MCRT L8: Neutron Transport

- Recap fission, absorption, scattering, cross sections
- Fission products and secondary neutrons
- Slow and fast neutrons
- Energy spectrum of fission neutrons
- Nuclear reactor safety and criticality geometries
- Nuclear medicine – boron-neutron capture therapy
- MCRT ideas… tracking neutrons, interactions, banking fission neutrons as sources for next generation…

Discovery of neutron

- In 1930 Boethe & Becker bombard beryllium with alpha particles and produced non-ionizing radiation thought to be γ rays
- The "γ rays" knock protons off paraffin wax. Protons had very high speeds implying huge energies of the "γ rays"
- Rutherford & Chadwick postulated the γ-rays were neutrons and this was confirmed by Chadwick in 1932

$$ {}^{4}_{2}\mathrm{He} + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + \mathrm{n} $$

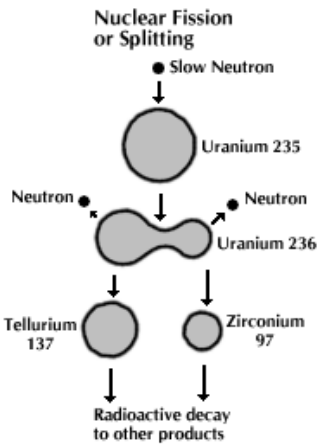
Discovery of fission

- Long history of radioactivity experiments: Walton & Cockcroft split the atom in 1932:

$$p + {}^{7}_{3}\mathrm{Li} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}$$

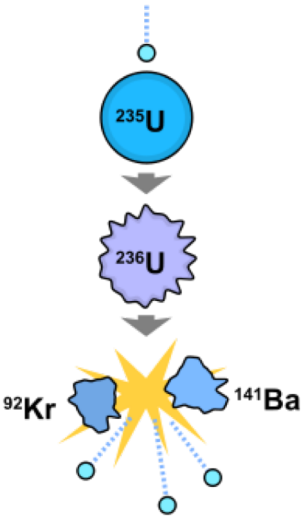
- Neutron experiments: uncharged so very penetrating with longer mean free path in matter than protons
- Fermi bombarded uranium (atomic number 92) with neutrons in 1930s, and thought he had produced elements with 93 and 94 protons, but others suggested fragmentation of the nucleus
- Fission of uranium by neutrons discovered by Hahn & Strassmann in 1938, produced barium (atomic number 56)

Fission mechanism



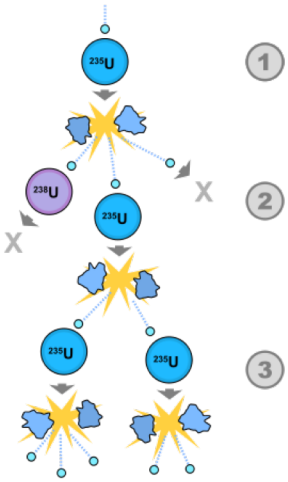
- How could nucleus be split?
- Liquid drop model (Bohr & Wheeler) + nuclear shell model (Wigner, Goeppert-Mayer, Jenses)
- Absorb neutron, raise energy of nucleus, deform the “droplet” to such an extent that it breaks apart
- Need enough energy to overcome the strong nuclear force (7 to 8 MeV) to separate the droplet so that EM repulsion takes over from strong force

Fission energy

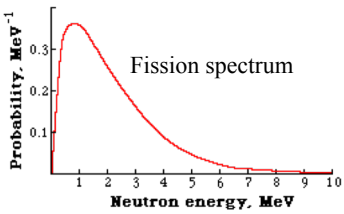


- Energy output: binding energy of U ~ 7.6MeV per nucleon, binding energy (energy released when assembling nucleus) of the fissile products ~8.5MeV per nucleon, so release ~0.9MeV per nucleon of fissioning material
- Energy available ~ 200MeV per fission
- Most energy released is kinetic energy of positively charged fragments blown apart by repulsive Coulomb force
- Fission also produces secondary neutrons…

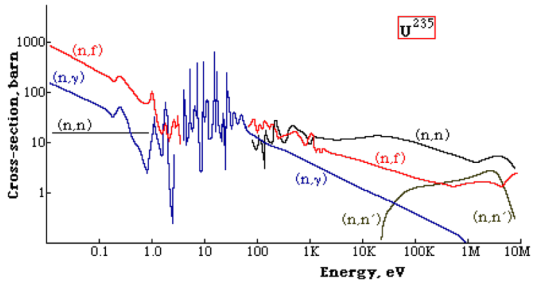
Chain reaction

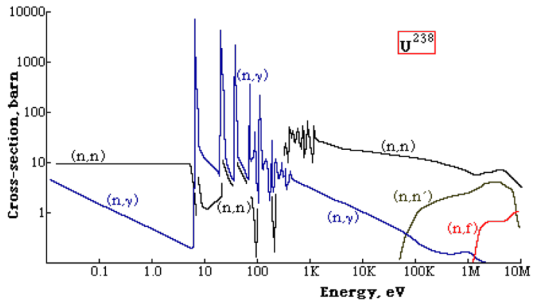


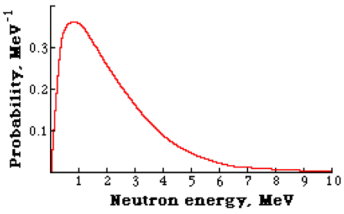
- Possibility of self-sustaining chain reaction
- On average 2.5 neutrons per fission
- Slow neutrons: controlled reaction for power
- Fast neutrons: uncontrolled explosion
- Fission neutrons have mode of 2MeV, but median of 0.75MeV
- Fissile & fissionable: *fissile* elements fission with the addition of any neutron (slow or fast); *fissionable* elements must absorb fast neutrons with $E > 1$MeV



Cross sections & fission spectrum







Spectra from Nuclear Physics, Sheffield Uni

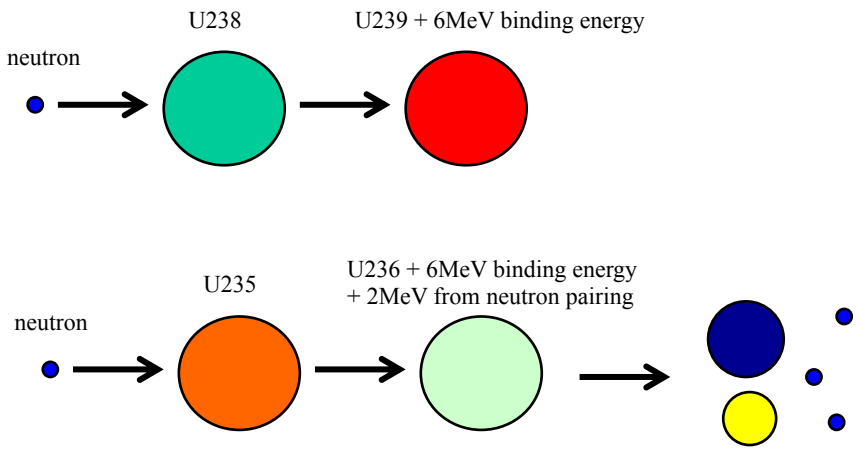
Neutron interactions

- Scattering (n, n) or (n, n’) – change direction (assume isotropic) and energy (if inelastic)
- Absorption (n, γ) – absorb neutron, raise energy of nucleus, emit photons and other particles
- Fission (n, f) – absorb neutron, raise energy of nucleus high enough to cause fission, fission products and secondary neutrons
- Slow and fast neutrons – fission energy spectrum produces fast neutrons, collisions with moderators slow down the neutrons
- Slow (thermal) neutrons can fission U235, but only fast neutrons can fission U238 (negligible fission cross section below 1MeV)
- Complex behaviour in range 1eV to 10keV – resonances in the nucleus

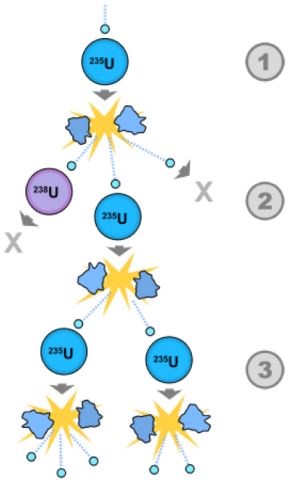
Why U235 fissions and U238 doesn't

- Adding an extra neutron (even a slow neutron) to the nucleus adds binding energy of ~ 6MeV
- Energy required for fission is 7 to 8MeV, so cannot fission unless have higher energy such as kinetic energy of fast neutrons
- But for odd nuclei, adding neutron releases additional binding energy: last two nucleons pair up releasing another ~1 to 2Mev (like Pauli exclusion) which takes total energy released above that to fission
- Hence U235 and Pu239 are fissile, but U238 is not
- Neutron fission spectrum – about ¾ neutrons have energies below 1MeV, so cannot fission U238

Why U235 fissions and U238 doesn't



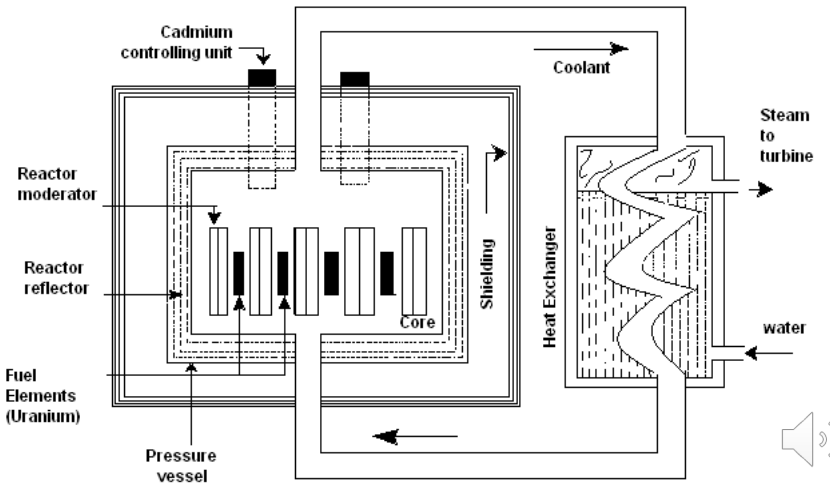
Neutron generations & criticality



- Successive generations of neutrons
- Produce on average 2.5 neutrons per fission
- If fission neutrons can be trapped (and slowed), can get chain reaction
- $k_{eff} = N_{i+1} / N_i$
- $k_{eff} < 1$: sub-critical
- $k_{eff} = 1$: critical
- $k_{eff} > 1$: super-critical
- Important to determine masses and geometries for critical systems

Nuclear Reactors

- Slow the fast fission neutrons by moderators so they can fission U235
- Natural U is only 0.7% U235: enrich to 3% (reactors) 80% (bombs)



MCRT Reactor Simulations

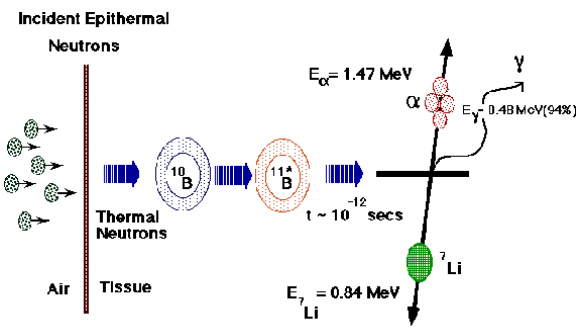
- Neutrons (and fission products) interact with fuel, moderators, control rods, reactor shields
- Simulate interactions – need cross sections and energy spectra
- Slow down fast neutrons (1MeV) by inelastic collisions with light nuclei (H and C are good moderators) to thermal energies (0.025eV) where U235 fission cross section is large
- Safety control rods – strong absorbers (large absorption cross section) of neutrons (e.g., boron) to stop chain reaction
- Safety shields – strong absorbers of radioactive products
- Goal – determine optimum geometries for fuel, moderators, control rods to sustain criticality and shielding geometry for safety

Neutron-boron capture therapy

- Neutron capture therapy proposed by Locher in 1936
- Boron attaches to cancer cells ^{10}B (20% of natural boron)
- Irradiate with neutrons to produce via capture and fission:

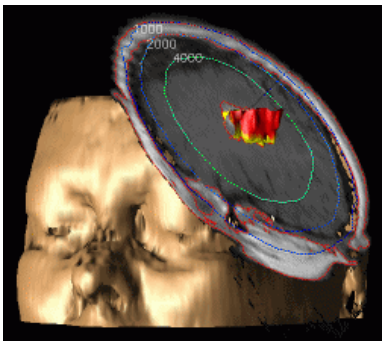
$$n + {}^{10}_{5}B \rightarrow {}^{4}_{2}He + {}^{7}_{3}Li + 2.3MeV$$

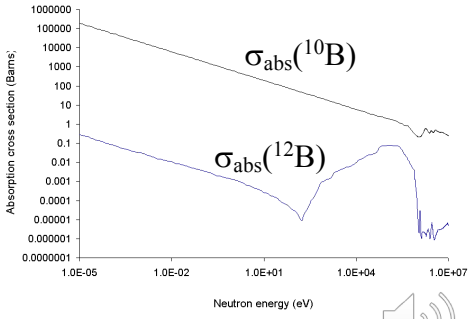
- The Li and α-particles produce ionizations within 10μm of the reaction: lethal to cells containing boron



MCRT for Boron-Neutron Therapy

- Determine penetration of neutrons into human bone and tissue
- Slowing down of neutrons through inelastic scattering
- Dose of neutrons and energy released – theraputic effects

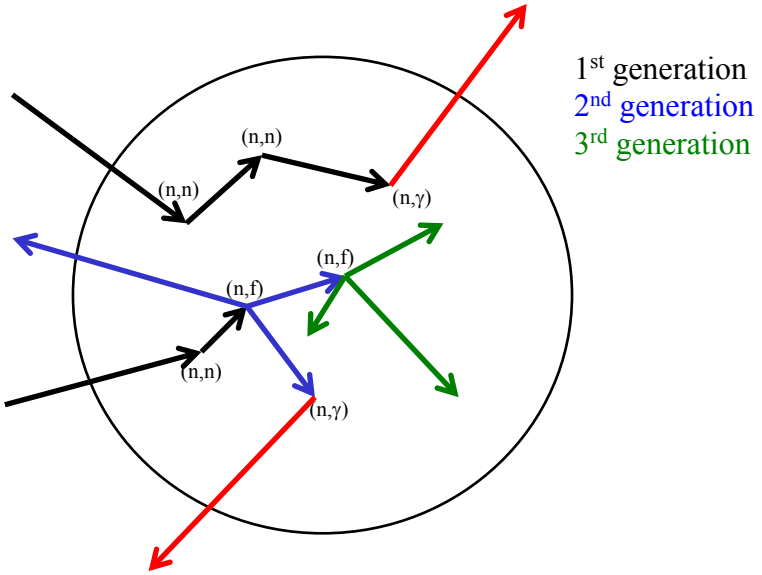




MCRT for Neutron Transport

- MC code – track neutrons until they interact
- What type of interaction – scatter, absorb, fission
- Scatter – change direction, and if change energy must change cross sections for subsequent random walk
- Absorb – terminate neutron, but could track γ-ray photon
- Fission – bank position of fission neutrons to be source locations for next generation
- Loop over neutron generations and determine $k_{eff} = N_{i+1} / N_i$

Neutron Generations



1st generation
2nd generation
3rd generation