Answer to Essential Question 29.5: It is best to use Equation 29.12 to find the number of nuclei remaining after a particular time interval. Equation 29.10 is designed to give the decay rate at a particular instant in time; however, it will give a good approximation of the number of decays that have taken place in a time interval if the time interval is much smaller than the half life.

29-6 Nuclear Fusion and Nuclear Fission

In Section 29-2, we calculated the mass defect for carbon-12, and used that information to determine the binding energy per nucleon for carbon-12. The basic process is:

- Calculate the total mass of the individual neutrons, protons, and electrons in an atom.
- Calculate the mass defect for the atom by subtracting the atomic mass from the total mass of the individual constituents.
- Convert the mass defect from mass to energy, using the conversion factor 931.5 MeV / u. This represents the atom's binding energy, which is almost all in the nucleus.
- Divide the binding energy by the number of nucleons (neutrons plus protons) to find the average binding energy per nucleon.

Following the procedure above, we obtain the graph in Figure 29.4, showing the average binding energy per nucleon for a variety of common isotopes. The most stable isotope, having the largest binding energy per nucleon, is nickel-62, followed closely by iron-58 and iron-56.

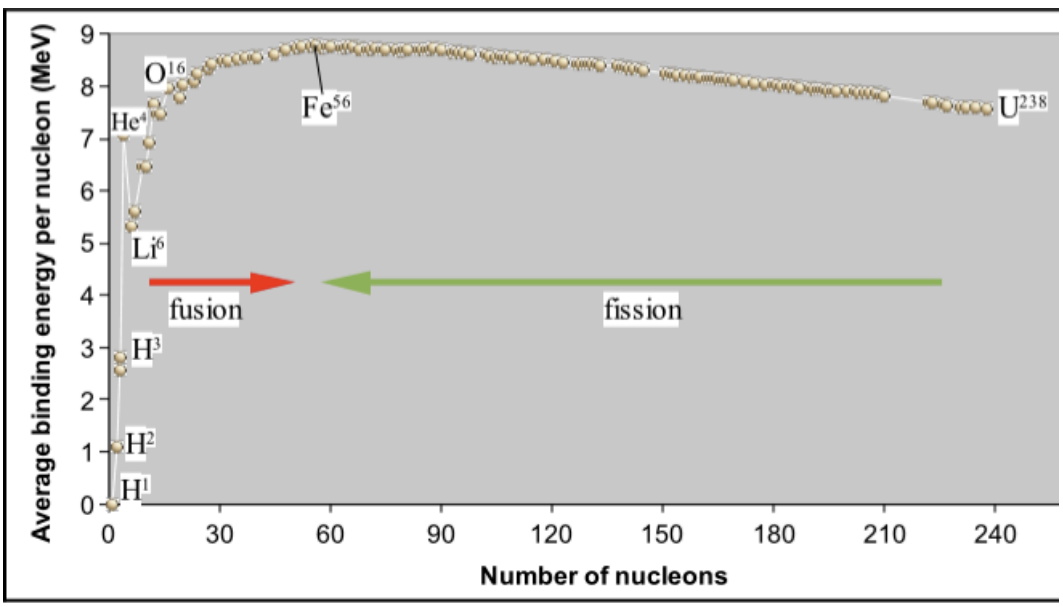

Figure 29.4: A graph of the average binding energy per nucleon for most common isotopes.

Nuclear fusion

The larger the average binding energy per nucleon, the more stable a particular isotope is. Thus, light elements (less than 50 nucleons, say) can, in general, become more stable by joining together to form a nucleus that has more binding energy per nucleon. This process is known as **nuclear fusion**, and it releases a significant amount of energy. Nuclear fusion is the process by which the Sun generates its energy, for instance. Currently, the Sun is made up mostly of hydrogen, which is gradually fusing together to become helium. When the hydrogen is used up, the helium atoms will fuse together with one another, or with other light atoms, to form heavier nuclei. All of these fusion reactions, resulting in atoms with more binding energy per nucleon, produce energy. The process continues for billions of years until the Sun's atoms fuse together to become nickel and iron, which are the most stable elements of all. At this point, the fusion reactions will cease, because the peak of stability will have been reached, and the Sun will, essentially, die of old age.

An example fusion reaction is the fusion of deuterium and tritium, which are both isotopes of hydrogen, into helium. This reaction may well form the basis, in future, of controlled fusion reactions that generate energy in a fusion reactor.

$$ {}_{1}^{2}\mathrm{H} + {}_{1}^{3}\mathrm{H} \Rightarrow {}_{2}^{5}\mathrm{He} \Rightarrow {}_{2}^{4}\mathrm{He} + {}_{0}^{1}\mathrm{n}. $$

The products of this reaction, the helium-4 atom and the neutron, carry away 17.6 MeV between them, 3.5 MeV for the helium atom and 14.1 MeV for the neutron. This is an enormous amount of energy compared to the several eV of energy produced in a typical chemical reaction.

Nuclear fission
At the heavy end of the scale in Figure 29.4, those nuclei with a large number of nucleons can reach a more stable state by splitting apart into smaller pieces that have a higher average energy per nucleon. This process is known as **nuclear fission**, and it is used in nuclear reactors, in well-controlled reactions, to generate energy. In uncontrolled reactions, a chain of fission reactions can occur so quickly that nuclear meltdown occurs, or a nuclear bomb explodes.

An example of a fission reaction that may occur in a nuclear reactor is

$$ {}_{0}^{1}\mathrm{n} + {}_{92}^{235}\mathrm{U} \Rightarrow {}_{92}^{236}\mathrm{U} \Rightarrow {}_{56}^{141}\mathrm{Ba} + {}_{36}^{92}\mathrm{Kr} + 3\left({}_{0}^{1}\mathrm{n}\right). $$

Note that the reaction is triggered by bombarding the uranium-235 atom with a neutron, temporarily creating a uranium-236 atom that quickly splits into krypton, barium, and three more neutrons. These neutrons can go on to cause more uranium-235 atoms to split apart. In a controlled reaction, the rate at which reactions occur should be constant, so if it takes one neutron to start a reaction, only one of the product neutrons (on average) are allowed to go on to produce further reactions. The other neutrons are absorbed by a moderator inside a reactor, which could be heavy water or a boron control rod embedded in the reactor core.

A typical fission reaction, like the one shown, above releases on the order of 200 MeV. As with typical fusion reactions, this is millions of times larger than the energy released by burning oil or gas in a chemical reaction, explaining why nuclear power is so appealing in comparison to the burning of fossil fuels. That huge advantage has to be weighed against the negative aspects of nuclear energy, including the fact that nuclear reactors produce radioactive waste products that must be handled carefully and stored securely for rather long times.

Related End-of-Chapter Exercises: 10, 11, 29 – 33.

Essential Question 29.6: The fission reaction shown above is just one possible way that a uranium-235 atom, bombarded with a neutron, can split up. What is the missing piece in another of the many possible reactions, which is shown here?

$$ {}_{0}^{1}\mathrm{n} + {}_{92}^{235}\mathrm{U} \Rightarrow {}_{92}^{236}\mathrm{U} \Rightarrow ? + {}_{38}^{94}\mathrm{Sr} + 2\left({}_{0}^{1}\mathrm{n}\right). $$