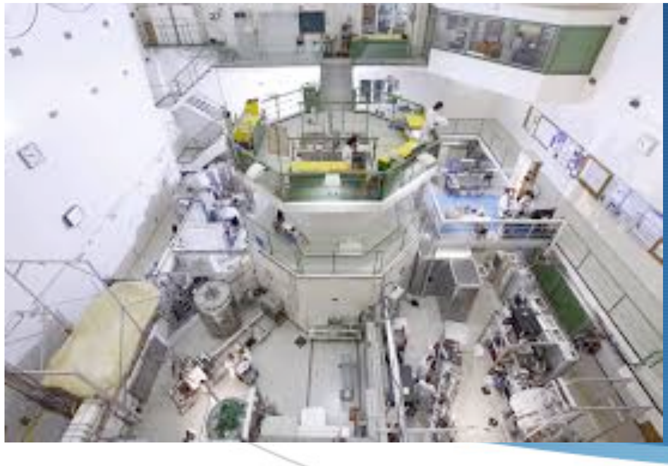
Neutrons

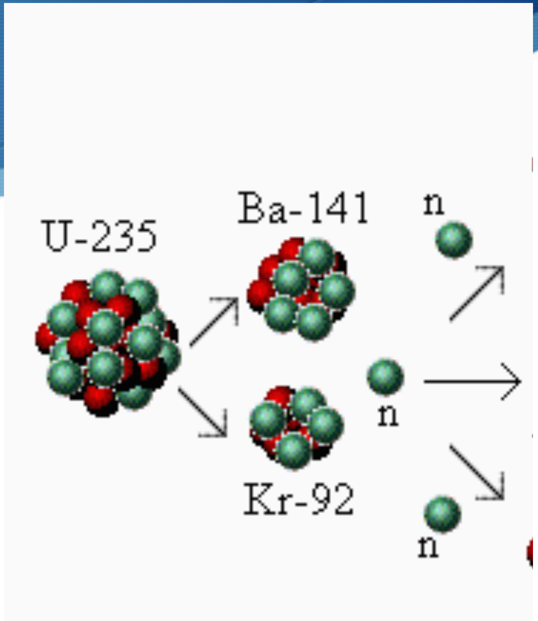
Interactions with matter and production

Index

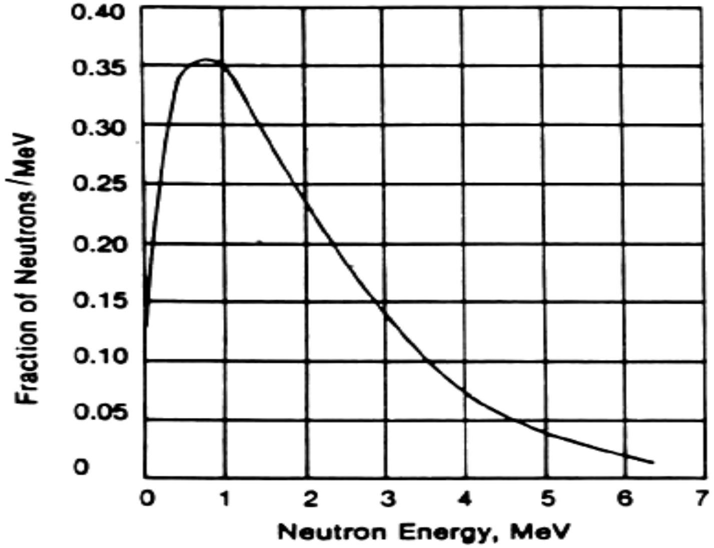
Neutron Sources



Nuclear Reactors



- Most prolific (~10^{15} n/s)
- 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



Spontaneous Fission sources

Spontaneous Fission Sources

- some heavy nuclei fission spontaneously 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

Alpha emitters

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

- the reactions that follow are:

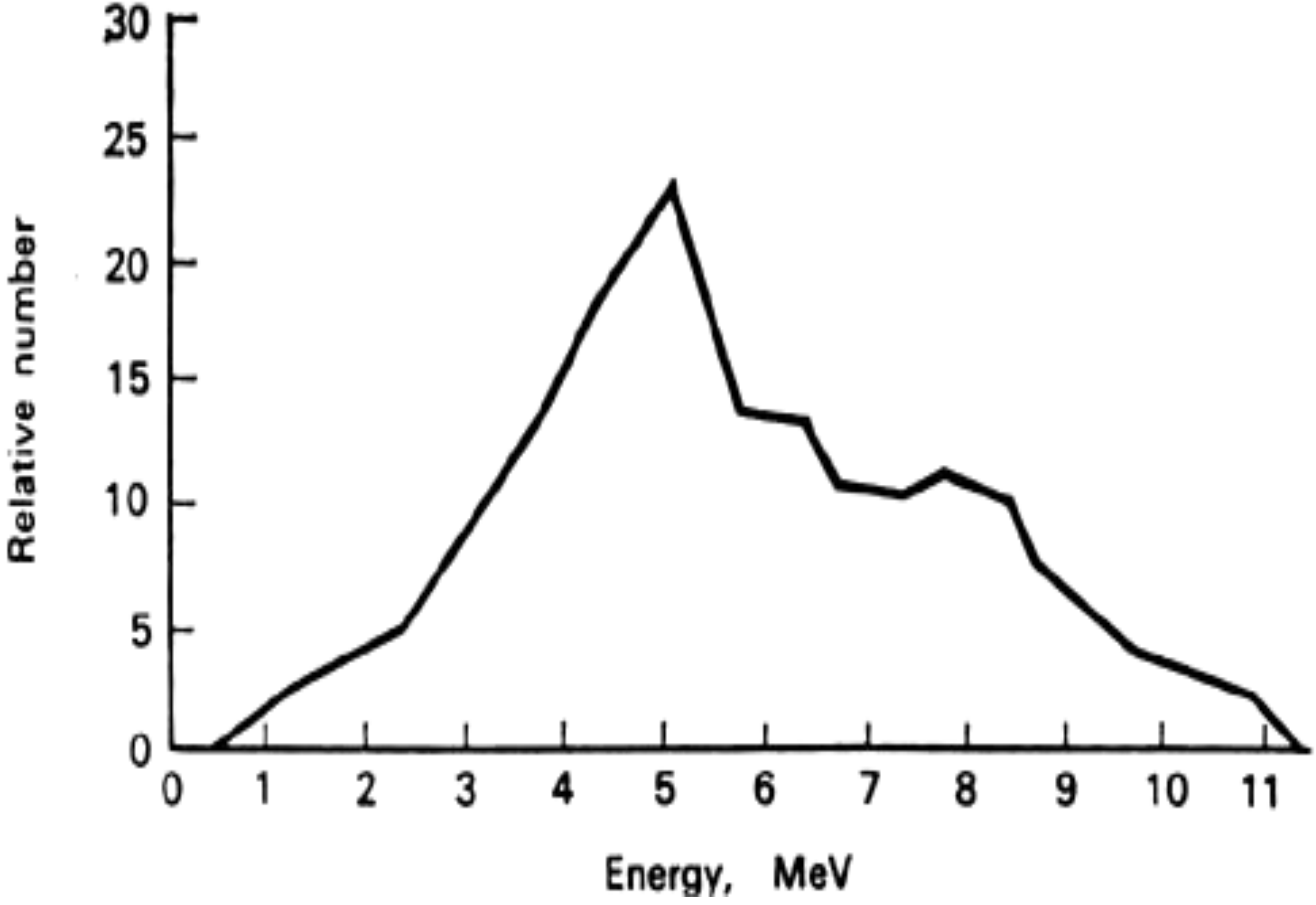
$$^{9}\mathrm{Be}(\alpha, n)^{12}\mathrm{C}$$

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

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

- there is a continuous energy spectrum

Typical Ra–Be (α, n) neutron source in a sealed container.



(α,n) sources

Source	Avg Neutron Energy (MeV)	Half-Life	$\frac{\text{n}}{\text{sec}}/\text{Ci}$
^{210}PoBe	4.2	138 d	9×10^5
^{210}PoB	2.5	138 d	4×10^5
^{226}RaBe	3.9	1602 yr	1.7×10^7
^{226}RaB	3.0	1602 yr	6.8×10^6
^{239}PuBe	4.5	24,400 yr	1×10^6

Gamma emitters

3. Photoneutron sources using (γ,n) reaction

- by choosing radioisotopes with a single γ-ray then monoenergetic neutrons can be produce
- the sources are produced in a reactor using conventional (n,γ) reactions except for ^{226}Ra
- γ 's then interact as follows:

$^{9}Be(\gamma,n)^{8}Be$

$^{2}He(\gamma,n)^{1}H$

(γ,n) sources

Source	Avg Neutron Energy (MeV)	Half-Life	$\frac{n}{sec}/Ci$
^{24}NaBe	0.83	15 hr	1.35×10^5
^{24}NaD_2O	0.22	15 hr	2.7×10^5
^{114}InBe	0.30	54 min	8.2×10^3
^{124}SbBe	0.024	60 d	1.9×10^5
^{140}LaBe	0.62	40 hr	3×10^3
^{226}RaBe	0.7 (max)	1622 yr	1×10^3

Spontaneous fission sources

- ^{252}Cf undergoes spontaneous nuclear fission at an average rate of 10 fissions for every 313 alpha transformations
- half-life of ^{252}Cf due to alpha emission is 2.73 years

  with spontaneous nuclear fission its effective half-life is 2.65 years
- 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

Accelerator neutrons (d/t)

Accelerator Neutrons

- 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

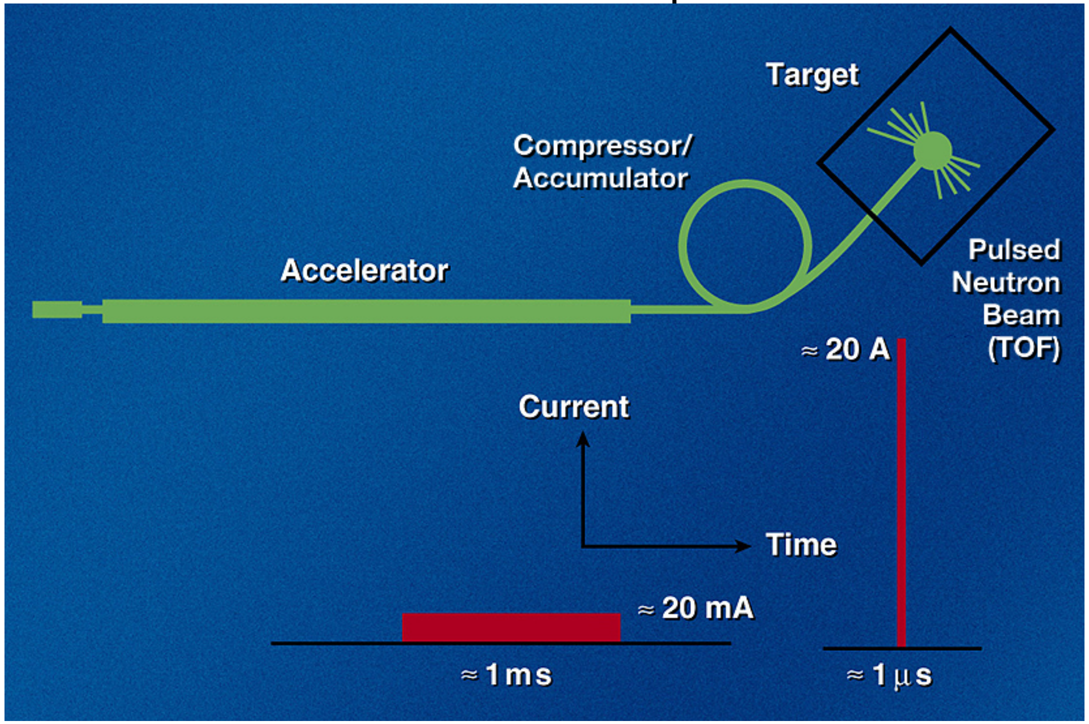
- positive Q-values means the nuclear reaction can be induced with only several hundred keV ions

Spallation source

- Spallation:

  p + heavy nucleus = 20 n + fragments

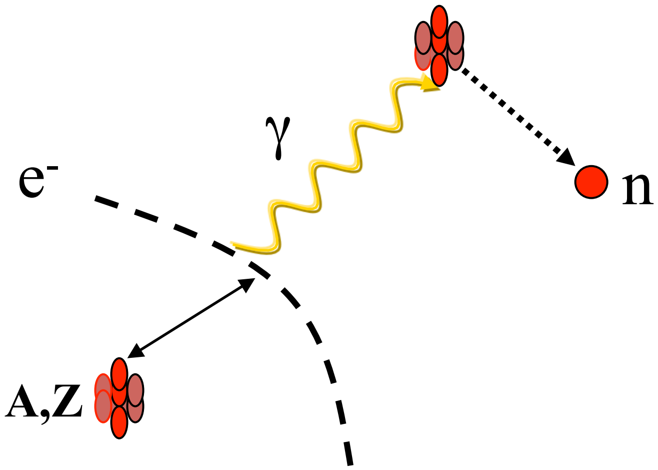
  1GeV e.g. W, Pb, U, Hg



Neutron Source

This source may be suitable for multiple applications, ranging from material analysis for industrial and cultural heritages purposes to chip irradiation and metrology. These applications envisage the development of properly designed beam lines with neutron moderation and possibly cold/thermal neutron transport systems The proposed new facility will represent a great opportunity for research and development of neutron instrumentation (e.g. detectors) as well as training of young scientist in the use and development of neutron techniques.

PRODUCTION MECHANISM



- **The electron stops in the target**
- **Brehmsstrahlung radiation**
- **(γ,n) reaction and nucleus evaporation**

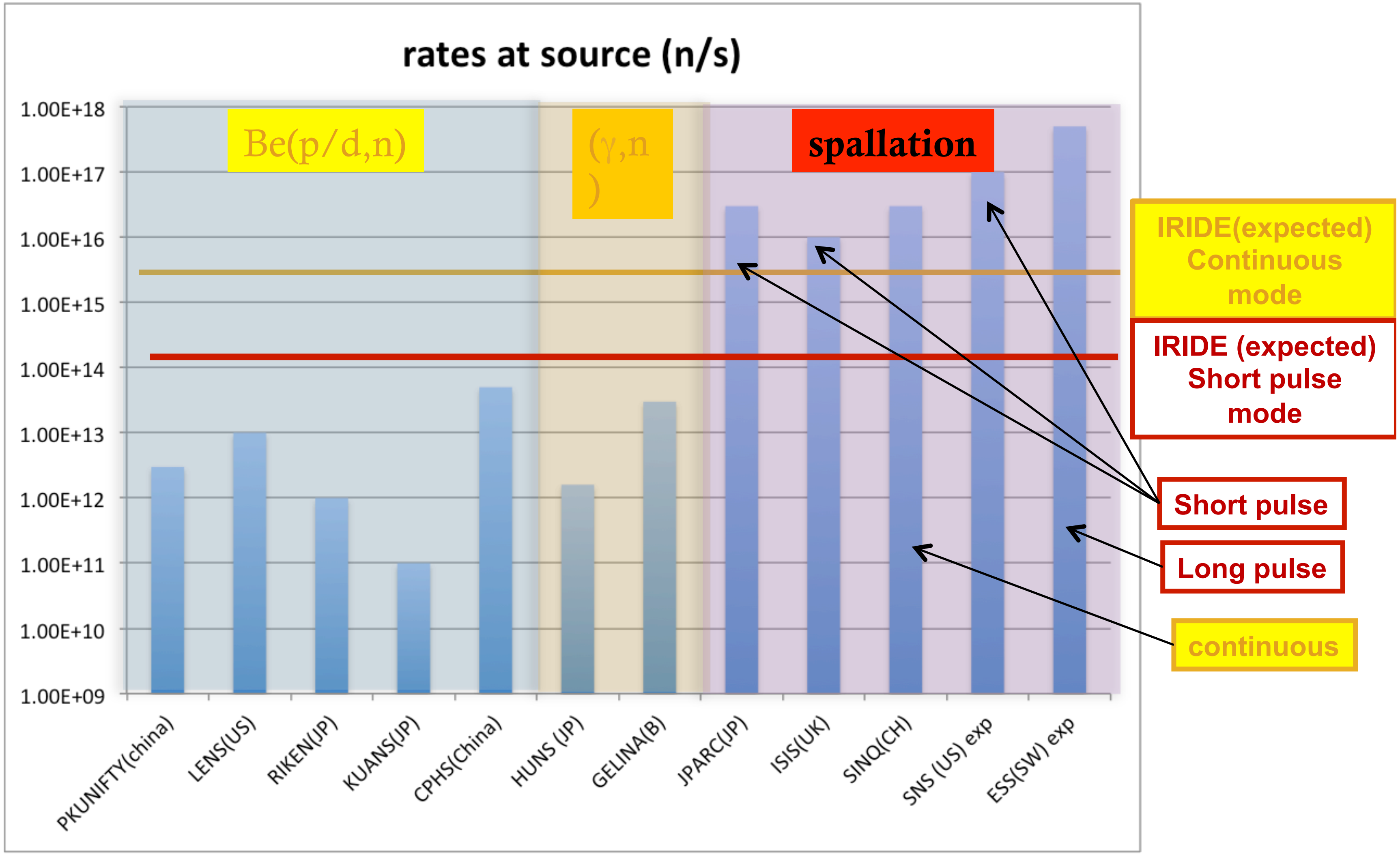
The neutronic yield depends mostly on material and geometry:

$Y <$ **0.1 n/e** for$E_e < 200$ MeV (W,Ta)
$Y \sim$ **0.2 n/e** for$E_e = 500$ MeV (W,Ta)
$Y \sim$ **0.7** forE_e=500 MeV (U)
$Y \sim$ **0.7** for$E_e > 1$ GeV (W,Ta)

For E_e>150 MeV pion-related hadronic processes: intra- e inter-nuclear interactions (and photo-fission in case of Uranium)

Estimates based on other existing facilities and on n@BTF results ➔ cooling might impose constraints not yet accounted for

Comparison with some accelerator driven sources



IRIDE(expected) Continuous mode

IRIDE (expected) Short pulse mode

Short pulse

Long pulse

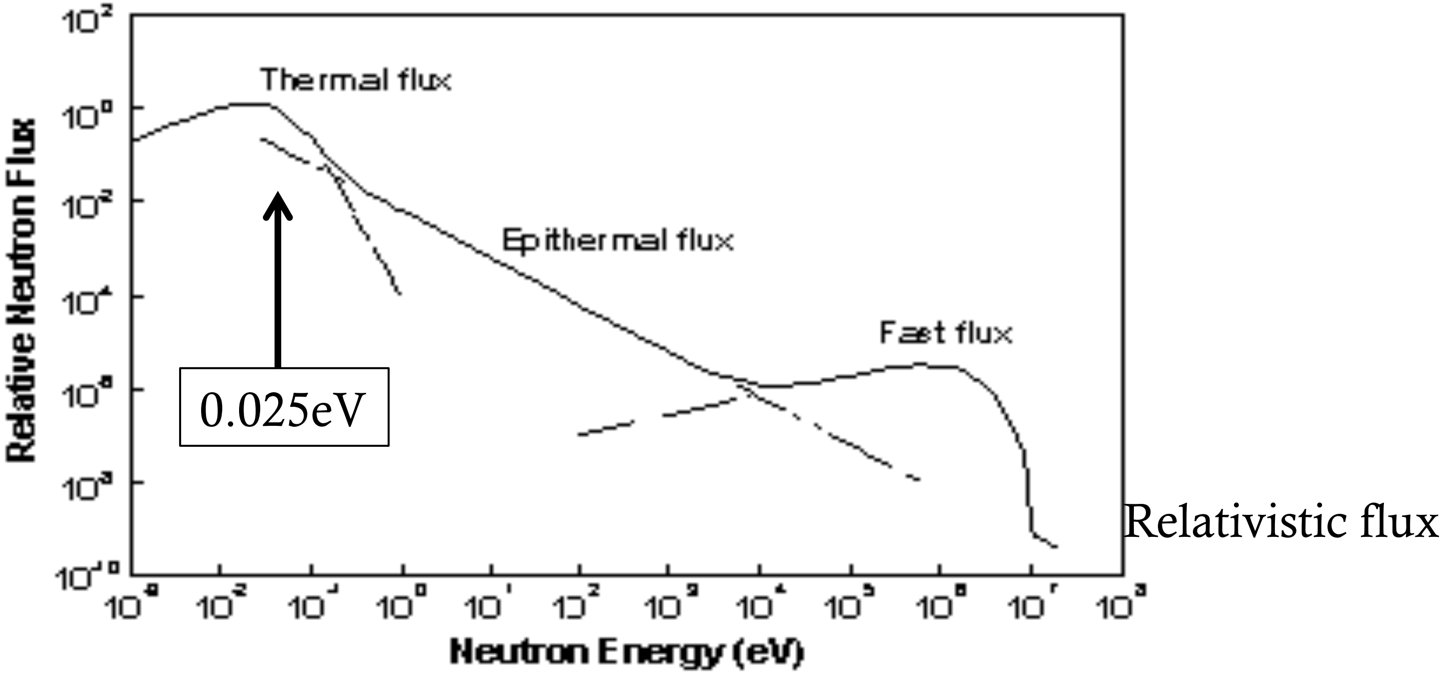
continuous

Summary

NEUTRON SOURCES	Example	Physical principle	
Reactor	TRICA	fission	Direct production in sources
Sealed sources	Cf252	Spontaneous fission	
Alpha emitters	AmBe	X(α,n)Y	Indirect production in sources
Gamma emitters	PoBe	X(γ,n)Y	
p/d accelerators	FNG	X(d/p,n)Y	Accelerators
spallation	ISS	X(p,n)Y	
photoproduction	Gelina	X(γ,n)Y	

Neutron Classification

Classification of Neutrons



Classification of Neutrons

- at thermal energies neutrons are indistinguishable from gas molecules at the same temperature and follow the Maxwell-Boltzman distribution:

$$f(E) = \frac{2\pi}{(\pi kT)^{3/2}} e^{-E/kT} E^{1/2}$$

- where:

  f (E) = fraction of neutrons of energy e/unit energy interval

  k = Boltzman constant × 10^{-23} J/ºK

  T = absolute temperature ºK

Neutron interactions

Interaction of Neutrons

- neutrons are uncharged and can travel appreciable distances in matter without interacting
- neutrons interact mostly by
  - elastic scattering X(n,n)X → moderation
  - inelastic scattering X(n,n)X*
  - Activation X(n,*)Y

Elastic cross section

- Resonance region due to formation of nuclear excitations

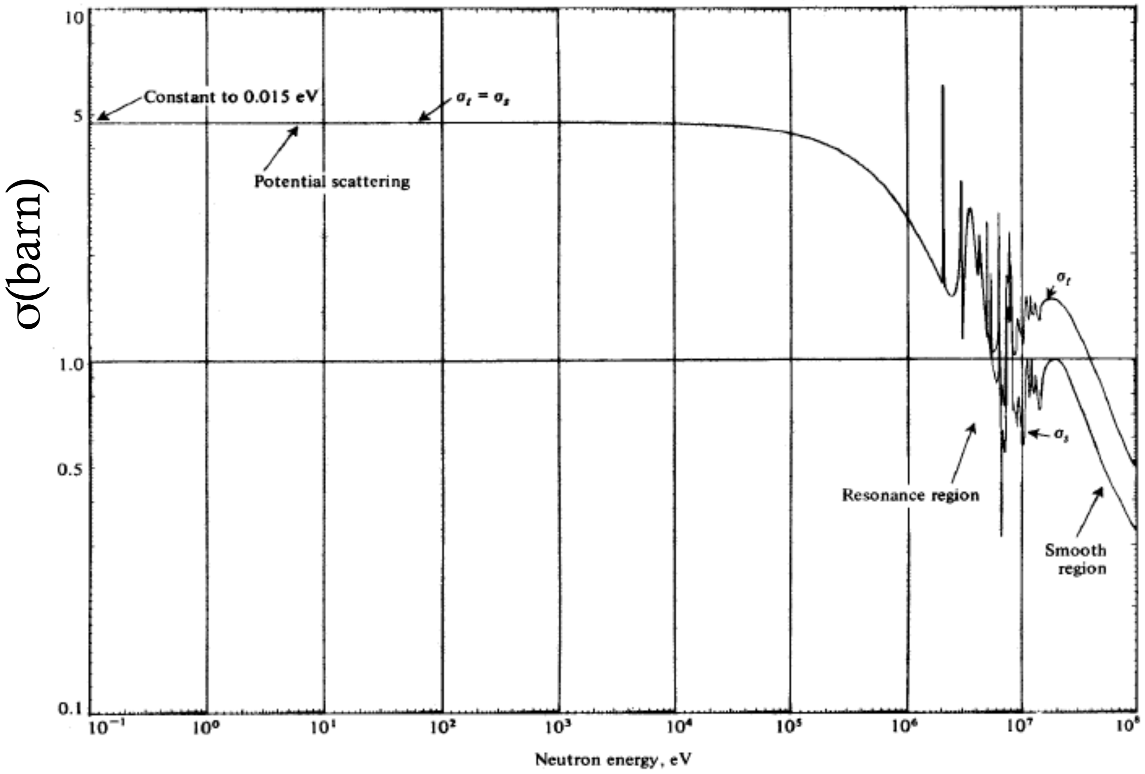


Fig 14.1 sezione d'urto di interazione neutroni -^{12}C

Elastic scattering

X(n,n)X

- most likely interaction between fast neutrons and low atomic number z
- most important process for slowing down ~MeV neutrons (moderation/energy transfer in reactors)
- Basic for neutron radiography/tomography

Elastic scattering

- total kinetic energy and momentum are conserved and we have:

$$\tfrac{1}{2}MV^2 = \tfrac{1}{2}MV_1^2 + \tfrac{1}{2}mv_1^2$$

$$\text{and } MV = MV_1 + mv_1$$

- solving for v_1 and substituting into:

$$V_1 = \frac{(M - m)}{(M + m)}V$$

Interaction of Neutrons

$$E_{max} = \tfrac{1}{2}MV^2 - \tfrac{1}{2}MV_1^2 = \frac{4mME}{(M+m)^2}$$

- when: $M = m$; $E = E_{max}$

- for neutrons in a head on collision with hydrogen all the kinetic energy can be transferred in one collision since the mass of neutrons and protons are almost equal

Maximum Fraction of Energy Lost, Q_{max}/E by Neutron in Single Elastic Collision with Various Nuclei

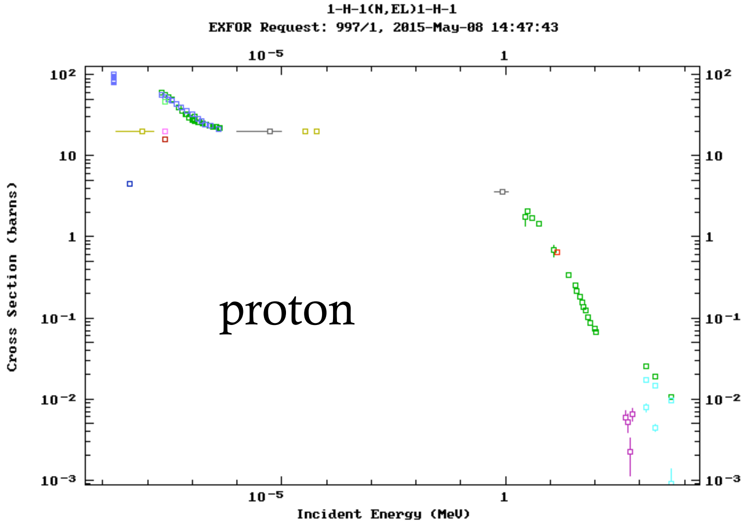
Nucleus	Q_{max}/E
^{1}H	1.000
^{2}H	0.889
^{4}He	0.640
^{9}Be	0.360
^{12}C	0.284
^{16}O	0.221
^{56}Fe	0.069
^{118}Sn	0.033
^{238}U	0.017

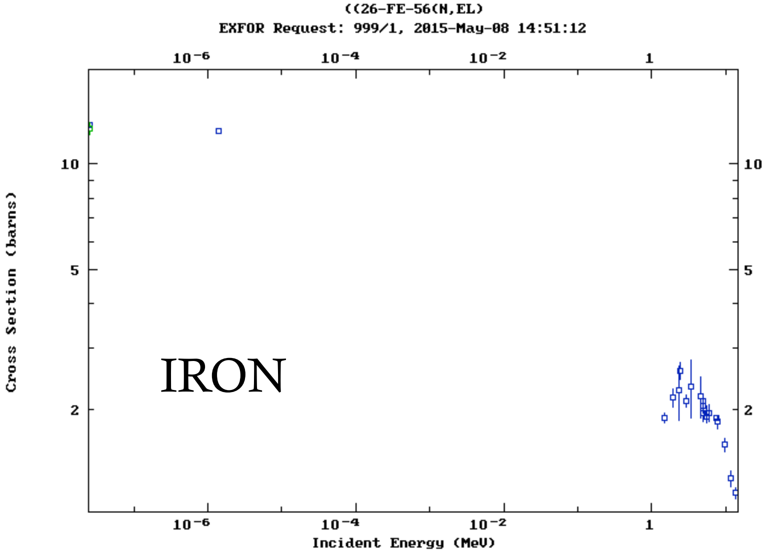
Exercize:

Find

1. the neutron elastic X section for neutrons on the materials on the left at 1 meV and 1 MeV
2. the B(n,α or $\alpha\gamma$) Li cross section at 1meV and 1MeV

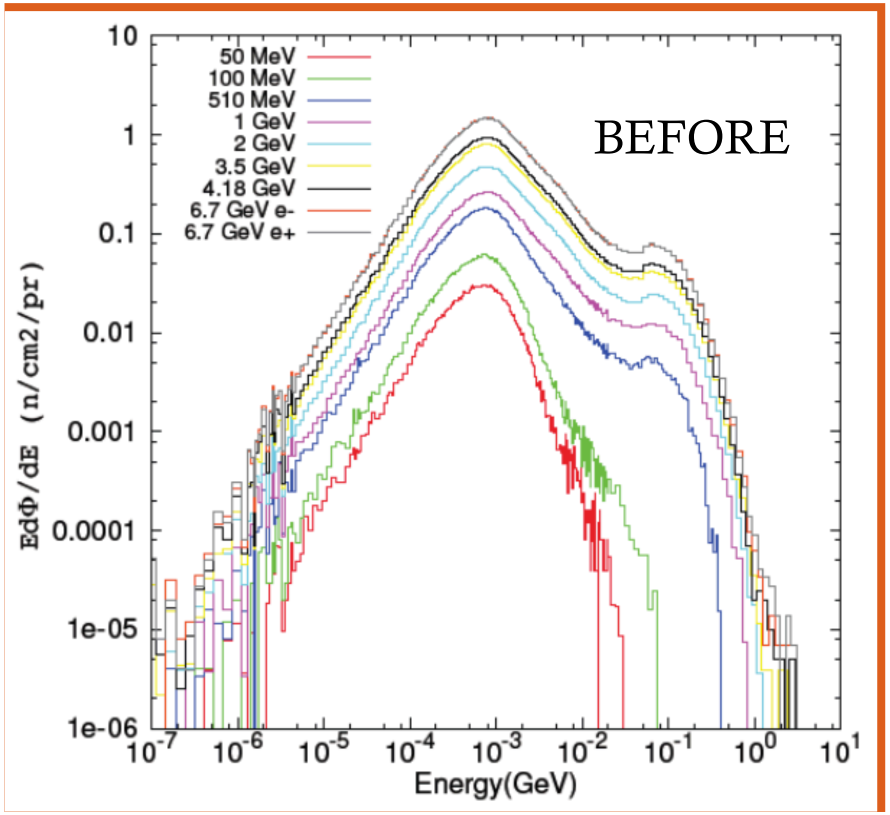
Elastic Cross-Section

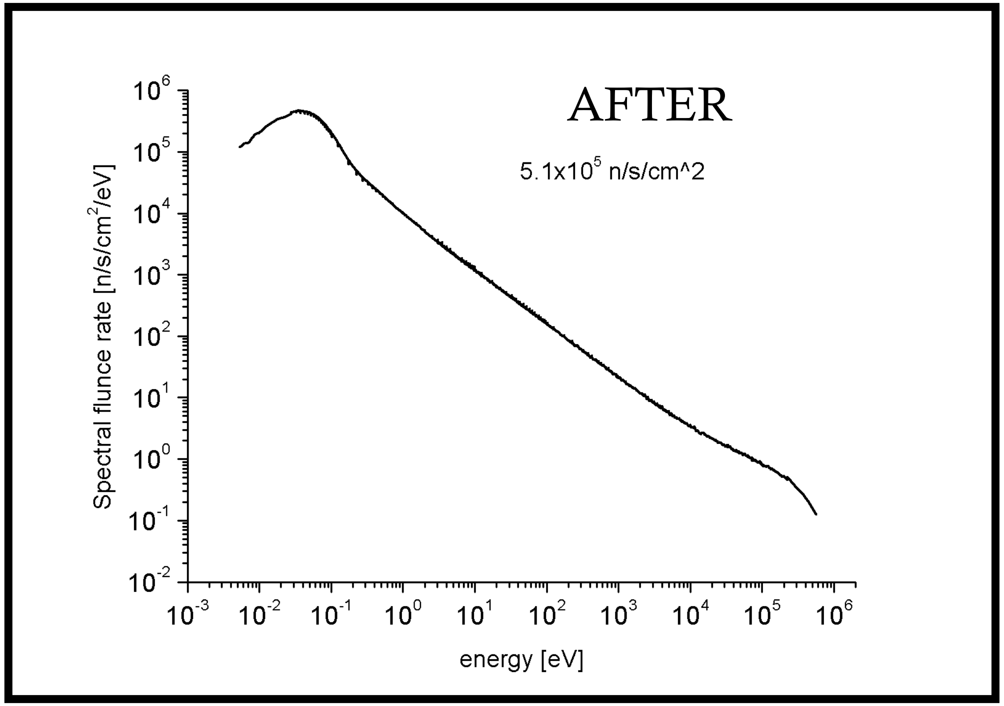




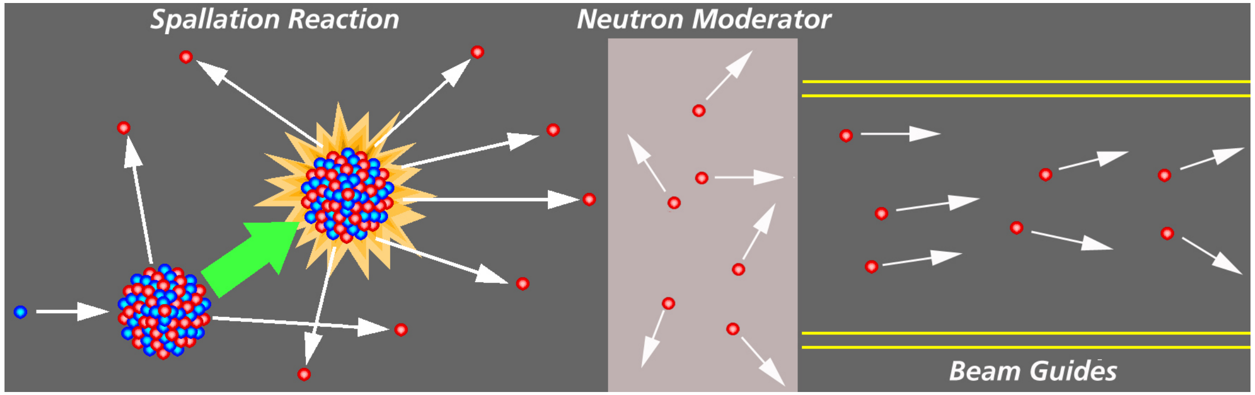
Moderation

- All sources produce fast neutrons
- Moderators are applied downstream to thermalize the spectra

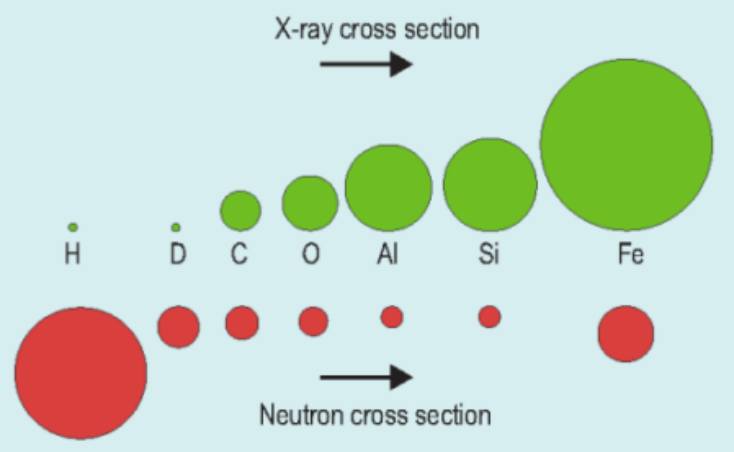


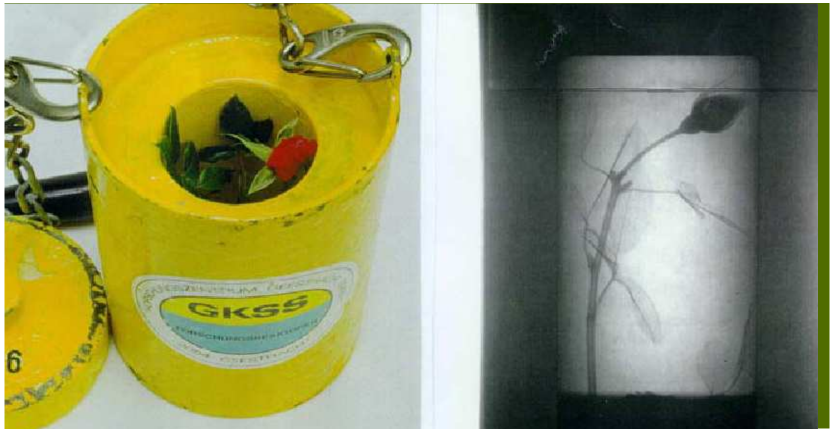


From source to beam



Neutron radiography

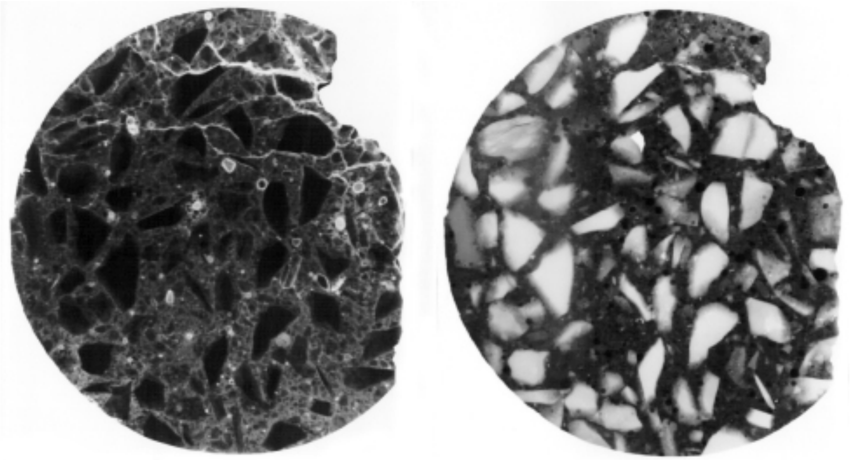




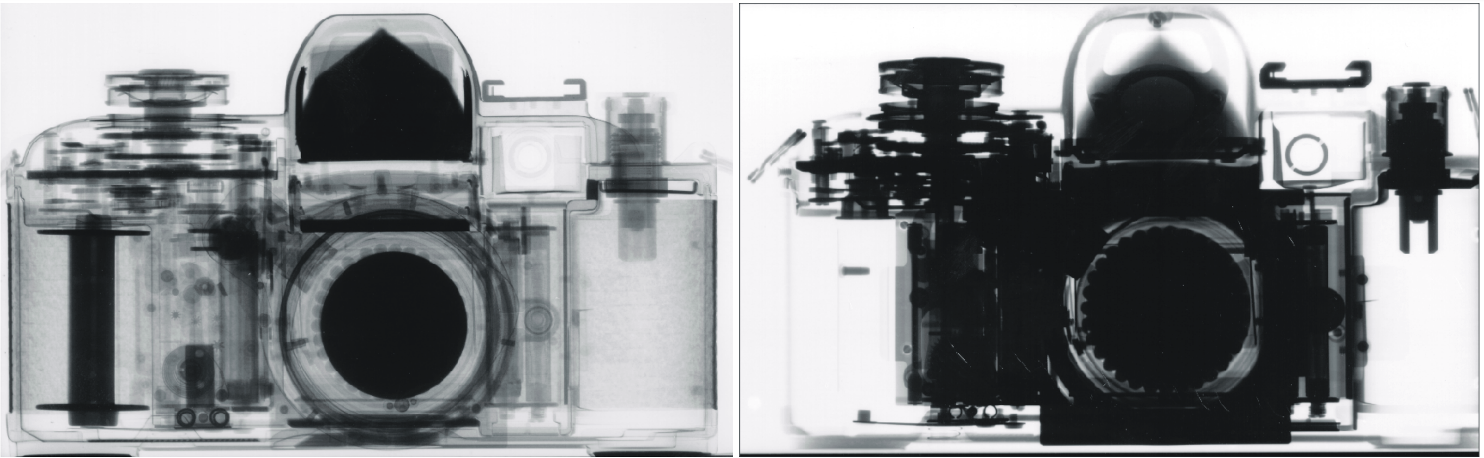
Neutron vs X-ray radiography

Neutron radiography provides a very efficient tool in the field of non-destructive testing as well as for many applications in fundamental research since are able to distinguish between different isotopes

X-ray radiography photography neutron radiography



X- ray radiography neutron radiography

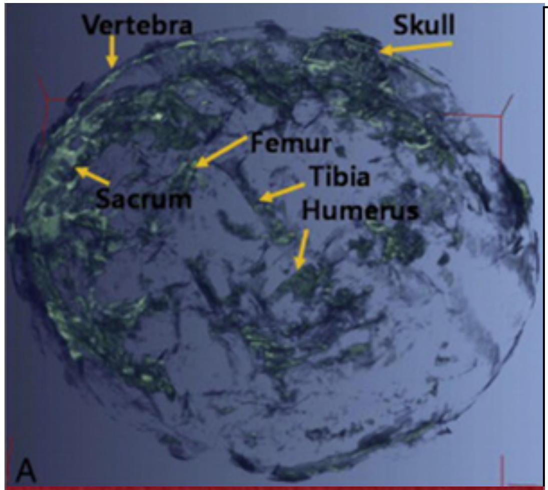


neutron radiography X-ray radiography

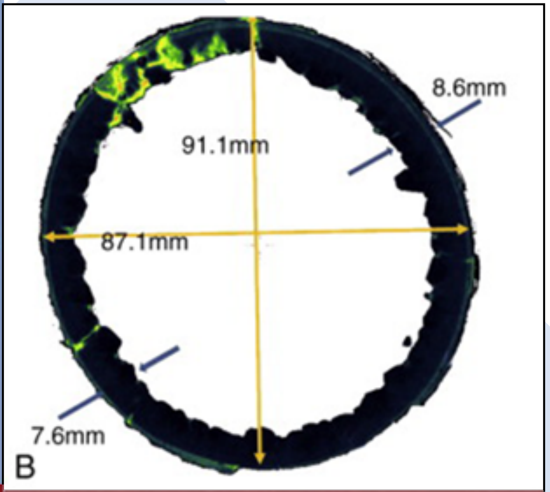
MOKA:
https://www.youtube.com/watch?v=KAiH9yAoLZ8

Neutron tomography (NT)

Imaging can lead to understanding of the evolution of life through 3D investigations of paleontological samples that are impenetrable by other non-destructive methods

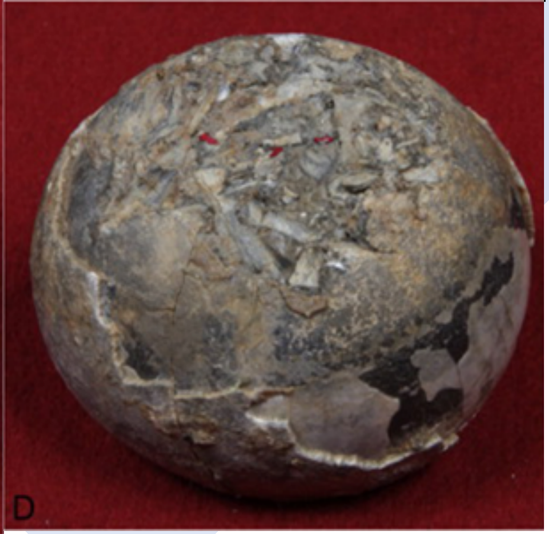


neutron tomography of a titanosaur showing a fairly articulated and complete embryo



dimensions of egg with embryo

view of inside of the egg with calcite crystals



part of the embryo skeleton surface where the eggshell was naturally eroded

Titanosaur embryo in ovo, which is the first of its kind discovered and is hence valuable for destructive testing.

NT permits full 3D imaging that provides a proof that lithostrotian titanosaurs were reproducing at the Aptian-Albian Algui Ulaan Tsav in Mongolia

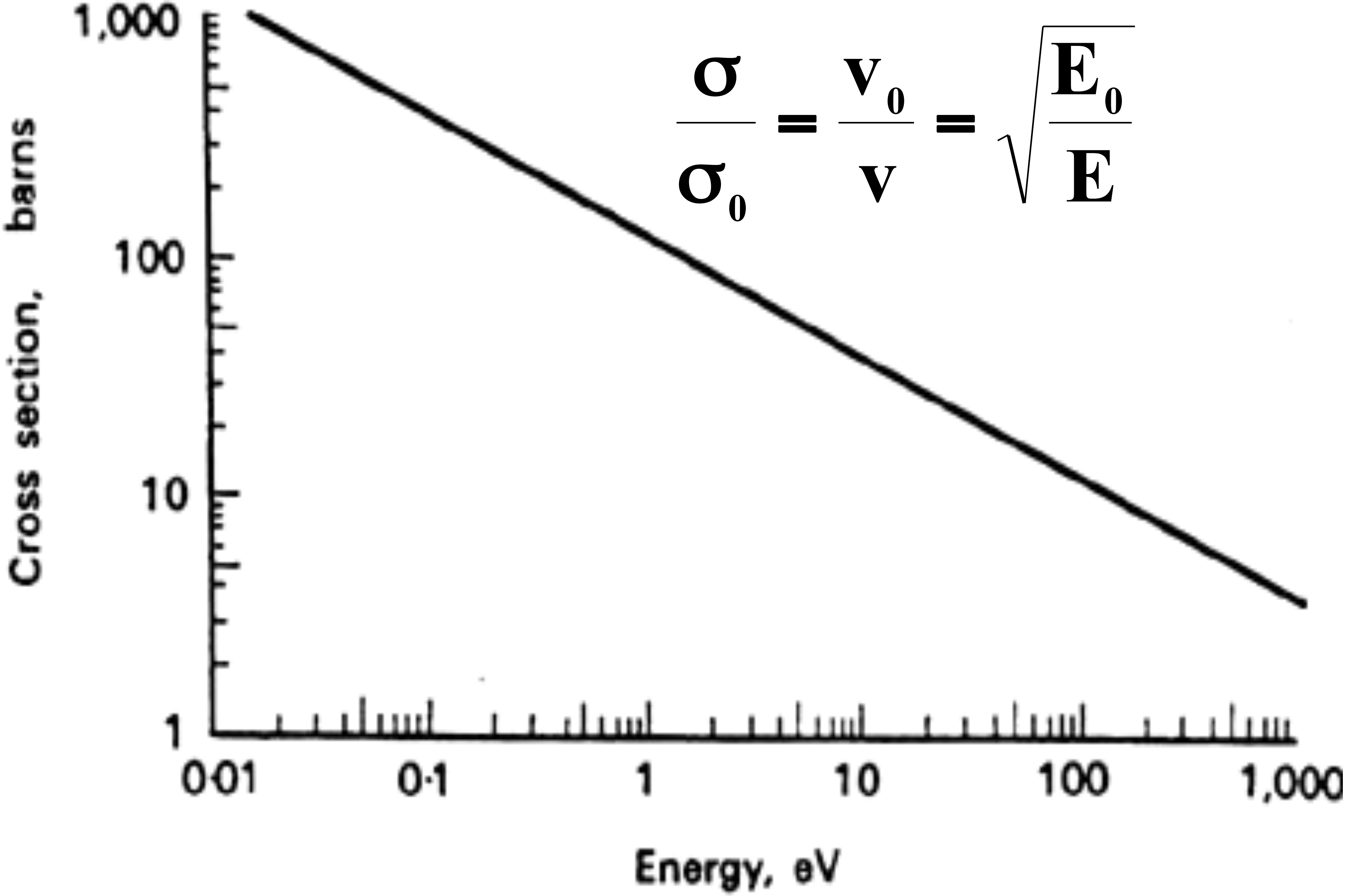
The contrast between fossilised material and the surrounding minerals, and thus the inner structure of fossils, at present can only be resolved by using the phase change of neutron waves

Inelastic scattering

- a part of the kinetic energy that is transferred to the target nucleus upon collision
- the nucleus becomes excited and a gamma photon/ photons are emitted:
- $^{12}C(n,n)^{12}C^*$
- Xsection:
  - Zero below threshold (6MeV for O, 1 MeV for U)
  - small, usually less than 1 barn for low energy fast neutrons but increases with increasing energy

Neutron Radiative Capture

- **capture cross-sections for low energy neutrons generally decreases as the reciprocal of the velocity as the neutron energy increases**
- **phenomenon called 1/v law**
- **valid up to 1000 eV**
- **if the capture cross-section σ_0 is known for a given neutron velocity v_0 or energy E_0, then the cross-section at some other velocity v or energy E can be estimated:**



$$\frac{\sigma}{\sigma_0} = \frac{v_0}{v} = \sqrt{\frac{E_0}{E}}$$

Prompt Gamma Activation

- Activated photons are “instantaneous”
- Lines depend on the elements present in the sample
  - Database of lines:

https://www-nds.iaea.org/pgaa/pgaa7/index.html

Exercize:

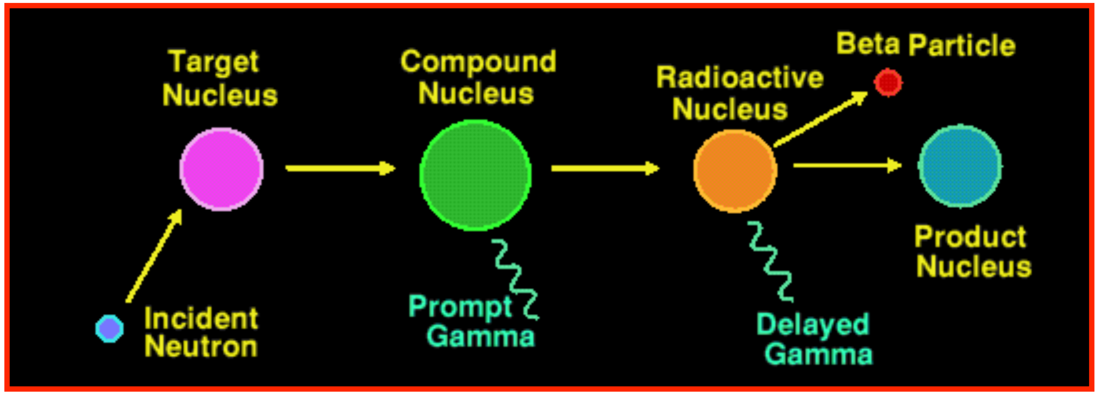
Find prompt gamma neutron activation lines for Ni, C, H

NEUTRON ELEMENTAL ANALYSIS

- **Neutron Activation Analysis (NAA)**:

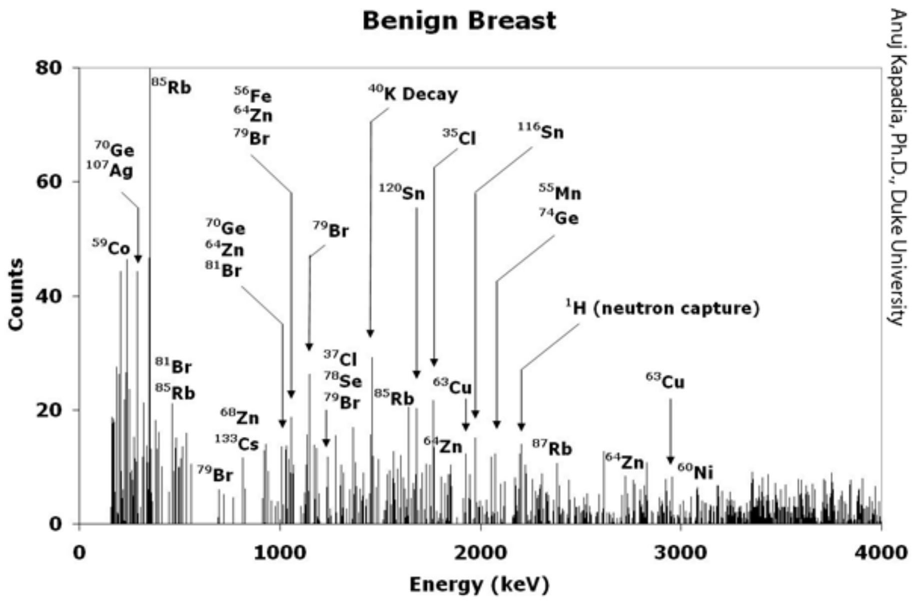
neutron is *captured* by the target, transmuting it into an unstable nucleus which then decays by fission or by the release of some particle or photon.

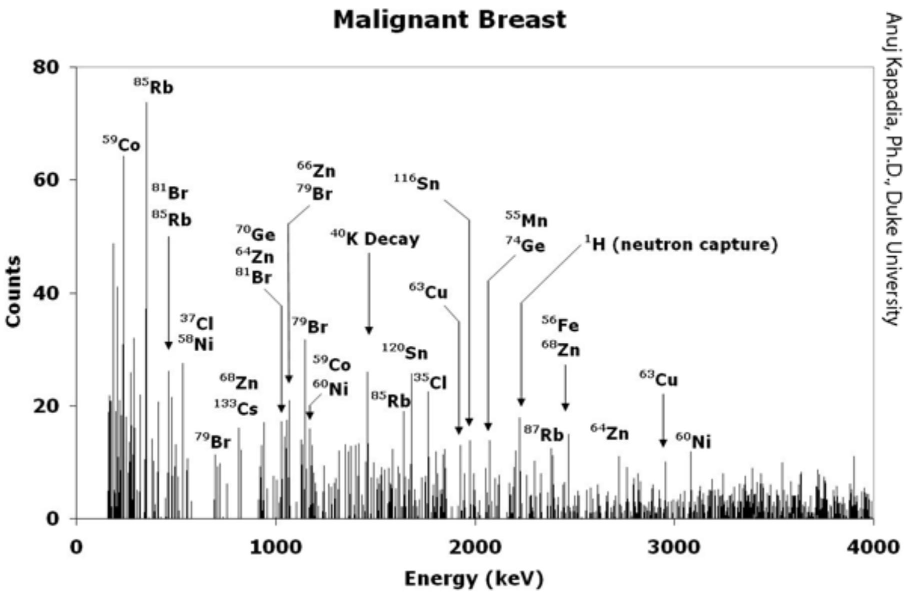
NAA, which uses low-energy thermal neutrons to transmute a wide range of nuclei into unstable isotopes, irradiation can take many hours while measurement of the decay energies and rates of the unstable transmuted isotopes can require days



NSECT MEDICAL APPLICATIONS

Several diseases in humans → Increased element concentration

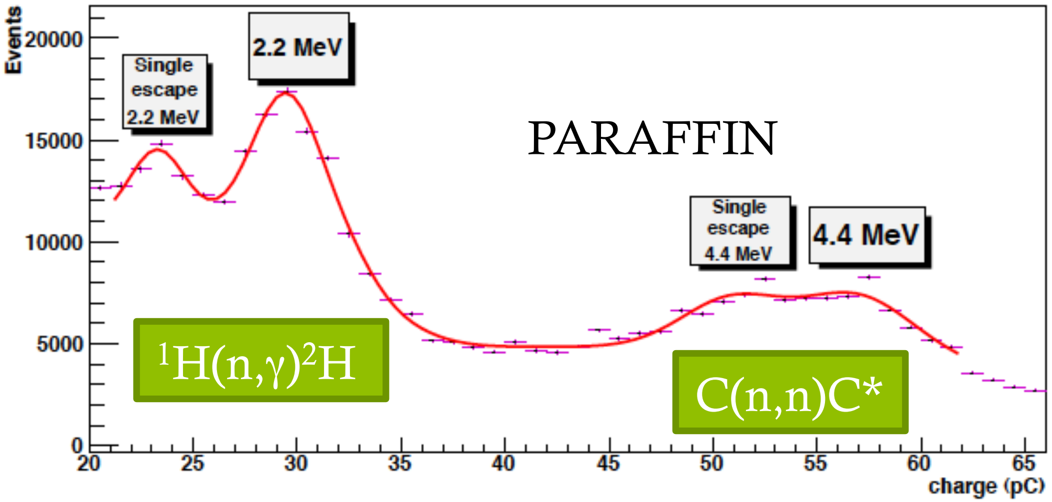


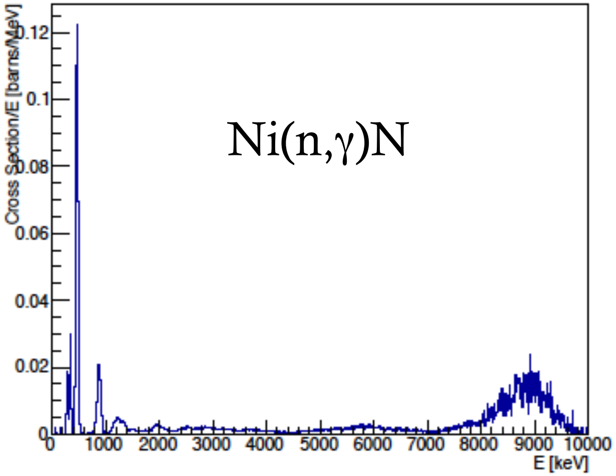


Energy keV	Element Match	Counts Benign	Counts Malignant	Diff	p-val
219	^{79}Br	6	19	13	0.01
397	^{59}Co, ^{79}Br	16	2	-14	0.01
1028	^{81}Br	13	29	16	0.05
1128	^{39}K, ^{68}Zn	0	13	13	0.001
1306	^{56}Fe	10	0	-10	0.01
2299	^{27}Al	0	13	13	0.001
2469	^{37}Cl, ^{56}Fe, ^{66}Zn	5	15	10	0.05
3635	^{35}Cl	3	14	11	0.01

Calibration Gamma Lines

- Use of paraffin and Ni to produce 2.2, 4.4 and 9.1 MeV lines





Other Neutron Reactions Important to Health Physicists

$^{1}H(n_{th},\gamma)^{2}H$

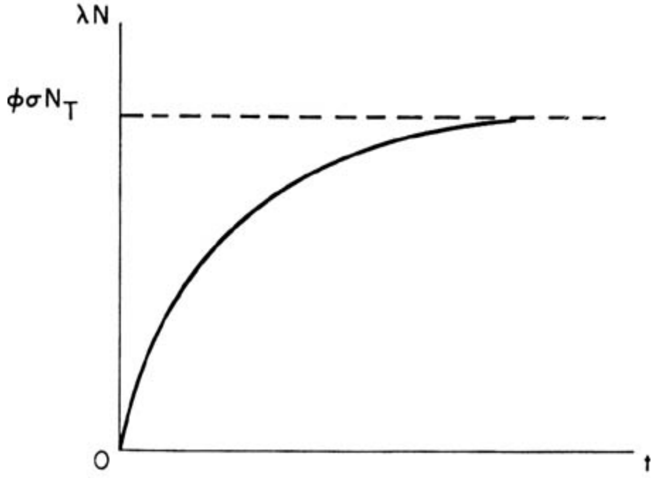
- which releases a 2.22 MeV γ-ray that irradiates the surrounding tissue
- it is one of the two important interactions by which thermal neutrons deposit energy in tissue
- often seen as a background gamma-ray in power and research reactors

$^{23}Na(n_{th},\gamma)^{24}Na$

- which activates human blood sodium
- the decay of ^{24}Na (half-life = 7 × 15 h; two γ's of 100% intensity: 1.37 and 2.75 MeV) can be used to quick-sort personnel after a suspected criticality

Non prompt activation

- **production of a radioactive isotope by the absorption of a neutron, eg:**
  - **(n, γ) (n,p) (n,α) (n,n')**
- **Well known activity vs time**



$$A = \phi \sigma N_T \left(1 - e^{-\lambda t}\right)$$

Neutron Activation

- the previous equation is the activity just at the end of production
- if one is interested in the activity sometime later the following terms must be added:

$$\lambda N = \phi \sigma N_T \left(1 - e^{-\lambda t_i}\right)\left(e^{-\lambda t_d}\right)\left(1 - e^{-\lambda t_c}\right)$$

  - where:
  - t_i = irradiation time
  - t_d = decay time
  - t_e = counting time

Note that calibration is needed to

Exercize

- Find lines and lifetimes for

$^{113}Cd(n_{th}, \gamma)^{114}Cd$

●which is used in neutron shielding and reactor control rods

$^{115}In(n_{th}, \gamma)^{116m}In$

●which is the basis for the popular indium foils used in many criticality dosimeters

$^{197}Au(n_{th}, \gamma)^{198}Au$

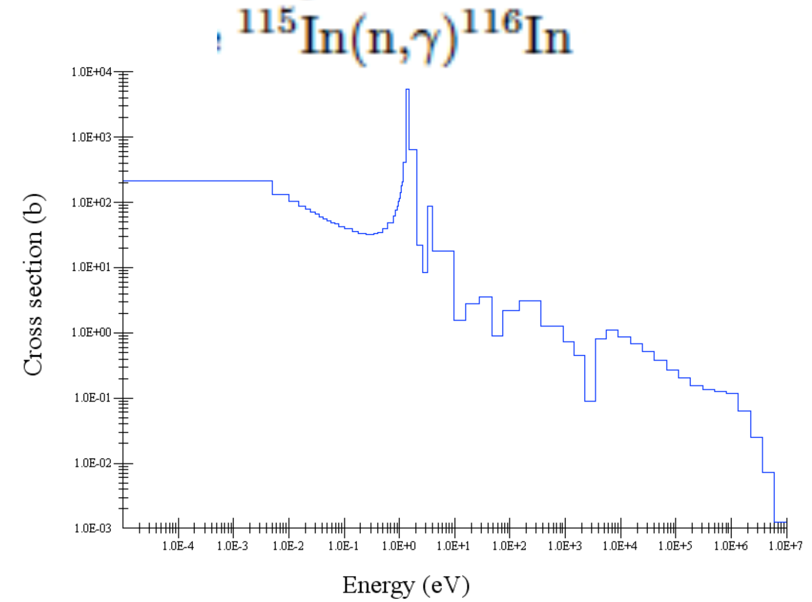
●used for criticality monitoring (gold foils)

Activation detectors: Indium disks

5cm Indium disks (30g total)

Two steps:

- Neutrons activate Indium
  - More sensitive to thermal neutrons
- Gamma lines @1293, 1047 and 416 keV with $T_{1/2}=\log(2)/\lambda=54$ min
- The activity (α) from an irradiation lasted t_r is measured with a HPGe detector (after a time t_a)



From activity to flux (ϕ)

$$\phi = \frac{\alpha}{N\sigma\left(1-\exp\left(-\lambda t_r\right)\right)\exp\left(-\lambda t_a\right)}$$

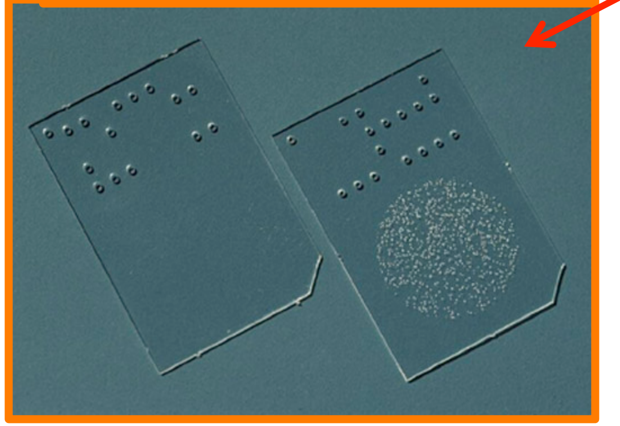
CR-39 detectors

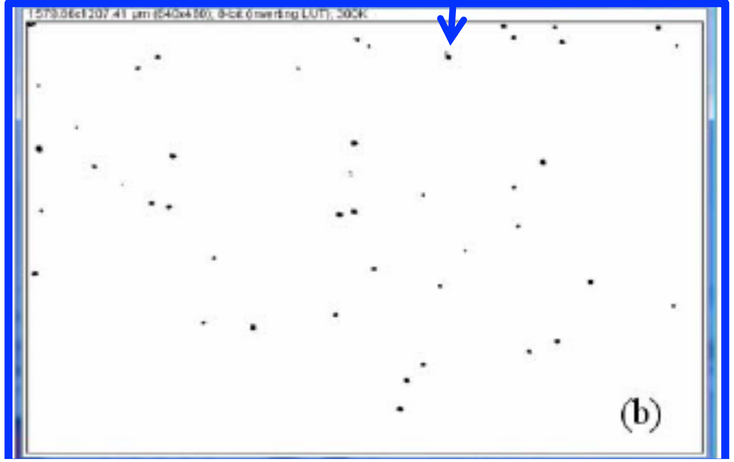
Slabs of poly-allyl-diglicol-carbonate (PADC) produced by intercast

R. Bedogni, et al, Radiat. Meas. **43**, S491 (2008)

Sensitive to **fast neutrons**:
- After n,p scattering protons leave a track
- Etching with potassium hydroxide at 70°C
- Read with a custom reader

Cut in pieces (2.224cm^2)





Number of tracks proportional to integrated impinging neutrons

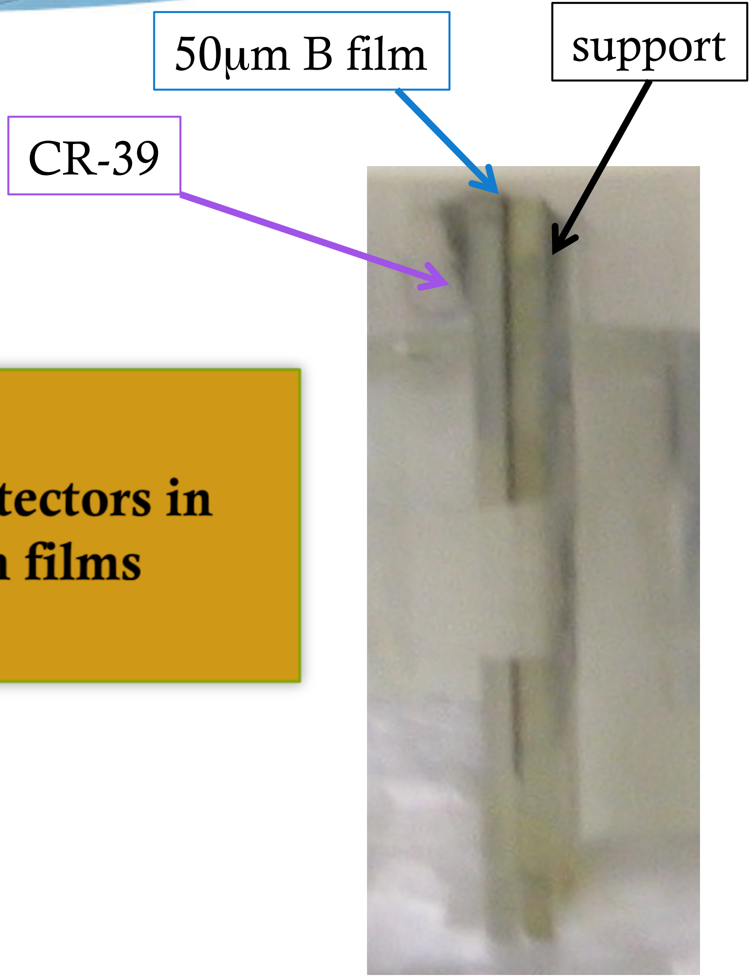
CR-39 detectors for thermal neutrons

<1.8 MeV α particles produced via

$B(n,\alpha)Li$

The α release tracks in CR-39 detectors

Wrap detectors in Boron films



Other Neutron Reactions Important to Health Physicists

$^{3}He(n_{th},p)^{3}H$

- which is the basis for the use of ^{3}He as a gas in several types of neutron proportional counters

$^{6}Li(n_{th},t)^{4}He$ or $^{6}Li(n_{th},\alpha)^{3}H$

- it is used in many neutron detection instruments, including thermoluminescent dosimeters (TLDs)

$^{10}B(n_{th},\alpha)^{7}Li$

- which is used in neutron shielding and as the basis for neutron detectors utilizing BF_3 gas or boron-lined counter tubes and Boron Neutron capture Therapy

Boron Neutron Capture Therapy

- Exploits high Xsection of thermal neutrons on Boron

- $n + {}^{10}_{5}B \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He \quad (BR\ 6\%)$
- $n + {}^{10}_{5}B \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He + \gamma(478\ keV) \quad (BR\ 94\%)$

- Boron is delivered to glioblastoma and melanoma via
  - BSH (borocaptured sodium)
  - BPA (borofenilananine)

- Requirements:
  - Thermal neutron flux $\Phi \sim 10^9/m^2/s$ to have treatment <30’

Other Neutron Reactions Important to Health Physicists

$^{32}S(n_f,p)^{32}p$

- which requires a neutron with a kinetic energy of at least 2.7 MeV in order to react (an energy threshold)
- this reaction is used in many threshold criticality dosimeters