The Nucleus

Rutherford's experiments showed that all of the atom's positive charge and nearly all of its mass is contained in the nucleus. The **nucleus** is the core of an atom made up of one or more protons and (except for one of the isotopes of hydrogen) one or more neutrons. The protons and neutrons that make up the nucleus of an atom are called nucleons.

Strong Nuclear Force

The positively charged protons in any nucleus containing more than one proton are separated by a distance of 10^{-15} meter. Consequently, a large repulsive Coulomb force exists between them. The gravitational force of attraction between protons is far too weak to counterbalance this electrostatic force of repulsion. Thus, there must exist a very strong attractive nuclear force to keep the protons concentrated in the nucleus of an atom. It is this **strong nuclear force,** which is an attractive force between protons and neutrons in an atomic nucleus, that is responsible for the stability of the nucleus.

The strong nuclear force of attraction between two protons in a nucleus is about 100 times stronger than the electrostatic force of repulsion. At distances greater than a few nucleon diameters, however, the strong nuclear force diminishes rapidly and becomes much less than the gravitational or electrostatic forces. Although the strong nuclear force is the strongest force known to exist, it is effective only over a short distance.

Universal Mass Unit

The mass of an individual atom is a very small fraction of a kilogram. Consequently, for convenience, scientists use another unit called the universal mass unit, u, to express such masses. The **universal mass unit,** or atomic mass unit, is defined as $\frac{1}{12}$ the mass of an atom of carbon-12, which is a carbon atom having 6 protons, 6 neutrons, and 6 electrons. In universal mass units, the mass of the proton is 1.0073 u, the mass of the neutron is 1.0087 u, and the mass of an electron is 0.0005 u. In SI units, a mass of one universal mass unit, or 1 u, equals 1.66×10^{-27} kilogram.

Mass-Energy Relationship

Einstein showed that mass and energy are different forms of the same thing and are equivalent. The energy equivalent of mass is directly proportional to both the mass and the speed of light in a vacuum squared. The following formula expresses this relationship.

$$E = mc^2$$

Energy E is in joules, mass m is in kilograms, and c is the speed of light in a vacuum, 3.00×10^8 meters per second. For example, if one kilogram of mass is converted to energy, the amount of energy produced is 9.00×10^{16} joules. Thus, the masses of subatomic particles can be expressed in joules, but more often they are expressed in an equivalent number of electronvolts.

SAMPLE PROBLEM

One universal mass unit equals 1.66×10^{-27} kilogram. Calculate the energy equivalent of one universal mass unit in megaelectronvolts.

SOLUTION: Identify the known and unknown values.

Known	Unknown
$m = 1.66 \times 10^{-27}$ kg	$E = ?$ MeV
$c = 3.00 \times 10^{8}$ m/s	
$1 \text{ eV} = 1.60 \times 10^{-19}$ J	
$10^{6} \text{ eV} = 1 \text{ MeV}$	

1. Write the formula that relates energy and mass.

$$E = mc^2$$

2. Substitute the known values and solve.

$$E = (1.66 \times 10^{-27} \text{ kg})(3.00 \times 10^{8} \text{ m/s})^2$$
$$E = 1.49 \times 10^{-10} \text{ J}$$

3. Use the relationship between electronvolts and joules to convert the energy in joules to electronvolts.

$$E = (1.49 \times 10^{-10} \text{ J})\left(\frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}}\right)$$

$$E = 9.31 \times 10^{8} \text{ eV}$$

4. Use the relationship between eV and Mev to convert eV to MeV.

$$E = (9.31 \times 10^{8} \text{ eV})\left(\frac{1 \text{ MeV}}{10^{6} \text{ eV}}\right)$$

$$E = 931 \text{ MeV}$$

Nuclear Mass and Energy

According to Einstein's mass-energy equation, any change in energy results in an equivalent change in mass. Mass-energy is conserved at all levels from cosmic to subatomic. For example, in a chemical reaction in which one kilogram of carbon combines with oxygen to form carbon dioxide, the amount of energy released is 3.3×10^{7} joules. Even though this is a significant amount of energy, it is equivalent to only 4×10^{-10} kilogram of mass. The mass of the carbon dioxide formed in the reaction is slightly less than the mass of the carbon and oxygen before they reacted. This change in mass is too small to detect or measure. The same is true for all chemical reactions and other ordinary energy changes. However, in reactions involving the nuclei of atoms, the changes in energy relative to the masses involved are much larger, and the corresponding changes in mass can be measured.

The mass of a proton is 1.0073 u and the mass of a neutron is 1.0087 u. Thus, the total mass of two protons and two neutrons is 2(1.0073 u + 1.0087 u), or 4.0320 u. However, the mass of a helium-4 nucleus, which consists of two protons and two neutrons, is only 4.0016 u. Thus, the mass of the atomic nucleus is less than the sum of the masses of its individual nucleons when measured separately. This is true of every nucleus, with the exception of hydrogen-1, which has only one nucleon.

When nucleons come together to form a nucleus, energy is released and an equivalent amount of matter is lost. To break up the nucleus and separate the nucleons, work must to be done against the strong nuclear force of attraction. The energy needed to separate the nucleons appears as an equivalent increase in their total mass.

SAMPLE PROBLEM

A helium nucleus consisting of two protons and two neutrons has a mass of 4.0016 universal mass units. The mass of a proton is 1.0073 universal mass units and the mass of a neutron is 1.0087 universal mass units.

(a) Find the difference between the mass of the helium nucleus and the total mass of its constituents.
(b) Find the energy equivalent of this mass difference in electronvolts.

SOLUTION: Identify the known and unknown values.

Known	*Unknown*
mass of helium nucleus = 4.0016 u	mass difference = ? u
mass of proton = 1.0073 u	E = ? eV
mass of neutron = 1.0087 u	
1 u = 931 MeV	

1. Determine the mass of the two protons and two neutrons.

mass of 2 protons = 2(1.0073 u) = 2.0146 u
mass of 2 neutrons = 2(1.0087 u) = 2.0174 u

Find the total mass of the four individual nucleons.
total mass = 2.0146 u + 2.0174 u = 4.0320 u

Find the difference between the masses of the individual nucleons and a helium nucleus.
mass difference = 4.0320 u − 4.0016 u = 0.0304 u

2. Use the relationship between the universal mass unit and MeV, 1 u = 931 MeV.

E = (0.0304 u)(931 MeV/u) = 28.3 MeV

Studying Atomic Nuclei

The structure of the atomic nucleus and the nature of matter have been investigated using particle accelerators. These devices use electric and magnetic fields to increase the kinetic energies of charged particles, such as electrons and protons, and project them at speeds near the speed of light in a vacuum into samples of matter. Collisions between the high speed particles and atomic nuclei may disrupt the nuclei and release new particles. The study of these ejected particles can give useful information about the structure and forces within the nucleus. Scientists continue to study the atomic nucleus because the nucleus, and thus the atomic structure of an atom of an element determines the particular physical and chemical properties of the element. Each type of atom is different and distinct. A growing understanding of nuclear forces and structure will increase understanding of matter and its interactions.

Review Questions

35. Which particles are most likely to be found in an atomic nucleus?
(1) neutrons, only
(2) protons, only
(3) both protons and neutrons
(4) both neutrons and electrons

36. Which description of the interaction which binds a nucleus together is most accurate?
(1) long-range and weak
(2) long-range and strong
(3) short-range and weak
(4) short-range and strong