Spallation Neutron Sources

I: Production of Neutrons

John M. Carpenter

Spallation Neutron Sources I
Outline

- I. Production of Neutrons
  - 1. What is a neutron?
  - 2. Reactions that produce neutrons
  - 3. Pulsed *vs*. steady operation
  - 4. Some practicalities
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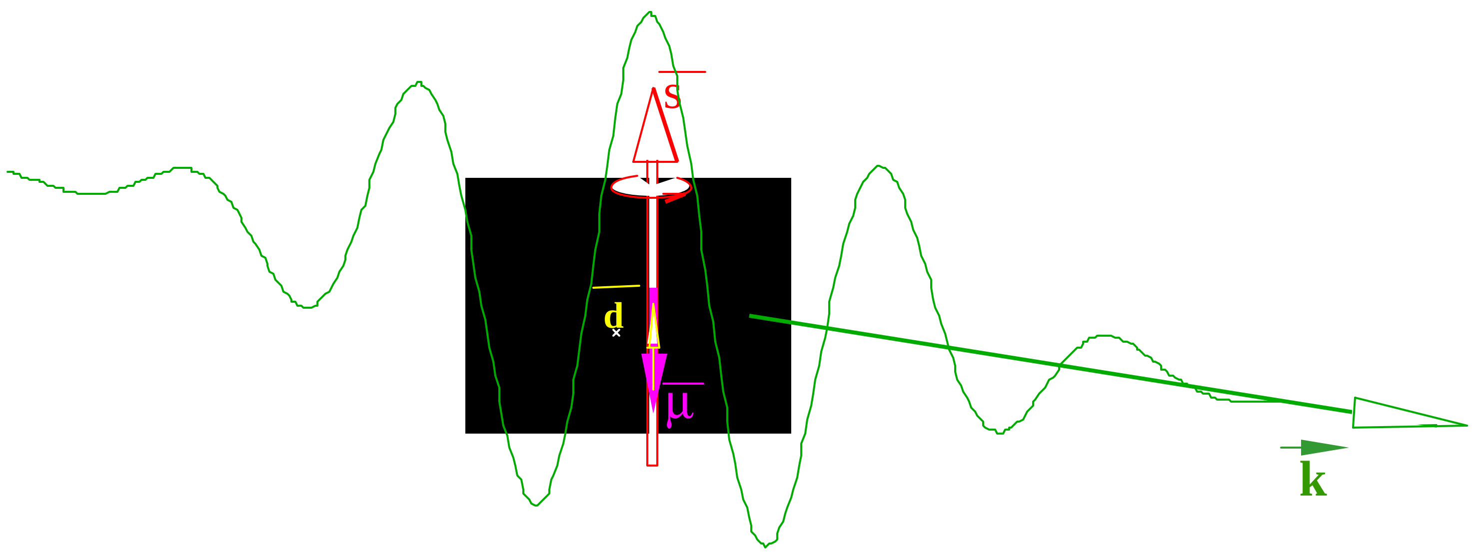
The neutron



1. What is a neutron?

- From one point of view, the neutron is the completion of the periodic table of the elements (at zero charge) and of the table of nuclides (on the low-mass side). Thus the neutron completes the picture of the atomic theory of matter, which is the basis of materials science.

- The quantum numbers of the neutron distinguish it from the other elements and other fundamental nuclear particles:
  - Charge number = 1 electron charge
  - Baryon number = 1
  - Spin = 1/2 h

- From the point of view of Quantum Chromodynamics, the neutron is a member of the family of particles within the Standard Model of particle physics.

The Standard Model

- According to the Standard Model, all matter consists of leptons, quarks,
- and mediators. Table 1 presents the properties of the quarks, which are the
- constituents of neutrons and their extended family, the hadrons.

Table 1. Some properties of the quarks

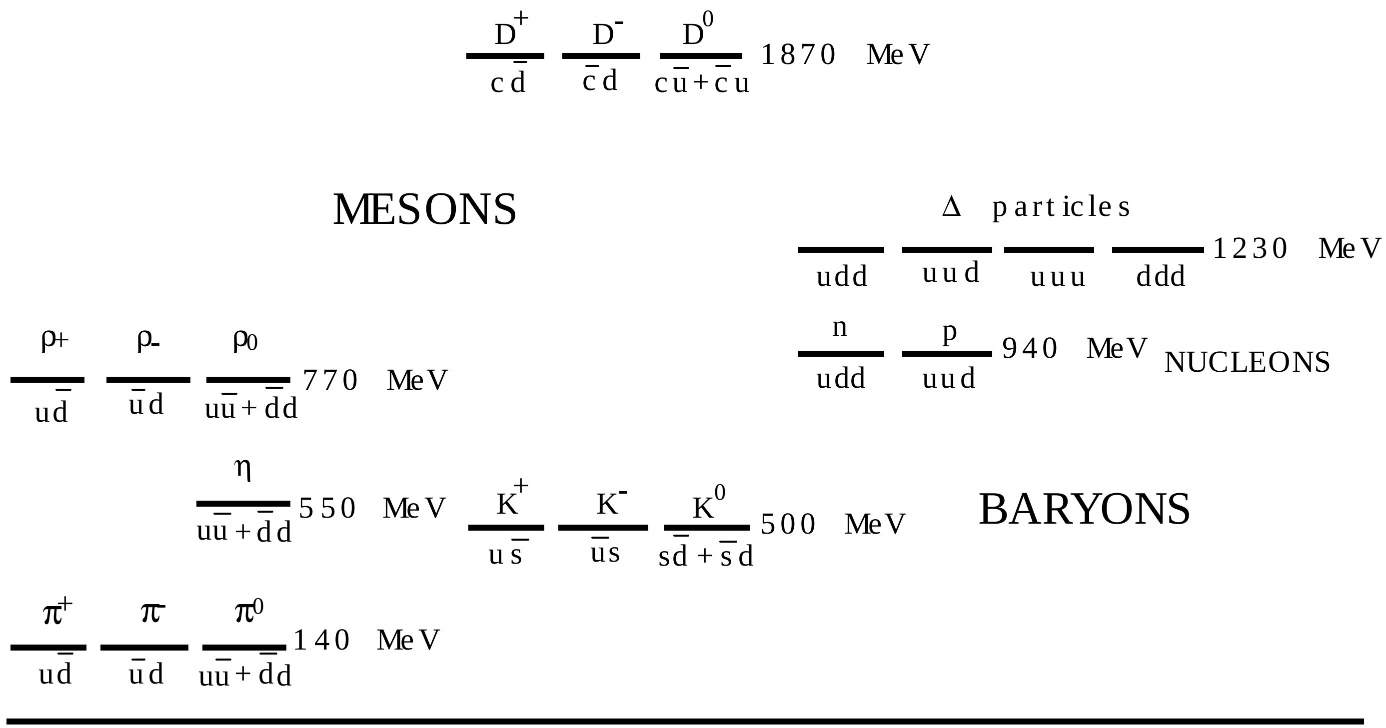
Generation	Flavor	Symbol	Charge, e units	Rest Energy, MeV
First	down	d	-1/3	5
First	up	u	2/3	10
Second	strange	s	-1/3	200
Second	charm	c	2/3	1500
Third	bottom	b	-1/3	5000
Third	top	t	2/3	175,000

QCD

- Quarks all have (axial vector) spin 1/2 and (scalar) baryon number 1/3; all have their "anti"-analogs. The "top" quark has only recently been observed. The quarks have one-to-one parallels among the leptons, that is, the electrons and neutrinos. There are three (and only three) generations, each, of quarks and leptons.
- Baryons are bound states of three quarks (and antibaryons are of three anti-quarks). The neutron (like the proton) is the ground state of a three-quark system and consists of one “up” and two “down” quarks (udd) with spin 1/2, baryon number 1, and zero charge. QCD enables calculation of particle masses and magnetic moments; predictions, 939 MeV and -1.86 nuclear magneton, compare well with measured values, 939.6 MeV and -1.913 nuclear magneton. The quark structure, (but <u>not</u> standard QCD) leads to the suggestion that the neutron, chargeless though it is, has an electric dipole moment. Its magnitude is not yet known but tiny, less than about 10^{-25} electron-cm and of no significance in considerations of neutron scattering, but experiments continue.

The Hadron Family

LOW-ENERGY HADRONS



More about the family

- Mesons consist of two quarks (a quark and an antiquark). The hadrons
- interact through the "nuclear" or "strong" force, which is mediated by
- exchange of gluons.

- The figure shows the quark composition and rest energies of the lowest-
- energy hadrons. The familiar photons (light, X-rays, gamma rays) are
- chargeless and massless and have spin 1. They represent excitations of the
- electromagnetic continuum and are the carriers of the electromagnetic force.
-

Neutron-nuclear interactions, neutron decay

- Nuclei are bound systems of neutrons and protons interacting through
- the nuclear, weak, electromagnetic, and gravitational forces. For our
- purposes, it is not necessary to deal with the substructure of the
- constituents of the nuclei; we need only to consider that neutrons
- interact with nuclei through the nuclear force and with electrons and
- the electromagnetic continuum through the magnetic dipole moment.

- Neutrons have a finite lifetime, decaying through the weak interaction
- according to
- $$n \rightarrow p + e^{-} + \bar{\nu}_e$$
- with a half-life outside the nucleus $T_{1/2} \approx 889.1 \pm 2.1$ seconds. Some
- theories beyond standard QCD predict that neutrons may decay into
- antineutrons. But these half-lives are so long that for all our purposes,
- we can consider that the neutron is a stable particle.

Neutrons and gravity

- Neutrons interact with other massive bodies (for example, the Earth)
- through the normal gravitational interaction. This interaction is
- negligible in neutron-nuclear collisions and is of no significance in most
- (except certain sensitive interferometry) measurements. However, in some
- everyday applications, it is necessary to account for the fall of neutrons in
- the Earth's gravitational field. As far as is known, the "gravitational mass”
- and the "inertial mass" are the same.

Practical relationships for the neutron

- For the neutron,

$$m = 1.67482 \times 10^{-24}\, gm,\ |m| = 1.91315\, nucl\ magneton\ .$$

- Fundamental (nonrelativistic) relationships are

$$E = \hbar^2 k^2 / 2m = h^2 / 2m\, l^2 = hf = m\mathrm{v}^2 / 2 = k_B T = m \cdot \boldsymbol{B}\ .$$

- In units of common practice,

$$E_{[meV]} = 2.0723\ k^2_{[A^{-1}]} = 81.81 / l^2_{[A]} = 4.136\ f_{[THz]} =$$

$$= 5.2267 \times 10^{-6} \mathrm{v}^2_{[m/s]} = 0.086173\ T_{[K]} = 6.0311 \times 10^{-8} (-\hat{\boldsymbol{s}} \cdot \hat{\boldsymbol{B}})\ B_{[Tesla]}\ .$$

$$\mathrm{v}_{[m/s]} = 3956. / l_{[A]}\ .$$

- For the photon,

$$E^{\gamma}_{[meV]} = hc / \lambda^{\gamma} = 0.123975 / l^{\gamma}_{[cm]} = \nu'^{\gamma}_{[cm^{-1}]} / 8.0661\ .$$

- Reference: S. A. Werner, NSSA Membership Card, 1992.

2. Neutron-Producing Mechanisms

- "Producing" neutrons in our context really only means releasing them from bound states within a nucleus to the free state where we want to make use of them. All nuclei except ^{1}H (proton) contain bound neutrons, which to our intents behave in the nucleus as structureless entities.

- Large categories of neutron producing mechanisms significant to us are:

- Charged-particle reactions, e. g., ^{9}Be + p—> ^{9}B + n, ^{2}H + ^{3}H—> ^{3}He + n
- Fission, e. g., ^{235}U + n —> A* + B* + xn; < x> ~ 2.5
- Photoproduction, e. g., γ + ^{181}Ta —> ^{180}Ta + n, γ + ^{2}H —> ^{1}H + n
- (n,xn), e. g., ^{9}Be + n—> ^{8}B* + 2n
- Excited-state decay, e. g., ^{13}C** —> ^{12}C* + n, ^{130}Sn** —> ^{129}Sn* + n,
- Spallation, e. g., p + ^{184}W —> A* + B* + xn, <x> ~ 20 .

Charged-particle reactions

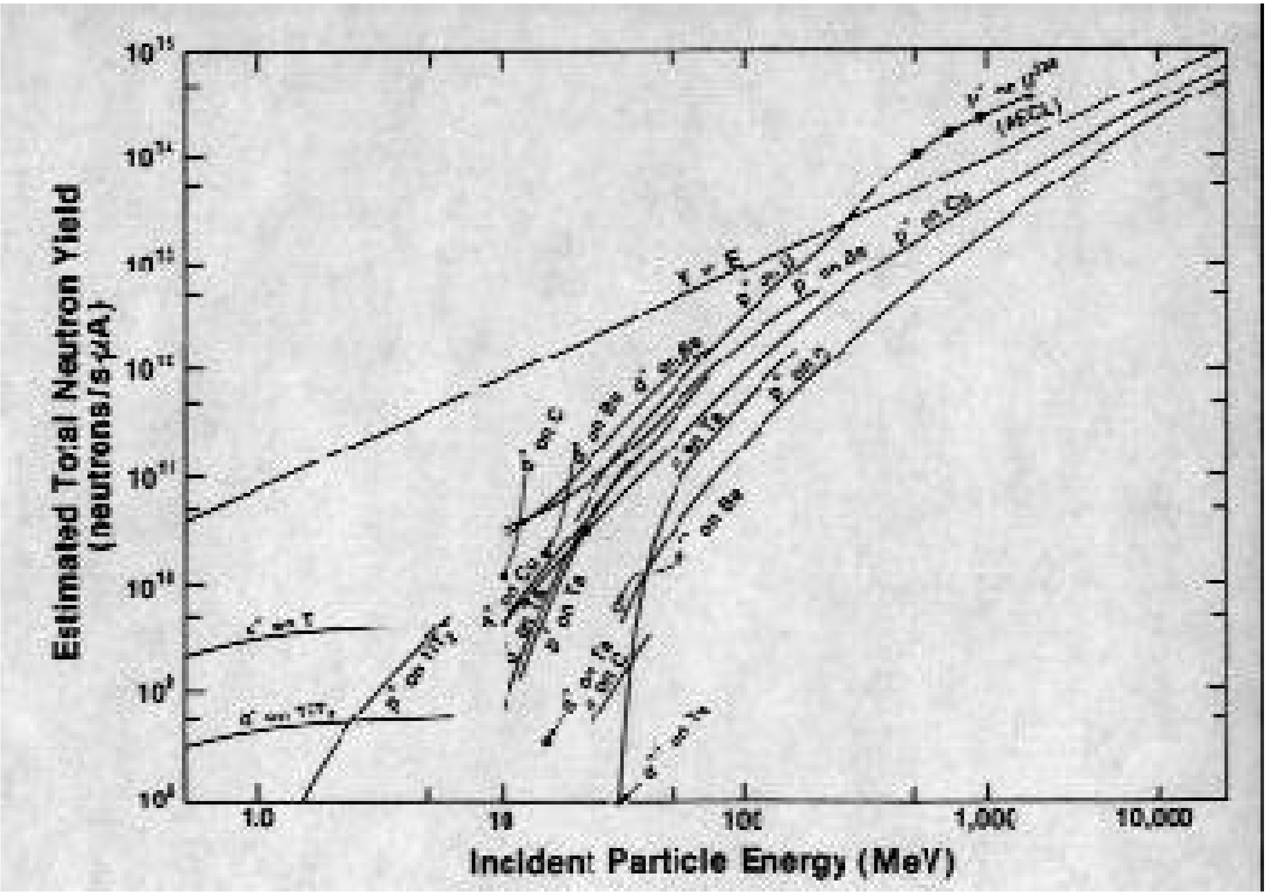
- In our context, we can distinguish between thin-target and thick-target neutron production. These are induced by relatively low-energy ($< \sim 10$ MeV) charged particles. Thin-target interactions are fundamental; thick-target interactions are of practical significance to us and are simply related to the thin-target cross sections integrated in terms of the slowing-down energy loss of the charged particle. The interactions typically involve only a single reaction channel, formation of a compound nucleus that decays rapidly, the products carrying off the net of the binding energy of the reactants and the kinetic energy of the incoming particle.

Charged-particle reactions, cont'd

- The energy and angular current of the emerging neutrons are strongly correlated to the angle of emission in relation to the incoming particle beam. The incoming charged particle loses most of its energy to excitation of electrons in the material (dE/dx loss), so low-energy reactions tend to be relatively inefficient processes. However, it is easy to accelerate the incident particles (e. g., p, d, α) in relatively inexpensive machines and to provide currents that tax the power-dissipating capabilities of the targets.

Charged-particle reactions, more

⌘ The figure summarizes the total neutron yield from a large number of charged-particle reactions as a function of particle energy.



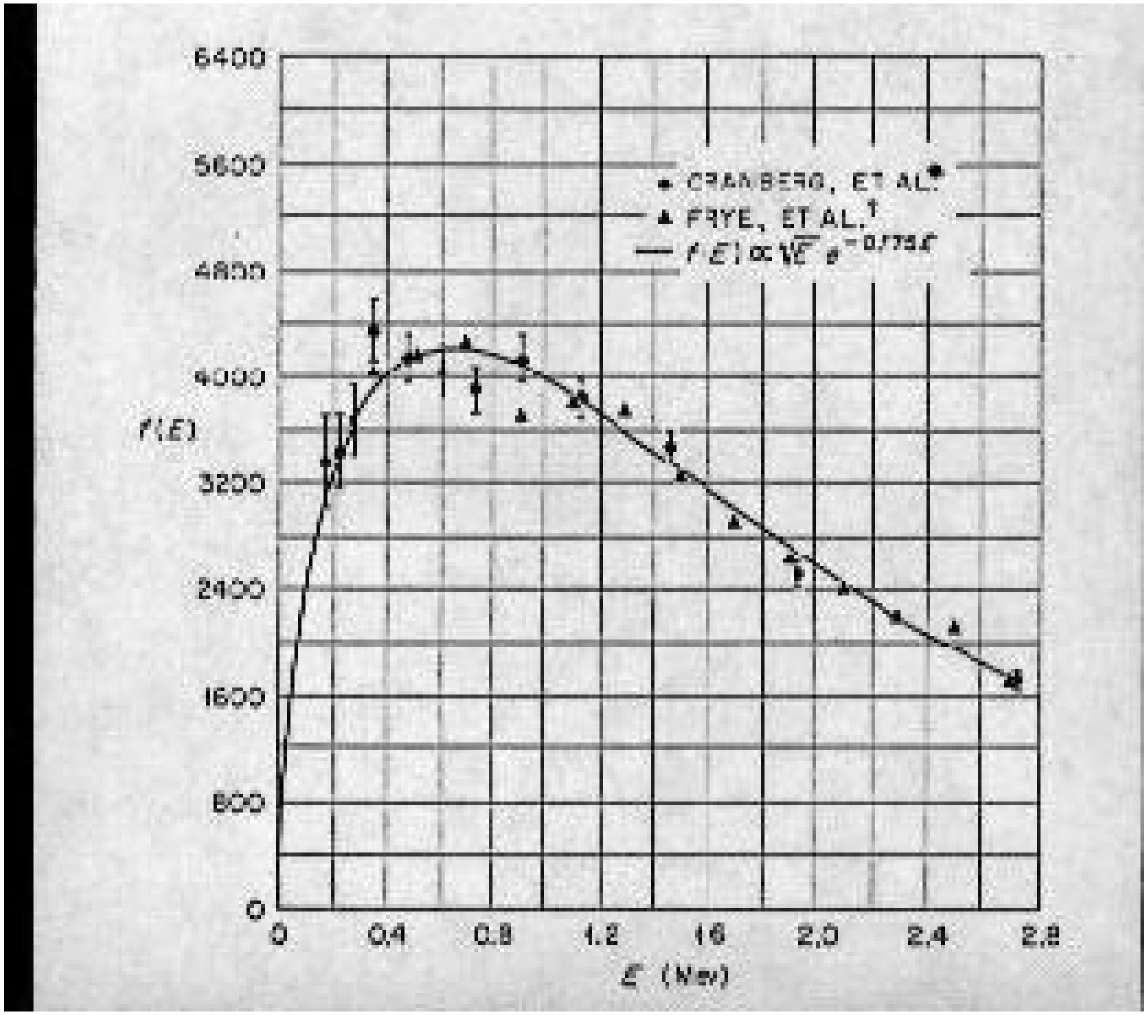
Fission

- Fission is the most common way of producing neutrons for scattering research. Installations are nuclear reactors in which self-sustaining fission chain reactions, for example, n + ^{235}U —> f + xn, where <x> ~ 2.5 n/fission. One neutron from each fission goes on to initiate another fission, leaving about <x> – 1 ~ 1.5 neutrons. Of the 1.5 excess, a certain fraction is lost to non-fission processes and to necessary absorption in control mechanisms, leaving ~ 1 available for use. About 200 MeV of energy accompanies each fission, mostly in the form of fission fragment energy, which must be removed from the reactor to gain the available neutron. About 5-10 MeV each of electrons, gamma rays, and neutrinos also accompany each fission.

Fission neutrons

- Fission neutrons are born with mean energies about 2 MeV, distributed in an “evaporation “ spectrum, $N(E) \sim E^{1/2} e^{-E/T}$ with $T \sim 1.29$ MeV. The mean energy is $3/2T = 1.94$ MeV.
- The coolant/moderator slows down most neutrons in the reactor core to low energies where they cause fission with higher probability than at their higher energies. Most of these are absorbed to carry on the fission chain.

Fission neutron spectrum

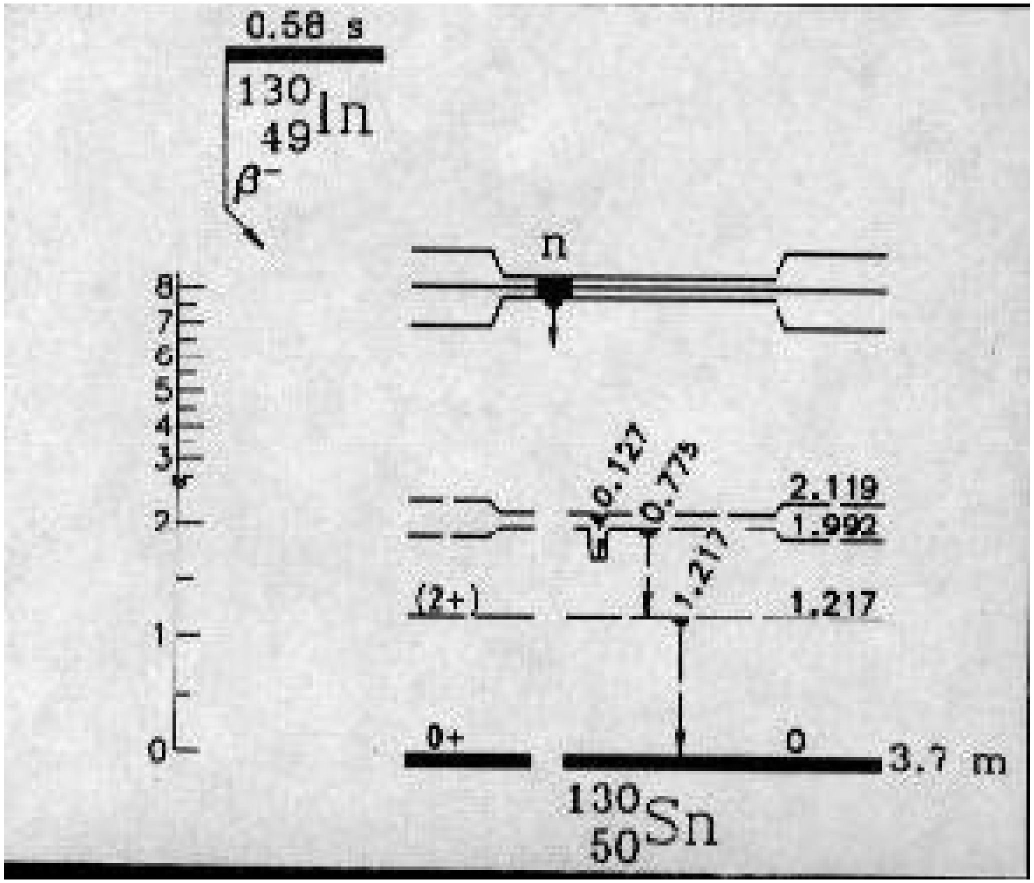


Delayed fission neutrons

- A small fraction of the neutrons that result from fission are born after a significant time delay that arises because the neutron emitter is the product of beta decay of a "precursor" nucleus:
- $(A,Z)^{**} \longrightarrow (A,Z\pm1)^{**} + e^{\pm}$, $(A,Z\pm1)^{**} \longrightarrow (A-1,Z\pm1)^{*} + n$.
- The beta decay step is typically slow (milliseconds…minutes) and the neutron decay is very rapid; the neutron appears delayed by the beta-decay lifetime of the precursor nucleus. There are a fairly large number of precursors, which for purposes of reactor dynamic analysis are usually classed together in about 6 groups. The figure shows the ^{130}In, ^{113}Sn decay scheme.

- Delayed neutrons are nearly monoenergetic because they result from decay of a single excited nuclear state.

Delayed fission neutrons: example, ^{130}In, ^{130}Sn



Fission, Reactors

- Research reactors have either H_2O or D_2O coolant/ internal moderator and use metallic fuel, both to provide for the highest power densities. Fuel material is invariably enriched ^{235}U. To provide for long life of the fuel 93% is most desired, but nonproliferation initiatives are now afoot which aim to provide fuel alloys with sufficient density to provide the desired reactor core lifetimes using 20% enriched uranium, less prone to diversion for illicit purposes.

- Research reactors vary in power (thermal power output) from ~ 10 MW ("mid-flux") to 100 MW (high-flux"). The high-flux reactors tax current engineering limits on power density, power removal, and core lifetime. Fuel and coolant temperatures are modest compared to power reactors. High-flux reactors typically have core lifetimes of about three weeks and require about one week to refuel.

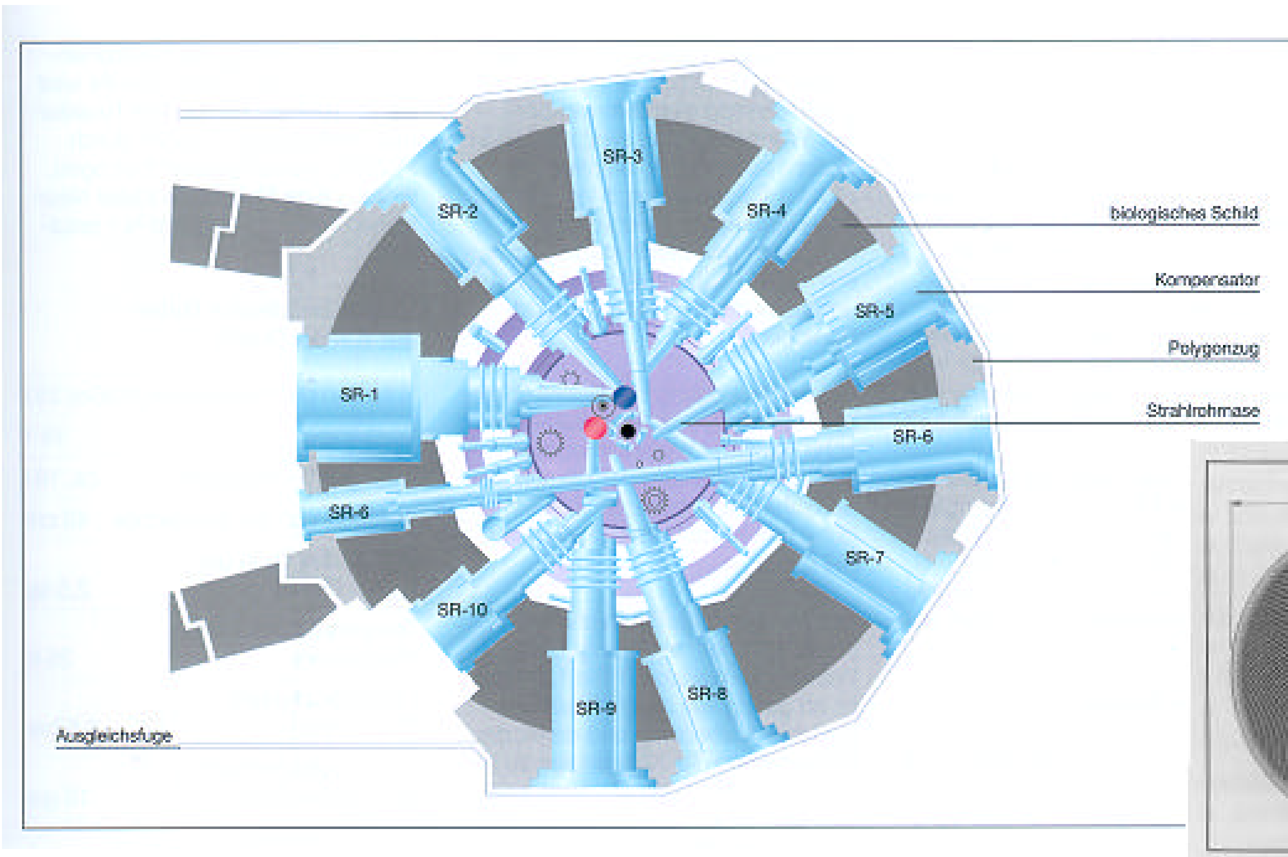
Fission Reactors, more

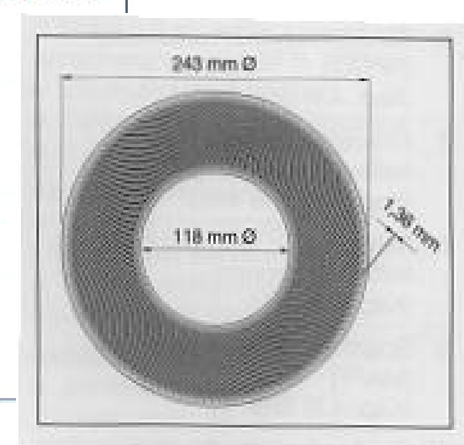
- Neutrons to be used in scattering experiments are the excess neutrons that leak out of the reactor at rather high energies. A reflector/ moderator of large volume, typically ~ 1 m thick, surrounds the reactor, which acts to enhance neutron efficiency and to slow down neutrons to thermodynamic equilibrium at about 300 K . Beryllium metal or D_2O serve best in the moderating function. The reactor shield needs to be about 2 meters thick, mostly concrete.

- Research reactors have many beam holes, which conduct neutrons through the shield to surrounding experiments. Most modern reactors also incorporate cold sources of liquid H_2 or D_2, which concentrate neutrons at low energies (T ~ 30 K) and serve clusters of neutron guides. Some also include a hot source (gamma-heated graphite at ~ 2000K) to provide more neutrons at ~ 150-meV energies than are present in the reflector/moderator.

A Modern Reactor, FRM-2

⌘ The FRM-2 reactor, which is nearing completion in Munich, Germany.



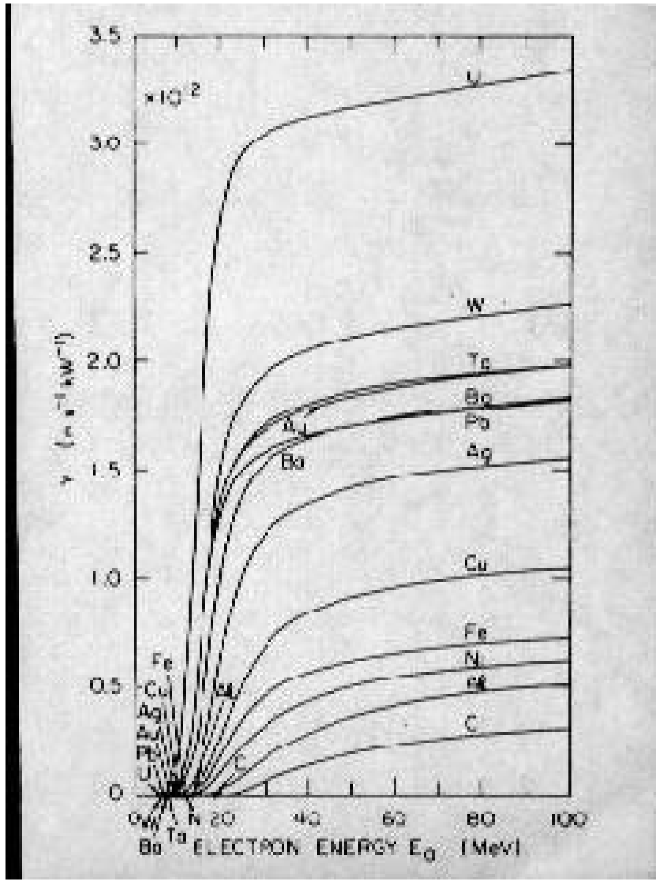


Photoproduction

- Gamma rays produce neutrons in a process in which the nucleus absorbs a photon, and the resulting excited nucleus de-excites by emitting a neutron. In heavy nuclei the absorption is through the giant resonance reaction, which is maximum for about 20-MeV photons. Most of the neutrons appear distributed in an evaporation spectrum with an average energy of about 2 MeV.

- There are numerous pulsed neutron sources based on ~ 100 -MeV electron linear accelerators, wherein the electrons strike a thick target of heavy metal where they stop, producing forward-directed, energetic bremsstrahlung photons. These photons subsequently interact in a neutron-producing target of heavy material, which may be one and the same with the electron target, producing photoneutrons. The figure shows the production rate as a function of electron energy for different materials. The process is rather inefficient, requiring dissipation of about 2000 MeV/neutron produced. Target engineering constraints limit target power to about 50 kW.

Bremsstrahlung photoproduction, heavy nuclei



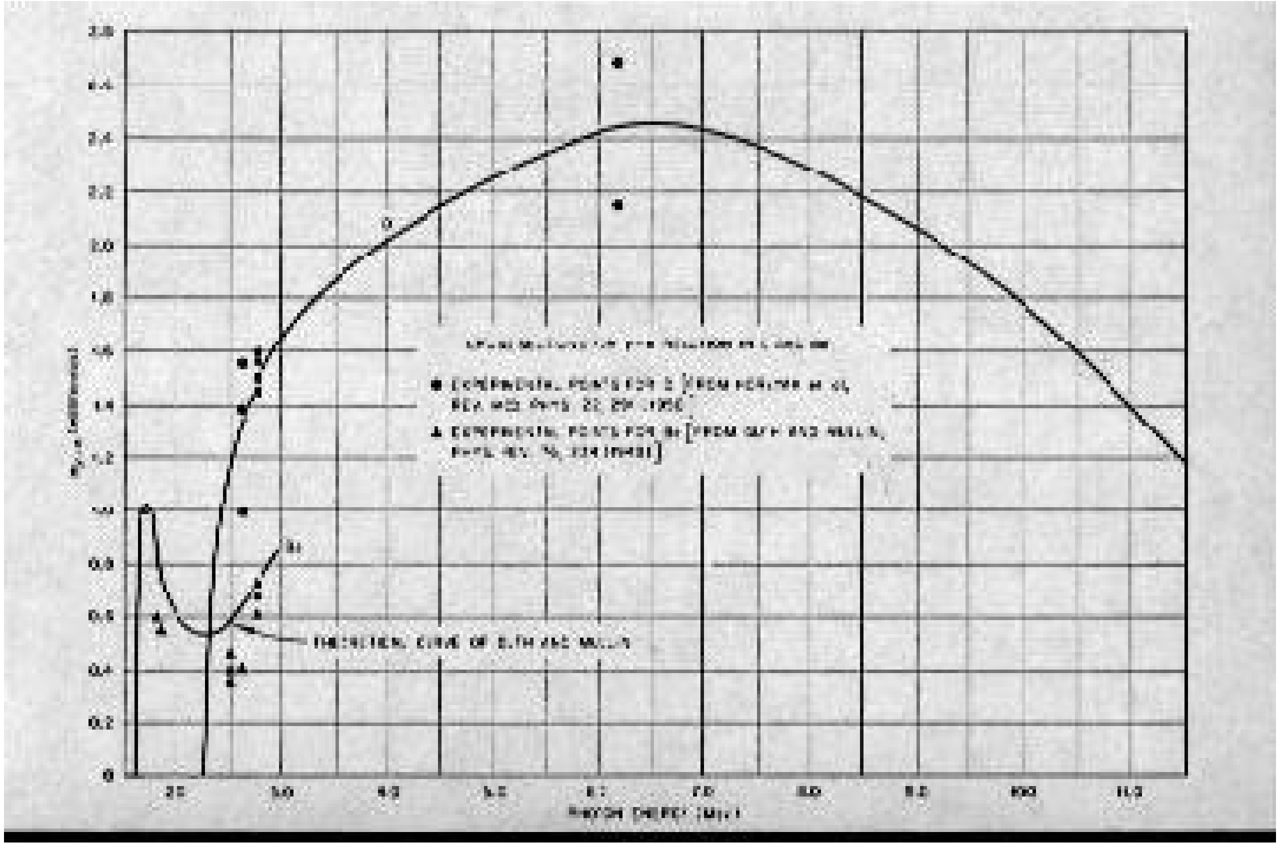
Photoproduction

- In light nuclei such as ^{2}H and ^{9}Be, which have a loosely bound neutron, the photodisintegration process is simpler and has a threshold at a center-of-mass energy corresponding to the neutron binding energy, 2.2 MeV for ^{2}H and 1.7 MeV for ^{9}Be. Neutrons appear with energies equal to the excess of photon energy over the binding energy.

- This process, initiated by energetic prompt gamma rays and delayed decay gamma rays, can take place in the beryllium reflectors and in D_2O coolant of reactors and in pulsed spallation neutron sources. In pulsed sources this is a potential source of background between pulses.

Photoproduction, light nuclei

- The (γ,n) cross sections for deuterium and beryllium



(n,xn) reactions

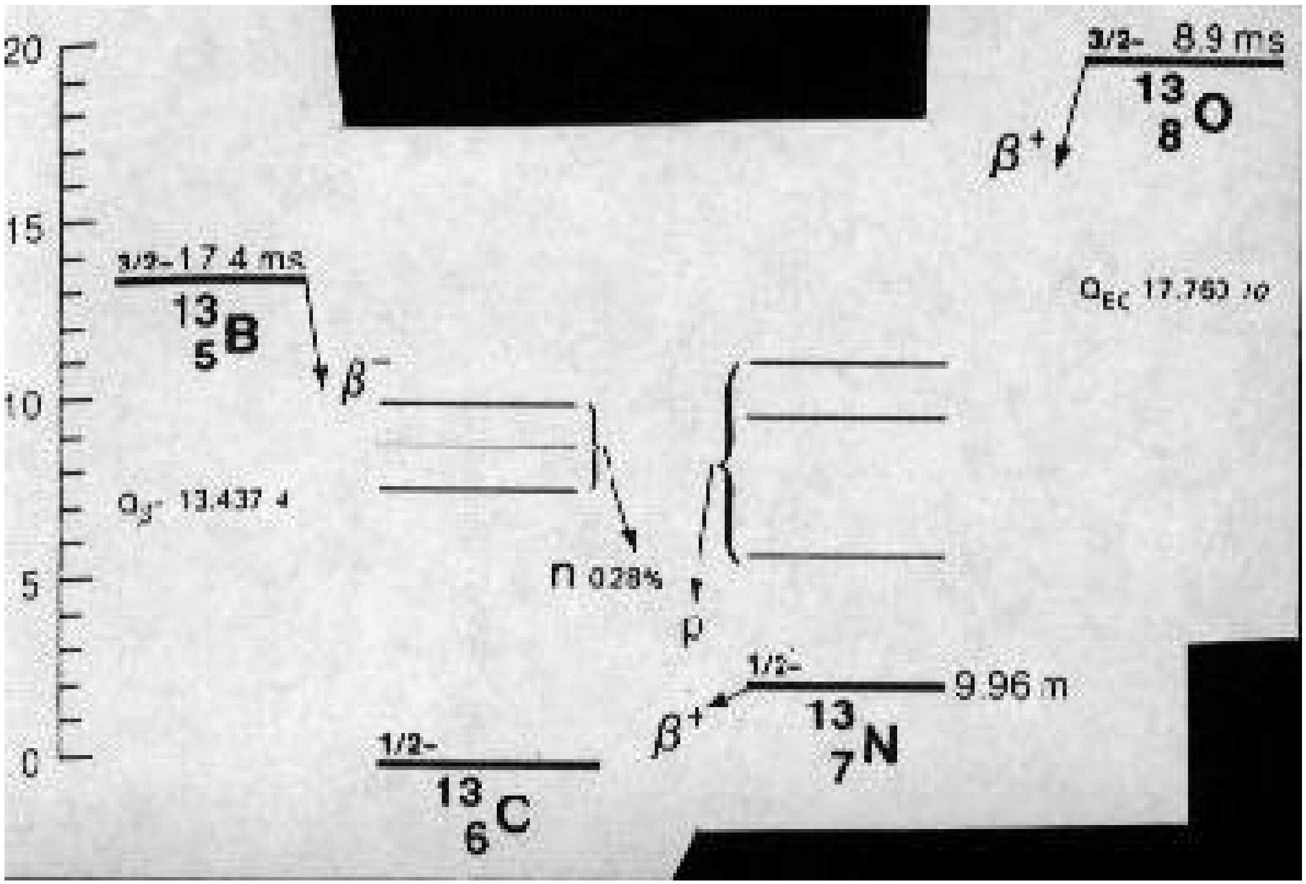
- In ^{2}H and ^{9}Be, an energetic neutron can impart sufficient energy in a collision to liberate the loosely bound neutron, and x = 1. Thresholds are approximately 4.0 MeV and 2.0 MeV, respectively. Cross sections above threshold rise to several hundred millibarns in each case.

- In heavy nuclei, each x value requires the separation energy of the x^{th} neutron, the cross section exhibiting roughly 6-MeV steps. This occurs famously in ^{238}U and in ^{209}Bi. In the case of ^{209}Bi, the set of threshold reactions provides a very useful activation detector for fast-neutron spectrum determination up to x ~ 9 (E_{th} ~ 50 MeV).

Neutron decay of excited states

- Products of fission and other reactions and their beta-decay daughters include nuclei that can decay by emitting a neutron. The best known examples are mid-mass fission product nuclei described earlier. However, there are light nuclei, produced as beta-delayed daughters of spallation products, which also decay by emitting a neutron, for example, ^{13}C, the product of beta decay of ^{13}B. The diagram shows the decay scheme, which results in a 5-MeV neutron delayed by the ^{13}B half-life, 17.4 milliseconds.

Neutron decay of excited states: light nuclei, e. g. ^{13} C



Spallation

- The term “spallation” refers to a complicated mess of reactions initiated by interaction of very high energy (~ GeV) particles (p, n, π, …) with (typically, in our context) heavy nuclei. W. H. Sullivan and G. T. Seaborg coined the term in 1947 to describe the phenomenon, which was already quite well known, in which the target emits a fairly large number of neutrons in a multiple-collision process.
- Early observations were of the spallation process initiated by high-energy protons (~ 1-10 GeV) of extra-solar origin, which lead to production of neutrons in the atmosphere and on the Earth’s surface. This is worth our knowing because these neutrons and their thermal-neutron progeny exist in our laboratories at fluxes of ~ 10^{-4} - 10^{-3} n/cm^2-sec. Intensities vary according to the thickness of the atmosphere as it changes with the barometric pressure. Some cold-fusion advocates confused these neutrons with hoped-for neutrons from their test cells. Otherwise, we must be aware that they are present when we test sensitive detectors.

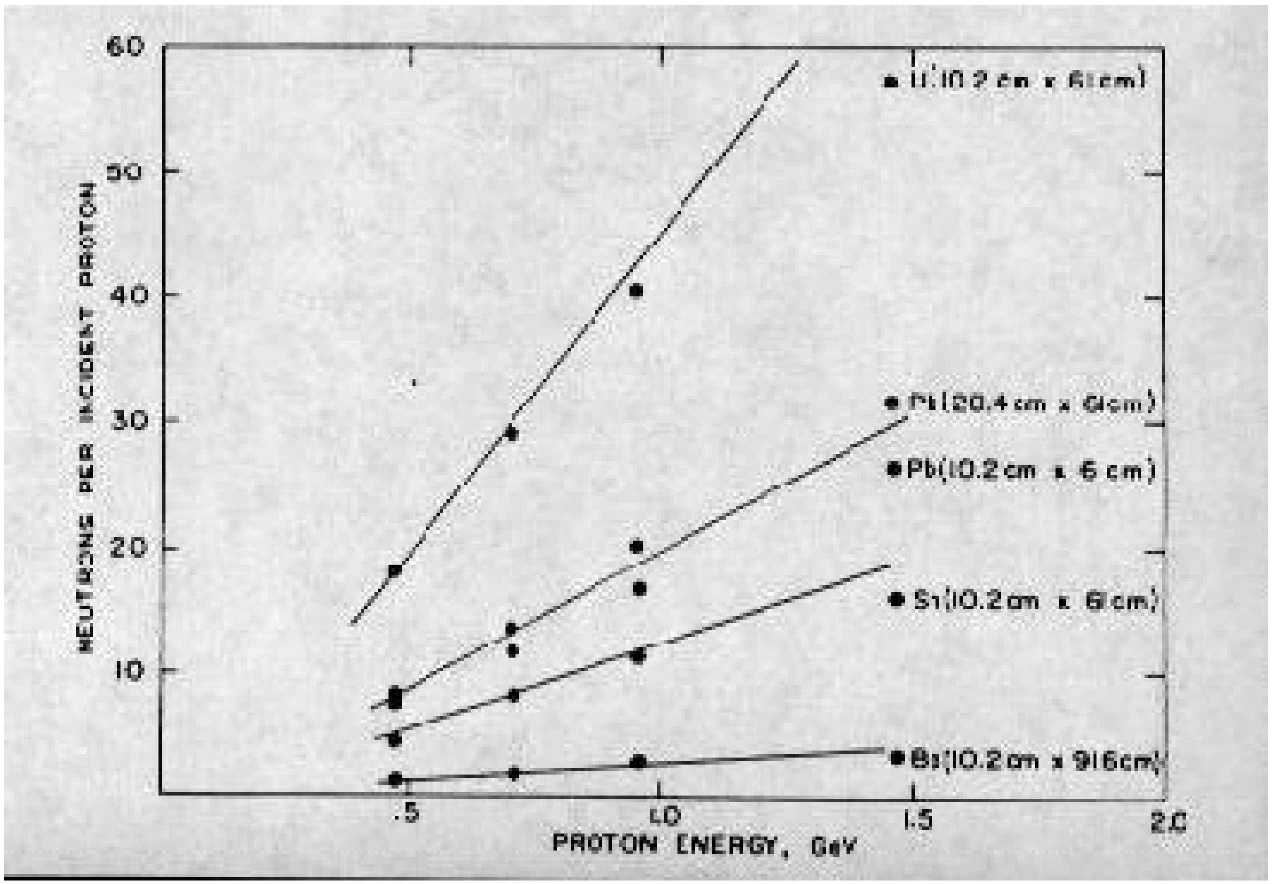
Spallation

- In 1965, Fraser and his colleagues carried out a systematic study of global, proton-induced, thick-target neutron yields from targets of different materials and as a function of proton energy. The figure shows their results. The data admit a simple fit, applicable for energies up to 1.5 GeV,

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

- These data made possible the confident design of neutron facilities based on proton-induced spallation neutron production. Concomitant and subsequent development and refinement of Monte Carlo nucleon-meson transport codes (NMTC) and nuclear models to simulate the intra- and internuclear cascade now make possible the detailed design of target systems for spallation neutron sources. There have been many experimental checks, which generally verify the Fraser data.

Spallation yield data of Fraser, et. al.

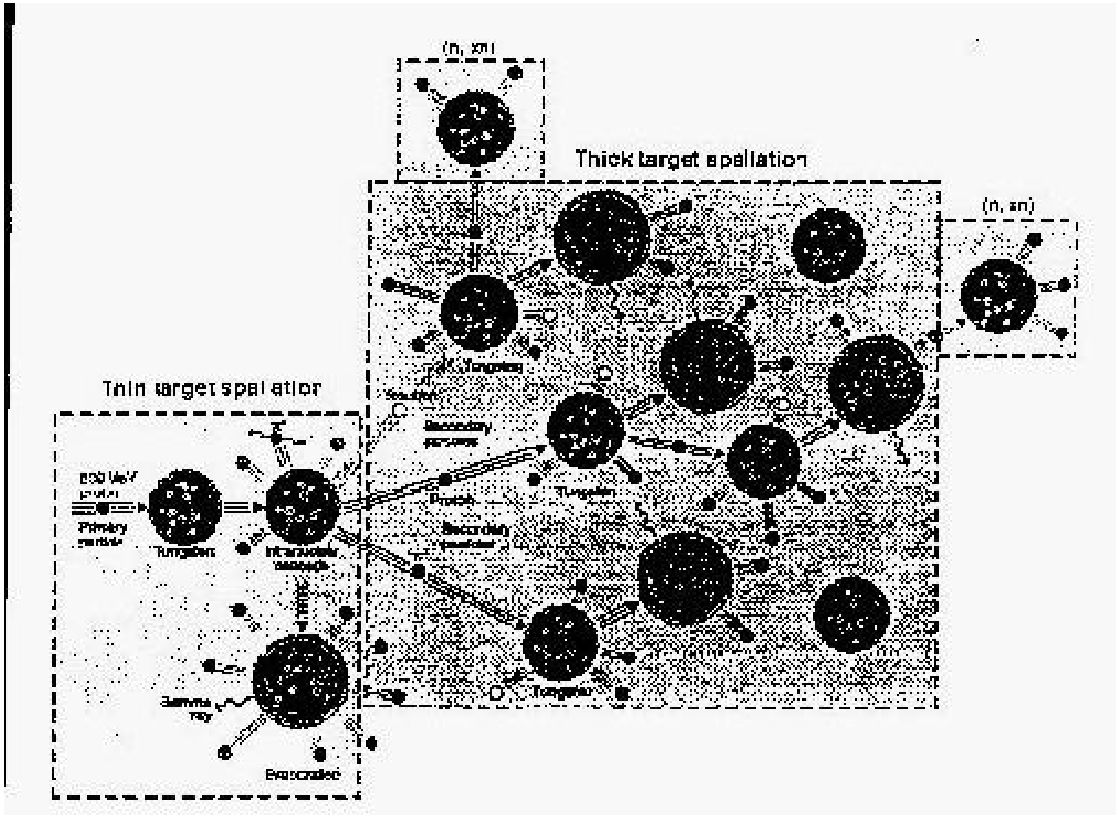


The spallation process

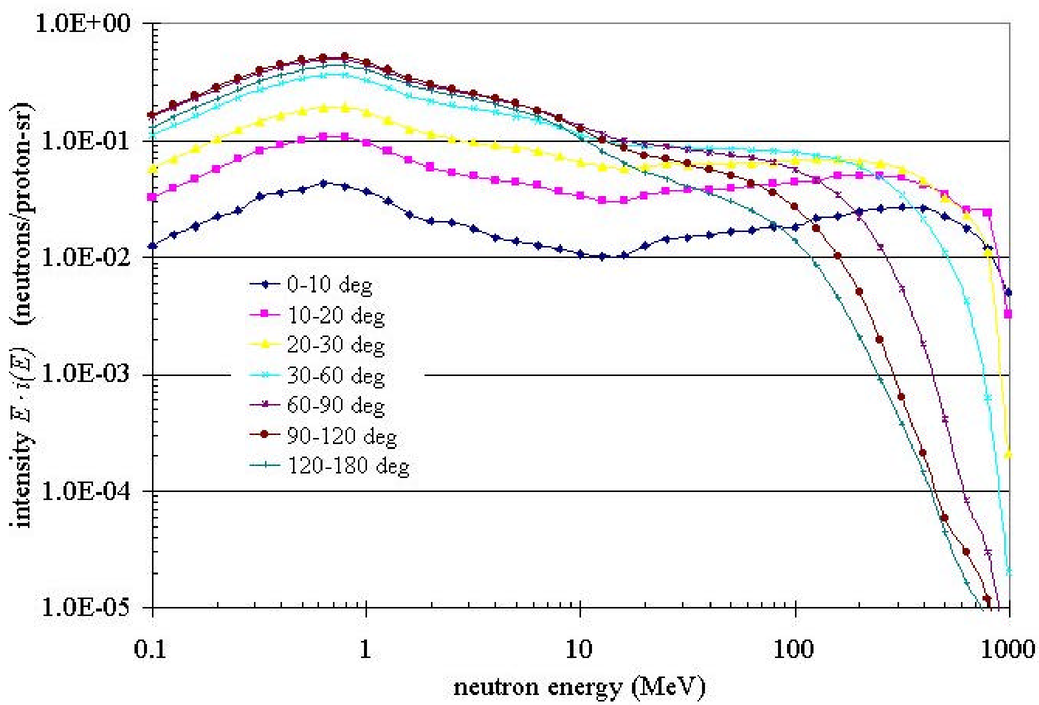
- Primarily, nuclei excited by interactions with primary protons and secondary particles (N, p, π, …) slough their energy mainly by evaporating neutrons. The following figure illustrates the complexity of spallation processes. Most of the neutrons appear isotropically in an evaporation spectrum similar to that of fission neutrons, with a mean energy of 2-3 MeV, but a small fraction (a few %) arise from direct collisions of incident protons with neutrons in the target nuclei. These have energies that extend up to the incident proton energy, strongly biased in the direction of the proton beam. The next figure shows spectra calculated for a thick W target irradiated with 1.0-GeV protons.
- Otherwise, the spallation process involves nearly all of the interactions described earlier. Even in nonfissionable target such as tungsten, lead, and mercury, GeV-protons bring sufficient energy to cause a few fissions. Except for fission, all the processes are endothermic; a notable fraction of the incoming charged-particle energy is taken up as neutron separation energy, at about 6 MeV per neutron, and kinetic energy, 2-3 MeV/neutron.

The spallation process

- The figure, drawn by Gary Russell, illustrates all the involved processes except fission, which occurs to only a small extent in W.



The spallation neutron spectrum and angular variation

- The figure shows the angular distribution of neutrons from a practical target of W, irradiated with 1.0-GeV protons. Angles are measured from the direction of the proton beam.
- 

The spallation neutron spectrum

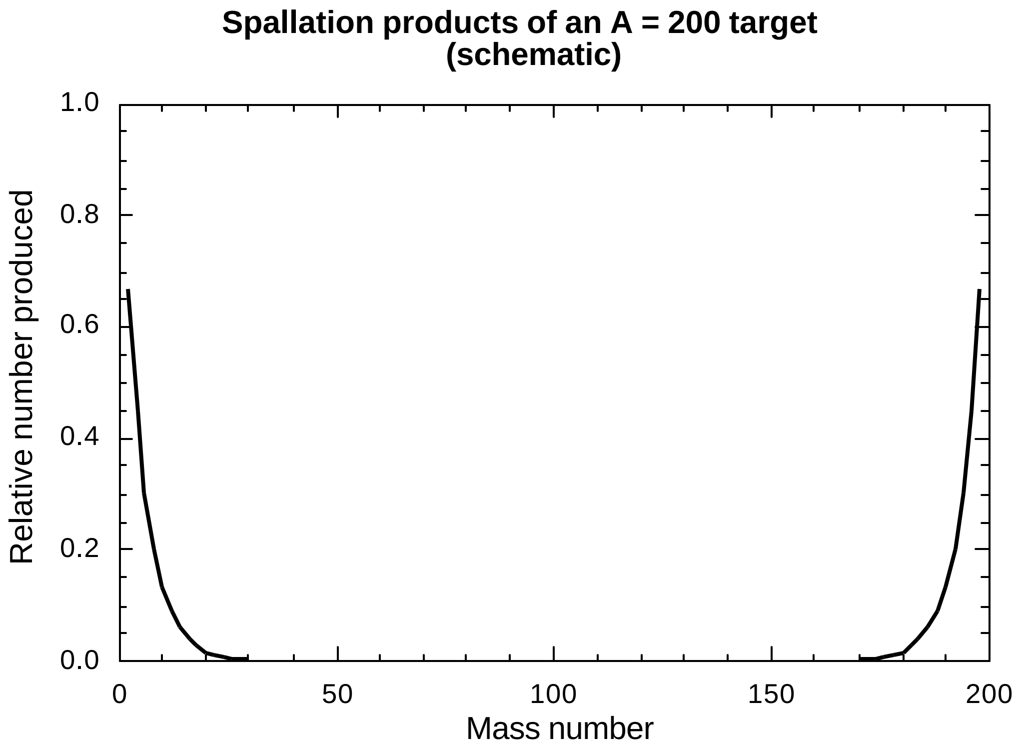
- In the backward direction (> 90°) the spectrum is a roughly isotropic evaporation spectrum (E ~ 2 MeV) softened by multiple collisions in the target material. Their number falls off toward forward directions because the neutrons must pass through the downstream target material.
- Many more high-energy neutrons emerge in the forward directions (< 90°) than in the backward directions because these arise from direct proton-neutron collisions in the target nuclei. Their energies extend up to the incoming proton energy. Since the neutron and proton masses are nearly the same, there are none of these at angles > 90°.
- High-energy neutrons (E > ~ 100 MeV) are very hard to stop, since collision cross sections are considerably smaller (~ x 3) than at ~ 1.0-MeV energies. This means that shielding must be much thicker than reactor shielding, typically about 5 m, mostly of iron.

The spallation process: efficiency

- A useful feature of spallation neutron production is that the energy deposited in the target per neutron produced is quite small. Taking numbers from the fit to the Fraser data, for mercury, A= 200.6, and for protons at E = 1.0 GeV, gives 19.4 neutrons per proton. The beam energy per neutron produced is thus about 50 MeV. However, the neutron separation energy and accompanying kinetic energy account for about 10 MeV/neutron and other losses, such as gamma rays, secondary protons, and π^{o}'s, in total reduce the sensible heat deposited in the target to about 60% of the beam energy. The rest, the energy that appears as heat in the target, is about 30 MeV per produced neutron. Spallation is therefore more than five times more efficient than uranium fission (~ 200 MeV/neutron), a significant engineering advantage.

Spallation products

⌘ Not only neutrons but also other heavier fragments emerge in the complex spallation process. These evaporate in small numbers from excited heavier nuclei. The figure illustrates schematically the distribution of spallation products.

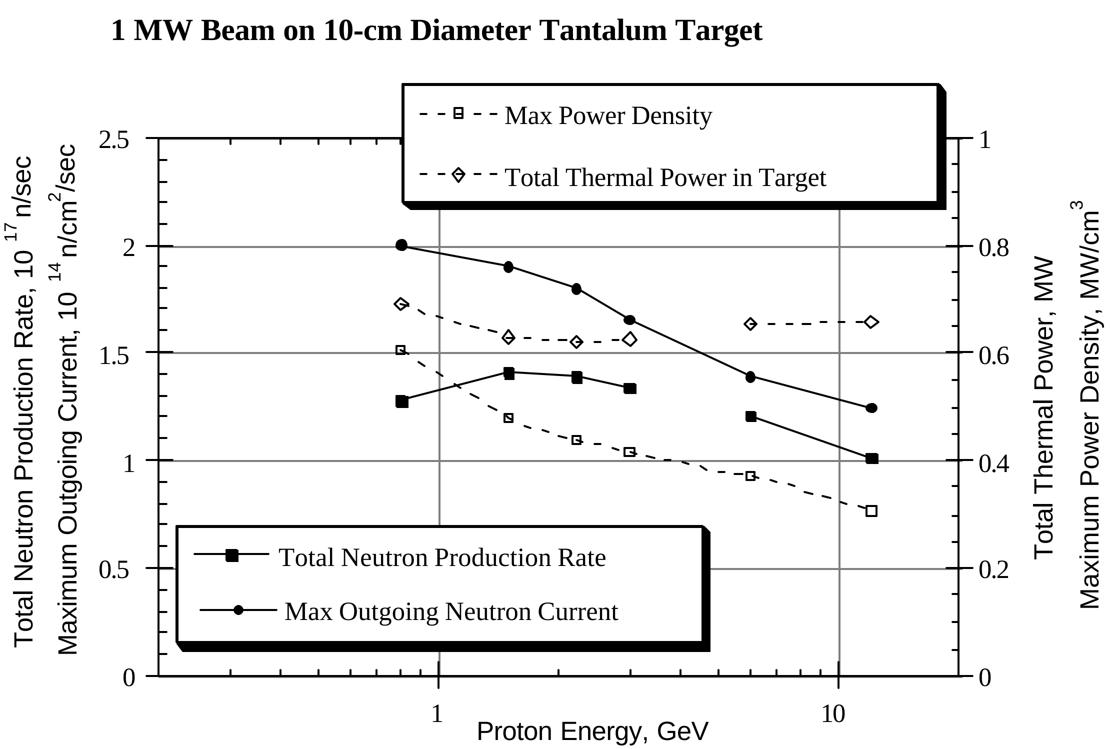


Variation of spallation neutron production with proton energy

- Although the data of Fraser, et. al. imply that the neutron production rate increases linearly with proton energy, this is only because of the limited range of energies in their data. Measurements and calculations at higher energies indicate that the yield falls away from the linear rule above about 1.0 GeV, instead approaching $E_p^{0.8}$. The cause of this is that as the energy increases, so does the rate of producing π^o's. These decay so rapidly that they do not take part in the internuclear cascade although the $\pi^\pm$ do—those live longer. The π^o's decay to a pair of 70 MeV gamma rays, which interact only weakly and produce few neutrons. Consulting the Hadron family tree, we see that 1 GeV is well above the threshold for π production, so the process is well established in the cascade for protons starting above 1 GeV. There are also other meson thresholds at higher energy, so another break may be present for energies well above 10 GeV.

Neutron and power production in spallation targets

- The figure shows the calculated variation of total thermal power, maximum power density, total neutron production, and maximum outgoing neutron current as a function of proton energy for a W target and shows the $E^{0.8}$ rule.



3. Pulsed *vs*. Steady Sources

- There are two types of neutron sources: steady, that is, constant in time, and pulsed. Among high-flux installations, pulsed accelerators drive most pulsed sources (the famous exception is the pulsed reactor at Joint Institute for Nuclear Research, Dubna, Russia). Most steady sources are research reactors (the famous exception is the cyclotron-driven spallation source at Paul Scherrer Institute, Villigen, Switzerland). Low-flux facilities driven by low-energy accelerators typically have adjustable duty cycles from pulsed to steady-state.

- The main defining characteristics of pulsed sources are the pulse length and the pulsing frequency.

- At the one extreme are what are known as "short-pulsed" sources, in which the source pulse is shorter than the shortest moderation time of interest, about 0.5 microsecond for slowing-down to 10 eV in dense hydrogenous moderators. Then the source pulse width is irrelevant, and only the frequency matters.

Pulsed *vs*. Steady Sources

- In between the steady and short-pulsed cases are "long-pulsed" sources, in which the pulse width is on the order of 1.0 millisecond, greater than the lifetime of moderated neutrons in most media.

- A prime advantage of pulsed operation is that the instantaneous intensity is much greater than the average, while the heat generated in the target and moderators, which is carried off slowly, dissipates at the time-average rate. The effective peak intensity is the average intensity divided by the duty cycle factor,

$$\hat{I} = \bar{I}/(f\,\tau) \ ,$$

- where τ is the width of the peak, which, if the intensity measure is the flux at the source surface in a short-pulsed source, depends on the energy of neutrons at which the peak is evaluated. In a long-pulsed source, τ is the duration of the source pulse.

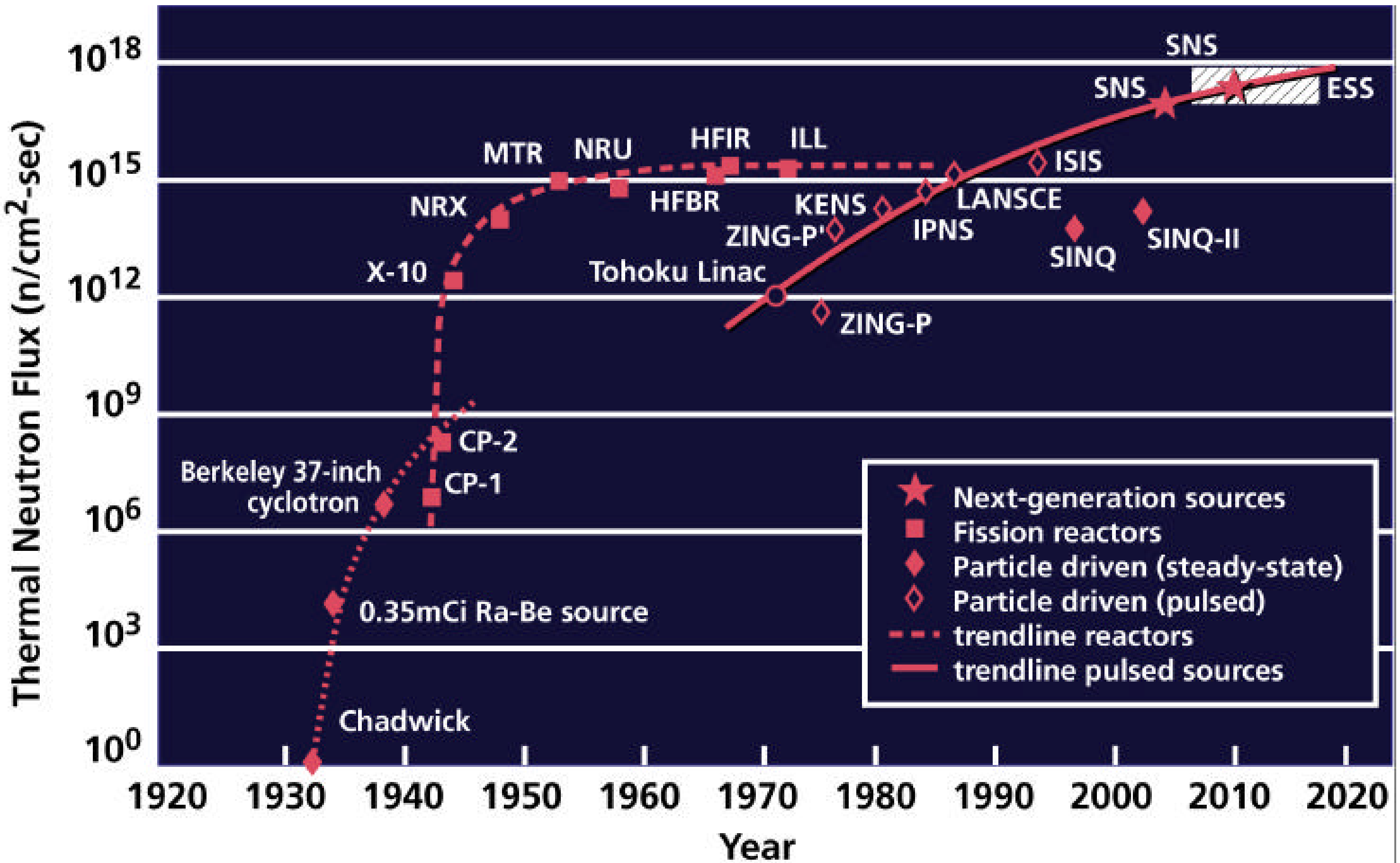
4. Some practicalities

- In low-energy charged particle sources, the incident particle range is so small and the dE/dx energy loss so great that targets must be very thin, even windowless. Neutron production efficiency is low, and available accelerators easily tax heat transfer limits.
- Bremsstrahlung photoneutron sources, driven by high-power electron linacs, have reached engineering limits on heat transfer; moreover, the photoneutron production process is rather inefficient.
- Reactors have reached engineering heat transfer limits, because the amount of energy to be dissipated for each neutron produced is fairly large.
- Spallation sources require big accelerator drivers, which, fortunately are developing as source technology evolves. Spallation neutron production requires dissipating substantially less heat than other methods. Moreover, accelerator technology for producing pulsed beams at useful frequency favors pulsed operation, giving high peak fluxes and enabling use of time-of-flight methods of spectroscopy that use a large fraction of the produced neutrons.

More practicalities

- Solid targets are suitable up to a few-MW beam power in small targets such as are of interest in neutron scattering applications. At higher beam power, the coolant dilution, if nothing else, requires dilution of the dense material to the point that mercury is the target material of choice.
-
- Short-pulsed sources are subject to the relatively unfamiliar thermo-mechanical shock, whereby the material heats up faster than it can expand to accommodate thermal expansion. High stresses result in solid targets and in the walls of both solid and liquid targets.
- Long-pulsed sources are free of the thermal shock effect if the pulse duration exceeds the time for sound waves to travel a typical target dimension. Methods for effective use of long-pulsed sources need further development.

5. Development of neutron facilities



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

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