Nuclear Physics - Summary - Nuclear reactions

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This summary is based on the book: Kenneth Krane - Introductory Nuclear Physics, Chapters 13 - 14.

1 Nuclear Reactions

Nuclear reactions are **induced** by energetic particles. ⇔ Decays are spontaneous processes.

The two main types are:
- fission
- fusion

Typical reaction:

$$a + X \rightarrow Y + b$$

where a is the projectile and X is the target. Typically a and b are light particles and X and Y are heavy particles. Another notation: $X(a,b)Y$ or (a,b)

2 Nuclear Fission

- Fission is the result of the **competition between the Coulomb force (Z^2) and the strong nuclear force (A)**. This is similar to α decay.
- A general method is to bombard heavy particles with neutrons.
- Neutron induced fission: $(n,n) \rightarrow$ produces more $n \rightarrow$ **chain reaction**
- There are two types of chain reactions:
  - controlled
  - uncontrolled

2.1 Theoretical explanation

- Heavy elements sit high in the potential well and the fission products can easily escape the well if there is a bit of energy supplied to the system. This energy is called the **activation energy**.
- The released energy gets carried away mostly by the fission products in the form of kinetic energy.
- Fission is more likely if the released energy is high.
- Spontaneous fission is possible too, but it is very rare and only relevant for the heaviest elements (A > 230).

2.2 Characteristics

- For low energy fission we usually get a heavy and a light fission product.
- Fission products are not uniquely determined, but follow a **distribution with a heavier and lighter element.**
- fission products tend to be radio active and fission is often followed by β decays.
- There are two types of emitted n:
  - **prompt** n**:** the fission products are very n rich → they emit ns immediately after the decay.
  - **delayed** n from β delayed n emission.
- The distribution is symmetric between the heavy and the light product.
- The number of emitted prompt n follows a Gaussian distribution.
- The average number of prompt n is ν
- We also distinguish neutrons based on their energy:
  - **thermal** n**:** low energy → they have a kinetic energy that is equivalent to the energy of the ambient medium.
  - **high energy** n: n produced in fission have high energies

2.3 Energy

$$^{235}U + n \rightarrow ^{236}U^*$$

$^{236}U^*$ is in an excited state.

$$E_{ex} = [m(^{236}U^*) - m(^{236}U))]c^2$$
$$m(^{236}U^*) = m(^{235}U) + m_n$$

The E_{ex} needs to be larger than the activation energy $\rightarrow$ fission.

- There is a difference in excitation energies for different isotopes.
- n capture by an odd N nucleus $\rightarrow$ easier to induce fission compared to n capture by an even N nucleus

2.4 Energy release

- most of the energy ($\sim 80\%$) gets carried away by the fission products, due to the Coulomb repulsion
- The carried energy depends on the inverse of the mass ratios
- a small amount of energy gets carried by the n
- Other energy release:
  - prompt γ rays
  - β decay of fragments
  - γ decay of fragments

2.5 Controlled fission reactions

Nuclear reactors typically utilize neutron induced fission. For ^{235}U the fission starts with thermal neutrons. During the fission more neutrons get produced, which can continue to induce fission $\rightarrow$ this is called a **chain reaction**. However, neutrons produced during fission are fast neutrons, to induce more fission reactions they need to be **moderated** (slowed down) to become thermal neutrons.

Energy production from fission power plants: Since the fission products carry most of the kinetic energy and they are encased in a solid material (fuel pellet), this manifests as heat in the reactor core. This heat is extracted generating steam $\rightarrow$ to run a steam turbine which then $\rightarrow$ produces electricity.

To **control a fission reactor**:

- controlling the number of n in the reaction
- **neutron reproduction factor** k_∞
  - $k = 1 \rightarrow$ pile is critical $\rightarrow$ steady reaction rate
  - $k < 1 \rightarrow$ pile is subcritical $\rightarrow$ reactions will eventually stop, however nuclear reactors usually aim for this for the prompt n, the reactions keep going because of the extra delayed n
  - $k > 1 \rightarrow$ pile is supercritical $\rightarrow$ increasing number of reactions
- $k_\infty = \eta\epsilon p f$ also known as the four-factor formula
  - η mean number of fission produced fast n
  - ϵ fast fission fraction (fast n fission with ^{238}U)
  - p resonance capture probability by ^{238}U
  - f thermal utilisation factor (available thermal n)

The **timescales** for n multiplication (τ):

$$N(t) = N_0 e^{(k-1)t/\tau}$$

which indicates an exponential decrease or increase in the number of n over time.

A **typical nuclear reactor** has the following main components:

- fuel: natural or enriched uranium or plutonium
- moderator: graphite, water, heavy water (^2H_2O), Be, BeO
- control rods: cadmium
- cooling system: water, heavy water, air, CO_2, He gas

Reactors can be **used for**:

- energy generation: extracting heat from the reactor $\rightarrow$ power a steam turbine $\rightarrow$ electricity
- research $\rightarrow$ e.g. producing neutrons, investigating nuclear processes
- conversion (breeder reactor) $\rightarrow$ to produce fissionable isotopes (e.g. ^{238}U $\rightarrow$ ^{239}Pu, ^{232}Th $\rightarrow$ ^{233}U)

There is one known natural fission reactor in Oklo (Gabon), where sustained natural fission happened $\sim$1.7 billion years ago.

3 Nuclear Fusion

- Fusing light nuclei to gain energy.
- Need to **overcome the nuclear Coulomb barrier** (very similar to a reverse α decay)
- If we add energy to the system by heating $\rightarrow$ **thermonuclear reaction.**
- Another option to add energy to the system is particle acceleration.

3.1 Basic fusion process

There is **natural fusion only inside stars**.

The most simple reaction is **deuterium fusion**:

$$^1H +^1 H \rightarrow^2 H + e^+ + \nu$$

The deuterium-deuterium **(D-D) reaction**:

$$^2H +^2 H \rightarrow^3 He + n$$

or:

$$^2H +^3 H \rightarrow^2 H + p$$

The more stable the end product $\rightarrow$ the larger the energy release. $\rightarrow$ ^4He is the most stable light element, which is the ideal product for fusion.

The deuterium-tritium **(D-T) reaction**:

$$^2H +^3 H \rightarrow^4 He + n$$

The D-T reaction is most often used in fusion experiments. It needs a similar input energy as the D-D reaction (Coulomb barrier is basically the same), but it has a larger energy release (more stable end product). Issues: tritium is rare and expensive and most kinetic energy goes to the n, which is difficult to extract energy from.

Typical fusion in the Sun:

- 4 ^{1}H $\rightarrow^4$He + 2 e$^+$ + 2 ν_e (net reaction).
- This can happen trough various reaction chains: the pp-1 chain, pp-2 or pp-3 chain. **The Sun primarily uses the pp chain for energy generation.**
- In practice we always have two particles reacting. It is very difficult and unlikely to get three particles into the same location for fusion.
- Once H fusion finished, He fusion can start in relatively high mass stars. This reaction is also referred to as the triple α reaction. The net reaction: 3 ^{4}He $\rightarrow$ ^{12}C

In **high mass stars** (more mass compared to the Sun), the **CNO cycle** is also an option to fuse H into He. In addition, once the all the H is fused to He, He and heavier element fusion is possible as well up until making Fe. However, the higher Coulomb barrier (from more protons) means that these reactions require more energy input $\rightarrow$ higher temperature.

We can get information about the solar fusion from the νs produced during the fusion.

- continuous spectrum from $^1H +^1 H \rightarrow D + \nu_e + e^+$
- discrete spectrum from $^7Be + e^- \rightarrow^7 Li + \nu_e$
- continuous spectrum from $^8B \rightarrow^8 Be + e^+ + \nu_e$

The $B \rightarrow Be$ is the most important for Solar models.

3.2 Energy release

- reacting particles have relatively small kinetic E$\sim$1-10 kev compared to $Q \sim$ MeV
- the energy release and the final total energy of the particles will be equal to Q

$$\frac{1}{2}m_b v_b^2 + \frac{1}{2}m_Y v_Y^2 \approx Q$$

Final momenta:

$$m_b v_b \approx m_Y v_Y$$

The energy gets distributed based on the mass ratio:

$$\frac{\frac{1}{2}m_b v_b^2}{\frac{1}{2}m_Y v_Y^2} = \frac{m_Y}{m_b}$$

The lighter particle gets most of the energy. For a D-T reaction the n gets 80% of Q. For a D-D reaction the n gets $\sim 75\%$ of the energy.

The reaction rate depends on:

- The probability of fusion, which depends on the Coulomb barrier $\rightarrow$ an exponential function of $Z_a Z_X$
- Temperature

3.3 Controlled fusion reactors

Plasma confinement:

- magnetic confinement
  - tokamak (torus shaped chamber)
  - magnetic mirror (linear chamber)
- inertial confinement
  - lasers
  - particle beams

Energy Balance = Efficiency $\times$ (Fusion energy release - radiation loss - conduction loss)

- Efficiency: ratio of useful energy produced over the energy needed to make the reaction happen
- radiation loss: bremsstrahlung from plasma
- conduction loss: particles escaping from the system

- Nuclear fusion reactors are in the experimental phase. (e.g. ITER experiment, JET experiment, TAE Technologies, Helion)
- **mostly use the D-T reaction** for energy gain
- alternate options for reactions:
  - $^1H +^{11} B \rightarrow 3^4He$
  - $D +^3 He \rightarrow^4 He +^1 H$