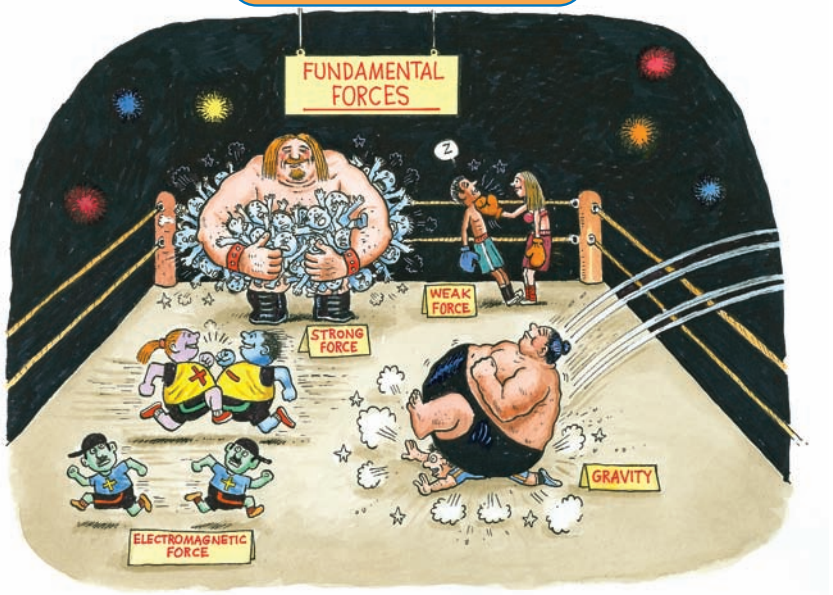
Section 6 The Strong Force: Inside the Nucleus

What Do You See?



Learning Outcomes

In this section, you will

- **Calculate** the number of protons, electrons, and neutrons in a neutral atom, given the atomic number and atomic mass.
- **Calculate** the Coulomb force of repulsion between protons in a nucleus.
- **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.

What Do You Think?

The alchemist's dream has always been to turn cheap lead into valuable gold.

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

Record your ideas about these questions in your *Active Physics* log. Be prepared to discuss your responses with your small group and your class.

Investigate

In this *Investigate*, you will learn more about the different parts of an atom. You will draw models to understand the structure of a nucleus and what is meant by atomic mass. You will investigate the presence of atoms with the same atomic number but different atomic mass. The investigation will help you understand the forces holding the particles together in the nucleus.

1. Recall that the nucleus has all the positive charge, due to positively charged particles called protons, and almost all the mass of the atom. The simplest atom is an atom of the chemical element hydrogen. The hydrogen atom has one proton and one electron, which orbits the nucleus in the pattern you examined earlier.

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 ${}^{35}_{17}\mathrm{Cl}$. The lower number in ${}^{35}_{17}\mathrm{Cl}$ 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 ${}^{35}_{17}\mathrm{Cl}$.

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

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

6. Consider the two carbon atoms ${}^{12}_{6}\mathrm{C}$ and ${}^{14}_{6}\mathrm{C}$. 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 ${}^{12}_{6}\mathrm{C}$ and ${}^{14}_{6}\mathrm{C}$.

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 $2R$? What happens where d is greater than $2R$?

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.

- 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?

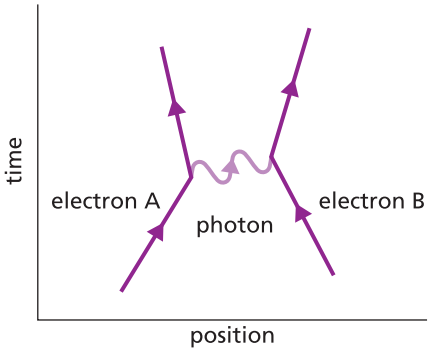
   b) How is the gravitational force between the penny and Earth communicated? Write down your thoughts on this question.

   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.

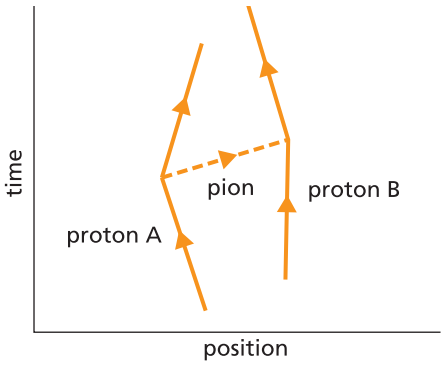
    b) Draw a Feynman diagram of a proton and proton repelling.

    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.

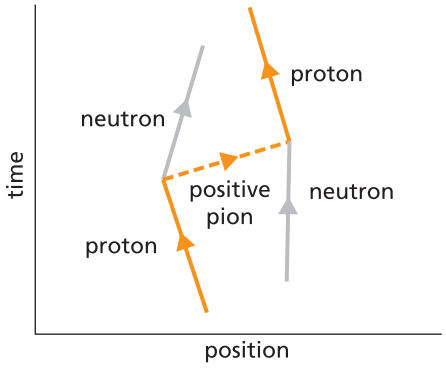
The protons and neutrons exchange mesons; the protons and protons exchange mesons; the neutrons and neutrons exchange mesons.

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.



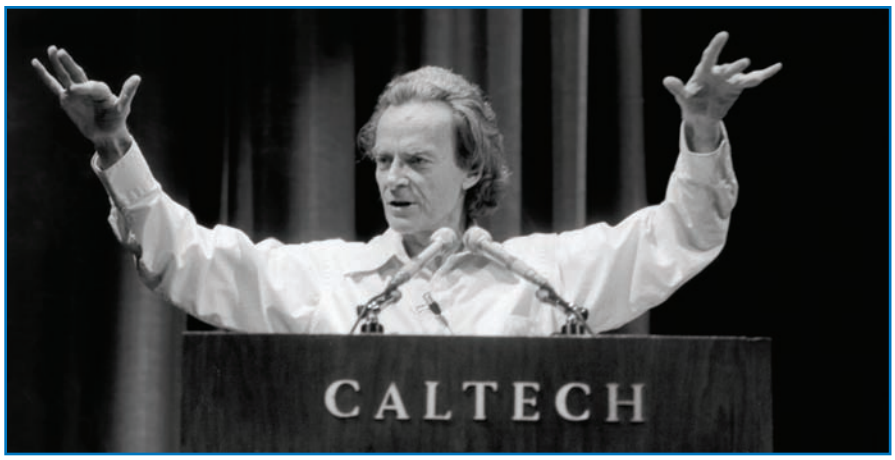
a) Draw the Feynman diagram for the attractive strong force between 2 neutrons.

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.



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.



Richard Feynman, Nobel Laureate.

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?

Active Physics *Plus*

+Math	+Depth	+Concepts	+Exploration
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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.

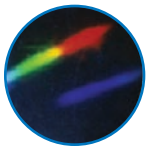
   c) Compare your graph of *2.a)* to the line of *2.b)* and discuss what happens to the ratio of neutrons to protons with increasing atomic numbers. What does this trend mean?

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?



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?

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 $6\times10^{-14}\,\text{m}$ within the nucleus.

5. Calculate the electrostatic force between an electron and a proton that are separated by $8\times10^{-9}\,\text{m}$ 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 $1\times10^{-15}\,\text{m}$ 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.