

Lecture 1

Neutron Fundamentals

Microscopic Interactions

22.106 Neutron Interactions and Applications
Spring 2010

Objectives

- Basic Neutron Properties
- Concept of Microscopic x.s.
- Brief review of Neutron Interactions
- Energy dependence of neutrons
 - Neutron – nucleus interactions
 - Neutron sources

Neutron

- Discovered by James Chadwick in 1932
 - No electric charge
 - Mass of 1.008664915 amu (slightly more than a proton)
 - Spin of $\frac{1}{2}$
- Its existence explained the atomic model and the cohesion of the nucleus. The strong nuclear forces are able to keep the protons from repulsion.

- Bound neutrons (i.e. in the nucleus) are stable
- Free neutrons are unstable
 - They are produced by:
 - Fission
 - Fusion
 - Photoneutrons
 - Alpha sources (PuBe, AmBe, AmLi)
 - Decays by beta emission
 - Half life of 885.7s (roughly 15 min)
- Bounded nucleus may also use beta decay if unstable
 - This is the case for the fission products who are neutron rich. Successive beta decay brings them closer to stability.

Stability of fission products

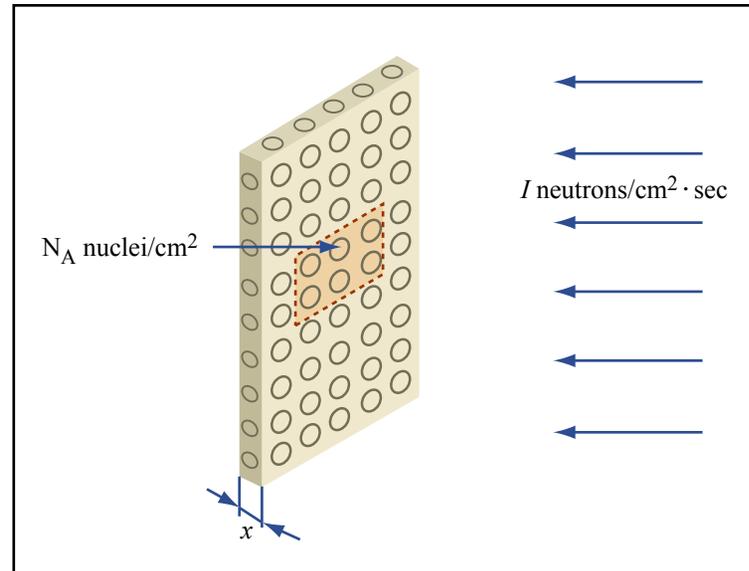
- Neutron rich fission products beta decay towards stability

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- Neutron interacts with materials for different purposes or consequences:
 - Detection
 - Based on the interaction of neutrons with other materials
 - Shielding
 - Neutron absorption or reflection prevents neutrons from escaping
 - Inducing fission
 - Active detection systems
 - Ionization chambers
 - Structural displacement
 - Material damage by creating defects in lattice
 - Material assay
 - Neutron Diffraction
 - Small Angle Neutron Scattering

Microscopic x.s.

- Probability of a particular event occurring between a neutron and a nucleus is expressed through the concept of a cross-section.
- Consider a beam of mono-energetic neutrons of intensity I (neutrons/cm².s) incident on a very thin sample material such that there are N_A atom per cm²



Microscopic Cross section

$$R = \sigma I N_A$$
$$\left[\frac{\#}{\text{cm}^2 \text{ s}} \right] \left[\text{cm}^2 \right] \left[\frac{\#}{\text{cm}^2 \text{ s}} \right] \left[\frac{\#}{\text{cm}^2} \right]$$

Probability of a neutron-nuclear reaction is characterized by the nuclear microscopic cross section.

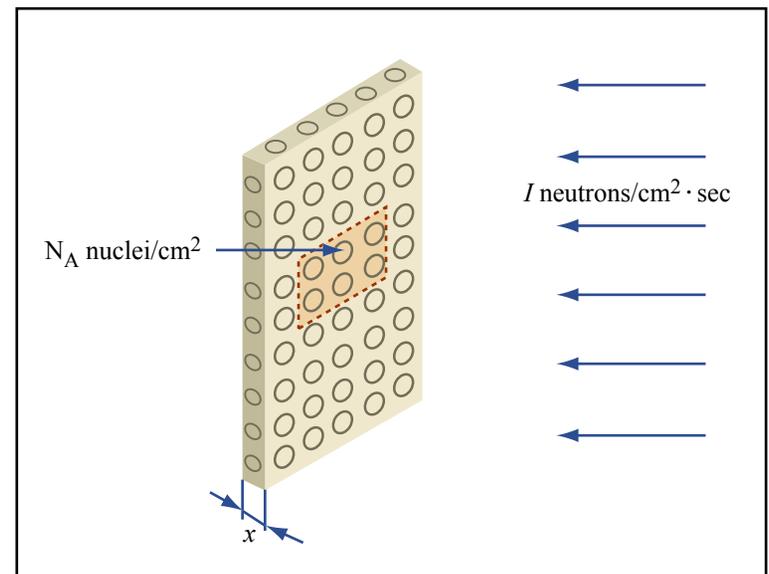


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- Cross-sections are strongly dependent of neutron incoming energy. This relation is important in the understanding of x.s. but also to estimate the time a neutron spends in a particular region.
 - Classical expression for K.E. is sufficiently accurate because rest mass of a neutron is fairly large (939.55 MeV)

$$E = \frac{1}{2} m v^2$$

$$E = 5.227 \times 10^{-15} v^2 \quad \text{or} \quad v = 1.383 \times 10^7 E^{1/2}$$

Examples

- 1 MeV neutron has a speed of
 - 1.383×10^7 m/s
 - Will cross a 15 cm sample in 11 nanoseconds
- 0.025 eV neutron has a speed of
 - 2187 m/s
 - Will cross a 15 cm sample in 70 microseconds
- Conclusion: When studying neutron distributions, the energy levels involved and the size of the systems usually make it possible to neglect the beta decay of the free neutron.

Types of Interactions

- Two major types
 - Scattering: Speed and Direction change but nucleus is left with same number of neutrons and protons
 - Absorption: Original neutron disappears within the nucleus

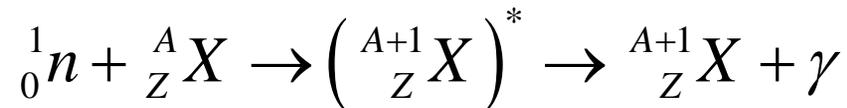
Elastic Scattering (n,n)

- One of the most difficult neutron interactions to measure and the most complicated to analyze theoretically.
 - It is also one of the most important reactions in reactors, characterization devices, ...
- Elastic Scattering requires to consider the double differential cross section which describes the angular distribution and the energy distribution as well as the total elastic cross-section.

Inelastic Scattering (n,n')

- Plays a key role in neutron slowing down at high energies
 - Requires a threshold energy to excite the nucleus to a quantum state
 - The neutron can thus lose a considerable amount of energy in one collision since most of it is used to bring the nucleus to this quantum state

Radiative Capture (n, γ)



- Neutron combines with target of mass A to produce nucleus of mass A+1 in a quantum state. The excitation of this state is equal to the sum of the neutron binding energy and the kinetic of the neutron.
- Energy is released in one or more gamma rays
- This reaction is very important in the production of radioactive medical isotopes.

Cobalt-60

- Production of radioactive medical isotopes
 - Sterilization
 - Medical Equipment
 - Food
 - Blood
 - Chemical tracer

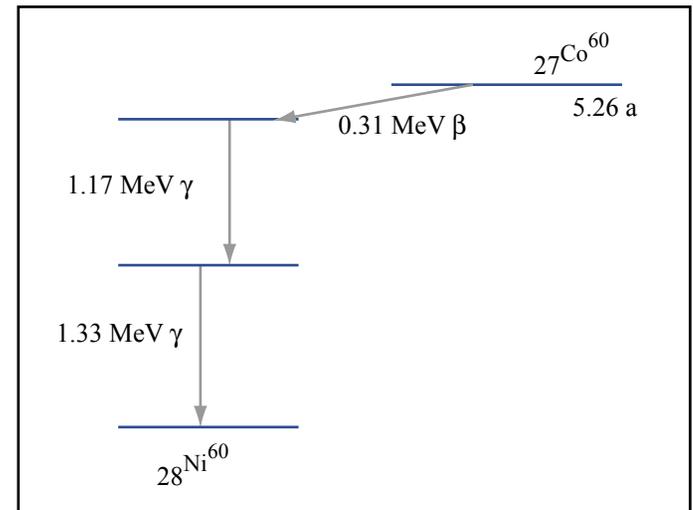


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Technetium-99m

- Technetium-99m is used in 20 million diagnostic nuclear medical procedures every year.
- It is a gamma ray emitting isotope used as a radioactive tracer that medical equipment can detect in the body. It is well suited to the role because it emits readily detectable 140 keV gamma rays (about the same wavelength emitted by conventional X-ray diagnostic equipment), and its [half-life](#) for gamma emission is 6.01 hours. The short half life of the isotope allows for scanning procedures which collect data rapidly, but keep total patient radiation exposure low.
- Molybdenum-99 is produced mainly by fission of HEU
 - Decays to Tc-99m (half-life of 66hrs)
 - Tc-99m is chemically extracted from Mo-99 fairly easily

$(n,2n), (n,3n), \dots$

- Two step process
 - Incident neutron is inelastically scattered by a target nucleus (threshold reaction)
 - If residual energy is left with excitation energy above binding energy of last neutron, the neutron is free to escape
- $(n,2n)$ threshold usually is 7-10 MeV
 - 1.8 MeV for Be
- $(n,3n)$ threshold usually is 11-30 MeV

$(n,2n)$, $(n,3n)$ for U-238

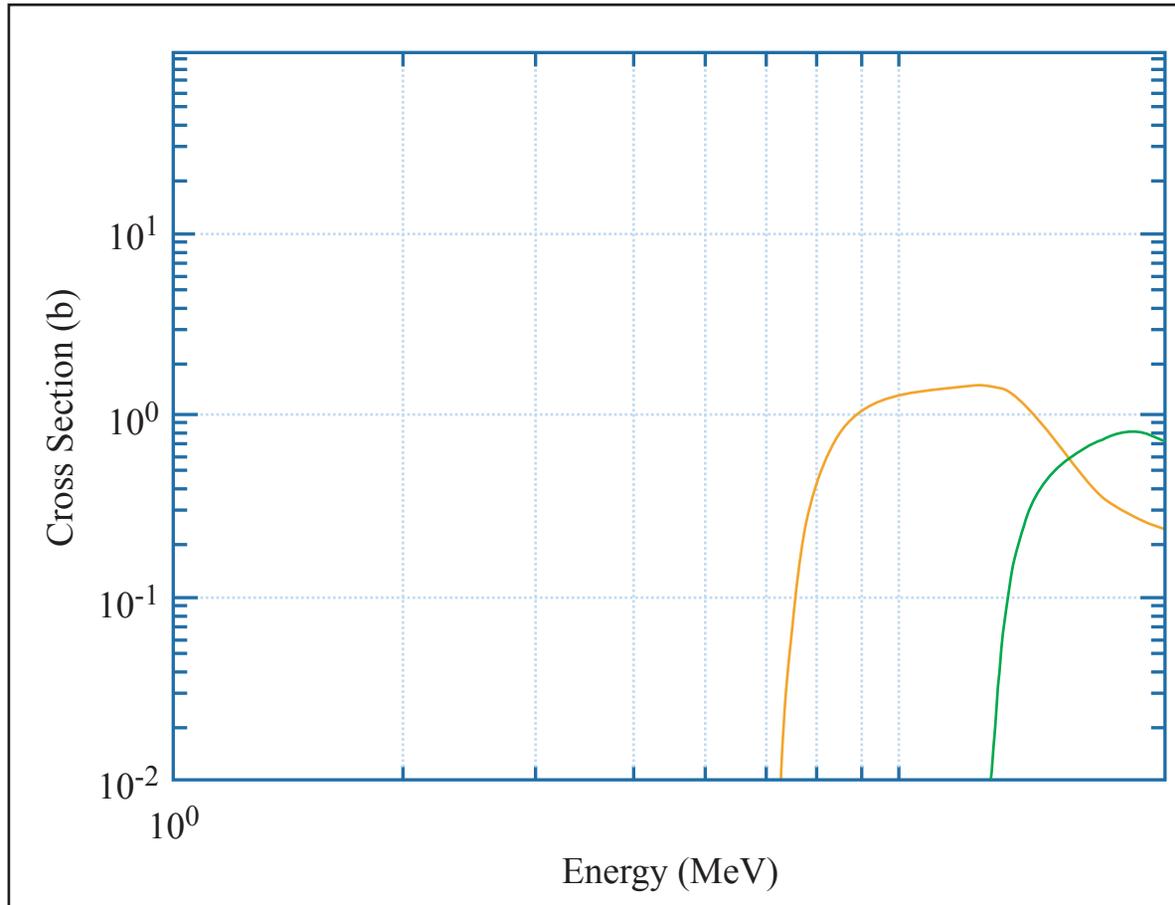
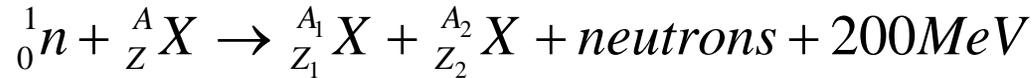


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Charged particles (n,p), (n, α)

- Usually requires lots of energy to happen with one notable exception
 - ^{10}B (n, α) ^7Li : very high x.s. at low energy which is why ^{10}B is used as a thermal absorber
- Very small x.s. in heavy nuclei, because emitted charge particle must overcome Coulomb barrier in order to escape nucleus
 - Delay is so long that compound nucleus (CN) will scatter (elastic or inelastic) instead.

Fission Reaction (n,f)



- Activation energy required to induce fission. Energy not available in ground state of ${}^{236}\text{U}$ but it is supplied in the form of the neutron binding energy in $({}^{236}\text{U})^*$
- Fission usually provides two fission products (FP)
 - Scission in 3 or more FPs is possible but very rare
 - 1/400 scission in 3 FPs
 - 1/3000 scission in 4 FPs
- Releases roughly 200MeV of energy and ν neutrons (typically 2-3).

Energy Dependence of x.s.

- General Rule: x.s. decreases with increasing energy of incoming neutron
- At low energies (<1 MeV), (n,n) is nearly constant whereas (n, γ) is proportional to “ $1/v$ ”
- In the keV range, resonances are superimposed on the “ $1/v$ ” trend, these resonances are formed when neutron energy + binding energy correspond to an excitation level of the nucleus.

- Heavy Nucleus
 - eV range: resonances appear
 - keV range: resonances are too close to be distinguished
 - MeV range: resonances are broader and small, x.s. becomes smooth and rolling.

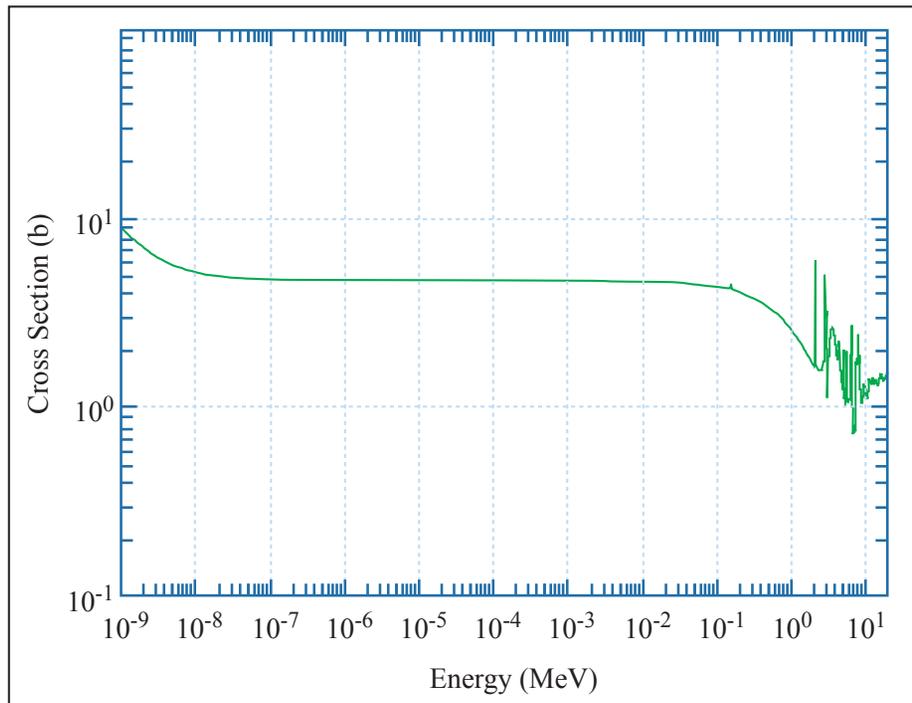
- Light Nucleus

- Resonances appear only in MeV range. They are broad and small

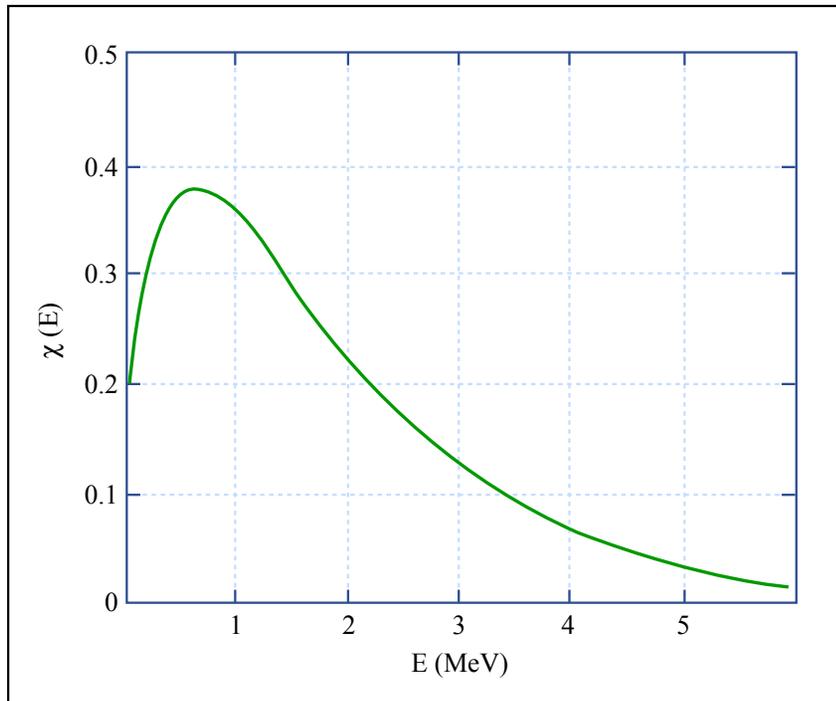
- Exceptions

- ^1H and ^2H have no resonances at all (no excitation level in the nucleus)
 - Nuclides with “magic number” of protons and neutrons may behave more like light nuclei

C-12 total x.s.

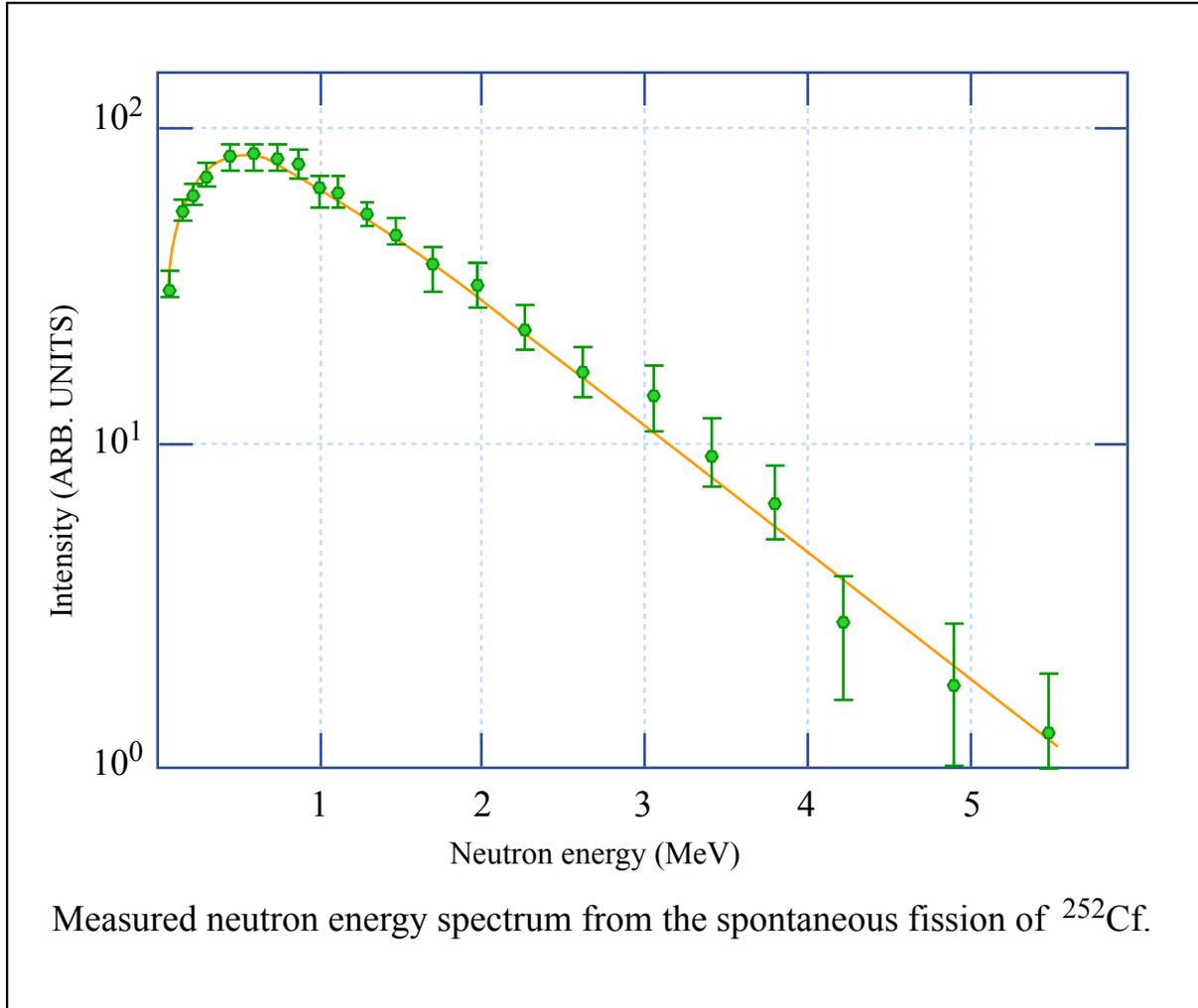


- Neutrons are produced with varying energy depending on the source.
 - Fission produces 2-3 neutrons/fission
 - Large fraction is prompt (10^{-13} seconds)
 - Small fraction is delayed (decay of FPs)



$$\chi(E) = 0.453e^{-1.036E} \sinh \sqrt{2.29E}$$

- Spontaneous Fission from Cf252



- Alpha Neutron Source

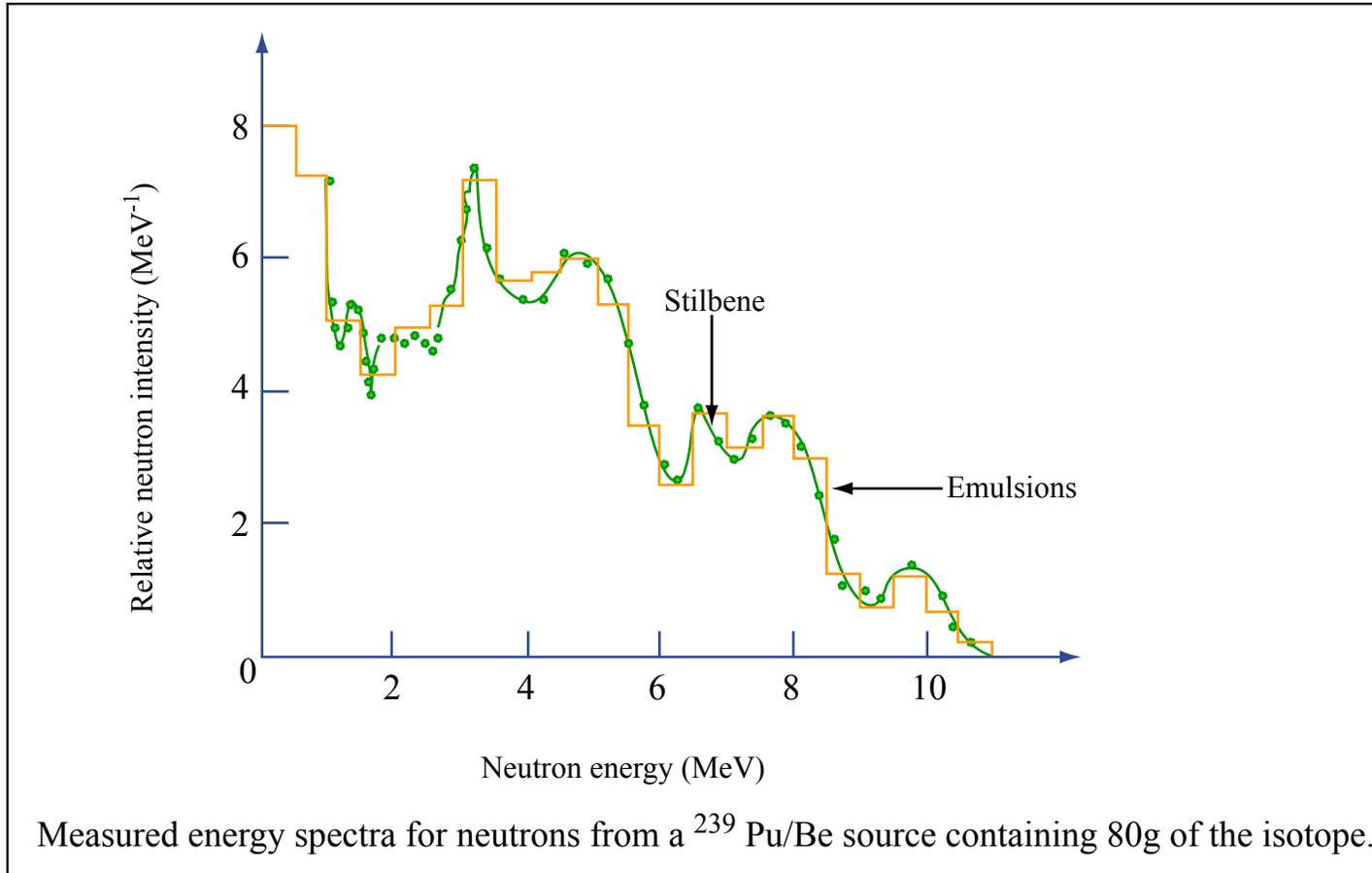


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- Spallation Neutron Source

- High energy proton bombard a heavy target and creates spallation particles

- 1) Negative hydrogen ions (1 proton and 2 electrons) are generated in pulses

- 2) Accelerated to 1 GeV (almost 90% of speed of light) by a linear accelerator

- 3) Electrons are stripped and protons are concentrated in a 2MW beam

- 4) Directed at liquid Mercury

- Liquid at room temperature
- Absorbs rapidly changes in temperature and can survive intense bombardment shock
- Ejects 20-30 neutrons per collision (avg energy of 20-25 MeV)

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