MASTER DI II LIVELLO IN RADIOPROTEZIONE

Neutron Passive Detectors

Adolfo Esposito

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Università Campus Bio-Medico di Roma - Via Álvaro del Portillo, 21 - 00128 Roma – Italia
www.unicampus.it

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Passive detectors

- Neutron dosimetry and spectrometry
  - **Superheated emulsions (also called bubble detectors)**
  - **Track etched detectors**
  - **Activation foils**
  - **Passive BSS (using TED, activation foils, TLDs)**

- Neutron dosimetry
  - **TLDs**

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Bubble detectors

Superheated-emulsion neutron detectors are based on a principle first proposed by Apfel (1979). Small droplets of a superheated liquid (i.e., a liquid at a temperature above its normal boiling point) are suspended in a viscoelastic medium.

The droplets remain in the liquid phase due to the absence of nucleation sites within the droplets, or at their interface with the host medium.

When a neutron interacts with a nucleus inside or near one of the droplets, the resulting secondary charged particles transfer energy to the droplet, and may cause localized evaporation.

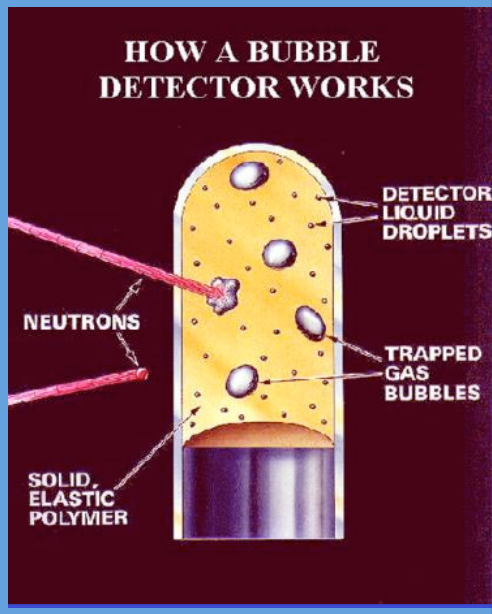
A small vapor bubble is formed and begins to expand by vaporizing adjoining liquid. If sufficient energy has been transferred, the bubble will exceed a critical radius and all of the liquid in the droplet will be vaporized. In this case, the bubble becomes visible and persists. If the energy transferred is not sufficient for the bubble to exceed the critical radius, the vapor will recondense.

The droplets consist of halocarbons, such as Freon™12 (CCl_2F_2), Freon™142B ($C_2H_3ClF_2$), Freon™114 ($C_2Cl_2F_4$) and C-318 (C_4F_8), and hydrocarbons, such as isobutane (C_4H_{10}).

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

- Passive neutron dosimeters
- Reusable
- Integrating
- Allow instant visible detection of neutrons

- Consist of minute droplets of a superheated liquid dispersed throughout an elastic polymer
- Neutrons strike droplets producing secondary charged particles
- Charged particles cause droplets to vaporize, producing bubbles
- Bubbles remain fixed in polymer
- Bubbles can be counted by eye or in automatic reader
- Dose is proportional to the number of bubbles



Bubble Detectors (BTI , CANDADA)

In the active version of the SDD, an acoustical detector is in contact with the vial containing the medium, so that each time a bubble is formed the pop that the bubble makes can be detected and recorded electronically (Apfel and Roy, 1984).

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Bubble Detectors (BTI , CANDADA)

Characteristics	BDPND	BD100R	BDT	BDS
Energy Range	< 200 keV - > 15 MeV	<200 keV- >15 MeV	Thermal ~1/V for epithermals	6 distinct thresholds: 10, 100, 600, 1000, 2500, 10000 keV
Dose Range	0.1 – 500 mrem	0.1 - 500 mrem	0.1 - 10 mrem	~ 50 mrem
Sensitivity (Typical)	0.33 - 33 bub/mrem 0.033 - 3.3 bub/fSv	0.33 - 33 bub/mrem .033 – 3.3 bub/ fSv	~ 30 bub/mrem 3.0 bub/fSv	1 - 2 bub/mrem 0.1 - 0.2 bub/fSv
Gamma Sensitivity	None but photon induced effect	None but photon induced effect	None but photon induced effect	None but photon induced effect
Tissue Equivalence	Yes	Yes	Yes	Yes
Temperature Compensation	Yes	No	Yes	No

Characteristics	BDPND	BD100R	BDT	BDS
Optimum Temp. Range	20 - 37°C	10-35°C	20-37°C	20°C
Angular Response	Isotropic	Isotropic	Isotropic	Isotropic
Size	145mm x 19mm dia	120mm x 16mm dia	145mm x1 9mm dia	80mm x 16mm dia
Weight	58 g	33 g	58 g	20 g
Re-use	Yes	Yes	Yes	>10 cycles
Warranty	90 days	90 days	90 days	90 days
Other		T Response Curve Provided	Thermal/fast Sensitivity 10/1	Special Recompression Chamber Available

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Application at accelerator facilities remain limited

Vantages

Easy to count

Very sensitive

No angular dependence

Energy response sufficiently good

Disadvantages

Temperature dependence

Unit cost

Potential counting difficulty in high bubbles density resulting from moderate to high doses

Limited life span

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Dosimetria passiva a tracce

Quando una particella carica passa attraverso un isolante la cessione di energia lungo la traccia determina un danneggiamento delle molecole lungo la traccia stessa.

Il danneggiamento può essere visualizzato attraverso un attacco del materiale a mezzo di un acido e/o di una base.

Le tracce vengono lette con vari metodi: dal loro numero e dalla loro forma si risale alla fluenza di particelle a cui è stato esposto il materiale, alla loro natura e alla loro energia.

I materiali che presentano tale fenomeno possono essere divisi in due grandi categorie: i cristalli inorganici e i polimeri organici. I più usati vista la loro sensibilita' sono i polimeri organici.

Gia' a partire dagli anni 70 del secolo scorso fu evidenziata la possibilita' di usare rivelatori a tracce nella dosimetria neutronica ma solo con l'introduzione di una plastica a buon mercato, il polyallyl diglicol carbonate (PADC) comunemente ma erroneamente chiamato CR-39®, crebbe l'interesse per tale particolare uso.
Il PADC infatti si poteva essere usato per rivelare protoni.
La sua abilita' nel rivelare protoni di rinculo ha fatto scendere la soglia di rivelazione dei neutroni veloci a circa 100 keV

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

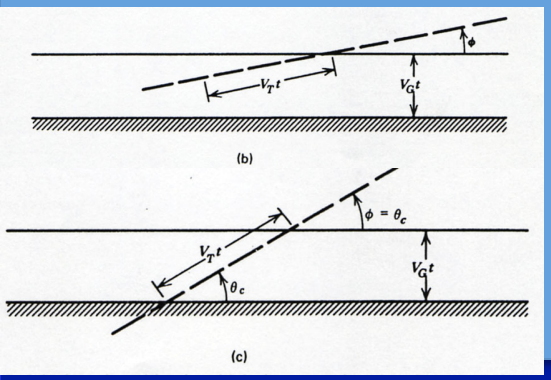
Durante l'attacco chimico la velocità di ablazione delle aree colpite dalle radiazioni e' maggiore delle aree non irradiate e pertanto dopo un certo tempo è possibile vedere a mezzo di un microscopio dei buchi sulla superficie del materiale. Il numero dei buchi per unità di superficie può essere senz'altro messo in relazione con la dose da neutroni. Il meccanismo è illustrato nella figura. Vale la pena notare che una particella incidente ad un angolo maggiore di un certo angolo detto angolo critico non viene rivelato poiché viene eliminato dall'attacco chimico.

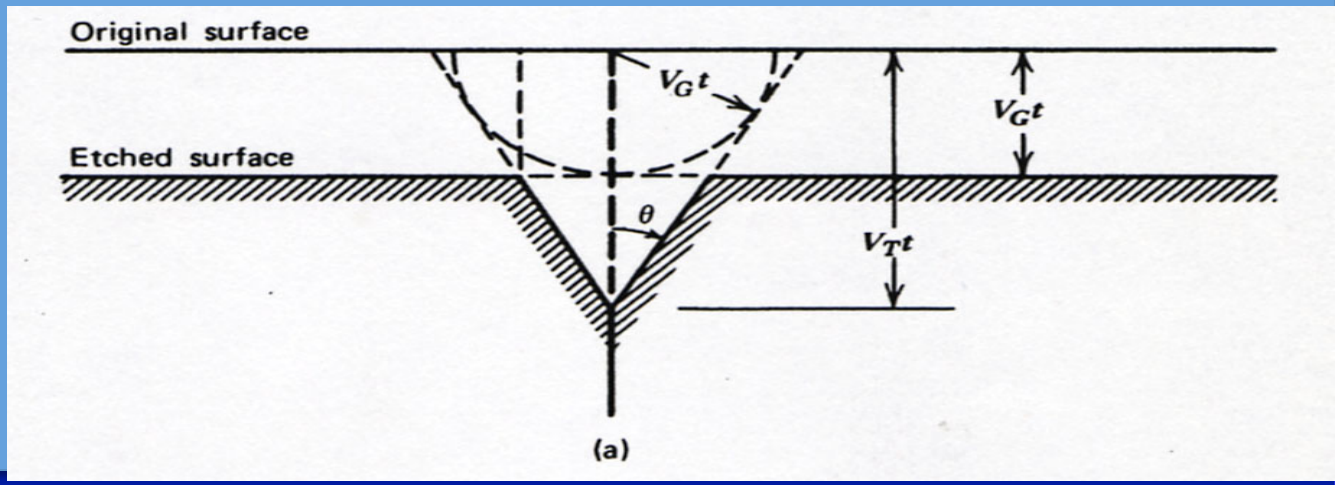
L'angolo critico è definito come

$$\vartheta = arcsin\left(\frac{V_G}{V_T}\right)$$

dove V_G è la velocità di oblazione della superficie danneggiata e V_T è quello della superficie integra.

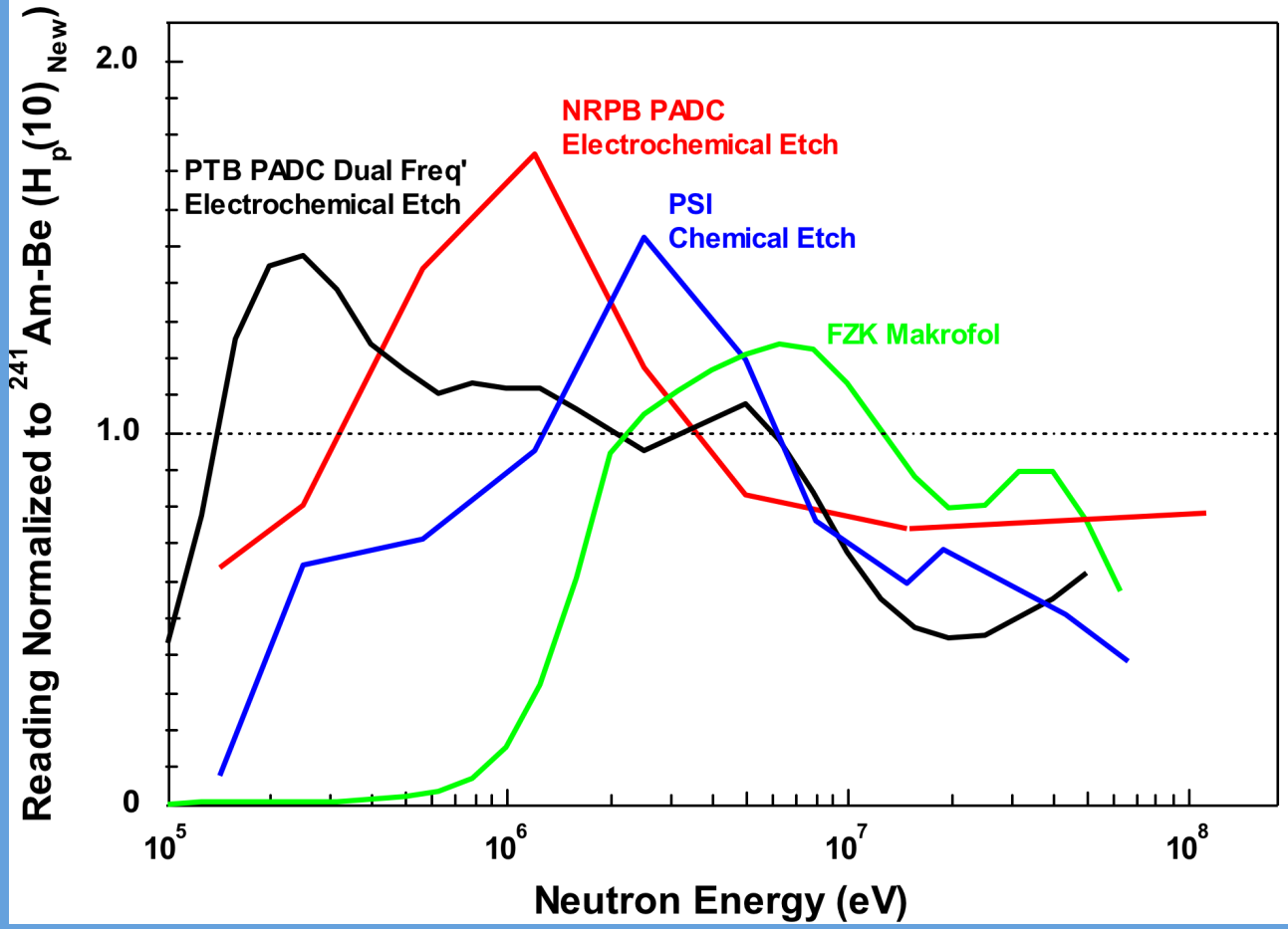
Detto angolo critico varia da 5° a 15°

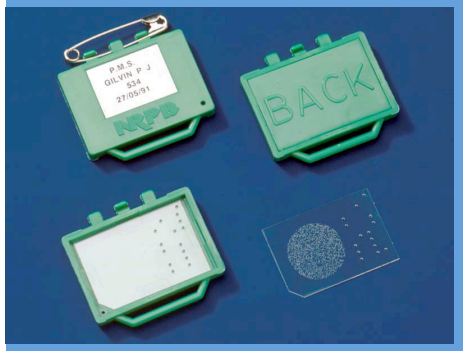


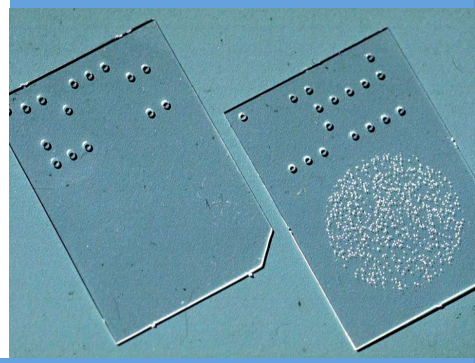


Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Etched Track Detector Response Characteristics







Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

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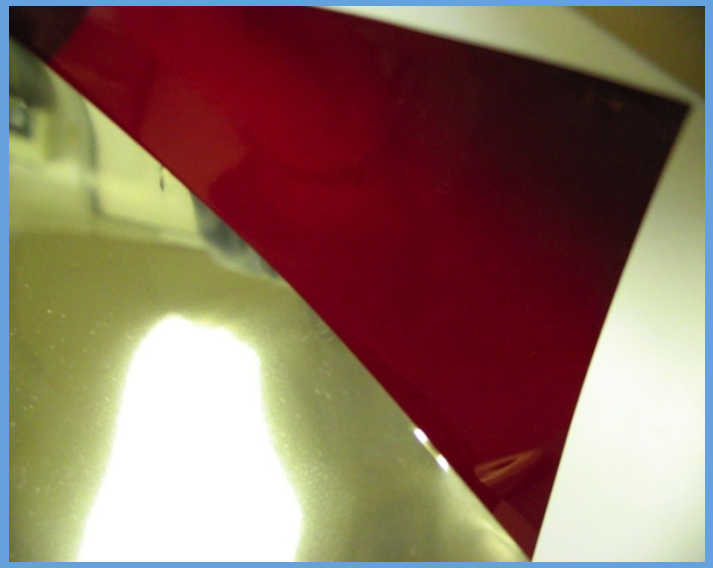
I rivelatori a tracce sono ampiamente utilizzati
- Nelle misure di radon
- Nella dosimetria dei neutroni veloci
- Nella dosimetria dei neutroni termici
- Nella rivelazione dei raggi cosmici

- I piu' diffusi sono

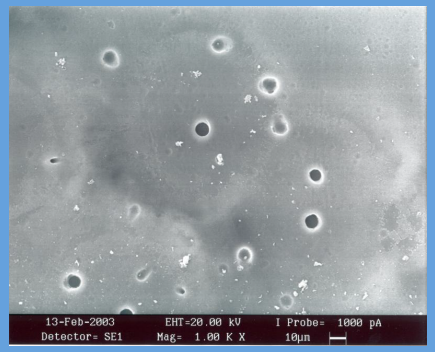


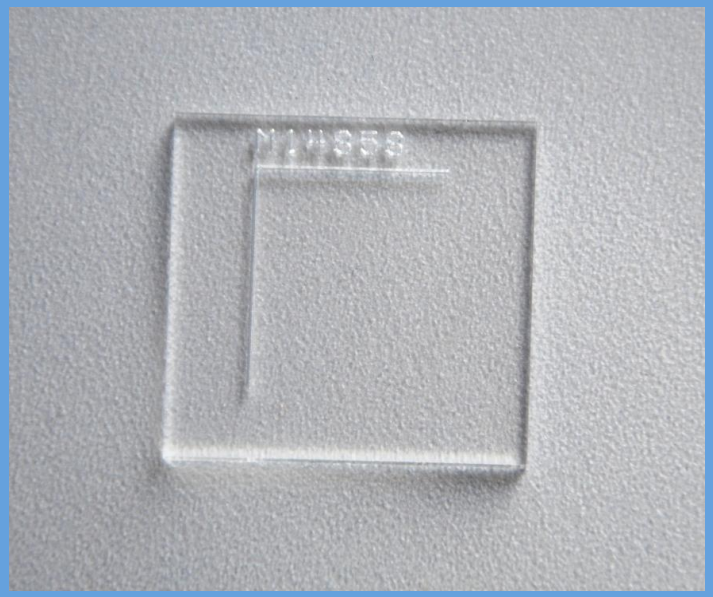
LR115

nitrate layer on a clear polyester base

CR-39

PADC- Poly allyl diglycol carbonate





Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Vantaggi

Sensibilita' adeguata per la dosimetria personale nella porzione dove la risposta e' "piatta" in funzione dell'energia

Risposta lineare fino a 4 mSv e corregibile fino a 100 mSv

Fading praticamente inesistente

Riproducibilita' eccellente

Relativamente basso costo

Rileggibile

Svantaggi

Forte dipendenza dall'angolo di incidenza

Fondo elevato dovuto in parte al radon e in parte ai difetti di fabbricazione del materiale.

Il numero di tracce e' fortemente dipendente dai parametri di sviluppo

Non facile etichettatura permanente

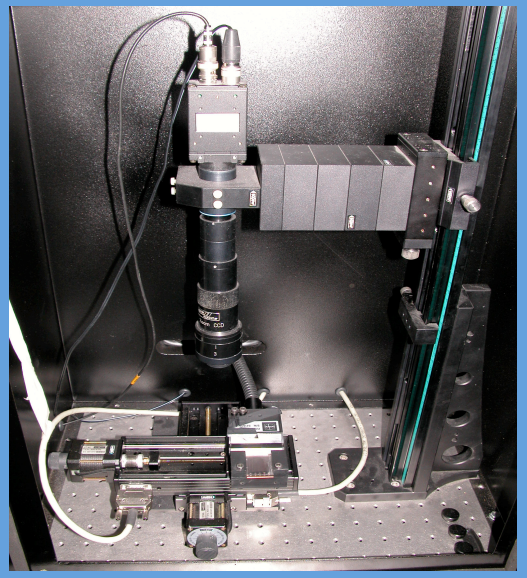
Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

At the INFN-LNF (Frascati, Italy) a CR-39® based fast neutron dosimetry service has been established. Home made chemical etching procedures and an automatic reader have been developed.

The whole system, based on a four elements dosemeter, has been characterized for ambient dosimetry applications around the DAFNE collider.

The reader shows high reproducibility, flexibility, accuracy and velocity features that are suitable for routine dosimetry.
The energy dependence of the dosemeter response has been experimentally determined. Moreover, the distribution of the background dosemeters has been extensively studied.

On this basis, an evaluation algorithm for the four elements dosemeter has been set up. The main result is the reduction of the MDDE to 30 μSv, which is a notable achievement for the low doses field.



The optical system is based on an epi-illumination low magnification microscope (about 10 x) on which a CCD camera is mounted.

The camera acquires images with 768 x 576 pixels and 256 grey levels. The optical system is contained in a black box, in order to eliminate any perturbation due to changes in the environmental illumination condition.

Two orthogonal 80 mm stepping motor translators, with accuracy best than 0.01 mm, allow moving the dosemeter in order to change the field to be analyzed.

The dosemeter, manually placed on the illumination plane, is kept in a reproducible position by a flexible blocking system.

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

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Activation detectors for measurements of neutron fluences

A sample of the material can be exposed to neutrons for a period of time, removed so that the induced radioactivity may be measure with conventional methods HpGe, NaI etc.
The measured radiation is used to deduce information about the neutron field.

When a stable isotope B of a target material is exposed to a high energy particle beam it is transmuted to a radioactive nuclide R which decays with its characteristic disintegration constant λ_R. The rate of accumulation of R, given by the rate of its formation minus the rate of disintegration, may be expressed by the following differential equation:

$$\frac{dN_R}{dt} = \sigma_{B,R}\varphi N_B - \lambda_R N_R \qquad (1)$$

where

φ is the particle fluence rate

$\sigma_{B,R}$ is the activation cross section

N_B is the number of atoms of B present in the target material

N_R is the number of radioactive atoms.

Through the integration of equation (1) the number of radioactive atoms present at the end of the irradiation time t will be given by:

$$N_R(t) = \frac{\sigma_{B,R}\varphi N_B}{\lambda_R}\left(1 - e^{-\lambda_R t}\right) \qquad (2)$$

and the number of disintegrations per second will be given by:

$$A_R(t) = N_R(t)\lambda_R = \sigma_{B,R}\varphi N_B\left(1 - e^{-\lambda_R t}\right) \qquad (3)$$

The induced activity build up with time and approaches a saturation activity. In fact for $t=\infty$ $A_\infty = \sigma_{B,R}\,\phi N_B$

The equation can be written $A(t)=A_\infty(1-e^{-\lambda t})$

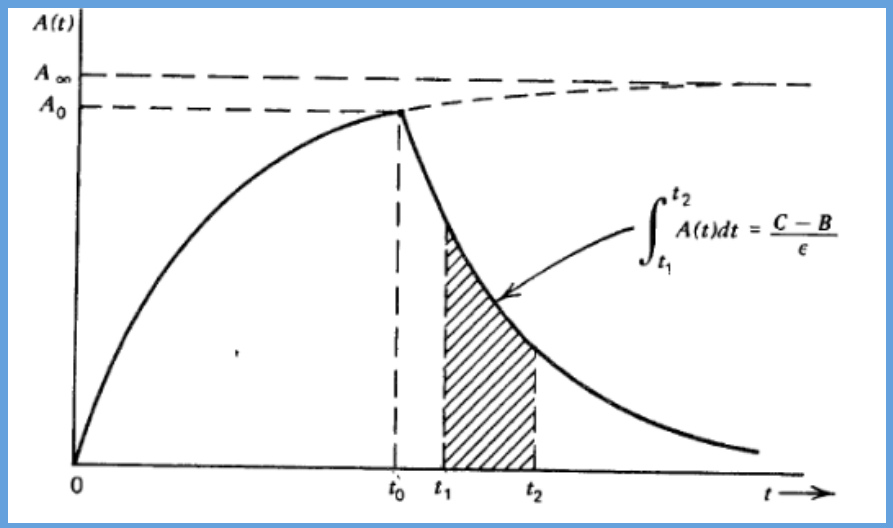
Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

For an irradiation for a time t_0 for a foil we obtain $A_0=A_\infty(1-e^{-\lambda t_0})$

After the exposure the activation of foil is tranferred to a appropriate counter for activity measurement. Because the activity is continuously decaying careful must be made in order to take into account each time involved

If the counting is carried out between t_1 and t_2 the number of counts will be

$$C = \varepsilon \int_{t_1}^{t_2} A_0 e^{-\lambda(t-t_0)}\, dt + B = \varepsilon \frac{A_0}{\lambda} e^{-\lambda t_0}(e^{-\lambda t1} - e^{-\lambda t_2}) + B$$



ε is the efficiency
B is the background between t_2 an t_1

$$A_\infty = \frac{\lambda(C-B)}{\varepsilon(1-e^{-\lambda t_0})e^{-\lambda t_0}(e^{-\lambda t1} - e^{-\lambda t_2})}$$

$A_\infty = \sigma_{B,R}\, \phi N_B$

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Activation detectors for measurements of neutron fluences

How to choose the material for activation detector?

Cross section

- (n,γ) reactions have typically largest cross sections near thermal energies and therefore such materials are preferentially chosen for intermediate neutrons.
- (n,p), (n,α), (n,2n) reactions needs higher energies or have a threshold energy such materials are preferentially chosen for fast neutrons

Magnitude of cross section

- The saturated activity is proportinal to the average cross section sections
- Higher sensitivity is achieved by selecting material with highest activation cross section

Half life of induced activity

- The best choice of the half life of induced activity of few hour is the optimum
- Long half lives require the use of long irradiation times to approach a saturation
- Specific activity is consequently small
- Very short half lives can give problems of transferring foils to the counter
- High activities can create a dead time effect

The material should be chosen with a very high degree of purity in order to avoid any interference from contaminant induced neutron activation.

The activated material decay emitting beta particles or gamma rays

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Activation detectors for measurements of neutron fluences

The main advantages of passive detectors are:

- No electronics is required at exposure and the detectors can be employed in difficult and hostile environments.
- They can be used with pulsed sources.
- Integration may cover short or long periods (provided that, for activation detectors, the exposure period is considerably less than the half·life of the radionuclide produced).
- Many passive detectors are inexpensive and an array of them can be used for radiation field mapping.
- Passive detectors can be very small although greater sensitivity can be obtained if larger detectors are used.
- Discrimination against gamma radiations is good

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Limitation and disantantages

Sensitivity is usually rather low (this is related to the small size of detectors commonly used and is not an inherent limitation if the induced nuclide emits gamma radiation).
The energy response is determined by the reaction cross section and cannot be "tailored" to the effective dose or ambient dose equivalent.
None information about time variation of neutron flux during the exposure

Activation passive detectors are mainly used

- as personal and installed dosemeters in criticality dosimetry,
- in monitoring of pulsed machines such as high energy accelerators
- in nuclear fusion experiments,
- in calibration experiments in standard neutron fluences.
- In neutron spectrometry

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

TABLE 3.3. ACTIVATION THRESHOLD DETECTORS *(after Holt [Ho 85])*

Reactions	Half-life of product	Energy of gamma ray (MeV)	Approxima threshold energy (MeV)
$^{7}Li(n,\alpha n')^{3}H$	12.3 a	0.019 (β)	3.8
$^{12}C(n,2n)^{11}C$	20.3 min	0.51	20
$^{12}C(n,spall)^{7}Be$	53.6 d	0.48	30
$^{19}F(n,2n)^{18}F$	109.7 min	0.51	13.1
$^{24}Mg(n,p)^{24}Na$	15.0 h	1.37, 2.75	7.5
$^{27}Al(n,p)^{27}Mg$	9.5 min	0.84, 1.01	3.8
$^{27}Al(n,\alpha)^{24}Na$	15.0 h	1.37, 2.75	4.9
$^{27}Al(n,spall)^{22}Na$	262 a	0.51, 1.28	25
$^{32}S(n,p)^{32}P$	14.3 d	1.71 (β)	3.3
$^{46}Ti(n,p)^{46}Sc$	83.9 d	0.89, 1.12	2.9
$^{47}Ti(n,p)^{47}Sc$	3.43 d	0.16	2.4
$^{48}Ti(n,p)^{48}Sc$	1.83 d	0.98, 1.13	7.1
$^{50}Cr(n,2n)^{49}Cr$	41.9 min	0.15	13.5
$^{52}Cr(n,2n)^{51}Cr$	27.7 d	0.32	12.4
$^{54}Fe(n,p)^{54}Mn$	303 d	0.84	2.2
$^{54}Fe(n,2n)^{53}Fe$	8.53 min	0.38	13.9
$^{56}Fe(n,p)^{56}Mn$	2.58 h	0.85	5.0
$^{58}Ni(n,p)^{58}Co$	71.3 d	0.51, 0.81	1.3
$^{58}Ni(n,2n)^{57}Ni$	36.0 h	0.51, 1.37	12.6
$^{59}Co(n,\alpha)^{56}Mn$	2.58 h	0.85	5.2
$^{59}Co(n,2n)^{58}Co$	71.3 d	0.51, 0.81	10.3
$^{63}Cu(n,2n)^{62}Cu$	9.76 min	0.51, 1.17	11.3
$^{64}Zn(n,p)^{64}Cu$	12.8 h	0.51, 1.35	2.0
$^{65}Cu(n,p)^{65}Ni$	2.56 h	1.12	3.2
$^{65}Cu(n,2n)^{64}Cu$	12.7 h	1.35, 0.51, 1.35	10.3
$^{90}Zr(n,2n)^{89}Zr^{g+m}$	78 h	0.91	12
$^{93}Nb(n,n')^{93}Nb^{m}$	13.6 a	0.019, 0.017	0.03

TABLE 3.3. (cont.)

Reactions	Half-life of product	Energy of gamma ray (MeV)	Approximate threshold energy (MeV)
$^{93}Nb(n,2n)^{92}Nb^{m}$	10.2 d	0.93	9
$^{103}Rh(n,n')^{103}Rh^{m}$	56.1 min	0.02	0.6
$^{115}In(n,n')^{103}Rh^{m}$	4.5 h	0.34	1.5
$^{127}I(n,2n)^{126}I$	12.8 d	0.39, 0.67	9.3
$^{197}Au(n,2n)^{196}Au$	6.2 d	0.36	8.6
$^{197}Au(n,4n)^{194}Au$	39.5 h	0.33	24
$^{197}Au(n,spall)^{149}Tb$	4.1 h	0.17	600
$^{199}Hg(n,n')^{199}Hg^{m}$	42.6 m	0.16, 0.37	0.53
$^{199}Hg(n,spall)^{149}Tb$	4.1 h	0.17	600

TABLE 3.2. THRESHOLD DETECTOR TECHNIQUES

Reaction	Sample material	Threshold (MeV)
^{32}S–^{32}P	Sulphur powder or pellets	3
^{27}Al–^{27}Mg	Aluminium discs or pellets	3
^{27}Al–^{24}Na	Aluminium discs or pellets	6
^{27}Al–^{22}Na	Aluminium discs or pellets	35
^{27}Al–^{18}F	Aluminium discs or pellets	35
^{19}F–^{18}F	Teflon cyclinders	12
^{12}C–^{11}C	Polyethylene cylinders or plastic scintillators	20
^{12}C–^{7}Be	Polyethylene cylinders or plastic scintillators	35
Bi–fission	Fission chamber	50

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

TABLE 3.5. ACTIVATION REACTIONS COMMONLY USED IN THE DETERMINATION OF THERMAL NEUTRON FLUX DENSITIES

Reaction	Decay products	Half-life	Detector	Sensitivity at saturation
$^{115}In(n,\gamma)^{116}In^{m}$	β^- γ: 0.47 MeV (36%) 1.09 MeV (53%) 1.25 MeV (80%)	54 min	γ spectrometer β particle detector	Four foils 7.6 × 15.2 cm, total mass 46 g, have a sensitivity of 300 cpm/unit flux density
$^{197}Au(n,\gamma)^{198}Au$	β^- γ: 0.42 MeV (95%)	64.8 h	β particle detector (a) γ spectrometer (b)	(a) 2.54 cm dia. foil, mass 0.5 g, has a sensitivity of 1.8 cpm/unit flux density (typical G-M counter background: 10 cpm) (b) 5.08 cm dia. foil, mass 2.0 g, has a sensitvity of 13.4 cpm/unit flux density. [NaI(Tl)] crystal background: 48 cpm
$^{23}Na(n,\gamma)^{24}Na$	β^- γ: 1.37 MeV (100%) 2.75 MeV (100%)	15 h	γ spectrometer	Used in form of Na_2CO_3 cylinder 4.5 cm dia. × 2 cm high, mass 12 g Na. 3.0 cpm/unit flux

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

A variety of passive detectors have been employed (TLD pairs, boron-covered PADC, activation foils, semi-active BSS) but the activation foils have been frequently preferred due to their insensitivity to photons and simple management.

The use of Gold, Indium and Dysprosium foils has been reported in literature, but gold foils are definitively the most popular even if

The foils should be chosen on the basis of:

- Neutron activation cross section
- Half-life, radioactive emission and counting system
- Presence of unwanted activation products and competing reactions (γ,n)
- Time structure of the beam

Nuclide	Abundance	Half life	counting
Au-197	100%	2.70 d	γ counters HpGe, NaI. β counters ZnS, GM
Dy-164	28%	2.33 h	β counters
In-115	96%	54 min	γ Counters or β counters

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Passive BSS

Gold Foil
Indium foil
Dysprosim foil

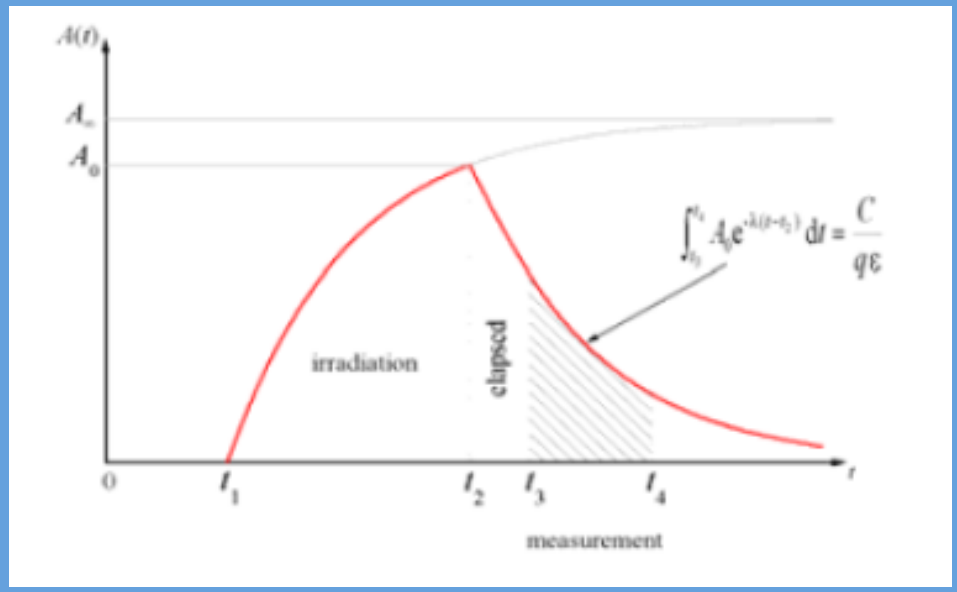
$$A_{sat}(mg^{-1}) = \frac{\lambda t_m \dot{C}}{mY\varepsilon} \cdot \frac{e^{\lambda(t_3-t_2)}}{(1-e^{\lambda(t_2-t_1)})(1-e^{\lambda(t_4-t_3)})}$$

Au-BSS exploits the reaction $^{197}Au(n,\gamma)^{198}Au$ and the beta and gamma emission from ^{198}Au ($T_{1/2}$=2.7 d; $E_{\beta ma}$=0.96 MeV, Eγ=0.41 MeV).

Indium foils are also used, exploiting the reaction $^{115}In(n,\gamma)^{116m}In$ and the beta and gamma emission from ^{116m}In ($T_{1/2}$=54 m; $E_{\beta max}$=0.6 MeV–1.0 MeV; Eγ=0.4–1.3 MeV).

The counting rate is much higher than for gold foils, but the very short half-life may constitute a serious limitation for operational measurements.

Dysprosium foils probably provide the optimal compromise for operational measurements. The exploited isotope is ^{164}Dy (28.2 % abundance in natural dysprosium). ^{165}Dy is a beta and gamma emitter with $E_{\beta max}$=1.3 MeV and $T_{1/2}$=2.334 h



Time variation of the induced radioactivity

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Bonner Sphere Spectrometers equipped with passive detectors (activation foils among these) are mainly used in workplaces characterized by one or more of the following element:

High neutron fluence rate
High photon component
Sharply pulsed time structures
Large electromagnetic background

Active BSS may be affected by pile-up, saturation or dead time effects or by noise due to RF

As

research particle accelerators (near targets or inside irradiation room)

medical electron Linacs,

hadro-therapy facilities,

PET cyclotrons

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

Incident fast and slow neutrons can be detected in a same detector.
Most TLD materials have some sensitivity to fast neutrons, but the dose-equivalent response is significantly lower, and often more energy dependent, than the dose-equivalent response to photons.

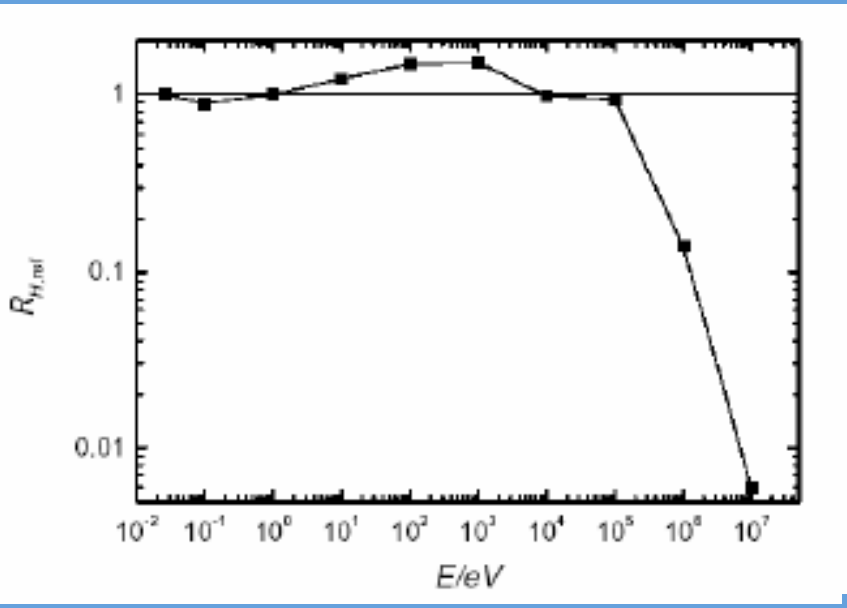
The reduced dose-equivalent response to neutrons is due to:
(1) lower TLD-to-tissue kerma ratios for neutrons than for photons;
(2) reduced TL efficiency for high-LET particles produced by neutrons;
(3) the effect of the quality factor being larger than unity, thus decreasing the dose to be measured for a dose equivalent equal to that produced by photons.

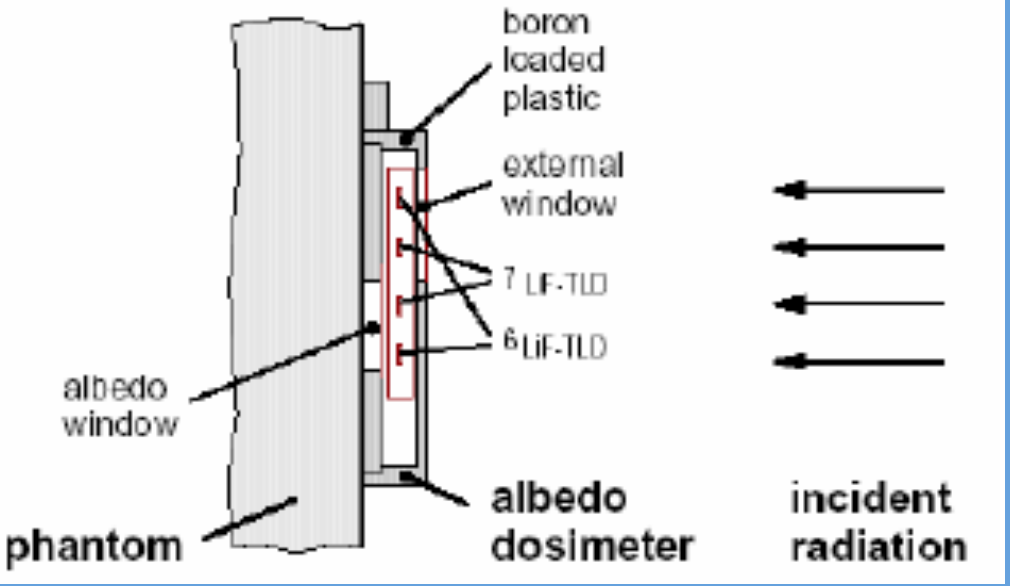
The sensitivity of TLDs to fast neutrons can be increased by using hydrogenous materials such as a proton radiator in contact with the TL material.
Unfortunately, it is difficult to make a detector with a sufficiently intimate contact between the hydrogenous radiator and the TL material that can also withstand the temperature needed to read the TLD.

Dr Adolfo Esposito
adolfo.esposito@lnf.infn.it

TLDs are more widely used in albedo dosimeters. TLD materials containing ^{6}Li or ^{10}B are used to detect low-energy (slow) albedo neutrons backscattered from the wearer's body or a phantom. These materials are much more sensitive to slow neutrons than to fast neutrons or photons, due to the large-cross-section reactions $^{6}Li(n,\alpha)^{3}H$ and $^{10}B(n,\alpha)^{7}Li$.
The sensitivity of a TL material to slow neutrons can be further enhanced by making it with materials enriched in these isotopes.

The materials most often used for slow-neutron detection are enriched lithium fluoride (6LiF:Mg,Ti and ^{6}LiF:Mg,Cu,P), natural lithium borate ($^{6}Li_2{}^{10}B_4O_7$:Mn) and enriched lithium borate ($^{6}Li_2{}^{10}B_4O_7$:Mn). Since TLDs are sensitive to photons, there must be a means to determine the net signal due to neutrons in a mixed field.





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