Nuclear Physics and Technology of Tokamak Reactors

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overview

• The tokamak plasma
  - fuels and power
  - viability

• The neutrons
  - neutron transport
  - activated material
  - tritium breeding
  - blanket technology

• Summary

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Fusion reactions exothermic up to $^{56}$Fe due to positive binding energy change.

Accurate binding energy ($B$) formulation from liquid-drop nuclear model:

$$-\frac{B}{A} = a - b\frac{1}{A^{1/3}} - c\frac{Z^2}{A^{4/3}} - d\frac{(N-Z)^2}{A^2} + \Delta$$

- 1. volume term,
- 2. surface term,
- 3. coulomb term,
- 4. asymmetry term,
- 5. paring term ($a, b, c, d > 0$).

Larger changes in lighter nuclides.

Excess ($Q$) released as kinetic energy of products.

Fuels and power production

Fusion reaction rates (1/3)

<table>
<thead>
<tr>
<th>reactants</th>
<th>products</th>
<th>$Q$ MeV</th>
<th>$\sigma_{\text{max}}$ barn</th>
<th>$E_{\text{max}}$ keV</th>
<th>branch ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p + p$ ($^*$)</td>
<td>$D + e^+ + \gamma$</td>
<td>1.4</td>
<td>$-10^{-24}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p + D$ ($^*$)</td>
<td>$^4\text{He} + \gamma$</td>
<td>5.5</td>
<td>$-10^{-28}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D + D$ ($^*$)</td>
<td>$^4\text{He} + 2\gamma$</td>
<td>23.9</td>
<td>$-10^{-28}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D + T$</td>
<td>$^3\text{He} + n$</td>
<td>3.3</td>
<td></td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>$T + T$</td>
<td>$^3\text{He} + n + n$</td>
<td>11.3</td>
<td>0.2</td>
<td>1,000</td>
<td>100%</td>
</tr>
<tr>
<td>$D + ^3\text{He}$</td>
<td>$^3\text{He} + p$</td>
<td>18.5</td>
<td>0.9</td>
<td>250</td>
<td>100%</td>
</tr>
<tr>
<td>$T + ^3\text{He}$</td>
<td>$^3\text{He} + n + p$</td>
<td>12.1</td>
<td>0.5</td>
<td>5,000</td>
<td>59%</td>
</tr>
<tr>
<td>$^4\text{He} + ^3\text{He}$</td>
<td>$^3\text{He} + p + p$</td>
<td>12.9</td>
<td></td>
<td>$-10,000$</td>
<td>100%</td>
</tr>
</tbody>
</table>

($^*$) electromagnetic, as opposed to strong, interactions.
Fusion power product of reaction rate and energy release: \( P = RQ \)

- \( R \) depends on: \( R = N_jN_o \sigma \nu \)
  - reaction likelyhood (i.e. cross section \( \sigma \)),
  - reactant density,
  - reactant temperature (i.e. energy, i.e. \( \nu \)).

- \( Q \) similar, but \( R \) (i.e. \( \sigma \)) can vary orders of magnitude depending on reaction and reactant temperature and density...

- ... hence importance of heating and confinement (i.e. plasma physics).

- For a given density, DT yields higher rate and at lower temperatures.

Cross section energy dependence reflects quantum and nuclear physics phenomena:

\[
\sigma(E) = \frac{S(E)}{E} \exp\left( -\left( \frac{E}{E_g} \right)^{1/2} \right)
\]

\( E_g \sim Z_i^2 Z_j^2 A_p \)

- \( S(E) \) very weak function of energy except for "resonant" reactions.
- Excited intermediate nuclear state implies \( S(E) \) very peaked function at the resonance energy:
  \[
  D + T \rightarrow ^4He \rightarrow ^4He + n
  \]
  \[
  D + ^3He \rightarrow ^5Li \rightarrow ^4He + p
  \]
• In reality $N = N(v)$, i.e. distribution function of particle velocities (energies) and so:

$$R = \int_0^\infty N_i(v) N_e(v) \sigma(v) v dv$$

$$N_i(v) = N_i \rho(v)$$

• In magnetically confined plasmas, can assume maxwellian distribution functions:

$$p(E) \sim v^2 \exp\left(-\frac{mv^2}{2kT}\right)$$

<\sigma v> parameter (a.k.a. reactivity)

$$R = \frac{N_i N_e \sigma(v)}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle = \int_0^\infty p(v) \sigma(v) v dv$$

$$R = N_i N_e \sigma(v)$$

$\sigma(v) v$
• Even more realistically, in a magnetically confined plasma \( N = N(v,x,y,z) \).

• Hence, in a tokamak, power (and DT neutron) emission intensity follows \( T \) and \( N \) profiles (i.e. magnetic contours):

\[
I = I_0 \left[ 1 - \left( \frac{a}{a_p} \right)^{2\Phi} \right]
\]

\[
\begin{array}{c}
PF=0.5 \\
PF=1.5 \\
PF=5
\end{array}
\]

viability

• Energy systems viability requires output larger than input.

• For physicists: fusion output > power required to maintain plasma:
  - breakeven: \( Pf > \) power required to maintain plasma temperature;
  - ignition: \( Pf > \) radiated power (self-sustained plasma).

• For engineers (and investors!), need to account for:
  - systems efficiency,
  - blanket energy multiplication,
  - balance-of-plant,
  - etc…
  - e.g. Lawson’s criterion (the 1957’s original, not the physicists version!),
  - more recently: systems analysis.

• Viability measured in terms of triple product \( NkT \).

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viability

Lawson’s criterion

• power from fusion:
  \[ P_f = N_a N_b \langle \sigma v \rangle_{ab} Q_{ab} \]

• plasma power loss:
  \[ P_p = \frac{1}{r} \left( \frac{3}{2} N_a k T_a + \frac{3}{2} N_b k T_b \right) \]

• radiation power loss:
  \[ P_r = \alpha N^2 (kT)^{1/2} \]

• assume \( N_a = N_b = N/2 \) and \( T_a = T_b = T \), and impose that
  \[ \eta P_{in} = \eta (P_f + P_p + P_r) > P_f + P_r \]
  where \( \eta \) is efficiency of the power conversion:

\[ \frac{\langle N k T \rangle_{Lawson}}{\langle N k T \rangle} \geq \frac{3 (kT)^2}{\eta (\sigma v)_{ab} Q_{ab} - \alpha kT} \]

viability

breakeven (a.k.a. “the physicist’s Lawson’s”)

• power from fusion:
  \[ P_f = N_a N_b \langle \sigma v \rangle_{ab} Q_{ab} \]

• plasma power loss:
  \[ P_p = \frac{1}{r} \left( \frac{3}{2} N_a k T_a + \frac{3}{2} N_b k T_b \right) \]

• assume \( N_a = N_b = N/2 \) and \( T_a = T_b = T \) and impose that \( P_f > P_p \):

\[ \frac{\langle N k T \rangle_{breakeven}}{\langle N k T \rangle} \geq \frac{12 (kT)^2}{\langle \sigma v \rangle_{ab} Q_{ab}} \]
viability

ignition

- alpha power from fusion:
  \[ P_a = \frac{1}{5} N_a N_e < \alpha \nu >_{ab} Q_{ab} \]
- plasma power loss:
  \[ P_p = \frac{1}{\tau} \left( \frac{3}{2} N_a k T_a + \frac{3}{2} N_e k T_e + \frac{3}{2} N_e k T_\beta \right) \]
- radiation power loss:
  \[ P_r = \alpha N^2 (kT)^{3/2} \]
- assume \( N_2 = N_e = N_2/2 \) and \( T_a = T_\beta = T_e \), but this time \( P_a > P_p + P_r \):

\[ (NkT_\tau)_{\text{ignition}} \geq \frac{60(kT)^{3/2} + 20\alpha N(kT)^{3/2} \tau}{< \alpha \nu >_{ab} Q_{ab}} \]
neutron transport

- Boltzmann transport equation:
  \[
  \frac{d}{dt} n(r, \vec{v}, t) = S^+ (r, \vec{v}, t) - S^- (r, \vec{v}, t)
  \]

- or:
  \[
  \vec{v} \cdot \nabla n(r, \vec{v}, t) + \frac{\partial}{\partial t} n(r, \vec{v}, t) = S^+ - S^-
  \]

- change co-ordinates:
  \[
  (r, \vec{v}, t) \rightarrow (r_\text{E}, \vec{\Omega}, t)
  \]

- define flux:
  \[
  \Phi(r, E, \vec{\Omega}, t) = \nu (r, E, \vec{\Omega}, t)
  \]

- assume neutrons and photons (no charge, i.e. no force, i.e. \( \vec{a} = 0 \)) and steady
  state:
  \[
  \sum_{\alpha} (r, E, \vec{\Omega}, t) \Phi(r, E, \vec{\Omega}, t) = \int \int \int_{E', \vec{\Omega}'} \int \int_{E, \vec{\Omega}} S(r, E, \vec{\Omega}, t) dE'd\vec{\Omega}'
  \]

  streaming
  interaction sink
  scattering source
  other sources (i.e. the plasma)
neutron transport

scattering

14.1 MeV
neutron transport

absorption (and transmutation): $n, \gamma$

neutron transport

absorption (and transmutation): $n, \alpha$
neutron transport

absorption (and transmutation): n,t

neutron transport

absorption (and transmutation): n,p
absorption (and transmutation): n,2n

interactions

- Interaction probabilities ~ cross sections.

\[ \sum = N \sigma \]

\[ \sigma_a = \sigma_{sc} + \sigma_{res} + \sigma_{th} \]

1. scattering
2. resonant reaction (keV-MeV)
3. threshold reaction (> MeV)
**Neutron damage:**

High energy collisions and build-up of transmutation products have important repercussions on systems performance and lifetime.

**Activated material:**

Needs to be disposed of, and the magnitude and implications of the activation radiation field need to be assessed during design and operation of a reactor.

Both damage and activation issues arise mainly from the high neutron energy (14.1 MeV) triggering threshold reactions such as \((n,p)\) and \((n,\alpha)\).

**Tritium breeding:**

Some transmutation reactions generate tritium, and this can be “encouraged” to produce the necessary fuel.
activated material

half-life

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beta decay

- Nuclei pursue stability by means of radioactive decay.
- Stability is achieved when mass is minimum, i.e. $B$ is maximum $\rightarrow$ beta decay achieves this.

$$\beta^- \rightarrow n + \beta^- + \nu \quad \beta^+ \rightarrow p + \beta^+ + \nu$$

$$-B/A = a + bA^{1/3} + c\frac{Z^2}{A^{1/2}} + d\left(N-Z\right)^2 + \Delta$$

---

Activated material

- $B/A$
- $-B/A$
- $A$ odd
- $A$ even
- $\Delta S = 1 - \frac{1}{T_{1/2}}$

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Tritium self-sufficiency is a requirement:
- atmospheric: ~50 kg (from cosmic-ray);
- civil nuclear: ~25 kg (from CANDU);
- power plant consumption of: ~1 kg per day.

Can produce it by fitting the blanket with a breeder, i.e. a material prone to undergo (n,t) or (n,n') reactions – e.g. Li.

\[ ^6\text{Li} + n \rightarrow ^4\text{He} + 4.78 \text{ MeV} \]
\[ ^7\text{Li} + n \rightarrow ^4\text{n} + ^4\text{He} - 2.47 \text{ MeV} \]

Can improve efficiency by also introducing a multiplier, i.e. a material prone to undergo (n,2n) reactions – e.g. Be, Pb.

Can also improve efficiency by enriching natural Li (7.5\% \(^6\text{Li}, 92.5\% \(^7\text{Li}\)) in \(^6\text{Li}\).
tritium breeding

- Need tritium breeding ratio (TBR) > 1.
- Extra result is additional energy (energy multiplication, a.k.a. blanket gain).
- TBR > 1 challenged by engineering, rather than physics:
  - structural material;
  - coolant;
  - FW coverage area (gaps, ports);
  - space limitations (particularly inboard).
- Current limitations in nuclear data uncertainties imply it is not possible to determine TBR with error < 5-10%.

blanket technology

- The blanket (and associated systems) is one of the major differences between ITER and a fusion power plant:
  - in ITER it only serves as a shield and heat sink (500 MW!);
  - in a power plant it must:
    - shield,
    - recover and transport high-grade heat for power production,
    - breed and recover tritium online.
- Test blanket module (TBM) programme in ITER: parties (not UK!) testing different blanket concepts for tritium generation and feasibility.
blanket technology

HCPB – helium cooled pebble bed

- Breeding zone: ~50cm thick, 70% vol Be PB, 10% vol Li$_2$SiO$_4$ (30% at $^6$Li)
- Achievable TBR: ~1.23 (90% coverage factor)
- Achievable gain: ~1.20
- Coolant $T_{\text{in}} / T_{\text{out}}$: 450 / 550°C

HCLL – helium cooled lithium-lead

- Breeding zone: ~70cm thick, 80% vol LiPb (90% $^6$Li)
- Achievable TBR: ~1.15 (90% coverage factor)
- Achievable gain: ~1.16
- Coolant $T_{\text{in}} / T_{\text{out}}$: 450 / 550°C
blanket technology

European HCLL and HCPB TBMs in ITER

summary

- DT is the only choice for fusion power this century (thanks to a \(^3\)He resonance).
- Tokamaks are on the verge of achieving DT physics breakeven (JET, TFTR): engineering feasibility still to come (ITER).
- DT neutrons damage and activate materials but also generate tritium.
- Damage and activation differ from fission due to high energy of neutrons (14.1 MeV) triggering threshold reactions: \((n,p), (n,\alpha)\).
- Tritium self-sufficiency physically possible with a combination of enriched lithium and neutron multiplier.
- Tritium self-sufficiency engineering, however, is challenging: calculations show current blanket concepts only marginally achieve TBR > 1.
- Experimental evidence crucially needed: all but one ITER parties (not UK) to test this key technology, nuclear data uncertainties need to be resolved.