Geochemistry

Notes I: Atoms, Isotopes, Nuclear Stability

I. Atoms and sub-atomic particles
II. Basic nomenclature
III. Constancy of isotopic composition and exceptions
IV. Binding energy, mass deficit, and stability

Particle/ray	Charge	Mass (amu)
proton	+1	1 (1.67 x 10^{-24} g)
neutron	0	1
electron (beta particle)	-1	1/1836
alpha particle	+2	4
positron	+1	1/1836
γ-ray	0	0

protons and neutrons are both nucleons
nucleus - 10^{-12} cm diameter
electron cloud - 10^{-8} cm diameter

Atoms of the same element have the same number of protons (and electrons - if neutral).
Size, shape, and chemical behavior of an element is determined by the electron cloud (and number of electrons)
Nuclides are sets of atoms with a specific number of neutrons and protons.
Isotopes of the same element have the same number of protons, but different numbers of neutrons

Nomenclature:

$${}^{A}_{Z}X^{\text{charge}}_{\text{stoichiometric number}}$$

X - chemical symbol
Z - number of protons - atomic number
N - number of neutrons
A - mass number = N+Z

Nuclides with the same mass number are called isobars

Typically Z is not shown because each element has a given Z and the element is known from the chemical symbol.

Atomic mass is the actual measured mass of a nuclide.

Atomic masses are typically given in Atomic mass units (amu). ^{12}C=12.000000..... amu. In general an atomic mass is not an integer.

Atomic weight is the abundance weighted average of the atomic masses of the mixture of isotopes making up an actual sample of an element.

**One of the fundamental observations of the material in the solar system is that the atomic weight of an element is constant no matter what its source or history, with the following classes of exceptions.

1. The isotopic composition of elements for which at least one nuclide is radiogenic (Sr, Nd, Th, Hf, Pb, Ar, Pa ....).

2. Elements that exhibit measurable mass-dependent fractionation (H, O, C, B, Li, Cl, S, Ca.....)

3. A few elements in primitive objects (oldest parts of the oldest meteorites) show measurable variations in isotopic composition, which are not mass dependent (O, Ti)

4. Elements for which at least one isotope is produced by nuclear reactions
   (a) instigated by cosmic rays (C-14, Be-10, Cl-36....).
   (b) from nuclear bombs or nuclear reactors (Sr-90, Pu, C-14, I-129, H-3....)
   (c) from natural nuclear reactions (Okla)

5. Elements for which an isotope may reside in a damaged site due to prior radioactive decay (U-234).

Stable Isotopes are nuclides that do not spontaneously decay into other isotopes. They can be divided into four categories.

A	Z	N	#of nuclides
Even	Even	Even	157
Odd	Even	Odd	53
Odd	Odd	Even	50
Even	Odd	Odd	4
		Total	264

Radioactive Isotopes are nuclides that spontaneously decay into other nuclides. This process can be considered a nuclear reaction.

Atomic mass and binding energy

A nuclide can be viewed as being made up of its constituent nucleons. For example, for He-4:

$$^{4}\text{He} + \text{energy} = 2p + 2n$$

If you compare the total mass on each side of the equation, you will find that the mass of the ^{4}He nucleus is lower than the mass of its constituent nucleons:

2 X 1.00782504 (proton) = 2.01565008
2 X 1.00866497 (neutron)=2.01732994
4.03298002
- ^{4} He =4.00260330
0.03037672 amu
X 931.502 MeV/amu
28.28 MeV

The difference is called the mass deficit. Using $E=mc^2$, one can calculate an energy equivalent to this mass deficit. This is called the binding energy (E_b) and can be viewed as the total amount of energy given off when a nucleus is made from its constituent nucleons. One can also consider either the binding energy per nucleon (E_b/A) or the mass deficit per nucleon. In the case of ^4He, the former is 28.28 MeV/4 nucleons = 7.07 MeV/nucleon. A nuclide with a high binding energy/nucleon is considered more stable than one with a low binding energy/nucleon.

Figures (some from Friedlander, Kennedy, Macias, and Miller (1981) - Nuclear and Radiochemistry) show that:

1. Even - even nuclides have higher binding energies/nucleon than adjacent even - odd or odd - even nuclides, which in turn have higher binding energies than adjacent odd - odd nuclides.

2. Binding energies/nucleon generally increases from H to Fe, then generally decrease.

3. At low $A<20$, stable nuclides tend to have Z /N approximately equal to 1, but with increasing A, N/Z gets progressively larger than 1 (coulomb repulsion).

4. Considering isobaric sections (A=constant, -binding energy vs. Z), for A=odd (even - odd or odd - even), the binding energies lie on a parabola. For A=even, the binding energies lie on two parabolas, one for odd-odd nuclides and one for odd-even nuclides.

**In three dimensions (binding energy vs. Z vs. N) one can see a "valley of stability". Radioactive decay is one mechanism whereby nuclides "move" down this valley.

A nuclide is energetically stable toward decay by some mode if its mass is smaller than the masses of the potential radioactive decay products.