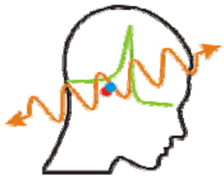

RADIATION PHYSICS

Lecture (9)

Nuclear Binding energy

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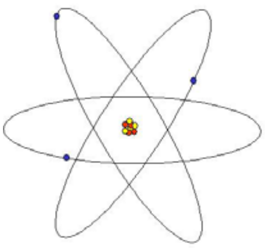
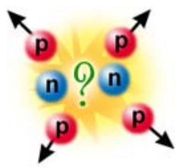
- ✓ Nuclear properties
- ✓ Binding energy
- ✓ Radioactivity



Atom

Nucleus

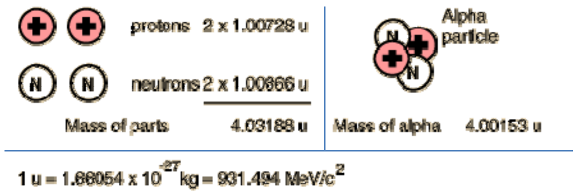


Protons and neutrons

NUCLEAR BINDING ENERGY

- Nuclei are made up of protons and neutron, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it.
- The difference is a measure of the nuclear binding energy which holds the nucleus together. This binding energy can be calculated from the Einstein relationship:

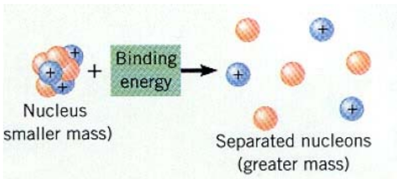
Nuclear binding energy = Δmc^2



- For the alpha particle Δm= 0.0304 amu which gives a binding energy of 28.3 MeV.

NUCLEAR BINDING ENERGY

- When any two particles attract one another, the sum of their separate masses exceeds the value of the mass of the bound system, since energy (or mass) must be added to the system to separate it into its component particles.



- The value of this energy is called the binding energy, can be computed from the mass difference by using the mass-energy conversion factor, 1amu = 931.494 MeV/c^2.
- Thus, the binding energy E_b of the neutron-proton forming a deuteron is given by

$$E_b + M_d c^2 = (M_p + M_n)\, c^2$$

$$E_b = (M_p + M_n - M_d)\, c^2$$

DEUTERON BINDING ENERGY

A deuteron (the nucleus of a deuterium atom, with no electron) consists of one proton and one neutron. The experimentally-measured masses of the constituents as free particles are

m_{proton} = 1.007825 amu;
$m_{neutron}$= 1.008665 amu;
$m_{proton} + m_{neutron}$ = 1.007825 + 1.008665 = 2.01649 amu.

The mass of the deuteron (also an experimentally measured quantity) is Atomic mass ^2H = 2.014102 amu.

The mass difference = 2.01649−2.014102 amu = 0.002388 amu.

Since the conversion between rest mass and energy is 931.494MeV/u, a deuteron's binding energy is calculated to be

$$E_b = 0.002388 \text{ amu} \times 931.494 \text{ MeV/amu} = 2.224 \text{ MeV}.$$

NUCLEAR PHOTOELECTRIC EFFECT

- Deuterium gas is irradiated with a beam of high energy monochromatic γ-ray photons. If the energy of the photons equals the deuteron's binding energy, photon absorption will produce a free neutron and a proton. If the photon energy exceeds the binding energy, the deuteron will be dissociated into a neutron and proton; each particle will also have kinetic energy.
- The nuclear reaction can be written as follows:

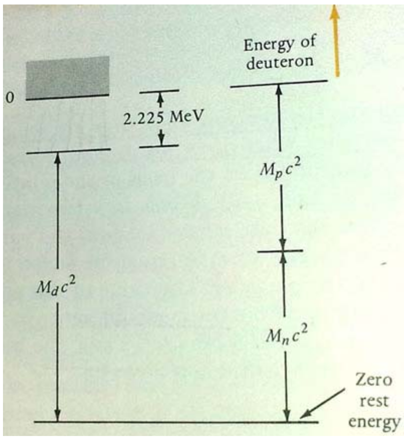
$$\gamma + d \rightarrow p + n$$

- Mass energy conservation requires that

$$hf + M_dc^2 = M_pc^2 + M_nc^2 + K_p + K_n$$

Where, K_p, K_n are the kinetic energy of the free proton and neutron

- This is called nuclear photoelectric effect or nuclear photodisintegration.



Energy level diagram of the proton-neutron system and the deuteron

- When K_p and K_n equal zero this is called threshold nuclear photodisintegration

$$hf_o = (M_p + M_n - M_d)\, c^2 = E_b$$

- The energy of photon is equal the binding energy and thus the mass of the neutron can be measured experimentally.

The inverse reaction to deuteron photodisintegration

- When neutron and proton at rest combine to form a deuteron in an excited state it decays to the ground state with the emission of a photon of 2.225 MeV.

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

EXAMPLE (1)

Calculate the total binding energy for the $^{12}_{6}C$

Solution:

This is equivalent to the energy required to separate the 12 component nucleons of the $^{12}_{6}C$

We will use the mass of the hydrogen atom, 1.007 825 amu, and the mass of an electron, 0.000549 amu

6 protons = 6 (1.007 825 - 0.000 549) amu

6 neutrons = 6(1.008 665) amu

Total nucleon masses = 12.098 940 – 6(0.000 549) amu

$^{12}_{6}C$ nuclear mass = 12.000 000 – 6 (0.000 549) amu

Mass difference = 0.098 940 amu

Total binding energy = 0.098 940 amu x 931.494 MeV/amu = **92.16 MeV**

E_b = 92.16 MeV this is the energy required to separate the 12 nucleons of the $^{12}_{6}C$

The average binding energy per nucleon = E_b/A = 92.16/12 = 7.68 MeV

EXAMPLE (2)

What is the energy needed to remove just one proton from ${}^{12}_{6}C$, leaving a nucleus with 5 protons and 6 neutrons, namely, the nucleus of ${}^{11}_{5}B$?

Solution:

The energy binding the last proton to the remaining 11 nucleons, the separation energy, is computed by using the rest masses of the particles

Mass of ${}^{1}_{1}H$ = 1.007 825 amu

Mass of ${}^{11}_{5}B$ = 11.009 305 amu

Mass of H + B = 12.017 130 amu

Mass of C = 12.000 000 amu

Mass difference = 0.017 130 amu

Separation energy = 0.017 130 amu x 931.494 MeV/amu = 15.96 MeV

Notice, The separation energy is greater than the average energy! Why?

PROBLEM: BINDING ENERGY

Calculate the average binding energy per nucleon of ${}^{93}_{41}Nb$

Given:

m_p= 1.007276u
m_n= 1.008665u

Find:

E_b = ?

In order to compute binding energy, let's first find the mass difference between the total mass of all protons and neutrons in Nb and subtract mass of the Nb:

Number of protons: $N_p = 41$

Number of neutrons: $N_n = 93 - 41 = 52$

Mass difference:

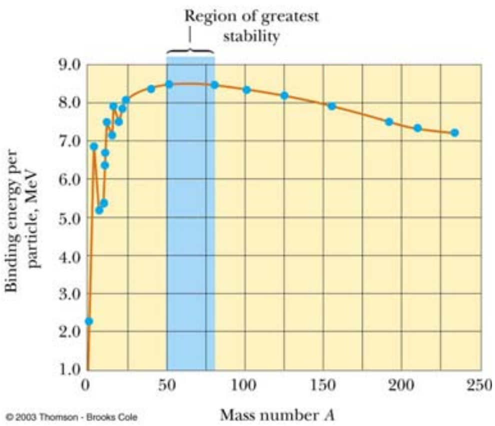
$$\Delta m = 41m_p + 52m_n - m_{Nb}$$
$$= 41(1.007825u) + 52(1.008665u) - (92.9063768u)$$
$$= 0.865028u$$

Thus, binding energy is

$$E_b = \frac{(\Delta m)c^2}{A} = \frac{(0.865028u)(931.5\,MeV/u)}{93} = 8.66\,MeV/\text{nucleon}$$

BINDING ENERGY

- The total energy of the bound system (the nucleus) is less than the combined energy of the separated nucleons
  - This difference in energy is called the *binding energy* of the nucleus
    - It can be thought of as the amount of energy you need to add to the nucleus to break it apart into separated protons and neutrons



Binding Energy per Nucleon

BINDING ENERGY NOTES

- Except for light nuclei, the binding energy is about 8 MeV per nucleon
- The curve peaks in the vicinity of A = 60
  - Nuclei with mass numbers greater than or less than 60 are not as strongly bound as those near the middle of the periodic table
- The curve is slowly varying at A > 40
  - This suggests that the nuclear force saturates
  - A particular nucleon can interact with only a limited number of other nucleons