Chemistry 1000 Lecture 2: Nuclear reactions and radiation

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Nuclear reactions

- Ordinary chemical reactions do not involve the nuclei, so we can balance these reactions by making sure that the number of atoms of each type is conserved.
- In nuclear reactions on the other hand, the nuclei themselves change.
- Nuclear reactions generate enormously more energy (by many orders of magnitude) than chemical reactions.
- Nuclear reactions also release various forms of radiation.

Examples of nuclear reactions

Fusion of hydrogen nuclei: $^{1}\mathrm{H} + {}^{1}\mathrm{H} \longrightarrow {}^{2}\mathrm{H} + \beta^{+}$
(β^{+} is a positive β particle, a.k.a. a positron or anti-electron.)

Spontaneous fission of ^{236}U: $^{236}\mathrm{U} \longrightarrow {}^{141}\mathrm{Ba} + {}^{92}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$
(${}^{1}_{0}$n is a neutron.)

α decay: $^{218}\mathrm{Po} \longrightarrow {}^{214}\mathrm{Pb} + {}^{4}_{2}\alpha$
(${}^{4}_{2}\alpha$ is an alpha particle, which is just a ^{4}He nucleus.)

Some particles and their symbols

Nucleon: proton or neutron

Alpha (α) particle: a helium nucleus, symbolized ${}^{4}_{2}\alpha$

Beta particle: an electron, usually symbolized ${}^{0}_{-1}\beta$, but sometimes also ${}^{0}_{-1}\mathrm{e}$

Positive beta particle: a positron, symbolized ${}^{0}_{1}\beta$

Neutron: symbolized ${}^{1}_{0}\mathrm{n}$

Proton: symbolized ${}^{1}_{1}\mathrm{p}$ (or ${}^{1}_{1}\mathrm{H}$)

Conservation laws in nuclear reactions

- The total charge is conserved.
  $\Longrightarrow$ the sum of the Z values on both sides of the reaction should be the same.

- The total number of nucleons is conserved.
  $\Longrightarrow$ the sum of the A values on both sides of the reaction should be the same.

Types of nuclear reactions

Alpha emission (or decay): an α particle is ejected from a nucleus.

Example: alpha decay of ${}^{222}_{86}$Rn

Beta emission (or decay): a ${}^{\ 0}_{-1}\beta$ particle is emitted, converting a neutron into a proton:

$$ {}^{1}_{0}\text{n} \longrightarrow {}^{1}_{1}\text{p} + {}^{\ 0}_{-1}\beta $$

Example: beta decay of ${}^{234}_{90}$Th

Positron emission: a ${}^{0}_{1}\beta$ particle is emitted, converting a proton into a neutron:

$$ {}^{1}_{1}\text{p} \longrightarrow {}^{1}_{0}\text{n} + {}^{0}_{1}\beta $$

Example: positron emission by ^{30}P

Types of nuclear reactions (continued)

Electron capture: the nucleus captures an electron, converting a proton into a neutron:

$$^{1}_{1}\mathrm{p} + {}^{0}_{-1}\beta \longrightarrow {}^{1}_{0}\mathrm{n}$$

Example: electron capture by ^{40}K

Fission: splitting of a nucleus into two lighter nuclei

Two types:

1. Spontaneous
   Example: fission of ^{240}Pu to produce ^{135}I and two neutrons
2. Induced (usually by neutrons)
   Example: fission of ^{235}U induced by a neutron, producing ^{133}Cs and three neutrons

Types of nuclear reactions (continued)

Fusion: combination of lighter nuclei to make a heavier nucleus
Example: fusion of ^{8}Be with ^{4}He

Bombardment: a variation on fusion in which heavy nuclei are bombarded with light nuclei (or sometimes just neutrons) in an accelerator
Example: synthesis of ^{247}Fm by bombardment of ^{239}Pu with ^{12}C

Einstein's energy equation

- In special relativity, we have the equation

$$E^2 = c^2p^2 + m_0^2c^4,$$

where E is the total energy of a particle, c is the speed of light in a vacuum, p is the momentum of the particle ($p = mv$), and m_0 is the particle's rest mass.

- For a particle traveling at a speed much less than c, we have $E = m_0c^2$ or, since the rest mass and mass are the same under these conditions,

$$E = mc^2$$

Energy in nuclear reactions

- Consider the nuclear reaction ${}^{1}\text{H} + {}^{1}\text{H} \longrightarrow {}^{2}\text{H} + {}^{0}_{1}\beta$.
  Ignoring the positron, calculate the change in mass:

$$\begin{aligned}\Delta m &= m_\text{D} - 2m_\text{H} \\ &= 2.014\,101\,7778 - 2(1.007\,825\,032\,07\text{ u}) \\ &= -0.001\,548\,2863\text{ u}\end{aligned}$$

- Where did the missing mass go?
  Energy!

Energy in nuclear reactions (continued)

- Since $E = mc^2$,
$$\Delta E = \Delta mc^2$$
- To use this formula, Δm must be in the SI unit of mass, the kg.

$$\begin{aligned}\Delta m &= -0.001\,548\,2863\,\mathrm{u} \\ &\equiv -0.001\,548\,2863\,\mathrm{g/mol} \\ &\equiv \frac{-0.001\,548\,2863\,\mathrm{g/mol}}{(1000\,\mathrm{g/kg})(6.022\,141\,29 \times 10^{23}\,\mathrm{mol^{-1}})} \\ &= -2.570\,9897 \times 10^{-30}\,\mathrm{kg}.\end{aligned}$$

Energy in nuclear reactions (continued)

$$
\begin{aligned}
\Delta E &= \Delta mc^2 \\
&= (-2.570\,9897 \times 10^{-30}\,\text{kg})(2.997\,924\,58 \times 10^{8}\,\text{m/s})^2 \\
&= -2.310\,6903 \times 10^{-13}\,\text{J}. \\
&\equiv (-2.310\,6903 \times 10^{-13}\,\text{J})(6.022\,141\,29 \times 10^{23}\,\text{mol}^{-1}) \\
&= -1.391\,5304 \times 10^{11}\,\text{J/mol} \\
&\equiv -139.153\,04\,\text{GJ/mol}
\end{aligned}
$$

- This is a massive amount of energy.

So why did we leave the positron out of the calculation?

$$ {}^{1}\text{H} + {}^{1}\text{H} \longrightarrow {}^{2}\text{H} + {}^{0}_{1}\beta $$

- The two hydrogen atoms on the left-hand side each have an electron, so really the whole system consists of two hydrogen nuclei and two electrons. The net charge is zero.
- The deuterium (^{2}H) atom on the right is made of a proton, a neutron, and one electron. The positron has a charge of $+1$. The net charge is $+1$.

  That can't be right? What happened to the second electron?

So why did we leave the positron out of the calculation? (continued)

- The positron is the anti-particle of the electron. When a positron and an electron meet, their mass is converted completely to energy:

$$ {}^{0}_{1}\beta + {}^{0}_{-1}\beta \longrightarrow \text{energy} $$

  The assumption of the calculation we have made is that the positron will meet an electron (somewhere) to balance the overall charge (i.e. to cancel the extra electron from the rhs of the reaction). The ΔE we calculated includes this annihilation energy.

Example: Fission of ^{235}U

We previously balanced the reaction

$$^{235}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{133}\mathrm{Cs} + {}^{100}\mathrm{Rb} + 3\,{}^{1}_{0}\mathrm{n}$$

Calculate the energy liberated by this reaction per mole of uranium fissioned.

Isotope	Mass/u
${}^{1}_{0}\mathrm{n}$	1.008 664 9160
$^{100}\mathrm{Rb}$	99.9499
$^{133}\mathrm{Cs}$	132.905 451 933
$^{235}\mathrm{U}$	235.043 9299

Answer: -1.539×10^{13} J/mol

Types of radiation

Radiation generally describes anything emitted from a material.

Ionizing radiation refers to radiation that can ionize matter (i.e. make ions by separating electrons from their atoms).

Alpha and beta radiation refer to the emission of α and β particles.

- α radiation is easily stopped (can be stopped by a piece of paper) but can under certain circumstances be highly damaging (e.g. ingestion of an alpha emitter).
- β radiation is somewhat harder to stop (can be stopped by a few millimeters of aluminium) and can cause radiation burns and other health effects.

Types of radiation (continued)

Neutrons are harder to stop because they are neutral, so they are very hard to stop. They can induce fission or ionize matter directly by knocking light nuclei (esp. hydrogen) out of their molecules.

Gamma radiation consists of high-energy electromagnetic radiation (like light, but much higher in energy). Most gamma radiation passes right through matter, but when it does interact with matter it can cause serious damage (e.g. mutations).

Neutrinos carry away most of the energy in many nuclear reactions. They are massless, chargeless particles that interact extremely weakly with matter. Accordingly, they have no biological effects.

Radiation exposure

- Ionizing radiation is measured in terms of the amount of separated charge it can create.
- Radiation exposure is measured as the amount of radiation required to create 1 coulomb of separated charges in 1 kg of matter (units: C/kg)

Absorbed dose

- The absorbed dose of radiation is measured as the amount of energy absorbed per unit mass.
- Unit: gray (Gy)
  $1\,\text{Gy} = 1\,\text{J/kg}$
- Older unit (still sometimes used): rad
  $1\,\text{rad} = 0.01\,\text{Gy}$

Equivalent dose

- Not all types of radiation are equally damaging.
- The equivalent dose gives the gamma ray equivalent of a radiation dose by multiplying by a factor called the relative biological effectiveness, usually denoted Q.
- Unit of equivalent dose: sievert (Sv)
  $1\,\text{Sv} = 1\,\text{J/kg}$ of gamma rays
- Older unit (still sometimes used): rem
  $1\,\text{rem} = 0.01\,\text{Sv}$

Type of radiation	Q
x-rays or gamma rays	1
β particles	1
α particles	20
neutrons	5–20

Absorbed and equivalent dose example

A radiation worker weighing 75 kg is exposed to a ^{252}Cf neutron source, receiving an estimated dose of 10^{12} neutrons in the process. For this source, $Q = 20$ and the neutrons have an average energy of 3×10^{-13} J. What are the absorbed and equivalent dose?

Answers: Absorbed dose 4 mGy, equivalent dose 80 mSv

Typical exposure and safe exposure limits

- Typical annual exposure to background radiation (cosmic rays, radiation from naturally occurring isotopes in environment, etc.): 3 mSv
- Single doses have very different effects and risks than the same dose spread over time, esp. if single dose is focused in one part of body.
- Single-dose LD_{50} (dose that is lethal 50% of the time): 4 Sv

Typical exposure and safe exposure limits
(continued)

- Legal limits to radiation exposure at work: no more than 50 mSv per year, and no more than 100 mSv over five years
- Long-term exposure to elevated levels of radiation increases the risk of many cancers.
  Typical lifetime occupational exposure for a radiation worker is less than 50 mSv (far below legal limits).
  At that level, cancer risk increases by about 5% over the general population (roughly 25% over a lifetime for gen. pop.).
- A worker who was exposed to the legal limit of 100 mSv every five years over a thirty year career would have a cancer risk about 60% higher than the general population (i.e. about 40% cancer risk).