

# 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.  $\Leftrightarrow$  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  $\alpha$  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

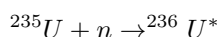
### 2.1 Theoretical explanation

- 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  $\beta$  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  $\beta$  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  $\nu$
- 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



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

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

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

## 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  $\gamma$  rays
  - $\beta$  decay of fragments
  - $\gamma$  decay of fragments

## 2.5 Controlled fission reactions

- controlling the number of  $n$  in the reaction
- neutron reproduction factor  $k_{\text{inf}}$ 
  - $k = 1 \rightarrow$  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
- $k_{\text{inf}} = \eta \epsilon p f$ 
  - $\eta$  mean number of fission produced fast  $n$
  - $\epsilon$  fast fission fraction (fast  $n$  fission with  $^{238}\text{U}$ )
  - $p$  resonance capture probability by  $^{238}\text{U}$
  - $f$  thermal utilisation factor (available thermal  $n$ )

The **timescales** for  $n$  multiplication ( $\tau$ ):

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

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  $\rightarrow$  power a steam turbine  $\rightarrow$  electricity
- research
- conversion (breeder reactor)

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

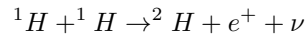
## 3 Nuclear Fusion

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

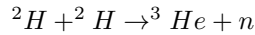
### 3.1 Basic fusion process

There is **natural fusion only in the stars**.

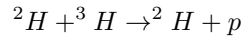
The most simple reaction is **deuterium fusion**:



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

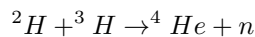


or:



The more stable the end product  $\rightarrow$  the larger the energy release.  $\rightarrow {}^4_2\text{He}$  is the most stable light element, which is the ideal product for fusion.

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



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:**

- $4 {}^1_1\text{H} \rightarrow {}^4_2\text{He}$  (net reaction).
- This can happen through 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  $\rightarrow$  higher temperature.

### 3.2 Energy release

- reacting particles have relatively small kinetic  $E \sim 1-10$  keV compared to  $Q \sim \text{MeV}$
- 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

We can get information about the solar fusion from the  $\nu$ s produced during the fusion.

- continuous spectrum from  ${}^1_1\text{H} + {}^1_1\text{H} \rightarrow D + \nu_e + e^+$
- discrete spectrum from  ${}^7_3\text{Li} + e^- \rightarrow {}^7_4\text{Be} + \nu_e$
- continuous spectrum from  ${}^8_2\text{B} \rightarrow {}^8_3\text{Li} + e^+ + \nu_e$

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:
  - ${}^1\text{H} + {}^{11}\text{B} \rightarrow 3{}^4\text{He}$
  - $\text{D} + {}^3\text{He} \rightarrow {}^4\text{He} + {}^1\text{H}$