CHARACTERIZATION OF ATOMIC NUCLEI

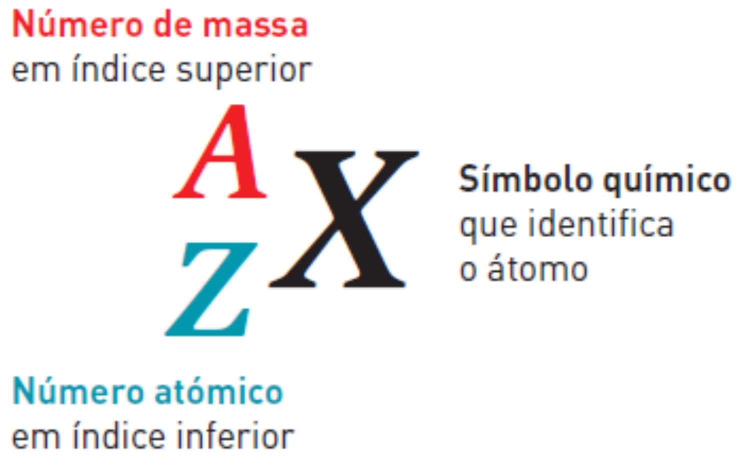
Nuclei are characterized by:

- **The atomic number Z - the number of protons in the nucleus.**

- **The mass number A – number of protons + neutrons in the nucleus.**

Since *atoms* are neutral, Z is also equal to the number of electrons in the atoms. But in ions this is no longer true.

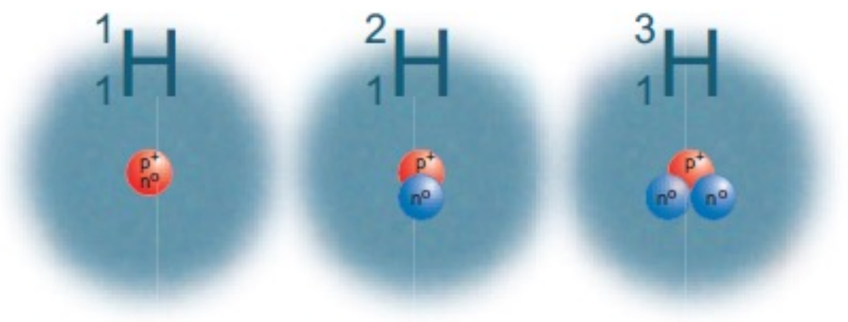
As a general rule the atomic number is not shown, since the chemical symbol already specifies *Z*.



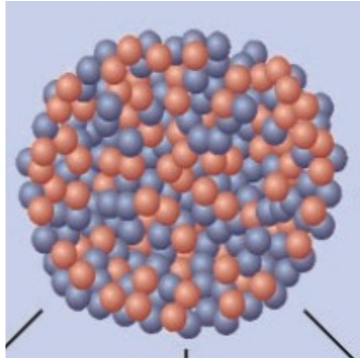
CHARACTERIZATION OF ATOMIC NUCLEI

- It is common to call *nucleons* the set of protons and neutrons.
- What characterizes a given *chemical element* is its number of protons – hence its atomic number, Z.
- Each element generally has several *ISOTOPES*: nuclei with the same number of protons (equal Z) but that differ in the number of neutrons (different mass number A).
- The *isotopes* have approximately the same *chemical* properties but can have very different *nuclear* behaviors.

For example, HYDROGEN has three isotopes: *deuterium* has one proton and one neutron, *tritium* has one proton and two neutrons.



Properties of Nuclei



- Made up of protons (p) and neutrons (n)
- **ATOMIC NUMBER** (Z) – number of protons in a nucleus
- Number of neutrons in a nucleus (N)
- **MASS NUMBER** (A) – sum of the number of protons and the number of neutrons

$$A = N + Z$$

Representation of a given nucleus (nuclide), X

$${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z}X \rightarrow {}^{A}X$$

We don't need N because we already have A and Z. We don't need Z because X indicates the element (and therefore Z – Z defines the element.)

CHARACTERIZATION OF ATOMIC NUCLEI

SOLVED EXERCISES

1. Give the atomic number and the mass number of each of the following atoms.

1.1 Hydrogen, which has only one proton.

1.2 Carbon, with six protons and six neutrons.

2. Describe the composition of the nucleus of a gold atom represented by $^{197}_{79}\mathrm{Au}$.

Solution:

1.1 The number of protons in this nucleus is 1 and the number of neutrons is 0.
Therefore, the atomic number is $Z = 1$ and the mass number is $A = 1 + 0 = 1$.
It is represented by $^{1}_{1}\mathrm{H}$.

1.2 The atomic number of carbon is $Z = 6$, since it has 6 protons, and the mass number is $A = 6 + 6 = 12$.
It is represented by $^{12}_{6}\mathrm{C}$.

2. The gold atom has atomic number $Z = 79$ and mass number $A = 197$.
Therefore, its nucleus contains 79 protons and $197 - 79 = 118$ neutrons.

Examples

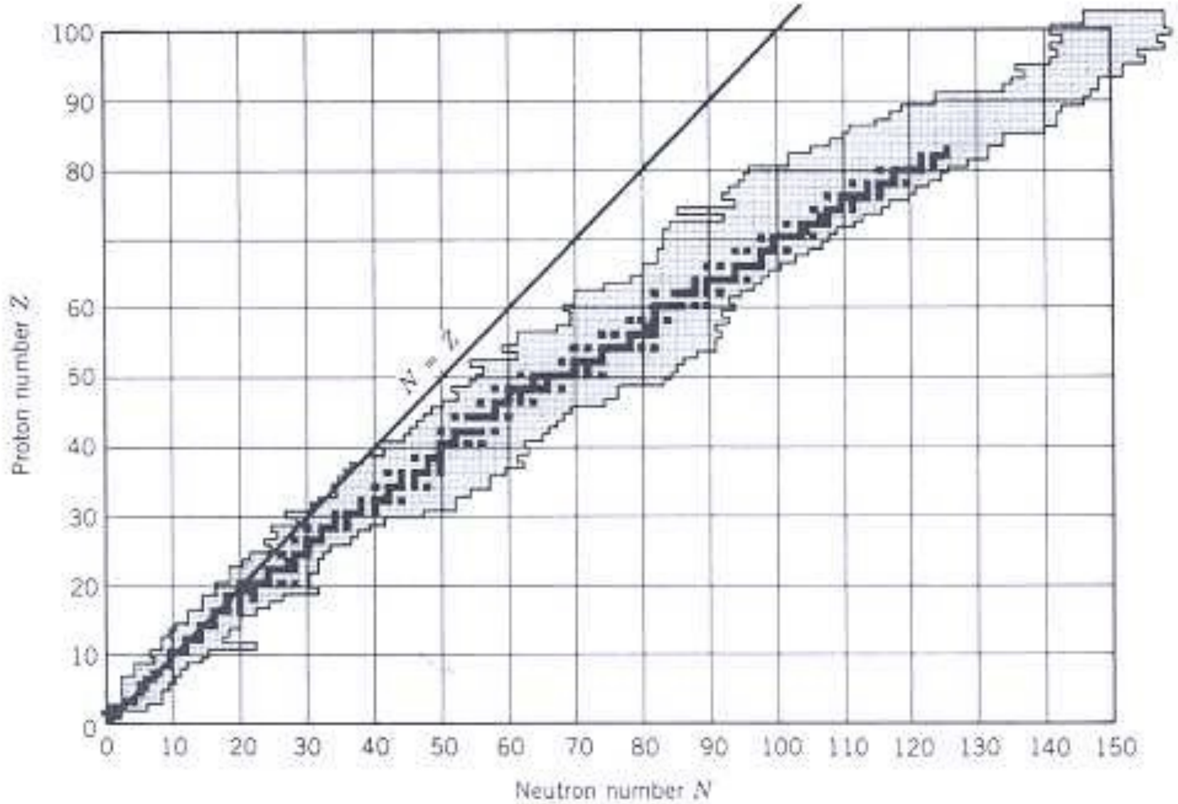
$${}^{16}_{8}O_{8} \rightarrow {}^{16}_{8}O \rightarrow {}^{16}O$$

The oxygen nucleus always has 8 protons. Atomic oxygen always has 8 protons and 8 electrons. If the number of electrons is different from 8 we have an ion, a positively or negatively charged particle depending on whether it has fewer or more electrons than 8.

$${}^{17}_{8}O_{9} \rightarrow {}^{17}_{8}O \rightarrow {}^{17}O$$

Isotope of oxygen.

ISOTOPES



Isotopes exist in nature with different abundances – many isotopes are unstable.

Stable nuclei shown in dark.

Note that for stable nuclei with lower Z, Z = N is a good approximation.

For heavier nuclei, the number of neutrons must be greater than the number of protons. The Coulomb repulsion of so many protons has to be compensated for with more neutrons.

Nuclear Families: Isotopes, isobars, isotones and isomers

Family	Nuclei with the same	Example
Isotopes	Atomic Number (Z)	C-12 and C-13
Isobars	Mass Number (A)	C-14 and N-14
Isotones	Number of Neutrons (A-Z)	N-17 and O-18
Isomers	Atomic and Mass Numbers but different energies	Tc-99 and Tc-99m

Technetium does not occur in nature, having been the first element to be obtained artificially. All of its isotopes are radioactive. Tc-99 is one of the fission products of uranium.

Isotopes of Hydrogen

nuclide symbol	Z(p)	N(n)	isotopic mass (u)	half-life	decay mode(s)[8]	Daughter Isotope(s)[n 1]
^{1}H	1	0	1.007 825 032 07(10)	Stable[n 3][n 4]		
^{2}H[n 5]	1	1	2.014 101 7778(4)	Stable		
^{3}H[n 7]	1	2	3.016 049 2777(25)	12.32(2) yr	β^-	^{3}He
^{4}H	1	3	4.027 81(11)	$1.39(10) \times 10^{-22}$ s [4.6(9) MeV]	n	^{3}H
^{5}H	1	4	5.035 31(11)	$>9.1 \times 10^{-22}$ s ?	n	^{4}H
^{6}H	1	5	6.044 94(28)	$2.90(70) \times 10^{-22}$ s [1.6(4) MeV]	3n	^{3}H
					4n	^{2}H
^{7}H	1	6	7.052 75(108)#	$2.3(6) \times 10^{-23}$ s#	4n	^{3}H

^{1}H, the most common isotope with an abundance of more than 99.98%.

^{2}H, deuterium, is the other stable isotope of Hydrogen. It has one proton and one neutron in its nucleus. The total deuterium on Earth is 0.0026 – 0.0184%. Deuterium is not radioactive. Water enriched in molecules that include deuterium is called heavy water, used as a neutron moderator and coolant in nuclear reactors. Deuterium is also a potential fuel for commercial nuclear fusion.

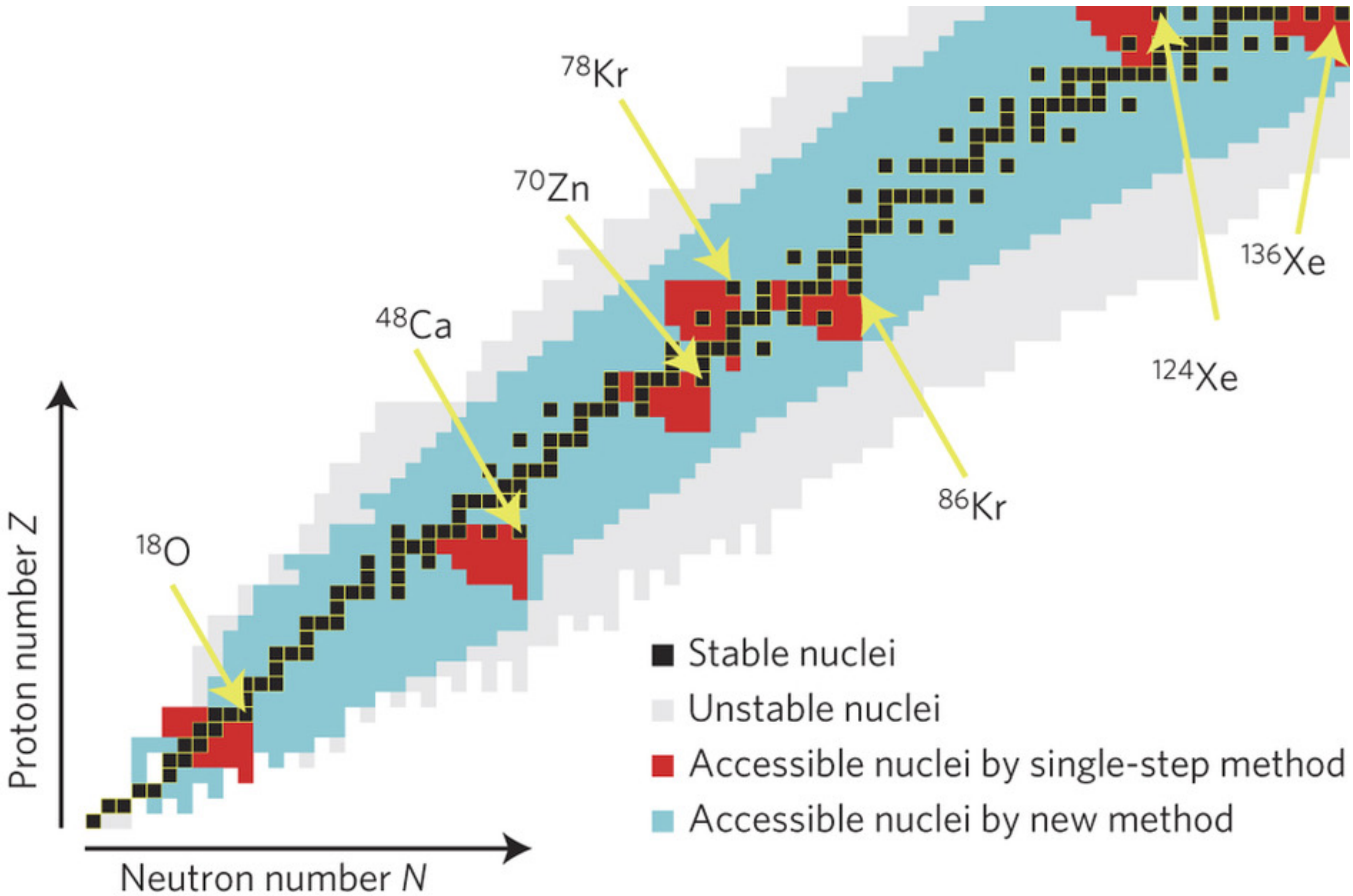
^{3}H, tritium, has one proton and two neutrons in the nucleus. It is radioactive and decays to ^{3}He with a half-life of 12.32 years. Tritium is used for example in nuclear fusion bombs but also as a tracer in chemistry and biology experiments.

Isotopes of Carbon

símbolo nuclídeo	Z(p)	N(n)	massa isotópica (u)	meia-vida	spin nuclear
	energia de excitação				
^{8}C	6	2	8.037675(25)	2.0(4) x 10^{-21} s [230(50) keV]	0+
^{9}C	6	3	9.0310367(23)	126.5(9) ms	(3/2-)
^{10}C	6	4	10.0168532(4)	19.290(12) s	0+
^{11}C	6	5	11.0114336(10)	20.334(24) min	3/2-
^{12}C	6	6	12 por definição	Estável	0+
^{13}C	6	7	13.0033548378(10)	Estável	1/2-
^{14}C	6	8	14.003241989(4)	5.70(3) x 10^{3} anos	0+
^{15}C	6	9	15.0105993(9)	2.449(5) s	1/2+
^{16}C	6	10	16.014701(4)	0.747(8) s	0+
^{17}C	6	11	17.022586(19)	193(5) ms	(3/2+)
^{18}C	6	12	18.02676(3)	92(2) ms	0+
^{19}C	6	13	19.03481(11)	46.2(23) ms	(1/2+)
^{20}C	6	14	20.04032(26)	16(3) ms [14(+6-5) ms]	0+
^{21}C	6	15	21.04934(54)#	<30 ns	(1/2+)#
^{22}C	6	16	22.05720(97)#	6.2(13) ms [6.1(+14-12) ms]	0+

Carbon has 15 isotopes, 2 of them stable, ranging from ^{8}C to ^{22}C. These isotopes are of great importance for various scientific studies: Carbon-11, Carbon-12 and Carbon-14. For example, the Carbon-12 isotope was adopted, in 1961, by the *IUPAC - International Union of Pure and Applied Chemistry* as the basis for determining the atomic mass of all chemical elements. Carbon-14, on the other hand, a radioactive isotope with a half-life of 5730 years, is used for dating organic specimens.

Stable and Unstable Isotopes



The Periodic Table

Periodic Table of the Elements

Atomic Number
Symbol
Name
Atomic Mass

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

(for the history of each element, see http://www.rsc.org/periodic-table/history)

Some Isotopes Used in Medicine

Carbon-11 (^{11}C), Nitrogen-13 (^{13}N), Oxygen-15 (^{15}O), Fluorine-18 (^{18}F) – PET Imaging.

Erbium-169 (^{169}Er) – Relief of arthritic pain.

Iodine-131 (^{131}I) – Treatment of thyroid cancer.

Strontium-89 (^{89}Sr) – Relief of pain in prostate cancer.

Cesium-131 and 137 (^{131}Cs, ^{137}Cs), Cobalt-60 (^{60}Co) , Iridium-192 (^{192}Ir) , Ruthenium-106 (^{106}Ru) , ... – Brachytherapy.

• • •

NUCLEAR MASSES

The mass of a nucleus is given by:

Z × (mass of a proton) + (A – Z) × (mass of a neutron) - (mass equivalent to the nuclear binding)

$$m_N\left({}^{A}_{Z}X\right) = Z \times m_p + (A - Z)m_n - \frac{B\left({}^{A}_{Z}X\right)}{c^2} \qquad (1)$$

B(X) is the *binding energy* of nucleus X, always positive by definition.

It is more common to express nuclear masses in *atomic mass units* (u), or else in units of the energy equivalent to the mass, generally *mega-electron Volt* (MeV).

UNITS AND CONVERSIONS

A unidade da massa atómica, que se representa por u, corresponde à massa de $\frac{1}{12}$ de um átomo de carbono-12:

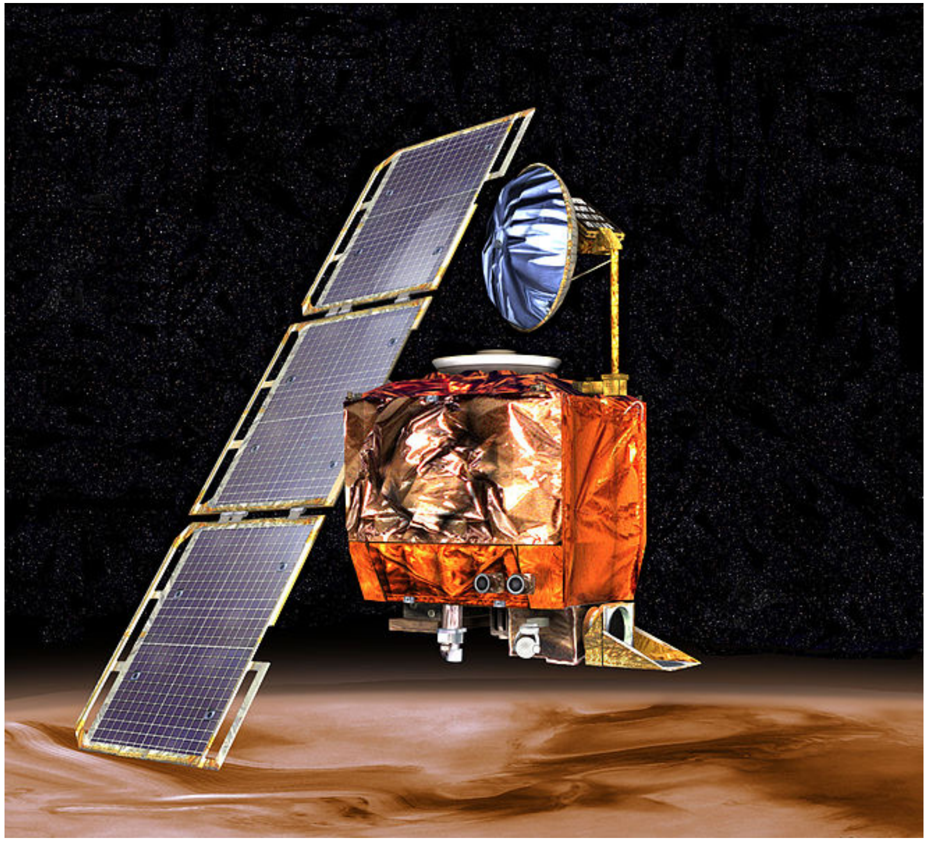
$$1\,u = \frac{\text{massa de um átomo de carbono 12}}{12} \cong 1{,}66 \times 10^{-27}\ \text{kg}$$

$$\mathbf{1\ u = 1.660566 \times 10^{-27}\ kg = 931.502\ MeV}$$

(actually 931.502 MeV/c^2)

When calculating nuclear masses and nuclear binding energies, the simplest approach is to convert all quantities into MeV.

THE IMPORTANCE OF USING THE CORRECT UNITS



The *Mars Climate Orbiter* burned up in the Mars atmosphere in September 1999.

THE CAUSE: software developed by Lockheed provided instructions to the engines in *imperial system units* while NASA had everything calculated in *international system (metric) units*.

125 million dollars...

NUCLEAR MASSES

- **As a general rule, we do not have *direct* access to the masses of nuclei, but rather to the masses of atoms.**

- **The relationship between the mass of an atom and that of the corresponding nucleus is given by**

MASS OF A NUCLEUS ≈ (MASS OF AN ATOM) – (MASS OF THE ELECTRONS)

- **That is, since neutral atoms have an equal number of protons and neutrons, it follows that**

$$m_N({}^A_Z X) = m({}^A_Z X) - Z\, m_e$$

- **Atomic masses, *m(X)*, are what is generally found tabulated.**

NUCLEAR MASSES

In general we only have the atomic masses, m_A, which include the electrons and their binding energies with the nucleus. Nuclear masses are therefore given by (for an element with Z protons and Z electrons)

$$m_N c^2 = m_A c^2 - Z m_e c^2 + \sum_{i=1}^{Z} E_i$$

$Z m_e c^2$ **energy corresponding to the mass of the Z electrons**

$\sum_{i=1}^{Z} E_i$ **binding energy of the Z electrons**

$m_A = m(^A X)$ **atomic mass of ^{A}X**

- **The last term has energies of the order of eV up to KeV. Nuclear masses are of the order of A times the proton mass, that is, A × 1000 MeV. Therefore the binding-energy term can be neglected.**

- **The energies E_i would have to be added in this expression, because they decrease the mass/energy of the atoms.**

Example

$$^{18}C \qquad Z = 6;\ N = 12; A = 18$$

$m_A(^{18}C) = 18.02676$ u

$$m_N c^2 = m_A c^2 - Z m_e c^2 + \sum_{i=1}^{Z} E_i \approx m_A c^2 - Z m_e c^2 \quad \Rightarrow \quad m_N = m_A - Z m_e$$

a) $m_N = 18.02676 - 6 \times 5.485803 \times 10^{-4} = 18.02347$ u

b) $m_N = 18.02347 \times 1.660566 \times 10^{-27} = 2.992916 \times 10^{-26}$ Kg

c) $m_N c^2 = 2.992916 \times 10^{-26} \times 9 \times 10^{16} = 2.693624 \times 10^{-9}$ J

d) $m_N c^2 = 2.693624 \times 10^{-9} / 1.602189 \times 10^{-19} = 1.681215 \times 10^{10}$ eV $= 1.681215 \times 10^{4}$ MeV

e) $m_N c^2 = 18.02347 \times 931.502 = 1.67889 \times 10^{4}$ MeV

$$m_p = 1.007276 \text{ u}; \quad m_n = 1.008665 \text{ u}; \quad m_e = 5.485803 \times 10^{-4} \text{ u}$$

Problems 1, 2 and 3 from series 1

NUCLEAR BINDING ENERGIES

The total mass of nuclei is LOWER than the sum of the masses of all the nucleons – this is why nuclei form – because they are more stable than their separate constituent particles. The energy corresponding to this mass difference is the binding energy of the nucleus, B, given by (by convention B > 0)

$$B = \left(Z\, m_p + N\, m_n - \left[m\,(^{A}X) - Z\, m_e\right]\right)c^2$$

Zm_p **total mass of the protons in the nucleus**

Nm_n **total mass of the neutrons in the nucleus**

$\left[m\,(^{A}X) - Zm_e\right]$ **mass of the nucleus (neglecting the binding energy of the electrons)**

$m\,(^{A}X)$ **atomic mass of ^{A}X**

NUCLEAR BINDING ENERGIES

There are other ways to present the nuclear binding energy depending on the data we have

$$B = \left(Zm_p + Nm_n - \left[m(^{A}X) - Zm_e \right] \right) c^2$$

$$B = \left(Z\, m(^{1}H) + (A - Z)\, m_n - m\,(^{A}X) \right) c^2$$

$$B = \left(Z\, m_p + (A - Z)\, m_n - m_N(^{A}X) \right) c^2$$

The larger B is, the more stable the nucleus is, because it is more strongly bound. But what is truly important is the value of B/A – the binding energy per nucleon. This allows us to compare the stability of different nuclei – the larger B/A is, the more strongly bound each nucleon will be and the more stable the nucleus will be.

NUCLEAR BINDING ENERGIES

$^{4}He \qquad Z = 2;\ N = 2$

$$m(^{4}He) = m_A(^{4}He) = 4.002603\ \text{u}$$

$$m_p = 1.007276\ \text{u}; \quad m_n = 1.008665\ \text{u}; \quad m_e = 5.485803 \times 10^{-4}\ \text{u}$$

$$1\ \text{u} = 931.502\ \text{MeV/c}^2$$

Calculation of the nuclear mass

$$m_N(^{4}He) = m_A(^{4}He) - 2 \times m_e = 3727.411\ \text{MeV/c}^2$$

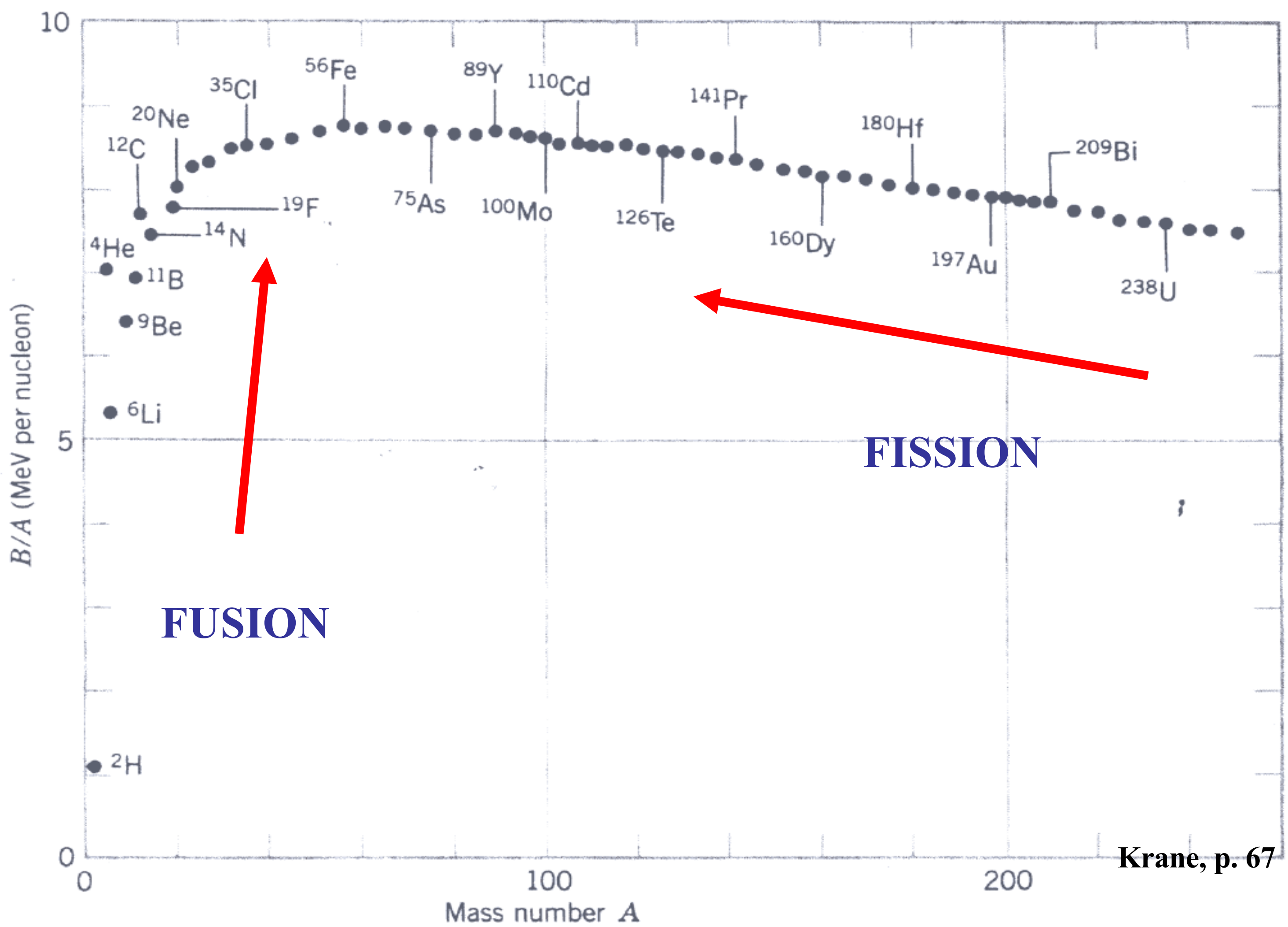
Calculation of the nuclear binding energy

$$B(^{4}He) = \left(2 \times m_p + 2 \times m_n - m_N(^{4}He)\right) c^2 = 28.296\ \text{MeV}$$

The binding energy per nucleon is

$$B / A = 7.074\ \text{MeV}$$

BINDING ENERGIES PER NUCLEON



There is no fundamental theory that allows us to calculate these energies. They are fitted to reproduce the data.

Up to A≈ 60, B/A increases, decreasing slowly afterward. We can generate energy in two ways.

• NUCLEAR FUSION – Fusing nuclei with A < 60 to give other nuclei of that type (only beneficial up to Iron – after that, energy must be supplied – STARS!)

• NUCLEAR FISSION – Splitting nuclei with A > 60 to obtain lighter nuclei.

Problem 4 from series 1

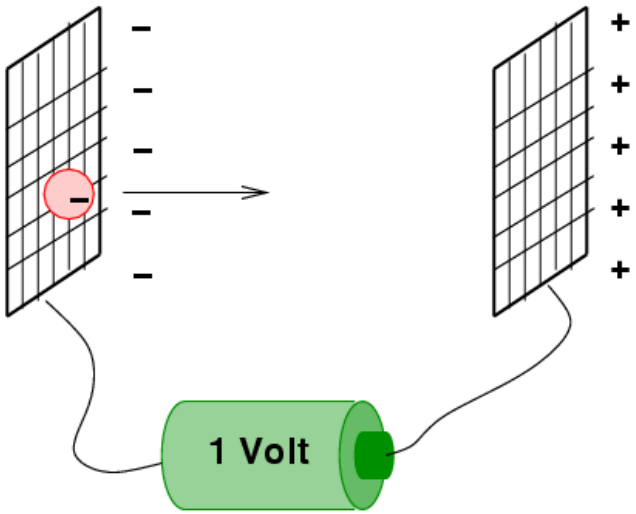
UNITS AND CONVERSIONS

S.I. Units **mass: kg (kilogram)** **energy: J (Joule)**

Relationship between mass and energy: $E = mc^2$

c is the speed of light, $c \approx 3 \times 10^8$ **m/s**

Electron-volt (eV): is the energy that an electron (with charge $q = 1.6 \times 10^{-19}$ C) acquires when subjected to a potential difference (voltage) of $\Delta V = 1$ Volt. From electromagnetism, that energy *E* is equal to



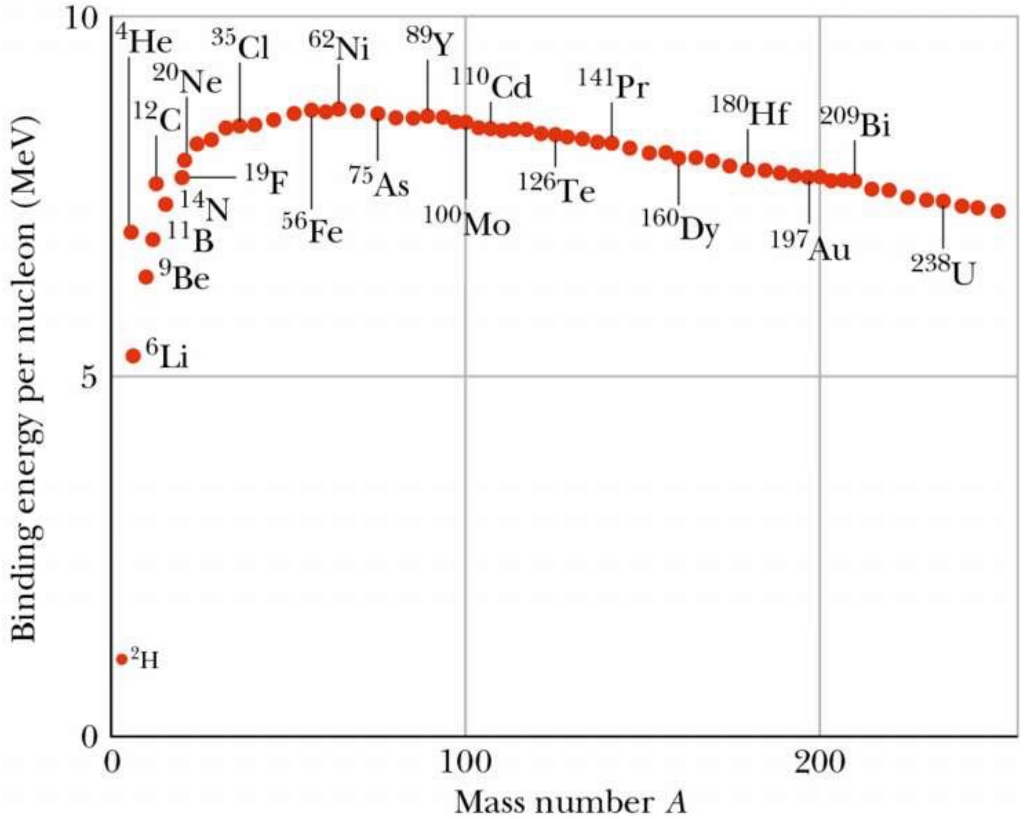
$$E = q\,\Delta V = 1.6 \times 10^{-19}\ J$$

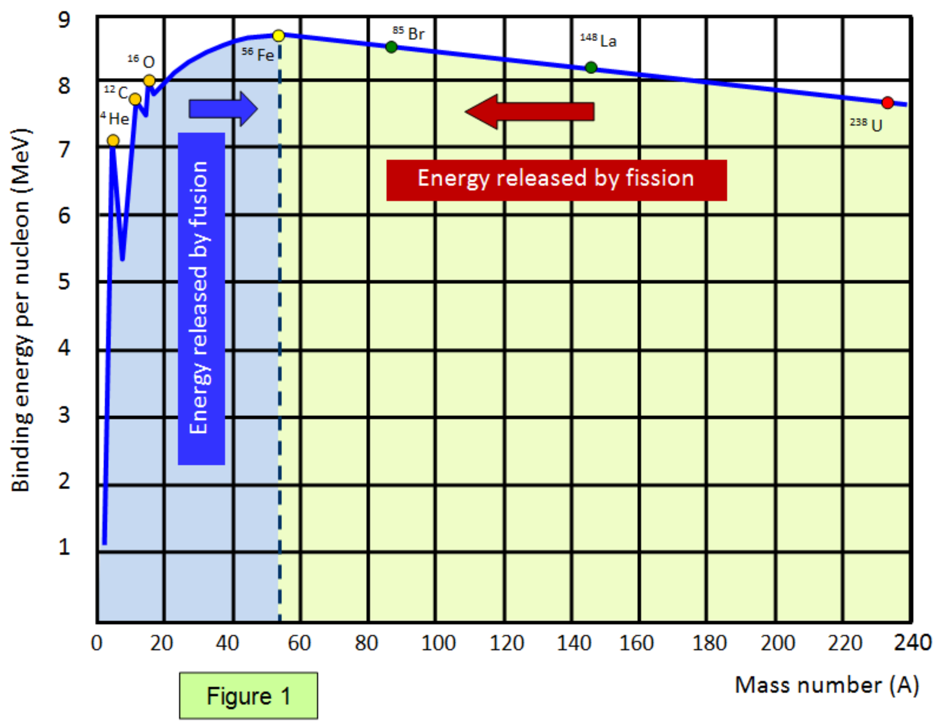
So,

$$1\ eV = 1.6 \times 10^{-19}\ J$$

BINDING ENERGY PER NUCLEON

A nucleus X is more stable the LARGER its binding energy per nucleon, B/A, is.





EXAMPLE

For the ^{24}Mg and ^{25}Mg nuclei, determine:

a) **Their atomic masses, in u, kg and MeV/c^2.**

b) **Their nuclear masses, in u, kg and MeV/c^2.**

c) **Their nuclear binding energies, in J and MeV.**

d) **Which of the two nuclei is more stable.**

SOLUTION:

a) **From the tables, we obtain the atomic masses in atomic mass units, u:**

$$m(^{24}\mathrm{Mg}) = \underline{23.985041\ \mathrm{u}}$$

$$m(^{25}\mathrm{Mg}) = \underline{24.985837\ \mathrm{u}}$$

Since 1 u $= 1.660566 \times 10^{-27}$ kg, we obtain

$$m(^{24}\mathrm{Mg}) = 23.985041 \times 1.660566 \times 10^{-27} \approx \underline{3.9828 \times 10^{-26}\ \mathrm{kg}}$$

$$m(^{25}\mathrm{Mg}) = 24.985837 \times 1.660566 \times 10^{-27} \approx \underline{4.1491 \times 10^{-26}\ \mathrm{kg}}$$

Since 1 u $= 931.502$ MeV/c^2, we obtain

$$m(^{24}\mathrm{Mg}) = 23.985041 \times 931.502 \approx \underline{22342.1\ \mathrm{MeV}/c^2}$$

$$m(^{25}\mathrm{Mg}) = 24.985837 \times 931.502 \approx \underline{23274.4\ \mathrm{MeV}/c^2}$$

b) Magnesium (Mg) has atomic number *Z = 12*, so the nuclear masses are obtained by subtracting from the atomic masses 12 times the mass of an electron. The easiest way is to do the calculation in MeV ($m_e = 0.511\ MeV$):

$$m_N(^{24}Mg) = m(^{24}Mg) - Z \times m_e = 22342.1 - 12 \times 0.511 \cong \underline{22336.0\ \ MeV}$$
$$m_N(^{25}Mg) = m(^{25}Mg) - Z \times m_e = 23274.4 - 12 \times 0.511 \cong \underline{23268.2\ \ MeV}$$

To obtain these values in *u*, just *divide* by the conversion factor,

$$m_N(^{24}Mg) = 22336.0/931.502 \cong \underline{23.9785\ \ u}$$
$$m_N(^{25}Mg) = 23268.2/931.502 \cong \underline{24.9792\ \ u}$$

And in *kg*, we have

$$m_N(^{24}Mg) = 23.9785 \times 1.660566 \times 10^{-27} \cong \underline{3.9818 \times 10^{-26}\ \ kg}$$
$$m_N(^{25}Mg) = 24.9792 \times 1.660566 \times 10^{-27} \cong \underline{4.1480 \times 10^{-26}\ \ kg}$$

c) The binding energies of each nucleus are obtained by subtracting the nuclear mass from the mass of all the protons and neutrons that make up each nucleus. The easiest way is to do the calculation in MeV – in that case, *it is not necessary to take into account the factor c^2 in equation. But if the masses were in kilograms, the factor of c^2 would have to be used to obtain energies in Joules.*

Thus, with the proton mass $m_p = 938.280\ MeV$ and the neutron mass $m_n = 939.573\ MeV$ we have:

$$B(^{24}Mg) = Z \times m_p + (A - Z) \times m_n - m_N(^{24}Mg) =$$
$$= 12 \times 938.280 + 12 \times 939.573 - 22336.0 \cong \underline{198.24\ \text{MeV}}$$

$$B(^{25}Mg) = Z \times m_p + (A - Z) \times m_n - m_N(^{25}Mg) =$$
$$= 12 \times 938.280 + 13 \times 939.573 - 23268.2 \cong \underline{205.61\ \text{MeV}}$$

Note the different number of neutrons (12 and 13) for each nucleus.
To obtain these values in *J*, just *multiply* by the conversion factor,

$$B(^{24}Mg) = 198.24 \times 1.6 \times 10^{-13} \cong \underline{3.17 \times 10^{-11}\ J}$$
$$B(^{25}Mg) = 205.61 \times 1.6 \times 10^{-13} \cong \underline{3.29 \times 10^{-11}\ J}$$

d) The most stable nucleus is the one with the *LARGEST* value of binding energy per nucleon, *B/A*. We have:

$$B(^{24}Mg)/A = 198.24/24 \cong 8.26$$
$$B(^{25}Mg)/A = 205.61/25 \cong 8.22$$

The most stable nucleus is therefore $\underline{^{24}Mg}$ (despite having a *smaller* binding energy value!).
ATTENTION to the importance of using enough decimal places in intermediate calculations.