8. Divisibility of atoms: Radioactivity

8.1 Discovery and classification

- Becquerel 1896: Uranium salt on top of wrapped-up photographic plate produces an image - radioactivity
- Marie and Pierre Curie extract Pollonium and Radium from the salt: much more radioactive
- 1 gram of Ra has power of 0.015 Watt
- Taking into account half-life of Ra (1500 years), emits 10000 times more energy than is released by burning 1g of coal

three different types of radiation:
- (β) - negatively charged particles (can be deflected in magnetic field)
- (α) - positively charged particles (can be deflected in magnetic field, but much weaker)
- (γ) - radiation, (not deflected using electromagnetic fields)
- β-particles identified as electrons by q/m value
- α-particles q/m = 4.826 \times 10^7 C/kg, half as much as hydrogen ion.
- Faraday beaker for collection of charges and counting number of particles: q=2e, thus \( \alpha = 4\text{He}^+ \)

8.2 Radioactive decay

- Radioactive decay: change of the type of element, atoms have no longer the unchangeable character attributed to them since the early days of Greek philosophy!
- \( _{226}^{88}\text{Ra} \rightarrow _{222}^{86}\text{Rn} + _2^4\alpha \rightarrow _{Z}^{A}\text{Element} \)
- atomic number \( Z \) reduced by 2 in α-decay, mass number \( A \) reduced by 4
- α: \( Z\rightarrow Z-2 \), \( A\rightarrow A-4 \)
- β - decay: \( Z\rightarrow Z-1 \), \( A\rightarrow A\); due to neutron changing to proton within nucleus
- Generally: resulting daughter nucleus also unstable, results in various decay series with end-product lead, Pb, which is stable
- 1919 Rutherford: artificial change of an element by bombarding Nitrogen with α-particles.

8.3 Nuclear properties

- How big is the nucleus? - can test by repeating Rutherford scattering experiment on different target nuclei. Obtain result: \( R = R_0 A^{1/3} \) \( R_0 = 1.2 \times 10^{-15} \text{ m} \)
- Radius dependent upon \( A^{1/3} \); volume \( \sim A \); density \( \sim \text{constant} \)
- Nuclear properties: before discussing masses of nuclei, lets look at masses of the building blocks: \( m_p = 1.007276 \text{ u} \) \( m_n = 1.008665 \text{ u} \) \( m_e = 0.000548580 \text{ u} \)
- Note we define 1 u such that 12g of carbon is exactly 1 mol of carbon atoms with 12 nucleons, or 6 protons, 6 neutrons and 6 electrons
- \( 1 \text{ g} = 6.02214179 \times 10^{23} \text{ u} \), \( 1 \text{ u} = \frac{1}{12} m(C) = 1.660538732 \times 10^{-27} \text{ kg} = 931.494028 \text{ MeV/c}^2 \)
- Nuclear isotopes - the same element can have different nuclear isotopes, where the number of neutrons N is not the same.
8.4 Mass defect

Nucleus: neutrons and protons, BUT mass of atoms not integer multiples of H-atom

- Example: C-atom: m(6p+6n+6e) = 20.089×10^{-27}kg
  m(C)=19.922×10^{-27}kg

- Mass defect Δm: when nuclei are formed from nucleons, energy is released.
  \[ \Delta m = \Delta E/c^2 \]
  - this energy release is potentially in the form of γ-rays

- Helium: (compare with Deuteron, 1p, 1n: \( \Delta E=2.224 \text{ MeV} \))
  \( m(2p+2n+2e)=6.6968×10^{-27}\text{kg}; m(\text{He}) = 6.6465×10^{-27}\text{kg} \)
  thus \( \Delta E=28.3 \text{ MeV} \) (relevant for nuclear fusion)

- Mass defect increases for more stable nuclei.

In 1932 Cockcroft and Walton split atoms: \( \frac{7}{3}Li+\frac{1}{1}p\rightarrow\frac{4}{2}\alpha+\frac{4}{2}\alpha \)
and found a release of energy of about 17MeV.

First nuclear confirmation of Einstein's relationship \( E=mc^2 \) results in Nobel Prize
for Cockcroft and Walton in 1951.

8.5 Nuclear stability

Not all nuclei stable, most nuclei unstable and undergo radioactive decay. Why?

Competing forces within the nucleus:
Nuclear binding force or strong nuclear force between nucleons
Also the electrostatic repulsion between the protons.

Competing forces reduce stability, or binding energy per nucleon if \( N \gg Z \) or \( Z \gg N \)

8.4 Mass defect

Calculate the average mass defect per nucleon in all the elements and isotopes
Obtain “nuclear binding energy curve”

\[ E_B = (ZM_H + Nm_n - \frac{4}{2}M)c^2 \]

Calculate the binding energy per deuteron:

\[ E_B = (1.007825 \text{ u} + 1.008665 \text{ u} - 2.014102 \text{ u})\times(931.5 \text{ MeV/u}) \]

\[ = 2.224 \text{ MeV} \]

Lowest point on graph = energy required to separate neutron and proton completely

8.5 Law of Radioactive decay

- N decaying atoms (N large), rate of decay (activity) proportional to N; λ, decay constant.
  \[ \frac{dN}{dt} = -\lambda \cdot N(t); \]

- Separation of variables:
  \[ \frac{dN}{N} = -\lambda \cdot dt; \]

- Integration:
  \[ \ln(N(t)) - \ln(N_0) = -\lambda (t-t_0); \]

- thus \( N(t) = N_0 \exp(-\lambda \cdot t) \)
  where we set \( t_0=0 \).

- Half-life \( T_{1/2} \): the time required for N to decrease from \( N_0 \) to \( N_0/2 \)
  \[ N(T_{1/2}) = N_0 \exp(-\lambda \cdot T_{1/2}) = N_0 / 2; \]

- Activity (decay rate): \( \cdot1 \text{ decay per second} = 1 \text{ Becquerel} = 1 \text{ Be} (\text{SI unit}) \)
  \( \cdot 1 \text{ Curie} = 1 \text{ Ci} = 3.70 \times 10^{10} \text{ Be} \)
  applet http://www.walter-fendt.de/ph14e/lawdecay.htm
8.7 Decays - α-decay

Origin of He-nucleus in α-decay?

\[ ^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + \alpha; \quad KE_\alpha = \frac{1}{2}mv^2 = 4.8 \text{ MeV} \]

As a result of the "tunneling" of an alpha particle out from inside the potential well defined by the nucleus and the nuclear interactions, "Tunneling" is easier, i.e. alpha-decay more likely, the more shallow the potential well and the less prominent the potential barrier that must be tunneled through – thus the half-life of a radioactive element is directly from this transition rate.

8.7 Decays - β-decay

• Origin of electrons in β-decay? If inside nucleus, should have energies of about 20MeV (Heisenberg’s Uncertainty Principle). Experimentally: less than 1MeV.

• β-decay: decay of neutron in the nucleus. \( n \rightarrow p + \beta^- + ? \)

• Electrons produced in β-decay have wide energy spectrum; need third particle that is produced in the decay (Pauli 1931): anti-neutrino, \( \bar{\nu} \), electrically neutral, zero rest-mass.

• Anderson, 1932, cosmic rays: "positively charged electron", opposite charge and different magnetic (spin) properties. (antimatter)

• Soon many other elementary particles were discovered.

8.7 Decays - decay chains

A radioactive element often is involved in a decay chain, with a succession of decays.

As long as it is energetically possible that a decay can occur, then it will occur; the only difference from one nucleus to another is the rate at which the decays occur or the decay constant \( \lambda \).

The inverse of the rate is the lifetime of the nucleus, which is equal to the half-life divided by \( \ln(2) \).

A stable endpoint can be reached, when it is no longer energetically feasible for the nucleus to undergo either alpha-decay or beta-decay.

8.7 Discovery of the neutron

• Why is charge to mass ratio not the same for all nuclides (problem of isotopes)?

• 1930 Bethe and Becker, bombardment of Beryllium, Boron and Lithium with α-particles: target particle emits radiation with greater penetration power than α-particles.

• 1932 Chadwick: new particles electrically neutral, mass approximately equal to proton: neutrons.

• Neutrons hard to detect directly (no ionisation). Interaction with nuclei (they are slowed down (moderated)) during scattering; penetrate the nucleus.

• Indirect detection: elastically knock out p from H-rich wax

\[ ^{4}_{2}He + ^{9}_{4}Be \rightarrow ^{12}_{6}C + ^{1}_{0}n \]

\[ ^{1}_{0}n + ^{10}_{5}B \rightarrow ^{7}_{3}Li + ^{4}_{2}He \]
8.8 Fusion and fission: Nuclear fission

Nuclear fission can occur when we induce or observe a heavy nucleus to split apart, usually induced by a neutron capture.

Nuclear fission is energetically possible, as we go to more stable nuclei, as the binding energy per nucleon increases, as we go from higher A to lower A - the mass defect increases and we release energy in an exothermic process.

Nuclear fission can be self sustaining, provided each fission produces at least one neutron to initiate another fission event. If more than one energetic neutron is produced then we can have a "chain reaction". An uncontrolled chain reaction leads to an explosive situation.

How were the heavy elements formed?

8.9 Fundamental Forces

(Read YF Chapter 44.1-44.4)

Strong

Electromagnetic

Weak

Gravity
8.10 Elementary particles

Short history of discovery of particles:
- $e^-$, $e^+$ - discovered Thomson - 1897
- $\gamma$, $\nu_\gamma$ - photon - interpreted as a particle - 1905
- $p$, $n$ - discovered Rutherford - 1918

Quantum mechanics could explain $H$-spectrum and other spectra.
- Problems at that time:
  - combining special relativity & quantum mechanics
  - continuous $\beta$ decay spectrum - why?
  - weight of nuclei of the elements - $Z$ vs $A$?
  - how do nuclei stay together?

Predictions of new particles:
- the need for a 'neutron' - Rutherford 1920 - $Z$ vs $A$
- Prediction of neutrino - Pauli 1930
- Prediction of positron - Dirac 1930
- Prediction of meson (pion) - Yukawa 1934
- Prediction of neutron - Chadwick 1932
- Prediction of heavy hydrogen - Urey 1932
- Prediction of neutrino - Reines and Cowan 1956

However by 1950s new problems due to particle zoo!
Solved by quark hypothesis - proven since mid 70's

8.11 Classification: The Standard Model (1970-73)

The fundamental constituents of all particles are now known and these are divided into Leptons and Quarks.

Leptons:
- electron; muon and tau - (finite rest mass)
- electron-neutrino; muon-neutrino and tauon-neutrino - (rest mass ~0?)

All of these also exist as anti-particles

Quarks:
- up; down; strange; charm; beauty; top - (all non-zero rest mass)
- all observed to have non-integer electric charges
- quarks also carry colour charge: red, green, blue - a new force described by quantum chromodynamics

All of these also exist as anti-particles

Leptons and quarks are fermions, wave-function describing a pair of identical particles is anti-symmetric with respect to particle exchange.

Particles with symmetric wave-function with respect to particle exchange: bosons

Quantum field theory explains all forces in terms of exchange of field quanta:

- Electromagnetic force:
  - photons
- Weak force:
  - 8 gluons (different colour pairs)
- Strong nuclear force:
  - 8 gluons (different non-colour pairs)
- Gravitation:
  - graviton (not yet discovered)
- Standard Model requires one further particle: Higgs bosons (from Higgs field) - which gives all particles their mass.

The Standard Model describes everything observed to date with precision.

However, the SM offers no explanation as to why the observed particles exist in the way they do nor why the observed universe is the way it is.

A so-called Theory Of Everything (TOE) would unify the theories for the four different fundamental forces. (But it would not mean the end of physics!)

Within the SM the Electro-magnetic and Weak nuclear force have been unified as two manifestations of a single electro-weak theory.

Theories unifying electro-weak theory with the strong nuclear force are called Grand Unified Theories (GUT). However, the predictions of the simplest of these theories (that the proton would decay) are inconsistent with observations.

No successful quantum theory of gravity currently exists.

Some Grand Unified Theories have attempted to incorporate gravity - one example is string theory - but it predicts that we should be in a 10-dimensional space, and is currently unable to make any firm predictions that can be experimentally tested.

Ongoing problem!

Figure for standard model: http://en.wikipedia.org/wiki/Image:Particle_chart.jpg
Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

**FERMIONS**

<table>
<thead>
<tr>
<th>Leptons spin = 1/2</th>
<th>Quarks spin = 1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavor</td>
<td>Mass GeV/c^2</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>(\nu_e) electron neutrino</td>
<td>(&lt;1\times10^{-9})</td>
</tr>
<tr>
<td>(e^+) electron</td>
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</tr>
<tr>
<td>(\mu^+) muon neutrino</td>
<td>(&lt;0.0002)</td>
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<tr>
<td>(\mu^-) muon</td>
<td>0.106</td>
</tr>
<tr>
<td>(\tau^+) tau neutrino</td>
<td>(&lt;0.002)</td>
</tr>
<tr>
<td>(\tau^-) tau</td>
<td>1.7771</td>
</tr>
</tbody>
</table>

Spin is the intrinsic angular momentum of particles. Spin is given in units of \(\hbar\), which is the quantum unit of angular momentum, where \(\hbar = \hbar/2\pi = 6.626\times10^{-34}\) kg m^2 s^{-1}. Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.6\times10^{-19} C.

The energy unit of particle physics is the electron volt (eV), the energy gained by one electron in gaining a potential difference of one volt. Masses are given in GeV (a reminder of the electron's rest mass). Remember that 1 GeV \(= 1.60\times10^{-10}\) joule. The mass of the proton is 0.938 GeV/c^2 = 1.67\times10^{-27} kg.

**BOSONS**

| Unified Electroweak spin = 1/2 |
|-------------------|-------------------|
| Name | Mass GeV/c^2 | Electric charge |
|-------------------|-------------------|
| \(\gamma\) photon | 0 | 0 |
| \(W^-\) | 80.4 | -1 |
| \(W^+\) | 80.4 | +1 |
| \(Z^0\) | 91.187 | 0 |

**PROPERTY OF THE INTERACTIONS**

**Gravitational**

**Weak (Electroweak)**

**Strong**

**Residual Strong Interaction**

**Momenes qq**

There are about 140 types of mesons.

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless \(\bar{c}\) = charge is shown). Particle and antiparticle have identical mass and spin, but opposite charges. Some electrically neutral bosons (e.g., \(Z^0\), \(\eta\), and \(\eta'/\eta_c\), but not \(\eta^+\) and \(\eta^-\) are their own anti-particles.

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

The Particle Adventure, a cool and engaging web site, has the Particle Adventure at http://ParticleAdventure.org.

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