MASTER DI II LIVELLO IN RADIOPROTEZIONE

Neutron detection and measurements

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Neutron detection and measurements

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- Neutron detection methods
- Neutron dosimetry
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The neutron was discovered by Chadwick in 1932.

The neutron is a nuclear particle having mass slightly greater than that of a proton (939.65 MeV, 938.27 MeV).

Unstable as free particle; disintegrates into a proton, an electron and an antineutrino ($T_{1/2}$)=12 min

It as no charge and hence suffers no Coulomb-force interaction with either the orbital electrons or the nucleus of an atom. Neutrons essentially interact only with the atomic nucleus

Since the discovery of neutron, the scope and importance of neutron physics have grown remarkably, and there is now a wide interest in the ideas, methods, and applications which have been developed in this field. Neutrons, because they are uncharged heavy particles, have properties which make them especially interesting and important in contemporary science and technology.

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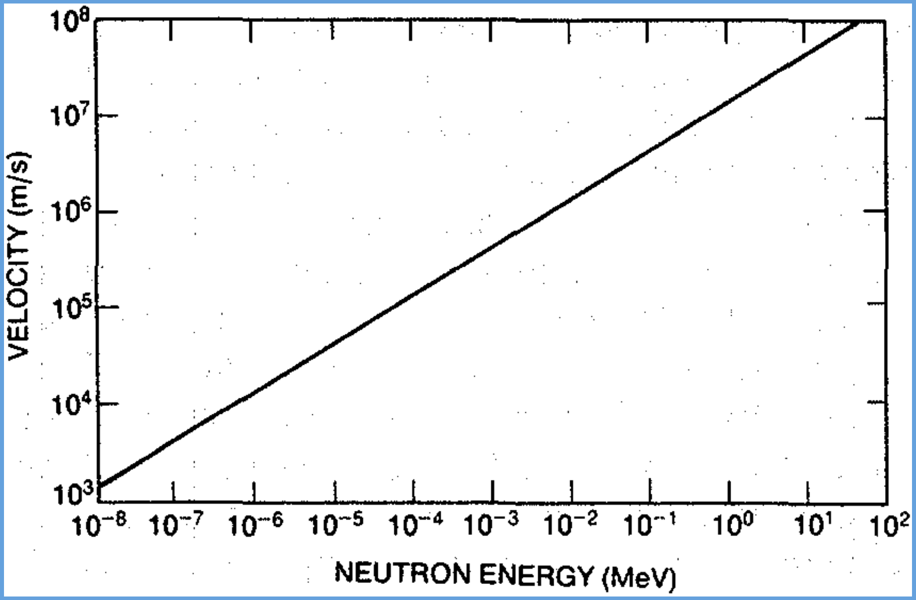
Neutrons are classified in terms of their energies into the following groups according to their kinetic energies and interactions although the borders between the various divisions are not sharply defined

Neutron groups by energies

Cold	< 0.0253 eV
Thermal	0.0253 eV
Epithermal	0.0253 eV- ~1 eV
Slow	0.0253 eV- 100 eV
Intermediate	0.5 - 10^4 eV
Fast	0.01 - 10 MeV
High Energy	≥ 10 MeV

The energy-velocity relationship



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Thermal Neutrons

Neutrons while interacting with the matter suffer collisions in which they lose energy until their energy is the same of as that of atoms of the surrounding medium and than in thermal equilibrium with medium at ordinary room temperature

The thermal neutron velocity/energy distribution is Maxwellian.

$$\frac{dN_0}{dE} = N(E) = \frac{2\pi N_0}{(\pi kT)^{3/2}} \sqrt{E} e^{-mv^2/2kT}$$

$$\frac{dN_0}{dv} = N(v) = \frac{4\pi v^2 N_0}{(2\pi kT)^{3/2}} e^{-mv^2/2kT}$$

where k is Boltzmann's constant; T is the absolute temperature of the medium; and N_0 is the total number of neutrons per unit volume

By setting the derivative of the N(E) and N(v) expressions equal to zero, the most probable energy and velocity, respectively, can be obtained.

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$$v_p = \sqrt{2kT/m}$$

V_p= the most probable energy

k= Boltzmann constant=1.38x10^{-23} J/K=8.617x10^{-5} eV/K

K= unit of temperature

m= neutron rest mass = 939 MeV=1.67x10^{-27} kg

$$v_0 = \sqrt{\frac{2kT}{m}} = \sqrt{\frac{2 \bullet 1.38 \bullet 10^{-23}(J/K) \bullet (273+20)(K)(kg \bullet m^2/s^2)}{1.675 \bullet 10^{-27}(kg)(J)}}$$

for a neutron at 20 °C=(293+20)K

2197 m/s

$$E_T = \frac{1}{2} m v_p^2 = \frac{1}{2} m\left(2kT/m\right) = kT$$

E_0=kT=(8.617x10^{-5} eV/K) (293+20)(K)=0.0253 eV

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(α-n), sources

One can manufacture a radioactive neutron source by combining an alpha emitting radionuclide such as ^{210}Po, ^{226}Ra, ^{239}Pu, ^{241}Am with a light metal such as Be or B

the reactions that follow are:

$$^{9}Be(\alpha, n)^{12}C$$

$$^{10}B(\alpha, n)^{13}N$$

$$^{11}B(\alpha, n)^{14}N$$

The neutron production persists and changes according to the radioactivity of the alpha source used.

there is a continuous energy spectrum

		Energy range	Average energy
Source	Reaction	(MeV)	(MeV)
Ac-Be	α,n		4.43
^{210}Po-Be	α,n		4.84
^{238}Pu-Be	α,n		5.11
^{238}Pu-F	α,n		3.64
^{241}Am-F	α,n		3.69
^{241}Am-Be	α,n		4.4
^{241}Am-B	α,n		2.8
^{226}Ra-Be	α,n	0-8 MeV	4.5

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(γ-n), sources

Similarly, Be and or an other low z material can also be used with a high-energy gamma emitter such as ^{24}Na, ^{88}Y, ^{124}Sb, ^{114}I as a photoneutron, or (γ, n) source of neutrons.

by choosing radioisotopes with a single γ-ray then monoenergetic neutrons can be produced

The main disadvantage is the fact that very large gamma rays activities must be used in order to produce very attractive intensities

the sources are produced in a reactor using conventional (n,γ) reactions except for ^{226}Ra

the reaction that follow is:

^{9}Be(γ, n)^{8}Be

^{2}He(γ,n)^{1}H

		Energy range	Average energy
Source	Reaction	(MeV)	(MeV)
^{124}Sb-Be	γ,n		0.024
^{88}Y-Be	γ,n		0.16
^{24}Na-D$_2$0	γ,n		0.22
^{88}Y-Be	γ,n		0.31

The neutron production persists and changes according to the radioactivity of the alpha source used.

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Spontaneous Fission Sources

some transuranic heavy nuclei have an appreciable spontaneous fission emitting neutrons

some sources include: ^{254}Cf, ^{252}Cf, ^{244}Cm, ^{242}Cm, ^{238}Pu and ^{232}U

in most cases the half-life for spontaneous fission is greater than alpha decay

^{254}Cf decays almost completely by spontaneous fission with a 60 day half-life

The most common spontaneous fission source is ^{252}Cf. Its half life is 2.64 y

^{252}Cf undergoes spontaneous nuclear fission at an average rate of 10 fissions for every 313 alpha transformations. SF 3% α 97%

neutron emission rate is 2.31×10^6 neutrons per second per microgram of ^{252}Cf

emitted neutrons have a wide range of energies with the most probable at ~ 1 MeV and the average value ~ 2.3 MeV

		Energy range	Average energy
Source	Reaction	(MeV)	(MeV)
^{252}Cf	sf	0-10 MeV	2.3

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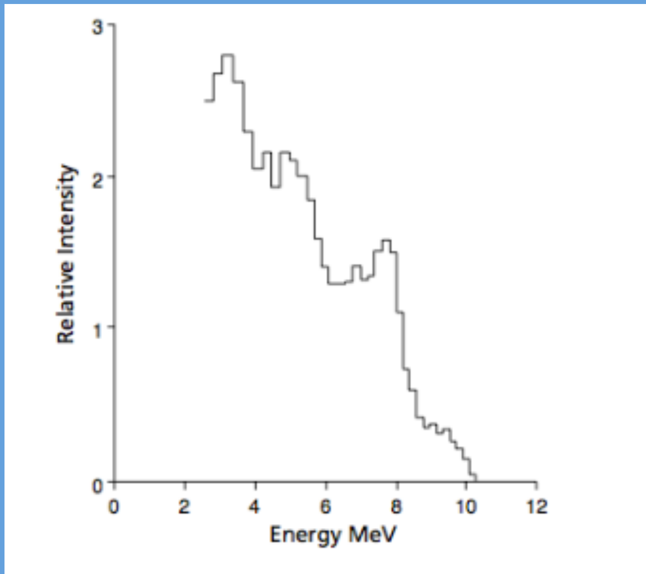
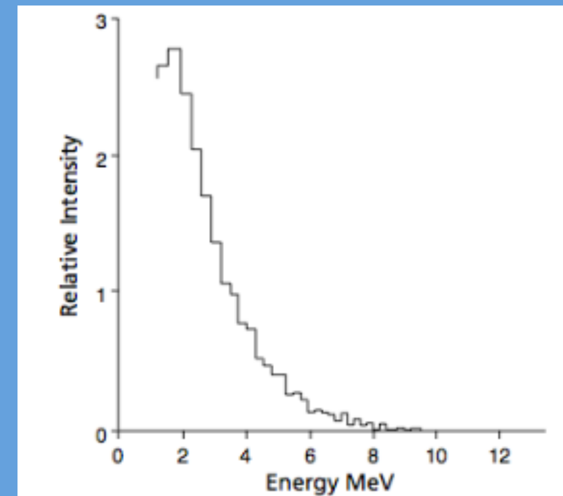
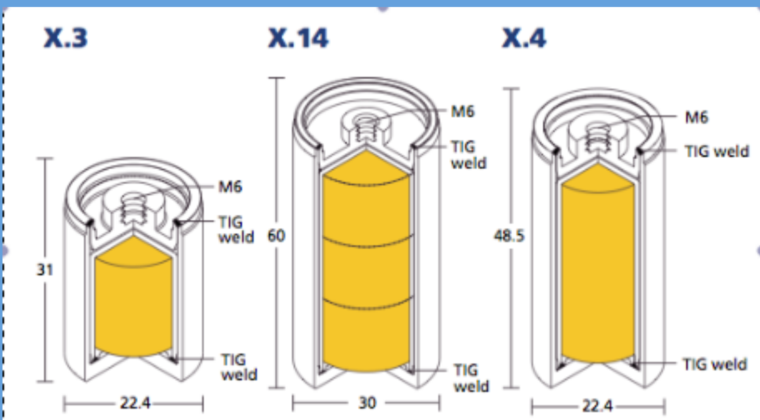
Neutron emission: ~2.2 x 10^6 n/sec per Ci
~6 x 10^7 n/sec per TBq

Nuclear Data	
Californium-252 decays by α-emission and spontaneous fission emitting neutrons.	
Half-life (α-decay):	2.73 years
Half-life (spontaneous fission):	85.5 years
Half-life (effective):	2.65 years
Neutron emission:	2.3 x 10^9 n/sec per mg
Average neutron energy:	~2MeV

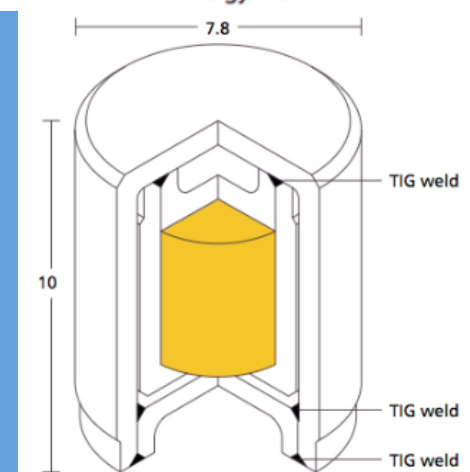


Half life = 432 y





Each source type has a 2mm "screwdriver" slot on the end face.



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Neutron sources

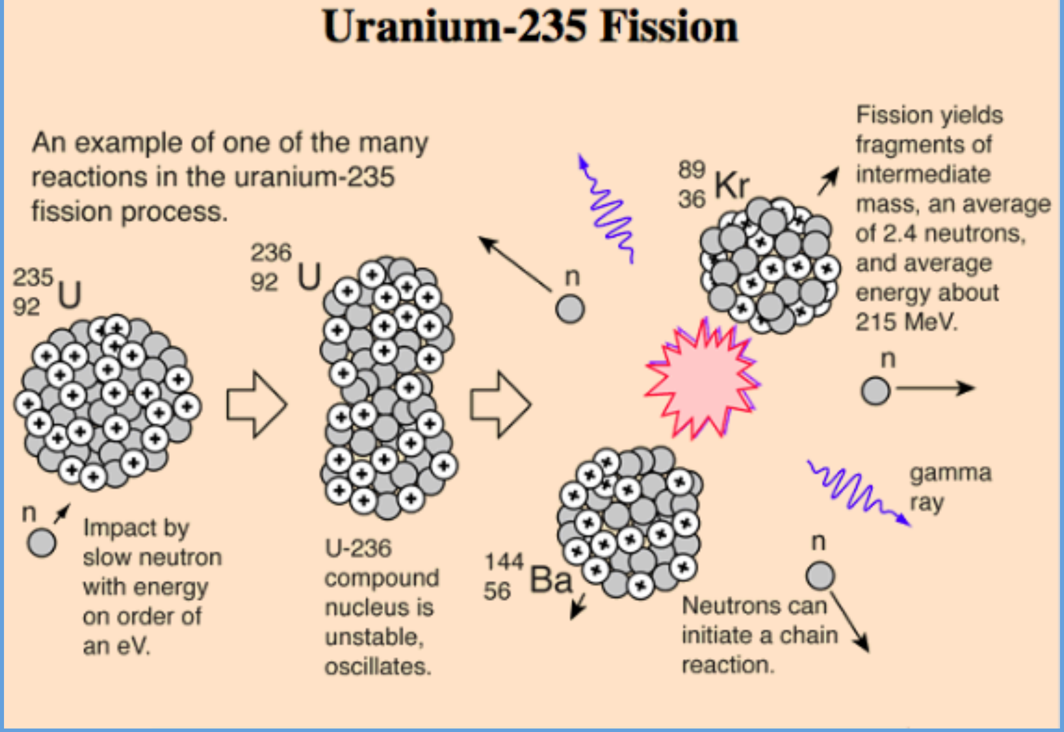
Nuclear reactors produce neutrons with a wide range of energies. These are immediate sources, and the production of neutrons terminates when they are shut down.

nuclear reactor most prolific source for each fission at least two neutrons and half are produced

- **energy spectrum from the fission of ^{235}U extends from several keV to more than 10 MeV**
- **most probable energy ~ 0.7 MeV**
- **average energy ~ 2 MeV**

$n + {}^{235}U \longrightarrow {}^{236}U$

$^{236}U \longrightarrow {}^{144}Ba + {}^{89}Kr + 3n + 177 MeV$



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Centro Ricerche ENEA Casaccia

nuclear reactor

Reattore TRIGA
(Training, Research, Isotopes, General Atomics)

Le caratteristiche principali del reattore sono:
potenza massima: 1 MW
flusso neutronico max: 2,7 10^{13} n · cm^{-2} · s^{-1} @ 1 MW
raffreddamento ad acqua in circolazione naturale

Triga Lena Universita' Pavia

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Accelerators produce neutrons with a wide range of energies. These are immediate sources, and the production of neutrons terminates when they are shut down.

particle accelerators are used to generate neutrons by means of nuclear reactions such as: D-T, D-N, P-N

$^{3}H(d,n)^{4}He$ - Q-value = 17.6 MeV → 14.1MeV neutrons

$^{2}H(d,n)^{3}He$ - Q-value = 3.27 MeV

$^{7}Li(p,n)^{7}Be$ - Q-value = 1.65 MeV

positive Q-values means the nuclear reaction can be induced with only several hundred keV ions

		Energy range	Average energy
$^{2}H^{2}H$ (D-D)	d,n		3.27
$^{2}H^{3}H$ (D-T)	d,t		14.1
^{7}Li ^{8}Be	p,n	0.05-0.3	
^{3}H ^{3}He	p,n	0.3-5	
^{2}H ^{3}He	d,n	2.5-6	
^{3}H ^{4}He	d,n	14-22	

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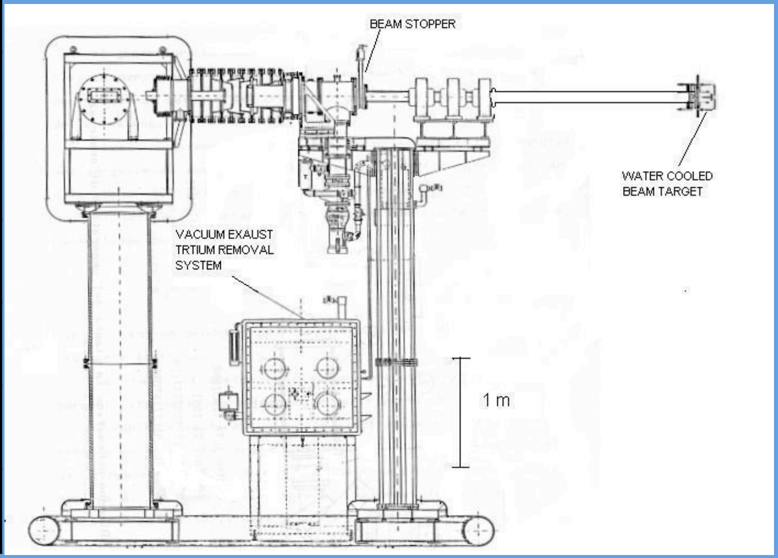
➢The *deuterium-tritium* (D-T) *generator* is a straightforward source of high-energy neutrons in which a tritium target is bombarded by deuterons that have been accelerated to about 200 keV.
The reaction is exoenergetic and releases 17.6 MeV, of which 14.1 MeV is given to the ejected neutron. The neutrons so produced are monoenergetic and are ejected isotropically, which causes the flux to fall off as the square of the distance.

The 14 MeV Frascati Neutron Generator (FNG)

	14 MeV	2.5 MeV
	D-T operation	*D-D operation*
Max neutron yield	$1*10^{11}$ n/s	$1*10^{9}$ n/s
Max neutron flux → volume	$5*10^{9}$ neutrons cm^{-2} s^{-1} → $1cm^3$	$5*10^{7}$ neutrons cm^{-2} s^{-1} → $1cm^3$
Max irradiation volume → flux	A few cm^3 → 10^7/s/($4*\pi*m^2$)	A few cm^3 → 10^5/s/($4*\pi*m^2$)
Max irradiation time-targets	25 hours (one target)	continuous
Average utilization/year	> 150 hours/years	
Free time available for irradiation	200 hours/years	
Maximum achievable fluence	$1*10^{15}$ n/cm^2 on a 1 cm^3 sample	$1*10^{13}$ n/cm^2 on a 1 cm^3 sample



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Neutron sources

Neutrons are produced using accelerators through the following photonuclear reactions reaction

In an electron accelerator, neutrons are produced through the photonuclear process (γ,n), (γ,αn), (γ,pn), etc., in which the bremsstrahlung radiation is the incident radiation. Because photons have substantially larger nuclear cross-sections than electrons, neutrons and other particles resulting from inelastic nuclear reactions are produced mainly by the photon component of the EM shower.

It is evident from the figure that these photo-nuclear processes have little importance in the development and attenuation of EM showers. Neutrons from photonuclear reactions are outnumbered by orders of magnitude by electrons and photons that form the cascade. However, some of these neutrons constitute the most penetrating component (except the special case of muons) of the prompt radiation field, and will therefore be determining factor for radiation fields behind thick shielding.

Three photoneutron production processes are important at high-energy electron facilities, as illustrated in figure

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Giant Resonance Production.

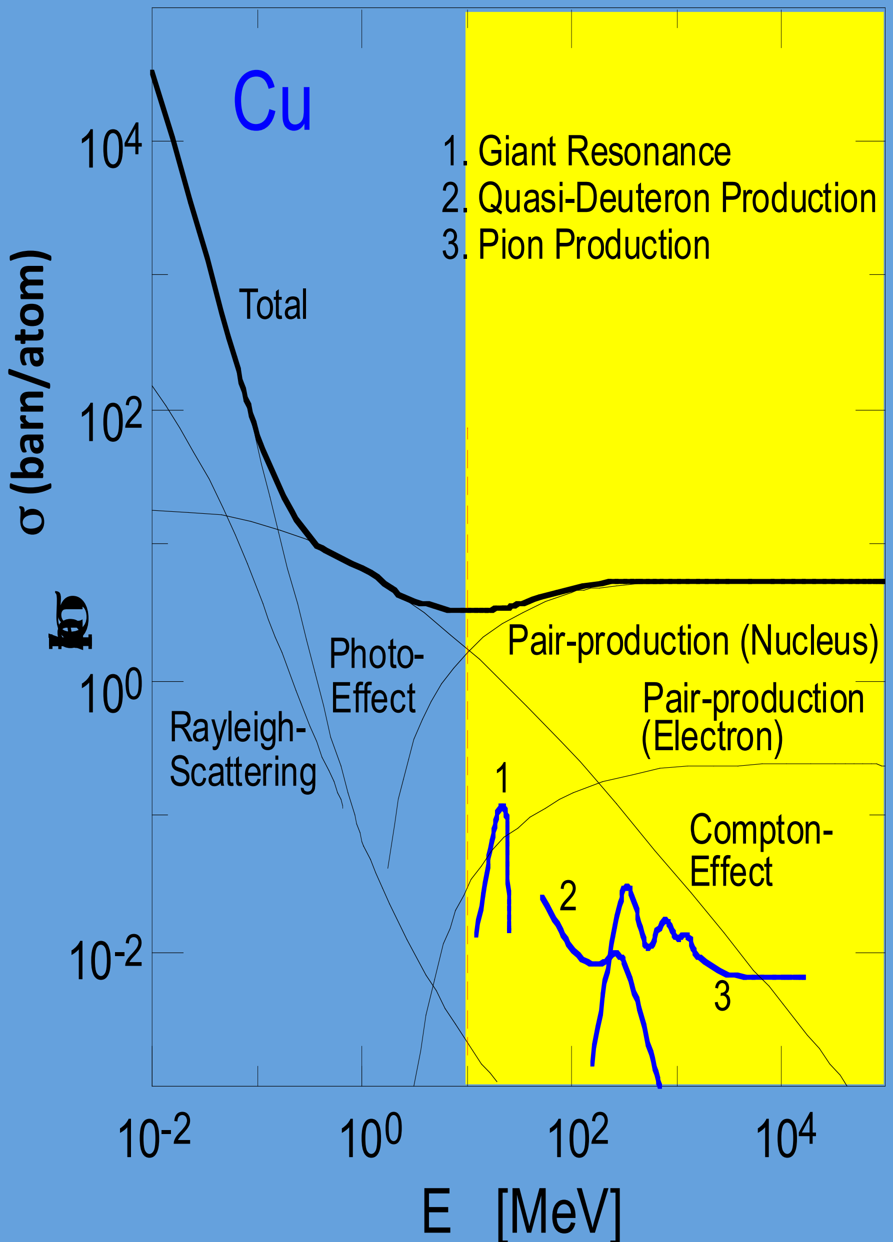
This process can be seen in two steps: excitation of the nucleus by photon absorption, and subsequent de-excitation by neutron emission, where memory of the original photon direction has been lost. As a result, the angular yield of giant resonance neutrons is nearly isotropic.

$E_{threshold}$ ≈ 10 - 19 MeV (low - Z)

≈ 4 - 6 MeV (high - Z)

The cross-section has large maximum around 20-23 MeV for light nuclei (mass number *A*≤40) and 13-18 MeV for heavier nuclei.

For A≥40 the energy of the cross-section peak is approximately given by $k_0 = 80.A^{-1/3}$ MeV.



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In order to estimate the neutron yield, this cross-section has to be folded with the photon spectrum in the target.

For thick targets, shapes of these spectra are assumed to vary as ~1/k^2, where k is photon energy.
The integrated giant resonance cross-section over the relevant energy interval of 0 to 30 MeV, weighted by a 1/k^2 spectrum, is σ_{-2} and it varies as ~ $A^{5/3}$.

For thin targets the bremsstrahlung spectrum is 1/k .
Similarly, one can obtain an integrated cross-section $\sigma_{-1} \sim A^{-4/3}$.

Neutron spectra from this process consist of "evaporation" and "direct emission" neutrons, where the former component is the dominant one.
Evaporation spectra can be described by a Maxwellian distribution, with nuclear temperatures typically between 0.5 and 1.0 MeV.

It is clear from the size of the giant resonance cross-section and the higher weight of low-energy photons in bremsstrahlung spectra that this is the dominant process of photoneutron production at electron accelerators at any electron energy.

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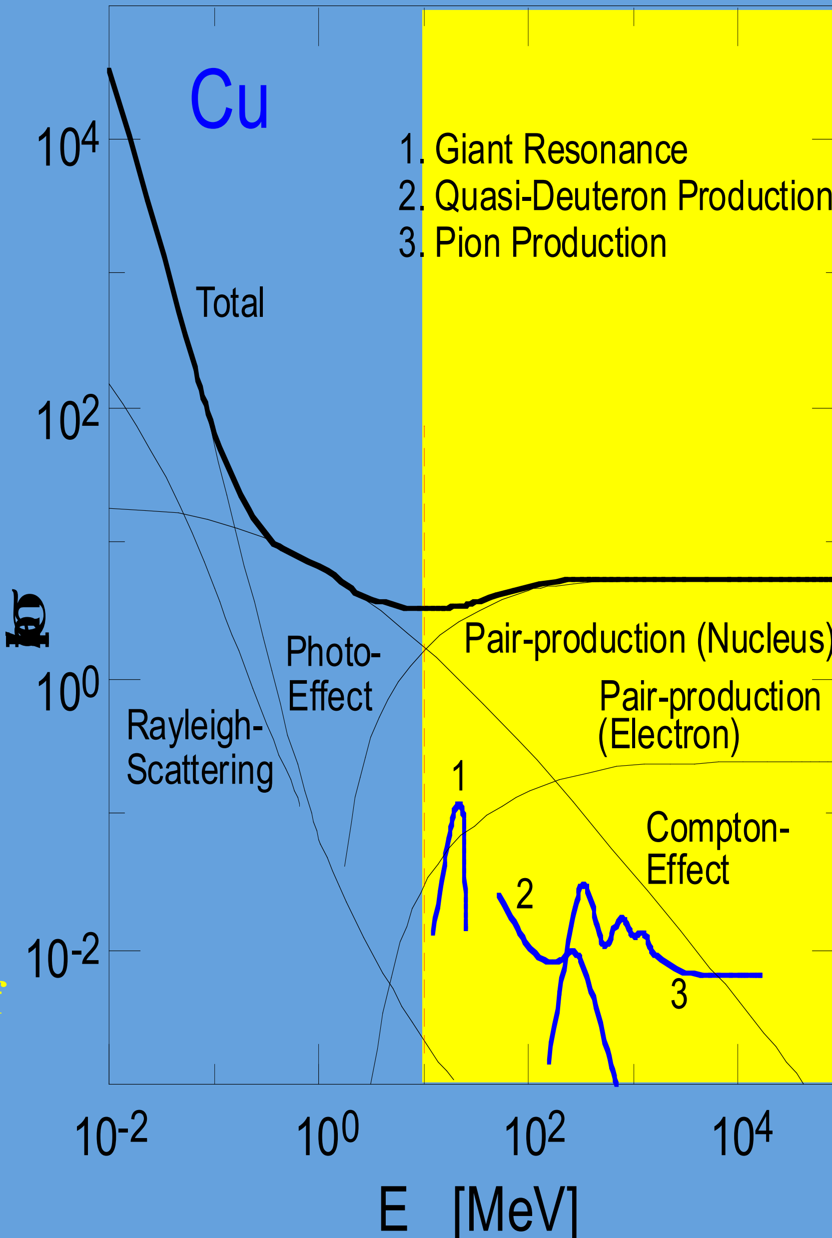
Pseudo-deuteron production.

At photon energies beyond the giant resonance, the photon is more likely to interact with a neutron-proton pair rather than with all nucleons collectively. This mechanism is important in the energy interval of 30 to ~300 MeV, contributing to the high-energy end of the giant resonance spectrum. Because the cross-section is an order of magnitude lower than giant resonance, with the added weighting of bremsstrahlung spectra, this process never dominates. In its more heavily weighted portion below 125 MeV, the cross-section varies as 1/*k*. Spectra of pseudo-deuteron neutrons can be approximately described by

$$\frac{dN}{dE_n} \approx E_n^{-\alpha} \qquad \text{for } 5\ \text{MeV} < E_n < E_0/2$$

where α varies from 1.7 to ~3.6, with values increasing from lighter to heavier nuclei.

***Photo-pion production*. Above the threshold of ~140 MeV production of pions (and other particles) becomes energetically possible. These pions then generate secondary neutrons as byproduct of their interactions with nuclei.**



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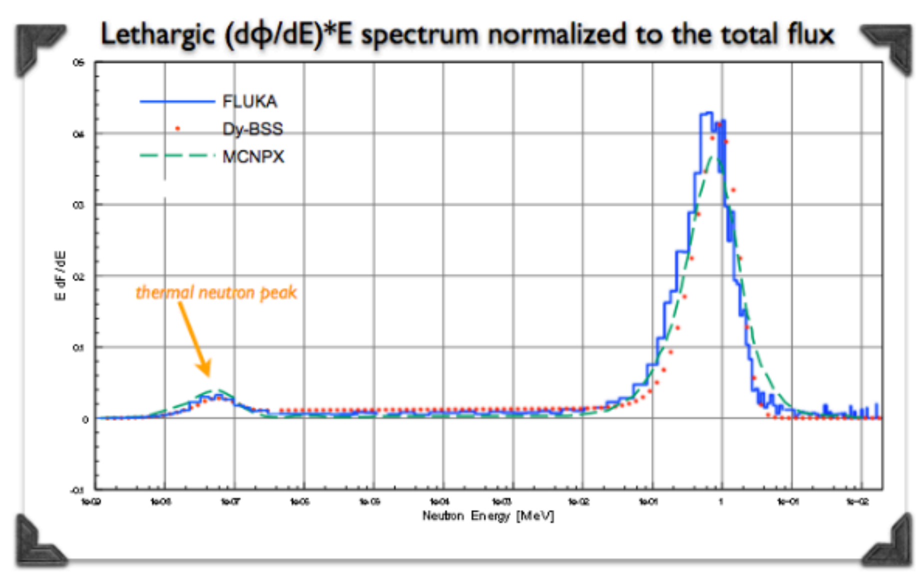
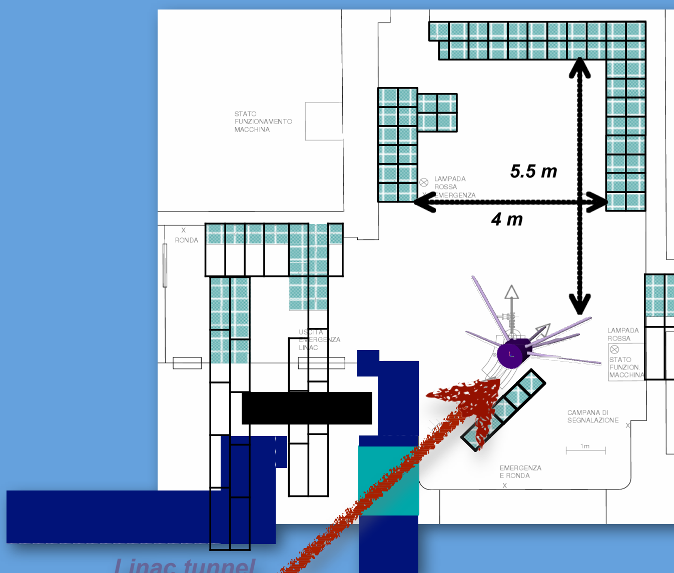
➢*Photoneutron sources* using electron accelerators : n@BTF

BTF main e- beam parameters E=500 MeV 1-10^{10} e-/pulse 1-10 Hz

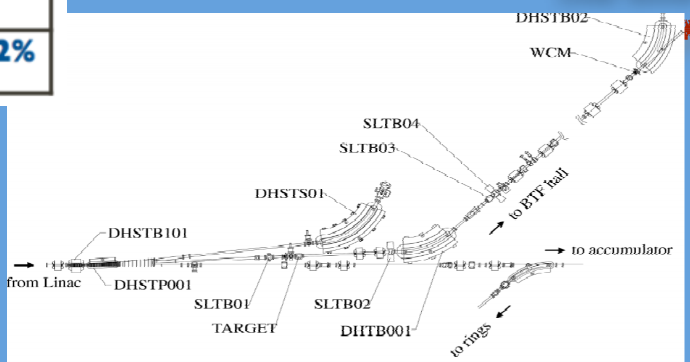


BTF Experimental Hall



Total Neutron Flux per primary particle		
Ex. Measurement	FLUKA	MCNPX
8.04E-7 ±3%	**8.10E-7 ±4%**	**8.02E-07 ±0.2%**

Neutron Flux at 1.5m from shield = 4E+5 n/cm2/s corresponds to Equivalent Dose=45 mSv/h



BTF Transfer Line

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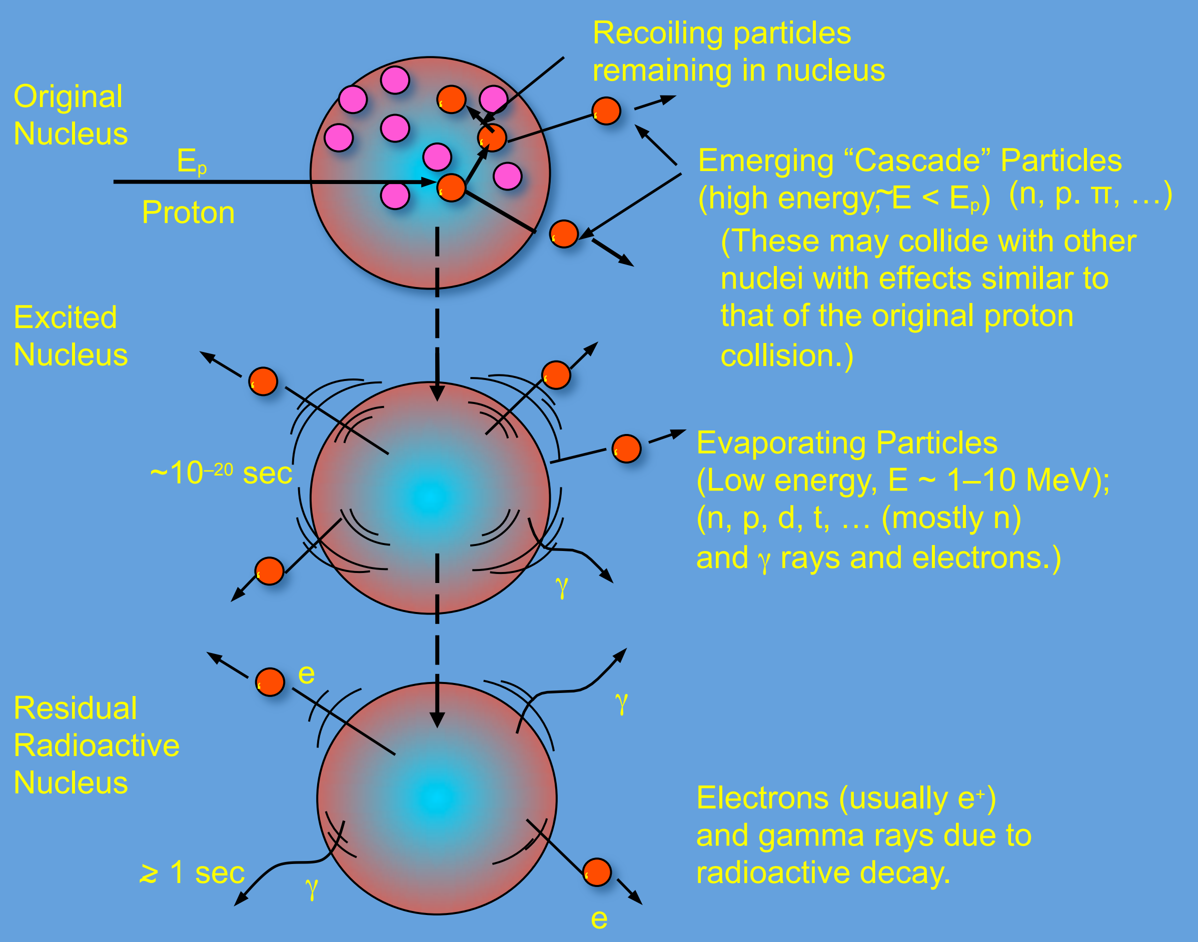
If an high energy particle hit a nucleus of an high z material *W, Pb, U* you can have a spallation nuclear reaction.

P + heavy nucleus = 20 n + fragments

1GeV 23MeV/n



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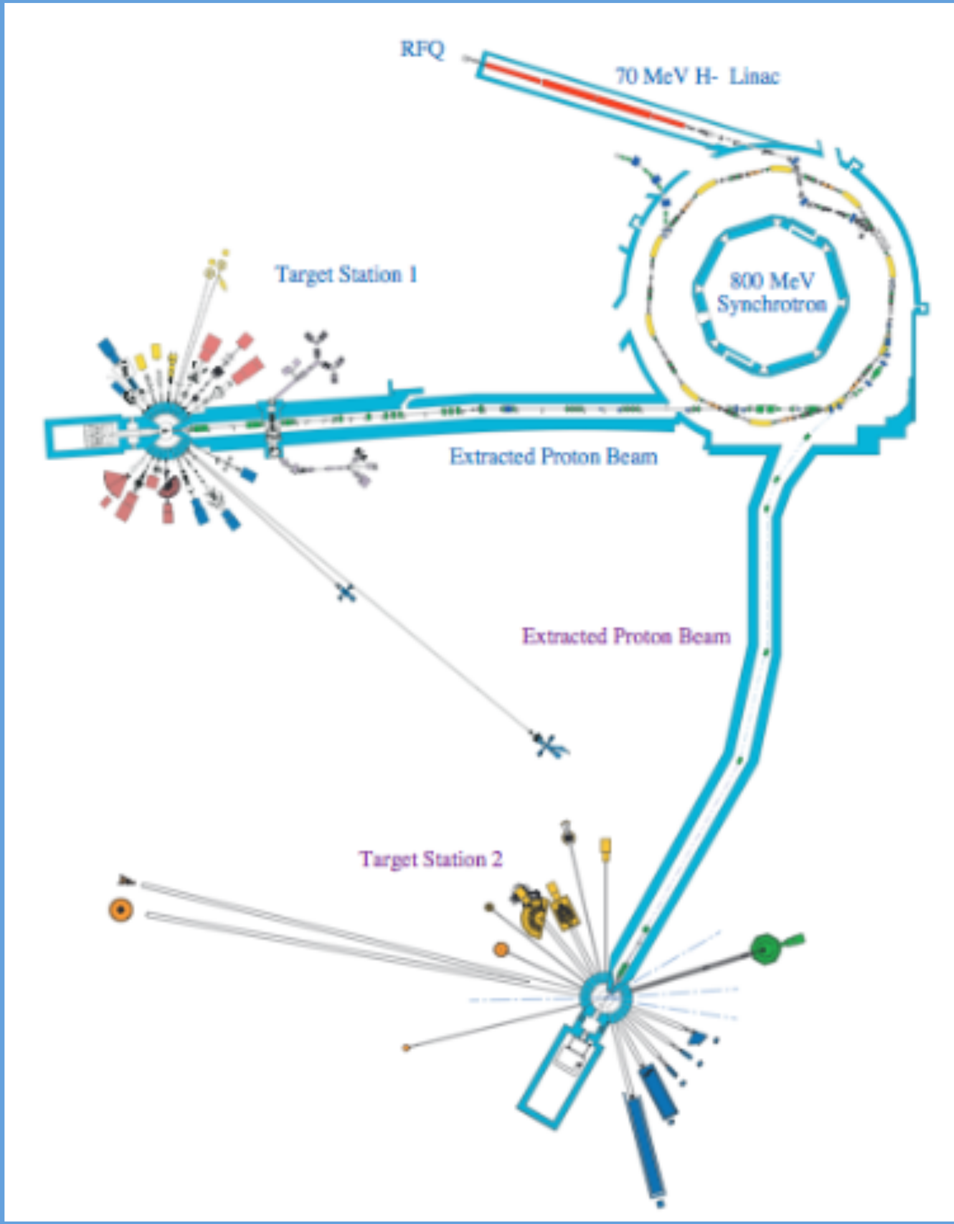
Rutherford Appleton Laboratory (RAL)

The ISIS neutron producing target (TS-1) is driven by a 50 Hz, 800 MeV, 200 μA proton beam from a rapid cycling synchrotron, which is fed by a 70 MeV H^- drift tube linac (DTL)



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Neutron Generators

Thermo Scientific™ MP 320 is a lightweight, portable neutron generator suited for most demanding field or laboratory applications. It has very low power requirements and may be operated from battery or vehicle power sources. It is available with either a Deuterium-Tritium (DT) or a Deuterium-Deuterium (DD) neutron tube

Power Consumption	60µA
Control Module Details	Integral, digital (Control)
Description	MP 320 Neutron Generator
Duty Cycle	5 to 100%
Neutron Energy	14MeV
Neutron Yield	1 x 10?n/sec.
Power Supply	Integral
Remote Control	RS-232/RS-485
Safety Features	Keylock: on/offEmergency: on/offNormal-open and normal-closed interlocksPressure switch
Voltage	90kV
Weight (English)	26.46 lb.
Weight (Metric)	12kg

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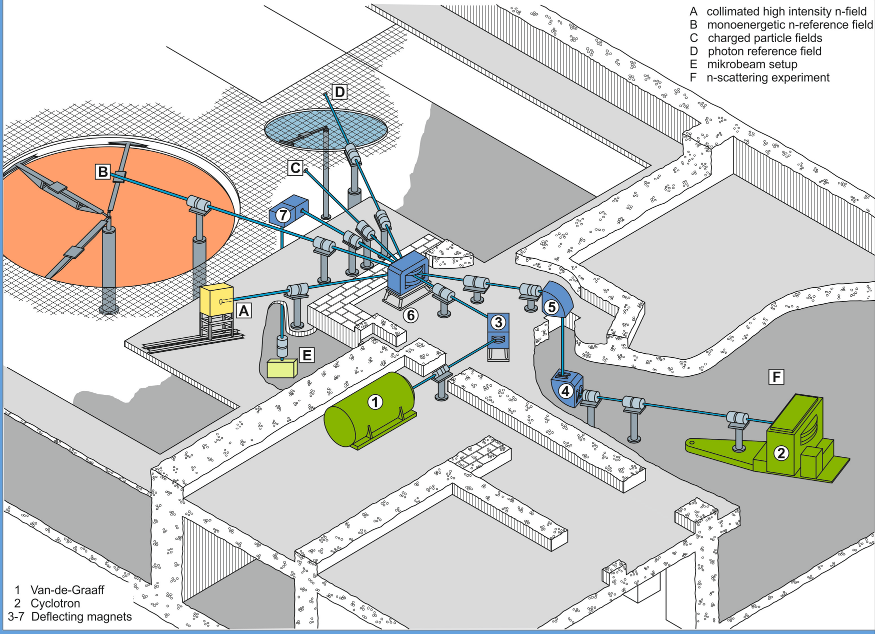
➢ ***Cyclotron-produced neutrons*** **are of high energy and are produced by accelerating high-energy deuterons onto a Be target. Neutrons released in the ^{9}Be (d, n) ^{10}B reaction are peaked in the direction of the deuteron beam and, depending on the number of deuterons in the incident beam, can produce intense focused beams of neutrons. The neutrons are not, however, monoenergetic but are distributed around a peak energy.**



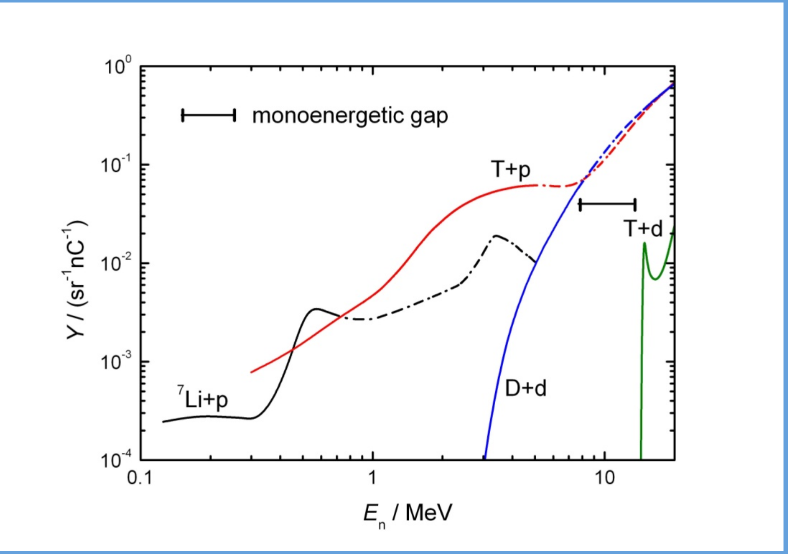


TABLE 1. Characteristic properties of the quasi-monoenergetic ISO reference fields at the PTB accelerator facility. Fluence rates ($d\Phi/dt$) and ambient dose equivalent rates ($dH^*(10)/dt$) at 1 m distances from the target are given for maximum proton or deuteron current. The relative contribution of neutrons scattered in the target is indicated by Φ_{sc}/Φ. The mean peak energy and the width (FWHM) of the distribution of direct neutrons are denoted by $\langle E\rangle$ and ΔE, respectively.

Reaction	$\langle E_n\rangle$ MeV	ΔE MeV	Target	$(d\Phi/dt)$ $cm^{-2}\cdot s^{-1}$	Φ_{sc}/Φ %	$(dH^*(10)/dt)$ $mSv\cdot h^{-1}$
$^{7}Li(p,n)^{7}Be$	0.024	0.002	LiOH	$1.7\cdot10^{2}$	3.6	0.012
$^{7}Li(p,n)^{7}Be$	0.144	0.024	LiOH	$5.0\cdot10^{2}$	2.0	0.23
$^{7}Li(p,n)^{7}Be$	0.25	0.019	LiOH	$2.5\cdot10^{2}$	6.2	0.19
$^{7}Li(p,n)^{7}Be$	0.565	0.015	LiOH	$1.2\cdot10^{3}$	1.8	1.5
$^{3}H(p,n)^{3}He$	1.2	0.091	Ti(T)	$2.0\cdot10^{3}$	3.1	3.1
$^{3}H(p,n)^{3}He$	2.5	0.127	Ti(T)	$4.9\cdot10^{3}$	1.4	7.3
$^{2}H(d,n)^{3}He$	5.0	0.200	D_2-gas	$5.2\cdot10^{3}$	<1.0	7.5
$^{2}H(d,n)^{3}He$	8.0	0.200	D_2-gas	$1.9\cdot10^{4}$	<1.0	27.5
$^{3}H(d,n)^{4}He$	14.8	0.431	Ti(T)	$1.3\cdot10^{4}$	3.0	24.3
$^{3}H(d,n)^{4}He$	19.0	0.300	Ti(T)	$8.5\cdot10^{2}$	1.2	1.8

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The quasi-monoenergetic neutron field facilities above 20 MeV

From EURADOS Report 2013-02

Facility	Energy range [MeV]	Peak neutron fluence rate at standard irradiation position [$cm^{-2}s^{-1}$]	Beam angle relative to primary beam	Remarks
iThemba[a]	35 – 200	10^4	0°, 4°, 8°, 12°, 16°	
TSL[b]	11 – 175	10^6 for $E_p < 100$ MeV 10^5 for $E_p > 100$ MeV	0°	large experimental area
TIARA[c]	40-90	10^4	0°	large irradiation room
CYRIC[d]	20-90	10^6	0°	
RCNP[e]	100 - 400	10^5	0° - 30°	up to 100 m ToF
NPI[f]	18 – 36	Up to 10^9	0°	Standard irradiation very close to source
NFS[g]	20 – 33	n.a. yet	0°	Start late 2014

The quasi-monoenergetic neutron field facilities in the list all make use of the $^7Li(p,n)$ reaction for neutron production. The resulting neutron energy distributions consist of a peak close to energy of the incoming proton and a broad and roughly even distribution down to zero energy.

Each of these components generally contain about half the neutron intensity

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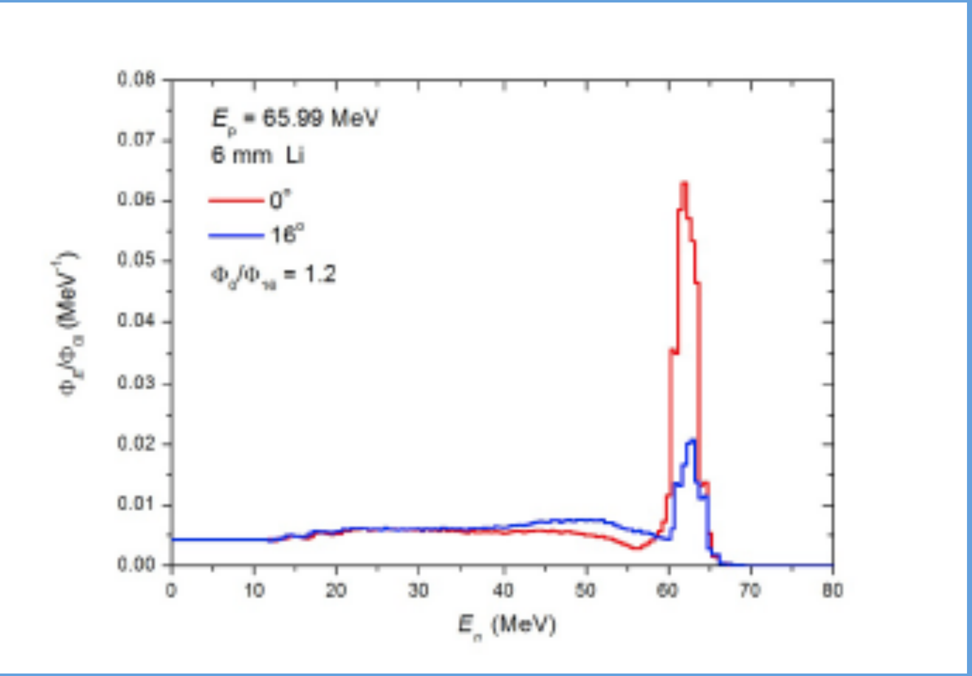
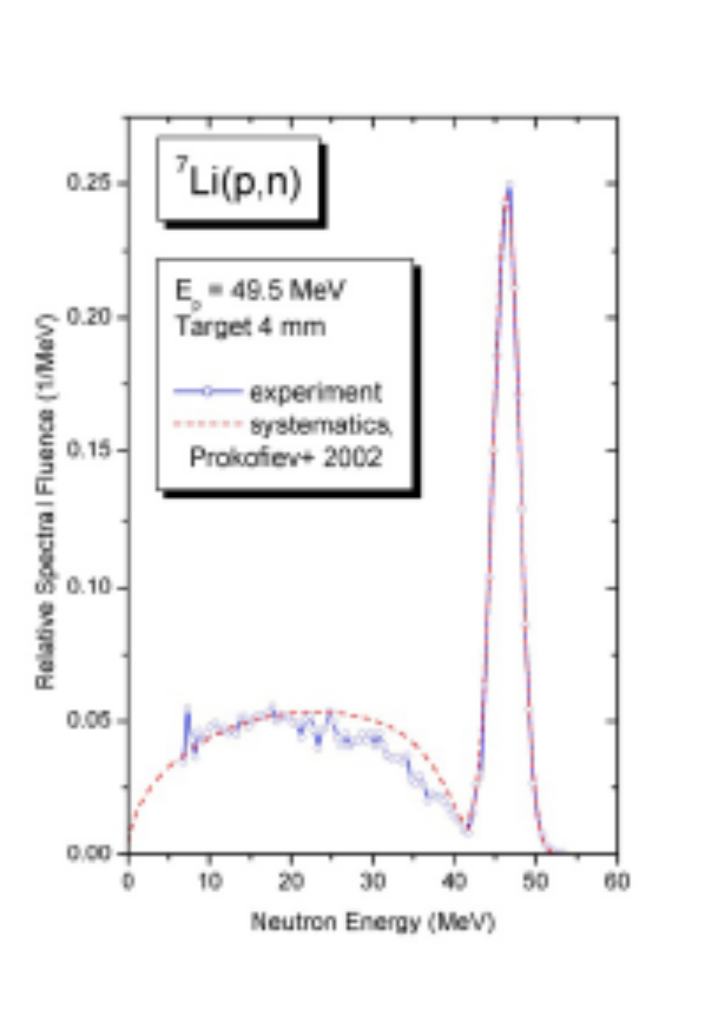


Neutron energy distributions of fluence at iThemba LABS for an incoming proton energy of 65.99 MeV and a Li target thickness of 6 mm. Energy distributions at two different angles are shown.



TSL neutron beam facility

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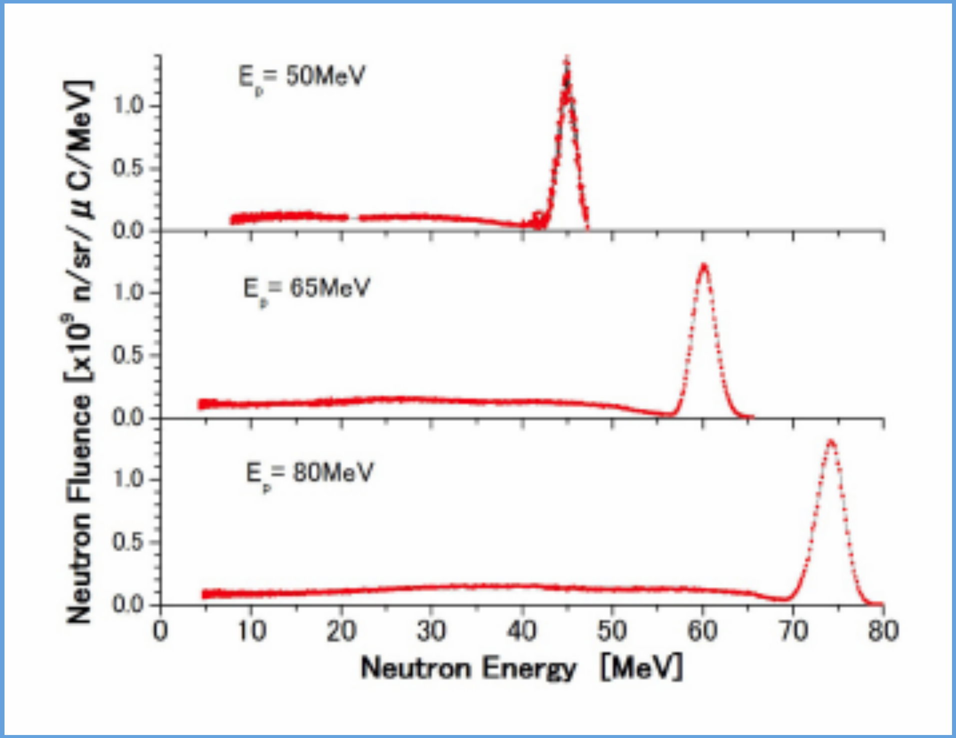

Neutron energy distributions per solid angle per electric charge measured with a 7.62 cm x 7.62 cm organic liquid scintillator by means of a time-of-flight method at TIARA. The neutrons were produced by the 7Li(p,n) reaction using 50 MeV, 65 MeV and 80 MeV protons.

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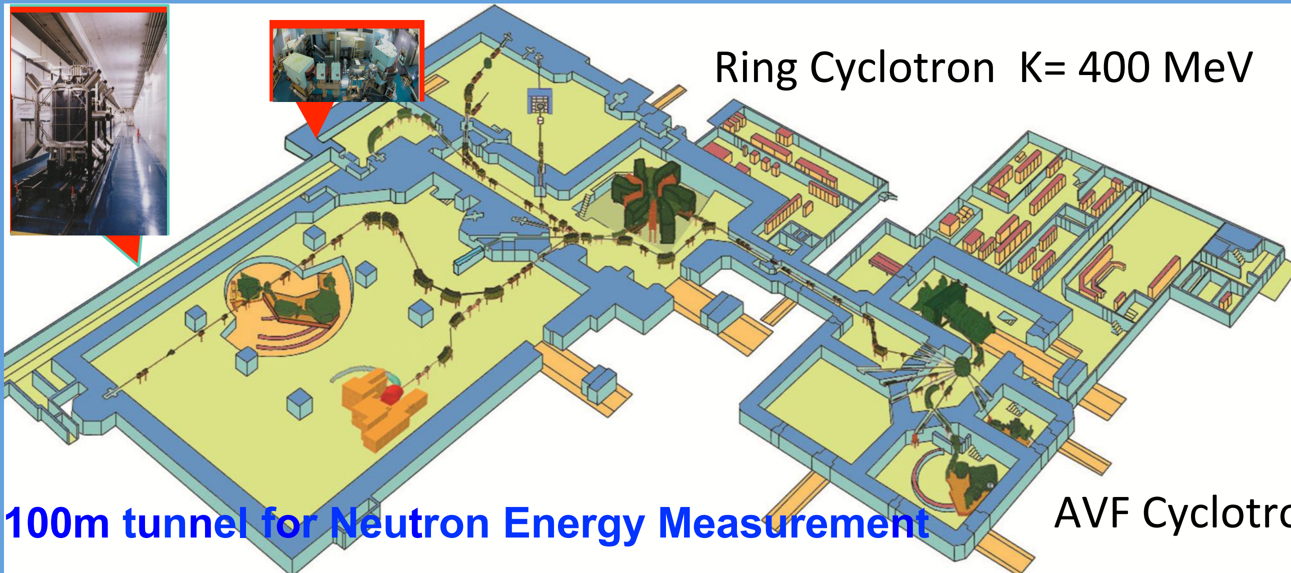

Ring Cyclotron K= 400 MeV

100m tunnel for Neutron Energy Measurement

AVF Cyclotron K= 140 MeV

From EURADOS Report 2013-02

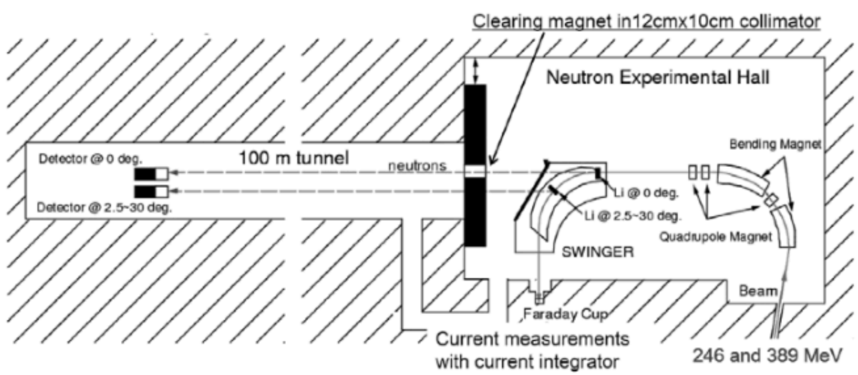

Figure 11: Illustration of the experimental set-up for neutron irradiation at RCNP.

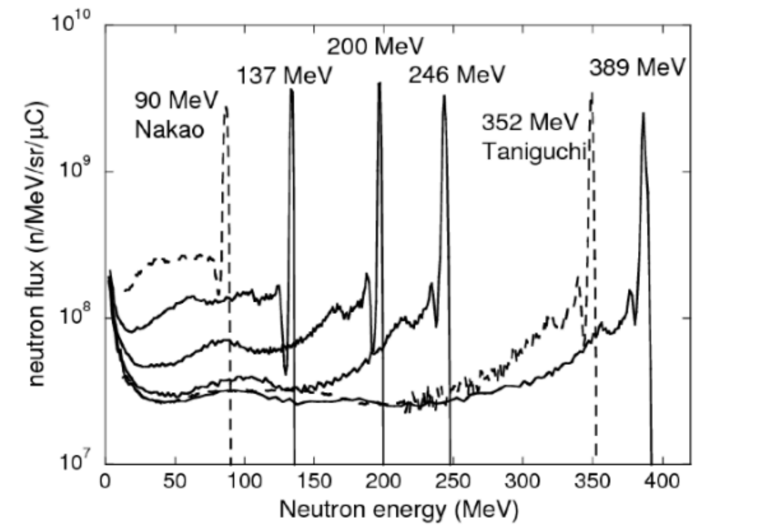

Figure 12: Neutron energy distribution per solid angle per electric charge for 137 MeV, 200 MeV, 246 MeV and 389 MeV produced by Li(p,xn) reaction at 0°; they are compared with the data obtained by Nakao et al., 1999, and Taniguchi et al., 2007.

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NPL

The primary standard for neutron emission rate

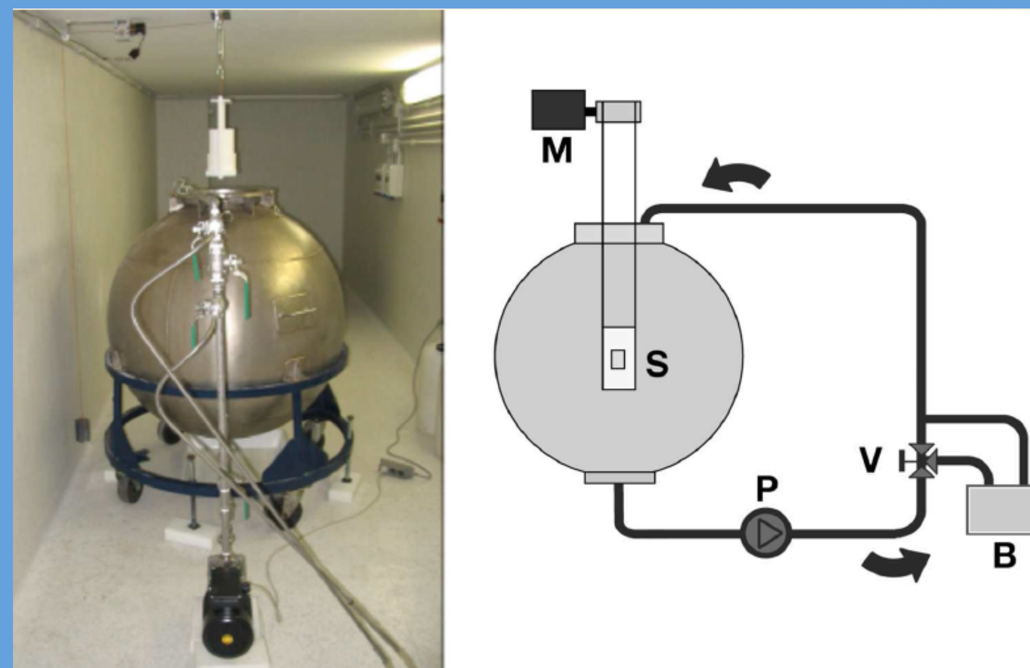
he $MnSO_4$ bathT

about 10 of such facilities worldwide

NIST

A new reduced-volume manganese bath permits calibration of low-intensity neutron sources a required for DHS applications. (Photograph by: NI&D Group.)

ENEA-INMRI



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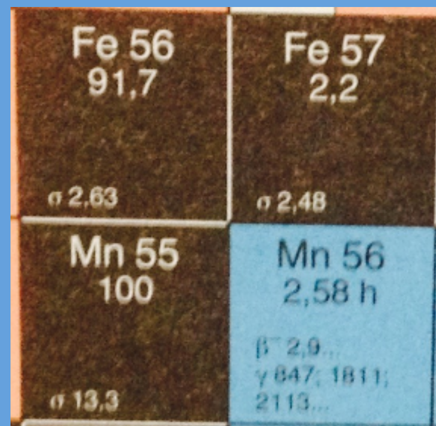
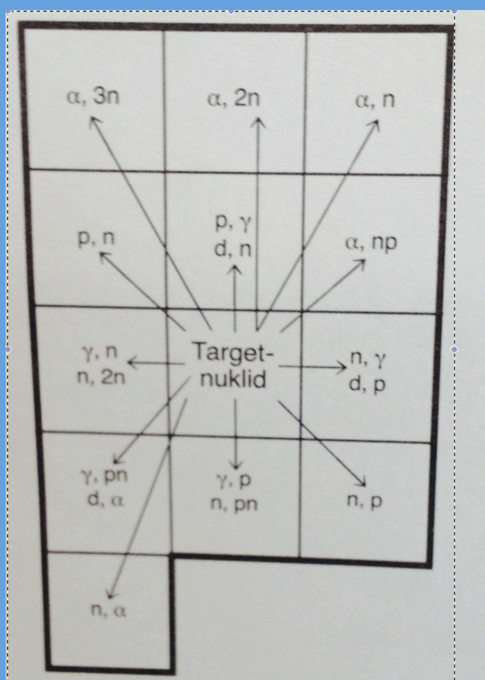
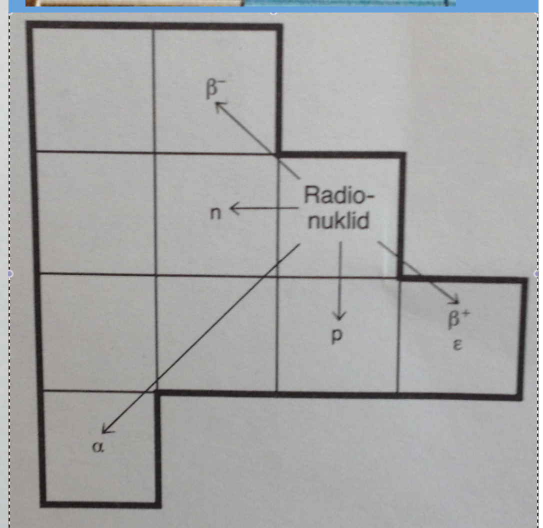
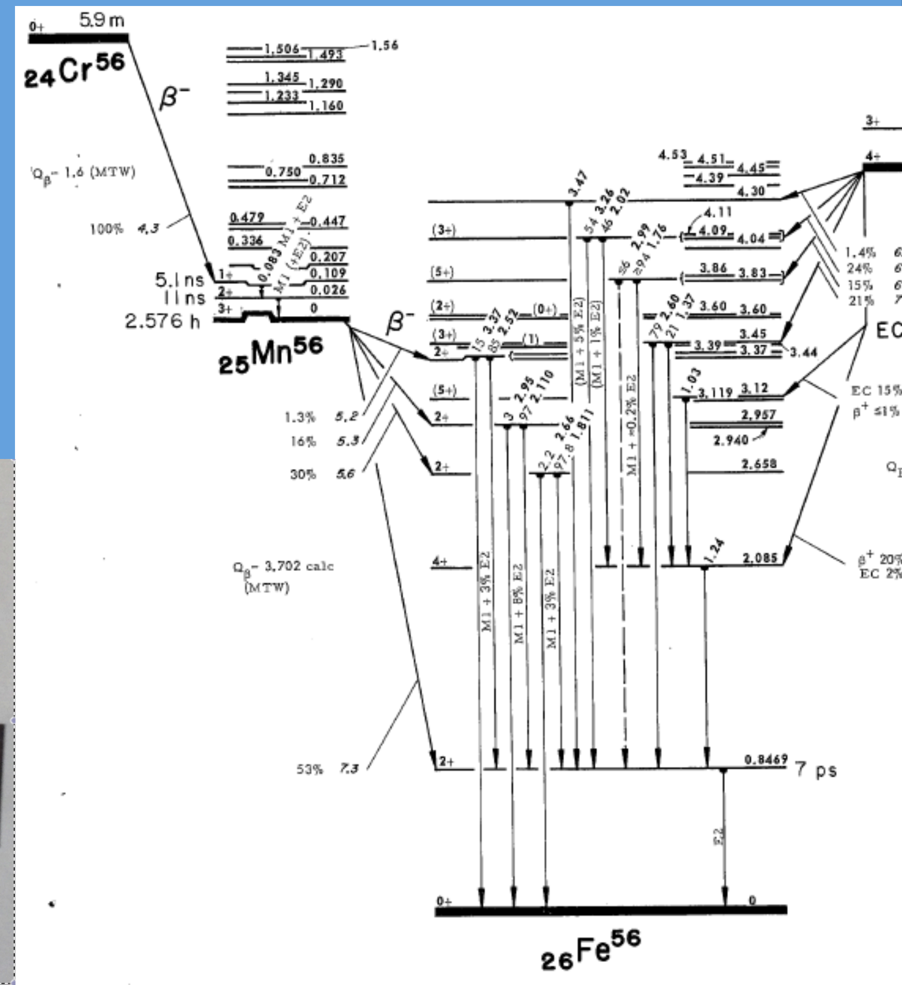
The neutron source will be inside the manganese Bath until the equilibrium of ^{56}Mn is reached (25 hours)

Ideally the neutron emitted from a source located at a center of manganese bath are slowed down by a series of collisions and finally captured by a ^{55}Mn nucleus to produce ^{56}Mn









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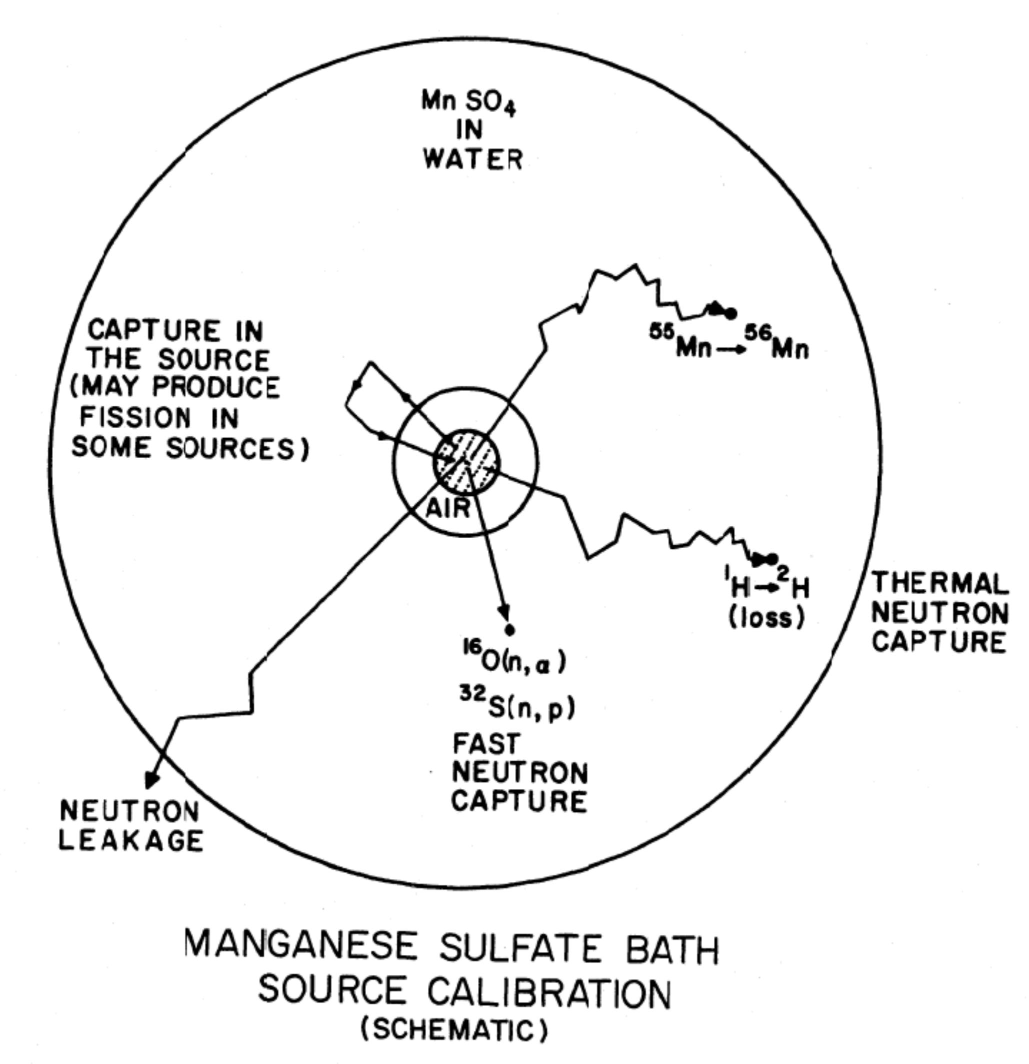
Neutron losses

Neutron absorption in Oxygen and Sulfur

Neutron leakage

Etc



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High-energy neutron fields are also produced by the interactions of cosmic radiation in the atmosphere, and of cosmic radiation with the spacecraft, its components, and crew.

A facility to simulate this neutron component at CERN in Switzerland is the CERN-EU Reference Field (CERF) facility, providing since 1992 a few weeks of beam time per year.

The field simulates closely the neutron field at commercial flight altitudes and in spacecraft (Mitaroff and Silari, 2002).

It also provides a stray radiation field similar to those typically encountered around high-energy hadron accelerators.

These radiation environments are dominated by neutrons with energy distributions ranging from thermal energies up to several GeV, but other components of the radiation field, mainly protons and photons, must also be considered when carrying out calibration of radiation detectors. In addition to the radiation field present behind thick shielding, high-energy particle cascades occurring close to the beam impact point are of frequent interest for radiation detector testing and material activation studies.

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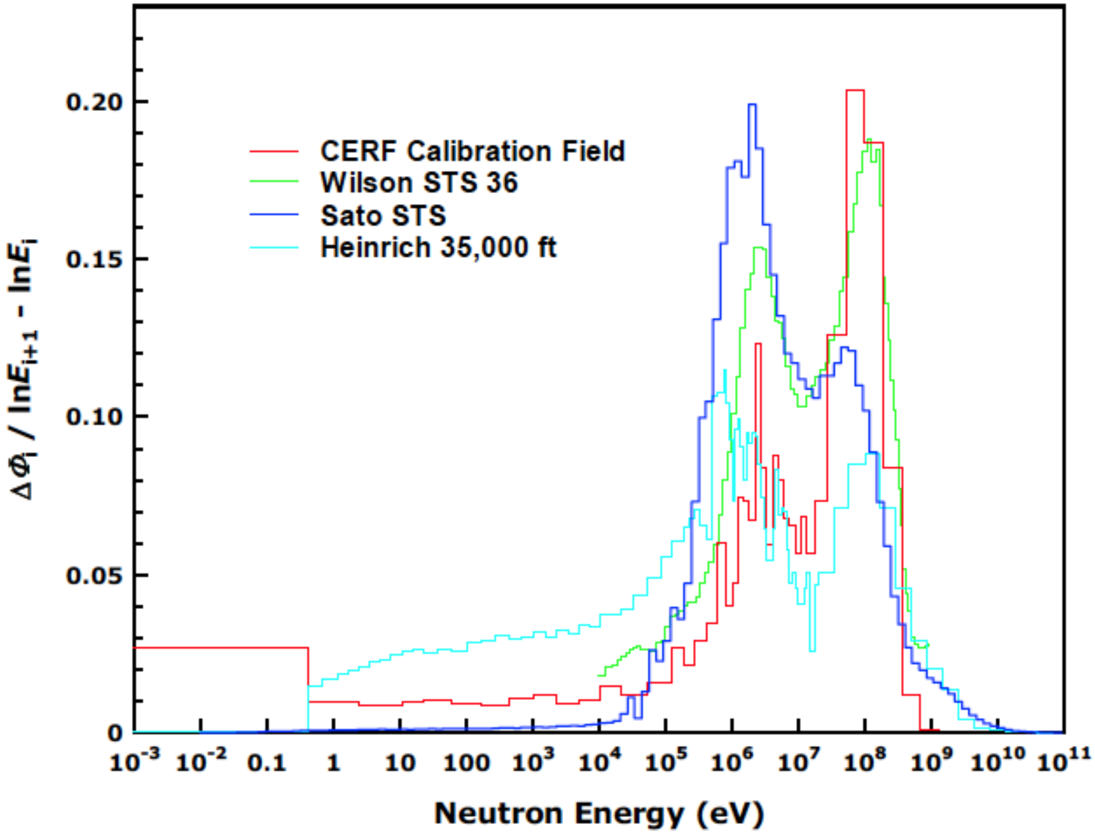

Figure 17: CERF calculated relative neutron energy distribution of energy fluence compared with those calculated for aircraft and spacecraft (Heinrich et al., 1999, Wilson et al., 2002, and Sato et al., 2006).

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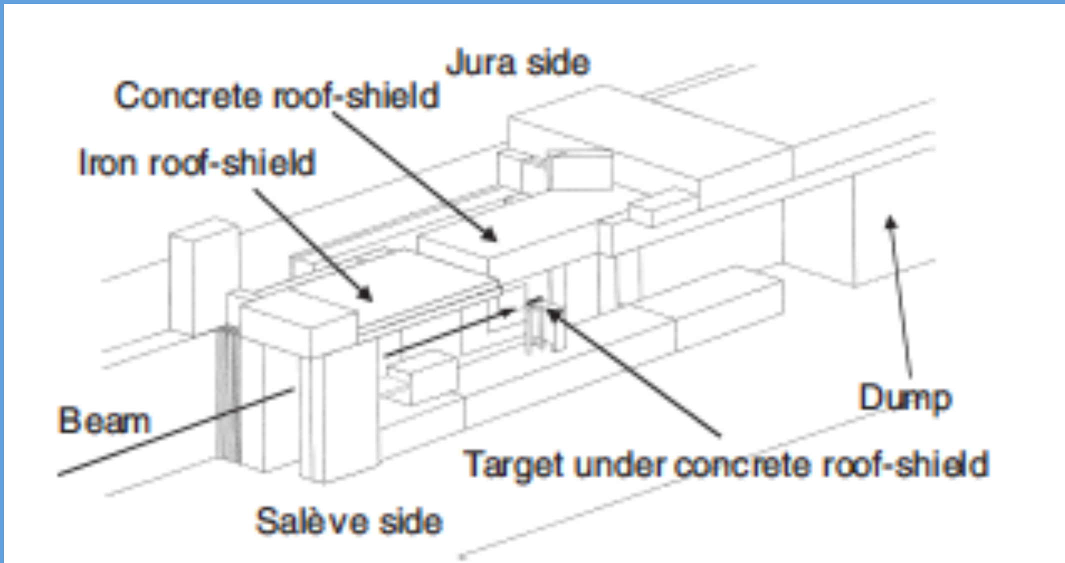

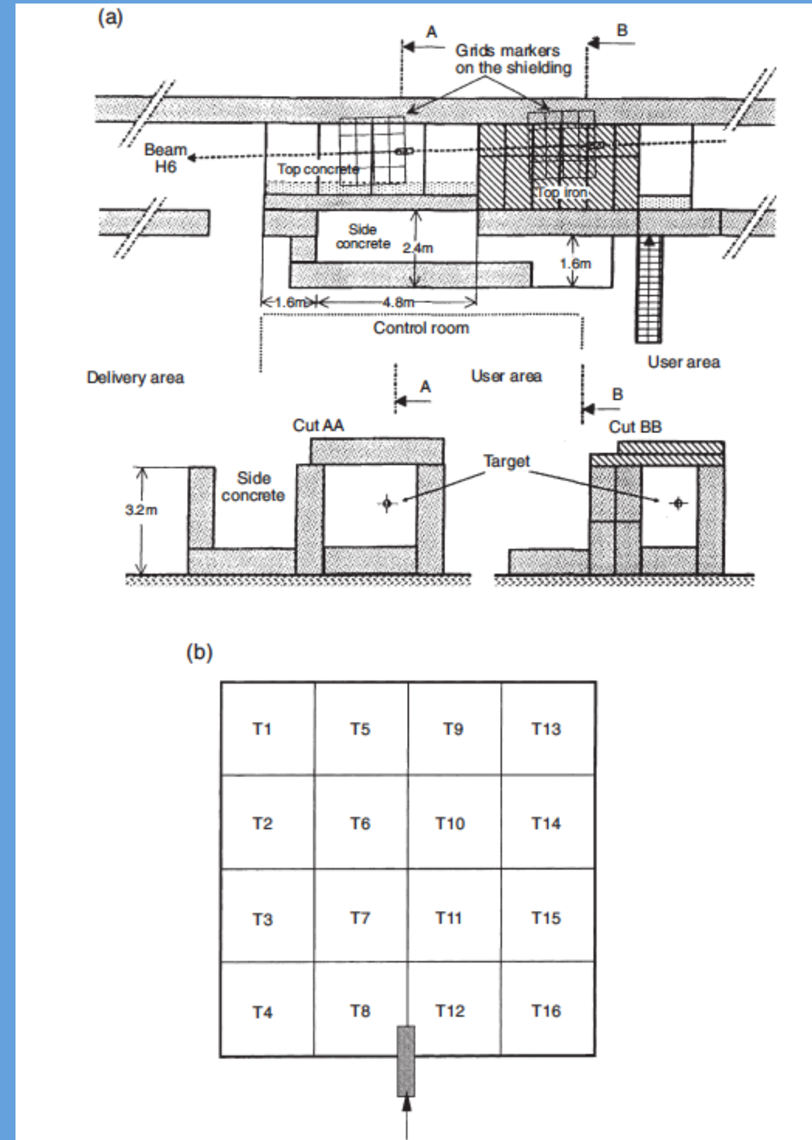

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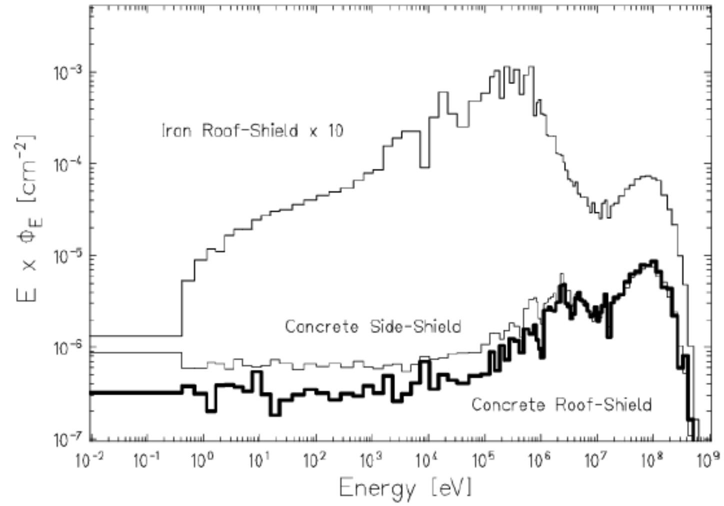

Figure 18: Neutron energy distributions of energy fluence on the concrete roof-shield, on the iron roof-shield and behind the 80 cm thick concrete side-shield (neutrons per primary beam particle incident on the copper target).

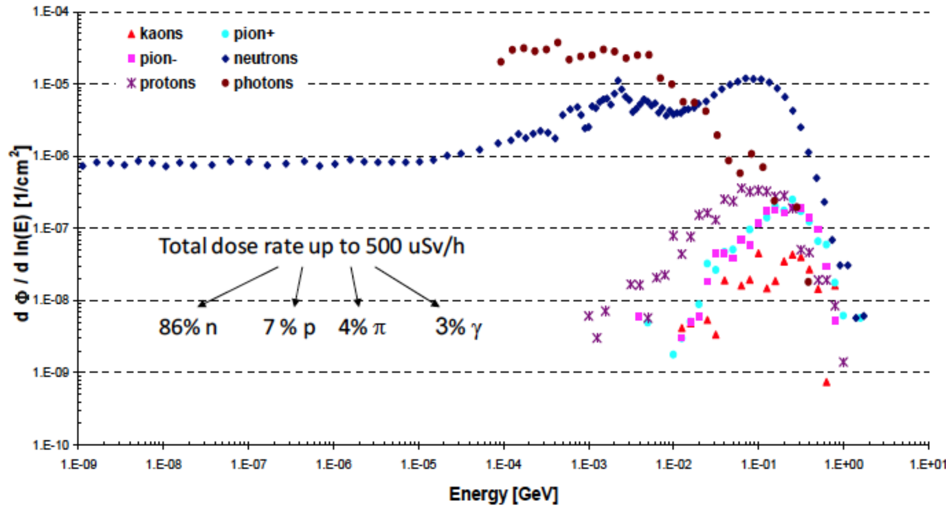

Figure 19: The composition of the energy distributions of particle energy fluence on the concrete roof-shield (particles per primary beam particle incident on the copper target).

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Industrial application of neutron sources

There are three sources of neutrons witch are of importance for industrial application

Nuclear reactors

- Production of radioisotopes
- Neutron activation analysis
- Neutron radiography
- Structural determination of materials
- Chemical processing
- Radiation curing

High voltage neutron generators

Portable neutron sources

Chemical analysis by nuclear methods

- Monitoring of liquid levels in tanks
- Borehole logging applications
- Information on the lithology
- Information on ground water salinity
- Measuring moisture in soil
- Porosity measurements
- Neutron diffraction

Scattering reactions

No change the identity of target.
Alter neutron spectrum.
Slow down fast neutrons.
Modify the neutron distribution in space and time.

Capture reactions

Add an extra neutron to target nuclei.
Alter the nuclear identity of the targets, by increasing their atomic weight by one unit or
by ionizating secondary reactions wich can change the atomic numbers of targets.
.

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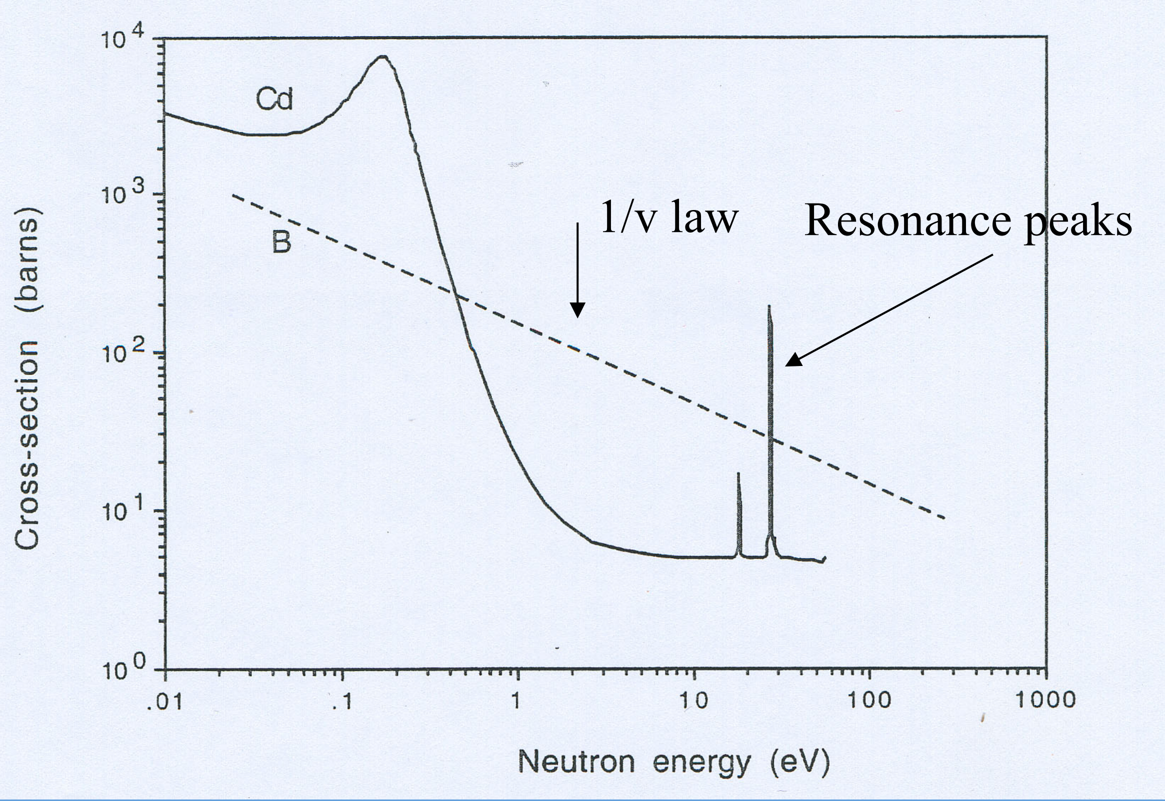
The two most important properties of neutrons relative to radiation protection are the probability of interaction in a medium, denoted by the cross section and the energy transferred to or deposited in the medium.
Cross sections are related directly to neutron energy and absorbing medium. Cross-sections can vary dramatically and erratically based on complex interactions between all the nucleons in the nucleus and the incident neutron.



Neutron absorption cross section for boron and cadmium

Neutrons interact with matter principally by elastic scattering in light materials and are slowed to thermal energies. They can also be depleted from a beam by absorption reactions that yield new products, some of which may be radioactive. The effects and products of such interactions need to be considered in neutron dosimetry, neutron shielding and detection of neutrons.

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Radiation protection for neutrons involves three types of interactions:

Elastic scattering (n.n),

Inelastic scattering (n.n'), (n,nγ)

Radiative capture (n,γ).

Each of these occurs between the neutron and the nuclei of target atoms; electrons of atoms are rarely involved in these interaction.

When a neutron is scattered by a nucleus, its speed and direction change but the nucleus is left with the same number of protons and neutrons it had before the interaction. The nucleus will have some recoil velocity and it may be left in an excited state that will lead to the eventual release of radiation

When a neutron is absorbed by a nucleus, a wide range of radiations can be emitted or fission can be induced

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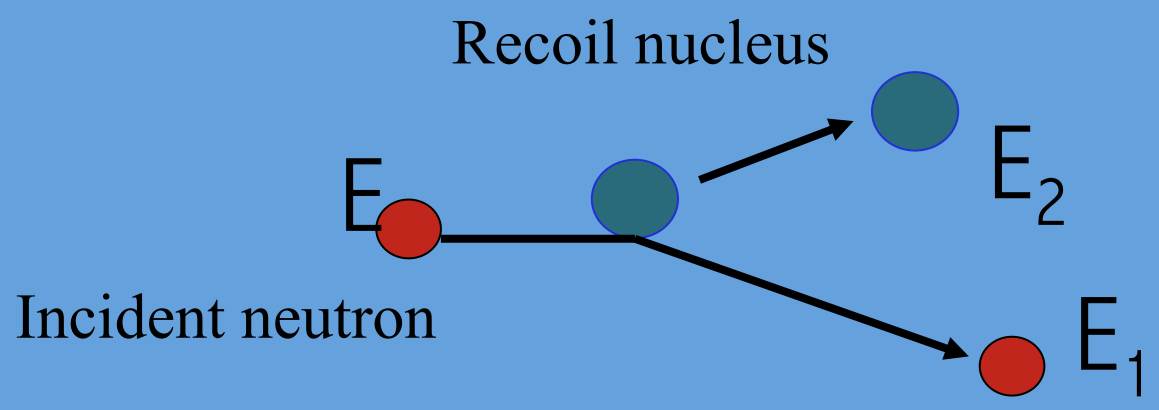
Elastic scattering interactions (n,n) **are quite effective in slowing down neutrons in light materials, especially hydrogen. The energy spectrum will change significantly, as these scattering reactions moderate the original neutron in the beam. A free neutron will eventually be captured; however, since the free neutrons are unstable, some may undergo radioactive transformation to create a hydrogen ion and a β^- particle before capture can occur. The energy and momentum are conserved.**

In the interaction of a neutron with a hydrogen atom the average energy lost is about 2/3 of the energy.



$$E = E_1 + E_2$$

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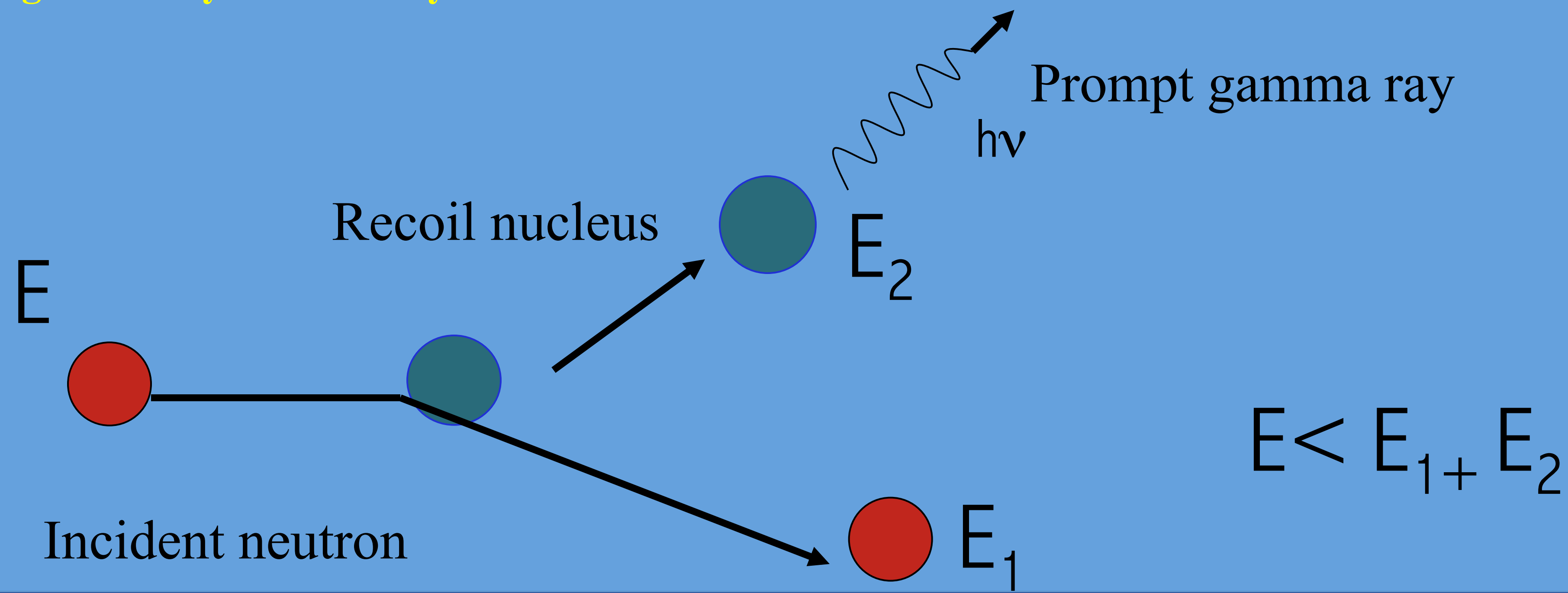
Inelastic scattering interactions (n,n') (n,nγ) **are also effective in slowing down neutrons.**
Inelastic scattering is only possible with fast neutrons and heavy nuclei. These produce excitation of nuclei in the absorbing medium, and this energy is released almost immediately by the emission of a photon.

Neutron shields will usually absorb the photons released in inelastic scattering reactions because the thickness required to absorb most of the neutrons is also sufficient to attenuate any gamma rays released by the excited nuclei.



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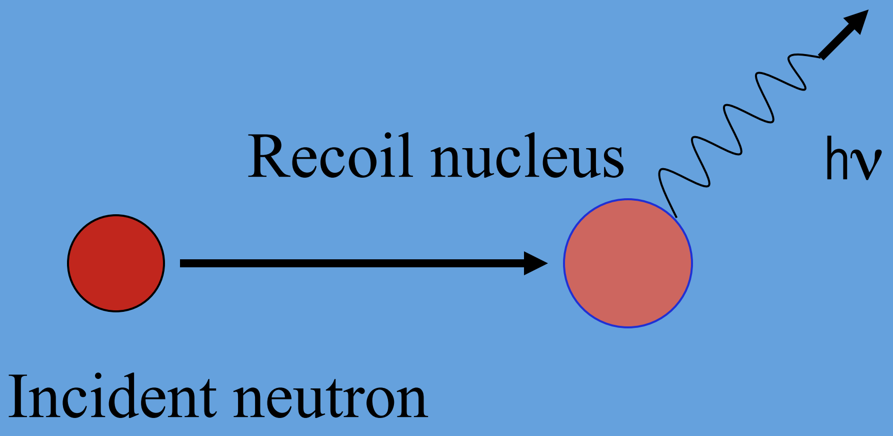
Capture reactions (n,γ)

are likely to occur after elastic and inelastic interactions slow neutrons down (or moderate them) to resonance or thermal energies so they can be readily absorbed in target nuclei of the absorbing medium.

capture cross-sections for low energy neutrons generally decreases as the reciprocal of the velocity as the neutron energy increases. 1/v law. Valid up to 1000 eV

Capture gamma rays can be quite energetic at several MeV and, depending on the shield material, may require additional consideration because of their very high energy.

$^{23}Na+n \longrightarrow {}^{24}Na$



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The amount of energy transferred to a target atom during elastic and inelastic interactions is most useful for radiation dose determinations because the recoiling target atoms will deposit all the energy transferred to them within a few micrometers of the sites of interactions.

For elastic collisions the average energy $\bar{E}$ **transferred to recoiling target atoms by neutrons of initial energy** ***E*** **is**

$$\bar{E} = 1/2(1-\alpha)E$$

Where

$$\alpha = (\frac{A-1}{A+1})^2$$

And A is the mass number of the target nucleus

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Scattering interactions in hydrogen, a large component of tissue, are unique.

Inelastic scattering cannot occur in either hydrogen or deuterium since these nuclei have no excited states.

Resonance scattering or absorption also does not occur and σ_s is constant up to above 10^4 eV (see following figures) and σ_a follows the 1/v law.

For elastic scattering interactions the average energy transferred is *E/2* since α for ^{1}H is zero.

$$\bar{E} = 1/2(1-\alpha)E = 1/2E$$

Hydrogen is thus important for neutron dosimetry because one-half of the energy of intermediate and fast neutrons is transferred to the recoiling hydrogen atoms. This energy transfer relationship also explains why hydrogenous materials are so effective in slowing down (or moderating) high-energy neutrons.

$^1H(n_{th},\gamma)^2H$
which releases a 2.22 MeV γ-ray that irradiates the surrounding tissue

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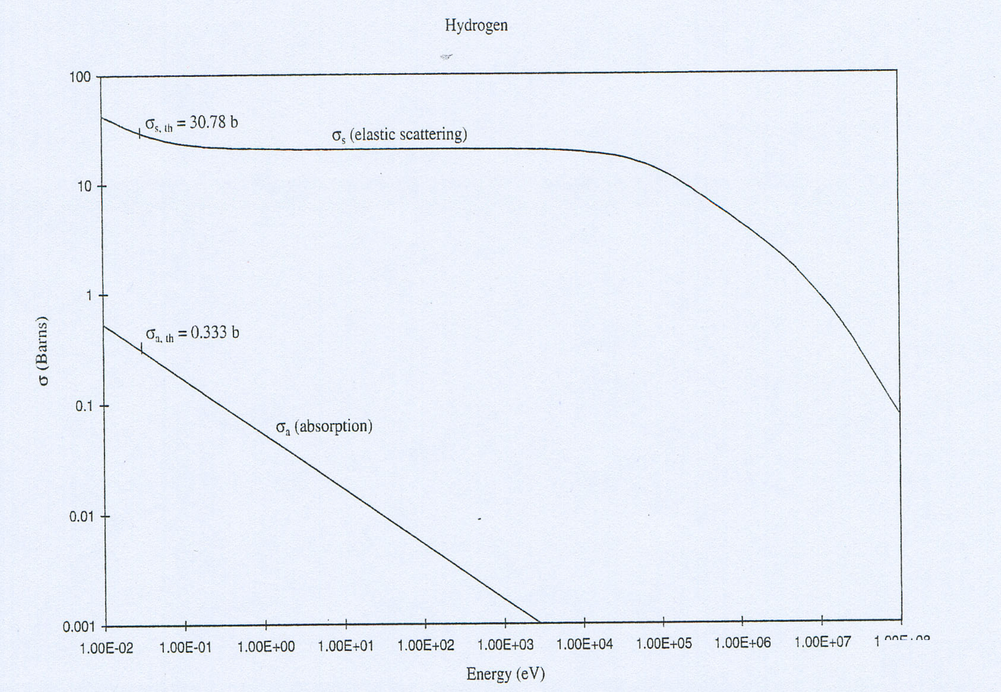

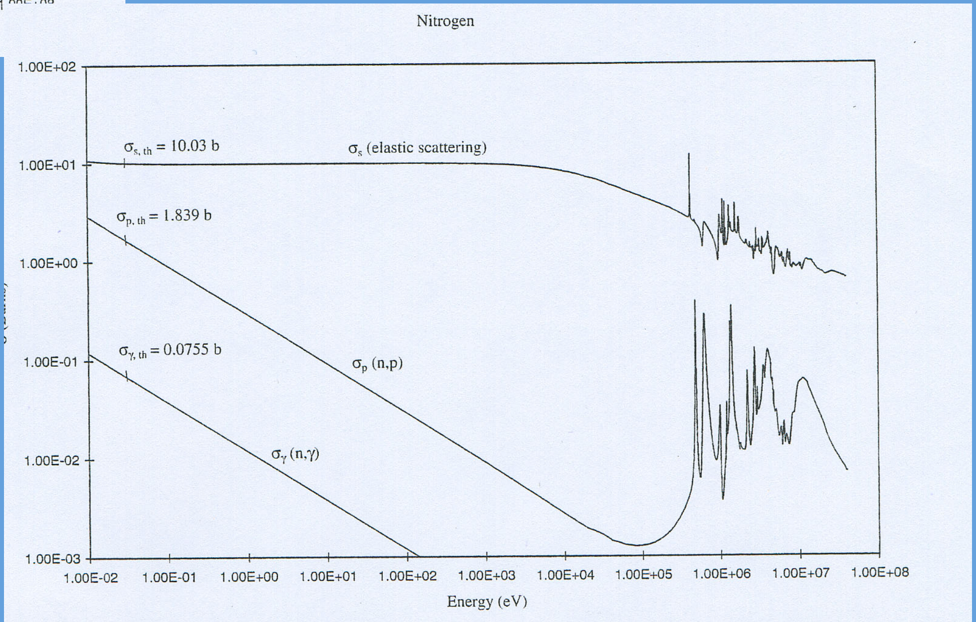

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For heavier media, the amount of energy transferred by elastic scattering interactions decreases appreciably and is less than 1% for lead and uranium absorbers.

Consequently, the principal mechanism of energy loss by high-energy neutrons in heavy materials is by inelastic scattering interactions.

Under these conditions, σ_{is} is generally quite a bit less than elastic scattering cross sections for fast neutrons (E> 1 MeV), but it is still the most effective mechanism for slowing neutrons in dense materials because of the large energy decrease that occurs with these interactions.

Neutrons of energy E will have an average energy $\bar{E}'_{is}$

after inelastic scattering in a medium of atomic mass A of approximately

$$\bar{E}'_{is} \cong 6.4\sqrt{\frac{E}{A}}$$

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Other capture reactions

n,2n n,p n,d n,α n,αp n,t n,f

In this process the incident neutron is captured by the target nucleus and particles such protons, deuterons, tritons may be emitted.
The n, 2n reaction can occur for energies >10 MeV.

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Elastic scattering

$${}^{1}_{0}n + {}^{2}_{1}H \rightarrow {}^{2}_{1}H + {}^{1}_{0}n \text{ can be written } {}^{2}_{1}H\,(n,n)\,{}^{2}_{1}H$$

Inelastic scattering

$${}^{1}_{0}n + {}^{238}_{92}U \rightarrow {}^{238}_{92}U + {}^{1}_{0}n + \gamma \text{ can be written } {}^{238}_{92}U\,(n,n\gamma)\,{}^{238}_{92}U$$

Absorption with emission of particles

$${}^{1}_{0}n + {}^{16}_{8}O \rightarrow {}^{16}_{7}N + {}^{1}_{1}p \text{ can be written } {}^{16}_{8}O\,(n,p)\,{}^{16}_{7}N$$

$${}^{1}_{0}n + {}^{10}_{5}B \rightarrow {}^{7}_{3}Li + {}^{4}_{2}\alpha \text{ can be written } {}^{10}_{5}B\,(n,\alpha)\,{}^{7}_{3}Li$$

Radiative Capture

$${}^{1}_{0}n + {}^{59}_{27}Co \rightarrow {}^{60}_{27}Co + \gamma \text{ can be written } {}^{59}_{27}Co\,(n,\gamma)\,{}^{60}_{27}Co$$

$${}^{1}_{0}n + {}^{2}_{1}H \rightarrow {}^{3}_{1}H + \gamma \text{ can be written } D(n,\gamma)T$$

$${}^{1}_{0}n + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + \gamma \text{ can be written } {}^{1}_{1}H(n,\gamma)\,{}^{2}_{1}H$$

Fotoproduzione

$$\gamma + {}^{2}_{1}H \rightarrow {}^{1}_{1}H + {}^{1}_{0}n \text{ can be written } {}^{2}_{1}H\,(\gamma,n)\,{}^{1}_{1}H$$

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Interazione dei neutroni con la materia

- **Diffusione**
  - elastica — n,n
  - inelastica — n,n’
- **Assorbimento**
  - cattura radiativa — n,γ
  - Con emissione di particelle cariche — n,α; n,p; n,d; n,t
  - Con emissione di particelle neutre — n,2n; n,3n; n,4n; n,xn
  - fissione — n,f

Gli effetti e i prodotti di tali interazioni devono essere presi in considerazione nella dosimetria neutronica nonché nella rivelazione e nella schermatura dei neutroni.

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