CONCEPTUAL EXAMPLE 31–4 **Counting nucleons.** Identify the element X in the fission reaction $n + {}^{235}_{92}\mathrm{U} \rightarrow {}^{A}_{Z}\mathrm{X} + {}^{93}_{38}\mathrm{Sr} + 2n$.

RESPONSE The number of nucleons is conserved (Section 30–7). The uranium nucleus with 235 nucleons plus the incoming neutron make $235 + 1 = 236$ nucleons. So there must be 236 nucleons after the reaction. The Sr has 93 nucleons, and the two neutrons make 95 nucleons, so X has $A = 236 - 95 = 141$. Electric charge is also conserved: before the reaction, the total charge is $92e$. After the reaction the total charge is $(Z + 38)e$ and must equal $92e$. Thus $Z = 92 - 38 = 54$. The element with $Z = 54$ (see Appendix B or the periodic table) is xenon, so the isotope is ${}^{141}_{54}\mathrm{Xe}$.

EXERCISE B In the fission reaction $n + {}^{235}_{92}\mathrm{U} \rightarrow {}^{137}_{53}\mathrm{I} + {}^{96}_{39}\mathrm{Y}$ + neutrons, how many neutrons are produced?

Figure 31–3 shows the distribution of fission fragments according to mass. Note that only rarely (about 1 in 10^4) does a fission result in equal mass fragments (small arrow in Fig. 31–3).

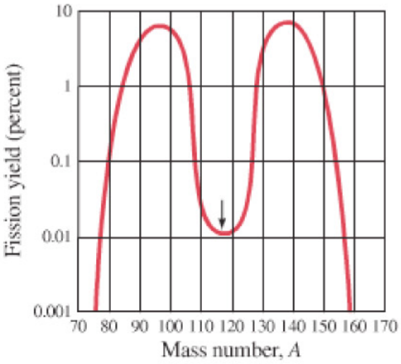

FIGURE 31–3 Mass distribution of fission fragments from ${}^{235}_{92}\mathrm{U} + n$. The small arrow indicates equal mass fragments $\left(\frac{1}{2} \times (236 - 2) = 117\right)$. Note that the vertical scale is logarithmic.

A tremendous amount of energy is released in a fission reaction because the mass of ${}^{235}_{92}\mathrm{U}$ is considerably greater than the total mass of the fission fragments plus neutrons. This can be seen from the binding-energy-per-nucleon curve of Fig. 30–1; the binding energy per nucleon for uranium is about 7.6 MeV/nucleon, but for fission fragments that have intermediate mass (in the center portion of the graph, $A \approx 100$), the average binding energy per nucleon is about 8.5 MeV/nucleon. Since the fission fragments are more tightly bound, they have less mass. The difference in mass, or energy, between the original uranium nucleus and the fission fragments is about $8.5 - 7.6 = 0.9$ MeV per nucleon. Since there are 236 nucleons involved in each fission, the total energy released per fission is

$$(0.9\ \mathrm{MeV/nucleon})(236\ \mathrm{nucleons}) \approx 200\ \mathrm{MeV}. \tag{31–5}$$

Energy released per fission

This is an enormous amount of energy for one single nuclear event. At a practical level, the energy from one fission is, of course, tiny. But if many such fissions could occur in a short time, an enormous amount of energy at the macroscopic level would be available. A number of physicists, including Fermi, recognized that the neutrons released in each fission (Eqs. 31–3 and 4) could be used to create a **chain reaction**. That is, one neutron initially causes one fission of a uranium nucleus; the two or three neutrons released can go on to cause additional fissions, so the process multiplies as shown schematically in Fig. 31–4. If a **self-sustaining chain reaction** was actually possible in practice, the enormous energy available in fission could be released on a larger scale.

Chain reaction

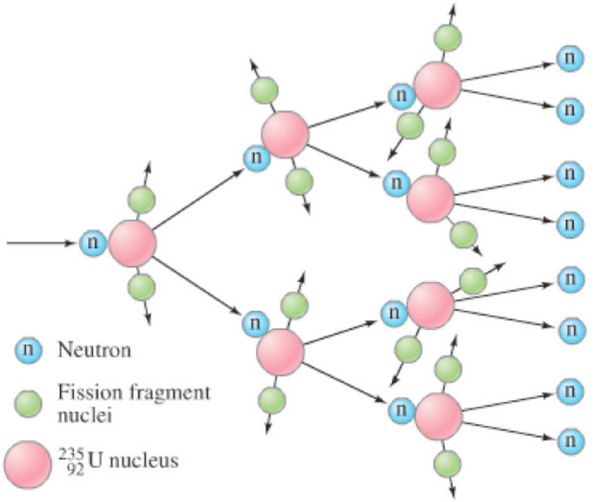

FIGURE 31–4 Chain reaction.