① Summary - nuclear reactions

nuclear reactions are <u>induced</u> by energetic particles (projectiles)

→ two types : - fission
- fusion

Typical reaction: $a + X \rightarrow Y + b$

a: projectile, X: target, Y: heavy, b: light

other notation
$X(a,b)Y$
↓
(a,b) classification

classification: ① scattering
② knockout reaction
③ transfer reaction

based on mechanism:
- direct reaction
- compound reaction
- resonance reactions

Fission:

→ A general method (~~type~~) is to bombard heavy particles with neutrons

→ Fission is the result between the competition of the Coulomb force (Z^2) and the strong force (A)

→ neutron induced fission (n, n) → produces more n → chain reaction
↓ controled ↓ uncontroled

How does it happen?

- Heavy elements sit high in the potential well and the fission products can escape the well if supplied by energy that is larger than the activation energy → fission → energy release

→ the energy gets mostly carried away by the fission products

→ fission is more likely is the released E is higher

→ spontanious fission is possible too, but it is very rare

Characteristics:

-> fission products are not uniquely determined but follow a distribution
-> distribution is symmetric between the heavy and the light product
-> for low energy fission we usually get a heavy and a light product
-> number of emitted n also follows a distribution
  ↳ average number of emitted n : ν
  -> prompt neutrons (energetic neutrons)
  -> delayed neutrons (β delayed neutron emission)
    ↳ from fission products

-> fission products tend to be radioactive -> decays

-> thermal neutrons (slow ones)

Energy: if $^{235}U + n \rightarrow {}^{236}U^{*} \rightarrow$ fission
  ↳ excited

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

$m({}^{236*}U^{*}) = m({}^{235}U) + m_n$ => E_{ex} needs to be larger than the activation E for fission

-> difference in excitation energies for different isotopes -> different n number
-> neutron capture by an odd N nuclei -> larger cross section ->
  -> easier to induce fission

Energy release:
-> most of the energy gets carried by the fission products (due to Coulomb repulsion)
  ↓
  about 80% of the energy
-> some by the n
-> carried energy depends on the inverse of the mass ratios

other E release: - prompt γ rays
- β decay
- γ decay of fragments

3) Controled fission reactions

↳ controling the numbers of the n in the reactor
→ neutron reproduction factor k_∞

→ reactor : fuel + moderator = chain-reaction pile

$k = 1$ pile in critical
$k < 1$ subcritical ⇒ usually we aim for this to have a slightly smaller value than 1. → religion β - delaye n
$k > 1$ supercritical

k_∞ depends on : - η : mean number of fission produced fast n
- ε : fast fission fraction (fast n fission with ^{238}U
- p : resonance capture probability of ^{238}U
- f : thermal utilization factor (available thermal n)

number of n : $\eta \varepsilon p f N$ four factor formula

$$\underline{k_\infty = \eta \varepsilon p f}$$

time scales involved for n multiplication (τ) → exponential increase or decrease

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

nuclear reactors have : fuel : Uranium
moderator : graphite
control rods : cadmium (n absorber)
cooling system : water, heavy water

reactors used for : - power generation
- research
- conversion (breading)

Electricity production : extracting heat from the reactor → steam turbine

4) Nuclear fusion

- fusing light nuclei to gain energy
- need to overcome the nuclear Coulomb barrier
  (very similar to α decay)

- if we add energy to a system by heating: thermonuclear fusion
  ↳ other option: particle acceleration

Basic fusion processes:

-> natural fusion only in stars

-> most simple reaction: $^1H + {}^1H \to {}^2H + e^+ + \nu$

$$\left.\begin{aligned} {}^2H + {}^2H &\to {}^3He + n \\ &\to {}^3H + p \end{aligned}\right\} \text{D-D reaction}$$

-> the more stable the end product the larger the E release
  ↳ ^4He is ideal to produce

$$^3H + {}^2H \to {}^4He + n \qquad \text{D-T reaction}$$

-> most often used in fusion experiments

-> similar input E to DD, but larger E release

-> issue: most kinetic E goes to the n, which is difficult to extract

Typical fusion in the Sun: $4p^+$ into ^4He (net reaction)
  ↳ trough various reaction chains: pp chain, or CNO cycle

-> in practice we always have 2 particles reacting, it is very difficult to get 3 particles in the same location for fusion

-> in stars He fusion and fusion of heavier elements is possible as well however: higher Coulomb barrier -> higher temperature

Energy release:

- reacting particles have kinetic E ~ 1-10 keV -> small compared to Q (~ MeV)
- the energy release and the final total E of the particles will be equal to Q: $\frac{1}{2}m_G v_G^2 + \frac{1}{2}m_Y v_Y^2 \simeq Q$

(5) final momenta: $m_B v_B \simeq m_Y v_Y$

→ energy gets distributed based on the mass ratio

$$\frac{\frac{1}{2} m_B v_B^2}{\frac{1}{2} m_Y v_Y^2} = \frac{m_Y}{m_B}$$

→ lighter particle (n) gets most of the E

for D-T : n gets 80% of Q
D-D ~75%

- reaction rate depends on the probability of fusion, which depends on the Coulomb barrier (potential) → exponential func. of $Z_a Z_X$
  → reaction rate also depends on temperature

→ How do we get information about the Solar fusion?
↳ observing ν from the reaction
↳ continous spectrum from $^1H + ^1H \to D + \bar{\nu} + e^+$
- discreet spectrum: $^7Be + e^- \to ^7Li + \nu$
- continous : $^8B \to ^8Be + e^+ + \bar{\nu}$ max E: 14 MeV
most important for Solar models

Controled fusion reactors

→ plasma containment : – magnetic confinement
↳ tokamak
→ magnetic mirror
– inertial confinement
↳ lasers
→ particle beams

⇒ in experimental phase: many experimental reactors

- mostly using D-T for energy gain
  - however T is very rare

- alternate options: $^1H + ^{11}B \to 3\,^4He$
  $D + ^3He \to ^4He + ^1H$