For Z greater than 83, the repulsive forces between protons cannot be compensated by the addition of more neutrons. That is, *elements that contain more than 83 protons do not have stable nuclei.* The long, narrow region in **Figure 3** (on the previous page), which contains the cluster of dots representing stable nuclei, is sometimes referred to as the *valley of stability.* Nuclei that are not stable decay into other nuclei until the decay product is one of the nuclei located in the valley of stability.

A stable nucleus's mass is less than the masses of its nucleons

The particles in a stable nucleus are held tightly together by the attractions of the strong nuclear force. In order to break such a nucleus apart into separated protons and neutrons, energy must be added to overcome this force's attraction. For most nuclei, the particles bound together in the nucleus have a lower energy state than the same set of particles would have if they were separated. Because they are so much higher in energy, isolated protons and neutrons are very rare.

binding energy

the energy released when unbound nucleons come together to form a stable nucleus, which is equivalent to the energy required to break the nucleus into individual nucleons

The quantity of energy needed to break a nucleus into individual unbound nucleons is the same as the quantity of energy released when unbound nucleons come together to form a stable nucleus. This quantity of energy is called the **binding energy** of the nucleus. It is equal to the difference in energy between the nucleons when bound and the same nucleons when unbound. (Note that except for very small values of A, unbound nucleons do not simply combine into a full-grown nucleus.) Binding energy can be calculated from the rest energies of the particles making up a nucleus as follows:

$$E_{bind} = E_{R,unbound} - E_{R,bound}$$

Using the equation for rest energy, we can rewrite this as follows:

$$E_{bind} = m_{unbound}c^2 - m_{bound}c^2 = (m_{unbound} - m_{bound})c^2$$

The mass of the nucleons when unbound minus the mass of the nucleons when bound is called the *mass defect* and is expressed as Δm. Thus, the previous equation for binding energy can be expressed as follows:

BINDING ENERGY OF A NUCLEUS

$$E_{bind} = \Delta mc^2$$

binding energy = mass defect × (speed of light)^2

Note that the total mass of a stable nucleus (m_{bound}) is always less than the sum of the masses of its individual nucleons ($m_{unbound}$). It is often useful to find the mass defect in terms of u so that it can be converted to energy as described earlier in this chapter (1 u = 931.49 MeV).

The mass of the unbound nucleus is the sum of the individual nucleon masses, and the mass of the bound nucleus is about equal to the atomic mass minus the mass of the electrons. Thus, $\Delta m = (Zm_p + Nm_n) - (\text{atomic mass} - Zm_e)$.