Answer to Essential Question 29.6: The reaction must satisfy conservation of nucleon number (there are 236 nucleons) and conservation of charge (in this case, there are 92 protons). For both sides of the reaction to have 236 nucleons and 92 protons, the missing piece must have 140 nucleons and 54 protons. The element with 54 protons is xenon so the missing piece is ${}^{140}_{54}\mathrm{Xe}$.

29-7 Applications of Nuclear Physics

Radiocarbon dating

One well-known application of nuclear physics is the use of carbon-14, which is radioactive, to determine the age of artifacts made from materials that used to be alive, such as bowls made of wood. The idea is that when the tree from which the wood was taken was alive, it was exchanging carbon with the atmosphere, and the ratio of carbon-14 to non-radioactive carbon-12 in the wood matched the corresponding ratio in the atmosphere. This ratio is maintained at an approximately constant value of 1 carbon-14 atom to every 10^{12} carbon-12 atoms by cosmic rays that turn nitrogen-14 in the atmosphere into carbon-14. After a tree dies or is cut down, the carbon-14 in the wood decays, decreasing the carbon-14 to carbon-12 ratio. The more time passes, the smaller the carbon-14 to carbon-12 ratio, so the carbon-14 to carbon-12 ratio can be used to estimate the time that has passed since the tree was cut down. This process is called **radiocarbon dating**.

A famous artifact dated using radiocarbon dating is the Shroud of Turin, which was long believed to be the burial cloth of Jesus Christ. Tests on small samples of the fabric indicate that the fabric dates not from 2000 years ago, however, but from around 700 years ago instead.

Carbon-14 decays via the beta-minus process, with a half-life of 5730 years, so radiocarbon dating works well for artifacts with an age ranging from several hundred years old to about 60000 years old, an age range corresponding to a reasonable fraction of the carbon-14 half-life to several times the carbon-14 half-life. To date much older artifacts, such as dinosaur bones, which are about 100 million years old, carbon-14 would not be appropriate, because so many carbon-14 half-lives would have passed in 100 million years that the amount of carbon-14 in the sample would be negligibly small. A similar process to radiocarbon dating can be carried out, however, using an isotope with a much longer half-life than carbon-14.

EXAMPLE 29.7 – Dating a bowl

While on an archeological dig, you uncover an old wooden bowl. With your radiation detector, you measure 560 counts per minute coming from the bowl, each of these counts corresponding to the beta-minus decay of a carbon-14 atom into a nitrogen-14 atom (your detector picks up the fast-moving electron that is emitted from each of these decays). Using the same kind of wood, but from a tree that was recently cut down, you make a similar bowl of the same shape and mass as the one you unearthed at the excavation site. This bowl registers 800 counts per minute in your detector. Estimate the age of the old bowl you unearthed.

SOLUTION

Our working assumption is that the old bowl would also have emitted 760 counts per minute originally, when it was first made from wood from a tree that had been recently cut down. This assumes the ratio of carbon-14 to carbon-12 in our atmosphere has remained constant over time, which is approximately true. Accurate dating involves correcting for effects such as the fluctuation of carbon-14 to carbon-12 in the atmosphere in the past, but we can get a good estimate of the age of the bowl without these corrections. Applying Equation 29.12 gives:

$$560 = 800 e^{-\lambda t} , \quad \text{which becomes} \quad \frac{560}{800} = 0.7 = e^{-\lambda t} .$$

Taking the natural log of both sides gives $\ln(0.7) = -\lambda t$. Bringing in the half-life via Equation 29.11, we get:

$$t = \frac{-\ln(0.7)}{\lambda} = \frac{-\ln(0.7)}{\ln(2)} T_{1/2} = \frac{-\ln(0.7)}{\ln(2)} (5730 \text{ y}) = 2900 \text{ y} .$$

Thus, the site you are exploring contains artifacts from approximately 3000 years ago.

Radiation therapy

A common method of treating cancer is with radiation therapy, which involves treatment with ionizing radiation associated with nuclear decays. For instance, x-rays can be directed at a tumor within the body, damaging the DNA of the cancer cells with the energy deposited by the photons. It is hard to avoid damaging healthy cells with this process, but if the tumor is targeted from various directions the energy deposited in the tumor can be maximized while the damage to surrounding healthy cells is minimized.

Another example of radiation therapy is in the treatment of prostate cancer, in which small radioactive rods, called seeds, are embedded in the prostate, damaging the DNA of the cancer cells with the energy that comes from the decay. The seeds may contain, for example, iodine-125 or palladium-103, which are emitters of gamma rays or x-rays.

Medical imaging – PET and MRI

Two more applications of nuclear physics are **positron emission tomography** (PET) and **magnetic resonance imaging** (MRI). If you get a PET scan (like that in Figure 29.5), you must first take in an isotope that is a positron emitter. A common example is to use fluorodeoxyglucose (FDG), in which the fluorine atom is fluorine-18, which decays via the beta-plus (positron) process with a half-life of about two hours – this short half-life minimizes your exposure to radiation. FDG is taken up by cells that use glucose, so FDG is useful for studying cells with significant glucose uptake, such as those in the brain or in a cancer tumor.

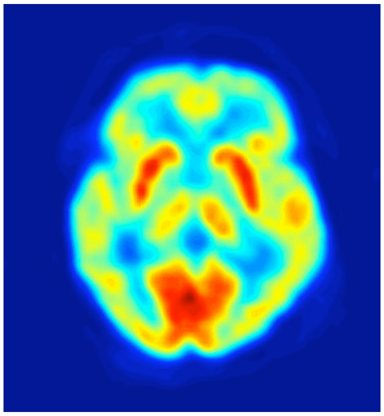

Figure 29.5: An image of a human brain obtained with positron emission tomography. The red and blue areas correspond to high and low positron activity, respectively. Image credit: Jens Langner, via Wikimedia Commons.

When a fluorine-18 atom decays, it emits a positron. The positron and a nearby electron annihilate one another, turning into two high-energy photons (gamma rays), which exit the body in almost exactly opposite directions. If the photons are detected by detectors surrounding the body, the path of the photons can be determined. After many such photon pairs have been detected, areas of high glucose uptake in the body can be reconstructed.

A different process is at work in MRI, in which hydrogen nuclei in our bodies (in water and lipid molecules, in particular) are excited by strong magnetic fields. Signals from these nuclei are then detected, and the signals can be used to create an image of what is going in inside a body being scanned. Such scans are often used to diagnose soft-tissue injuries. The image that opens this chapter shows such an MRI scan.

Related End-of-Chapter Exercises: 12, 26, 27, 35, 58, 59.

Essential Question 29.7: The ratio of carbon-14 to carbon-12 in a wooden implement, unearthed at an archeological dig, is only ¼ as large as it is in a growing tree today. Estimate its age.