

29-1 What Holds the Nucleus Together?

Before answering the question of what keeps the nucleus together, let's go over the basics of what a nucleus is. A nucleus is at the heart of the atom. It is positively charged, because it contains the atom's protons. It also contains the neutrons, which have no net charge. We actually have a word, **nucleons**, for the particles in a nucleus. The atomic mass number, A , for a nucleus is the total number of nucleons (protons and neutrons) in a nucleus. The atomic number, Z , for a nucleus is the number of protons it contains.

The protons and neutrons can be modeled as tiny balls that are packed together into a spherical shape. The radius of this sphere, which represents the nucleus, is approximately:

$$r \approx (1.2 \times 10^{-15} \text{ m}) A^{1/3}. \quad (\text{Eq. 29.1: The radius of a nucleus})$$

This is almost unbelievably small, orders of magnitude smaller than the radius of the atom.

An atom of a particular element contains a certain number of protons. For instance, in the nucleus of a carbon atom there are always 6 protons. If the number of protons changes, we get a new element. There can be different numbers of neutrons in the nucleus, however. Carbon atoms, for instance, are stable if they have six neutrons (by far the most abundant form of natural carbon), seven neutrons, or eight neutrons. These are known as **isotopes** of carbon – they all have six protons, but a different number of neutrons.

The general notation for specifying a particular isotope of an element is shown in Figure 29.1. The notation is somewhat redundant – by definition, aluminum is the 13th element in the periodic table, and thus has an atomic number of $Z = 13$. A little redundancy is not a bad idea, however – it will help us keep things straight later when we write equations for radioactive decay processes and for nuclear reactions.

Figure 29.1: The general notation for specifying a particular isotope is shown at left, where X represents the chemical symbol for the element, A is the atomic mass number (the number of protons + neutrons) and Z is the atomic number (the number of protons). A specific case, the isotope aluminum-13, is shown at right.



The masses and charges of the three basic building blocks of atoms are shown below in Table 29.1. In addition to specifying the mass in kilograms, the mass is also shown in atomic mass units (u). By definition, 1 atomic mass unit is 1/12th the mass of a neutral carbon-12 atom.

$$1 \text{ u} = 1.660540 \times 10^{-27} \text{ kg}.$$

Particle	Charge	Mass (kg)	Mass (u)
neutron	0	$1.674929 \times 10^{-27} \text{ kg}$	1.008664
proton	$+e$	$1.672623 \times 10^{-27} \text{ kg}$	1.007276
electron	$-e$	$9.109390 \times 10^{-31} \text{ kg}$	0.00054858

Table 29.1: The charge and mass of the neutron, proton, and electron. Recall that $e = 1.602 \times 10^{-19} \text{ C}$.

Related End-of-Chapter Exercises: 1, 41, 42.

EXPLORATION 29.1 – Holding the nucleus together

Let's explore what it is that holds a nucleus together, starting by considering whether what holds the nucleus together is a force we already know about.

Step 1 – First, apply Coulomb's Law to calculate the electrostatic force between two protons that are separated by 1×10^{-15} m. Can this force hold the nucleus together? Substituting the appropriate values into Coulomb's Law gives:

$$F = \frac{k(+e)(+e)}{r^2} = \frac{(9.0 \times 10^9)(1.602 \times 10^{-19} \text{ C})^2}{(1.0 \times 10^{-15} \text{ m})^2} = 231 \text{ N} .$$

This is a repulsive force, so it certainly cannot be the force holding the nucleus together – the electrostatic repulsion between the protons is trying to spread the protons apart.

Step 2 – Let's use Newton's Law of Universal Gravitation to find the gravitational force between the two protons. Is the gravitational force sufficient to keep the nucleus together? Substituting the appropriate values into the law of gravitation gives:

$$F = \frac{Gmm}{r^2} = \frac{(6.67 \times 10^{-11} \text{ N m}^2 / \text{kg}^2)(1.6726 \times 10^{-27} \text{ kg})^2}{(1.0 \times 10^{-15} \text{ m})^2} = 1.87 \times 10^{-34} \text{ N} .$$

This gravitational force is an attractive force, but at about 36 orders of magnitude less than the electrostatic force, it is negligible compared to the electrostatic force.

Step 3 – Are any of the other forces we have encountered already in this book responsible for holding the nucleus together? Other forces we have dealt with include forces of tension and friction, and normal forces. These forces are macroscopic manifestations of forces between charges, however, and they do not apply at the microscopic level of the nucleus. Another force we looked at is the magnetic force applied on charged objects but, as we discussed in Chapter 26, magnetism can actually be interpreted as another manifestation of the electrostatic force.

Step 4 – What do you conclude about the force responsible for holding the nucleus together? Our conclusion must be that there is a force we have not yet discussed that is responsible for holding the nucleus together. The basics of this force are given in the box below.

The force that holds a nucleus together is the **nuclear force**, a short-range force between nucleons. At very small separations, the nuclear force is repulsive, keeping the protons and neutrons from getting too close to one another. In general, however, protons and neutrons exert attractive forces on other protons and neutrons via the nuclear force, up to a separation distance of about 1.3×10^{-15} m (at larger separations the nuclear force is negligible). To keep a nucleus together, the net attraction from all the nuclear forces between nucleons must balance the net repulsion from all the protons mutually repelling one another.

Key idea: Nuclei are held together, against the electrostatic repulsion trying to tear them apart, by the nuclear force, a (generally) attractive, but short-range, force between nucleons (neutrons and protons). **Related End-of-Chapter Exercise: 16.**

Essential Question 29.1: Your friend says that two isotopes of carbon are specified by $^{12}_6\text{C}$ and $^{14}_8\text{C}$. Do you agree with your friend? Explain why or why not.