Workshop Tutorials for Introductory Physics

Solutions to QI4: **The Nucleus**

A. Review of Basic Ideas:

The nucleus

The nucleus is made up of **protons** and **neutrons,** which are collectively called **nucleons**. A nucleus can be described by three numbers, N, Z and A. **N** is the number of neutrons in the nucleus, and Z is the number of **protons**, also called the **atomic** number. A is the **mass** number and is the total number of nucleons which is equal to N + Z.

The neutrons are **neutral**, and the protons are positively charged. So if the only significant force in the nucleus was the Coulomb force, the nuclei would blow apart. **Gravity** is very weak compared to the Coulomb force, so it doesn't hold them together. The force that holds them together is very strong, and acts over short distances between nucleons. Hence it is called the "strong nuclear force".

Because there is a strong force which pulls nucleons together, they have lower potential **energy** when they are bound together in a nucleus than if they were free. In the same way, an electron has lower potential energy when it is bound by the Coulomb force to a **nucleus** to form an atom. In the same way that you need to give an electron energy to allow it to escape from an atom, you need to give a nucleon energy to pull it apart from the nucleus. For an electron this is called the ionisation energy, for a nucleon it is called the **binding** energy.

The binding energy tells us how **stable** a nucleus is, how hard it is to break it apart. This is usually shown in charts as a binding energy per nucleon, which is the amount of energy you need to pull a nucleus completely apart into protons and neutrons, divided by the number of protons and neutrons (A). The **bigger** this energy, the more stable the nucleus. The binding energy can also be expressed as a mass. The mass of a nucleus is a bit less than the sum of the masses of its protons and neutrons. The difference is called the mass **defect** which, using $E=mc^2$, is equivalent to the binding energy.

Discussion questions

Matter consists of positively charged protons and negatively charged electrons. Charged particles attract each other if their charge is different and repel each other if the charge is the same. Coulomb measured the force between 2 small charged balls and showed that the force was proportional to the magnitude of the charges and inversely proportional to the square of the distance between them. This is force is known as the Coulomb force.

The gravitational force is an attractive force between two bodies and inversely proportional to the square of the distance between them. It is this force, attraction between the sun and the earth that keeps the earth in orbit around the sun. There is no repulsive gravitational force [yet discovered].

Your nose stays on your face because of the attractive electrical forces (Coulomb forces) in the bonds, which hold matter together. It is this force which also holds the negatively charged electrons around the positively charged nucleus of the atom.

In the nucleus, which comprises the positively charged protons and the neutral neutrons, there is a force acting, called the strong nuclear force. This helps to hold the nucleus together. This force is necessary because of the strong repulsive forces, which exist between the closely packed protons. This force only acts over atomic distances within the nucleus and, if the nucleus becomes too big, it will become unstable and decay.

B. Activity Questions:

1. Binding energies

a. The diagram shows the amount of energy per nucleon that you would need to pull that nucleus into its component protons and neutrons. This is sometimes also expressed as a mass defect, which is the difference between the mass of the nucleus and the sum of the masses of the same number of neutrons and protons.

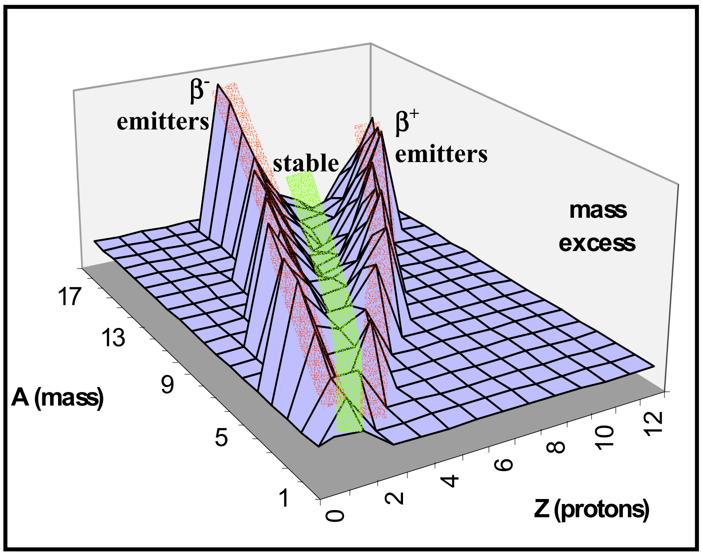
b. Both fission and fusion can release energy by increasing the mass defect or binding energy of an atom. The lower the binding energy, the less stable the atom.

c. Small nuclei such as hydrogen are more likely to undergo fusion, moving them along the binding energy chart to the right, with increasing binding energy. Large nuclei with small binding energies, those to the far right of the peak, will undergo fission to produce smaller nuclei with higher binding energies. Remember that the binding energy is how much you have to put in to break the nuclei, not how much energy the nuclei have, hence higher is more favourable.

2. Coolite Balls
When the coolite balls have the same charge they repel each other, and when they have opposite charges they attract. If the only force acting on the protons in the nucleus was the Coulomb force, they would repel each other and the nucleus would fall apart.

C. Qualitative Questions:

1. The transporter error.
a. Captain Picard is composed mostly of carbon, oxygen, nitrogen and hydrogen. The most common isotopes of C, N and O all have the same number of protons as neutrons, so it won't make any difference to these atoms. However hydrogen has one proton, one electron and no neutron, so the transporter error which swaps protons for neutrons will leave Picard with lots of extra neutrons, a huge deficit of protons but the same number of electrons.
b. This will be a very negative experience for Captain Picard, and his chemical structure will fall apart as he emits neutrons and the electrons disperse over him.
c. Data is mostly metal and most metals such as aluminium, copper and iron have more neutrons than protons to prevent the repulsive Coulombic force from breaking apart the nucleus. Hence the swap will leave the metals with too many protons, which will decay until the metals have stable nuclei again. With too many protons, Data is likely to emit β^+ radiation to convert protons to neutrons.



2. The valley of stability.
a. The region in which the nuclei are stable is in the 'valley' of the graph, called the "valley of stability", where the number of protons and the number of neutrons are approximately equal.
b. The nuclei to the left are unstable because they have too many neutrons for the number of protons, these are called neutron-rich isotopes.
c. The nuclei to the right are unstable because they have too many protons for the number of neutrons, these are called proton-rich isotopes.
d. The neutron rich light elements decay via:
[1] $n \rightarrow p + e^-$ [β^- decay - an electron]
The proton rich light elements decay via:
[2] $p \rightarrow n + e^+$ [β^+ decay - a positron]
Heavy proton-rich elements decay by alpha emission
e. In [1] the atomic number, Z, increases by 1 and the number of neutrons decreases by 1. In [2], Z decreases by one and the number of neutrons increases by 1. In both cases the number of nucleons, A, stays the same.

D. Quantitative Question:

a. The binding energy per nucleon for a deuteron:
Deuteron *B.E.* = 2.22 MeV and there are two particles, hence *B.E.* = 2.22 MeV / 2 nucleons = 1.11 MeV / nucleon
b. Mass of proton = 1.007276 amu, Mass of neutron = 1.008665 amu, total = 2.015941 amu.
Mass of deuteron = 2.014102 amu
Δm = 2.015941 - 2.014102 = 0.001849 amu
c. Fusion of 2 H nuclei and 2 neutrons to form a He nucleus:
2 H = 2.014552 amu and 2 n = 2.017330 amu; total = 4.031882 amu
mass of He atom =4.002603 amu
$\Delta m = [2m_p + 2m_n]$ - [mass He] = 0.030377 amu
And we can use $E = \Delta mc^2$:
As Δm is in u and ΔE is in MeV we can use the conversion factor between amu and MeV- (1 amu = 931.3 MeV)
E =[0.030377 u] c^2 [931.3 MeV/amu c^2] = 28.3 MeV.
d. The amount of energy released in the fission of ^{235}U to ^{228}Th + ^{4}He
[U] 232.0371 $\rightarrow$ [Th] 228.0287 + [He] 4.0026 = 232.0313 amu.
Δm = 0.0058 amu so ΔE = [0.0058 amu] c^2 [931.3 MeV/amu.c^2] = 5.4 MeV
e. The answers to **c** and **d** illustrate that more energy is released in the process of fusion than fission.