Unit 17: Nuclear Chemistry

Mass Defect

This worksheet will explore nuclear **mass defect**, a crucial concept in nuclear chemistry distinct from chemical reactions due to significant energy changes causing measurable alterations in mass. This relationship between energy and mass, demonstrated by Einstein's equation **$E = mc^2$**, highlights how the binding energy of nucleons within the nucleus contributes to its total mass. The negative mass defect represents the energy required for nuclear stability, affecting the binding energy, released or absorbed during processes like fusion or fission, powering reactions and impacting stellar energy production, as well as explaining nuclear stability and element creation in stars based on higher binding energies leading to greater stability.

Questions:

1. When a heavy nucleus undergoes fission, it splits into two smaller nuclei. How does mass defect contribute to the energy release in this type of nuclear reaction, and what factors influence the choice of fissionable materials in nuclear reactors?

2. Discuss how the binding energy per nucleon changes as you move across the periodic table from lighter elements to heavier elements. What trends or patterns do you observe, and how do these relate to nuclear stability?

3. The actual mass of a Chlorine-37 atom is 36.966 amu. Calculate the mass defect (amu/atom) for a Chlorine-37 atom.

4. The mass defect for an isotope was found to be 0.410 amu/atom. Calculate the binding energy in kJ/mol of atoms. ($1\ J = 1\ kgm^2/s^2$)

5. Oxygen has an unstable isotope O-17 that has a mass of 17.00454 amu. If the mass of a neutron is 1.00867 amu and the mass of a proton is 1.00728 amu, calculate the binding energy of the oxygen nucleus in MeV.

Answer Key:

1. When a heavy nucleus undergoes fission, it splits into two smaller nuclei. How does mass defect contribute to the energy release in this type of nuclear reaction, and what factors influence the choice of fissionable materials in nuclear reactors?

When a heavy nucleus undergoes fission, the mass defect contributes to the energy release by converting a portion of the original mass into energy, following Einstein's equation $E=mc^2$. The factors influencing the choice of fissionable materials in nuclear reactors include their ability to sustain a chain reaction, stability of resulting nuclei, and control of the reaction for practical energy production and safety.

2. Discuss how the binding energy per nucleon changes as you move across the periodic table from lighter elements to heavier elements. What trends or patterns do you observe, and how do these relate to nuclear stability?

The binding energy per nucleon generally increases as you move from lighter elements to heavier elements across the periodic table. This trend is due to the fact that heavier nuclei benefit more from the strong nuclear force, which overcomes the electrostatic repulsion between protons. Basically, higher binding energy is indicative of greater nuclear stability, as it reflects a stronger binding of nucleons within the nucleus, making the nucleus less prone to spontaneous decay or fragmentation.

3. The actual mass of a Chlorine-37 atom is 36.966 amu. Calculate the mass defect (amu/atom) for a Chlorine-37 atom.

To calculate mass defect, we will need multiple pieces of information:

# of protons in Chlorine-37 = 17 protons

# of neutrons in Chlorine-37 = 20 neutrons

Mass of proton (in amu) = 1.00728 amu

Mass of neutron (in amu) = 1.00867 amu

Equation for Mass defect = $[(\#\text{ of } p^+ \times mass_p) + (\#\text{ of } n^0 \times mass_n)]$ – actual mass

= [(17 x 1.00728 amu) + (20 x 1.00867 amu)] – 36.966 amu

= **0.33116 amu is the mass defect**

4. The mass defect for an isotope was found to be 0.410 amu/atom. Calculate the binding energy in kJ/mol of atoms. (1 J = 1 kgm^2/s^2)

To calculate binding energy, the following equation will be used: $E=mc^2$

Where,

E = binding energy

m = mass defect (in units of kg)

c = speed of light = 3×10^8 m/s

We will convert the mass defect units from amu/atom to kg/moles. This is because the units to convert to joules will include kg and the final answer is asking for the units of moles instead of atoms (so we will also utilize Avogadro's number as well).

Some necessary conversions are:

1 amu = $1.66 x 10^{-27}$ kg

Avogadro's number = $6.022 x 10^{23}$ atoms/moles

Converting from amu/atom to kg/moles:

$$0.410 \frac{amu}{atoms} x \left(\frac{1.66x10^{-27}\, kg}{1\, amu}\right) x \left(\frac{6.022x10^{23} atoms}{1\, mole}\right) = \frac{4.09857x10^{-4}\, kg}{moles}$$

Now we can plug the mass defect into Einstein's equation:

$$E = \left(4.09857x10^{-4} \frac{kg}{moles}\right)\left(3x10^{8} \frac{m}{s}\right)^2 = 3.6887x10^{13} \frac{kg*m^2}{s^2} * \frac{1}{moles}$$

The conversion to Joules is simple since we know that 1 J = 1 kgm^2/s^2, therefore, all we need to do is convert J to kJ:

$$3.6887x10^{13} \frac{kg*m^2}{s^2} * \frac{1}{moles} \rightarrow 3.6887x10^{13} \frac{J}{moles} x \left(\frac{1\, kJ}{1000\, J}\right) = 3.69x10^{10} \frac{kJ}{moles}$$

5. Oxygen has an unstable isotope O-17 that has a mass of 17.00454 amu. If the mass of a neutron is 1.00867 amu and the mass of a proton is 1.00728 amu, calculate the binding energy of the oxygen nucleus in MeV.

First we will calculate the mass defect of Oxygen-17 and then convert to kg to find binding energy (in Joules):

Equation for Mass defect = [(# of p^+ x m_p) + (# of n^0 x m_n)] – actual mass

= [(8 x 1.00728 amu) + (9 x 1.00867 amu)] – 17.00454 amu

= 0.13173 amu x (1.66×10^{-27} kg/amu) = 2.1867×10^{-28} kg

We can plug in the mass defect now into $E = mc^2$ and then convert J to eV using the conversion that 1eV = 1.6022×10^{-19} J. We can then convert eV to MeV

$$E = \left(2.1867x10^{-28}\,kg\right)\left(3x10^{8}\,\frac{m}{s}\right)^{2} = 1.968x10^{-11}\,J$$

$$1.968x10^{-11}\,J\,x\left(\frac{1\,eV}{1.6022x10^{-19}\,J}\right)x\left(\frac{1\,MeV}{10^{6}eV}\right) = 123\,MeV$$