TRAINING COURSE ON NEUTRON DOSIMETRY, RADIOBIOLOGY AND INSTRUMENTATION:

Passive detectors:

activation detectors and superheated emulsions

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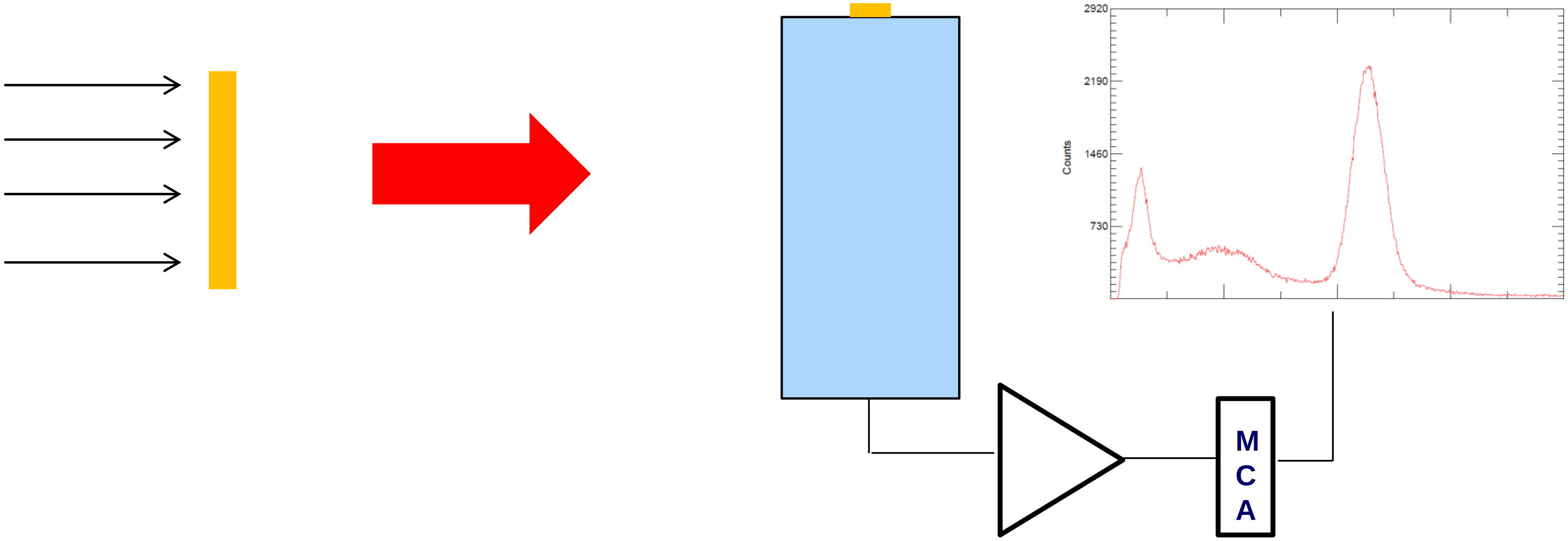
Wed. 24/6/2015, 17:00 – 18:00 pm

ACTIVATION DETECTORS: introduction

- The method consists in measuring the induced activity of a target exposed to a neutron field and relating it to the neutron fluence rate.



ACTIVATION DETECTORS: basic principles

- The reaction rate (s^{-1}) is related to the neutron fluence rate by:

$$R = N_{TOT} \int_{0}^{\infty} \sigma_E \Phi_E dE$$

- where:

$$N_{TOT} = \frac{N_{AV}}{AW} W$$

- is the total number of nuclei inside the target, N_{AV} is the Avogadro number, AW the atomic weight and W the target weight.

ACTIVATION DETECTORS: thermal and epithermal neutrons

- The following simplified method assumes that,
  - for thermal neutrons

$$\sigma_E = \frac{\sigma_0 v_o}{v}$$

    - where v is the neutron velocity, v_0 the neutron velocity @ 0.025 eV (22o0 m s^{-1}), σ_0 is the neutron cross section @ 0.025 eV;

  - and, for epithermal neutrons:

$$\Phi_E = \frac{\Phi_{epi}}{E}$$ (1/E slowing-down behaviour)

    - where Φ_{epi} is the epithermal fluence rate per unit ln(E)

ACTIVATION DETECTORS: thermal and epithermal neutrons

- the reaction rate R can be written as:

$$R = N_{TOT} \int_{0}^{E\max} \sigma_E \Phi_E dE = N_{TOT} \left(\int_{0}^{0.5eV} \frac{\sigma_0 v_0}{v} n_{th,E} v dE + \int_{0.5eV}^{E\max} \sigma_E \frac{\Phi_{epi}}{E} dE \right) =$$

$$= N_{TOT} \left(\sigma_0 v_0 \int_{0}^{0.5eV} n_{th,E}\, dE + \Phi_{epi} \int_{0.5eV}^{E\max} \frac{\sigma_E}{E} dE \right) =$$

$$= N_{TOT} \sigma_0 n_{tot} v_0 + N_{TOT} RI \Phi_{epi} = N_{TOT} \sigma_0 \Phi_0 + N_{TOT} RI \Phi_{epi}$$

- where:

$$RI = \int_{0.5eV}^{E\max} \frac{\sigma_E}{E} dE$$ is the resonance integral (barn)

  - Φ_0 is the neutron fluence rate defined as the thermal neutron density times the 2200 m s^{-1} neutron velocity.

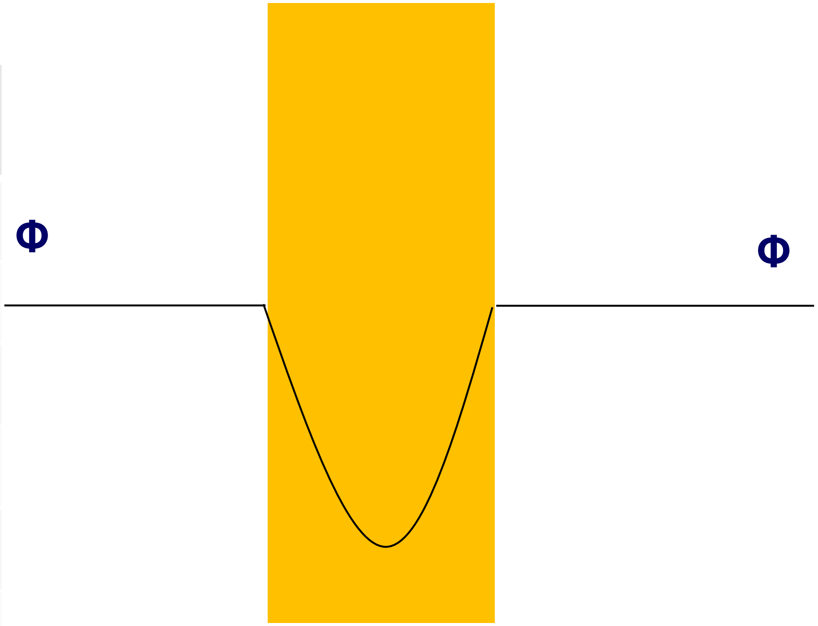
ACTIVATION DETECTORS: thermal and epithermal neutrons

- The expression in the previous slide is valid for an infinitely thin target:
- but an activation target shows a given thickness and the reaction rate expression must be corrected for the fluence rate depression factors, G_{th} and G_{epi}

$$R = G_{th} N_{TOT} \sigma_0 \Phi_0 + G_{epi} N_{TOT} RI \Phi_{epi}$$

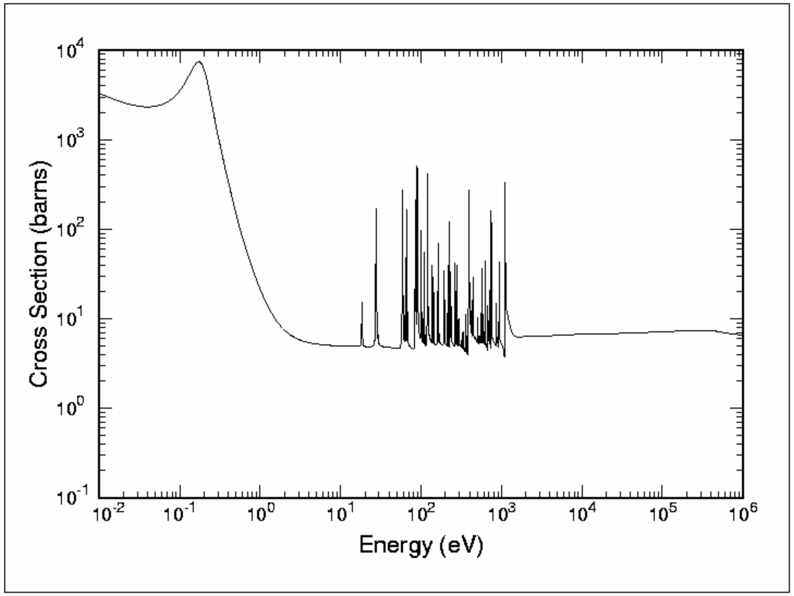
- G_{th} and G_{epi} depend on the target material and thickness

Target thickness (mg cm^{-2})	**Gold**		**Indium**	
	G_{th}	G_{epi}	G_{th}	G_{epi}
5	0.995	0.763	0.987	0.649
7.5	0.994	0.698	0.981	0.573
10	0.992	0.645	0.976	0.519
20	0.985	0.521	0.956	0.400
40	0.969	0.410	0.924	0.294



ACTIVATION DETECTORS: thermal and epithermal neutrons

- The thermal neutron component can be discriminated by the epithermal one with a cadmium cover;
- cadmium cut-off @ 0.5 eV



ACTIVATION DETECTORS: target reaction rate and activity

- By neglecting:
  - neutron capture on already activated nuclei;
  - the target burn-up;
- The number of activated nuclei during irradiation is:

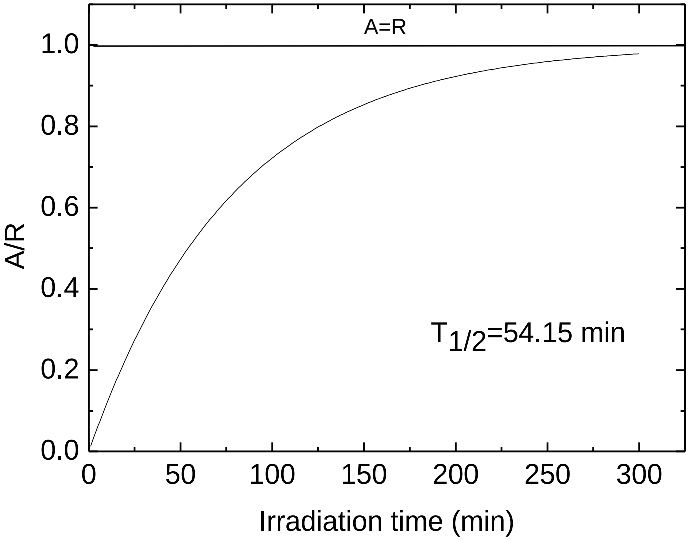
$$\frac{dN^*}{dt} = R - \lambda N^*$$

- At the end of irradiation (@ time t_{irr}):

$$N^*(t_{irr}) = \frac{R}{\lambda}\left(1 - e^{-\lambda t_{irr}}\right)$$

- The induced activity at the end of irradiation is:

$$A(t_{irr}) = R\left(1 - e^{-\lambda t_{irr}}\right)$$



ACTIVATION DETECTORS: target reaction rate and activity

- After a waiting time t_w (the time from the end of irradiation up to the beginning of counting):

$$A(t_w) = A(t_{irr})e^{-\lambda t_w}$$

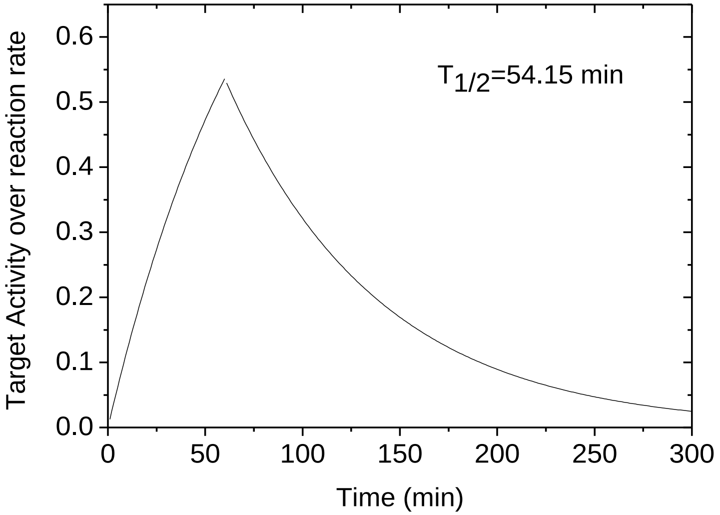
- The total counts acquired from t_w up to t_{meas} (i.e. counting time t_{meas}) are:

$$C_{tot}(t_{meas}) = R\varepsilon b\left(1-e^{-\lambda t_{irr}}\right)e^{-\lambda t_w}\int_{t_w}^{t_w+t_{meas}} e^{-\lambda t}dt =$$

$$= R\varepsilon b\left(1-e^{-\lambda t_{irr}}\right)e^{-\lambda t_w}\,\frac{1-e^{-\lambda t_{meas}}}{\lambda}$$

- If $\lambda t_{meas} << 1$:

$$\frac{1-e^{-\lambda t_{meas}}}{\lambda} = \frac{1}{\lambda}\left(1-1+\lambda t_{meas}\right) = t_{meas}$$



ACTIVATION DETECTORS: target reaction rate and activity

- The reaction rate is assessed by measuring the saturation activity of the activated material (gamma rays with a NaI(Tl) or a Ge detector, β^- particles with a GM detector):

$$R = \frac{C_{tot}}{\varepsilon b(1-e^{-\lambda t_{irr}})e^{-\lambda t_w}\frac{1-e^{-\lambda t_{meas}}}{\lambda}}$$

- Where b is the branching ratio and ε is the detector (peak) efficiency.

- If a bare and a cadmium covered target are used to separate the thermal and the epithermal components, the cadmium correction factor F_{Cd} should be used;
  - since cadmium is not completely transparent to epithermal neutrons.

$$C_{epi} = F_{Cd} C_{Cd}$$

  - where C_{epi} are the counts due to epithermal neutrons to be subtracted from the counts from the bare target and C_{Cd} are the counts from the Cd-covered target.
  - F_{Cd} depends on the thickness of the target material and of the Cd cover.

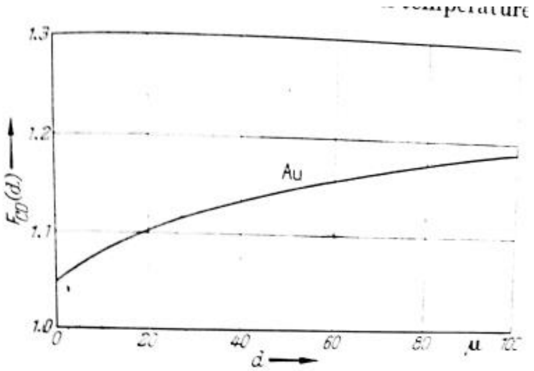


Fig. 12.2.2. The Cadmium correction factor for Gold foils in an isotropic neutron field as a function of Gold foil thickness. Cd filter thickness 1 mm

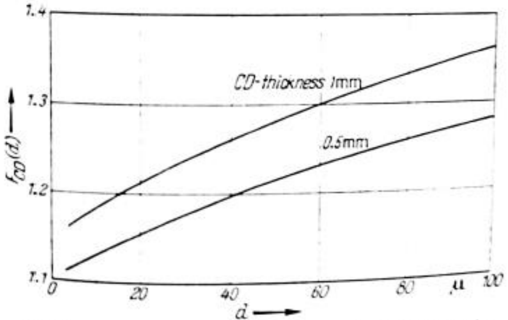


Fig. 12.2.3. The Cadmium correction factor for Indium foils in an isotropic neutron field as a function of Indium foil thickness. Cd filter thickness 0.5 and 1 mm

From K.H. Beckurts and K. Wirtz, Neutron Physics, Springer (1964)

ACTIVATION DETECTORS: target reaction rate and activity

- The specific saturation activities should be subtracted for obtaining that due to thermal neutrons only:

$$R_{th} = \left(\frac{R_{bare}}{W_{bare}} - \frac{R_{epi}}{W_{Cd}} \right) W_{bare}$$

  - where W_{bare} and W_{Cd} are the weights of the bare and Cd-covered target, respectively.
  - Finally, for estimating Φ_0 and Φ_{epi}:

$$\Phi_0 = \frac{R_{th}}{G_{th} N_{tot} \sigma_0}$$

$$\Phi_{epi} = \frac{R_{epi}}{G_{epi} N_{tot} RI}$$

  - It should be remembered that in the epithermal region:

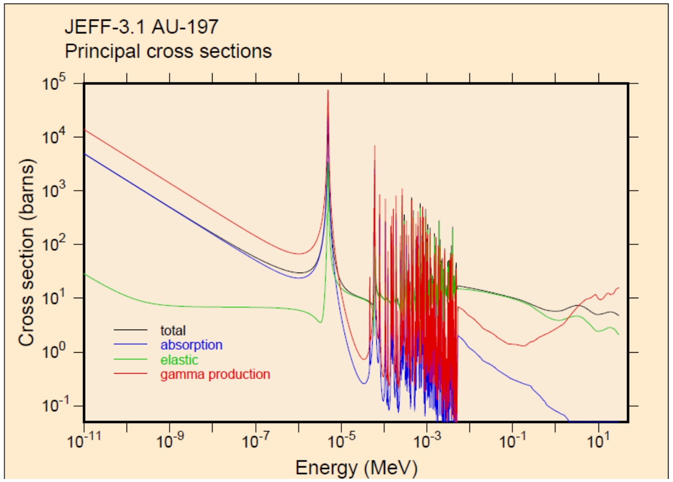
$$\Phi = \int_{0.5eV}^{E_{\max}} \frac{\Phi_{epi}}{E} dE = \Phi_{epi} \ln\left(\frac{E_{\max}}{0.5eV} \right)$$

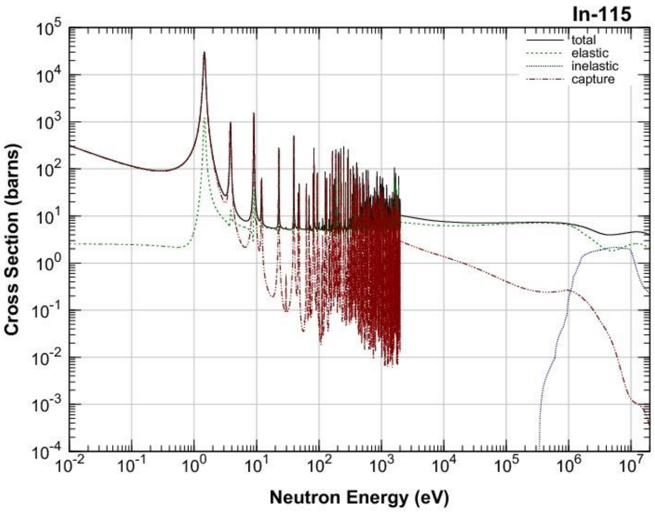
ACTIVATION DETECTORS: target materials for thermal and epithermal neutron detection

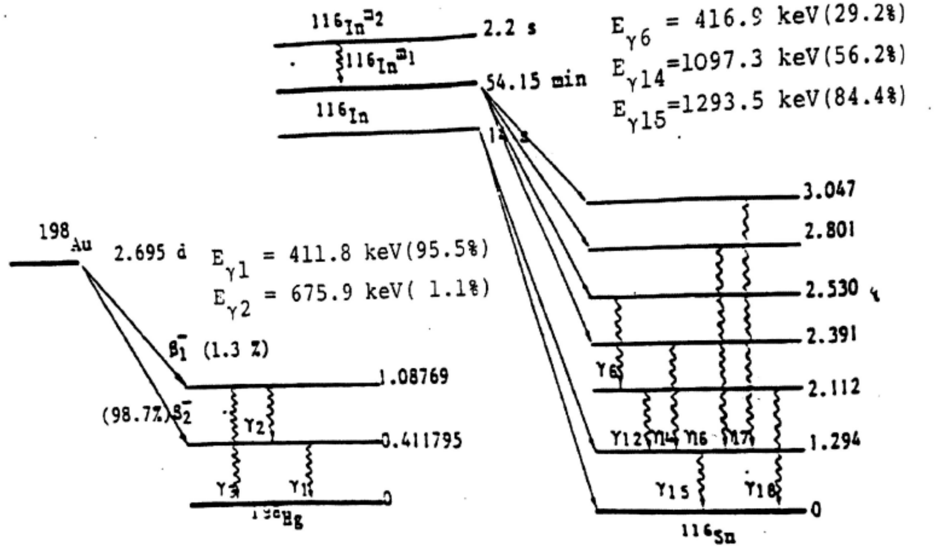
- Main activation reactions for thermal neutron detection:
  - ✓ $^{197}Au(n,\gamma)^{198}Au$: $T_{1/2}$=2.69 d, σ(0.025 eV)=98.5 b;
  - ✓ $^{115}In(n,\gamma)^{116m}In$: $T_{1/2}$=54.15 min, σ(0.025 eV)=157 b;
  - ✓ Other materials: Dy, Co, Cu, Ag.

	Gold	Indium
Half-life	2.695 d (^{198}Au)	54.15 min (^{116m}In)
σ_0 (0.025 eV)	98.8 b	157 b
RI	1560 b	2600 b

ACTIVATION DETECTORS: gold and indium foils







Au-198 and In-116m decay schemes with branching ratios (in brackets)

ACTIVATION DETECTORS: fast neutrons

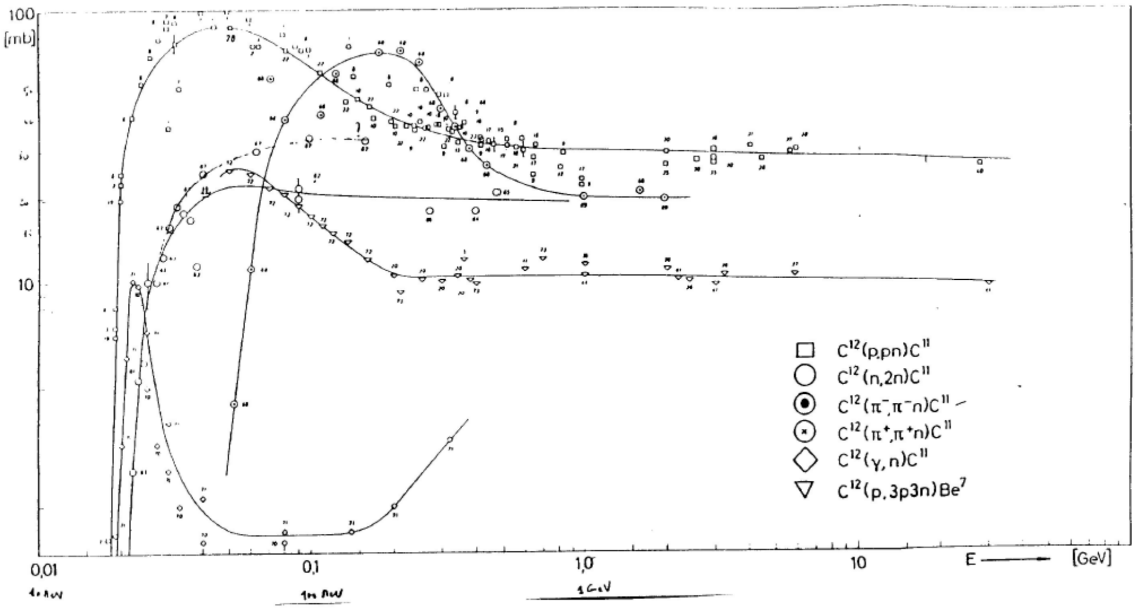
- Several threshold reactions can be exploited, e.g.:

✓ ^{58}Ni(n,p)^{58}Co	E_{th} = 1.9 MeV
✓ ^{59}Co(n,α)^{56}Mn	E_{th} = 5.2 MeV
✓ ^{54}Fe(n,p)^{54}Mn	E_{th} = 2.2 MeV
✓ ^{58}Ni(n,2n)^{57}Ni	E_{th} = 13.0 MeV
✓ ^{115}In(n,n')^{115m}In	E_{th} = 0.339 MeV
✓ ^{32}S(n,p)^{32}P	E_{th} = 2.0 MeV
✓ ^{12}C(n,2n)^{11}C	E_{th} = 20 MeV
✓ ^{27}Al(n, α)^{24}Na	E_{th} = 4.9 MeV
✓ ^{27}Al(n, p)^{27}Mg	E_{th} = 3.8 MeV

- The neutron spectrum can be reconstructed from the saturation activities assessed with a set of activation foils;
  - → The reaction cross section against energy (the “detector response”) must be known for this purpose.

ACTIVATION DETECTORS: high-energy hadrons

- The hadron fluence above about 20 MeV can be assessed through the activation of ^{11}C (x-sec≅20 mb, slightly dependent on hadron energy), i.e. for neutrons through the reaction:
  - ✓ $^{12}C(n,2n)^{11}C$ E_{th} = 20 MeV $T_{1/2}$=20.5 min
  - A plastic scintillator is exposed to the hadron field and
  - → the ^{11}C activity is measured by coupling the scintillator to a PM and by counting the positrons emitted by ^{11}C decay.



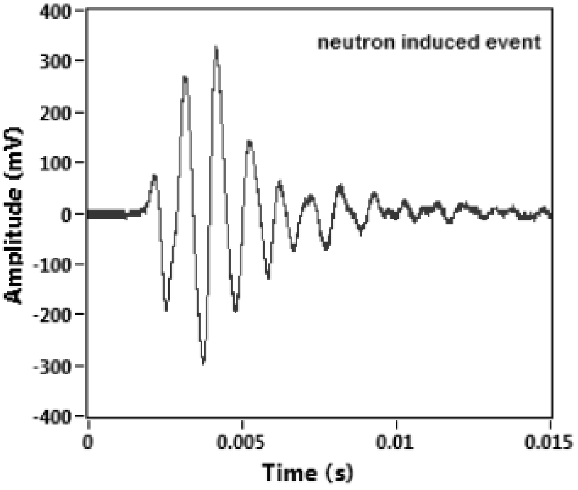
SUPERHEATED EMULSIONS

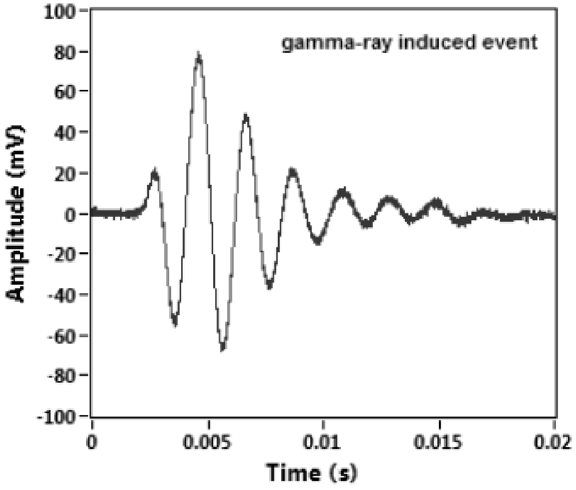
- “Superheated emulsion” is the name adopted by ISO and ICRU for detectors based on a superheated liquid suspended in a gel, also known as bubble detectors or superheated drop detectors.
  - ✓ The suspended droplets consist of an over-expanded halocarbon and/or hydrocarbon which vaporizes upon exposure to the high-LET recoils from neutron interactions.
  - ✓ The superheated emulsion is contained in a vial and acts as a continuously sensitive, miniature bubble chamber.
  - ✓ The total number of bubbles evolved from the radiation-induced nucleation of drops gives an integrated measure of the total neutron exposure.

Courtesy of F. d’Errico, Yale Univ. and DMNP Pisa Univ.

SUPERHEATED EMULSIONS

- ✓ Bubbles can be counted either optically (by eye) of through an acoustic transducer transforming the micro-explosion following bubble formation into an electronic signal.

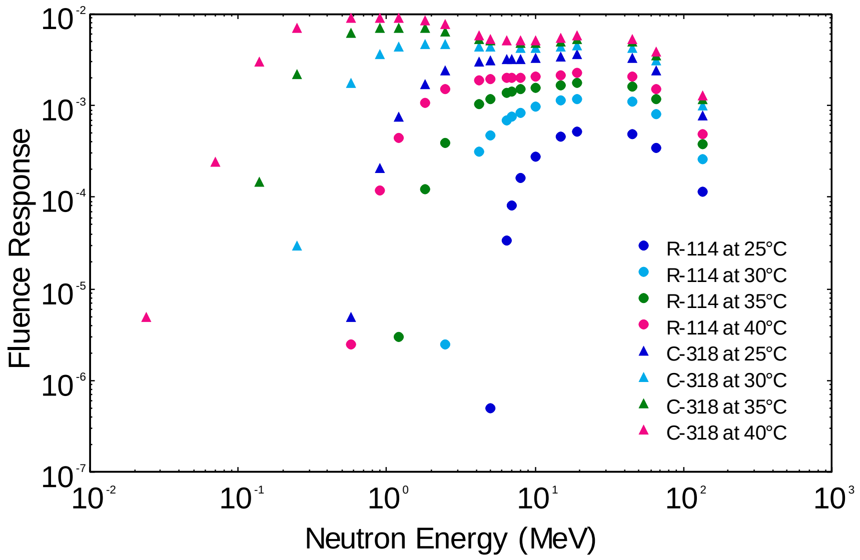


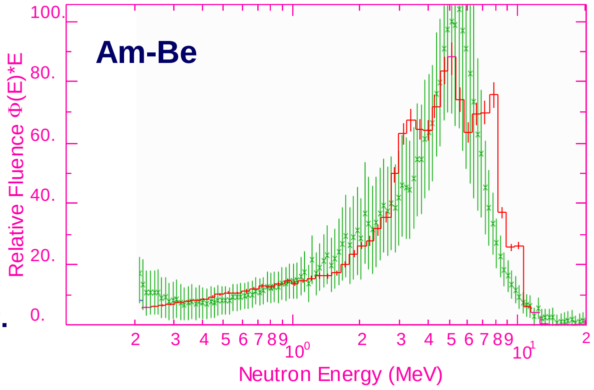


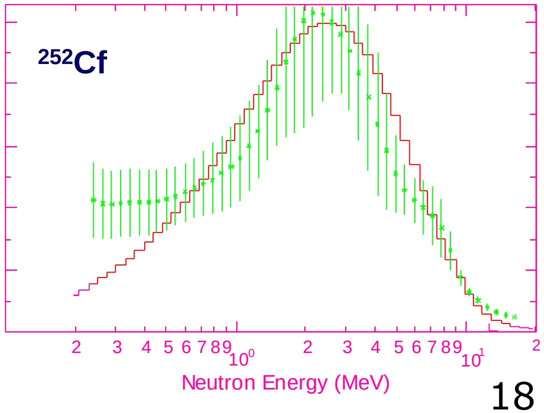
P.K. Mondal et al. Nucl.Instrum.Meth. A729 (2013) 182-187

SUPERHEATED EMULSIONS

- Superheated emulsions are currently used either as personal and environmental dosemeters or as neutron spectrometers.
  - ✓ Neutron spectrometry is performed by exploiting the different response to neutron energy against temperature or pressure of the superheated liquid.
  - ✓ Dosemeters: one of their advantages is the possibility of determining an average ambient dose equivalent rate in a pulsed neutron field.
  - ✓ They are completely insensitive to low-LET radiation, X and γ rays as well as muons, which is a clear advantage when measuring the neutron component in mixed fields.



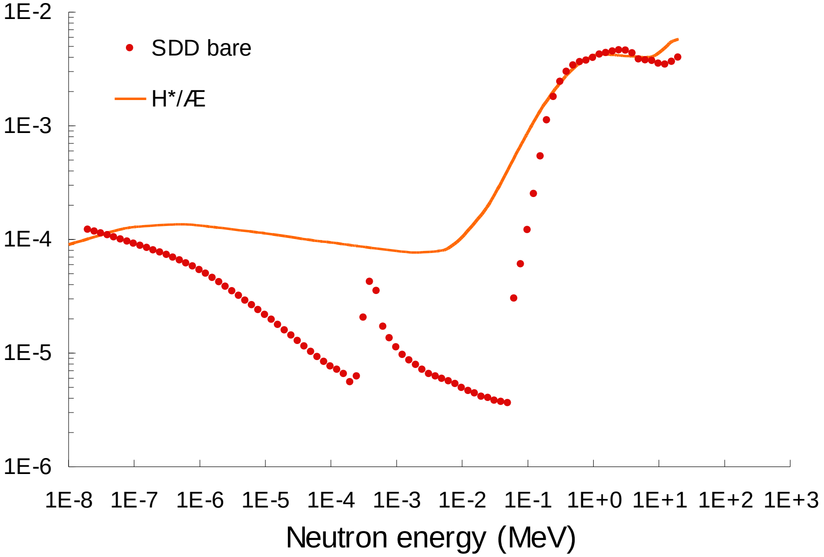


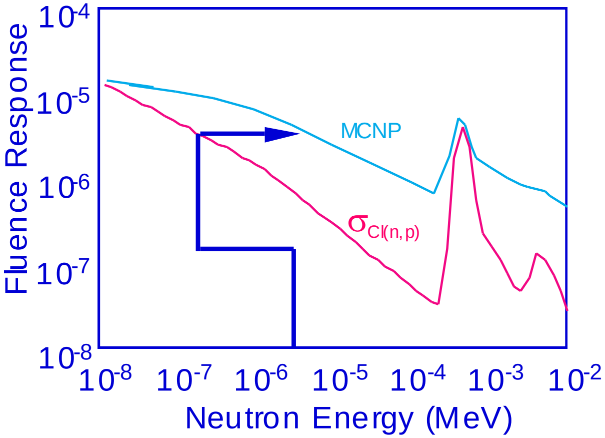


All figures in this slide:
Courtesy of F. d'Errico, Yale Univ. and DMNP Pisa Univ.

SUPERHEATED EMULSIONS

- The *H**(10) response is underestimated for epithermal neutrons (up to about 100 keV) and is fairly accurate in the neutron energy interval from 100 keV up to about 10 MeV**.**





- Low energy response: MCNP calculations
- Fast neutron response: PTB calibrations

All figures in this slide:
Courtesy of F. d'Errico, Yale Univ. and DMNP Pisa Univ.

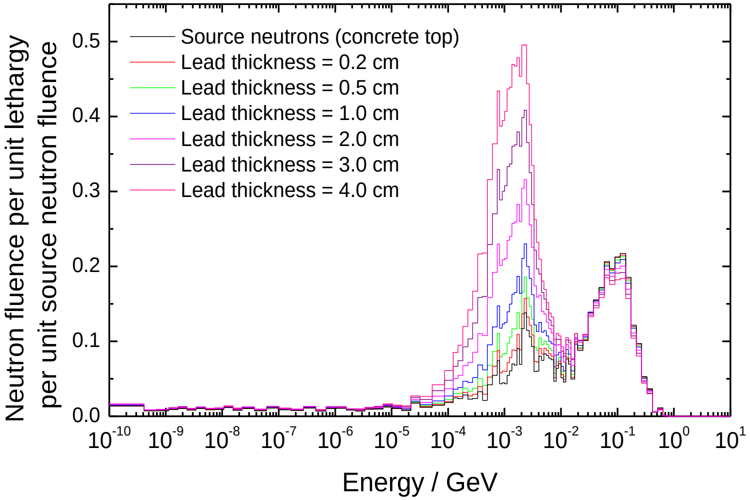
SUPERHEATED EMULSIONS

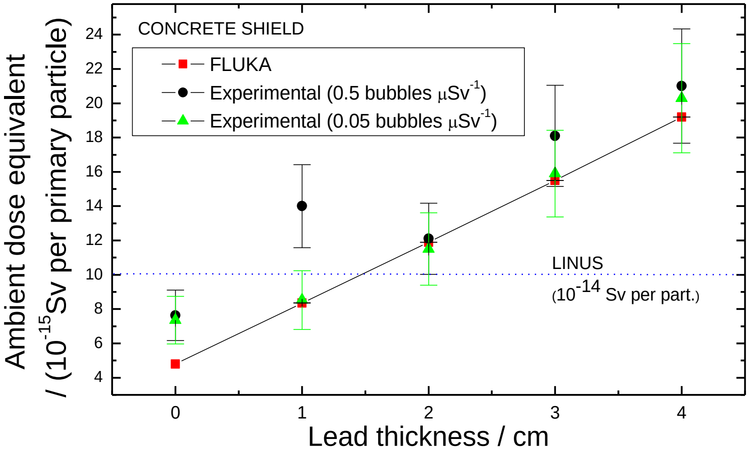
- The response to higher energies was measured by irradiating bubble detectors with quasi-monoenergetic neutrons in the energy interval 46-133 MeV. The results showed a significant underestimate of the $H^*(10)$ (d'Errico et al. RPD 100 (2002) 529-532).
- Measurements were also performed in the mixed field of high-energy radiation available at CERF. An underestimation of about 40% with respect to the reference ambient dose equivalent was observed in that experiment (Mitaroff et al., RPD 102 (2002) 7-22).
- Measurements in high-energy neutron fields generated by various types of hadron beams performed at CERN showed that bubble detectors underestimate the $H^*(10)$ by a factor 0.4-0.7 depending on the neutron spectrum (Agosteo et al. Health Phys. 75 (1998) 619-629).

Detector	Ambient dose equivalent rate (µSv h^{-1})			
	front NA44	side NA44	dump NA45	NA45
LINUS$_{sph,UMi}$	21.2±0.2	22±1	227±22	108±10
bubble detectors	19±4	13±1.5	210±44	78±6

SUPERHEATED EMULSIONS

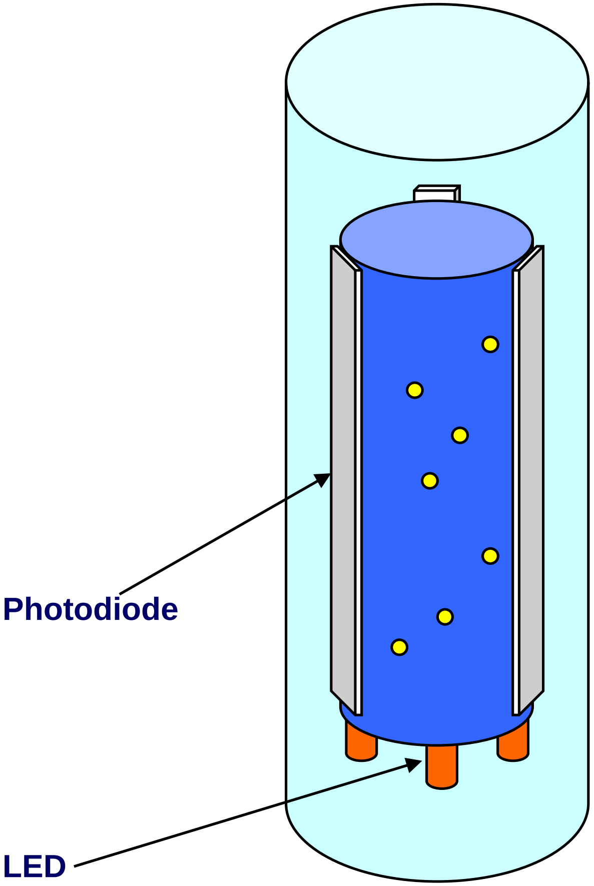
- The possibility of extending the response of bubble detectors to HE neutrons was investigated by exposing the dosemeters inside lead converters of varying thickness at the CERF facility.
  - ✓ MC simulations showed that, as the thickness of the lead converter increases, a growing number of evaporation neutrons are generated by the high-energy component of the neutron field, thus enhancing the detector sensitivity.
  - ✓ This behaviour was confirmed experimentally. The comparison with the reference *H**(10) indicates that the required thickness of the lead converter is in the interval 1-1.5 cm.





SUPERHEATED EMULSIONS: OPTICAL BUBBLE COUNTING

- The application of large volume detector chambers for the three-dimensional dosimetry of brachyterapy implants lead to study novel position-sensitive systems for assessing the bubble spatial distribution.
    - ✓ Optical tomography was proposed by d'Errico et al, 2008 for this purpose.
- The satisfactory results obtained with this technique lead to apply scattered light for bubble counting of superheated emulsions for individual dosimetry (d'Errico et al, 2008).
- The dosemeter is placed in a light-shielded enclosure and illuminated from the bottom by LEDs (light-emitting diodes). The light scattered by the bubbles is detected by photodiodes positioned along the detector wall.
- A very good linearity of the response (photodiode voltage against number of bubbles) of this system was observed.
- The uniformity in size of the drops suspended in the gel was found to be of primary importance for a smooth behaviour of the system. This feature is guaranteed by the manufacturing technique for the superheated emulsions which is capable of providing drops with size in the range 50-150 μm with a dispersion lower than 10%.



Adapted from:
d'Errico, F., Di Fulvio, A., Mariañski, M. , Selici, S., Torriginai, M., Radiation Measurements 43 (2008) 432-436.