Neutron Sources

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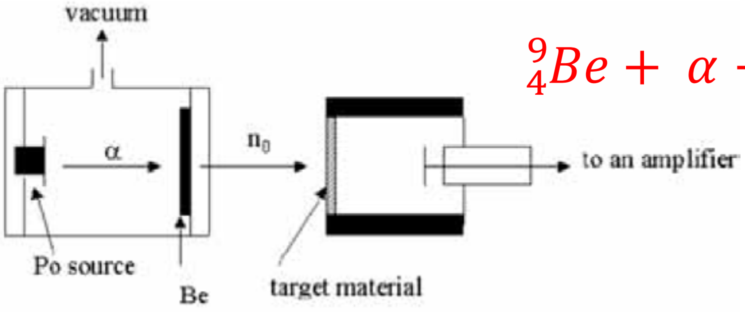
Neutrons: discovery

- In 1920, Rutherford postulated that there were neutral, massive particles in the nucleus of atoms. James Chadwick (Nobel prize in physics in 1935), a colleague of Rutherford, discovered the neutron in 1932.
- Chadwick bombarded a beryllium target with alpha particles producing neutrons that recoiled into a block of paraffin. The produced neutrons were detected when they knocked protons of paraffin wax. By measuring protons emerging from the paraffin with a Geiger counter, Chadwick inferred that the neutron had a mass comparable to that of the proton.



$$ {}_{4}^{9}Be + \alpha \rightarrow {}_{6}^{12}C + n $$

Chadwick's apparatus: 1st neutron generator

Basic properties of neutrons
Rest mass = 1.675×10^{-27} kg = 939.55 MeV/c^2 Electrical charge = Zero Mean life = 14.76 min

$$ \mathrm{n} \xrightarrow{t_{1/2}=611\ \mathrm{s}} \mathrm{e}^- + \mathrm{p} + \bar{\nu}_e + 782\ \mathrm{keV} $$

Key properties of neutrons

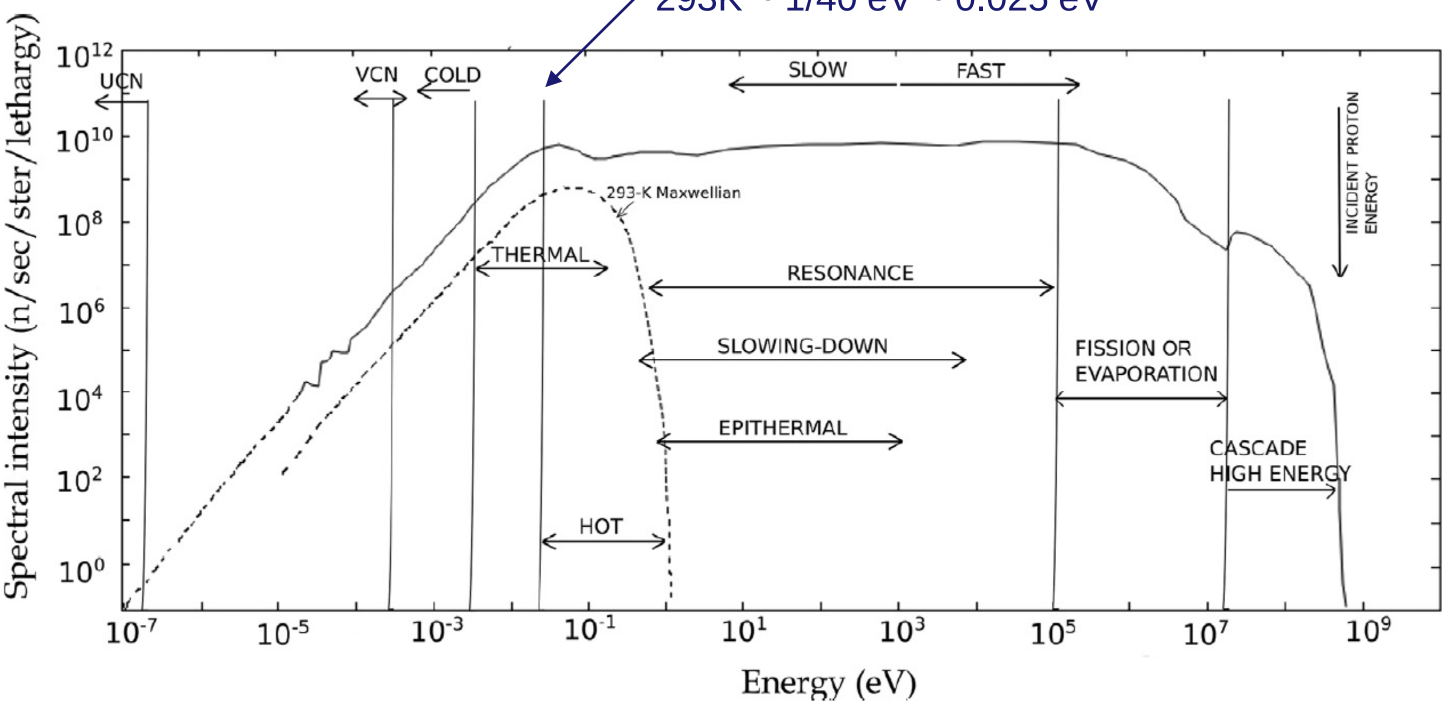
- The mass of the neutron is 939.565 MeV/c^2
- Neutrons are ½ spin particles – fermionic statistics
- Neutrons are neutral particles – no net electric charge.
- Neutrons have non-zero magnetic moment.
- Free neutrons (outside a nucleus) are unstable and decay via beta decay. The decay of the neutron involves the weak interaction and is associated with a quark transformation (a down quark is converted to an up quark).
- Mean lifetime of a free neutron is 882 seconds (i.e. half-life is 611 seconds).
- A natural neutron background of free neutrons exists everywhere on Earth and it is caused by muons produced in the atmosphere, where high energy cosmic rays collide with particles of Earth's atmosphere.
- Neutrons cannot directly cause ionization. Neutrons ionize matter only indirectly.
- Neutrons can travel hundreds of feet in air without any interaction. Neutron radiation is highly penetrating.
- Thermal or cold neutrons have the wavelengths similar to atomic spacings. They can be used in neutron diffraction experiments to determine the atomic and/or magnetic structure of a material.

Classification of free neutrons according to kinetic energies

Neutron categories according to energy distribution

Slow neutrons: $E < 1000$ eV Thermal neutrons: 0.005 eV $< E < 0.5$ eV		Fast neutrons: $E > 1000$ eV Epithermal neutrons: 0.05 eV $< E < 1000$ eV
Cold neutrons: $E < 0.005$ eV	Very cold neutrons: $\sim 8\ \mu$eV $< E < 800\ \mu$eV	Ultracold neutrons: $E < 8\ \mu$eV

293K ~ 1/40 eV ~ 0.025 eV



The expected neutron spectrum emitted from a 100 K liquid methane moderator of the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (ANL)

Small neutron sources

- **Radioisotopes which undergo spontaneous fission**: Certain isotopes undergo spontaneous fission with emission of neutrons. The most commonly used spontaneous fission source is the radioactive isotope californium-252. When purchased new a typical Cf-252 neutron source emits between 1×10^7 to 1×10^9 neutrons per second but, with a half life of 2.6 years. The price of a typical Cf-252 neutron source is from $15,000 to $20,000.

- **Radioisotopes which decay with alpha particles packed in a low-Z elemental matrix**: Neutrons are produced when alpha particles impinge upon any of several low-atomic-weight isotopes including isotopes of beryllium, carbon, and oxygen. This nuclear reaction can be used to construct a neutron source by mixing a radioisotope that emits alpha particles such as radium, polonium, or americium with a low-atomic-weight isotope, usually by blending powders of the two materials. Typical emission rates for alpha reaction neutron sources range from 1×10^6 to 1×10^8 neutrons per second. The size and cost of these neutron sources are comparable to spontaneous fission sources. Usual combinations of materials are plutonium-beryllium (PuBe), americium-beryllium (AmBe), or americium-lithium (AmLi).

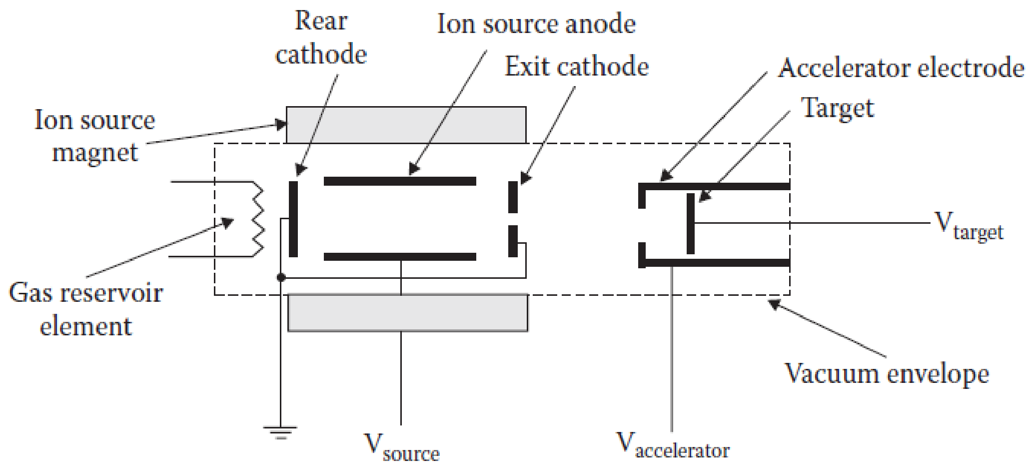
Small neutron sources

- **Radioisotopes which decay with high-energy photons co-located with beryllium or deuterium**: Gamma radiation with an energy exceeding the neutron binding energy of a nucleus can eject a neutron (a photoneutron). Two example reactions are:

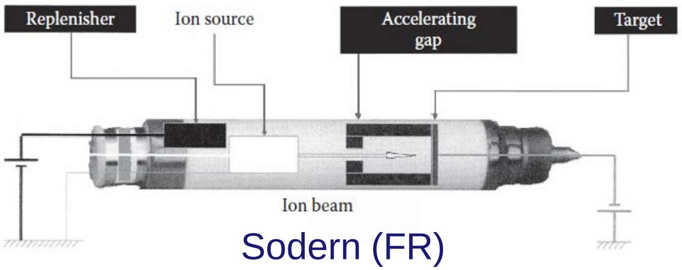
  ^{9}Be + >1.7 Mev photon → 1 neutron + 2 ^{4}He

  ^{2}H + >2.26 MeV photon → 1 neutron + ^{1}H

- **Sealed-tube neutron generators**: Some accelerator-based neutron generators induce fusion between beams of deuterium and/or tritium ions and metal hydride targets which also contain these isotopes.



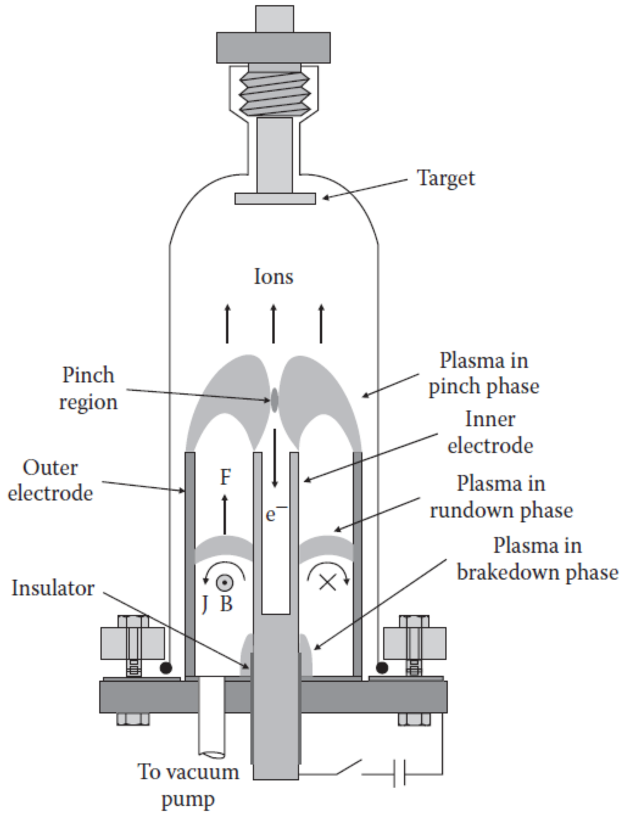
VNIIA (RF)

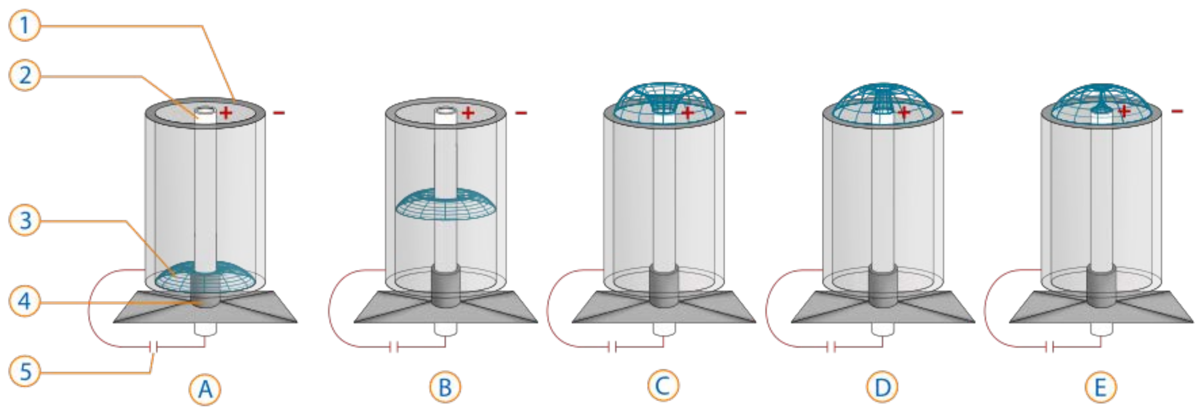


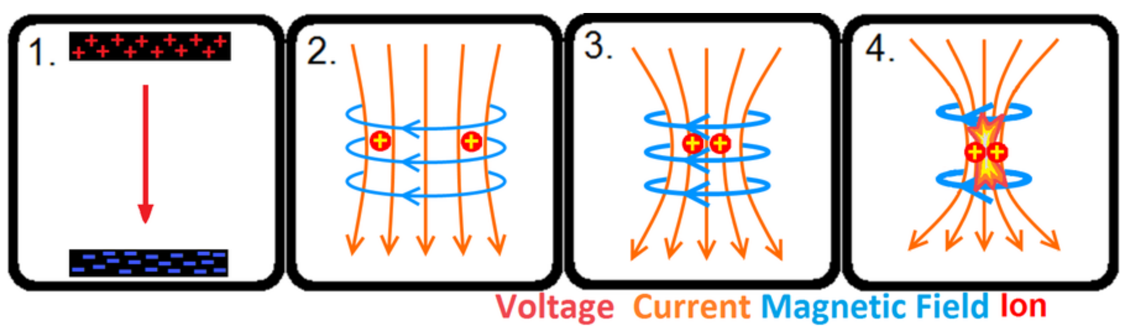
Sodern (FR)

Medium-sized neutron sources

- **Plasma focus and plasma pinch devices**: The dense plasma focus neutron source produces controlled nuclear fusion by creating a dense plasma within which heats ionized D and/or T gas to temperatures sufficient for creating fusion.

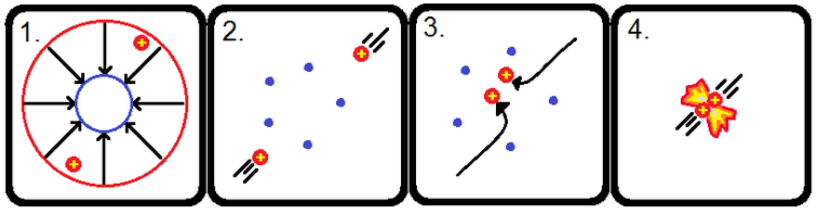


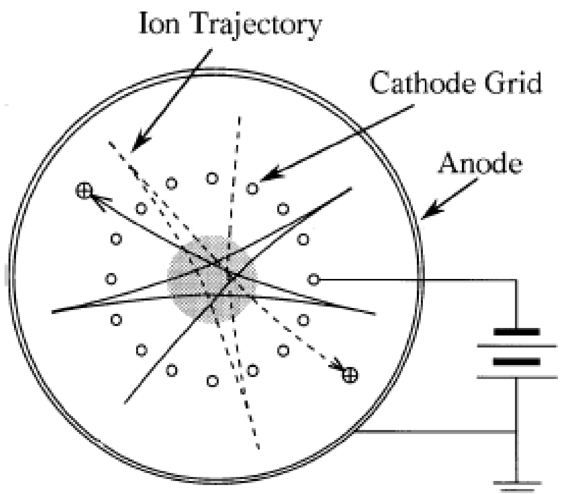


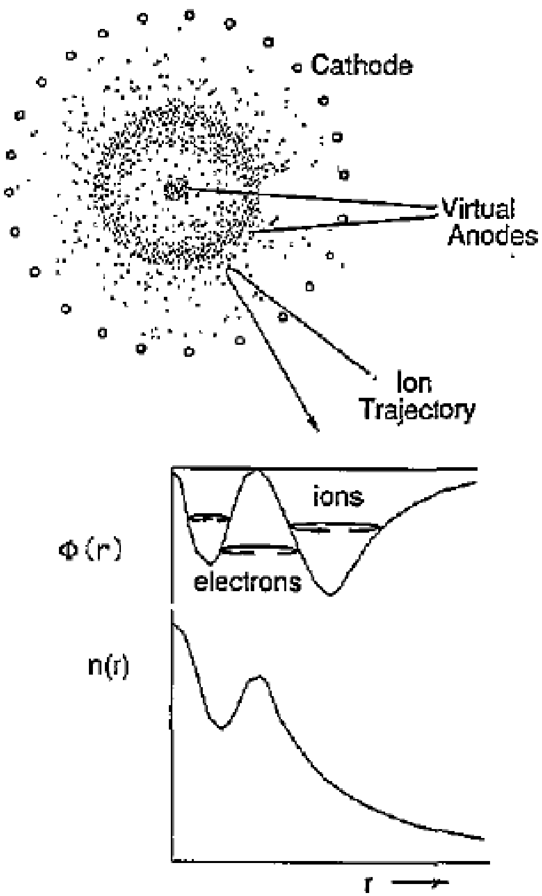


Medium-sized neutron sources

- **Inertial electrostatic confinement (IEC)**: Inertial electrostatic confinement devices such as the Farnsworth-Hirsch fusor use an electric field to heat a plasma to fusion conditions and produce neutrons. The ions are believed to be confined in the electrostatic potential well.

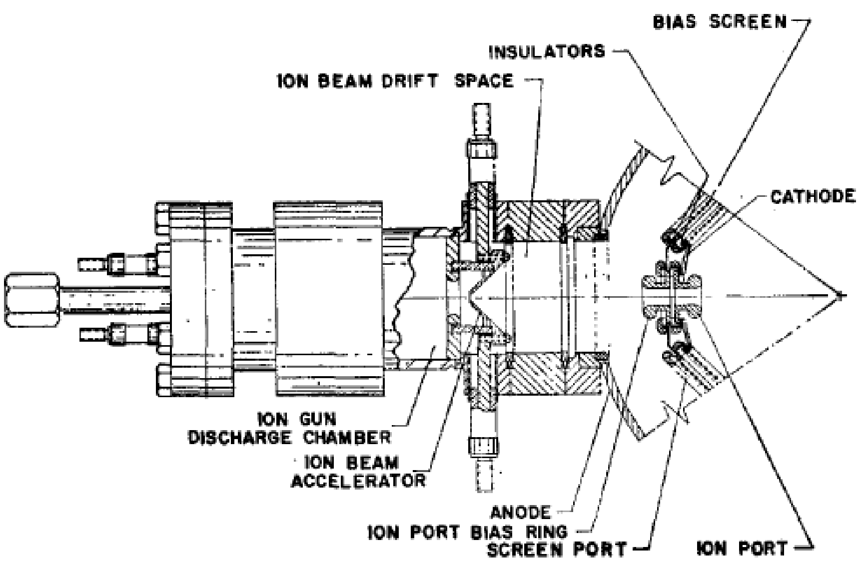


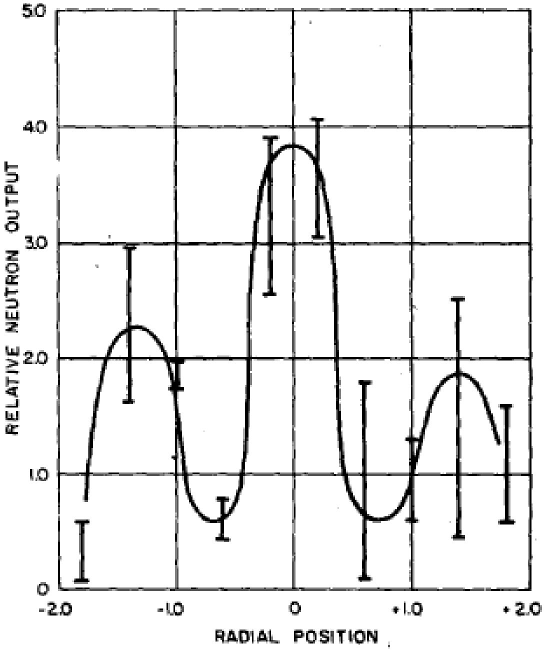




Medium-sized neutron sources

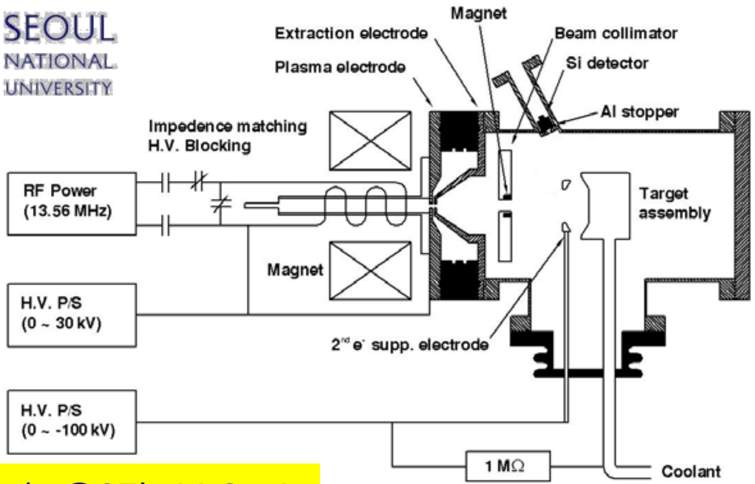
- **IEC: Hirsch's experiment (1967)**:
  - Achieved $3\text{x}10^9$ n/s for D-T (150 kV, 10 mA), $6\text{x}10^7$ n/s for D-D (150 kV, 10 mA)
  - The neutron rate decreased with increasing pressure
  - The neutron rate increased with beam energy
  - The neutron rate scaled linearly with injected ion current
  - Neutron collimation study / Gamma collimation study
  - Multiple potential well is hypothesized



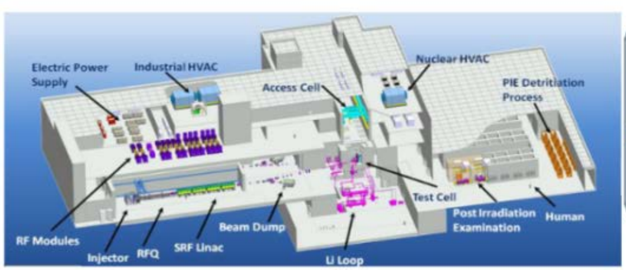


Medium-sized neutron sources

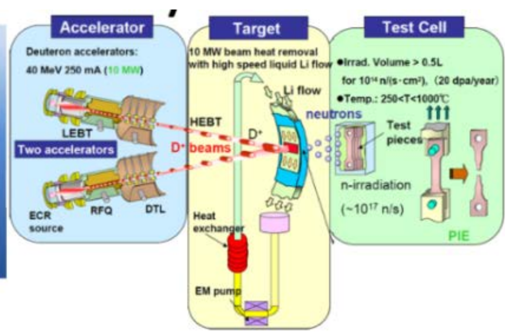
- **Light ion accelerators**: Traditional particle accelerators with hydrogen (H), deuterium (D), or tritium (T) ion sources may be used to produce neutrons using targets of deuterium, tritium, lithium, beryllium, and other low-Z materials.



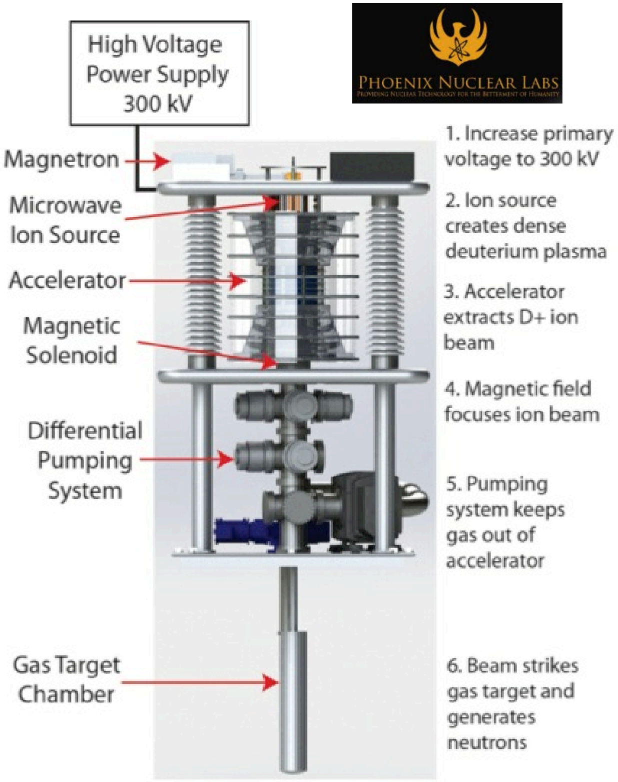
2x10^8 n/s @97keV, 8mA



IFMIF artist's view



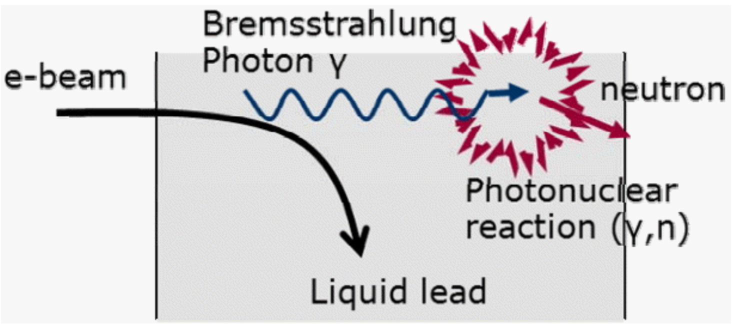
IFMIF utilizes liquid Li as a target

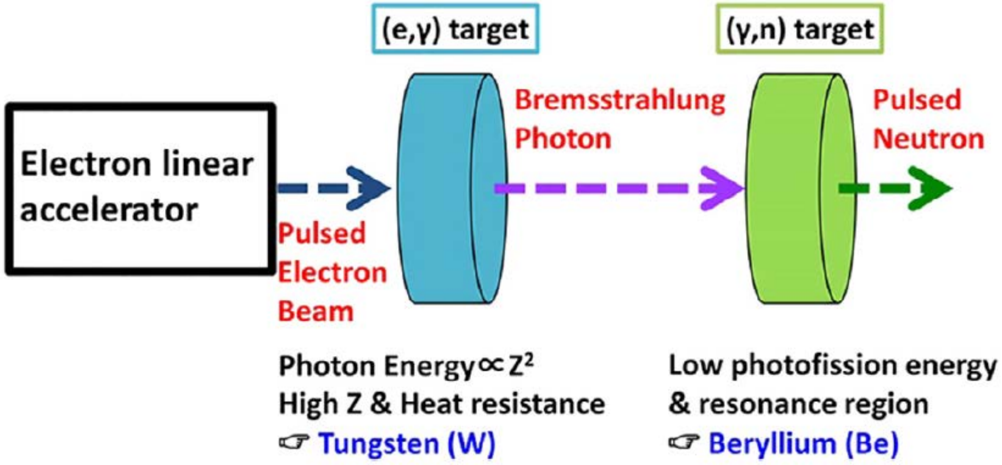


3x10^{11} n/s @300keV, 50mA

Medium-sized neutron sources

- **High-energy bremsstrahlung photoneutron/photofission systems**: Neutrons are produced when photons (>10 MeV) above the nuclear binding energy of a substance are incident on that substance, causing it to undergo giant dipole resonance after which it either emits a neutron (photoneutron) or undergoes fission (photofission).





Large 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. A small number of large scale nuclear fusion experiments also exist including the National Ignition Facility in the USA, JET in the UK, and soon the ITER experiment currently under construction in France. None are yet used as neutron sources. Inertial confinement fusion has the potential to produce orders of magnitude more neutrons than spallation.

- **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.

Nuclear fission

- Fission reactor sources rely on a neutron-propagated chain reaction in the fuel (usually ^{235}U). Power reactors are optimized for heat extraction and efficient use of fuel, so they have quite a different design from research reactors that are optimized for high (external) thermal neutron flux.

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow \mathrm{X} + \mathrm{Y} + 2.5\,\mathrm{n}\,,$$

$$(\sim 200\,\mathrm{MeV}\ \text{total energy release}, \sim 2\,\mathrm{MeV}\ \ \text{per neutron})$$

- In a typical research reactor design, one of the neutrons produced per fission is needed to sustain the chain reaction, ~0.5 is lost, and one is available for external use (i.e., ~200 MeV of heat is produced for each available neutron).

Table 2.1 Existing medium- and high-flux reactor sources and their respective parameters

Country	United States	United States	Canada	France	France	Germany	Germany	Australia	Korea	Japan
Neutron source	HFIR	NBSR	NRU	HFR	ORPHEE	BENSC	FRM-II	OPAL	HANARO	JRR-3 M
Organization	Oak Ridge National Laboratory	National Institute of Standards and Technology	Atomic Energy of Canada Limited	Institut Laue-Langevin	Laboratoire Léon Brillouin	Helmholtz-Zentrum Berlin	Technische Universitat Munchen	Australian Nuclear Science and Technology Organization	Korea Atomic Energy Research Institute	Japan Atomic Energy Agency
Power (MW)	85	20	120	58	14	10	20	20	24 (present) 30 (designed)	20
Flux ($\mathrm{n \cdot cm^{-2} \cdot s^{-1}}$)	1.5×10^{15}	3×10^{14}	3×10^{14}	1.5×10^{15}	3×10^{14}	2×10^{14}	8×10^{14}	3×10^{14}	2×10^{14}	3×10^{14}
Number of cold/hot sources	1/0	1/0	0/0	2/1	1/1	1/0	1/1	1/0	1(planned)/0	1/0
Number of instruments	9(present) + 6 (planned by 2012)	24	5	26	22	22	20 (present) + 10 (under construction)	6	6	24
Existing neutron imaging instrument		BT-2 [14]			[15]	CONRAD [16]	ANTARES [17]		NR-port [18]	TNRF [19] And TNRF-2 [20]
Facility operating since	1967	1970	1957	1972 (refurbished 1993)	1980	1973	2004	2006	1997	1990

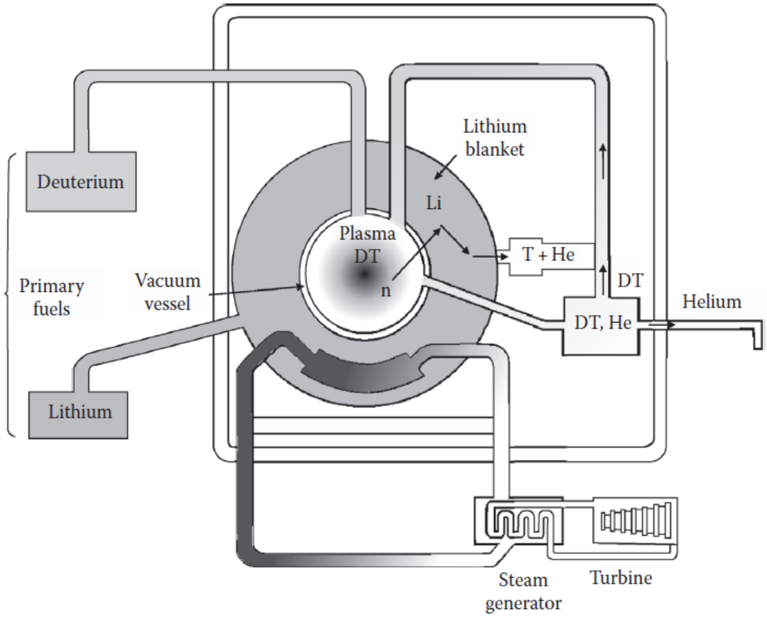
HFIR: High-Flux Isotope Reactor [21]; NBSR: National Bureau of Standards Reactor [22]; NRU: National Research Universal Reactor, Chalk River, Canada [23]; HFR: High-Flux Reactor at ILL [1, 2]; ORPHEE: reactor at LLB [24]; BENSC: Berlin Neutron Scattering Centre [25]; FRM-II: Forschungsneutronenquelle Heinz Maier-Leibnitz [5]; OPAL: Open Pool Australian Light-water Reactor [6]; HANARO: High-flux Advanced Application Reactor [4]; JRR-3 M: Japan Research Reactor No. 3 Modified [3]. Consult the web sites for these facilities to obtain additional information and current details. A number of smaller research reactors, primarily at universities, are not listed here.

Thermonuclear fusion

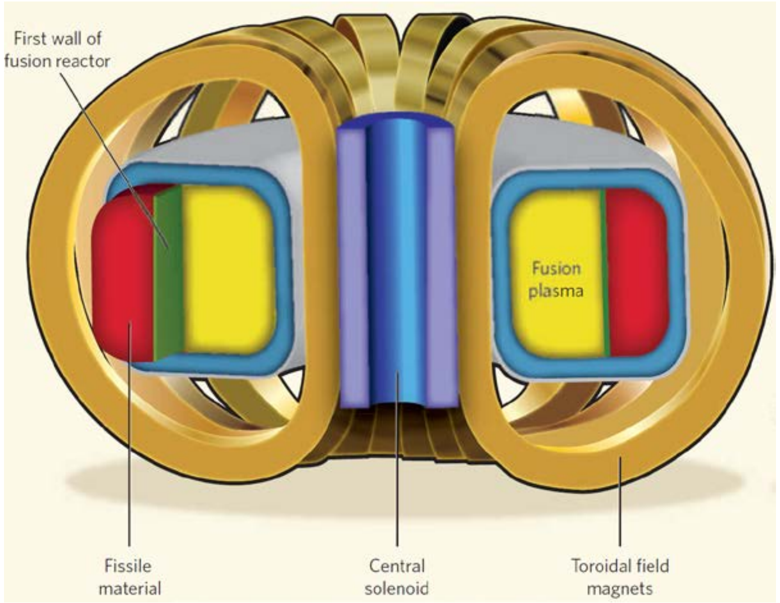
- A number of experiments around the world have verified the principles of d + t fusion; however, it still has to be demonstrated that a gain in energy can be achieved.

$$d + t \rightarrow \alpha\ (3.5\ \mathrm{MeV}) + n\ (14\ \mathrm{MeV}).$$

- In hybrid reactors, high-energy neutrons generated by fusion reactions drive fission in the surrounding blanket of fissile material, burning up long-lived radioactive by-products produced by the fission process.



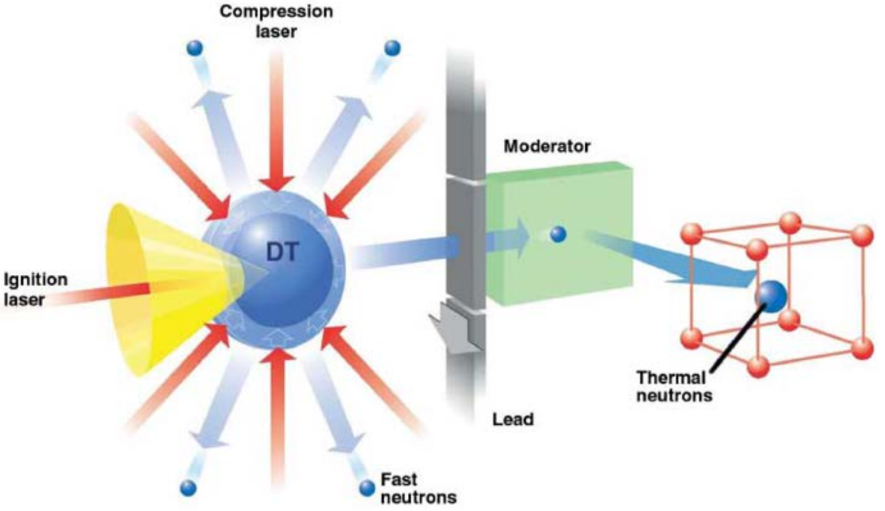
D-T fusion reactor

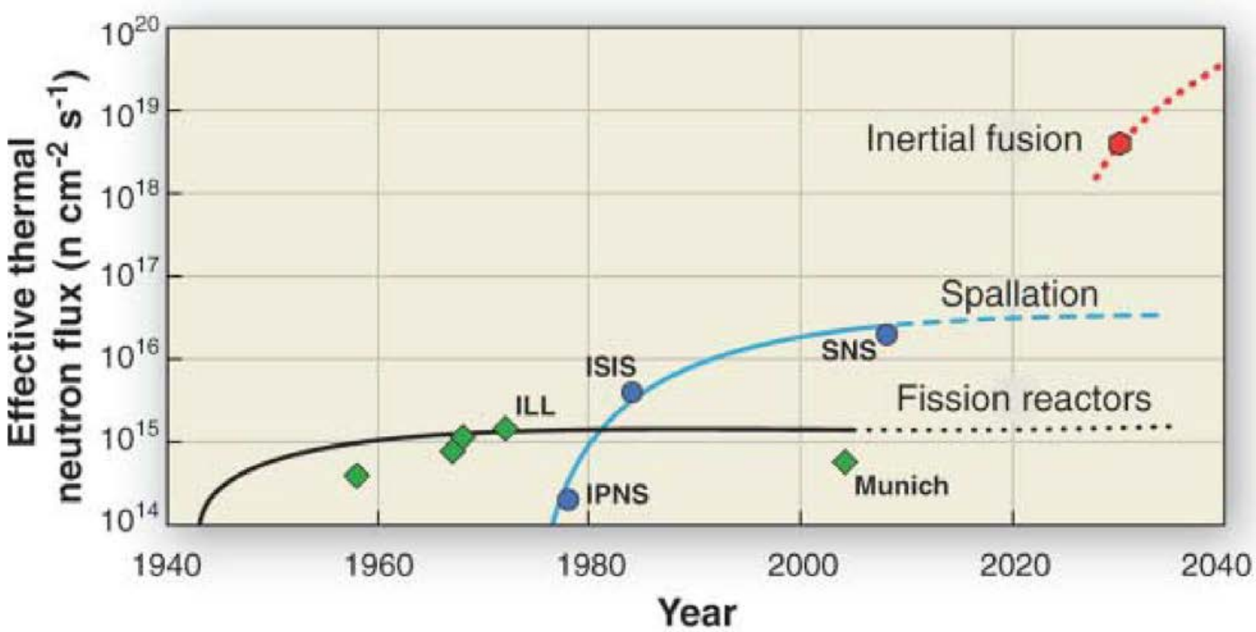


Fusion-fission hybrid reactor

Inertial confinement fusion

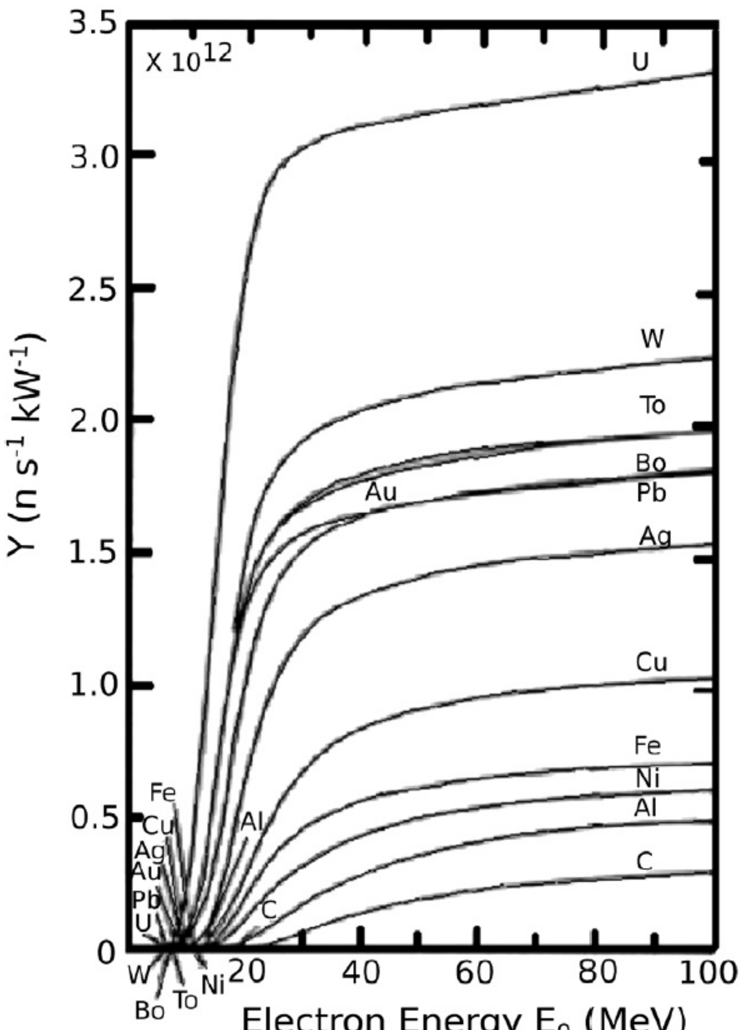
- Compression laser beams are focused on the millimeter-diameter Deuterium-Tritium capsule. The ignition short-pulse beam enters ~10 ns later via a gold cone through the compressed plasma.





Photoneutron by electron beam

- Energetic electrons striking high-mass targets slow down to emit bremsstrahlung (e,γ) photons. Photons proceed to interact with target nuclei to produce (γ,n) photoneutrons.
- Early work at accelerator-driven sources was based on cyclotrons and pulsed electron-linac-driven bremsstrahlung photoneutron sources.
- The e-linac-driven sources soon reached a power limit of about 50 kW, imposed by heat transfer engineering constraints on target design which is subjected to about 2000-MeV heating per neutron production.
- The bremsstrahlung photoneutron sources also produced high-energy gamma ray backgrounds that can be problematic for many neutron scattering applications.
- Heavy elements are clearly best as bremsstrahlung photoneutron sources.



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Spallation neutron sources

- Spallation is a violent reaction in which a target is bombarded by very high-energy particles. The incident particle, such as a proton, disintegrates the nucleus through inelastic nuclear reactions. The result is the emission of protons, neutrons, α-particles, and other particles.
- A big advantage of spallation sources is that they produce neutrons with a wide spectrum of energies, ranging from a few eV to several GeV. Another advantage is their ability to generate neutrons continuously or in pulses as short as a nanosecond.

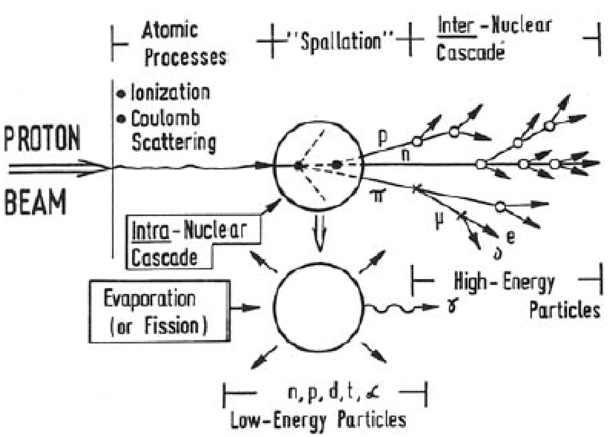


Table 2.2 Past, existing, and future spallation source and their respective parameters

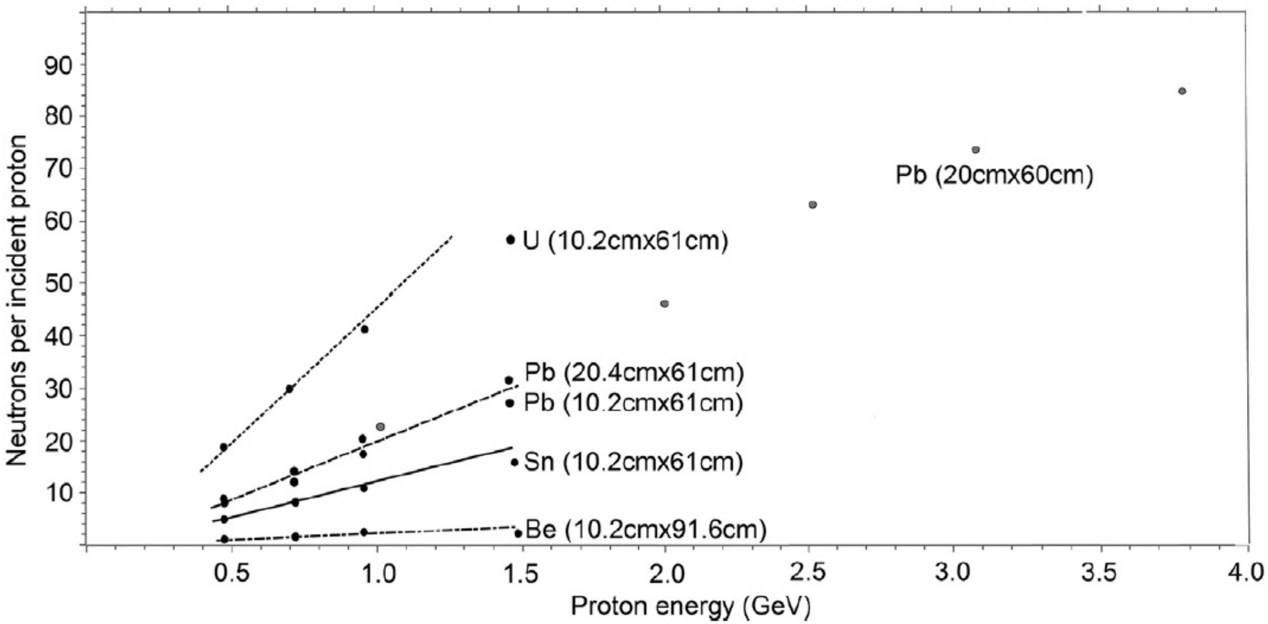
Country	United States	United States	United States	U.K.	Switzerland	China	Europe	Japan	Japan
Neutron source	IPNS	LANSCE	SNS	ISIS	SINQ	CSNS	ESS	KENS	JSNS
Organization	Argonne National Laboratory	Los Alamos National Laboratory	Oak Ridge National Laboratory	Rutherford Appleton Laboratory	Paul Scherrer Institute	Institute of High Energy Physics	Undecided	High Energy Accelerator Research Organization	Japan Atomic Energy Agency
Proton energy (MeV)/ Current (μA)	450/15	800/70	1000/1400	800/200	590/1500	1600	1333/7500	500/9	3000/333
Proton beam power	7 kW	56 kW	1.4 MW	160 kW	1 MW	100 kW	5 MW	4.5 kW	1 MW
Repetition rate (Hz)	30	20	60	50/10 (2 targets)	Continuous	25	16 (long pulse)	20	25
Target material	Depleted Uranium	Tungsten	Mercury	Tantalum	Zircaloy	Tungsten	Mercury	Tungsten	Mercury
Moderator	S-CH_4/L-CH_4	L-H_2/H_2O	L-H_2/H_2O	L-H_2/L-CH_4/ H_2O	L-D_2/D_2O	H_2OL-CH_4L-H_2	L-H_2	S-CH_4/H_2O	L-H_2
Number of instruments	12	7	24 (beam ports)	22 (TS1) 7 (TS2)	15		20 (beam ports)	15	23 (beam ports)
Existing neutron imaging instrument					NEUTRA [30] and ICON [31]				
Facility operating since or planned to operate in	1981 (closed 2008)	1983	2006	1985 (TS1) 2008 (TS2)	1996	2014	Under planning	1980 (closed 2005)	2008

IPNS: Intense Pulsed Neutron Source [32]; LANSCE: Los Alamos Neutron Science Center [33]; SNS: Spallation Neutron Source [8, 9]; ISIS: [34, 35]; SINQ: Swiss Spallation Neutron Source [36, 37]; CSNS: Chinese Spallation Neutron Source [10, 11]; ESS: European Spallation Source [38, 39]; KENS: Koh-Energy-ken Neutron Source [40, 41]; JSNS: Japanese Spallation Neutron Source [8, 9]. Consult the websites for these facilities to obtain additional information and current details.

Neutron yield for spallation

- Threshold energy of spallation reaction by protons in heavy nuclei is ~100 MeV.
- It shows excellent neutron production efficiency compared with other techniques. For example, a 1-GeV proton on tungsten (A = 184) produces 18 neutrons and deposits ~30 MeV of heat per neutron.
- The yield is approximately a linear function of the mass number, A, of the target material and the incident particle energy.

$$Y(E, A) = \begin{cases} 0.1(E_{\mathrm{GeV}} - 0.120)(A + 20) \text{ except for fissionable materials} \\ 50(E_{\mathrm{GeV}} - 0.120) \text{ for } ^{238}\mathrm{U}. \end{cases}$$

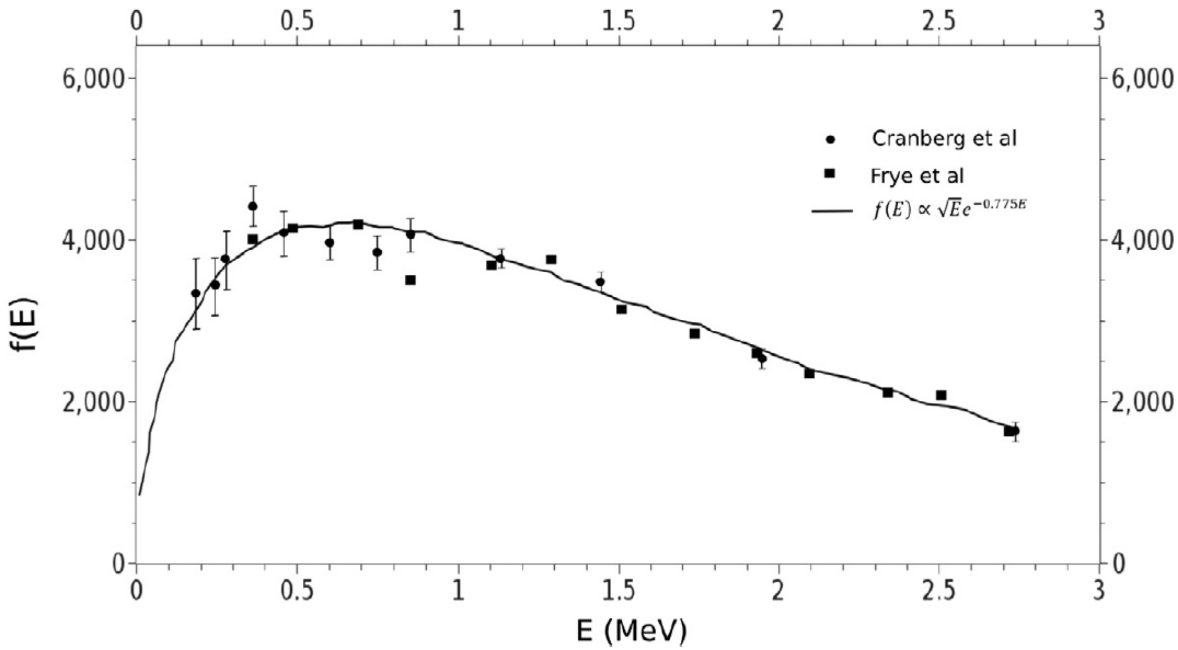


Neutron spectrum for spallation

- Neutrons from fission and from spallation have similar spectra, since both arise from evaporation of neutrons from excited nuclei.
- The function is roughly as follows. The mean energy is approximately 2 MeV.

$$f(E) \propto \sqrt{E}\exp(-0.775E)$$

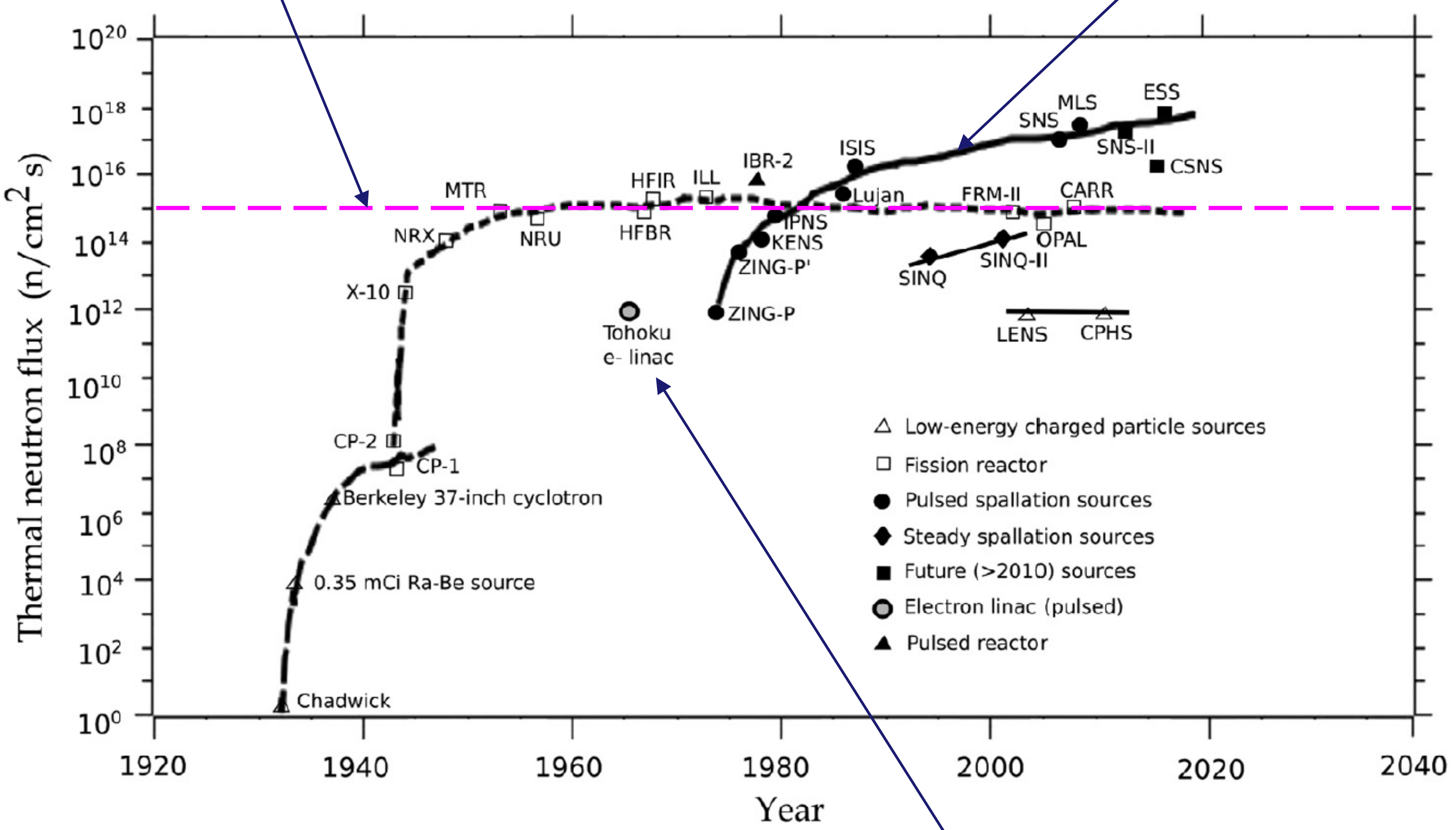
- Most of the spallation neutrons appear in the evaporation spectrum. But a few (~2%) are cascade neutrons, distributed with energies up to the incident proton energy (over ~ 100 MeV) and traveling in forward directions.



History of flagship neutron facilities

Limitation of fission reactors (~200 MeV / neutron)

Spallation sources (~30 MeV / neutron)



Electron-linac-driven photoneutron source (~2000 MeV / neutron)

Nuclear reactions driven by low-energy charged particles

- The targets used in spallation sources are generally high-Z materials, such as lead, tungsten, silver, and bismuth. However, it is also possible to generate neutrons by bombarding light elements with high-energy charged particles. Two examples of such reactions involve the production of neutrons by bombarding lithium and beryllium targets with relatively low-energy protons.

$$p + {}^{7}_{3}\mathrm{Li} \rightarrow {}^{7}_{4}\mathrm{Be} + n$$
$$p + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{9}_{5}\mathrm{B} + n$$

- At energies below ~50 MeV, the de Broglie wavelength of the proton or deuteron is comparable to the size of a nucleus (~10^{-13} cm), so the particle–nucleus reaction can be considered as occurring through only one or two reaction channels.

Reaction types	Examples
(p, n)	^{3}H(p, n)^{3}He, ^{6}Li(p, n)^{6}Be, ^{7}Li(p, n)^{7}Be, ^{9}Be(p, n)^{9}B, ^{10}Be(p, n)^{10}B, ^{10}B(p, n)^{10}C, ^{11}B(p, n)^{11}C, ^{12}C(p, n)^{12}N, ^{13}C(p, n)^{13}N, ^{14}C(p, n)^{14}N, ^{15}N(p, n)^{15}O, ^{18}O(p, n)^{18}F, ^{36}Cl(p, n)^{36}Ar, ^{39}Ar(p, n)^{39}K, ^{59}Co(p, n)^{59}Ni
(d, n)	^{2}H(d, n)^{3}He, ^{3}H(d, n)^{4}He, ^{7}Li(d, n)^{8}Be, ^{9}Be(d, n)^{10}B, ^{11}B(d, n)^{12}C, ^{13}C(d, n)^{14}N, ^{14}N(d, n)^{15}O, ^{15}N(d, n)^{16}O, ^{18}O(d, n)^{19}F, ^{20}Ne(d, n)^{21}Na, ^{24}Mg(d, n)^{25}Al, ^{28}Si(d, n)^{29}P, ^{32}S(d, n)^{33}Cl
(t, n)	^{1}H(t, n)^{3}He
(α, n)	^{3}H(α, n)^{6}Li, ^{7}Li(α, n)^{10}B, ^{11}B(α, n)^{14}N, ^{13}C(α, n)^{16}O, ^{22}Ne(α, n)^{25}Mg

Neutron yield by low-energy charged particles

- In general, the targets are light elements, and the neutron yields from low-energy charged particles are smaller than those from spallation and fission by several orders of magnitude. Yet the density of heat deposited in the target is large because of the very short range of low-energy charged particles in a solid target.