Discovery of the Proton and Neutron

In 1911, Ernest Rutherford's gold foil experiment revealed that atoms contain a small, dense core with an overall electric charge (later determined to be positive).

In 1917, while scattering particles off nitrogen gas, Rutherford was shocked to discover hydrogen nuclei being emitted from a collision. Rutherford proposed that the hydrogen nucleus was a fundamental building block for all atoms.

Isotopes

Atoms with the same number of protons but different numbers of neutrons are called **isotopes**. Equivalently, isotopes of a particular element have the same atomic number but different mass numbers. The term *isotope* comes from the Greek for "the same place," as all isotopes of the same element occupy the same position in the periodic table. All elements heavier than californium ($Z = 98$) have no naturally occurring isotopes on Earth and must be artificially produced.

Nuclear Force and Binding Energy

Objects with the same electric charge repel one another. Protons within the nucleus are positively charged, yet they stay together in the nucleus rather than flying apart due to the attractive **nuclear force** (more specifically, the *strong* nuclear force) that opposes the electric force that would otherwise push the protons apart. The nuclear force acts between pairs of nucleons, including both protons and neutrons. The nuclear force only acts across distances about the size of the nucleus and drops to zero at longer ranges.

According to Einstein's mass-energy equivalence relation $E = mc^2$, the energy required to keep the nucleus intact can be thought of as adding mass to the nucleus. We refer to this energy as **binding energy**. Binding energy can also be thought of as the energy required to separate a nucleus into its constituent protons and neutrons.

Nuclear Stability

Binding energy per nucleon peaks around $A = 56$, suggesting that elements in this region, such as iron and nickel, exhibit a great degree of stability, since it requires more energy on average to pull apart the nucleus, nucleon by nucleon.

For elements below $Z = 20$, stable atoms contain roughly equal numbers of protons and neutrons. Heavier atoms require more neutrons than protons in the nucleus in order to be stable. There are no stable nuclei for elements beyond $Z = 83$, regardless of how many neutrons are present.

Stable nuclei also share a pattern of recurring numbers of protons and neutrons, often called "magic numbers." The first such magic numbers are 2, 8, 20, 28, 50, 82, and 126. Nuclei that have a neutron number and a proton number both equal to a magic number—for example, helium-4 and oxygen-16—are sometimes referred to as "doubly magic" and exhibit an extremely high degree of stability.

Magnetic Properties of the Nucleus

Protons and neutrons are both spin-1/2 particles (fermions), and thus they have an intrinsic magnetic moment. Nuclei with even numbers of both protons and neutrons will have no overall spin because individual nucleons of opposite spin will pair up and cancel out to minimize energy.

This spin oscillation is the basis for the medical imaging technique of magnetic resonance imaging (MRI). In MRI, a strong magnetic field is applied to a patient which aligns the hydrogen nuclei in water molecules contained within the body. The primary advantage of MRI over other medical imaging techniques such as X-rays is the low risk for cellular damage while maintaining a high spatial resolution.