Synopsys

- Gas-cooled reactors (AGR & Magnox).
- Light water graphite moderated reactors (RBMK).
- Fast neutron reactors and breeders (FBR).
- Back-end and auxiliary equipment. Fuel types and fuel handling equipment.
Books & Other Literature

1. Nuclear Reactor Theory (Hiroshi Sekimoto, TIT)
3. An introduction to Nuclear Materials (Linga K. Murty and Indrajit Charit, Wiley-VCH, Berlin)
6. Introductory Nuclear Physics (Kenneth S. Krane, Willey)
8. SF Nuclear Physics (Maria Stamenova, TCD)
History – Brief Aspects

- 1808 Dalton: Atomic theory
- 1876 Goldstein: Cathode rays
- 1891 Stoney: Prediction of electrons
- 1895 Roentgen: X-rays
- 1896 Becquerel: Radioactivity
- 1897 Thomson: Cathode rays = electrons
- 1898 Thomson: Cathode rays = electrons
- 1900 Planck: Quantum theory
- 1905 Einstein: Special relativity theory
- 1911 Rutherford: Atomic model
- 1912 Thomson: Isotope
- 1914-1918 World War 1
- 1919 Aston: Mass spectrometer
- 1921 Harkins: Prediction of neutrons
- 1930 Bothe: Be (α, ?)
- 1932 Irene and Frederic Joliot-Curie: Be (α, γ)
- Chadwick: Neutron discovery
- 1934 Fermi: Delayed neutrons
- Szilard: Chain reaction
- 1939-1945 World War 2
- 1939 Hahn, Strassman, Meitner: Discovery of nuclear fission
- 1942 Fermi: CP-1 made critical
- 1944 First plutonium production reactor made critical (Hanford, USA)
- 1945 Test of atomic bomb (USA)
- 1945 Natural uranium heavy water research reactor (ZEEP) made critical (Canada)
- 1946 Fast reactor (Clementine) made critical (USA)
- 1950 Swimming pool reactor (BSR) made critical (USA)
- 1951 Experimental fast breeder reactor (EBR-1) made critical and generates power (USA)
- 1953 Test of hydrogen bomb (USSR)
- “Atoms for Peace” Initiative (United Nations, USA)
- 1954 Launch of the nuclear submarine “Nautilus” (USA)
- Graphite-moderated water-cooled power reactor (AM-1) generates power (USSR)
Nuclear fission

- The process in which a nucleus splits into (usually) two fragments of similar mass, together with an energy release.

For the same reasons as in alpha decay: \( m_1 E_1 = m_2 E_2 \)

- Two types will be considered:
  - spontaneous fission (radioactive decay)
  - induced fission (by particle bombardment).

- Many aspects of the theories of alpha decay and spontaneous fission are similar…..
Spontaneous fission

- Like alpha decay – occurs only for very heavy nuclei $A>230$, in region where $B/A$ decreases as $A$ increases:
Spontaneous fission—conditions

For the decay: \( \frac{A}{Z} X \rightarrow \frac{A_1}{Z_1} Y + \frac{A_2}{Z_2} Z + k n \) to occur it is required that

\[
Q > 0 \Rightarrow m_X > m_Y + m_Z, \text{ i.e. } B_X < B_Y + B_Z
\]

(neutron emission, neglected above, will be considered later)

From this and von Weizsäcker's SEM formula it can be shown that, for fission to be energetically possible, \( A > 90 \).

However, because of the mechanism of the process, spontaneous fission is unmeasurably slow until \( A \sim 230 \).

Analogous to the \( \alpha \)-decay \( \rightarrow \) a quantum-mechanical tunnelling process.

As \( A \) increases further, spontaneous fission very rapidly becomes more likely.
Fission barriers from liquid drop model

(a) $A < 90$
Fission energetically impossible

(b) $90 < A < 230$
Fission inhibited by Coulomb barrier

(c) $230 < A < 300$
Fission observable with tunnelling through barrier

(d) $A > 300$
Nucleus unbound
Spontaneous fission – examples

- The rate of spontaneous fission (SF) increases exceptionally rapidly with $A$:

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$A$, $Z$</th>
<th>$t_{1/2}$ (y)</th>
<th>SF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th</td>
<td>232, 90</td>
<td>$1.4 \times 10^{10}$</td>
<td>$1.2 \times 10^{-8}$</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>238, 92</td>
<td>$4.5 \times 10^{9}$</td>
<td>$4 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{252}$Cf</td>
<td>252, 98</td>
<td>2.6</td>
<td>3.1</td>
</tr>
</tbody>
</table>

- Increasing $A$, both $t_{1/2}$ decreases and the SF % increases.
- For each of these three nuclides the rest of the decays occur by alpha emission.
- $^{252}$Cf is a very useful source of neutrons.
Energy release in fission

- For example, $B/A \ (^{252}\text{Cf}) = 7.4 \text{ MeV/nucleon}$, but for fragments with $A = 126$, $B/A = 8.4 \text{ MeV/nucleon}$.
- Energy release is $\sim 1 \text{ MeV/nucleon}$ or about $200 \text{ MeV}$!
- These values increase only very slowly with $A$. 
Fission fragment masses distribution

- Fission is normally asymmetrical, i.e. the fragment masses are unequal.

**Fission of $^{252}_{98}$Cf →**

- The SEM formula fails to predict this, even the energy release in fission is maximised when each fragment has the same mass.
- This paradox remained unsolved for many years to be explained by magic numbers.
Induced fission

- The almost instantaneous fissioning of a nucleus when struck by radiation – usually a neutron, i.e. no Coulomb barrier to be overcome.
- Induced fission always proceeds in two steps.
  \[ {^{235}_{92}U + n \rightarrow ^{236}_{92}U^* \rightarrow 2 \text{ fragments} + k \text{ n}} \]
- Discovered in 1938 by Hahn and Strassmann, then explained by Meitner and Frisch.
- First observed by Fermi in 1934 – but famously misinterpreted by him.
Induced fission fragments for $^{235}_{92}$U

- Similarly to spontaneous fission, an asymmetric distribution of fragment masses →
- Doubly magic fragments more likely.
- Increasing the energy of the neutron, the gap is filled – nucleus has more energy to release and less time to form magic fragments →
Stages of the induced fission

- **Fission fragments**: $E_{\text{kin}} \sim 170$ MeV
- **γ-rays** emitted immediately with the fission process; $\sim 6$ MeV.
- **Prompt neutrons** emitted from neutron-rich fragments $\sim 10^{-14}$ s after fission

Average number of prompt neutrons emitted per fission = $2.5 \times 2$ MeV $\approx 5$ MeV.
Stages of the induced fission - 2

- **Electrons**: from three or four beta decays of each fragment; ~5 MeV total (also neutrinos).
- **Fragments from $^{235}$U fission** are initially formed on the red dashed line joining $^{235}$U to the origin – neutron rich.
- **$\beta$-decays along the isobaric lines**, shown are a typical light and heavy fragments
Isobaric fragment decay chains – 1

Some 80 of those are known, for instance:

[Diagram showing the decay chain from $^{35}$Br to $^{38}$Sr, including
$^{36}$Kr and $^{87}$Rb as intermediates.]
Notice the second $\beta$-decay branch leading to $n$ emission:
More fission products

- More $\gamma$ rays from fragments, *after* both fission and $\beta$-decay; $\sim 7$ MeV.

- **Delayed neutrons** occasionally emitted from fragments $\sim 1$ min after fission during the $\beta$-decay process.
  - The neutrons are *delayed* with respect to the original fission event, but are emitted *immediately* once the excited state of the $^{86}$Kr nucleus is formed (instead of $\gamma$-emission).

- Average $\#(\text{d. n. per fission}) = \text{only } 1\%$ (but essential for reactors control, avg. lifetime of prompt n is $\sim 1$ms, exponential instability)

<table>
<thead>
<tr>
<th>Prompt energy</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission fragments</td>
<td>170</td>
</tr>
<tr>
<td>Prompt neutrons</td>
<td>5</td>
</tr>
<tr>
<td>$\gamma$-emission</td>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radio-activity</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$-decay (electrons + neutrino)</td>
<td>7 + 12</td>
</tr>
<tr>
<td>$\gamma$-emission</td>
<td>7</td>
</tr>
</tbody>
</table>
Nuclear fission reactors

- Basic reaction:

\[
^{235}_{92}\text{U} + \text{n} \rightarrow \text{(two fragments)} + 2.5 \text{n} + 200 \text{MeV}
\]

- Most of the 200 MeV immediately appears as heat when the fragments stop within the uranium fuel (range \(\sim 10 \mu\text{m}\)).

- More than 1 neutron emitted, so further fissions can occur, leading to a chain reaction and large-scale power production (without \(\text{CO}_2\)).

- Neutron multiplication factor (\(k\)) is the ratio of number of fission-causing neutrons between subsequent generations:

  \(k < 1\) – subcritical, \(k \approx 1\) – critical (reactor), \(1 < k < 1/(1-\beta_{d.n.})\) (delayed supercritical, control), \(k > 1/(1-\beta_{d.n.})\) – bomb.
Fission chain reaction

- First four generations of a fission chain reaction.

- If yield $k > 1$ the neutron numbers increase exponentially.
Possible neutron life histories

- Escape from reactor:
  - minimum physical reactor core size
  - neutron reflector (e.g. graphite) around core.

- Capture by non-fissile material:
  - coolants must have low capture cross section (also to minimise induced radioactivity)
  - neutron absorbents used to control/stop chain reaction

- Capture by uranium without fission.
- Capture by uranium with fission.
Natural uranium

- Contains: 
  \[0.7\% \left( \frac{^{235}U}{^{92}U} \right) + 99.3\% \left( \frac{^{238}U}{^{92}U} \right)\]

- Only \(^{235}U\) can undergo fission with 'thermal neutrons'.

- \(^{235}U\) is fissile and \(^{238}U\) is fertile!

- Neutrons emitted in \(^{235}U\) fission are fast: \(E_{\text{kin}} \approx 1-2\ \text{MeV}\)

- The fission cross-sections \(\sigma_f\) for fast neutrons are too low for a natural uranium 'fast reactor':
  \[\sigma_f \left( ^{235}U \right) = 1\ \text{b} \quad \text{and} \quad \sigma_f \left( ^{238}U \right) = 0.5\ \text{b}\]

- Either enrich (to > 20%) in \(^{235}U\) – difficult and expensive (UF\(_6\) diffusion, or centrifuging, or laser separation)

- Or thermalize neutrons – slow them down → thermal equilibrium with the surroundings, i.e. their kinetic energies \(\sim kT = 0.025\ \text{eV}\) at room temperature.
Fissile vs Fertile

- Fissile – can undergo fission with thermal neutrons
- Fertile – can breed to produce fissile nuclides
- \(^{235}\text{U}\) is fissile and \(^{238}\text{U}\) is fertile!
- The cross-section for fission of \(^{238}\text{U}\) induced by thermal neutrons, \(\sigma_f \approx 0\text{ b.}\)
- But \(^{238}\text{U}\) can initiate breeder reactions

\[
\frac{^{238}\text{U}}{92} + n \rightarrow \frac{^{239}\text{U}}{92}\text{(23 m)} \rightarrow \frac{^{239}\text{Np}}{93}\text{(2.4 d)} \rightarrow \frac{^{239}\text{Pu}}{94}\left(2.4 \times 10^4\text{ y}\right)
\]

- \(^{239}\text{Pu}\) is fissile too, just like \(^{238}\text{U}\)!
- As neutrons are uncharged a general trend applies:

\[
\sigma_f \propto \left\{ \begin{array}{c}
\text{the time spent close to nucleus} \\
\frac{1}{v}
\end{array} \right\}
\]

- For thermal neutrons \(v = 2.2\text{ km/s}\), and \(\sigma_f\) rises to 580 b.
Neutron interaction cross-sections of $^{235}\text{U}$

- Three processes involved: scattering, radiative capture [or (n,γ)-reaction] and fission:
- Large fission cross-section $\propto 1/v$ below 1 eV (incl. thermal n).
- Resonances from 1 eV to 100 eV (from metastable $^{236}\text{U}$).
- Scattering: $\sigma_s \approx 10$ b (almost independent of energy).

![Graph showing cross-sections of $^{235}\text{U}$]

$\sigma_f \propto 1/v$

$\sigma_T = \sigma_s + \sigma_c + \sigma_f$
Neutron interaction cross-sections of $^{238}\text{U}$

- Scattering cross-section $\sigma_s \approx 8$ b dominates for most energies.
- At resonances the radiative capture ($n,\gamma$) prevails (no fission) – important source of absorption in reactors.
- Some non-zero fission cross-section for energetic neutrons (above 1 MeV).

$\sigma_s \approx 8$ b

$\sigma_s \approx 8$ b
Scattering + fission cross-sections

\[ \sigma_f \propto \frac{1}{\nu} \]

Thermal n-induced fission

\[ \sigma_T = \sigma_s + \sigma_c + \sigma_f \]

\[ \sigma_s \approx 8 \text{ b} \]
Critical energy for induced fusion

- Cross-sections for fission (and other neutron-induced nuclear reactions) are largest for slow neutrons only if enough energy is available for the reaction to proceed.

- For both $^{235}\text{U}$ and $^{238}\text{U}$ fission, the intermediate $^{236}\text{U}^*$ and $^{239}\text{U}^*$ must be excited by a critical energy of 6 MeV or more in order to achieve tunnelling through the potential barrier.

- We know nucleon separation energy is about 7 MeV:

  $^{236}\text{U} + 7 \text{ MeV} \rightarrow ^{235}\text{U} + 7 \text{ MeV} \rightarrow ^{235}\text{U} + \text{slow neutron}$

  $^{235}\text{U} + \text{slow neutron} \rightarrow ^{236}\text{U}^* (\text{excited by 7 MeV})$

- To fission $^{238}\text{U}$, neutron kinetic energies of at least 1 MeV are required.
# Comparison of critical energies

<table>
<thead>
<tr>
<th>Target Nucleus</th>
<th>Critical Energy $E_{crit}$</th>
<th>Binding Energy of Last Neutron $BE_n$</th>
<th>$BE_n - E_{crit}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}_{90}$Th</td>
<td>7.5 MeV</td>
<td>5.4 MeV</td>
<td>-2.1 MeV</td>
</tr>
<tr>
<td>$^{238}_{92}$U</td>
<td>7.0 MeV</td>
<td>5.5 MeV</td>
<td>-1.5 MeV</td>
</tr>
<tr>
<td>$^{235}_{92}$U</td>
<td>6.5 MeV</td>
<td>6.8 MeV</td>
<td>+0.3 MeV</td>
</tr>
<tr>
<td>$^{233}_{92}$U</td>
<td>6.0 MeV</td>
<td>7.0 MeV</td>
<td>+1.0 MeV</td>
</tr>
<tr>
<td>$^{239}_{94}$Pu</td>
<td>5.0 MeV</td>
<td>6.6 MeV</td>
<td>+1.6 MeV</td>
</tr>
</tbody>
</table>

- The bottom three do not need the kinetic energy of the neutrons to undergo fission. They are fissile.
Moderators

- Bulk material surrounding the uranium fuel rods, designed to slow down fission neutrons from fast to thermal speeds.

- Thermalisation by elastic collisions with moderator nuclei within $\sim 10^{-1}$ m (avoid capture by $^{238}$U).
- Ideally, in fewer collisions, with large energy losses per collision – moderator made of light nuclei (low A).
- This geometry was first thought of in 1939 by the transistor pioneer, William Shockley.
Moderators – more facts

- In graphite ($^{12}$C) to moderate $E_n$ from 1 MeV to 0.1 eV, ~ 100 collisions are required.
- But in $^{238}$U (without a separate moderator) ~ 2000 collisions would be required.
- Many of the neutrons would instead be captured by $^{238}$U and cause no fission.
- Even with a moderator, any neutron which happens to acquire an energy falling within a $^{238}$U resonance peak (width 2 – 4 eV) may still be captured without fission occurring.
- To minimise this, moderation must occur in large steps $>>$ 4 eV (next slide), i.e. in a separate light moderator not mixed in with the fuel.
Moderators – more facts

- With this geometry, the fuel interior can be effectively shielded from neutrons of any $^{238}\text{U}$ resonance energies by the surface layer of fuel itself as it captures such neutrons.

- Spatial self-shielding effect relies on the small amount of neutron moderation in the fuel.

- It cannot happen if the fuel and moderator were a homogeneous mixture.
Light water as moderator

- Light water: H$_2$O, where the hydrogen atom is $^1$H.
- Heavy water: D$_2$O, where the deuterium (D) atom is $^2$H.
- Both are used as neutron moderators.
- Deuterium is a stable isotope of hydrogen, present naturally to 0.015 atomic%.
- It can be shown that the average fraction, $f$, of energy lost by a neutron (mass $m_n$) per elastic collision with a nucleus of mass $m$, is given by

$$f = \frac{2m_nm_n}{(m_n + m)^2}$$

- For $^1$H (in light water) $m = m_n = 1$, so $f = 0.5$. 
Light water moderator + natural uranium?

- For, say, $E_n = 100\,\text{eV}$, energy lost = 50 eV.
- This is $>>$ than the widths of $^{238}\text{U}$ resonance peaks in this energy region.
- Few neutrons are lost through capture by $^{238}\text{U}$ as they slow down.

- But the cross section for the neutron absorption reaction $p + n \rightarrow d + \gamma$ (0.3 b at 0.025 eV) is too high for operation of reactors fuelled by natural uranium and with a light water moderator. (d is for deuteron, nucleus of deuterium)

- Natural uranium salt solutions can’t go ‘critical’ (no chain reaction growth).
Uranium enriched to 2 – 3% (or more) in $^{235}$U if light water is to be used as a moderator.

**Pressurised water reactor (PWR)** – light water moderator and coolant.

**Boiling water reactor (BWR)** – light water moderator and boiling water coolant

From commercial power reactors in service (by 2012): 60% PWRs and 20% BWRs.
Heavy water as moderator

- Average fraction $f$ of neutron energy lost by collision with a deuteron = 0.44, so, once again, energy lost $\gg$ resonance peak widths.
- But this time the neutron absorption cross section = only 0.5 mb at 0.025 eV.
- Reactors using heavy water moderators can, if wished, be fuelled by natural uranium.
- This avoids the expense of enrichment. Heavy water is expensive, but an operating reactor does not consume it.
- Example of heavy water moderated reactors are the CANDU reactors (about 30 in the world).
WWII examples

- The 1945 attempts of Heisenberg and von Weizsäcker in Haigerloch, Germany.....

- 664 natural U cubes, 5 cm edge, total mass 1.5 tons

- Graphite-lined vessel for heavy water moderator
Graphite as a moderator

- Low neutron absorption, refractory and relatively cheap.
- It can be used with natural uranium as fuel.
- First critical assembly: the “Chicago Pile” (Fermi, Chicago, 1942).
- U.K. Gas-cooled Magnox reactors (being phased out).
- Eastern European power reactors (LWGR).
- U.K. AGRs (advanced gas-cooled reactors) – these use enriched uranium.
- With graphite, the fraction $f$ of neutron energy lost by collision with a carbon nucleus = 0.14 (still larger than the resonance peak widths).
- A moderator does not 'slow down the reaction rate' – in fact it speeds it up!