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

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 γrays
  - β decay of fragments
  - γ decay of fragments

2.5 Controlled fission reactions

- controlling the number of n in the reaction
- neutron reproduction factor k_{inf}
  - $k = 1$ → pile is critical → steady reaction rate
  - $k < 1$ → pile is subcritical → 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
  - $k > 1$ → pile is supercritical → increasing number of reactions
- $k_{\text{inf}} = \eta \epsilon p f$
  - 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: uranium or plutonium
- moderator: graphite
- control rods: cadmium
- cooling system: water or heavy water

Reactors can be **used for**:
- energy generation: extracting heat from the reactor → power a steam turbine → electricity
- research
- conversion (breeder reactor)

There is one known natural fission reactor in Oklo (Gabon), where sustained natural fission happened ~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 → thermonuclear reaction.
- Another option to add energy to the system is particle acceleration.

3.1 Basic fusion process

There is **natural fusion only in the 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 → the larger the energy release. → ^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 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:
- $4^1H \rightarrow^4 He$ (net reaction).
- This can happen trough various reaction chains: pp chain or CNO cycle. However, the Sun only uses the pp chain.
- In practice we always have two particles reacting. It is very difficult and unlikely to get three particles into the same location for fusion.

In **high mass stars** (more mass compared to the Sun), He and heavier element fusion is possible. However, the higher Coulomb barrier (from more protons) means that these reactions require more energy input → higher temperature.

3.2 Energy release

- reacting particles have relatively small kinetic E∼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 → an exponential function of $Z_a Z_X$
- 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.

3.3 Controlled fusion reactors

Plasma confinement:

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

- Nuclear fusion reactors are in the experimental phase.
- **mostly use the D-T reaction** for energy gain
- alternate options for reactions:
  - $^1H +^{11} B \rightarrow 3^4He$
  - $D +^3 He \rightarrow^4 He +^1 H$