In the early 1900’s investigators found radioactive emissions from atoms were of 3 types: alpha , beta and gamma. Of these three types, alpha is the least penetrating (stopped by several sheets of paper), beta are more penetrating and gamma can pass through the human hand. Rutherford was able to prove that alpha particles were helium atoms.

12.1 Discovery of the neutron

Reasons that electrons can not exist in nuclei
1: size: in order to confine an electron to the nucleus, the uncertainty principle puts a lower limit on its kinetic energy that is much lower than any kinetic energy observed for an electron emitted from nuclei.
2: spin: protons and electrons have spin ½. If a deuteron (A=2, Z=1) consists of protons and electrons, the deuteron must contain 2 protons and 1 electron in order to have A=2 and Z=1. however, 3 fermions must have a half-integer spin but deuteron has a spin of 1.
3: Nuclear magnetic moment: The magnetic moment of the electron is over 1000x larger than that of the proton. However, measured nuclear magnetic moments are of the same order of magnitude as the proton’s.

What is the minimum KE of a **proton** in a medium sized nucleus having a diameter of 8x10^{-15}m?

$$\Delta p \, \Delta x \geq \frac{\hbar}{2} \Rightarrow \Delta p = \frac{\hbar}{2 \Delta x} = 0.041 \, \mathrm{eV \, s/m} \Rightarrow KE = \frac{p^2}{2m} = 1.29862733 \times 10 - 14 \, \mathrm{joules} = 0.081 \, \mathrm{MeV}$$

1920: Rutherford proposed a neutral particle existed called the neutron. It was observed that 5.7 MeV particles were emitted when alpha particle struck Be and the radiation passed through paraffin. The energies needed to produce such high energies were not available at the time. 1932: Chadwick proposed the new radiation was neutron radiation. Thus the discovery of the neutron.

12.2 Nuclear Properties

We designate the atomic nucleus by:

$${}^{A}_{Z}X_{N}$$

Z=atomic number (number of protons)
N=neutron number (number of neutrons)
A=mass number (Z+N)
X=Chemical element symbol

Each nuclear species with a given Z and A is a nuclide. Sometimes the extra symbols are omitted since A=N+Z. Examples: ${}^{16}_{8}O_{8}$ ${}^{16}_{8}O$ ${}^{16}O$ are all the same most abundant isotope of oxygen with Z=8,N=8, A=16.

Other stable isotopes of oxygen are ${}^{17}O$ ${}^{18}O$ which have extra neutrons.

Nuclides with the same neutron number are called isotones

Ex: ${}^{14}_{6}C$ ${}^{15}_{7}N$ ${}^{16}_{8}O$ ${}^{17}_{9}F$

Nuclides with the same value of A are called isobars

Ex: ${}^{16}_{6}C$ ${}^{16}_{7}N$ ${}^{16}_{8}O$ ${}^{16}_{9}F$

Chemical properties are determined by the electron configuration. The chemical properties are almost not determined by N although there are some effects that can be observed among the isotopes (tunneling, for example, will be lower for deuterium than hydrogen).

Atomic masses are measured in atomic mass units u. They are defined in terms of ${}^{12}_{6}C$ which is defined to be exactly 12 u. Nucleons are collectively either protons or neutrons and neutrons are observed to be slightly more massive than protons.

Sizes and shapes of nuclei

A reasonable assumption is the nuclei are spherical in shape. However, observation of what the radius can be need to be considered carefully:

(1) matter radius

(2) force radius: strong nuclear force: determined by neutrons

(3) charge radius: electron measurement

The nuclear radius is approximated as:

$$R = r_0 A^{\frac{1}{3}}; r_0 \approx 1.5x10^{-15} m$$

We use the fm to measure nuclear distances: $1fm = 1x10^{-15} m$.

Also, though the term fermi is often used for this distance measurement .

The shape of the nuclear charge distribution is:

$$\rho(r) = \frac{\rho_0}{1 + e^{\frac{r-R}{a}}}$$

where $a \approx 0.6 fm$ and this is approximately level until about 5 fm and then drops to zero by about 9 fm.

Example: what is the nuclear radius of ${}^{40}Ca$?

Here, we have the radius given by:

$$R = r_0 A^{\frac{1}{3}}; r_0 \approx 1.2x10^{-15} m \Rightarrow R = 1.2(40)^{\frac{1}{3}} = 4.1 fm.$$

What is the ratio of the radii of ${}^{238}U$ and ${}^{4}He$?

$$\frac{R_{238}}{R_4} = \sqrt[3]{\frac{238}{4}}$$

If the shape of the nucleus is approximately a sphere, then we have for the volume of the nucleus:

$$V=\frac{4}{3}\pi r_0^3 A$$

you can now calculate the mass density for a nucleus of about $2.3\text{x}10^{17}$ kg/m^3 which is about 10^{14} times that of normal matter. That’s a pretty big difference. The neutron and also the proton are fermions with spin quantum numbers of s=1/2.

The proton, the electron and also the neutron each have an intrinsic magnetic moment. The nuclear magnetic moment is given by:

$$\mu_N=\frac{e\hbar}{2m_p}$$

The “N” is used here because it is the nuclear Bohr magneton and is about 1800 times smaller than the electron’s moment.

$$\mu_p=2.79\mu_N$$

$$\mu_e=-1.00115\mu_B$$

$$\mu_n=-1.91\mu_N$$

The negative signs indicate that the moment points in the opposite direction to the spin. The fact that the neutron has a magnetic moment implies that the neutron is composed of an electron and a proton at different radii which means that the internal charge distribution is quite complex.

12.3 The deuteron

The next simplest nucleus after the single proton is the deuteron.

$${}_1^2H_1$$

We can determine how strongly the neutron and the proton are bound:

$$m_d=2.013553\,u, M_{datom}=2.014102\Rightarrow m_{datom}-m_d=0.000549\,u=m_e$$

We can neglect the binding energy of 13.6 eV. We want to calculate the binding energy of the nucleus. This calculation comes from:

$$m_d=m_p+m_n-\frac{B_d}{c^2}$$

We can also then add an electron to each side:

$$m_d+m_e=m_p+m_n+m_e-\frac{B_d}{c^2}$$

But m_d+m_e is the atomic deuterium mass and m_p+m_e is the atomic hydrogen mass (neglecting a small amount of binding energy). Thus we have:

$$M\left({}^2H\right)=m_n+M\left({}^1H\right)-\frac{B_d}{c^2}$$

So you can use atomic masses for this calculation. We thus tabulate each of the quantities:

$$m_n = 1.00866\,\mathrm{u}$$
$$M(^1H) = 1.007825\,\mathrm{u}$$
$$M(^2H) = 2.014102\mathrm{u}$$
$$\Rightarrow \frac{B_d}{c^2} = m_n + M(^1H) - M(^2H) = 0.002388\mathrm{u}$$

You can now calculate this in terms of MeV as 2.224 MeV.
Remember what a MeV is? this is the kinetic energy obtained by accelerating an electron through 10^6 V.
This calculation can be checked by looking at the reaction of:

$$\gamma + d \rightarrow n + p$$

Experiment shows that photons of energy less than 2.22 MeV can not disintegrate the nucleus.

The deuteron also has a nuclear spin quantum number of 1. This means than the proton and the neutron spins are aligned parallel to each other. The nuclear magnetic moment of a deuteron is $0.86\mu_N$ which is close to the sums for the values for the proton and the neutron:

$$2.79\mu_N - 1.91\mu_N = 0.88\mu_N$$

which supports the theory of parallel spins.