MASTER DI II LIVELLO IN RADIOPROTEZIONE

Fast neutron detection methods

Adolfo Esposito

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UNIVERSITA' CAMPUS BIO-MEDICO DI ROMA

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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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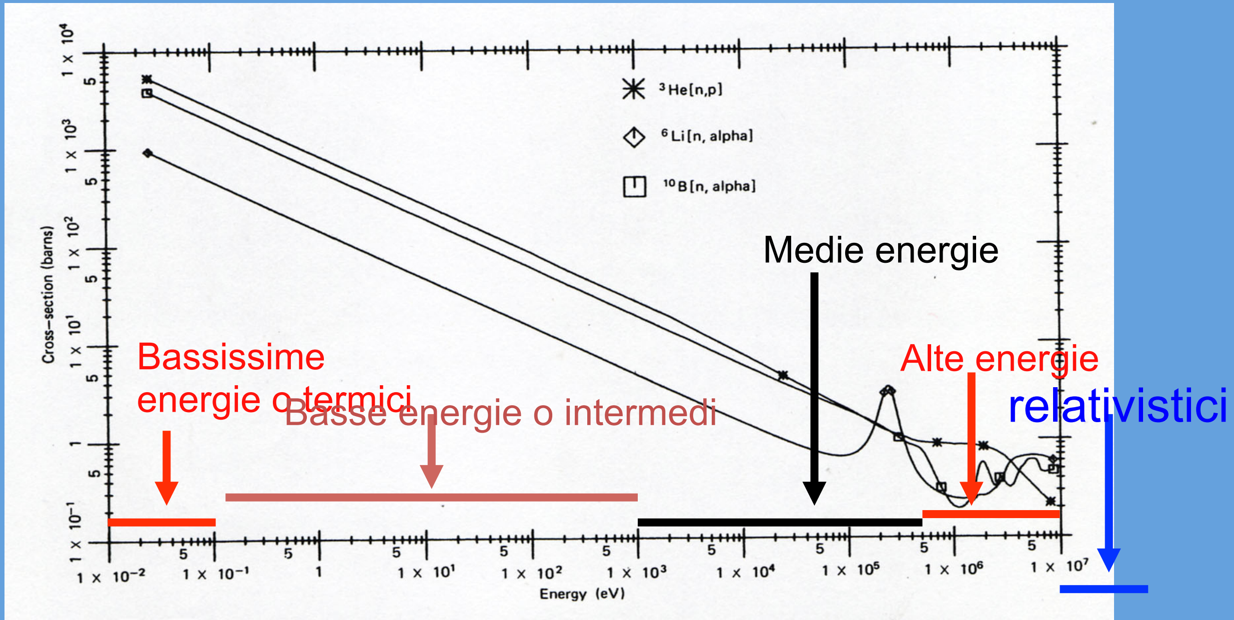
Fast Neutron Detection Method

In principle, all reactions previously discussed could be applied to detect fast neutron well, however, the probability that a neutron will interact by one of these reactions decreases rapidly with increasing neutron a result, conventional bare BF_3 tubes have an extremely low detection efficiency for fast neutrons and consequently are almost never used for this purpose.



Cross section versus neutron energy for some reactions of interest in neutron detection.

So we prefer to use the same counters but inside a moderator assembly.

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COUNTERS BASED ON NEUTRON MODERATION

General Considerations

The inherently low detection efficiency for fast neutrons of any slow neutron detector can be somewhat improved by surrounding the detector with a few centimeters of hydrogen containing moderating material. The incident fast neutron can then lose a fraction of its initial kinetic energy in the moderator before reaching the detector as a lower energy neutron, for which the detector efficiency is generally higher.

By making the moderator thickness greater, the number of collisions in the moderator will tend to increase loading to a lower value of the most probable energy when the neutron reaches the detector.

One would therefore to expect the detection efficiency to increase with moderator were the only factor under consideration.

A second factor, however, tends to decrease the efficiency with increasing moderator thickness: the probability that an incident neutron ever reaches the detector will inevitably decrease as the moderator is made thicker.

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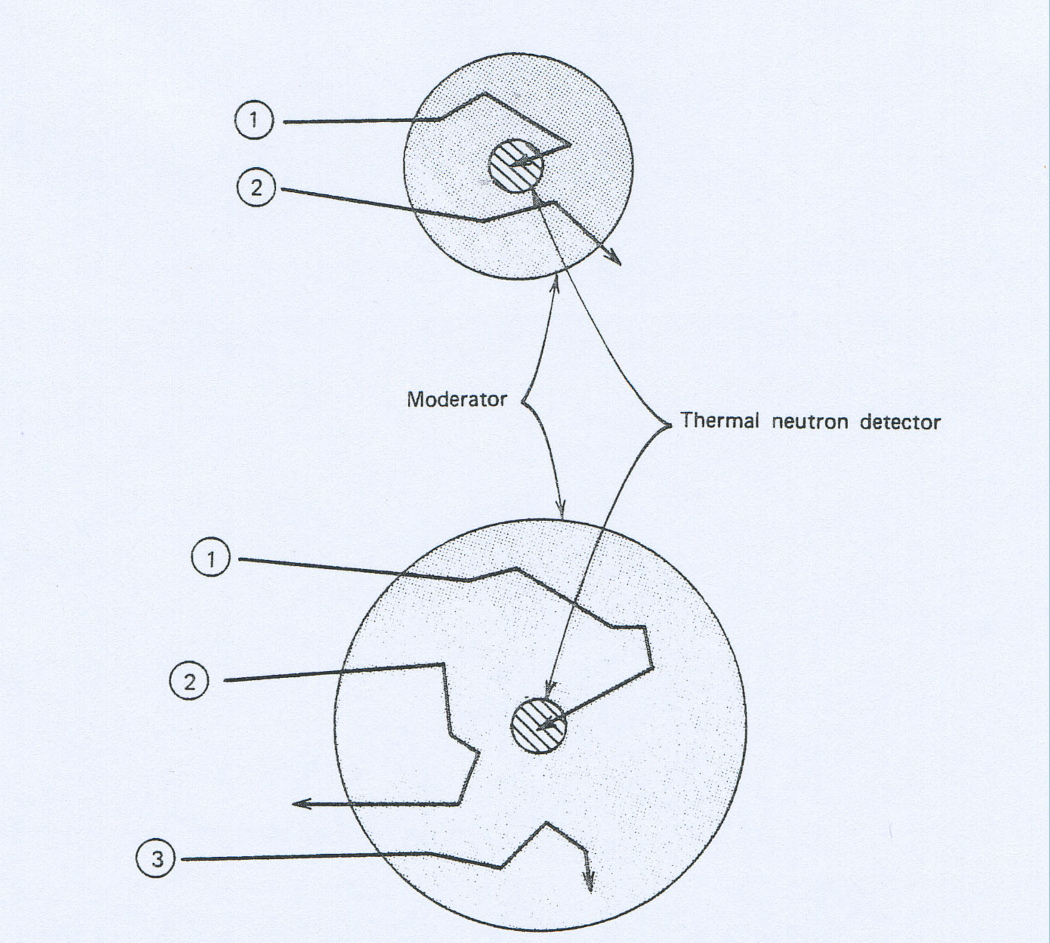
There are several effects to take into account. As the detector become a smaller and smaller fraction of the total volume of the system, there will be a lower probability that a typical neutron path will intersect the detector before escaping from the surface of the moderator. Furthermore, a neutron may be absorbed within the moderator before it has a chance of reaching the detector. The absorption probability will increase rapidly with increasing moderator thickness because absorption cross sections generally are larger at lower neutron energies.



Schematic representation of neutron histories in moderated detectors. The small thermal neutron detector at the center is shown surrounded by two different thicknesses of moderator material. Histories labeled 1 represent incident fast neutrons That are successfully moderated and detected. Those labeled 2 are partially or fully moderated but escape without reaching the detector. History 3 represents those neutrons that are parasitically captured by the moderator. Larger moderators will tend to enhance process 3 while reducing process 2.

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As a result of all these factors, the efficiency of a moderated slow neutron detector when used with a mono-energetic fast neutron source will show a maximum at a specific moderator thickness.

Assuming that the moderator is the usual choice of material such as polyethylene or paraffin, we find that the optimum thickness will range from a few centimeters for keV neutrons up to several tens of centimeters for neutrons in the MeV energy range.

If the thickness of the moderator is fixed at a fairly large value, the overall counting efficiency of the system versus incident neutron energy will also tend to show a maximum.

Low-energy neutrons will not penetrate far enough into the moderator before they are likely to be captured in the moderator itself, whereas high-energy neutrons will not be adequately moderated for efficient detection.

By careful choice of the diameter and the composition of the moderator-detection system, its overall efficiency versus energy be shaped and tailored to suit a specific application.

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Quantities in Radiological Protection

Radiance energy — joule

Description of sources & fields

Absorbed dose — Gray=joule/kg

Energy absorption per unit mass in point of tissue

Equivalent dose — Sievert

Includes biological effectiveness & radiation quality in specified human tissue/organ approximation

$$H_T = \sum_R w_R D_{TR}$$

Effective dose — Sievert

Weighted "sum" over various organ & tissue surrogate for body-average

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{TR}$$

The body-related protection quantities, equivalent dose and effective dose, are not measurable in practice. Therefore, operational quantities are used for the assessment of effective dose or mean equivalent doses in tissues or organs. These quantities aim to provide a conservative estimate for the value of the protection quantities related to an exposure, or potential exposure, of persons under most irradiation conditions.

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The **ambient dose equivalent,** $H^*(d)$, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded and aligned field, in the ICRU sphere at a depth, d, on the radius opposing the direction of the aligned field.

Unit: J kg^{-1}

The special name for the unit of ambient dose equivalent is sievert (Sv).

The **personal dose equivalent,** $H_p(d)$, is the dose equivalent in soft tissue, at an appropriate depth, d, below a specified point on the body.

Unit: J kg^{-1}

The special name for the unit of personal dose equivalent is sievert (Sv).

The **directional dose equivalent,** $H'(d, \Omega)$, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded field, in the ICRU sphere at a depth, d, on a radius in a specified direction, Ω.

Unit: J kg^{-1}

The special name for the unit of directional dose equivalent is sievert (Sv).

ICRP Publication 103

Table B.5. Application of operational dose quantities for monitoring of external exposures.

Task	Operational dose quantities for	
	area monitoring	individual monitoring
Control of effective dose	ambient dose equivalent, $H^*(10)$	personal dose equivalent, $H_p(10)$
Control of doses to the skin, the hands and feet and the lens of the eye	directional dose equivalent, $H'(0.07,\Omega)$	personal dose equivalent, $H_p(0.07)$

The definition of operational quantities $H^*(10)$, $H_P(10)$
Practical problems in the instrument design and calibration

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Quantities in Radiological Protection

Primary Physical Quantities

fluence, Φ

energy fluence, Ψ

air kerma, K_a

exposure, X

Calculation for simple phantom (spheres or slab) validation by measurement

Calculation using W_R , W_t and anthropomorphic phantom

interaction coefficients for energy absorption

Operational Quantities

ambient dose equivalent, H*(d)

directional dose equivalent, H' (d,Ω)

personal dose equivalent, Hp (d)

ICRP Protection quantities

absorbed dose,D

equivalent dose, H_T

effective dose, E

Related by calibration and calculation

Monitored quantities

Instruments response

Estimation by measurements and calculation using usando w_R and anthropomorfic phantom

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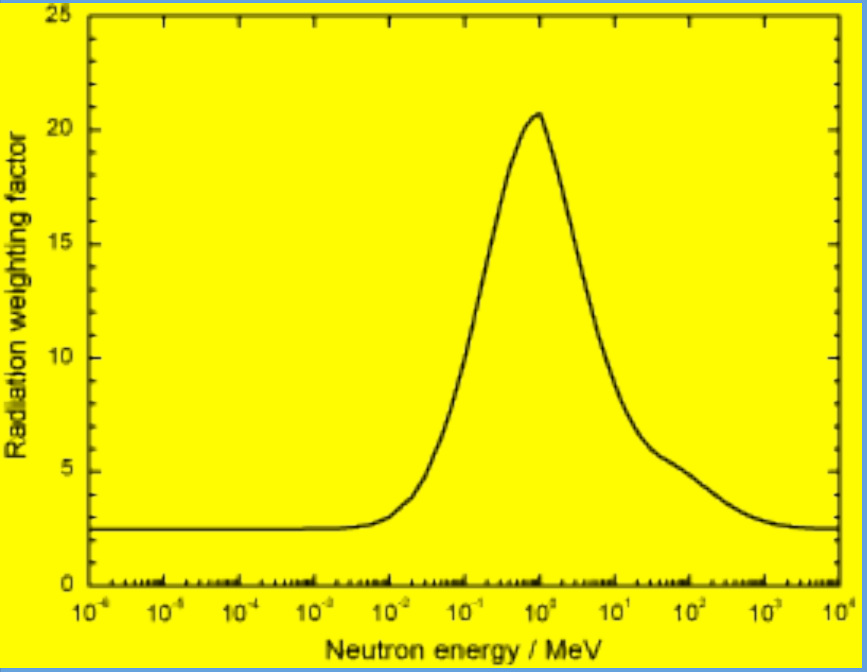
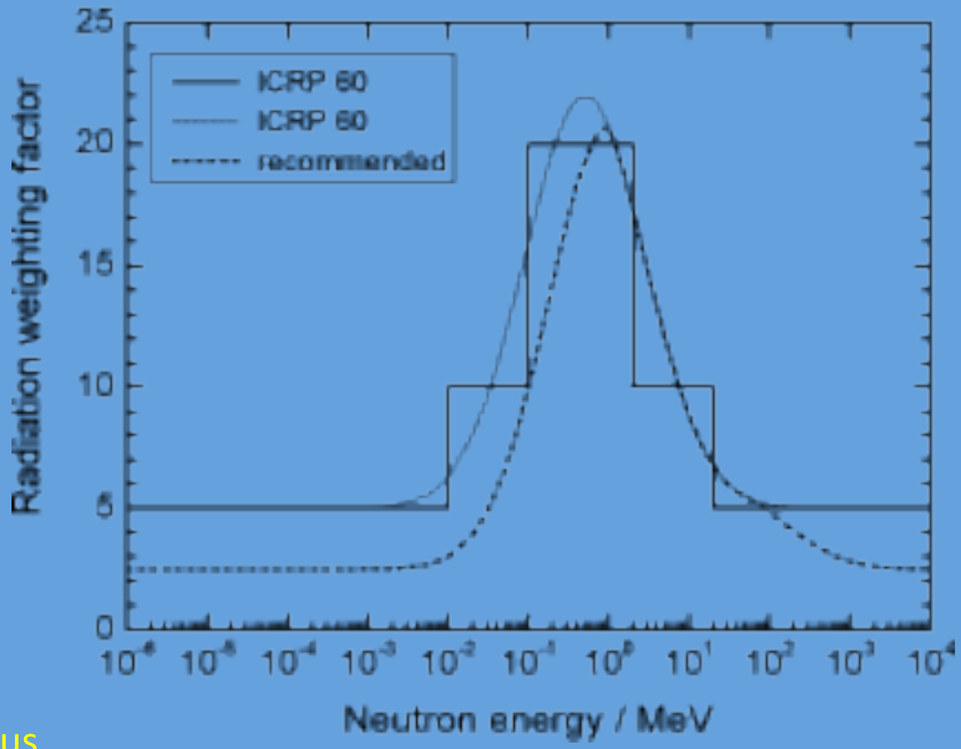
ICRP 103





Radiation weighting factor, w_R, for neutrons versus neutron energy

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Dosimetry of neutron radiation

- High-energy electron accelerators
    - high-energy neutrons
    - bremsstrahlung photons

- High-energy proton accelerators
  - research facilities
  - medium-energy cyclotrons and synchrotrons for advanced radiation therapy with protons or light ion beams (E > 200 MeV)
      - neutrons, with 30% to 50% of the ambient dose equivalent coming from neutrons > 20 MeV
      - photons, charged particles

- The radiation field at flight altitudes is similar to the field outside the shield of high-energy proton accelerators

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Active instrumentation

Neutron dosimetry and spectrometry

Rem counters (using BF_3 or ^3He proportional counters)
Active BSS
Scintillation counters

Detector based on microdosimetric principles

- **Tissue Equivalent Proportional Counters**
- **Recombination chambers**

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**

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✧Most of neutron fields encountered in operational radiation protection exhibit broad energy distribution.

✧An accurate knowledge of the neutron spectrum is often necessary for assessing the radiation protection conditions at workplace

✧The accuracy of determining the operational quantities with neutron spectrometry depends entirely on the accuracy with the energy and direction distributions of neutron fluences are determined

✧The dosimetry of neutron radiation is one of the most complicate task in radiation protection, due mainly to the following causes.

- The definition of operational quantities $H^*(10)$, $H_P(10)$
- Practical problems in the instrument design and calibration
- Non ideal properties of dosimeters/non ideal response characteristics

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For area monitoring ICRU recommends the use of H*(10) which is to provide a conservative estimate of effective dose.

H*(10 is not a measurable quantity)

Two approaches are possible to determining the value of the Ambient Dose Equivalent H*(10) in a neutron field.

$$H^*(10) = \int_0^{E\max} \Phi_E(E) h^*_\Phi(E) dE$$

$\Phi_E = \Phi \cdot \varphi(E)$

***$\varphi(E)$* is the energy distribution of the neutron fluence normalized to 1 cm^{-2}**

h^*_Φ neutron fluence to dose equivalent conversion factor

- Deriving $\Phi(E)$ by means of spectrometric techniques
- Using an instruments with flat energy response in terms of H*(10)

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Dosimetry of neutron radiation

This last approach is possible in a limited energy range.

Due to high energy variability of the fluence-to-ambient dose-equivalent conversion coefficients and the diversity of the interaction mechanisms in the human body and the dosimetric material, the instruments responses usually show a very important energy dependence.

Moreover the energy neutrons in the workplace fields can range over 10 order of magnitude

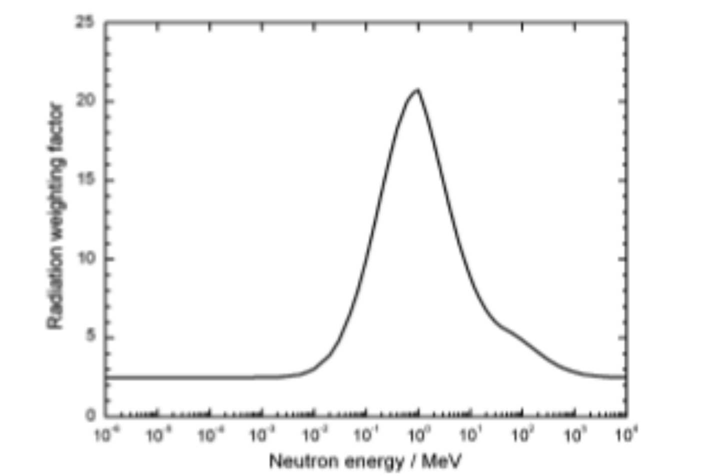
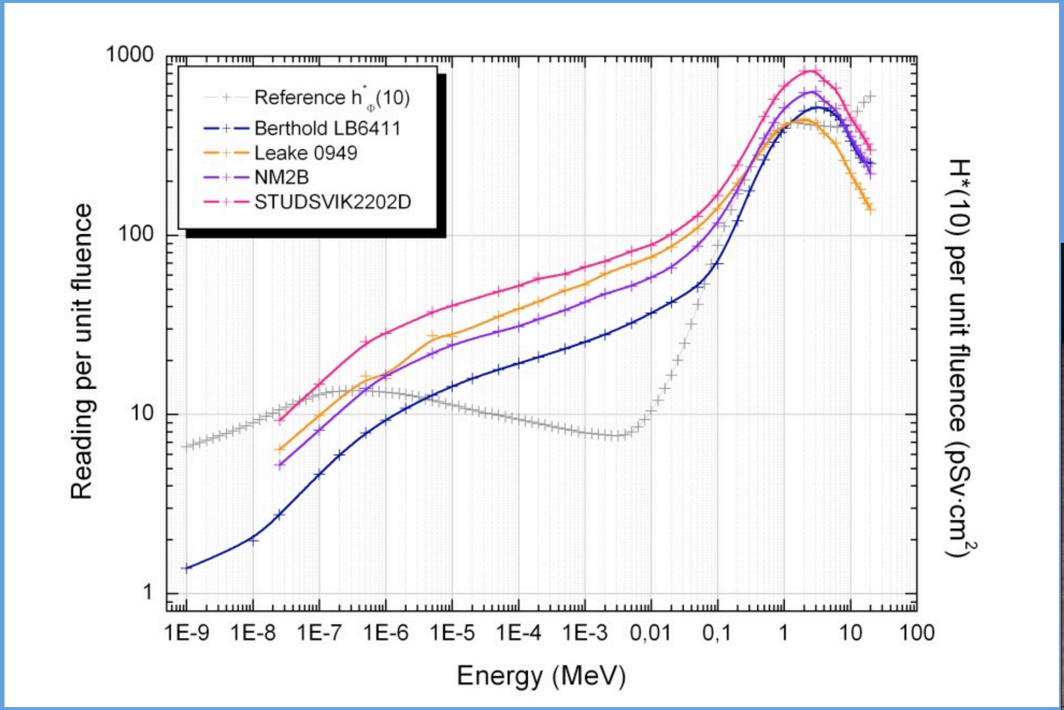
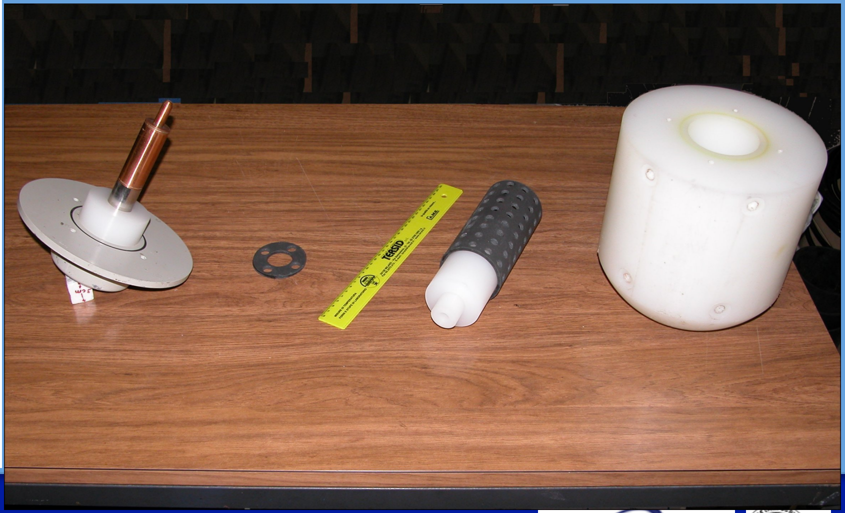


Fig. 1. Radiation weighting factor, w_R, for neutrons versus neutron energy.





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Dosimetry of neutron radiation

Detector

❖ cylindrical BF_3 proportional counter (95% 10B enrichment);

❖diameter = 2.54 cm;

❖active length = 5.08 cm;

❖pressure = 8.0x10^4 Pa.

Lead attenuator

❖ thickness = 1 cm

❖outer polyethylene: thickness = 7 cm.

Response

The response function is extended to several hundred MeV.

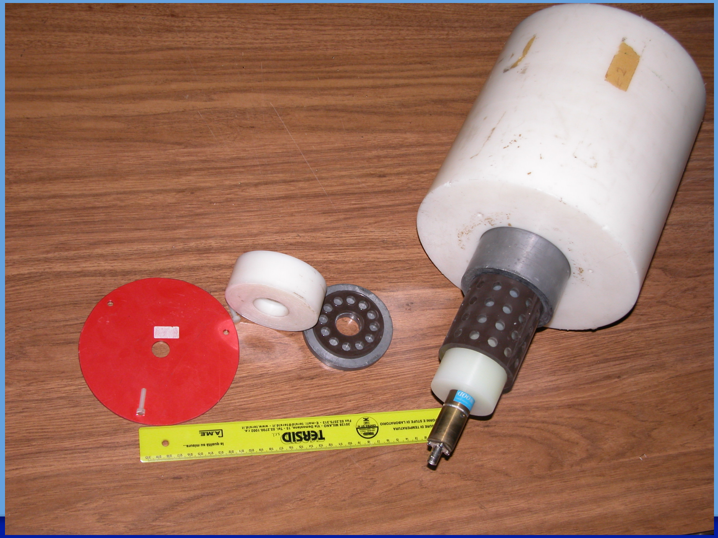
The Long Interval NeUtron Survey-meter (LINUS) is a new type of rem counter developed by INFN (LNF Radiation Protection Group and Section of Milan)

Moderator

❖ inner polyethylene : thickness =1.9 cm;

❖ boron doped synthetic rubber attenuator:

- outer diameter=7.6 cm;
- length =14 cm;
- thickness = 0.6 cm;



The enhancement of instrument response because the reaction (n,xn)

These high Z materials have large (n,xn) cross sections for high energy neutrons and thus function as high energy neutron multipliers. Neutrons can loose a significant portion of energy through the (n,n') reaction, and can produce multiple exiting neutrons through (n,2n), (n,3n), and (n,xn) reactions where the x is a number greater than 3

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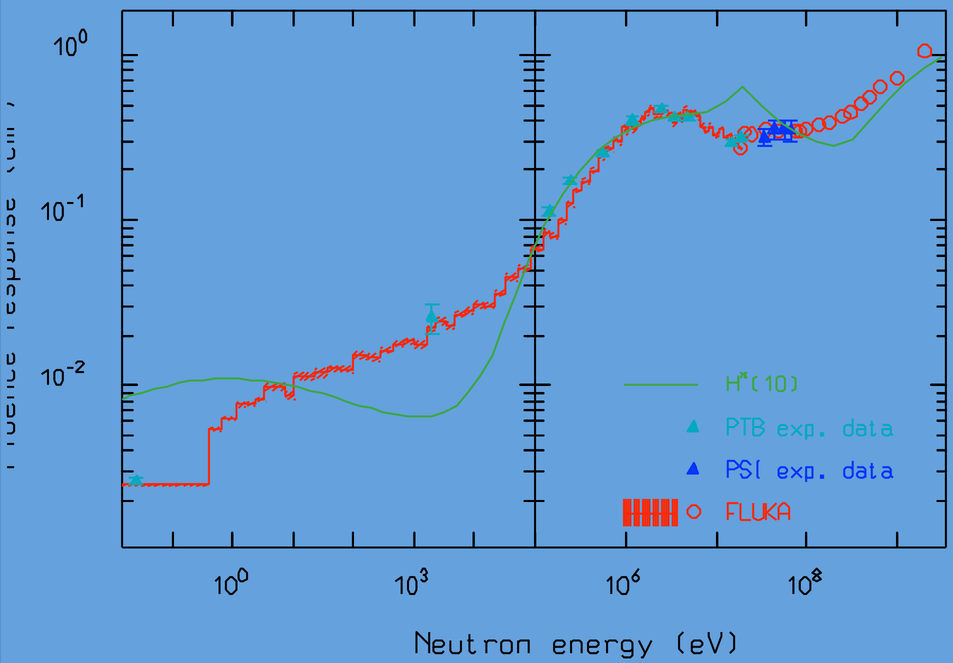
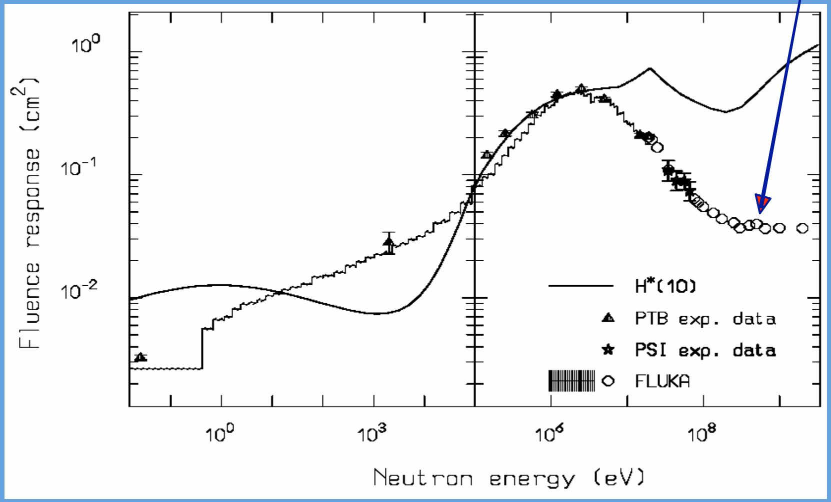
Absolute neutron fluence response of the of the rem counters LINUS and SNOOPY



LINUS (extended range)
Long **I**nterval **N**e**U**tron **S**urvey meter

Heavily underestimated above a few MeV



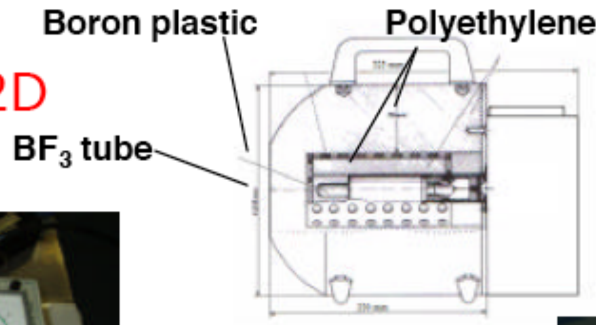
$$M = C \int R_\Phi(E)\,\Phi(E)\,dE$$

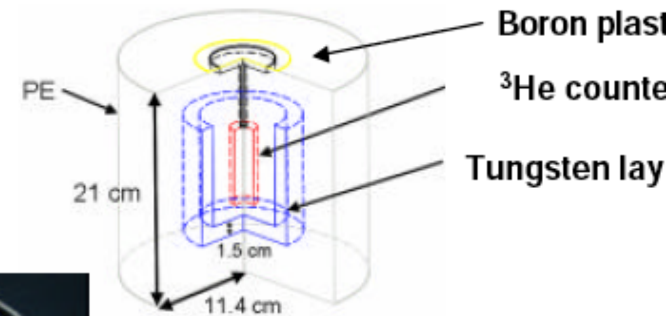
SNOOPY (conventional unit)

Birattari, Esposito, Ferrari, Pelliccioni, Silari, NIM A324 (1993) 232-238

Birattari, Esposito, Ferrari, Pelliccioni, Rancati, Silari, RPD 76 (1998) 135-148

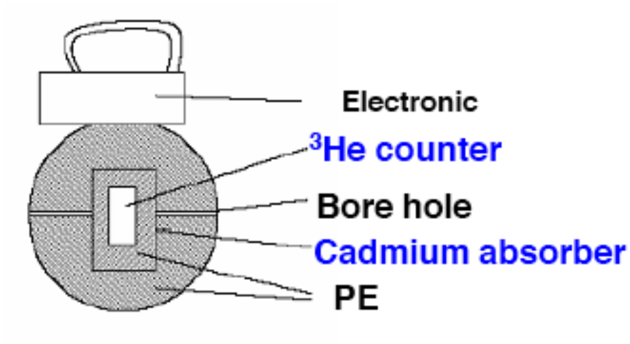
Studsvik 2202D

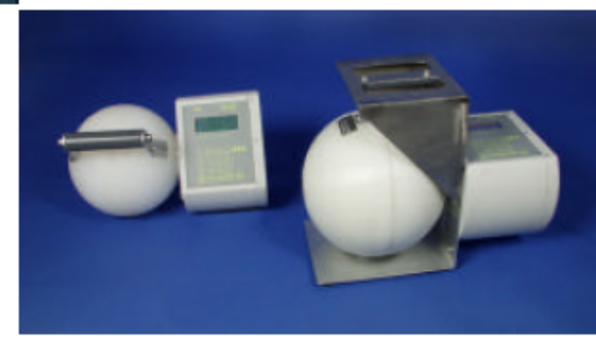




Eberline WENDI-2

Berthold LB6411 (also LB6411Pb)





MAB SNM500(X)

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Dosimetry of neutron radiation

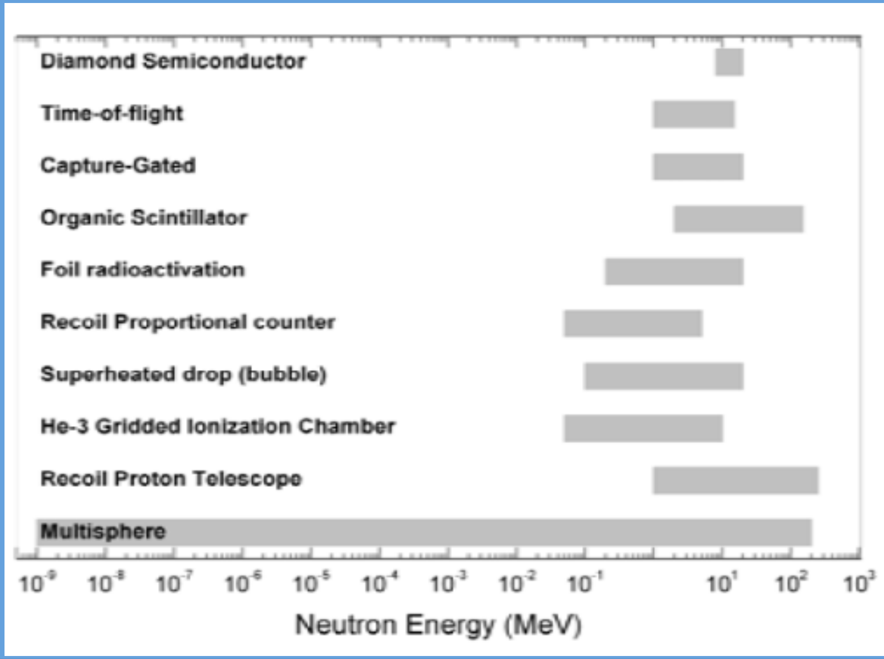
An accurate determination of H*(10) in workplace field of unknown direction distribution can be achieved through the use of suitable neutron spectrometer.

◆Neutron scattering and measurement of the energies of recoil nuclei.

◆Measurement of the energies of charged particles released in neutron-induced nuclear reactions.

◆Methods in which the velocity of neutrons is measured TOF

◆Threshold spectrometry



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◆ The most used neutron spectrometry technique in workplaces is the so called Bonner Sphere Spectrometer (BSS).

NUCLEAR INSTRUMENTS AND METHODS 9 (1960) 1–12; NORTH-HOLLAND PUBLISHING CO.

A NEW TYPE OF NEUTRON SPECTROMETER†

RICHARD L. BRAMBLETT, RONALD I. EWING and T. W. BONNER

The Rice University, Houston Texas

Received 4 July 1960

Neutrons are detected in a small $Li^6I(Eu)$ scintillator placed at the center of polyethylene moderating spheres with sizes ranging from 2 to 12 inches in diameter. The efficiency of this neutron counter has been experimentally determined using monoenergetic neutrons from thermal energies to 15 MeV. The counter has excellent energy sensitivity from 0.1 to 2 MeV and is particularly useful for determining the shapes of continuous neutron spectra. The pronounced difference in the efficiencies for the five sizes of spheres which have been calibrated provides a basis for accurate neutron energy determination. The good γ ray discrimination of the counter allows it to be used with a radium-beryllium neutron source. Neutron spectra from a variety of sources have been determined with this counter. These include the two groups of neutrons from the $C^{14}(p,n)N^{14}$ reaction, the evaporation spectrum of the neutrons from the reaction $Rh^{103}(p,n)Pd^{103}$, the energy spectra of inelastically scattered neutrons, and the neutron spectrum from the scattering of fast neutrons by the floor and walls of a building.

◆The advantages of such type of spectrometer are

- ◆ the isotropy of the response,
- ◆the possibility to extend the energy range up to GeV neutrons
- ◆the availability of different active or passive central detectors to be chosen according to the field intensity and time structure.

Nevertheless, the unfolding process remains the most difficult task in Bonner Sphere spectrometry, because unfolding codes are usually very complex and require quite detailed "a priori" information on the spectrum to be measured.

With the aim of providing a useful and friendly tool for spectrometry in workplaces, the INFN-LNF Radiation Protection Group developed FRUIT, a new unfolding code specially designed for routine applications where no detailed pre information on the neutron field are available.

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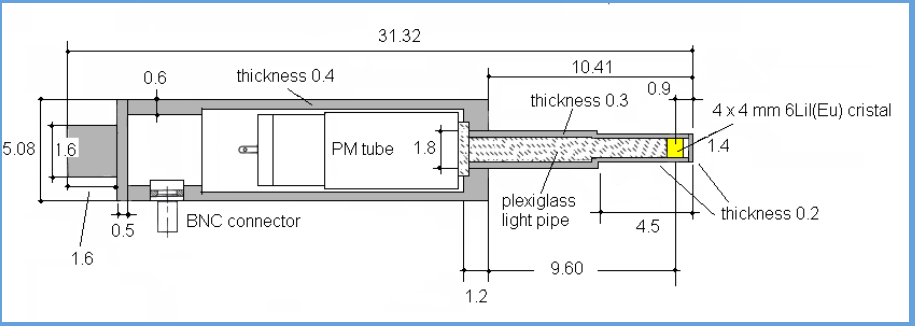
The LNF-ERBSS, available from Ludlum Measurements, USA, includes

- eleven polyethylene spheres (density 0.95 g·cm^{-3})
  (2”, 2.5”, 3”,3.5”, 4.5”, 5”, 7”,8”, 10”, 12”)

- three polyethylene spheres (density 0.95 g·cm^{-3}) loaded with copper and lead
  (7” Cu, 7” Pb, 12” Pb)
- a 4x4 ^{6}LiI(Eu) active scintillator

Special aluminum holders were designed to expose TLD pairs and a gold or dysprosium foil in the same sphere.

LiI(Eu)



All spheres are designed to hold the scintillator

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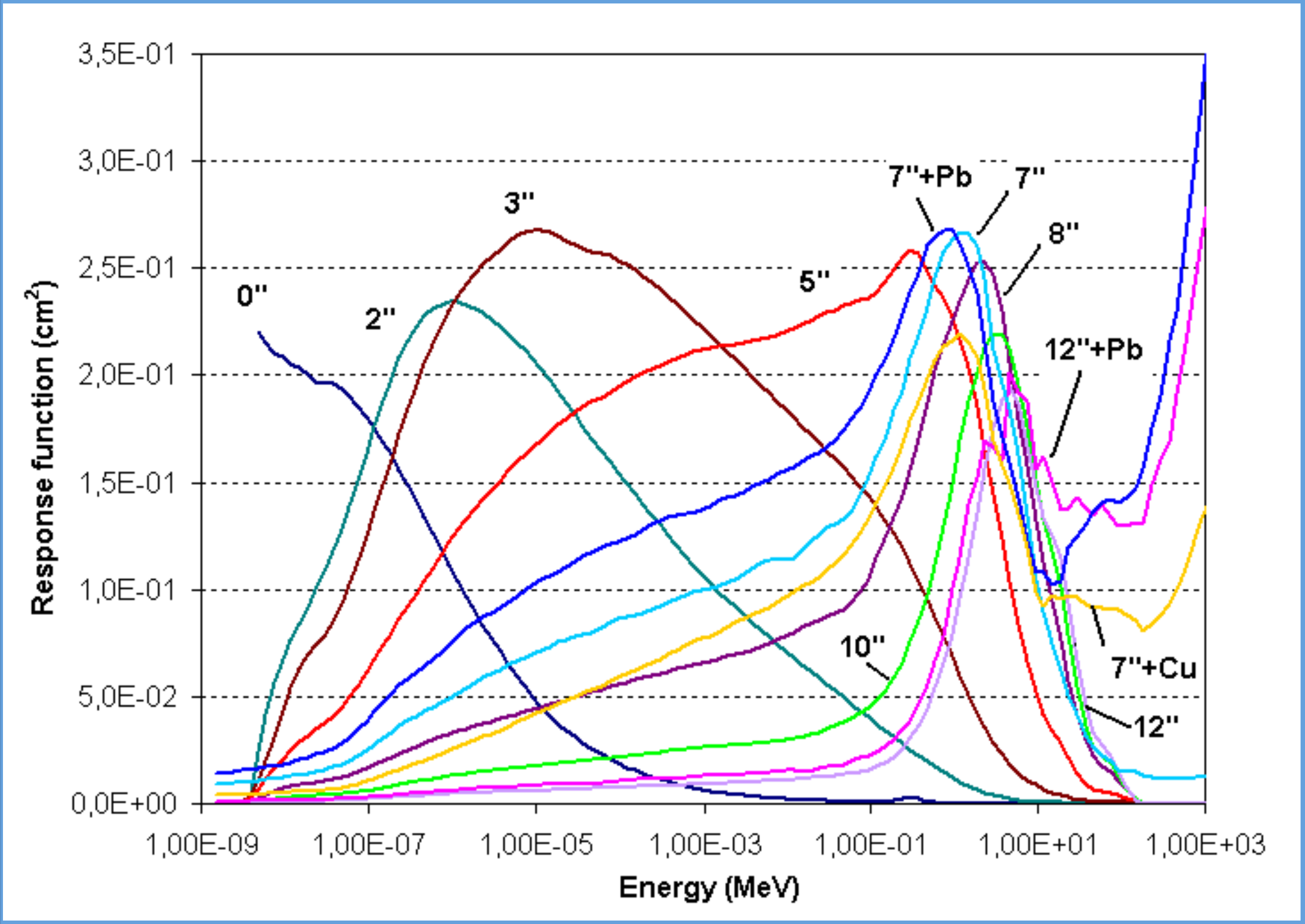
The response functions of the active ERBSS were calculated with MCNPX Monte Carlo transport code.
The data were interpolated to produce a response matrix with 120 logarithmic equidistant intervals from 1.5 meV to 1.16 GeV.



The response matrix of the ERBSS was validated in reference neutron fields (PTB, TSL) and its overall uncertainty was estimated to be $\sigma_{matrix} = \pm 3\%$.

The response functions of the high-energy spheres.

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The reading C_i, of the thermal neutron sensor inside the i[th] Bonner sphere, when exposed in a point of a neutron field, can be expressed as

$$C_i = \Phi \int_{E_{min}}^{E_{max}} R_i(E)\varphi(E)dE$$

where:

- ***Φ* is the neutron fluence in cm^{-2};**

- ***$R_i(E)$* is the response function of the sphere (in cm^{-2}). It is usually derived with Monte Carlo calculations and represents the reading per unit fluence as a function of the monoenergetic neutron energy, E. The set of response functions for all Bonner spheres forms the "response matrix".**

- ***φ(E)* is the energy distribution of the neutron fluence normalized to 1 cm^{-2} and its unit is MeV^{-1} (also termed "unit spectrum").**

The energy distribution of the neutron fluence (also termed "spectrum"), is given by
$\Phi_E = \Phi \cdot \varphi(E)$ and its unit is $cm^{-2} \cdot MeV^{-1}$.

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When a set of *m* Bonner spheres is exposed to the same neutron fluence, a set of readings C_1, i=1,..,m is collected. The neutron fluence Φ and its energy distribution φ(E) may be derived by inverting a set of *m* equations, that for computer calculation purposes can be expressed in the following discrete form:

$$C_i = \Phi \sum_{J=1}^{N_g} R_{i,j} \varphi_j \Delta E_j \qquad \mathrm{i} = 1 \ldots \mathrm{m}$$

Where N_g is the number of energy group

The unfolding problem in Bonner Sphere Spectrometry is under-determined, i.e. the number of independent measurements, *m,* is largely lower than the number of unknowns, N_g.

This implies that a set of infinite mathematical functions could satisfy the equation. Nevertheless, only a limited number of them is physically acceptable.

Many codes have been developed for unfolding neutron spectra .

At LNF we developed the FRUIT (FRascati Unfolding InteRactive code) code

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Unfolding code

The neutron spectra were derived from the raw data using the FRUIT (FRascati Unfolding Interactive Tool) developed at the INFN-LNF for the needs of the operational workplace neutron monitoring.

Main features of FRUIT

High level of interactivity

User friendliness and visual operation

No needs of "educated" default spectrum

Uncertainties treatment

And above all

The user doesn't need to be an expert of computer codes

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FRUIT is a parametric code written using the Lab-Views software.
It models the neutron spectra with at most seven numerical positive parameters.

Provided the response matrix and the energy the only numerical data required by the code are the Bonner sphere readings and their relative uncertainties.

The type of ''radiation environment'' is selected, using a check-box window, among the following options:

(a) fission-like fields, such as those found in the vicinity of nuclear reactors or fuel elements;

(b) radionuclide neutron sources;

(c) evaporation-based field, such as those found in medical LINACs or PET cyclotrons;

(d) high-energy electron fields;

(e) high-energy hadron accelerators;

(f) Gaussian peak;

(g) user-defined (in this case a parameter file is required).

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A neutron spectrum in FRUIT is described as the linear superposition of up to four components

$\Phi(E)= P_{th}\varphi_{th}(E) + P_e\varphi_e(E) + P_f\varphi_f(E) + P_{hi}\varphi_{hi}(E)$ where

$\varphi_{th}(E)$ is the thermal Maxwellian component,

$\varphi_e(E)$ the epithermal one,

$\varphi_f(E)$ the fast one

$\varphi_{hi}(E)$ the high energy component.

Each component is individually normalized to the unit fluence by mean of an adequate normalization factor.

P_{th}, P_e, P_f and P_{hi} represent the fraction of thermal, epithermal, fast and high-energy neutrons, respectively.

The ''robust convergence theory'' was modified and adapted to reduce the influence of the initial hypothesis on the results and to speed up the convergence procedure.

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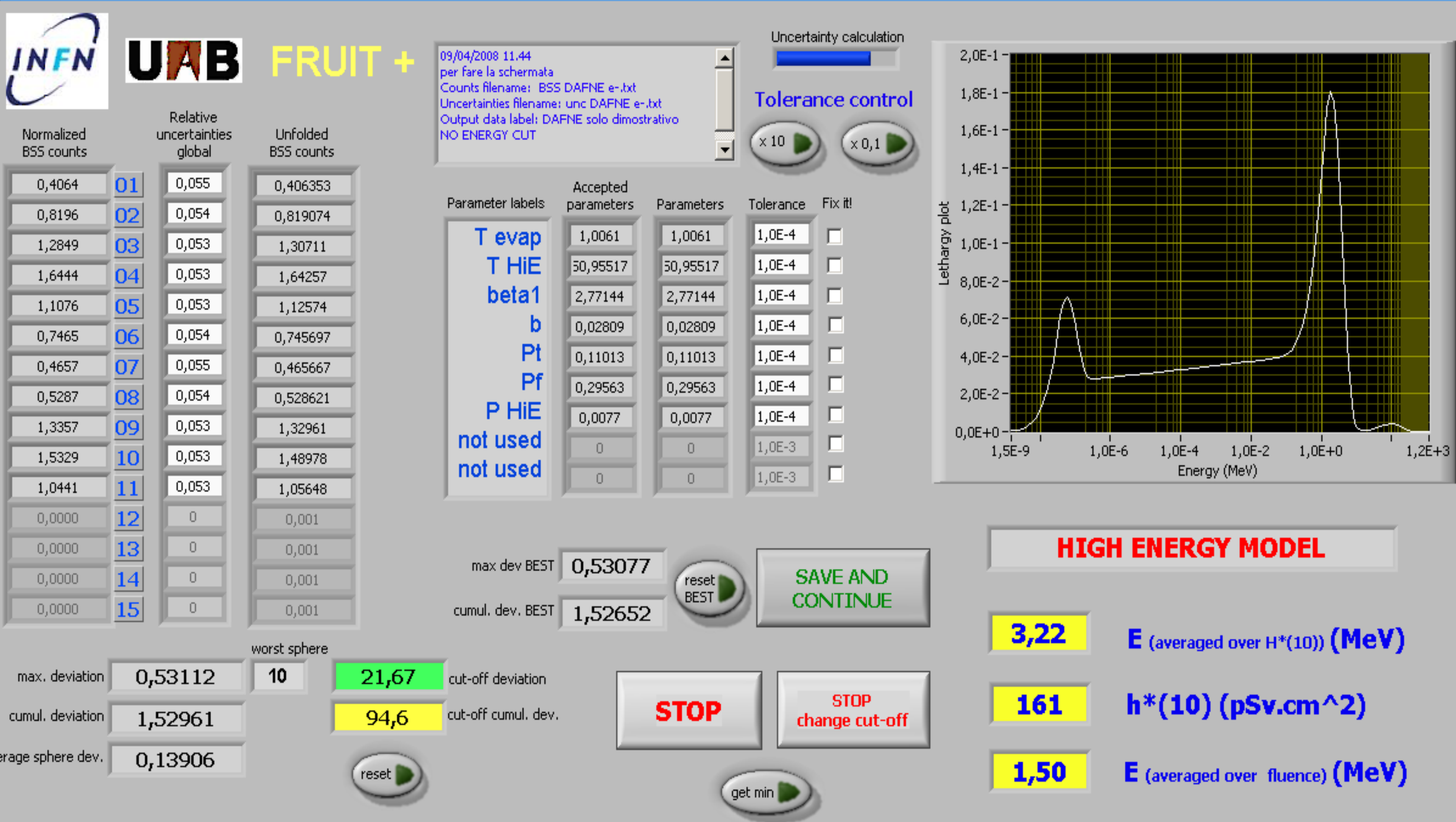

h*(10) = the spectrum averaged fluence-to-ambient dose equivalent conversion coefficient

E_{ϕ}= the fluence-average neutron energy $E_{H*(10}$= the ambient dose equivalent average neutron energy

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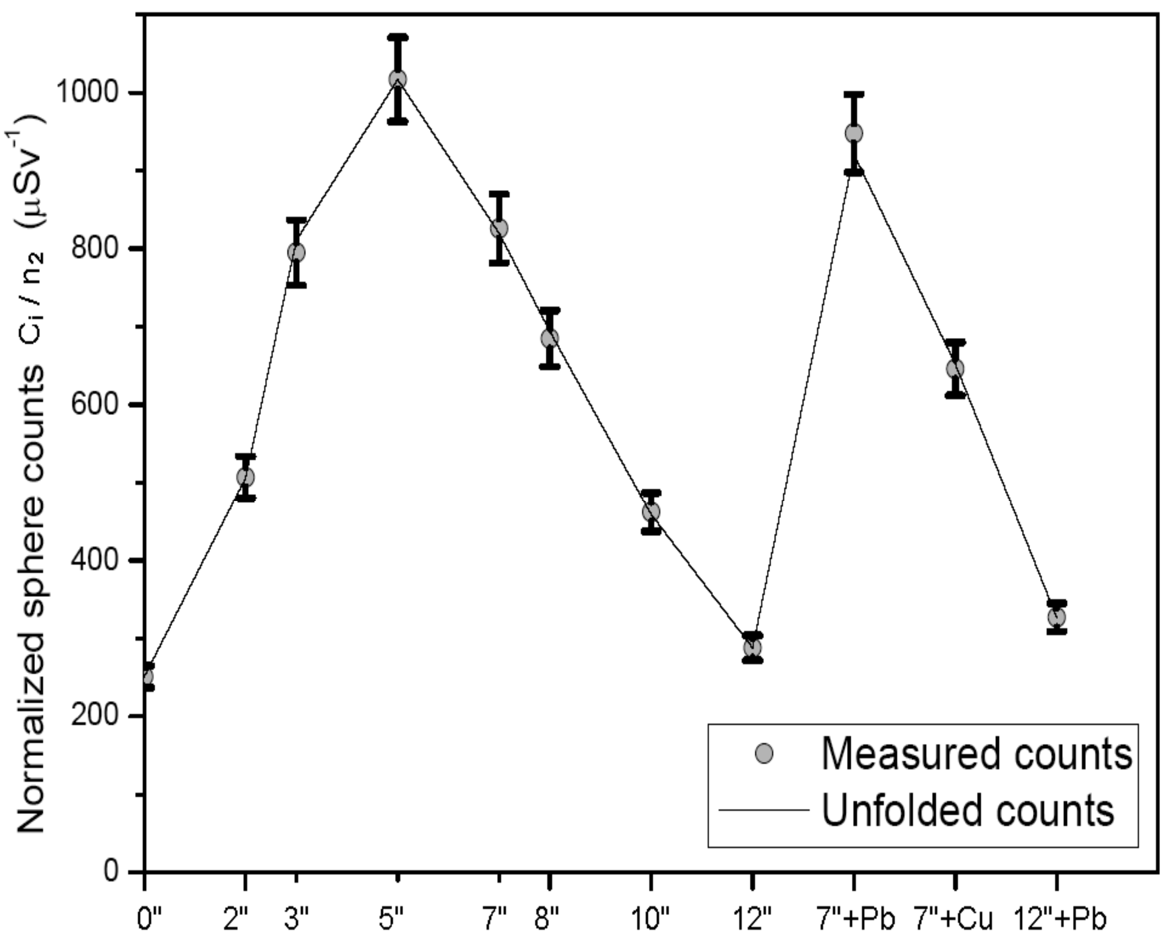

The “unfolded counts” are calculated by applying the response function of each sphere to the spectrum unfolded with FRUIT.

The maximum difference between “measured” and “unfolded” counts is 3% (7”+Pb).

The figure show the consistency between the unfolded spectrum and the set of sphere counts.

Comparison between measured and unfolded sphere counts, for the different spheres.

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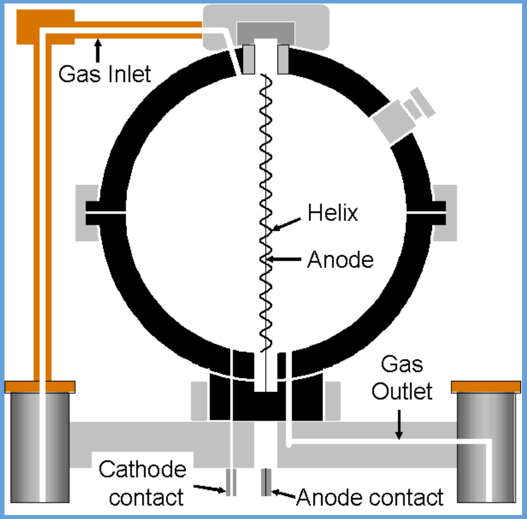
- Measure the probability distribution of absorbed dose d(y) in terms of lineal energy y (the ratio of energy imparted to matter in a volume by a single deposition event to the mean chord length in that volume)
- Used in radiation biology, radiation chemistry, radiation protection, radiation therapy, dosimetry
- From the probability distribution of absorbed dose d(y) one can evaluate the dose equivalent through a function Q(y) which relates the quality factor to the lineal energy



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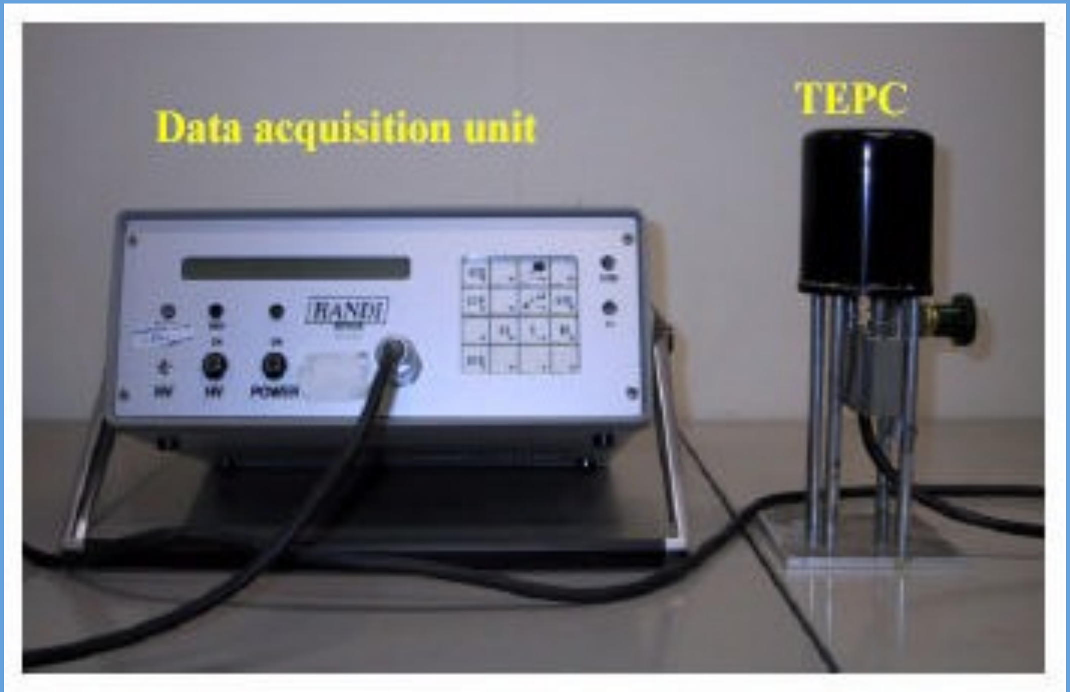
HANDI TEPC



The energy deposition in the TE(tissue Equivalent) gas is measured through ionization of primary charged particles and/or secondary particle generated mainly in the walls of the detector

One of the main features their capability of measuring the dose equivalent in mixed radiation fields

A TEPC is a proportional counter constituted by a tissue-equivalent gas contained in a cavity inside walls of a TE plastic. Acting on the gas pressure it is possible to simulate the events of energy deposition in microscopic volumes

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