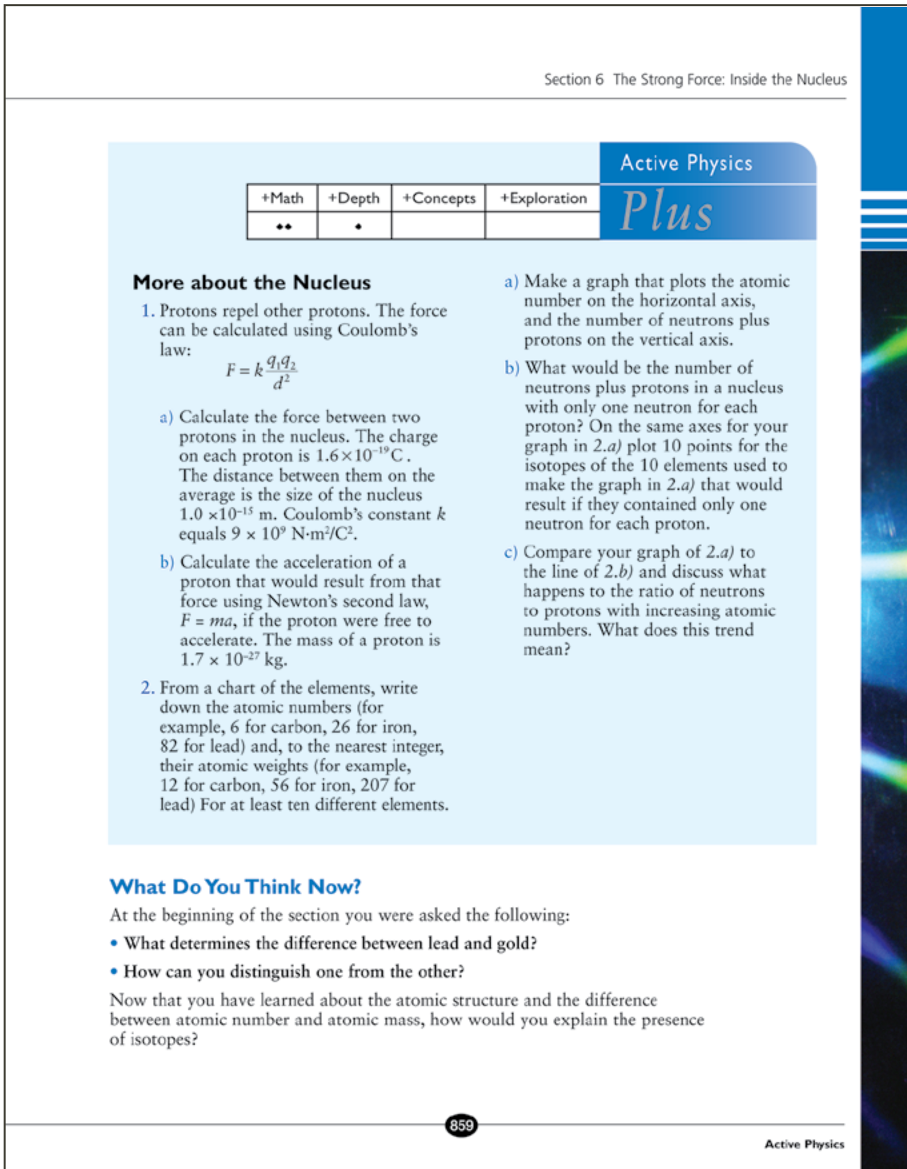
Chadwick's discovery of the neutron allowed scientists to reconcile the charge in the nucleus with the charge on the electrons circling the nucleus to account for a neutral atom. In addition, when the mass of the protons and the mass of the neutrons were added, it agreed with the observed mass of the nucleus.

2.

The strong force, which acts over an extremely short distance, is the force that holds protons together in the nucleus and counteracts the repulsive Coulomb force between protons.

3.

Protons and neutrons are affected by the strong force (baryons), and it has no effect on the electrons orbiting the nucleus.


Section 6 The Strong Force: Inside the Nucleus

Active Physics Plus

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••	•		

More about the Nucleus

1. Protons repel other protons. The force can be calculated using Coulomb's law:
$$F = k\frac{q_1 q_2}{d^2}$$
   a) Calculate the force between two protons in the nucleus. The charge on each proton is 1.6×10^{-19} C. The distance between them on the average is the size of the nucleus 1.0×10^{-15} m. Coulomb's constant k equals 9×10^9 N·m²/C².
   b) Calculate the acceleration of a proton that would result from that force using Newton's second law, $F = ma$, if the proton were free to accelerate. The mass of a proton is 1.7×10^{-27} kg.
2. From a chart of the elements, write down the atomic numbers (for example, 6 for carbon, 26 for iron, 82 for lead) and, to the nearest integer, their atomic weights (for example, 12 for carbon, 56 for iron, 207 for lead) For at least ten different elements.
   a) Make a graph that plots the atomic number on the horizontal axis, and the number of neutrons plus protons on the vertical axis.
   b) What would be the number of neutrons plus protons in a nucleus with only one neutron for each proton? On the same axes for your graph in *2.a)* plot 10 points for the isotopes of the 10 elements used to make the graph in *2.a)* that would result if they contained only one neutron for each proton.
   c) Compare your graph of *2.a)* to the line of *2.b)* and discuss what happens to the ratio of neutrons to protons with increasing atomic numbers. What does this trend mean?

What Do You Think Now?

At the beginning of the section you were asked the following:

- **What determines the difference between lead and gold?**
- **How can you distinguish one from the other?**

Now that you have learned about the atomic structure and the difference between atomic number and atomic mass, how would you explain the presence of isotopes?

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Active Physics

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Students calculate the Coulomb force between two protons in the nucleus and the acceleration of the proton if the proton were free to accelerate under the influence of this force. They plot the atomic number of 10 different elements vs. the number of neutrons and protons each nucleus would contain if the neutron number always equaled the proton number.

On the same set of axes, students then plot the atomic number of the same 10 isotopes against the actual number of neutrons in their nuclei to demonstrate the necessity of extra neutrons in the nucleus to maintain nuclear stability as atomic number and mass increase.

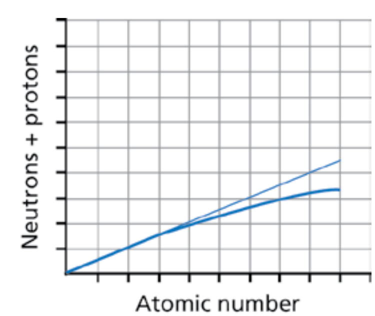
1.a) and b)

$$F = \frac{kq_1q_2}{d^2} = \frac{\left(9\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2\right)\left(1.6\times10^{-19}\ \text{C}\right)^2}{\left(1.0\times10^{-15}\ \text{m}\right)^2}$$
$$= 230\ \text{N}$$

$$a = F/m = \frac{230\ \text{N}}{1.7\times10^{-27}\ \text{kg}} = 1.36\times10^{29}\ \text{m/s}^2$$

2.a)

The student graphs will vary somewhat depending upon the choice of elements. The general shape of the graph should be as shown below. Assuming the x-axis and y-axis scales are equal, the graph should have an initial slope of one-half, but the slope will decrease with increasing atomic number as additional neutrons are added to the nucleus. This is shown as the thick line on the graph.



2.b)

The number of neutrons plus protons would be double the number of protons alone. The thin line on the graph represents this relationship if it were true for all elements.

2.c)

As the atomic number of an element increases, additional neutrons must be added to the nucleus to maintain stability.

CHAPTER 8

What Do You Think Now?

Students should now update and revise their answers to the *What Do You Think?* questions. They should be able to explain why lead and gold are different using what they know about atomic mass and atomic number. You may want to share *A Physicist's Response* provided to you and answer questions to clear any doubts students might still have. The *What Do You Think Now?* answers should articulate the difference in the physical characteristics of these two elements and what nuclear properties make them different. Let students know that you will be determining whether they have reached an understanding of the physics concepts from their answers; therefore, they must write their responses carefully, making sure that they include an explanation of how nuclear particles determine the characteristics of an element.

Physics

Essential Questions

What does it mean?

The nucleus has many protons in a tiny space. How is it that the repulsion between the positive charges does not cause the protons to move away from each other, thereby destroying the nucleus?

How do you know?

What evidence do you have that the electrostatic force between protons exists at very large distances, but the strong, nuclear force exists only at small distances?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Force and motion	Change and constancy	* Good, clear, explanation, no more complex than necessary

* Physicists explain motion and stability in terms of forces. List five forces that you have encountered in your study of physics. Newton's second law states that accelerations are caused by forces. Why did physicists decide that it was preferable to invent a new force (the strong, nuclear force) than to say that Newton's second law does not work inside the nucleus?

Why should you care?

The nucleus is a "battle" of two forces—the repulsive Coulomb force between protons and the attractive strong, nuclear force, the strong force, between protons. How can you depict this battle in a museum display that will both capture people's attention and instruct them as well?

Reflecting on the Section and the Challenge

The nucleus is a crowded place. It contains all of the protons and neutrons of the atom. These protons and neutrons are held together by a strong, nuclear force, called the strong force. The strong force is short-range and very attractive. In a stable nucleus, the strong, nuclear force balances the Coulomb repulsive force between protons. Communicating the size of the nucleus and how it is held together will be quite a creative challenge.

Physics to Go

1. In the notation for a carbon nucleus $^{13}_{6}C$, what do each of the numbers represent?
2. In "nuclear notation" a proton is represented as $^{1}_{1}p$ and a neutron is represented as $^{1}_{0}n$.
   a) Why do they both have superscripts of one?

Physics Essential Questions

What does it mean?

The repulsive force is very large because of the small distances between protons, but is very small in comparison to the attractive nuclear force between these protons.

How do you know?

In the *Investigate* of *Section 1* of this chapter you observed the electrostatic force when pieces of tape repel each other and when lightning strikes. This demonstrates the long-range nature of electrical forces. If the nuclear force was long range, then this force would be strong enough to attract other nuclei, making one large nucleus. There would be no limit to the size of a nucleus when neighboring nuclei would combine. Since you didn't observe this, the strong force must be short-range.

Why do you believe?

Five forces that we have encountered are gravitational force, electrostatic force, magnetic force, tension forces, and normal forces.

Why should you care?

Have two people pull on a rope and ask them to explain how their forces and the tension in the rope act. Like protons, they are pulling (repulsive Coulomb electrostatic force) and the tension in the rope is pulling (attractive nuclear force) them.

Reflecting on the Section and the Challenge

Allow students time to read and reflect on what they have learned so far. Ask them to make a list of the new physics terms they have been introduced to in this section. Determine if students understand the necessity of a short-range attractive force in the nucleus. Because the physics of how forces are transmitted is a complex phenomenon to grasp in the beginning, you may want to discuss the significance of the Feynman diagrams and how students understand the exchange of virtual particles.

Encourage them to review the *What Do You See?* illustration at the beginning of this section. Point out that even though the force of gravity is depicted as a heavy person, the mass of an entire planet is needed for this force. In reality, gravity is the weakest of these forces. Emphasize that their *Chapter Challenge* display requires that they also explain how the nucleus is held together.

Physics to Go

1.

The 6 represents 6 protons and 6 electrons; the 13 represents the sum of the protons and neutrons. Since there are 6 protons, there must be $13 - 6 = 7$ neutrons.

2.a)

Both have a mass of 1.

NOTES

CHAPTER 8

NOTES

2.b)

The proton has a charge of 1; the neutron has no charge.

3.a)

All have 6 protons and 6 electrons; the number of neutrons are 6, 7, 8.

3.b)

All have 20 protons and 20 electrons; the numbers of neutrons are 20, 21, and 22.

3.c)

Both have 92 protons and 92 electrons; the numbers of neutrons are 143 and 146.

4.

$$F = kq_1q_2/d^2 = \frac{\left(9\times10^{9}\ \mathrm{N\cdot m^2/C^2}\right)\left(1.6\times10^{-19}\ \mathrm{C}\right)^2}{\left(6\times10^{-14}\ \mathrm{m}\right)^2}$$

$= 0.064\ \mathrm{N}$

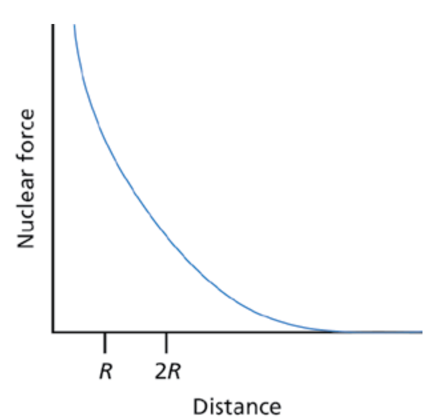
5.a)

$$F = kq_1q_2/d^2 = \frac{\left[\left(9\times10^{9}\ \mathrm{N\cdot m^2/C}\right)\left(1.6\times10^{-19}\ \mathrm{C}\right)\times\left(-1.6\times10^{-19}\ \mathrm{C}\right)\right]}{\left(8\times10^{-9}\ \mathrm{m}\right)^2}$$

$= 3.6\times10^{-12}\ \mathrm{N}$

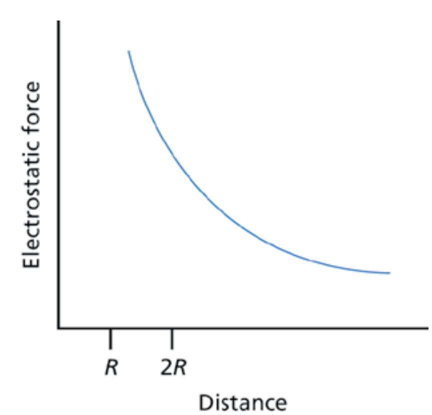
6.

A graph of the force vs. distance between protons should show the force being large when the protons touch or overlap, but zero when the protons do not touch. The graph would appear similar to the one below.



7.

The graph is shown below. The force falls off much more slowly than the nuclear force with distance.



Section 6 The Strong Force: Inside the Nucleus

b) Why do they have different subscripts?

3. Isotopes are elements that have identical atomic numbers but different atomic masses. For the following sets of isotopes, list the number of protons, neutrons, and electrons:

a) $^{12}_{6}C$, $^{13}_{6}C$, $^{14}_{6}C$

b) $^{40}_{20}Ca$, $^{41}_{20}Ca$, $^{42}_{20}Ca$

c) $^{235}_{92}U$, $^{238}_{92}U$

4. Calculate the electrostatic force between two protons that are separated by 6×10^{-14} m within the nucleus.

5. Calculate the electrostatic force between an electron and a proton that are separated by 8×10^{-9} m in an atom.

6. Sketch a graph showing how the nuclear force between two protons varies over distance.

7. Sketch a graph showing how the electrostatic force between two protons varies over distance.

8. Complete a chart indicating if the following pairs of particles interact by the electrostatic force and/or the nuclear force: proton-proton; proton-electron; proton-neutron; neutron-electron; electron-electron; neutron-neutron.

9. Two protons are separated by 1×10^{-15} m in a nucleus.

a) Calculate the gravitational force between them.

b) Calculate the electrostatic force between them.

c) Can the gravitational force be responsible for holding the nucleus together? Explain.

10. When your fingertips touch, your skin deforms. Explain why this happens and why the deformation increases when you press harder.

11. *Preparing for the Chapter Challenge*
Could a museum exhibit help visitors understand how the nuclear force is able to hold the nucleus together but not pull neighboring nuclei together? Could it be interactive? Could it capture people's attention within 30 s? Describe such an exhibit.

Inquiring Further

Chadwick's experiment

Prepare a research report and/or a simulation of the experiment that Chadwick performed to discover the neutron in 1932.

8.

Particles interacting	Electrostatic force interaction	Nuclear force interaction
Proton-proton	Yes	Yes
Proton-electron	Yes	No
Proton-neutron	No	Yes
Neutron-electron	No	No
Electron-electron	Yes	No
Neutron-neutron	No	Yes

9.a)

$$F_G = Gm_1m_2/r^2 = \frac{\left[\left(6.67 \times 10^{-11}\ \text{N} \cdot \text{m}^2/\text{kg}^2\right) \times \left(1.7 \times 10^{-27}\ \text{kg}\right)^2\right]}{\left(1 \times 10^{-15}\ \text{m}\right)^2}$$

$$= 1.9 \times 10^{-34}\ \text{N}$$

9.b)

$$F = \frac{kq_1q_2}{d^2} = \frac{\left(9 \times 10^9\ \text{N} \cdot \text{m}^2/\text{C}^2\right)\left(1.6 \times 10^{-19}\ \text{C}\right)^2}{\left(1 \times 10^{-15}\ \text{m}\right)^2}$$

$$= 230\ \text{N}$$

9.c)

The gravitational force cannot be responsible for holding the nucleus together. The gravitational force is attractive but much too weak to overcome the electrostatic force.

10.

The electrons in one fingertip repel the electrons in the other fingertip and the skin gets depressed.

11.

Student answers will vary.

Inquiring Further

Students report on the discovery of the neutron by James Chadwick. A brief summary of the experiment is that Chadwick used alpha particles to bombard berylium, which ejected unknown particles, which were not affected by electric or magnetic fields (thus uncharged). He then allowed these unknown particles to strike paraffin, which has many hydrogen atoms with only a single proton in the nucleus. When the unknown rays struck the paraffin, protons were discovered being ejected. After measuring the charge and velocity of the ejected protons, Chadwick used the principles of conservation of energy and mass to show that the unknown, uncharged particle had to have a mass almost identical to that of a proton.

SECTION 6 QUIZ

8-6b **Blackline Master**

1. An atom of zinc is indicated by the notation $^{66}_{30}\text{Zn}$. The number of protons in the zinc nucleus is

a) 30. b) 36.

c) 66. d) 96.

2. Which atoms in the groups below (all marked with the symbol X) could be isotopes?

a) $^{25}_{12}\text{X}$ and $^{25}_{10}\text{X}$ b) $^{25}_{12}\text{X}$ and $^{27}_{12}\text{X}$

c) $^{25}_{11}\text{X}$ and $^{26}_{10}\text{X}$ d) $^{25}_{10}\text{X}$ and $^{26}_{11}\text{X}$

3. Which statement below best describes the forces that act inside the nucleus of an atom?

a) The Coulomb force tries to push the nucleus apart while the strong force tries to hold the nucleus together.

b) The strong force tries to push the nucleus apart while the Coulomb force tries to hold the nucleus together.

c) The strong force and the Coulomb force try to push the nucleus apart while gravity tries to hold the nucleus together.

d) The strong force tries to push the nucleus apart while gravity and the Coulomb force try to hold it together.

4. The strong nuclear force acts upon which of the following particles?

a) protons, electrons and neutrons b) protons and electrons

c) neutrons and electrons d) protons and neutrons

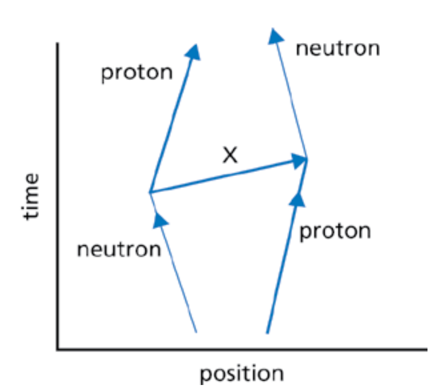
5. In the Feynman diagram at right, a particle (X) is passed between a proton and a neutron. According to the diagram particle X

a) must be positive because a proton is converted into a neutron.

b) must be negative, because a proton is converted into a neutron.

c) must be neutral by conservation of charge.

d) can be either positive or negative.



SECTION 6 QUIZ ANSWERS

1. a) 30. The number of protons is also known as the atomic number, and is the subscript number in the atom's symbol.

2. b) ${}^{25}_{12}X$ and ${}^{27}_{12}X$. Isotopes of an element have the same number of protons, but different numbers of neutrons. In the atomic symbols, this means that the lower number has to be the same for them to be isotopes.

3. a) The Coulomb force tries to push the nucleus apart while the strong force tries to hold the nucleus together. Inside the nucleus, the attractive force that holds the particles inside the nucleus together is the strong force. The force associated with electric repulsion (the Coulomb force) tries to repel the protons and push the nucleus apart. Gravity is far too weak a force to hold the nucleus together against the electric force.

4. d) protons and neutrons. The strong nuclear force only acts upon baryons (protons and neutrons) and does not affect electrons.

5. b) must be negative, because a proton is converted into a neutron. In the diagram, the arrow shows the direction of the path of travel of the particle. When the particle is passed from the neutron on the left side to the proton on the right side, the neutron is converted into a proton. To do this, a negative charge equal to the charge on a proton must have been removed from the neutron and sent over to the proton on the other side. When this negative particle is absorbed by the proton, it cancels its positive charge and converts the proton into a neutron.