Lecture 2
- Nuclear and Radiation Chemistry
  - Nucleons, nuclides and isotopes
  - Nuclear fusion and stellar nucleogenesis
  - Natural Radioactivity

Lecture 3
- Nuclear Stability, Decay Rates and Carbon Dating

Housekeeping:
Download lecture notes from:
or from Chemistry webserver.

Useful textbook: Silberberg, CHEMISTRY, 3rd Ed.

All repeat students to go to first year office and get lab exemption immediately!

Dalton’s Big Idea

Dalton’s Atomic Theory (1808)
- All matter consists of indivisible particles known as atoms.
- Atoms of one element cannot be converted into atoms of another element.
- Atoms of an element are identical, but are different from atoms of any other element.
- Compounds result from chemical combination of a specific ratio of atoms of different elements.

Current Atomic Theory (2005)
- Atoms are made of subatomic particles - protons, neutrons, electrons
- Atoms can be interconverted by nuclear reactions.
- Atoms of an element have identical atomic number, but may have different atomic masses (isotopes).
- Generally true, but some exceptions.

How do we identify atoms?
How do we know about different isotopes?
Nucleons - The Sub-Atomic Particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Charge</th>
<th>Mass (a.m.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>p</td>
<td>+1</td>
<td>1.007276</td>
</tr>
<tr>
<td>neutron</td>
<td>n</td>
<td>0</td>
<td>1.008665</td>
</tr>
<tr>
<td>electron</td>
<td>e</td>
<td>-1</td>
<td>0.000549</td>
</tr>
<tr>
<td>positron</td>
<td>e⁺</td>
<td>+1</td>
<td>0.000549</td>
</tr>
</tbody>
</table>

The unit of mass is atomic mass units (a.m.u.), defined by setting the mass of the isotope $^{12}_{6}$C to exactly 12.000000. 1 a.m.u. = 1.66 x 10⁻²⁷ kg.

Nuclides and Isotopes

The composition of any nucleus is defined by two numbers.
- The **atomic number** is the number of protons in the nucleus.
  - This defines the chemical nature of the atom.
  - It is equal to the total charge on the nucleus.
- The **mass number** is the total number of nucleons (protons and neutrons) in the nucleus.

E.g. $^{12}_{6}$C has an atomic number of 6 and a mass number of 12.

- A **nuclide** is an atom with a particular mass number and atomic number.
- Nuclei with the same atomic number but different mass numbers are called **isotopes**.

Nuclides and Isotopes

Nuclei with the same atomic number but different mass numbers are called **isotopes**.

E.g. Carbon may exist as a number of isotopes

- $^{12}_{6}$C: Unstable nucleus; trace amounts present in living matter.
- $^{13}_{6}$C: Stable nucleus; accounts for 1.11% of natural carbon.
- $^{14}_{6}$C: Stable nucleus; 98.89% of natural carbon.
How Mass Spectrometry Works

In a mass spectrometer, the atoms or molecules to be studied are vaporized and then ionized, usually by an electrical discharge.

In the conventional design of a mass spectrometer, ions follow a curved path and their deflection depends on the mass-to-charge ratio, \( m/z \) (sometimes denoted \( m/e \)). This deflection was originally recorded as impact on a strip of photographic film, but now use digital current or luminescence detectors.

Mass Spectrometry

Aston’s results established the existence of isotopes. (They were already known for radioactive elements, but never shown for stable elements.)

1920 - Aston measured two isotopes of Ne (20 and 22), three of S (32, 33, 34), three of Si (28, 29, 30), six of Kr (78, 80, 82, 83, 84, 86), and many others.
Development of Mass Spectrometry

Francis William Aston

“for his discovery, by means of his mass spectrograph, of isotopes, in a large number of non-radioactive elements, and for his enunciation of the whole-number rule”

1919 - Aston separates isotopes in a mass spectograph.
1946 - Pulsed gas injection and time-of-flight detectors
1956 - Mass spectrometry to identify complex organic molecules.
1977 - Accelerator Mass spectrometry developed for trace analysis.
2002 - Nobel Prize in Chemistry to Koichi Tanaka and John Fenn for developments to Mass Spec. allowing the study of large (bio)molecules.

Triumph of Mass Spectrometry

1996 Nobel prize to Kroto, Curl and Smalley.... Grad students missed out!
Nuclides and Isotopes

The atomic mass of an element is the average of the atomic masses and abundances of each of the naturally-occurring isotopes.

E.g. The atomic mass of carbon is 12.01...

That is \((12.0000 \times 98.89 + 13.00335 \times 1.11)/100\)

\(\text{Mass of nuclide is the reference for a.m.u scale.}\)

\(\text{Mass of nuclide taken from a reference table}\)

Nucleogenesis

Where do the elements come from?

How are atoms (nuclei) formed?

All atoms are generated from the simplest element, hydrogen \(^1\text{H}\), by nuclear reactions.

Clouds of atomic hydrogen are pulled together by gravity and begin to heat as they are compressed. Eventually high enough temperatures for nuclear fusion are achieved and the cloud ignites as a star.

http://antwrp.gsfc.nasa.gov/apod/ap960625.html
Nucleogenesis

The fundamental nuclear reaction is

\[ {^1}_1H + {^1}_1H \rightarrow {^1}_1H + {^0}_1e \]

This denotes a positron of mass 0 and charge 1.

In nuclear reactions, where the nuclide is changed, we must balance both the charge and the mass numbers.

In a nuclide, the charge is the same as the atomic number – the number of protons.

See - http://www.nobel.se/physics/articles/fusion/index.html

Nucleogenesis

The fundamental nuclear reaction is

\[ {^1}_1H + {^1}_1H \rightarrow {^1}_1H + {^0}_1e \]

This is rapidly followed by two other nuclear reactions

\[ {^2}_2H + {^1}_1H \rightarrow {^3}_2He + \gamma \]

This denotes high energy, short wavelength gamma radiation, which has no mass or charge.

and

\[ {^3}_2He + {^2}_4He \rightarrow {^4}_2He + 2^0_1p \]

Again note that both mass numbers and charges (atomic numbers) must balance.

See - http://www.nobel.se/physics/articles/fusion/index.html
Nucleogenesis

The overall "hydrogen burning reaction"

\[ {^1}_4H \rightarrow {^1}_2He + 2 \, e + \gamma \]

releases energy into the surroundings as heat (exothermic) and radiation (also releases neutrinos \( n \)).

As the star exhausts its hydrogen, it begins helium burning to fuse heavier nuclei to form increasingly larger atoms.

E.g.

\[ {^4}_2He + {^4}_2He + \frac{2}{5}He \rightarrow {^{13}}_6C \]

Heavier nuclei like \( ^{12}C \), \( ^{13}N \), \( ^{14}N \), \( ^{15}N \), \( ^{15}O \)... are produced by red giant stars, still heavier nuclei in supergiants, and true heavy elements form in supernovae.

Where did the energy come from? How much energy?

The overall "hydrogen burning reaction"

\[ {^1}_4H \rightarrow {^1}_2He + 2 \, e + \gamma \]

Mass on LHS is: \( 4 \times 1.007825032 \) g/mol = \( 4.031300128 \) g/mol

Mass on RHS is: \( 4.002 \, 603 \, 2497 \times 2 \times 0.000548579911 \) g/mol = \( 4.003700410 \) g/mol

Missing mass is \( 4.031300128 - 4.003700410 = 0.027599718 \) g/mol

\[ E = mc^2 \]

\[ E = 0.027599718/1000 \, \text{kg} \times (2.9979 \times 10^8 \, \text{ms}^{-1})^2 \]

\[ = 2.480 \times 10^{12} \, \text{J/mol} \]

Where did the energy come from? How much energy?

The overall "hydrogen burning reaction"

\[ {^1}_4H \rightarrow {^1}_2He + 2 \, e + \gamma \]

\[ E = 2.480 \times 10^{12} \, \text{J/mol of reaction (4 atoms)} \]

\[ = 6.2 \times 10^{11} \, \text{J/mol of H atoms} \]

Compare with burning hydrogen with oxygen, chemically:

\[ E = 1.4 \times 10^9 \, \text{J/mol of H atoms} \]

Nuclear "burning" liberates 4 million times more energy!

So we won't be doing that in class…
This star went supernova in 1572

http://seds.lpl.arizona.edu/~spider/spider/Vars/sn1572.html

Caution: enya
Life Cycle of Stars

Hydrogen burning

T ~ 10^7 K

Heavy elements

40 Ca
58 Ni

formed (C and O burning)

T < 3 x 10^9 K

Helium burning

T < 2 x 10^8 K

Carbon core

Helium burning

T < 2 x 10^8 K

Red Giant

Planetary Nebula

Neutron Star

Black Hole

Second-generation stars

Supernova explosions inject carbon, oxygen, silicon and other heavy elements up to iron into interstellar space. They are also the site where most of the elements heavier than iron are produced. This heavy element enriched gas will be incorporated into future generations of stars and planets.

We know from the presence of heavy elements in our sun that it is (at least) a second-generation star, currently undergoing hydrogen burning.

Without supernovae, the fiery death of massive stars, there would be no carbon, oxygen or other elements that make life possible.

Nucleogenesis ...and the periodic table
Natural Radioactivity

Nucleogenesis produces nuclides that can be stable or unstable. Unstable nuclei decay through a range of mechanisms involving the release of particles with high kinetic energy or of γ-radiation. These high-energy products are collectively known as radioactivity.

Henri Becquerel

*in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity*

Pierre Curie

*in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel*

Marie Curie

The four most important radioactive decay mechanisms are

1. α decay
   e.g. \( \frac{212}{83}Bi \rightarrow \frac{208}{81}Tl + ^4\alpha \)
   The α particle is simply a helium nucleus with mass 4 and charge 2+. As with all nuclear reactions, both mass and charge are balanced.

2. β⁻ decay
   e.g. \( \frac{12}{5}B \rightarrow \frac{12}{6}C + ^{−}β \)
   A β⁻ (or β⁻) is an electron ejected from the nucleus. One neutron is changed into a proton in this nuclear reaction to balance the charge.

3. Positron (β⁺) emission
   e.g. \( \frac{12}{7}N \rightarrow \frac{12}{6}C + ^{+}β \)
   When a positron (β⁺) is ejected from the nucleus it usually collides with its antiparticle (the electron) in the surrounding environment very soon: \( e^- + e^+ \rightarrow γ \)

4. Electron capture
   e.g. \( \frac{54}{25}Fe + ^{−}e^- \rightarrow \frac{55}{25}Mn \)
   Electron capture is followed by emission of x-rays as electrons fall into lower energy states to fill the vacancy left by the captured electron. (x-rays are not generally classified as radioactivity, although they can cause radiation damage.)
Natural Radioactivity - worked example

Balance the following nuclear decay reactions and identify the emitted particle where appropriate.

1. $^{234}_{92}\text{U} \rightarrow ^{234}_{86}\text{Pa} + ^{4}_{2}\text{He}$ or $^{23}_{14}\text{He}$

2. $^{63}_{27}\text{Ni} \rightarrow ^{63}_{26}\text{Co} + ^{1}_{0}\text{He}$

3. $^{36}_{17}\text{Cl} + ^{1}_{0}\text{He} \rightarrow ^{36}_{18}\text{Ar}$

Nuclear Reactions - worked example

Nuclear reactions are balanced in the same way, but may involve more than one reactant. Balance the following nuclear reactions and identify the missing nuclide or particle.

1. $^{14}_{7}\text{N} + ^{4}_{2}\text{He} \rightarrow ^{16}_{8}\text{O} + ^{1}_{0}\text{He}$ or $^{1}_{0}\text{H}$

2. $^{239}_{93}\text{Pu} + ^{4}_{2}\text{He} \rightarrow ^{239}_{92}\text{Cm} + ^{1}_{0}\text{He}$

3. $^{14}_{7}\text{N} + ^{4}_{1}\text{He} \rightarrow ^{15}_{7}\text{P} + ^{1}_{0}\text{n}$

Natural Radioactivity - $\gamma$ and x-rays

Both x-rays and $\gamma$ radiation are high energy (= high frequency or short wavelength) forms of light.
Unstable heavy nuclei decay spontaneously by a series of steps through unstable intermediates. Over time, unstable nuclei give rise to a family of decay products in a decay series. E.g. $^{238}\text{U}$ decays into...

\[
\begin{align*}
^{238}\text{U} &\rightarrow ^{234}\text{Th} + ^4\text{He} \\
^{234}\text{Th} &\rightarrow ^{234}\text{Pa} + ^0\beta \\
^{234}\text{Pa} &\rightarrow ^{234}\text{U} + ^0\beta \\
^{234}\text{U} &\rightarrow ^{234}\text{Th} + ^4\text{He} \\
^{234}\text{Th} &\rightarrow ^{226}\text{Ra} + ^6\alpha
\end{align*}
\]

...etc, etc,...
Summary
You should now be able to
• Recognise nuclear reactions, including the major spontaneous decay mechanisms.
• Define and distinguish between nucleons, nuclides & isotopes, x-rays & gamma rays, decay series and daughter isotopes.
• Explain stellar nucleogenesis.
• Calculate the average atomic mass from isotope information.
• Balance nuclear reactions.

Next Lecture
• Nuclear Stability
  • Which nuclei are stable and why.
  • Where decay mechanisms come from.
• Decay Rates
  • How fast does an unstable nucleus decay?
  • Half-lives.
• Radiocarbon Dating
• Madame Curie (née Sklodowska) and friends