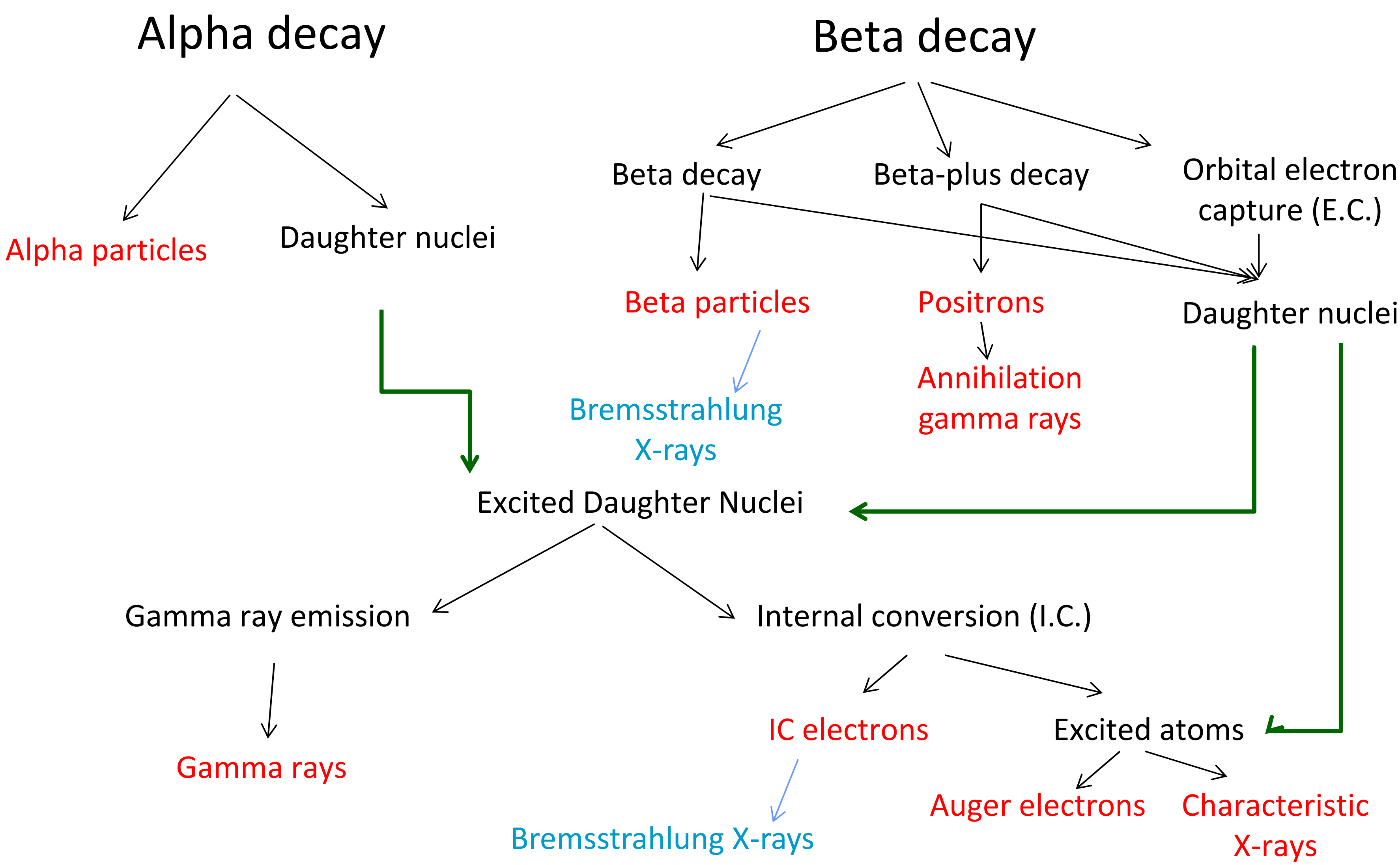
Typical Decay Products from Unstable Radioisotopes

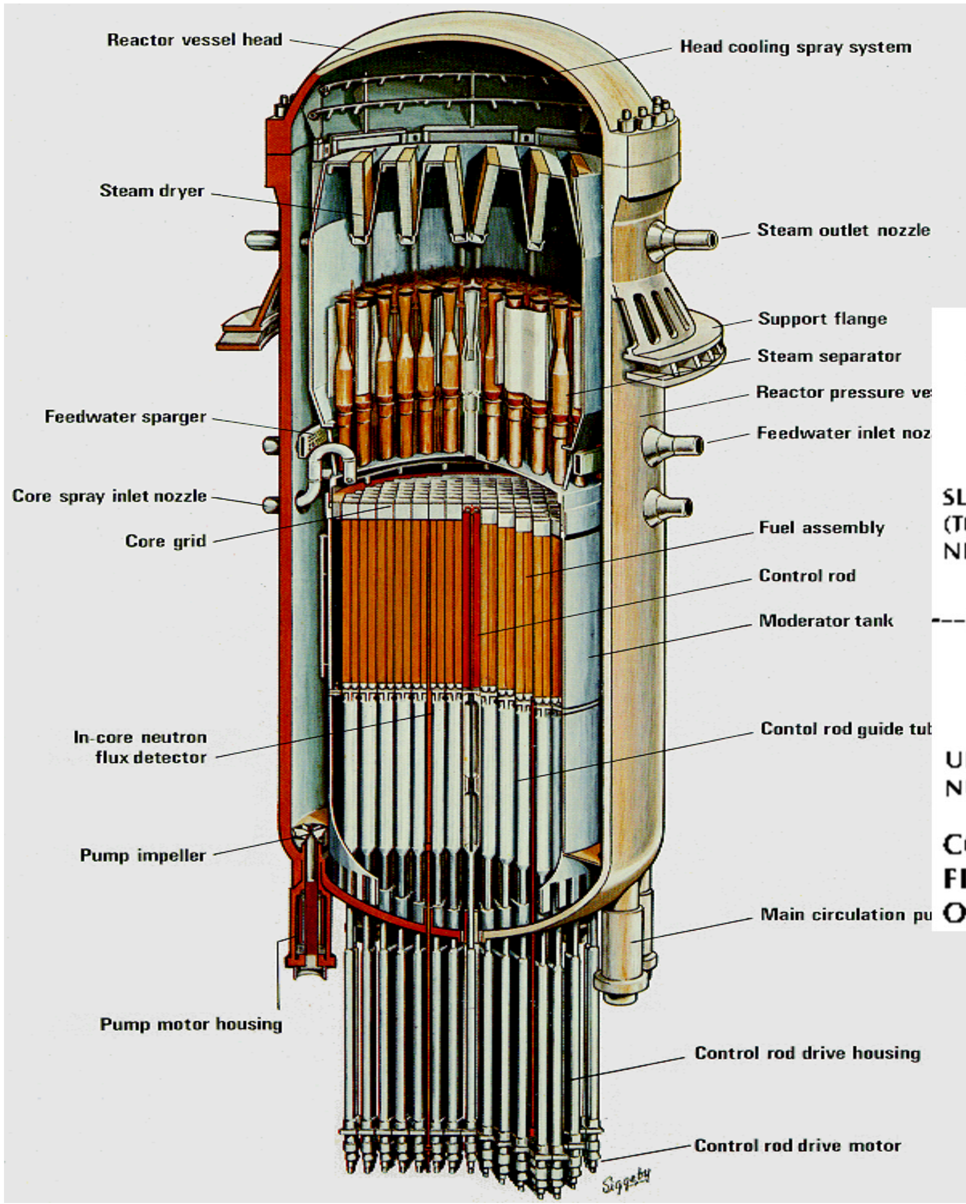


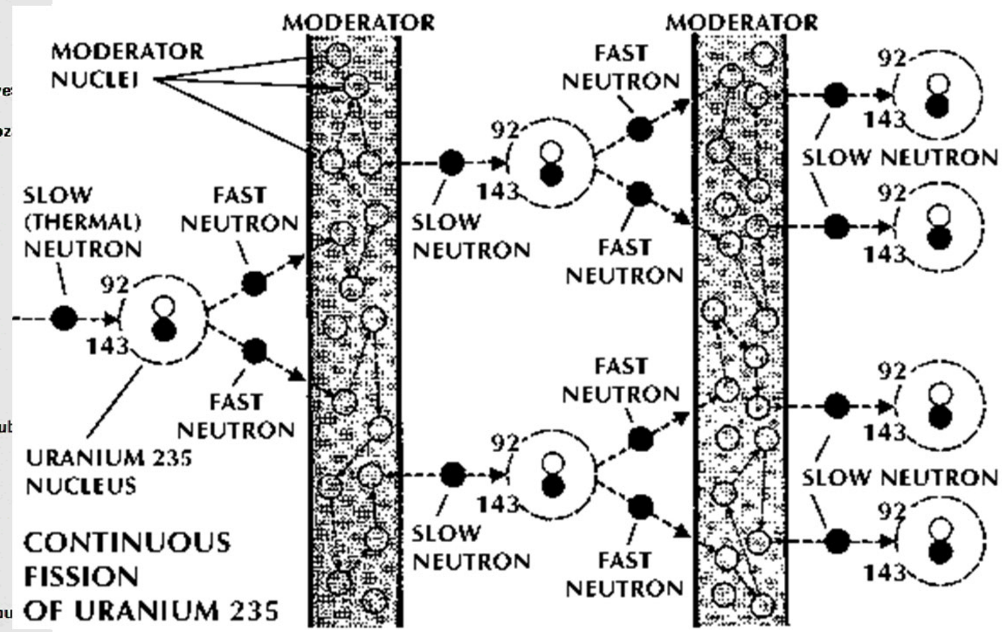
Neutron Sources

Typical Scenarios Involving Neutron Radiation

- Portable neutron sources
- Nuclear reactors
- Medical applications

Inside a Nuclear Reactor





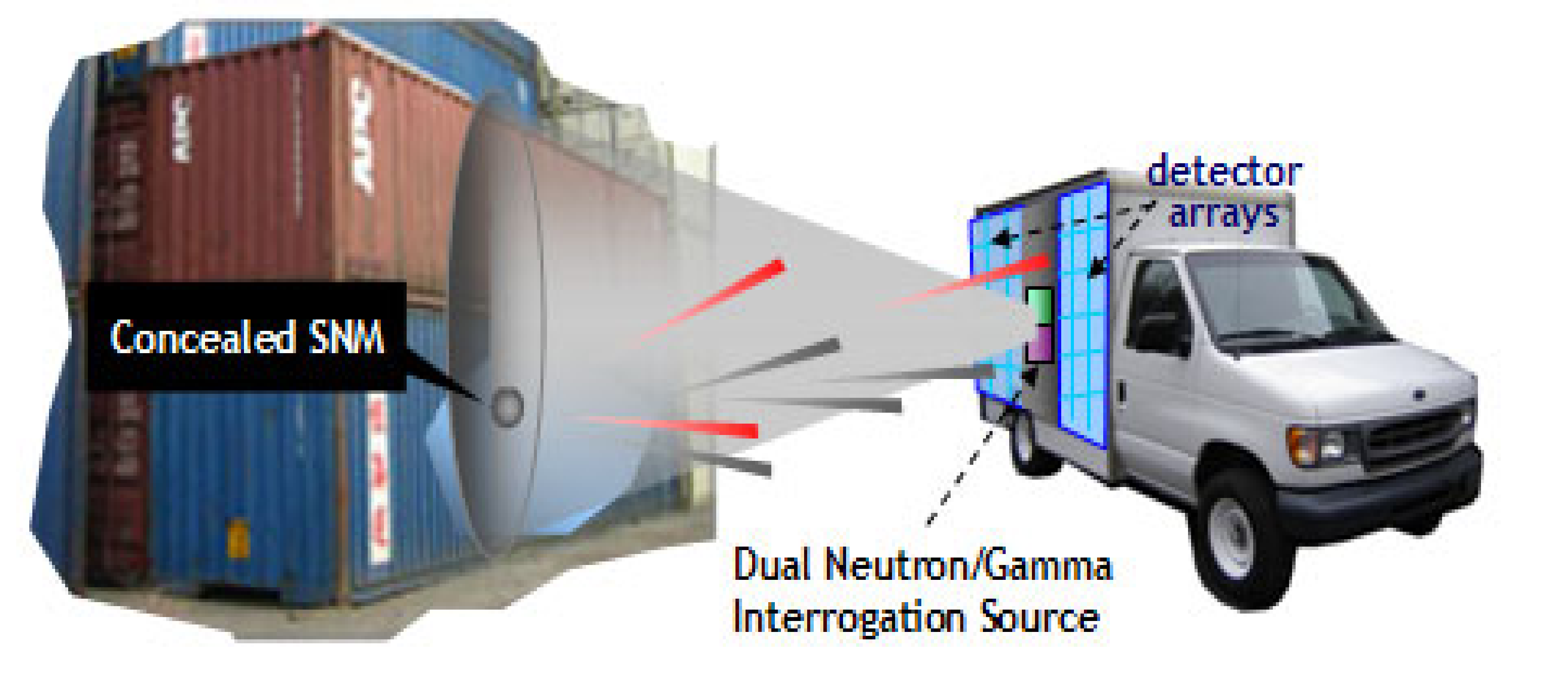
Neutron Sources – Spontaneous Fission

Cf-252 neutron source can be made extremely compact

An engineer tests the prototype Timed Neutron Detector, a device that detects landmines. The neutron source of the landmine detector holds a tiny amount of californium-252. (Photo credit: Pacific Northwest National Lab)

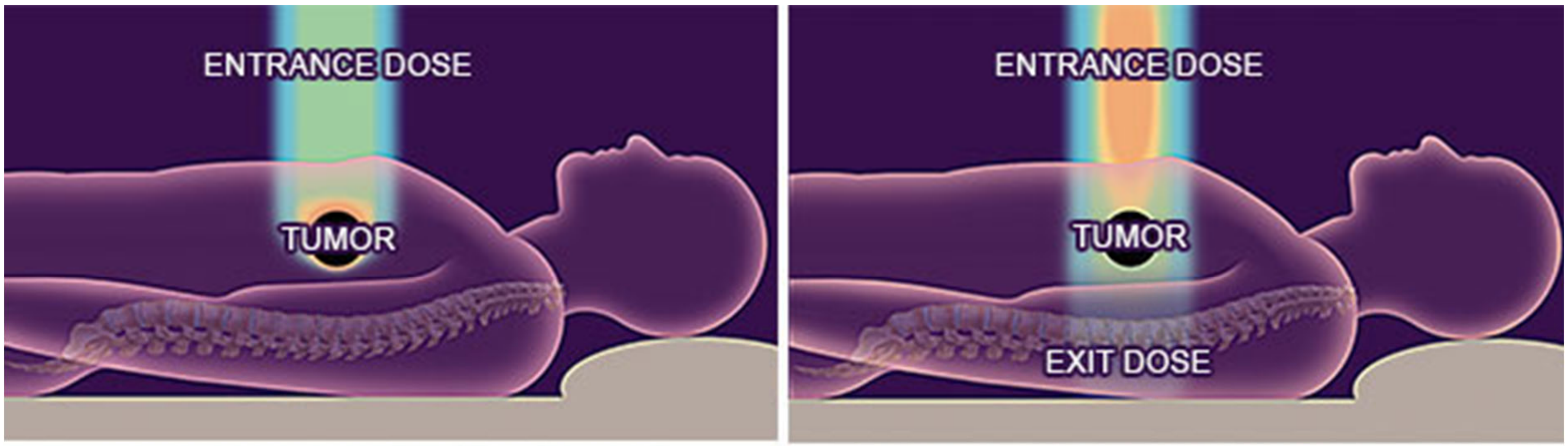
Active Interrogation for Finding Special Nuclear Materials

Mobile Dual Neutron/Gamma Interrogation System



Proton Therapy

http://www.floridaproton.org/what-is-proton-therapy/benefits



TARGETED PROTON THERAPY:
Deposits most energy on target

CONVENTIONAL RADIATION THERAPY:
Deposits most energy before target

The downside of this strategy is that proton interactions with materials in the beamline will create high-energy secondary neutrons. The high linear energy transfer (LET) of neutrons makes them extremely efficient at ionization, and far more likely to cause cell death than low-LET particles, such as X-rays or protons.

FIGURE 1

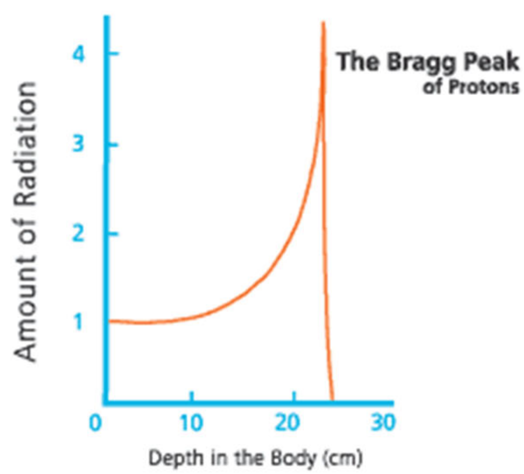
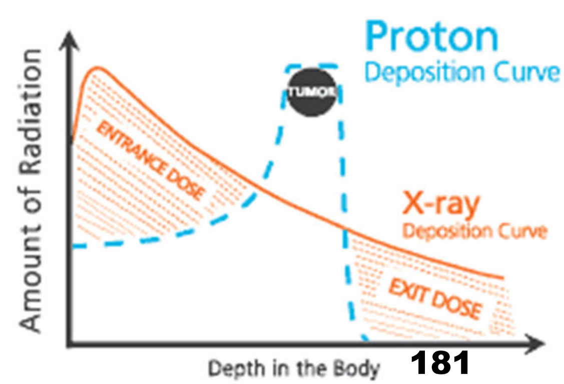


FIGURE 2



Thermal Neutron Capture Radiation Therapy

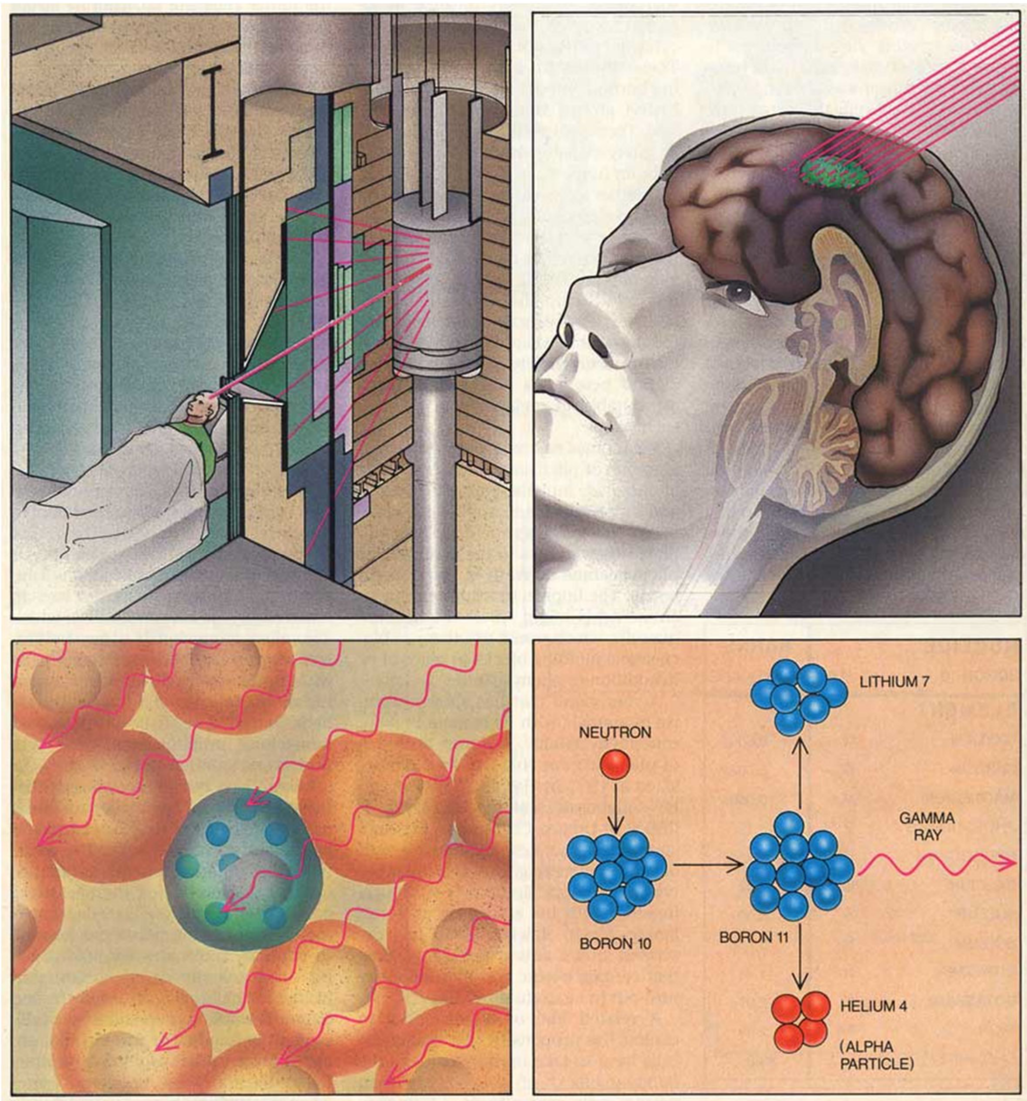


Figure from: http://en.wikipedia.org/wiki/File:NeutronCaptureTherapyImage.jpg

Fig.1 boron neutron capture therapy (BNCT) can be performed at a facility with a nuclear reactor or at hospitals that have developed alternative neutron sources. A beam of epithermal neutrons penetrates the brain tissue, reaching the malignancy. Once there the epithermal neutrons slow down and these low-energy neutrons combine with boron-10 (delivered beforehand to the cancer cells by drugs or antibodies) to form boron-11, releasing lethal radiation (alpha particles and lithium ions) that can kill the tumor.[1]

Barth, Rolf F.; Soloway, Albert H.; Fairchild, Ralph G. (1990). "Boron Neutron Capture Therapy for Cancer". Scientific American 263 (4): 100–3, 106–7. Bibcode:1990SciAm.263d.100B. doi:10.1038/scientificamerican1090-100. PMID 2173134.

Neutrons Sources

Neutron Sources – Spontaneous Fission

Neutron Sources – Spontaneous Fission

Cf-252 neutron source can be made extremely compact

An engineer tests the prototype Timed Neutron Detector, a device that detects landmines. The neutron source of the landmine detector holds a tiny amount of californium-252. (Photo credit: Pacific Northwest National Lab)

TABLE 7.1 NEUTRON TERMINOLOGY

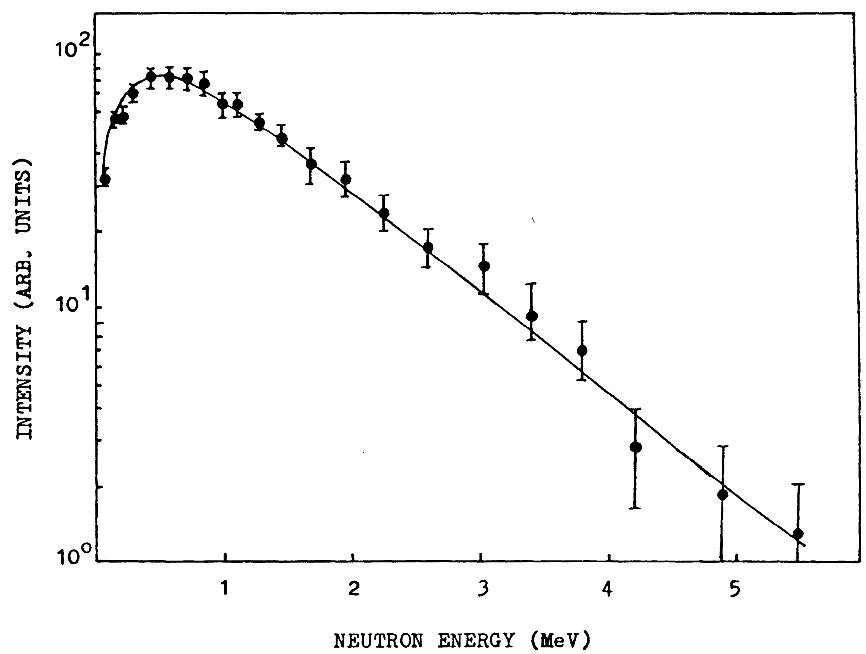
Term	Energy Range	Velocity
Ultracold	<2 × 10^{-7} eV	6 m/s
Very cold	2 × 10^{-7} eV to 5 × 10^{-5} eV	100 m/s
Cold neutrons	5 × 10^{-5} eV to 0.025 eV	—
Thermal[c]	0.025 eV	2200 m/s
Epithermal	1 eV–1 keV	4.4 × 10^{5} m/s
Cadmium	<0.4 eV	8800 m/s
Epicadmium	>0.6 eV	1.1 × 10^{4} m/s
Slow	<1 to 10 eV	1.4 × 10^{4} m/s
Resonance[a]	1 to 300 eV	2.4 × 10^{5} m/s
Intermediate	1 keV to 0.1 MeV	4.4 × 10^{6} m/s
Fast	>0.1 MeV	1.4 × 10^{7} m/s
Ultra fast (relativistic)	>20 MeV	—
Fission[b]	100 keV to 15 MeV	—

[a]In pile neutron physics usually refers to neutrons which are strongly captured in the resonance of U-238, and of a few commonly used detectors, e.g., In, Au.
[b]Most probable energy 0.8 MeV, Average energy 2.0 MeV.
[c]Maxwellian distribution of 20°C extends to about 0.1 eV.

Neutron Sources – Spontaneous Fission

Spontaneous fission of tarnsuranic heavy nuclides, such as ^{252}Cf, produces several fast neutrons, in addition to heavy fission products, prompt fission gamma rays and beta and gamma ray activities.

- Half-life: 2.65 years
- Neutron yield: 0.116n/s per Bq, or 2.3×10^{6} n/s per mg
- Neutron energy peaking at 0.5MeV and extends beyond 10MeV.



Measured neutron energy spectrum from spontaneous fission of ^{252}Cf

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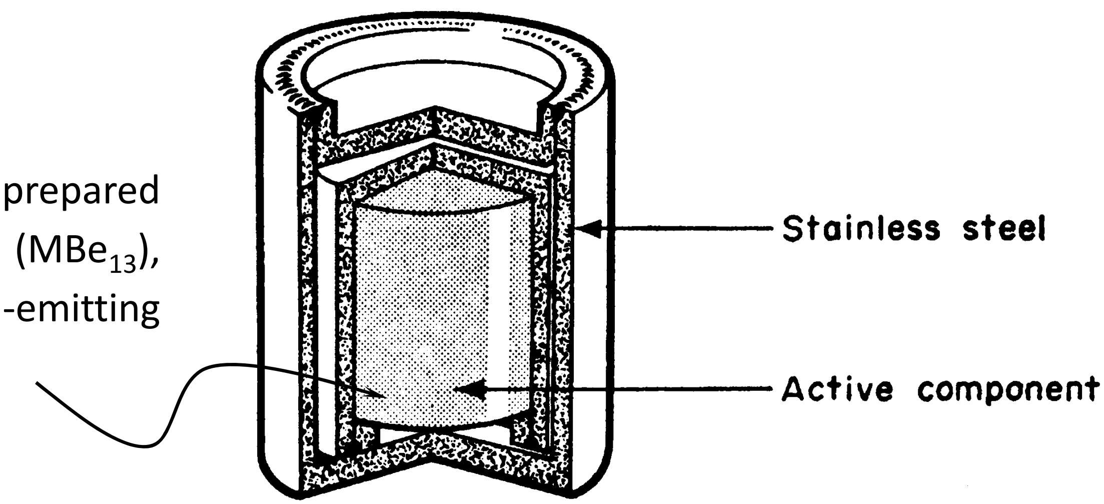
Radioisotope (α,n) Sources

Neutron Sources – Radioisotope (α,n) Sources

Energetic alpha particles can induce (α,n) reaction in certain target materials.

$$ {}^{4}_{2}\alpha + {}^{9}_{4}Be \Rightarrow {}^{12}_{6}C + {}^{1}_{0}n \qquad \text{Q-value}: 5.71\text{MeV} $$

The source is normally prepared in the form of alloy (MBe_{13}), where M is alpha-emitting radioisotopes



A practical neutron source

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Neutron Sources – Radioisotope (α,n) Sources

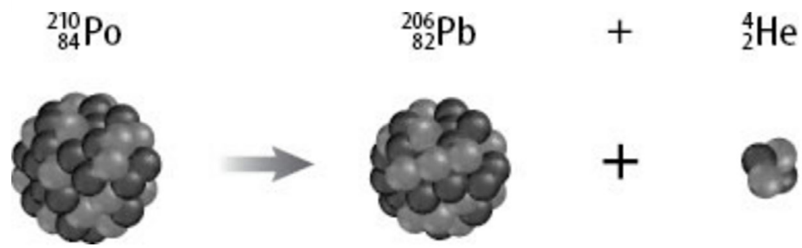


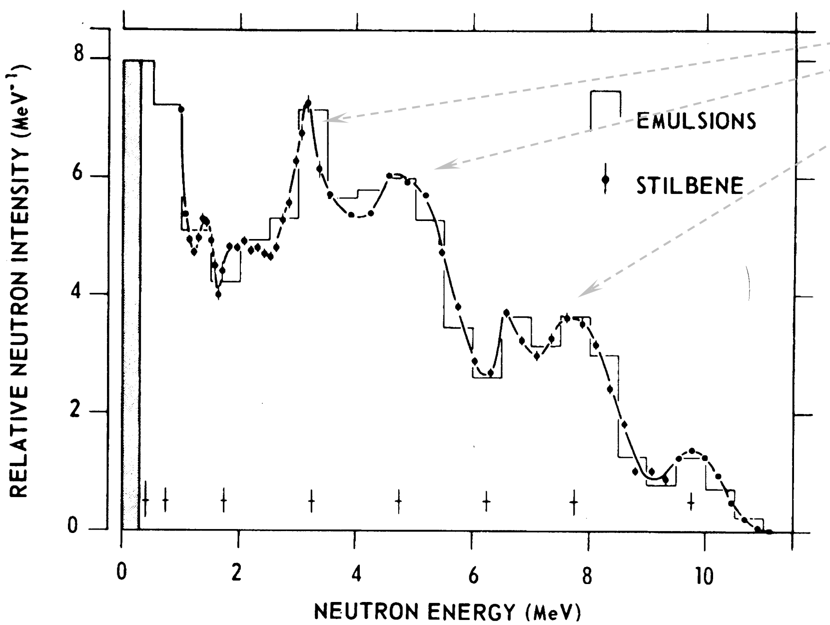
TABLE 9.2. (α,n) Neutron Sources

Source	Average Neutron Energy (MeV)	Half-life
^{210}PoBe	4.2	138 d
^{210}PoB	2.5	138 d
^{226}RaBe	3.9	1600 y
^{226}RaB	3.0	1600 y
^{239}PuBe	4.5	24100 y

James Tuner, Atoms, radiation and Radiation Protection, p210-p211.

Neutron Sources – Radioisotope (α,n) Sources

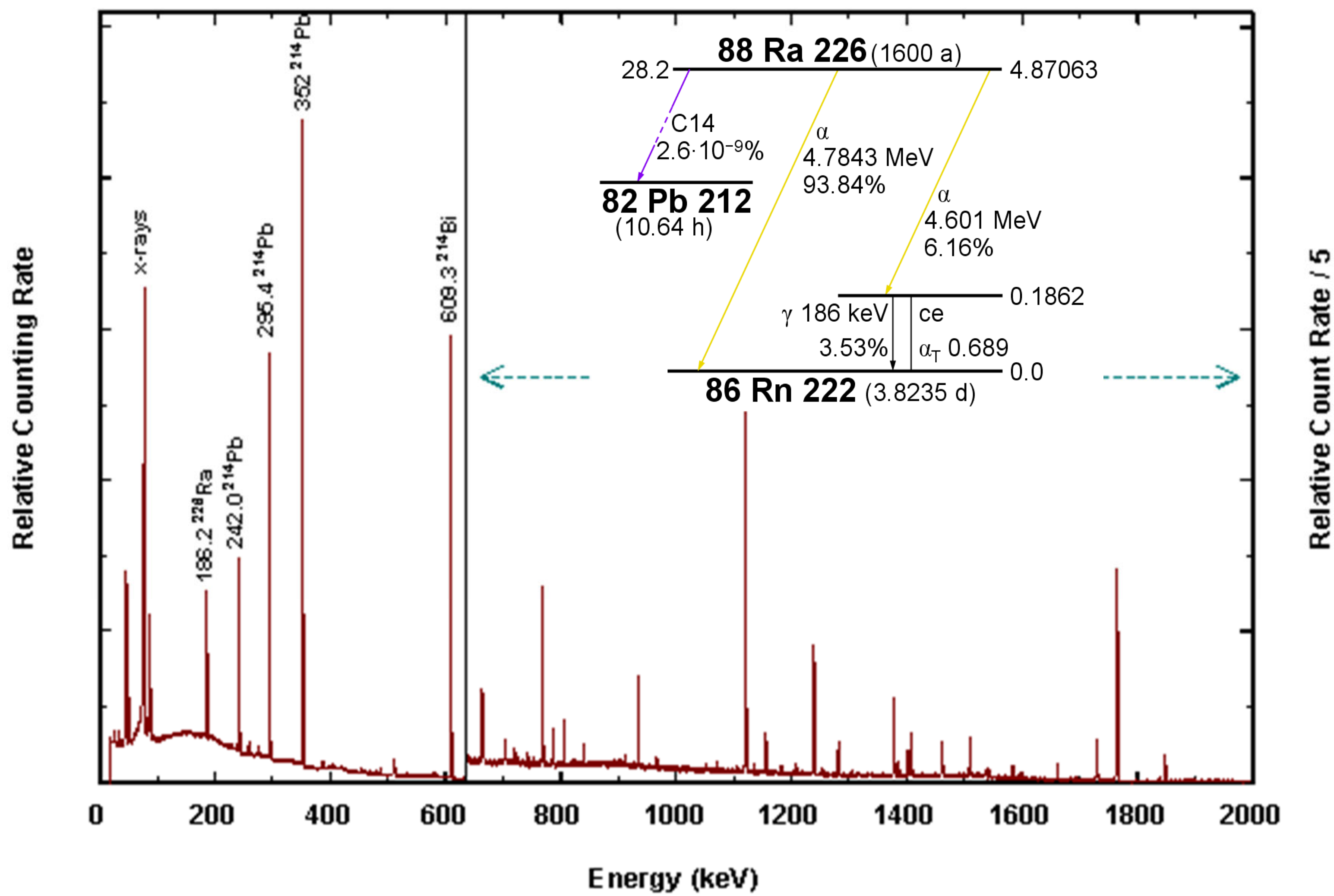
A typical neutron energy spectrum from an ^{239}Pu/Be source.



- The various peak and valley are due to the distinct excited states of the ^{12}C product nucleus.
- The continuum is the result of variable energy possessed by the alpha particles before reaction.

Page 19-27, Radiation Detection and Measurements, Third Edition, G. F. Knoll, John Wiley & Sons, 1999.

Neutron Sources – Radioisotope (α,n) Sources



Radium-226 gamma ray spectrum from high purity germanium (HPGe) detector

Neutron Sources – Radioisotope (α,n) Sources

Practical considerations for choosing appropriate α emitter.

- Radioisotope (α,n) sources are normally associated with other significant background radiations, especially when ^{226}Ra and ^{227}Ac are used.
- Choice has to be made between specific activity of the alpha emitter (and therefore neutron yield), source life-time and the availability of the isotope.

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Neutron Sources – Photon-Neutron Sources

- Some radioisotope gamma ray emitters can also be used to produce neutrons when combined with an appropriate target material.

$$^{9}_{4}Be + h\nu \Rightarrow ^{8}_{4}Be + ^{1}_{0}n, \quad Q-value: -1.666 MeV$$
$$^{2}_{1}H + h\nu \Rightarrow ^{1}_{1}H + ^{1}_{0}n, \quad Q-value: -2.226 MeV$$

- A gamma ray photon with an energy greater than the negative of the Q -value is required.

- Some practical gamma ray emitter include: ^{226}Ra, ^{124}Sb, ^{72}Ga, ^{140}La and ^{24}Na.

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Neutron Sources – Photo-neutron Sources

If the gamma rays are monoenergetic, the neutrons are also nearly monoenergetic!

$$E_n(\theta) \cong \frac{M(E_\gamma + Q)}{m+M} + \frac{E_\gamma[(2mM)(m+M)(E_\gamma+Q)]^{1/2}}{(m+M)^2}\cos(\theta)$$

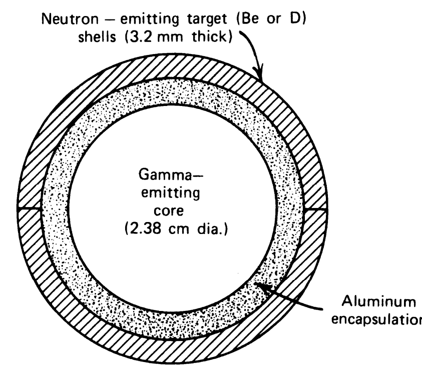
where

θ = angle between gamma photon and neutron direction

E_γ = gamma energy

M = mass of recoil nucleus $\times c^2$

m = mass of neutron $\times c^2$



Typical structure of photon neutron sources

The neutron energy is blurred by

- The slight angular dependency.
- Neutron scattering inside the source.

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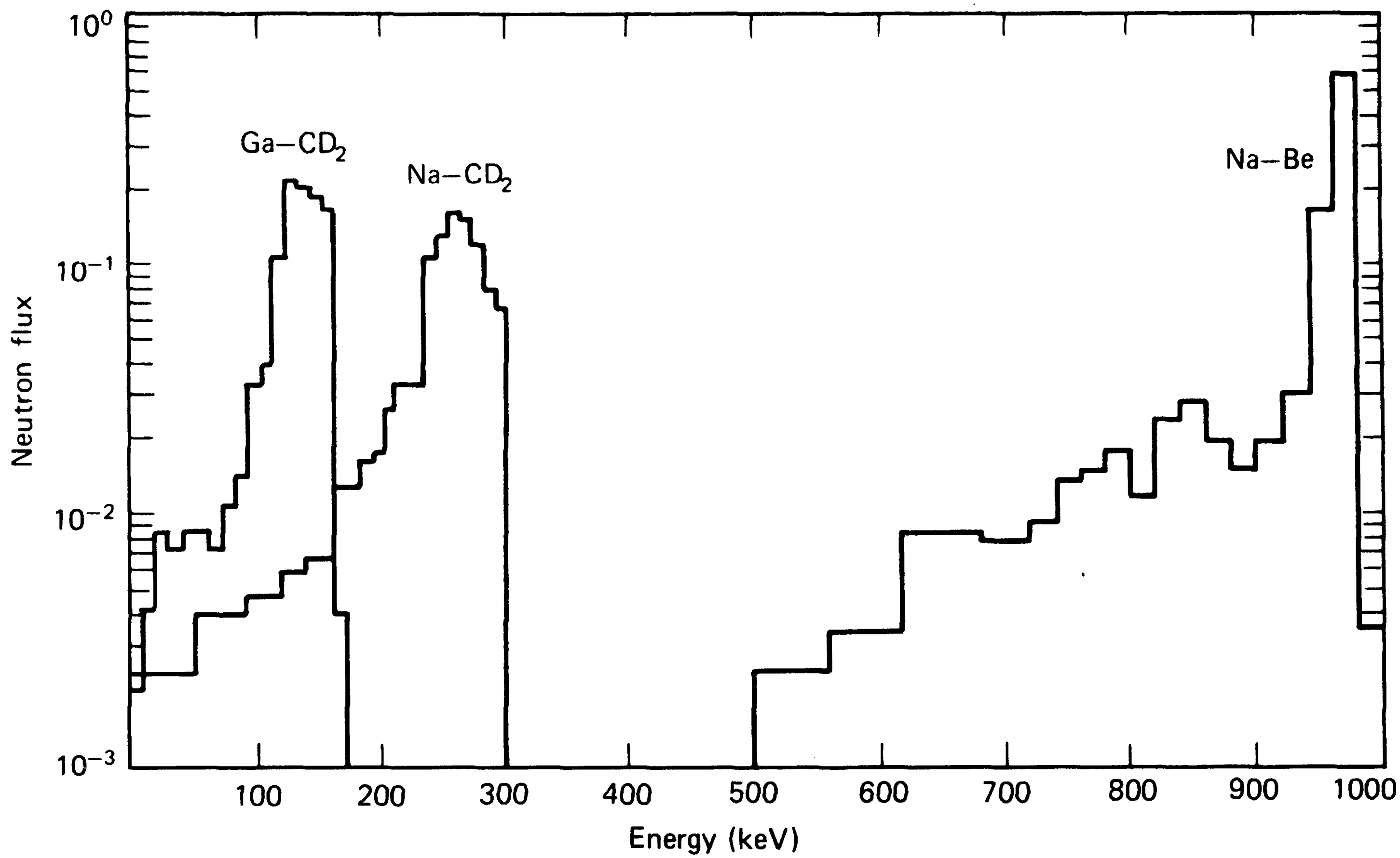
Neutron Sources – Photo-neutron Sources



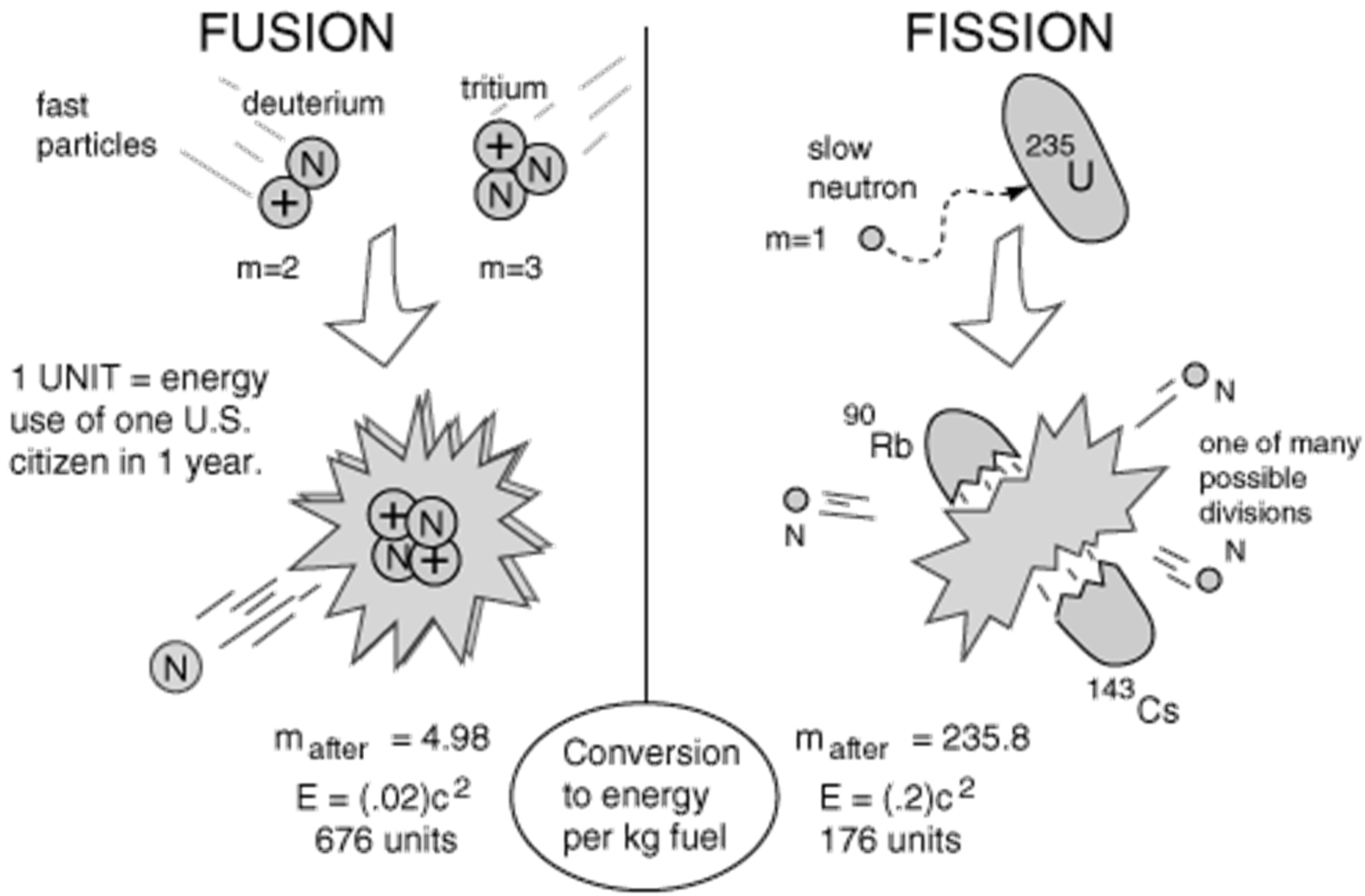
Calculated neutron energy spectra

TABLE 7.2 **SOURCES OF NEUTRONS** (From ICRU 26, 1977)

Source	Reaction	Half Life	Average Neutron Energy (MeV)	Yield n/s/Ci	Characte[r] Problems
Mock Fission (Po+Be+B+Li+F)	α,n	134.4 d	Fission spectrum	4×10^5	α
^{24}Na + Be	γ,n	15 h	0.83	1.3×10^5	γ
^{24}Na + D_2O	γ,n	15 h	0.22	2.7×10^5	γ
^{56}Mn + Be	γ,n	2.58 h	0.1 (90%) 0.3 (10%)	2.9×10^4	γ
^{56}Mn + D_2O	γ,n	2.58 h	0.22	3.1×10^3	γ
^{72}Ga + Be	γ,n	14.1 h	0.78	5×10^4	γ
^{72}Ga + D_2O	γ,n	14.1 h	0.13	6×10^4	γ
^{88}Y + Be	γ,n	107 d	0.16	1×10^5	γ
^{88}Y + D	γ,n	107 d	0.31	3×10^3	γ
^{116}In + Be	γ,n	14 s	0.30	8.2×10^3	γ
^{124}Sb + Be[b]	γ,n	60.2 d	0.024	1.9×10^5	γ
^{140}La + Be	γ,n	40.3 h	0.62	3×10^3	γ
^{140}La + D_2O	γ,n	40.3 h	0.15	8×10^3	γ
^{228}Ra + Be	γ,n	5.75 y	0.83	3.5×10^4	γ
^{228}Ra + D_2O	γ,n	5.75 y	0.20	9.5×10^4	γ
^{226}Ra + Be	α,n	1600 y	Spectrum	3.0×10^4	α, γ, Rn
^{226}Ra + Be	α,n	1600 y	5.0	1.7×10^7	α, γ, Rn
^{226}Ra + B	γ,n	1600 y	3.0	6.8×10^6	α, γ, Rn
^{226}Ra + D_2O	α,n	1600 y	0.12	1×10^3	α, γ, Rn
^{222}Rn + Be	α,n	3.82 d	5	1.5×10^7	α, γ, Rn
^{210}Po + Be	α,n	134.4 d	4	3×10^6	α
^{210}Po + B	α,n	134.4 d	2.5	9×10^5	α
^{210}Po + F	α,n	134.4 d	1.4	4×10^5	α
^{210}Po + Li	α,n	134.4 d	0.42	9×10^4	α
^{227}Ac + Be	α,n	21.8 y	—	—	α
^{238}Pu + Be	α,n	87.7 y	4.5	2.3×10^6	α
^{239}Pu + Be	α,n	2.41×10^4 y	4 (3.2)	1.7×10^6	α
^{241}Am + Be	α,n	432 y	4.5	2.2×10^6	α
^{241}Am + Li	α,n	432 y	0.54	6.0×10^4	α
^{239}Pu (WG)[c]	Spon. Fission	2.41×10^4 y	1.94	63.6	α
^{252}Cf	Spon. Fission	2.64 y	Fission spectrum[a] (2.35)	10^6	α

[a]3.80 ± 0.035 neutrons per fission.
[b]Typically used in reactors – inserted as ^{123}Sb and resultant activation to ^{124}Sb occurs.
[c]WG = Weapons grade, >93% Pu-239.

Average Binding Energy Per Nucleon Comparing Fusion and Fission Reactions



http://230nsc1.phy-astr.gsu.edu/hbase/hframe.html

Neutrons Generated by Accelerated Charged Particles

Neutrons Generated by Accelerated Charged Particles

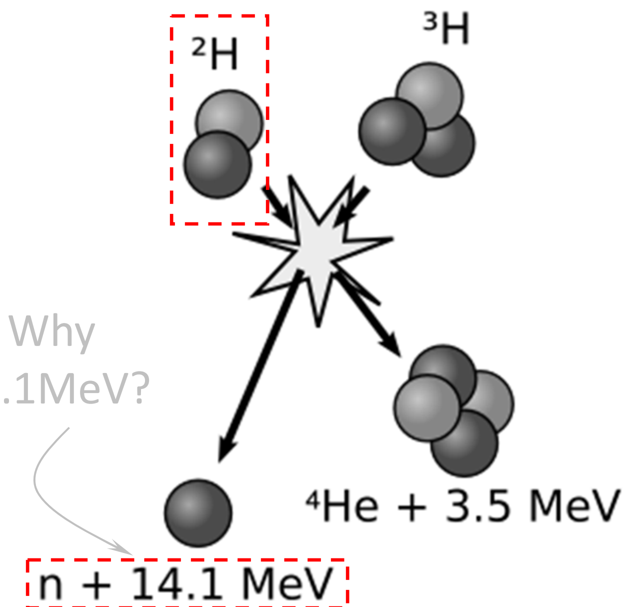
- Neutrons can be produced by nuclear reaction between accelerated charged particles.

The D-D reaction: ${}^{2}_{1}H + {}^{2}_{1}H \Rightarrow {}^{3}_{2}He + {}^{1}_{0}n,$ Q-value: 3.26MeV, En=2.5MeV

The D-T reaction: ${}^{2}_{1}H + {}^{3}_{1}H \Rightarrow {}^{4}_{2}He + {}^{1}_{0}n,$ Q-value: 17.6MeV, En=14.1MeV

Why accelerated?

Why 14.1MeV?



- Due to the Coulomb barrier between the incident deuteron and the light target nucleus, a relatively small accelerating potential is required (about 100 to 300kV) to induce the reaction.

- The neutrons produced by a given nuclear reaction (D-D or D-T) have roughly the same energies.

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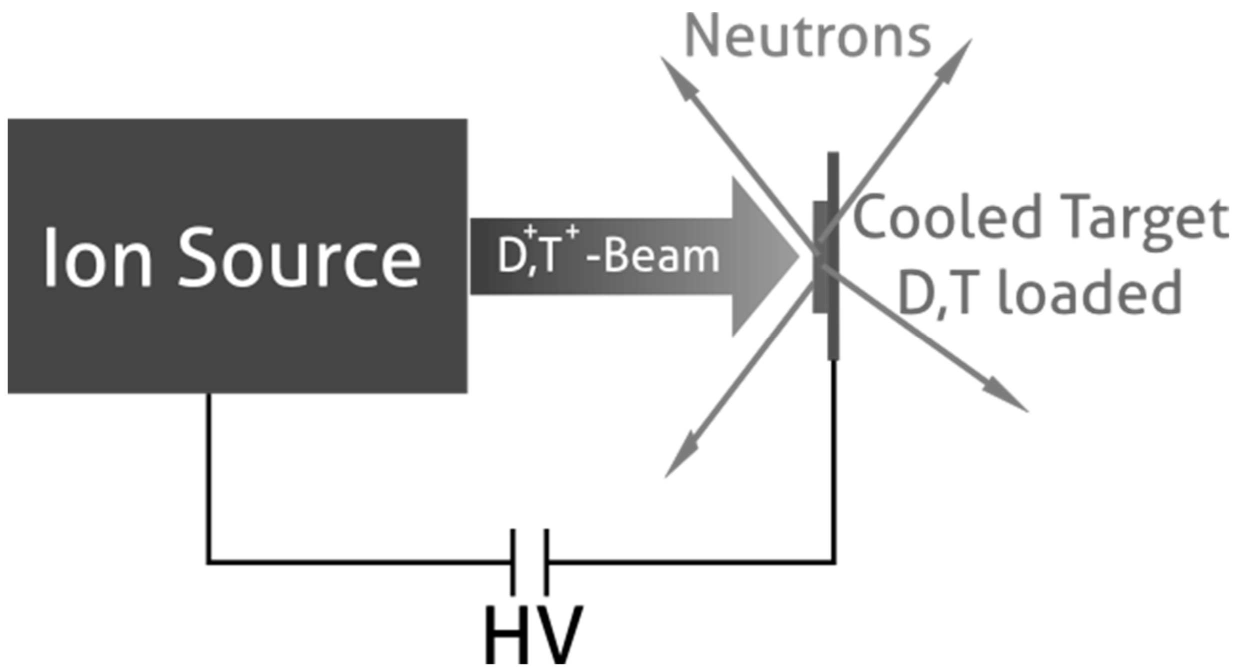
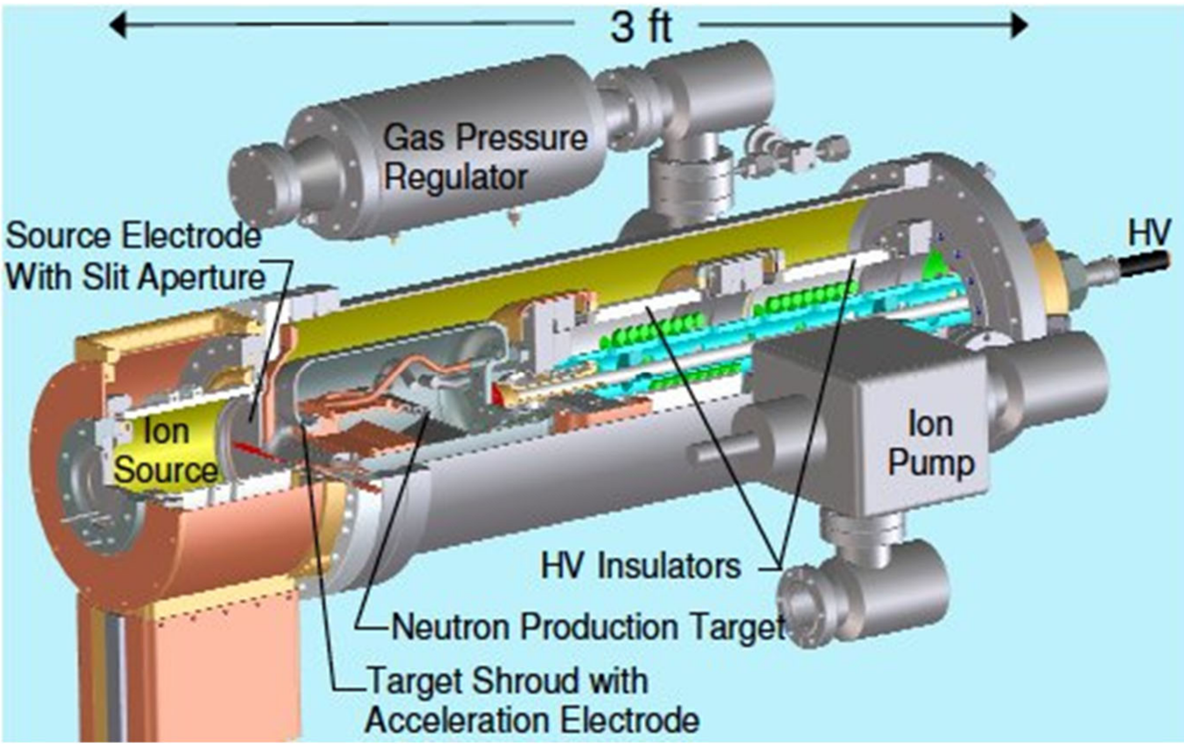
Neutrons Generated by Accelerated Charged Particles



A schematic of a neutron generator. On the left hand side is an ion source from which a Hydrogen isotope ion beam is extracted. This beam is accelerated with a high voltage towards a target on the right hand side, loaded with Deuterium and Tritium, to produce neutrons in a nuclear fusion process.

http://ibt.lbl.gov/neutrongamma.html

A Typical D-T Neutron Generator

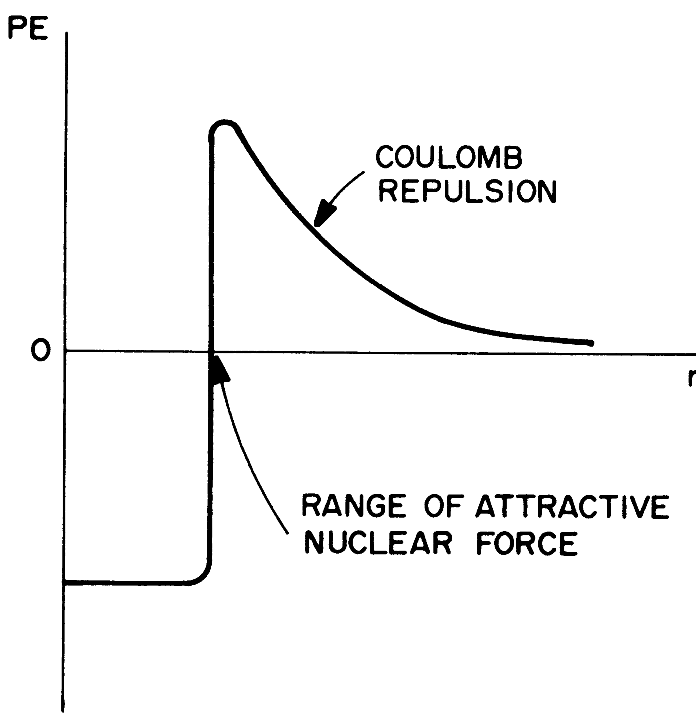


This compact and simple device can generate 5e11 neutrons per second by accelerating deuterium or tritium (depending on the desired neutron spectrum) into a deuterated or tritiated neutron production target.

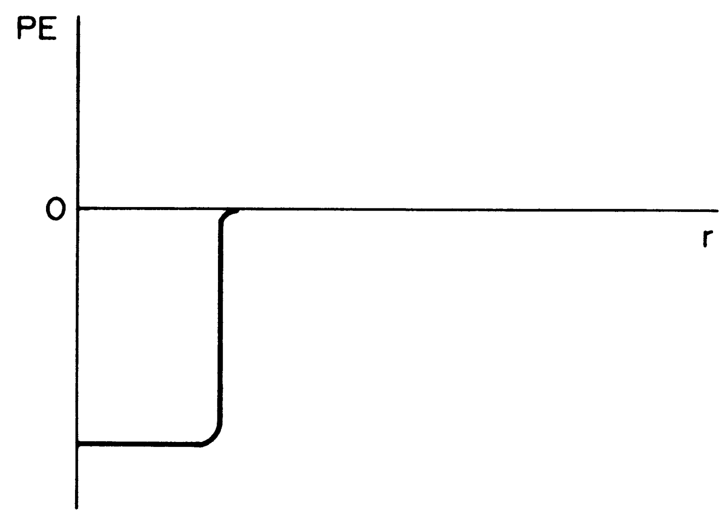
http://ibt.lbl.gov/neutrongamma.html

Coulomb Barrier

- Nucleons are bounded together in nucleus by the strong force, which has a short range of ~10^{-15}m.
- The strong force is powerful enough to overcome the Coulomb repulsion between the positively charged protons.



(a) PROTON - NUCLEUS



(b) NEUTRON - NUCLEUS

Neutrons Generated by Accelerated Charged Particles

TABLE 9.1. Reactions Used to Produce Monoenergetic Neutrons with Accelerated Protons (p) and Deuterons (d)

Reaction	Q Value (MeV)
$^{3}H(d,n)^{4}He$	17.6
$^{2}H(d,n)^{3}He$	3.27
$^{12}C(d,n)^{13}N$	−0.281
$^{3}H(p,n)^{3}He$	−0.764
$^{7}Li(p,n)^{7}Be$	−1.65

James Tuner, Atoms, radiation and Radiation Protection, p210-p211.

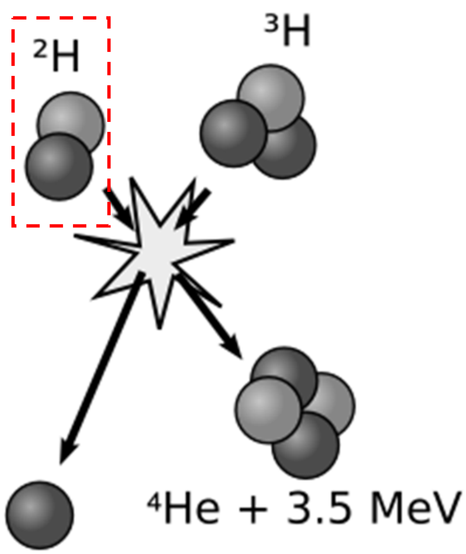
Neutrons Generated by Accelerated Charged Particles

- Neutrons can be produced by nuclear reaction between accelerated charged particles.

The D-D reaction: ${}^{2}_{1}H + {}^{2}_{1}H \Rightarrow {}^{3}_{2}He + {}^{1}_{0}n$, Q-value: 3.26MeV, En=2.5MeV

The D-T reaction: ${}^{2}_{1}H + {}^{3}_{1}H \Rightarrow {}^{4}_{2}He + {}^{1}_{0}n$, Q-value: 17.6MeV, En=14.1MeV

Why accelerated?



- Due to the coulomb barrier between the incident deuteron and the light target nucleus, only a relatively small accelerating potential is required (about 100 to 300kV) to induce the reaction.

- The neutrons produced by a given nuclear reaction (D-D or D-T) have roughly the same energies.

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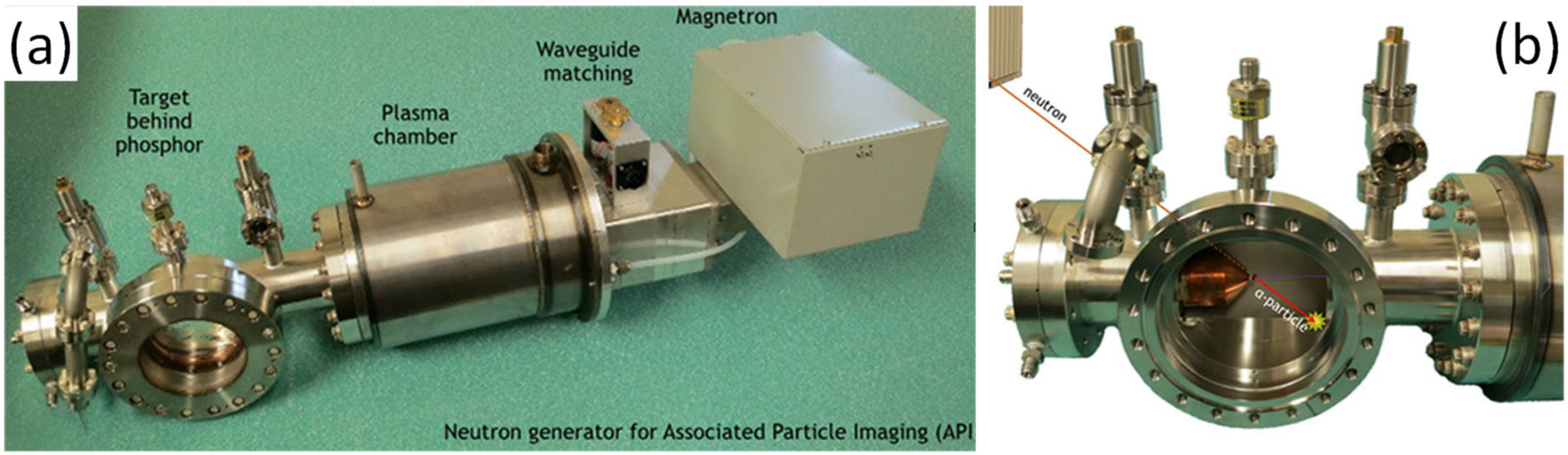
NDE of Potential Misloading with Time-Tagged Neutron Interrogation Techniques (Technical Approach)



(a) The commercial associate particle neutron generator (DT108API) from Adelphi Technology. (b) The internal assembly of the anode and the alpha-detector inside the APNG. Both images from [23].

$$D(p,n) + T(p,2n) \rightarrow \alpha(2p,2n) + n.$$

Large Sized Neutron Sources

Nuclear fission reactors

Nuclear fission which takes place within in a reactor produces very large quantities of neutrons and can be used for a variety of purposes including power generation and experiments.

Nuclear fusion systems

Nuclear fusion, the combining of the heavy isotopes of hydrogen, also has the potential to produces large quantities of neutrons. Small scale fusion systems exist for research purposes at many universities and laboratories around the world. A small number of large scale nuclear fusion systems also exist including the National Ignition Facility in the USA, JET in the UK, and soon the recently started ITER experiment in France.

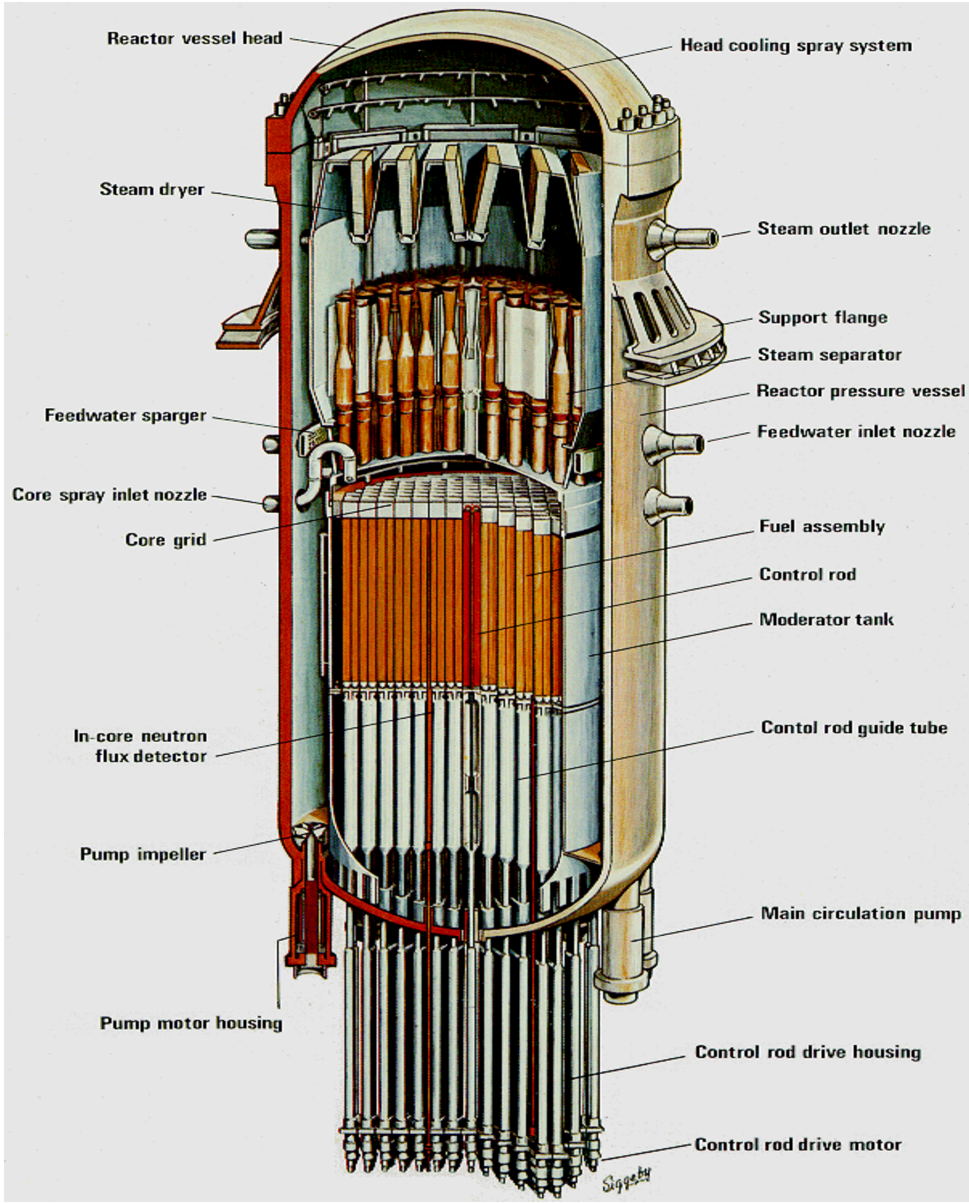
High energy particle accelerators

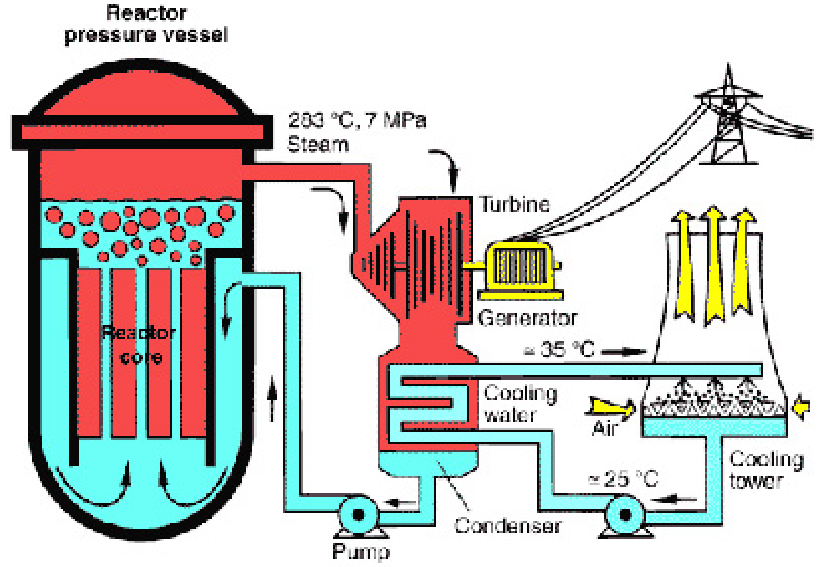
A spallation source is a high-flux source in which protons that have been accelerated to high energies hit a target material, prompting the emission of neutrons.

James Tuner, Atoms, radiation and Radiation Protection, p210-p211.

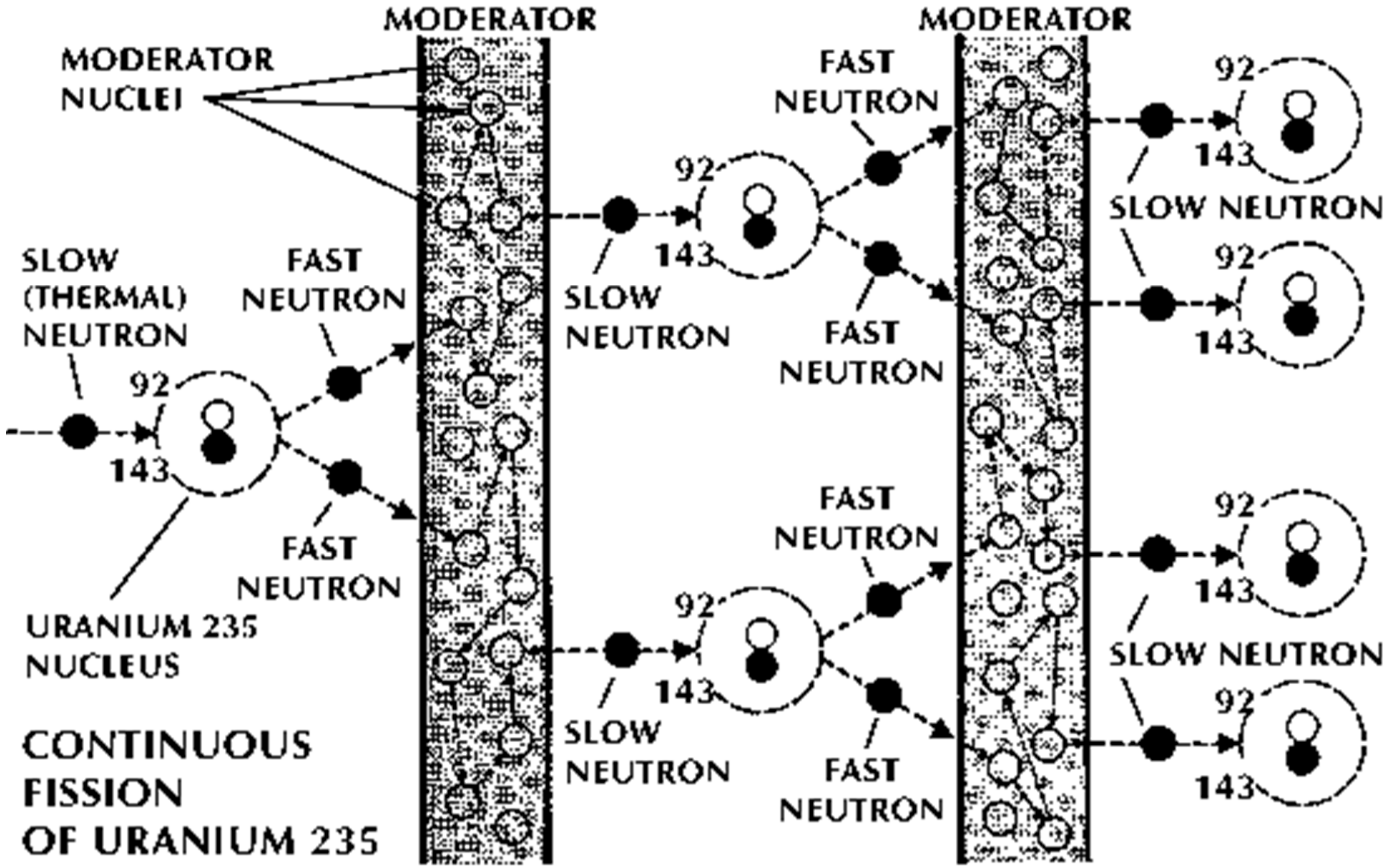
Nuclear Reactor

Inside a Nuclear Reactor

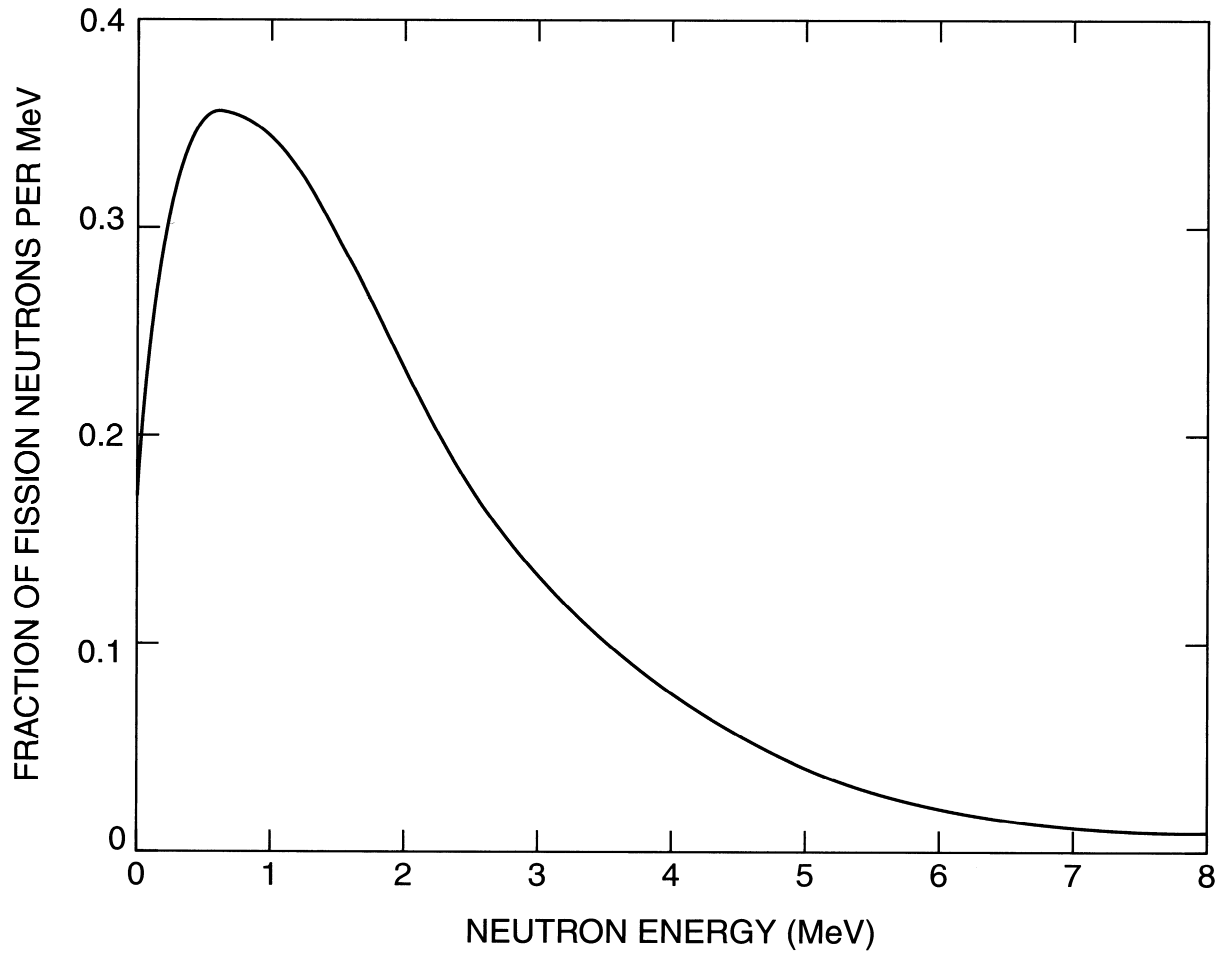




Nuclear Fission from Slow Neutrons and Water Moderator



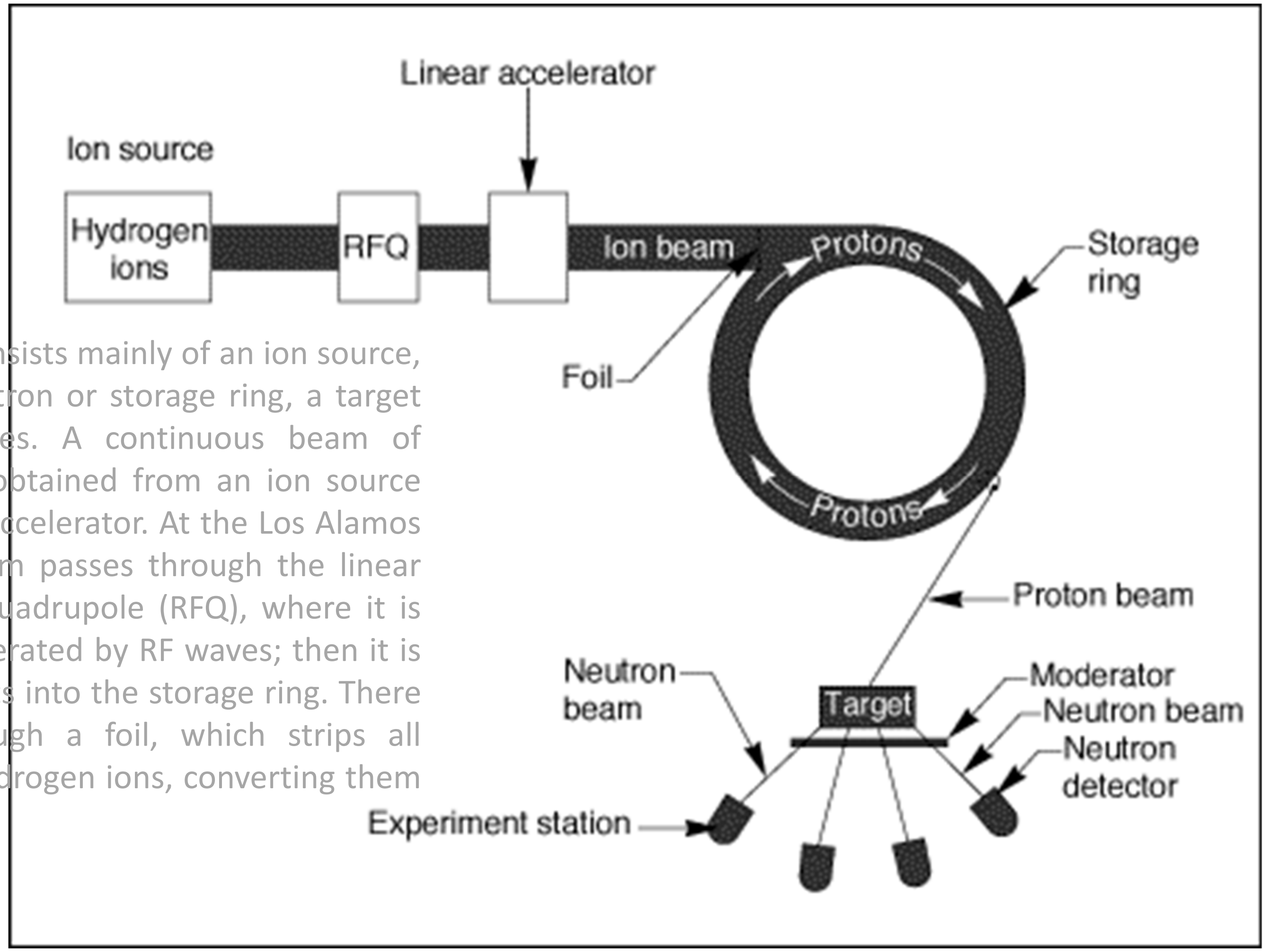
Nuclear Fission from Slow Neutrons and Water Moderator



IGURE 7.3 ◈ Prompt Neutron Energy Spectrum for Thermal Fission of U-235.
rom DOE-HDBK-1019/1-93)

Spallation Neutron Sources

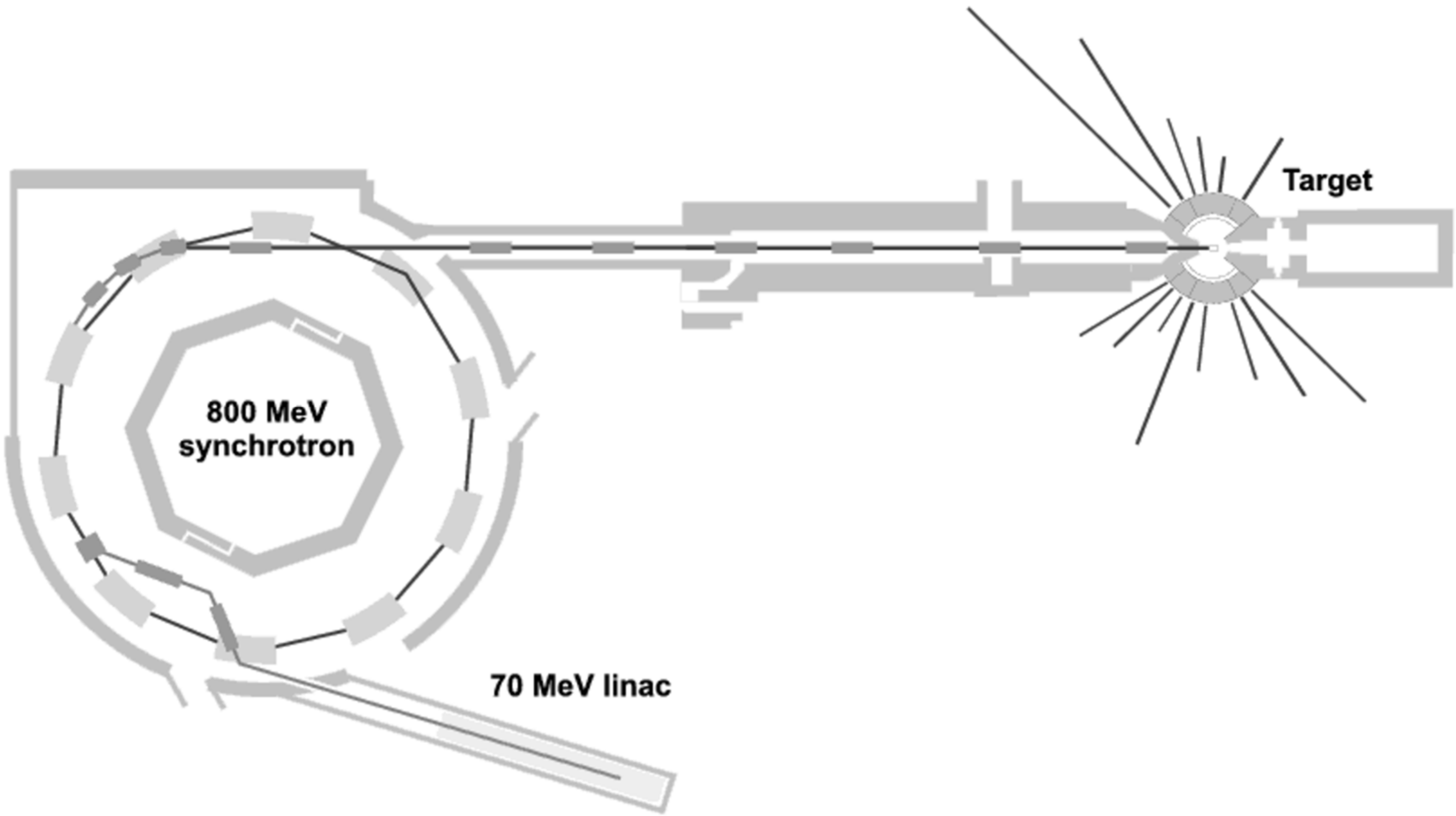
Spallation Neutron Sources



A spallation neutron source consists mainly of an ion source, a linear accelerator, a synchrotron or storage ring, a target area, and neutron beam lines. A continuous beam of negative ions of hydrogen is obtained from an ion source and accelerated by the linear accelerator. At the Los Alamos spallation source, the ion beam passes through the linear accelerator's radiofrequency quadrupole (RFQ), where it is bunched into pulses and accelerated by RF waves; then it is focused by quadrupole magnets into the storage ring. There the negative ions pass through a foil, which strips all electrons from the negative hydrogen ions, converting them into positive ions, or protons.

http://web.ornl.gov/info/ornlreview/rev28-1/text/rnd.htm

Spallation Neutron Sources



A schematic diagram of a pulsed source (based on ISIS, UK)