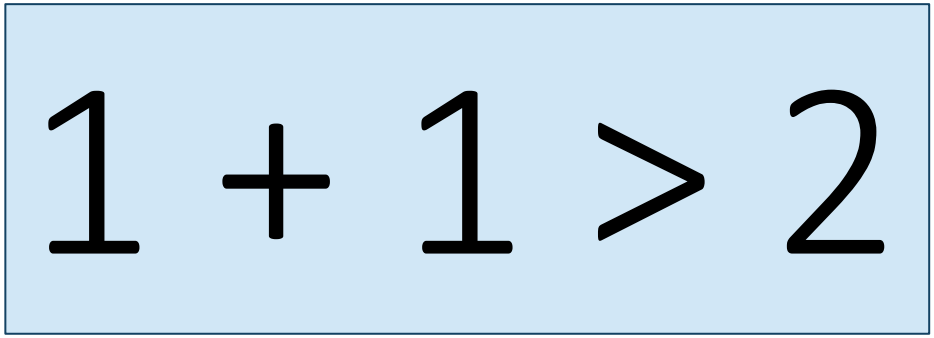



# Energy and Mass Defects

IB PHYSICS | ATOMIC PHYSICS

# Unified Atomic Mass Unit

When measuring and reporting the mass of individual atoms and subatomic particles, kilograms are inconveniently large…

The **unified atomic mass unit** is defined as one-twelfth of the mass of an isolated carbon-12 atom

*1 mole of Carbon Atoms = 0.012 kg*

$$\frac{0.012\ \text{kg}}{6.02 \times 10^{23}} = 1.99 \times 10^{-26}\ \text{kg}$$

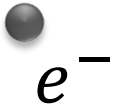
$$\frac{1.99 \times 10^{-26}\ \text{kg}}{12} = 1\ \text{u} = 1.661 \times 10^{-27}\ \text{kg}$$

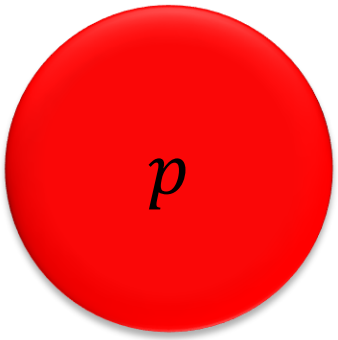
# Unified Atomic Mass Unit

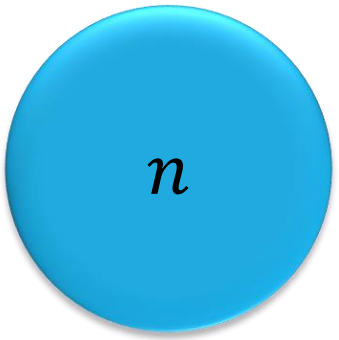
| | | |
|---|---|---|
| Electron ($m_e$) | $9.110 \times 10^{-31}$ kg | 0.000549 u |
| Proton ($m_p$) | $1.673 \times 10^{-27}$ kg | 1.007276 u |
| Neutron ($m_n$) | $1.675 \times 10^{-27}$ kg | 1.008665 u |

| | |
|---|---|
| Unified atomic mass unit | $1.661 \times 10^{-27}$ kg |

*This is the only time that we will ever use 7 sig figs. In this case, rounding to 1.01 u just wouldn't cut it…*



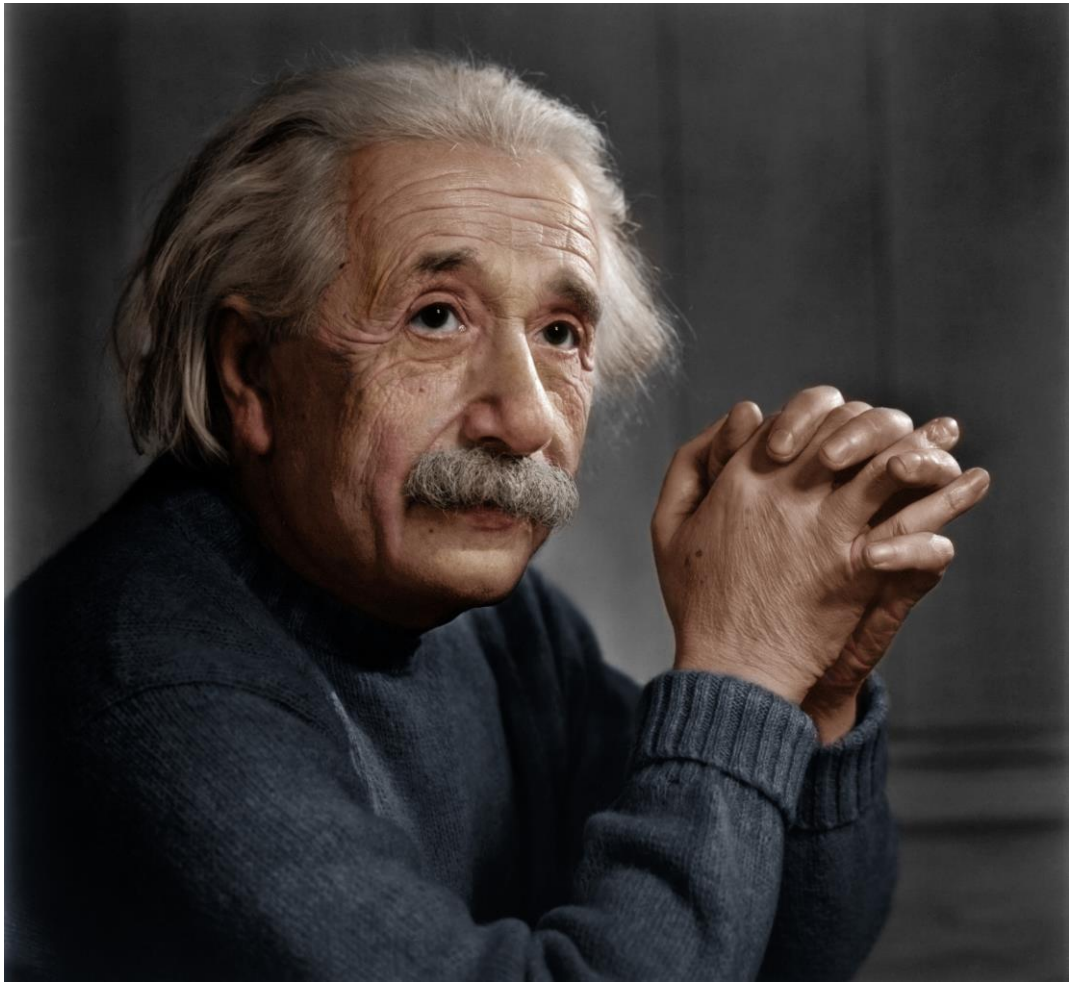



# IB Physics Data Booklet

## Fundamental constants

| Quantity | Symbol | Approximate value |
|---|---|---|
| Speed of light in vacuum | $c$ | $3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}$ |
| Planck's constant | $h$ | $6.63 \times 10^{-34}\,\mathrm{J\,s}$ |
| Elementary charge | $e$ | $1.60 \times 10^{-19}\,\mathrm{C}$ |
| Electron rest mass | $m_e$ | $9.110 \times 10^{-31}\,\mathrm{kg} = 0.000549\,\mathrm{u} = 0.511\,\mathrm{MeV\,c^{-2}}$ |
| Proton rest mass | $m_p$ | $1.673 \times 10^{-27}\,\mathrm{kg} = 1.007276\,\mathrm{u} = 938\,\mathrm{MeV\,c^{-2}}$ |
| Neutron rest mass | $m_n$ | $1.675 \times 10^{-27}\,\mathrm{kg} = 1.008665\,\mathrm{u} = 940\,\mathrm{MeV\,c^{-2}}$ |
| Unified atomic mass unit | u | $1.661 \times 10^{-27}\,\mathrm{kg} = 931.5\,\mathrm{MeV\,c^{-2}}$ |
| Solar constant | $S$ | $1.36 \times 10^{3}\,\mathrm{W\,m^{-2}}$ |
| Fermi radius | $R_0$ | $1.20 \times 10^{-15}\,\mathrm{m}$ |

# Einstein's Famous Equation



According to Albert Einstein, *"mass and energy are different manifestations of the same things"*

# Einstein's Famous Equation

$$E = mc^2$$

What is the energy equivalence of 1 g of matter?

# Einstein's Famous Equation

$$E = mc^2$$

Energy [J]

Mass [kg]

Speed of Light $3.00 \times 10^8\ m\ s^{-1}$

What is the energy equivalence of 1 g of matter?

$$E = (0.001\ kg)(3.00 \times 10^8\ m\ s^{-1})2 = 9 \times 10^{13}\ J$$

# IB Physics Data Booklet

| Sub-topic 7.1 – Discrete energy and radioactivity | Sub-topic 7.2 – Nuclear reactions |
|---|---|
| $E = hf$<br>$\lambda = \frac{hc}{E}$ | $\Delta E = \Delta m\, c^2$ |

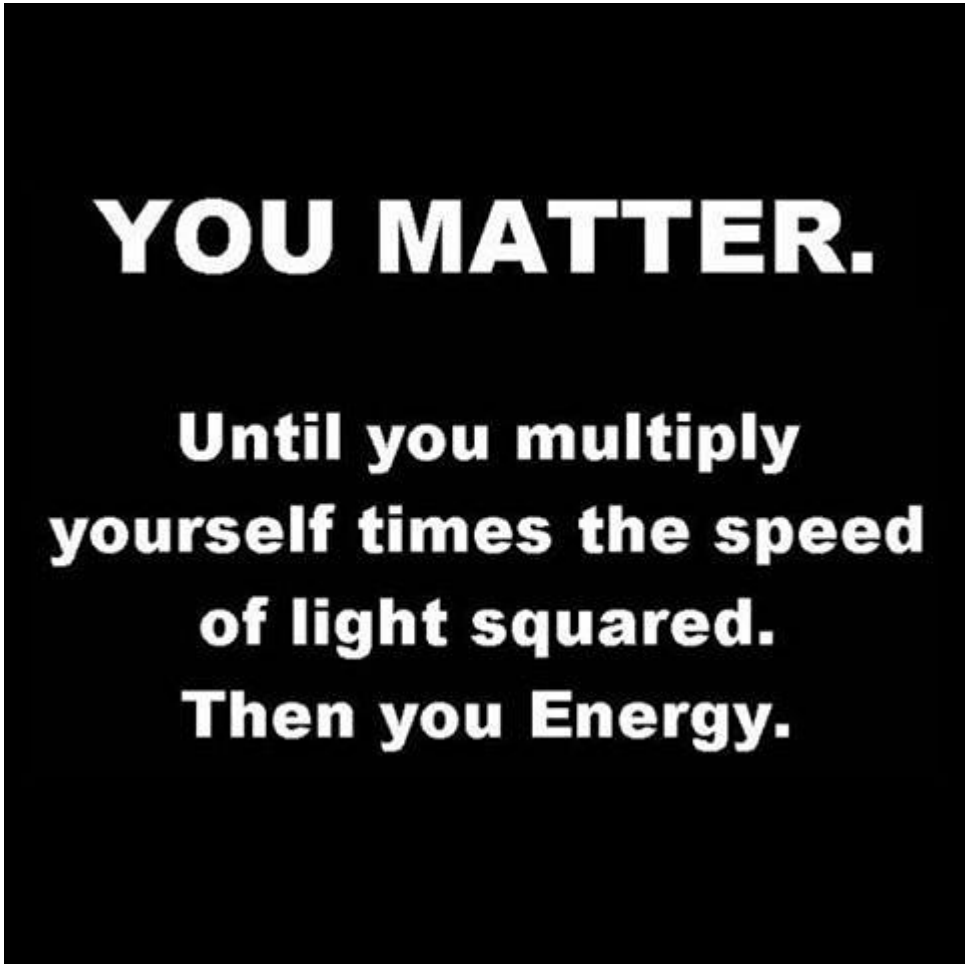
**Sub-topic 7.3 – The structure of matter**

| Charge | Quarks | | | Baryon number |
|---|---|---|---|---|
| $\frac{2}{3}e$ | u | c | t | $\frac{1}{3}$ |
| $-\frac{1}{3}e$ | d | s | b | $\frac{1}{3}$ |
| All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of –1 | | | | |

| Charge | Leptons | | |
|---|---|---|---|
| –1 | e | μ | τ |
| 0 | $\upsilon_e$ | $\upsilon_\mu$ | $\upsilon_\tau$ |
| All leptons have a lepton number of 1 and antileptons have a lepton number of –1 | | | |

| | Gravitational | Weak | Electromagnetic | Strong |
|---|---|---|---|---|
| Particles experiencing | All | Quarks, leptons | Charged | Quarks, gluons |
| Particles mediating | Graviton | $W^+$, $W^-$, $Z^0$ | γ | Gluons |

# $E = mc^2$


YOU MATTER.
Until you multiply
yourself times the speed
of light squared.
Then you Energy.

# New Unit for Energy!

| Electron-Volt | eV |
|---|---|
| 1 MeV = $10^6$ eV | |

$$\{Energy\ in\ eV\} = \frac{\{Energy\ in\ J\}}{1.60 \times 10^{-19}}$$

What is the energy equivalence of 1 proton ($1.673 \times 10^{-27}$ kg)?

$$E = (1.673 \times 10^{-27})(3 \times 10^{8})^2 = 1.5057 \times 10^{-10}\ \text{J}$$

$$\frac{1.5057 \times 10^{-10}\ \text{J}}{1.60 \times 10^{-19}} = 941{,}062{,}500\ eV \approx \mathbf{941\ MeV}$$

# New Unit for Mass

$$E = mc^2$$

$$m = \frac{E}{c^2} = \frac{MeV}{c^2} = \boxed{\boldsymbol{MeV\ c^{-2}}}$$

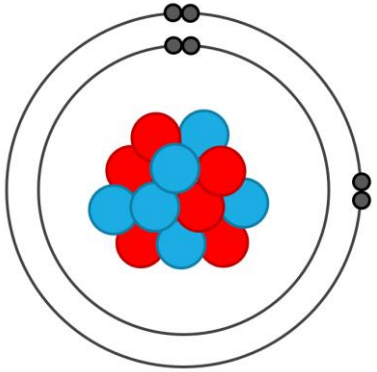
# Unified Atomic Mass Unit

| | | | |
|---|---|---|---|
| Electron rest mass ($m_e$) | $9.110 \times 10^{-31}$ kg | 0.000549 u | 0.511 MeV $c^{-2}$ |
| Proton rest mass ($m_p$) | $1.673 \times 10^{-27}$ kg | 1.007276 u | 938 MeV $c^{-2}$ |
| Neutron rest mass ($m_n$) | $1.675 \times 10^{-27}$ kg | 1.008665 u | 940 MeV $c^{-2}$ |
| Unified atomic mass unit | $1.661 \times 10^{-27}$ kg | 1.000000 u | 931.5 MeV $c^{-2}$ |

# Mass of the Nucleus

A neutral Carbon-12 atom contains:

6 protons
6 neutrons
6 electrons



| | |
|---|---|
| Electron rest mass ($m_e$) | 0.000549 u |
| Proton rest mass ($m_p$) | 1.007276 u |
| Neutron rest mass ($m_n$) | 1.008665 u |
| Unified atomic mass unit | 1.000000 u |

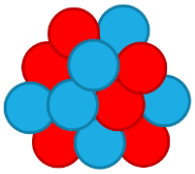
If the mass of Carbon-12 is defined as exactly 12.00000*u*, then the nucleus mass is:

$$12.00000\text{u} - (6 \times 0.000549\text{u}) = \mathbf{11.996706u}$$

# Component Mass

A nucleus of Carbon-12 contains:

6 protons
6 neutrons



What is the total mass in terms of u?

| | |
|---|---|
| Electron rest mass ($m_e$) | 0.000549 u |
| Proton rest mass ($m_p$) | 1.007276 u |
| Neutron rest mass ($m_n$) | 1.008665 u |
| Unified atomic mass unit | 1.000000 u |

$6 \times 1.007276$ u
$6 \times 1.008665$ u
} 12.095646 u

# Mass Defect | 1+1 > 2

Mass sum of the Carbon-12 subatomic particles:

$$(6 \times 1.007276\text{u}) + (6 \times 1.008665\text{u}) = 12.095646\text{u}$$

Mass of Carbon-12 nucleus: $11.996706\text{u}$

---

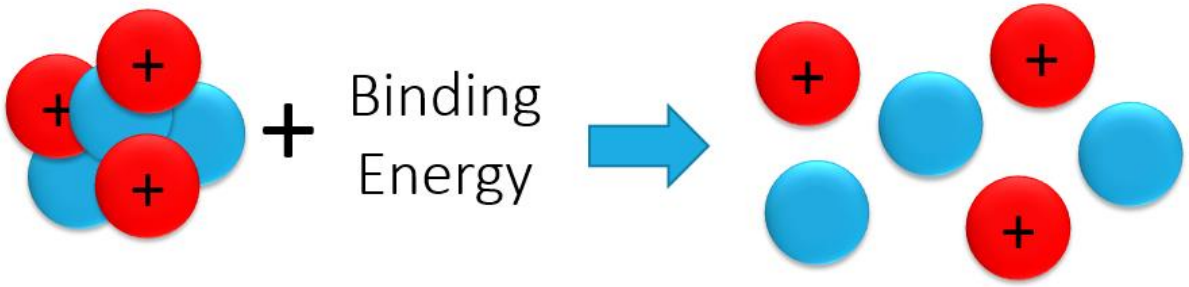
Mass Defect → $12.095646\text{u} - 11.99670\text{u} = \mathbf{0.098946u}$

Where did the mass go?

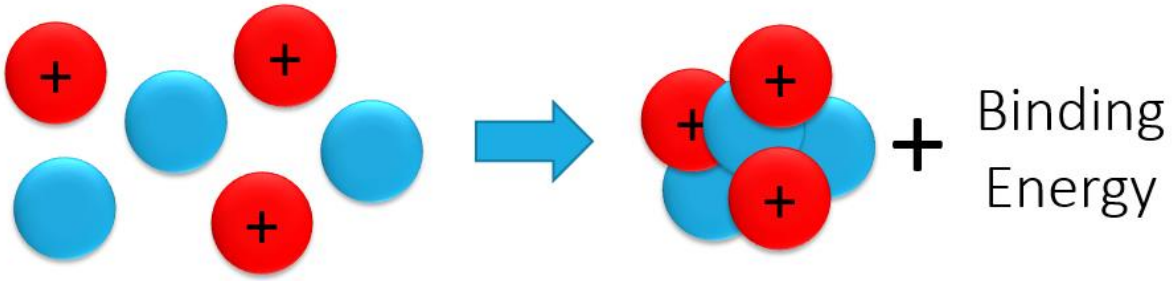
Energy

# Binding Energy

Binding Energy is the energy required to separate all of the nucleons




…or the energy released when a nucleus is formed from its nucleons



# Mass Defect → Binding Energy

| | | | |
|---|---|---|---|
| Unified atomic mass unit | $1.661 \times 10^{-27}$ kg | 1.000000 u | 931.5 MeV $c^{-2}$ |

$$\mathbf{0.098946u} = 0.098946 \times 931.5\ MeV\ c^{-2} =$$

$$92.1682\ MeV\ c^{-2}$$

$$E = mc^2$$

$$= (92.1682\ MeV\ \cancel{c^{-2}})(\cancel{c^{2}})$$

$$= \mathbf{92.17\ MeV}$$

# Binding Energy per Nucleon

Binding Energy for Carbon-12 = 92.2 MeV

Number of Nucleons
for Carbon-12 = **12**

- 6 protons
- 6 neutrons

Binding Energy per Nucleon = $\frac{92.16\ MeV}{12} =$

$7.68\ MeV\ per\ Nucleon$

# Calculate Binding Energy per Nucleon

| Nuclide | # of p | # of n | Nucleus Mass |
|---|---|---|---|
| Iodine-127 | 53 | 74 | 126.87544u |

| | |
|---|---|
| $m_e$ | 0.000549u |
| $m_p$ | 1.007276u |
| $m_n$ | 1.008665u |
| 1u | 931.5 MeV $c^{-2}$ |

Mass Defect

$$\begin{array}{r} 53 \times 1.007276\ \text{u} \\ 74 \times 1.008665\ \text{u} \\ \hline 128.026838\text{u} \end{array} - 126.87544\text{u} = 1.15140\text{u}$$

$$1.15140\ u \times \frac{931.5\ MeV\ c^{-2}}{1\ u} = 1072.53\ MeV\ c^{-2}$$

Convert mass to MeV $c^{-2}$

$$E = mc^2 = (1072.53\ MeV\ c^{-2})c^2 = 1072.53\ MeV$$

$$1072.53\ MeV/127 = \boxed{8.45\ MeV\ per\ Nucleon}$$

# Calculate Binding Energy per Nucleon

*For your assigned nuclide, calculate the binding energy per Nucleon and record data in shared spreadsheet

Use a periodic table to determine atomic # for your element

| | |
|---|---|
| $m_e$ | 0.000549u |
| $m_p$ | 1.007276u |
| $m_n$ | 1.008665u |
| 1u | 931.5 MeV $c^{-2}$ |

| | Element | Nucleus Mass (u) |
|---|---|---|
| 1 | Hydrogen-2 | 2.013553 |
| 2 | Helium-3 | 3.014931 |
| 3 | Hydrogen-3 | 3.015500 |
| 4 | Helium-4 | 4.001505 |
| 5 | Lithium-6 | 6.013476 |
| 6 | Lithium-7 | 7.014356 |
| 7 | Beryllium-9 | 9.009987 |
| 8 | Carbon-12 | 11.996706 |
| 9 | Nitrogen-14 | 13.999231 |
| 10 | Oxygen-16 | 15.990523 |
| 11 | Fluorine-19 | 18.993462 |
| 12 | Magnesium-24 | 23.978454 |
| 13 | Phosphorus-31 | 30.965527 |
| 14 | Sulfur-34 | 33.959083 |
| 15 | Potassium-39 | 38.953275 |

| | Element | Nucleus Mass (u) |
|---|---|---|
| 16 | Iron-56 | 55.920662 |
| 17 | Arsenic-75 | 74.903478 |
| 18 | Krypton-84 | 83.891734 |
| 19 | Zirconium-90 | 89.882739 |
| 20 | Silver-107 | 106.879287 |
| 21 | Tin-120 | 119.874752 |
| 22 | Iodine-127 | 126.875373 |
| 23 | Cesium-140 | 139.873608 |
| 24 | Europium-153 | 152.886650 |
| 25 | Tungsten-184 | 183.910307 |
| 26 | Gold-197 | 196.923199 |
| 27 | Lead-206 | 205.929447 |
| 28 | Bismuth-209 | 208.934833 |
| 29 | Uranium-235 | 234.993420 |
| 30 | Uranium-238 | 238.000282 |

# Binding Energy per Nucleon