Lesson 42: Inside the Nucleus

Nuclear physics gets its name from the fact that we are concerned with only the nucleus of the atom.
- *Chemistry* needs to pay attention to the electrons of the atom, since electrons determine how the chemical bonds form.
- *Nuclear physics* is concerned with the nucleus, since the nucleus determines the element as well as the nuclear reactions that can happen.

The Nucleons

Nucleon is the name given to anything that you find in the **nucleus**. This includes protons and neutrons.

Protons

> Remember "e" stands for "elementary charge", and does not necessarily have anything to do with electrons.

- symbol is p^+
- positive charge = +e
- mass = m_p = 1.6726e-27 kg
- number of protons in a nucleus = **atomic number** → symbol is **Z**

It is the number of protons in the nucleus that determine which element you are dealing with. A single proton is the entire nucleus of the simplest atom, hydrogen

Neutrons

> Notice that a neutron does have a slightly bigger mass than a proton. This will be important later.

- symbol is n^0
- no charge
- mass = m_n = 1.6749e-27 kg
- number of neutrons in a nucleus = **neutron number** → symbol is **N**

The total number of **nucleons** (**protons** + **neutrons**) in a nucleus is called the **atomic mass number** → symbol is **A**.

$$\mathbf{A} = \mathbf{Z} + \mathbf{N}$$

A = atomic mass number = # of nucleons
Z = atomic number = # of protons
N = neutron number = # of neutrons

Writing out Symbols

To write down which nucleus we have, we use the chemical symbol from the periodic table along with the **A** and **Z** values.
- The **A** and **Z** values are always written to the left of symbol, with **A** on top.

$$_{Z}^{A}X$$

Example 1: An nucleus has 7 protons and 8 neutrons. **Identify** what element it is, and write out its symbol.

According to the periodic table, the element with 7 protons is nitrogen.
Since nitrogen has **7 protons**, its **Z** value is **7**.
To get the **A** value, we have to add the number of **protons** and **neutrons** to get **15**.

$$^{15}_{7}N$$

Since we can just look up the atomic number of an element on the periodic table, we often skip writing the value for **Z** so…

$$^{15}N$$

We read this as ***nitrogen-fifteen*** or ***N-15***.

Example 2: If a nucleus has the symbol $^{23}_{11}Na$ then **identify** as much as you can about it.

- From the periodic table we can see that this is the symbol for **sodium**. We can also see this from the atomic number being 11, which is the atomic number for sodium. Specifically, we would call it **sodium-23**.
- This also means that the nucleus has **11 protons**.
- To figure out the number of neutrons, we will take 23 – 11 to get **12 neutrons**. Notice that to find the number of neutrons in the nucleus, do the calculation A – Z.

Isotopes

It is possible to find atoms of the same element that have different numbers of neutrons in the nucleus, even though the number of protons stays the same.
- These are called **isotopes**.
- Chemically, isotopes react almost identically when compared to each other. Only physics needs to be really concerned with different isotopes of an element.

For example, although carbon with 6 neutrons is the most common isotope of carbon, there are other isotopes of carbon.
- Although they all have different numbers of neutrons, the number of protons stays the same.
- Carbon-12 is the most common, so it has the highest percent abundance, a measurement of how much of each isotope would be found in an average sample of the element.

Isotope	$^{11}_{6}C$ carbon-11	$^{12}_{6}C$ carbon-12	$^{13}_{6}C$ carbon-13	$^{14}_{6}C$ carbon-14
Number of Protons	6	6	6	6
Number of Neutrons	5	6	7	8
Natural Abundance	Trace	98.93%	1.07%	Trace

The masses on your periodic table (e.g. carbon is 12.01) are weighted averages based on the natural abundances.
- Since most carbon is carbon-12, the number is pretty close to 12.
- But, the little bit of carbon-13 does pull up the number a bit, so we get 12.01.

- This is sort of like if you get 55% on a unit exam, and 75% on a tiny quiz.
  - If your mark was just an average, we'd add these and divide by two to get 65%.
  - But in most classes the exam will be worth a lot more than the quiz (the exam is weighted more than the quiz), so maybe the quiz can only pull up your overall mark a bit to maybe 57% .

The number of neutrons strongly affects the stability of the nucleus.
- As we will see later, having just the right number of neutrons makes a nucleus more stable. This is why some isotopes are more common than others.
- In unstable isotopes, the number of neutrons partly determines the rate at which the nucleus decays and releases radiation.

Because different isotopes have different masses, they can be separated from each other using a mass spectrometer (Lesson 18).
- Depending on the mass of the isotope, it will have a specific radius as it travels through a magnetic field.

Atomic Mass Units

Masses of atoms are sometimes given as **atomic mass units** (**amu**), which has the unit "u."
- Although not part of the metric system, it is still popular when discussing nuclear physics.
  - This is because measuring super-tiny stuff like protons in kilograms seems a bit silly.
- The atomic mass unit is based on a neutral atom of carbon-12, which is given a mass of exactly 12.000000u.
  - So 1 u = 1/12th the mass of carbon-12.
  - 1 u = 1.660 539e-27 kg

So, the masses of subatomic particles measured in amu are…

$m_p = 1.0072765$ u
$m_n = 1.0086649$ u
$m_e = 0.0005486$ u

The mass of an electron is so small compared to protons and neutrons that it is usually ignored in calculations.

Binding Energy

We know that protons are packed together pretty tightly in the nucleus, so why doesn't the electrostatic force between them cause them to flying apart.
- Since nuclei are obviously not flying apart, there must be something that is holding the nucleons together. Could it be the gravitational attraction of the masses?
  - For this to be true, the gravitational force F_g would have to be greater than the electrostatic force F_e.
    - Let's check it out for just two protons. We can grab the numbers for protons from the data sheet and figure out the ratio between F_g and F_e.
    - As long as the ratio is bigger than "1" we will know F_g is holding the nucleus together stronger than F_e trying to push things apart.

$$\frac{F_g}{F_e} = \frac{\dfrac{G\,m_1 m_2}{r^2}}{\dfrac{k\,q_1 q_2}{r^2}} = \frac{G\,m_1 m_2}{k\,q_1 q_2} = \frac{6.67\text{e-}11\,(1.67\text{e-}27)(1.67\text{e-}27)}{8.99\text{e}9\,(1.60\text{e-}19)(1.60\text{e-}19)} = \frac{1.86\text{e-}64}{2.30\text{e-}28} = 8.08\text{e-}37$$

- Woof! The ratio is a lot *smaller* than 1! The force of gravity trying to pull the protons together is much smaller than the electrostatic force trying to push them apart. In fact, the gravitational force is insignificant in comparison.
- This means that the force of gravity is way too weak to hold the nucleus together against the electrostatic force pushing it apart.

This was such a problem in physics that physicists came up with a new *attractive* force to explain what was holding the nucleons (especially protons) together... the **strong nuclear force**.

- The strong nuclear force can only act over incredibly small distances, measured in femtometres.
  - The strong nuclear force is so short range that it can actually only attract other nucleons that are right next to each other. Nucleons that are on opposite sides of the nucleus do not affect each other by the strong nuclear force.
  - This is in contrast to the electrostatic force which (although it weakens according to $1/r^2$) acts over infinite distances. A proton on one side of a nucleus can repel another proton on the other side because of the electrostatic repulsion between them.
- In stable nuclei the strong nuclear force is strong enough to hold nucleons together in the nucleus.
  - There is a constant battle between the strong nuclear force trying to hold the nucleus together and the electrostatic force trying to throw it apart.

As long as the nucleus is stable, energy must be added to separate the nucleons from each other and move them far enough apart that the strong nuclear force can't hold them together.

- This is called the **binding energy**.
  - Since energy must be added to move the nucleons apart, separate nucleons must have more energy.
  - When nucleons are bound in the nucleus they have not had energy added yet, so they have less energy.
- Einstein's formula...

$$E = mc^2$$

E = energy (J)
m = mass (kg)
c = speed of light (3.00e8m/s)

...shows that energy is directly related to mass.

  - So, since separate nucleons have more energy, they must have more mass.
  - Nucleons bound in the nucleus have less energy, so they have less mass.
    - This means that separate nucleons are always heavier than when they are stuck together in a nucleus.

$$\sum m_p + \sum m_n > m_{nucleus}$$

o It would be like building something out of lego pieces, and in the end it weighs less than what the individual pieces weighed at the start.

The difference between the mass of the nucleus and its individual nucleons is called the **mass defect** (Δm).
- The mass defect is directly related to the binding energy added to break apart the nucleus according to the formula $E = mc^2$.
- We often use atomic mass units in physics, so we need to remember that 1 u = 1.660 539e-27 kg. That way we can convert mass from amu into kg.

Example 3: The mass of a zirconium-93 atom is 92.90647 u. **Determine** the mass of the nucleus, the mass defect, and the binding energy of this isotope of zirconium. Don't worry too much about sig digs for this question.

From the periodic table we know the atomic number of zirconium is 40. The symbol for this isotope would be $^{93}_{40}Zr$. This means that this isotope has 40 protons, 40 electrons (as long as it is neutral), and 53 neutrons (calculated from 93-40).

The mass of a zirconium-93 atom includes the mass of the 40 electrons, which we must subtract to get the mass of the nucleus.

$m_{nucleus} = m_{atom} - 40(m_e)$
$= 92.90647\ u - 40\ (0.0005486\ u)$
$m_{nucleus} = \textbf{92.884526 u}$

> It is likely that in most questions they will simply give you the mass of the nucleus and you'll be able to skip this step.

What would the mass of the nucleus be if we found the total mass of all the nucleons (protons and neutrons) as separate masses...

$m_{nucleons} = 40(m_p) + 53(m_n)$
$= 40(1.0072765u) + 53(1.0086649u)$
$= 40.29106 + 53.4592397$
$m_{nucleons} = \textbf{93.7502997 u}$

The mass defect is the difference between the actual mass of the nucleus and what the total mass of all the protons and neutrons would be if separate.

$\Delta m = m_{nucleons} - m_{nucleus}$
$= \textbf{93.7502997} - \textbf{92.884526}$
$\Delta m = 0.8657737\ u = 1.43765099402e\text{-}27\ kg$

> Remember that 1 u = 1.660539e-27 kg

The binding energy is related to the mass defect.
$E_B = \Delta m\ c^2$
$= 1.43765099402e\text{-}27\ (3.00e8)^2$
$E_B = 1.29388589462e\text{-}10\ J$

> Remember that 1 eV = 1.60e-19 J

We often state binding energies in MeV, where M is the prefix for 10^6.
$E_B = 1.293886e\text{-}10\ J$
$= 8.08678684e8\ eV$
$= 808.678684e6\ eV$
$E_B = 809\ MeV$

Later we will find that calculations such as these are useful to figure out how much energy is released in certain reactions.

Homework

p791 #1, 2
p792 #1, 2
p794 #1, 2
p795 #1, 2