22.2 Nuclear Forces and Radioactivity

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe the structure and forces present within the nucleus
- Explain the three types of radiation
- Write nuclear equations associated with the various types of radioactive decay

Teacher Support

Teacher Support The learning objectives in this section will help your students master the following standards:

- (5) Science concepts. The student knows the nature of forces in the physical world. The student is expected to:
  - (H) describe evidence for and effects of the strong and weak nuclear forces in nature.
- (8) Science concepts. The student knows simple examples of atomic, nuclear, and quantum phenomena. The student is expected to:
  - (B) compare and explain the emission spectra produced by various atoms; and
  - (C) describe the significance of mass-energy equivalence and apply it in explanations of phenomena such as nuclear stability, fission, and fusion.

Section Key Terms

Teacher Support

Teacher Support [BL][OL][AL]As in the beginning of Section 1, have students create a list of facts they have learned about the atom. Have the students update their list throughout this section.

There is an ongoing quest to find the substructures of matter. At one time, it was thought that atoms would be the ultimate substructure. However, just when the first direct evidence of atoms was obtained, it became clear that they have a substructure and a tiny nucleus. The nucleus itself has spectacular characteristics. For example, certain nuclei are unstable, and their decay emits radiations with energies millions of times greater than atomic energies. Some of the mysteries of nature, such as why the core of Earth remains molten and how the Sun produces its energy, are explained by nuclear phenomena. The exploration of radioactivity and the nucleus has revealed new fundamental particles, forces, and conservation laws. That exploration has evolved into a search for further underlying structures, such as quarks. In this section, we will explore the fundamentals of the nucleus and nuclear radioactivity.

The Structure of the Nucleus

At this point, you are likely familiar with the neutron and proton, the two fundamental particles that make up the nucleus of an atom. Those two particles, collectively called nucleons, make up the small interior portion of the atom. Both particles have nearly the same mass, although the neutron is about two parts in 1,000 more massive. The mass of a proton is equivalent to 1,836 electrons, while the mass of a neutron is equivalent to that of 1,839 electrons. That said, each of the particles is significantly more massive than the electron.

When describing the mass of objects on the scale of nucleons and atoms, it is most reasonable to measure their mass in terms of atoms. The atomic mass unit (u) was originally defined so that a neutral carbon atom would have a mass of exactly 12 u. Given that protons and neutrons are approximately the same mass, that there are six protons and six neutrons in a carbon atom, and that the mass of an electron is minuscule in comparison, measuring this way allows for both protons and neutrons to have masses close to 1 u. Table 22.1 shows the mass of protons, neutrons, and electrons on the new scale.

Tips For Success

For most conceptual situations, the difference in mass between the proton and neutron is insubstantial. In fact, for calculations that require fewer than four significant digits, both the proton and neutron masses may be considered equivalent to one atomic mass unit. However, when determining the amount of energy released in a nuclear reaction, as in Alpha Decay Energy Found from Nuclear Masses, the difference in mass cannot be ignored.

Another other useful mass unit on the atomic scale is the MeV/c^2 . While rarely used in most contexts, it is convenient when one uses the equation $E = mc^2$, as will be addressed later in this text.

Table 22.1 Atomic Masses for Multiple Units

To more completely characterize nuclei, let us also consider two other important quantities: the atomic number and the mass number. The atomic number, Z, represents the number of protons within a nucleus. That value determines the elemental quality of each atom. Every carbon atom, for instance, has a Z value of 6, whereas every oxygen atom has a Z value of 8. For clarification, only oxygen atoms may have a Z value of 8. If the Z value is not 8, the atom cannot be oxygen.

The mass number, A, represents the total number of protons and neutrons, or nucleons, within an atom. For an ordinary carbon atom the mass number would be 12, as there are typically six neutrons accompanying the six protons within the atom. In the case of carbon, the mass would be exactly 12 u. For oxygen, with a mass number of 16, the atomic mass is 15.994915 u. Of course, the difference is minor and can be ignored for most scenarios. Again, because the mass of an electron is so small compared to the nucleons, the mass number and the atomic mass can be essentially equivalent. Figure 22.16 shows an example of Lithium-7, which has an atomic number of 3 and a mass number of 7.

Teacher Support

Teacher Support [BL]Students may confuse the terms *mass number* and *atomic number*. Remind them that the mass is based on both protons and neutrons and so mass number is a measure of both combined. The atomic number differentiates between two different atoms, which only protons can do. A few examples showing pictures of nuclei and having students identify the mass and atomic numbers of each should help.

How does the mass number help to differentiate one atom from another? If each atom of carbon has an atomic number of 6, then what is the value of including the mass number at all? The intent of the mass number is to differentiate between various isotopes of an atom. The term isotope refers to the variation of atoms based upon the number of neutrons within their nucleus. While it is most common for there to be six neutrons accompanying the six protons within a carbon atom, it is possible to find carbon atoms with seven neutrons or eight neutrons. Those carbon atoms are respectively referred to as carbon-13 and carbon-14 atoms, with their mass numbers being their primary distinction. The isotope distinction is an important one to make, as the number of neutrons within an atom can affect a number of its properties, not the least of which is nuclear stability.

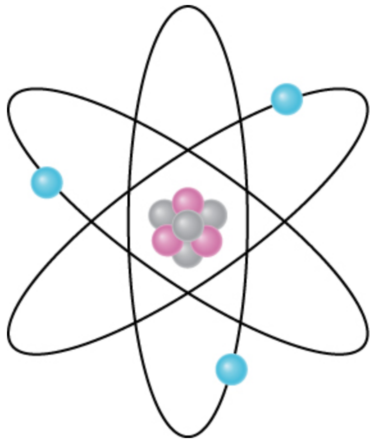

Figure 22.16 Lithium-7 has three protons and four neutrons within its nucleus. As a result, its mass number is 7, while its atomic number is 3. The actual mass of the atom is 7.016 u. Lithium 7 is an isotope of lithium.

Teacher Support

Teacher Support Point out to students that the number of electrons is irrelevant to discussions of mass number, atomic number, and isotopes.

To more easily identify various atoms, their atomic number and mass number are typically written in a form of representation called the nuclide. The nuclide form appears as follows: ${}^{Z}_{A}X_{N}$, where X is the atomic symbol and N represents the number of neutrons.

Let us look at a few examples of nuclides expressed in the ${}^{Z}_{A}X_{N}$ notation. The nucleus of the simplest atom, hydrogen, is a single proton, or H 1 1 (the zero for no neutrons is often omitted). To check the symbol, refer to the periodic table—you see that the atomic number Z of hydrogen is 1. Since you are given that there are no neutrons, the mass number A is also 1. There is a scarce form of hydrogen found in nature called *deuterium*; its nucleus has one proton and one neutron and, hence, twice the mass of common hydrogen. The symbol for deuterium is, thus, ${}^{2}_{1}\mathrm{H}_{2}$. An even rarer—and radioactive—form of hydrogen is called *tritium*, since it has a single proton and two neutrons, and it is written ${}^{3}_{1}\mathrm{H}_{2}$. The three varieties of hydrogen have nearly identical chemistries, but the nuclei differ greatly in mass, stability, and other characteristics. Again, the different nuclei are referred to as isotopes of the same element.

There is some redundancy in the symbols A, X, Z, and N. If the element X is known, then Z can be found in a periodic table. If both A and X are known, then N can also be determined by first finding Z; then, $N = A - Z$. Thus the simpler notation for nuclides is

${}^{A}X,$

which is sufficient and is most commonly used. For example, in this simpler notation, the three isotopes of hydrogen are ^{1}H, ^{2}H, and ^{3}H . For ^{238}U, should we need to know, we can determine that $Z = 92$ for uranium from the periodic table, and thus, $N = 238 - 92 = 146$.

Teacher Support

Teacher Support This explanation is provided to help students understand nomenclature later on in the text. However, it may be useful to have students practice writing nuclide notation to build confidence with the concept.

Radioactivity and Nuclear Forces

In 1896, the French physicist Antoine Henri Becquerel (1852–1908) noticed something strange. When a uranium-rich mineral called pitchblende was placed on a completely opaque envelope containing a photographic plate, it darkened spots on the photographic plate.. Becquerel reasoned that the pitchblende must emit invisible rays capable of penetrating the opaque material. Stranger still was that no light was shining on the pitchblende, which means that the pitchblende was emitting the invisible rays continuously without having any energy input! There is an apparent violation of the law of conservation of energy, one that scientists can now explain using Einstein's famous equation $E = mc^2$. It was soon evident that Becquerel's rays originate in the nuclei of the atoms and have other unique characteristics.

To this point, most reactions you have studied have been chemical reactions, which are reactions involving the electrons surrounding the atoms. However, two types of experimental evidence implied that Becquerel's rays did not originate with electrons, but instead within the nucleus of an atom.

First, the radiation is found to be only associated with certain elements, such as uranium. Whether uranium was in the form of an element or compound was irrelevant to its radiation. In addition, the presence of radiation does not vary with temperature, pressure, or ionization state of the uranium atom. Since all of those factors affect electrons in an atom, the radiation cannot come from electron transitions, as atomic spectra do.

The huge energy emitted during each event is the second piece of evidence that the radiation cannot be atomic. Nuclear radiation has energies on the order of 10^6 eV per event, which is much greater than typical atomic energies that are a few eV, such as those observed in spectra and chemical reactions, and more than ten times as high as the most energetic X-rays.

Teacher Support

Teacher Support To emphasize the point that most reactions are chemical, have students brainstorm a list of reactions from chemistry class. Have them describe the changes that cause the reactions to take place. Are the reactions the result of nuclear interactions or electron interactions?

But why would reactions within the nucleus take place? And what would cause an apparently stable structure to begin emitting energy? Was there something special about Becquerel's uranium-rich pitchblende? To answer those questions, it is necessary to look into the structure of the nucleus. Though it is perhaps surprising, you will find that many of the same principles that we observe on a macroscopic level still apply to the nucleus.

Nuclear Stability A variety of experiments indicate that a nucleus behaves something like a tightly packed ball of nucleons, as illustrated in Figure 22.17. Those nucleons have large kinetic energies and, thus, move rapidly in very close contact. Nucleons can be separated by a large force, such as in a collision with another nucleus, but strongly resist being pushed closer together. The most compelling evidence that nucleons are closely packed in a nucleus is that the radius of a nucleus, r, is found to be approximately

$$r = r_o A^{\frac{1}{3}},$$

22.35

where $r_o = 1.2$ femtometer (fm) and A is the mass number of the nucleus.

Note that $r^3 \propto A$. Since many nuclei are spherical, and the volume of a sphere is $V = \left(\frac{4}{3}\right)\pi r^3$, we see that $V \propto A$ —that is, the volume of a nucleus is proportional to the number of nucleons in it. That is what you expect if you pack nucleons so close that there is no empty space between them.

Figure 22.17 Nucleons are held together by nuclear forces and resist both being pulled apart and pushed inside one another. The volume of the nucleus is the sum of the volumes of the nucleons in it, here shown in different colors to represent protons and neutrons.

So what forces hold a nucleus together? After all, the nucleus is very small and its protons, being positive, should exert tremendous repulsive forces on one another. Considering that, it seems that the nucleus would be forced apart, not together!

The answer is that a previously unknown force holds the nucleus together and makes it into a tightly packed ball of nucleons. This force is known as the strong nuclear force. The strong force has such a short range that it quickly fall to zero over a distance of only 10^{-15} meters. However, like glue, it is very strong when the nucleons get close to one another.

Teacher Support

Teacher Support The relationship between the repulsive Coulomb force and the attractive nuclear force can be modeled using a balloon. Squeeze the balloon, or have one student hold a balloon while the other pushes on it. The pressure of the air inside the balloon will model the Coulomb force while the push from the student models the nuclear force.

The balancing of the electromagnetic force with the nuclear forces is what allows the nucleus to maintain its spherical shape. If, for any reason, the electromagnetic force should overcome the nuclear force, components of the nucleus would be projected outward, creating the very radiation that Becquerel discovered!

Understanding why the nucleus would break apart can be partially explained using Table 22.2. The balance between the strong nuclear force and the electromagnetic force is a tenuous one. Recall that the attractive strong nuclear force exists between any two nucleons and acts over a very short range while the weaker repulsive electromagnetic force only acts between protons, although over a larger range. Considering the interactions, an imperfect balance between neutrons and protons can result in a nuclear reaction, with the result of regaining equilibrium.

Table 22.2 Comparing the Electromagnetic and Strong Forces

The radiation discovered by Becquerel was due to the large number of protons present in his uranium-rich pitchblende. In short, the large number of protons caused the electromagnetic force to be greater than the strong nuclear force. To regain stability, the nucleus needed to undergo a nuclear reaction called alpha ( ) decay.

The Three Types of Radiation

Radioactivity refers to the act of emitting particles or energy from the nucleus. When the uranium nucleus emits energetic nucleons in Becquerel's experiment, the radioactive process causes the nucleus to alter in structure. The alteration is called radioactive decay. Any substance that undergoes radioactive decay is said to be radioactive. That those terms share a root with the term *radiation* should not be too surprising, as they all relate to the transmission of energy.

Teacher Support

Teacher Support Students have plenty of preconceptions about radioactivity. Discuss their preconceptions. Are their concerns related to the radioactive decay process or to the energy transmitted in the process?

Radioactivity can be understood as a tendency for a nucleus to reach equilibrium. Discuss with students other instances of objects desiring equilibrium. Such macroscopic interactions may help to make their understanding of radioactivity more tangible.

Alpha Decay Alpha decay refers to the type of decay that takes place when too many protons exist in the nucleus. It is the most common type of decay and causes the nucleus to regain equilibrium between its two competing internal forces. During alpha decay, the nucleus ejects two protons and two neutrons, allowing the strong nuclear force to regain balance with the repulsive electromagnetic force. The nuclear equation for an alpha decay process can be shown as follows.

X Z A N $\rightarrow$ Y Z$-$2 A$-$4 N + H 2 4 e

22.36

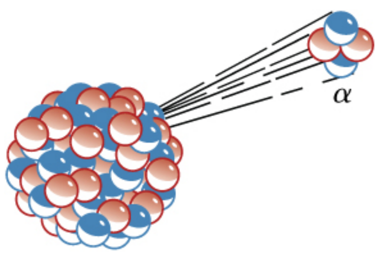

Figure 22.18 A nucleus undergoes alpha decay. The alpha particle can be seen as made up of two neutrons and two protons, which constitute a helium-4 atom.

Three things to note as a result of the above equation:

1. By ejecting an alpha particle, the original nuclide decreases in atomic number. That means that Becquerel's uranium nucleus, upon decaying, is actually transformed into thorium, two atomic numbers lower on the periodic table! The process of changing elemental composition is called transmutation.
2. Note that the two protons and two neutrons ejected from the nucleus combine to form a helium nucleus. Shortly after decay, the ejected helium ion typically acquires two electrons to become a stable helium atom.
3. Finally, it is important to see that, despite the elemental change, physical conservation still takes place. The mass number of the new element and the alpha particle together equal the mass number of the original element. Also, the net charge of all particles involved remains the same before and after the transmutation.

Teacher Support

Teacher Support Differentiate between ionization and transmutation to reinforce that alpha radiation is an elemental change.

Beta Decay Like alpha decay, beta (β) decay also takes place when there is an imbalance between neutrons and protons within the nucleus. For beta decay, however, a neutron is transformed into a proton and electron or vice versa. The transformation allows for the total mass number of the atom to remain the same, although the atomic number will increase by one (or decrease by one). Once again, the transformation of the neutron allows for a rebalancing of the strong nuclear and electromagnetic forces. The nuclear equation for a beta decay process is shown below.

$${}_{Z}^{A}X_{N} \rightarrow {}_{Z+1}^{A} Y_{N-1} + e + v$$

The symbol v in the equation above stands for a high-energy particle called the neutrino. A nucleus may also emit a positron, and in that case Z decreases and N increases. It is beyond the scope of this section and will be discussed in further detail in the chapter on particles. It is worth noting, however, that the mass number and charge in all beta-decay reactions are conserved.

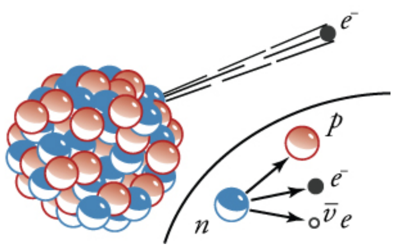

Figure 22.19 A nucleus undergoes beta decay. The neutron splits into a proton, electron, and neutrino. This particular decay is called β^{-} decay.

Teacher Support

Teacher Support [AL]The mass number of the nucleus is conserved, but is the mass? Mention that that mass of a proton is slightly less than the mass of the neutron. Have students consider where that mass goes. Note—Not all of it goes to the electron.

Gamma Decay Gamma decay is a unique form of radiation that does not involve balancing forces within the nucleus. Gamma decay occurs when a nucleus drops from an excited state to the ground state. Recall that such a change in energy state will release energy from the nucleus in the form of a photon. The energy associated with the photon emitted is so great that its wavelength is shorter than that of an X-ray. Its nuclear equation is as follows.

$${}_{Z}^{A}X_{N} \rightarrow X_{N} + \gamma$$

22.37

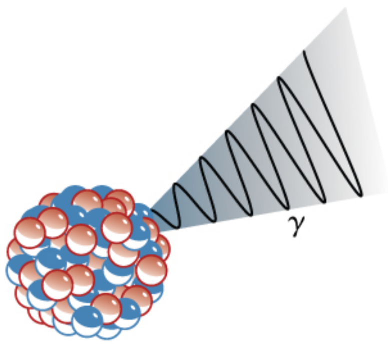

Figure 22.20 A nucleus undergoes gamma decay. The nucleus drops in energy state, releasing a gamma ray.

Teacher Support

Teacher Support [OL][AL]To differentiate between the three types of decay, you can have the students construct a large Venn diagram of their radioactive properties. For students struggling with the idea, it may be easier to have them first construct a table of what they know about each type of decay.

Worked Example

Creating a Decay Equation Write the complete decay equation in ${}^{A}_{Z}X_{N}$ notation for beta decay producing ${}^{137}\text{Ba}$. Refer to the periodic table for values of *Z*.

Strategy

Beta decay results in an increase in atomic number. As a result, the original (or parent) nucleus, must have an atomic number of one fewer proton.

Solution

The equation for beta decay is as follows

X Z A N → Y Z+1 A N−1 +e+v .

22.38

Considering that barium is the product (or daughter) nucleus and has an atomic number of 56, the original nucleus must be of an atomic number of 55. That corresponds to cesium, or Cs.

C 55 137 s N → B 56 137 a N−1 +e+v

22.39

The number of neutrons in the parent cesium and daughter barium can be determined by subtracting the atomic number from the mass number (137 – 55 for cesium, 137 – 56 for barium). Substitute those values for the N and N – *1* subscripts in the above equation.

C 55 137 s 82 → B 56 137 a 81 +e+v

22.40

Discussion

The terms *parent* and *daughter* nucleus refer to the reactants and products of a nuclear reaction. The terminology is not just used in this example, but in all nuclear reaction examples. The cesium-137 nuclear reaction poses a significant health risk, as its chemistry is similar to that of potassium and sodium, and so it can easily be concentrated in your cells if ingested.

Worked Example

Alpha Decay Energy Found from Nuclear Masses Find the energy emitted in the α decay of ^{239}Pu.

Strategy

Nuclear reaction energy, such as released in α decay, can be found using the equation $E = mc^2$. We must first find Δm, the difference in mass between the parent nucleus and the products of the decay.

The mass of pertinent particles is as follows

^{239}Pu: 239.052157 u

^{235}U: 235.043924 u

^{4}He: 4.002602 u.

Solution

The decay equation for ^{239}Pu is

P 239 u→ U 235 + H 4 e .

22.41

Determine the amount of mass lost between the parent and daughter nuclei.

$$\Delta m = m\left(^{239}\text{P u}\right) - \left(m\left(^{239}\text{U}\right)\ +\ m\left(^{4}\text{He}\right)\right)$$
$$\Delta m = 239.052157\ \text{u} - (235.043924\ \text{u} + 4.002602\ \text{u})$$
$$\Delta m = 0.0005631\ \text{u}$$

22.42

Now we can find E by entering Δm into the equation.

$E = (\Delta m)\, c^2 = (0.005631 \text{ u})\, c^2$

22.43

And knowing that $1 \text{ u} = 931.5 \text{ meV}/c^2$, we can find that

$E = (0.005631)\left(931.5 \text{ MeV}/c^2\right)\left(c^2\right) = 5.25 \text{ MeV}.$

22.44

Discussion

The energy released in this α decay is in the MeV range, about 10^6 times as great as typical chemical reaction energies, consistent with previous discussions. Most of the energy becomes kinetic energy of the α particle (or ^{4}He nucleus), which moves away at high speed.

The energy carried away by the recoil of the ^{235}U nucleus is much smaller, in order to conserve momentum. The ^{235}U nucleus can be left in an excited state to later emit photons (γ rays). The decay is spontaneous and releases energy, because the products have less mass than the parent nucleus.

Properties of Radiation

The charges of the three radiated particles differ. Alpha particles, with two protons, carry a net charge of +2. Beta particles, with one electron, carry a net charge of –1. Meanwhile, gamma rays are solely photons, or light, and carry no charge. The difference in charge plays an important role in how the three radiations affect surrounding substances.

Teacher Support

Teacher Support [OL][AL]Show table 22.3 to students after they read the preceding paragraph. See if they can explain the penetration distances based on charge difference alone.

[BL]-See if students can come up with a relationship between penetration distance and particle charge. If there were a radiation particle with a charge of –4, what would you expect its penetration distance to be?

Alpha particles, being highly charged, will quickly interact with ions in the air and electrons within metals. As a result, they have a short range and short penetrating distance in most materials. Beta particles, being slightly less charged, have a larger range and larger penetrating distance. Gamma rays, on the other hand, have little electric interaction with particles and travel much farther. Two diagrams below show the importance of difference in penetration. Table 22.3 shows the distance of radiation penetration, and Figure 22.21 shows the influence various factors have on radiation penetration distance.

Table 22.3 Comparing Ranges of Radioactive Decay

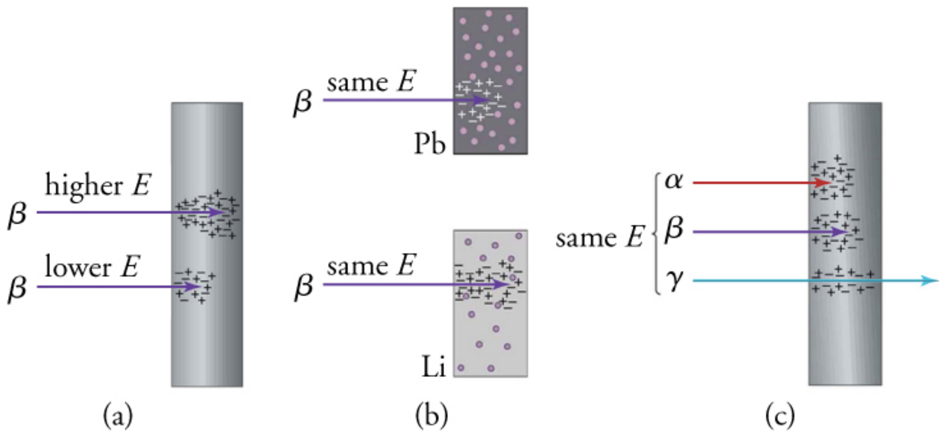

Figure 22.21 The penetration or range of radiation depends on its energy, the material it encounters, and the type of radiation. (a) Greater energy means greater range. (b) Radiation has a smaller range in materials with high electron density. (c) Alphas have the smallest range, betas have a greater range, and gammas have the greatest range.

Links To Physics

Radiation Detectors The first direct detection of radiation was Becquerel's darkened photographic plate. Photographic film is still the most common detector of ionizing radiation, being used routinely in medical and dental X-rays. Nuclear radiation can also be captured on film, as seen in Figure 22.22. The mechanism for film exposure by radiation is similar to that by photons. A quantum of energy from a radioactive particle interacts with the emulsion and alters it chemically, thus exposing the film. Provided the radiation has more than the few eV of energy needed to induce the chemical change, the chemical alteration will occur. The amount of film darkening is related to the type of radiation and amount of exposure. The process is not 100 percent efficient, since not all incident radiation interacts and not all interactions produce the chemical change.

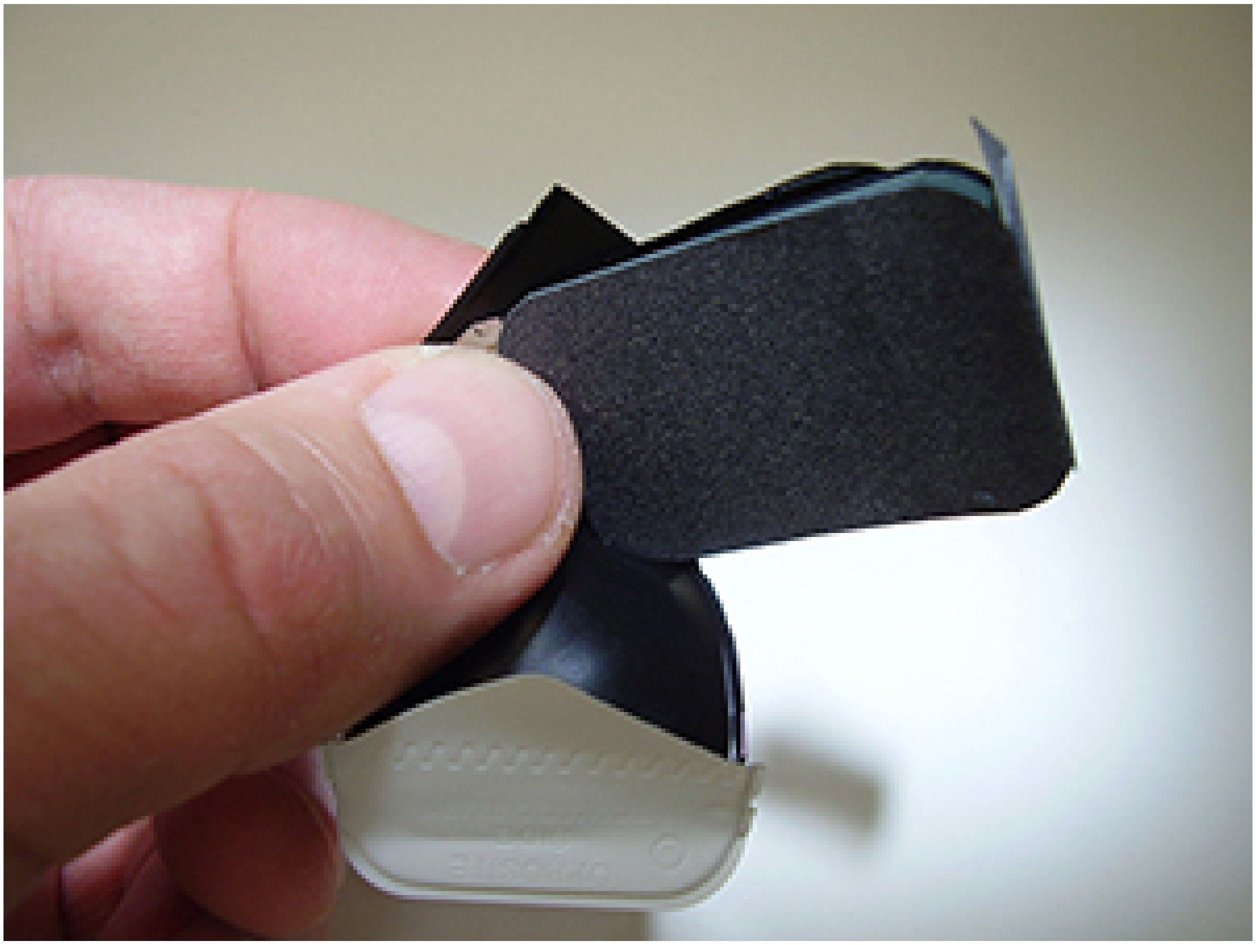

Figure 22.22 Film badges contain film similar to that used in this dental X-ray film. It is sandwiched between various absorbers to determine the penetrating ability of the radiation as well as the amount. Film badges are worn to determine radiation exposure. (credit: Werneuchen, Wikimedia Commons)

Another very common radiation detector is the Geiger tube. The clicking and buzzing sound we hear in dramatizations and documentaries, as well as in our own physics labs, is usually an audio output of events detected by a Geiger counter. These relatively inexpensive radiation detectors are based on the simple and sturdy Geiger tube, shown schematically in Figure 22.23. A conducting cylinder with a wire along its axis is filled with an insulating gas so that a voltage applied between the cylinder and wire produces almost no current. Ionizing radiation passing through the tube produces free ion pairs that are attracted to the wire and cylinder, forming a current that is detected as a count. Not every particle is detected, since some radiation can pass through without producing enough ionization. However, Geiger counters are very useful in producing a prompt output that reveals the existence and relative intensity of ionizing radiation.

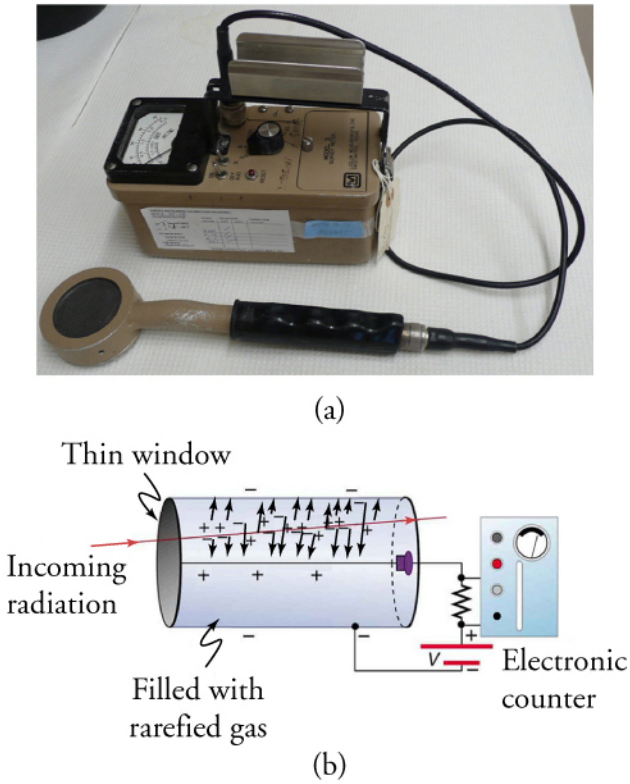

Figure 22.23 (a) Geiger counters such as this one are used for prompt monitoring of radiation levels, generally giving only relative intensity and not identifying the type or energy of the radiation. (credit: Tim Vickers, Wikimedia Commons) (b) Voltage applied between the cylinder and wire in a Geiger tube affects ions and electrons produced by radiation passing through the gas-filled cylinder. Ions move toward the cylinder and electrons toward the wire. The resulting current is detected and registered as a count.

Another radiation detection method records light produced when radiation interacts with materials. The energy of the radiation is sufficient to excite atoms in a material that may fluoresce, such as the phosphor used by Rutherford's group. Materials called scintillators use a more complex process to convert radiation energy into light. Scintillators may be liquid or solid, and they can be very efficient. Their light output can provide information about the energy, charge, and type of radiation. Scintillator light flashes are very brief in duration, allowing the detection of a huge number of particles in short periods of time. Scintillation detectors are used in a variety of research and diagnostic applications. Among those are the detection of the radiation from distant galaxies using satellite-mounted equipment and the detection of exotic particles in accelerator laboratories.

Virtual Physics

Beta Decay Click to view content

Watch beta decay occur for a collection of nuclei or for an individual nucleus. With this applet, individuals or groups of students can compare half-lives!

Check Your Understanding

2.

What leads scientists to infer that the nuclear strong force exists?

a. A strong force must hold all the electrons outside the nucleus of an atom.
b. A strong force must counteract the highly attractive Coulomb force in the nucleus.
c. A strong force must hold all the neutrons together inside the nucleus.
d. A strong force must counteract the highly repulsive Coulomb force between protons in the nucleus.