TRAINING COURSE ON RADIATION DOSIMETRY:

Quantities and units in radiation protection

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Wed. 21/11/2012, 17:30 – 18:30 pm

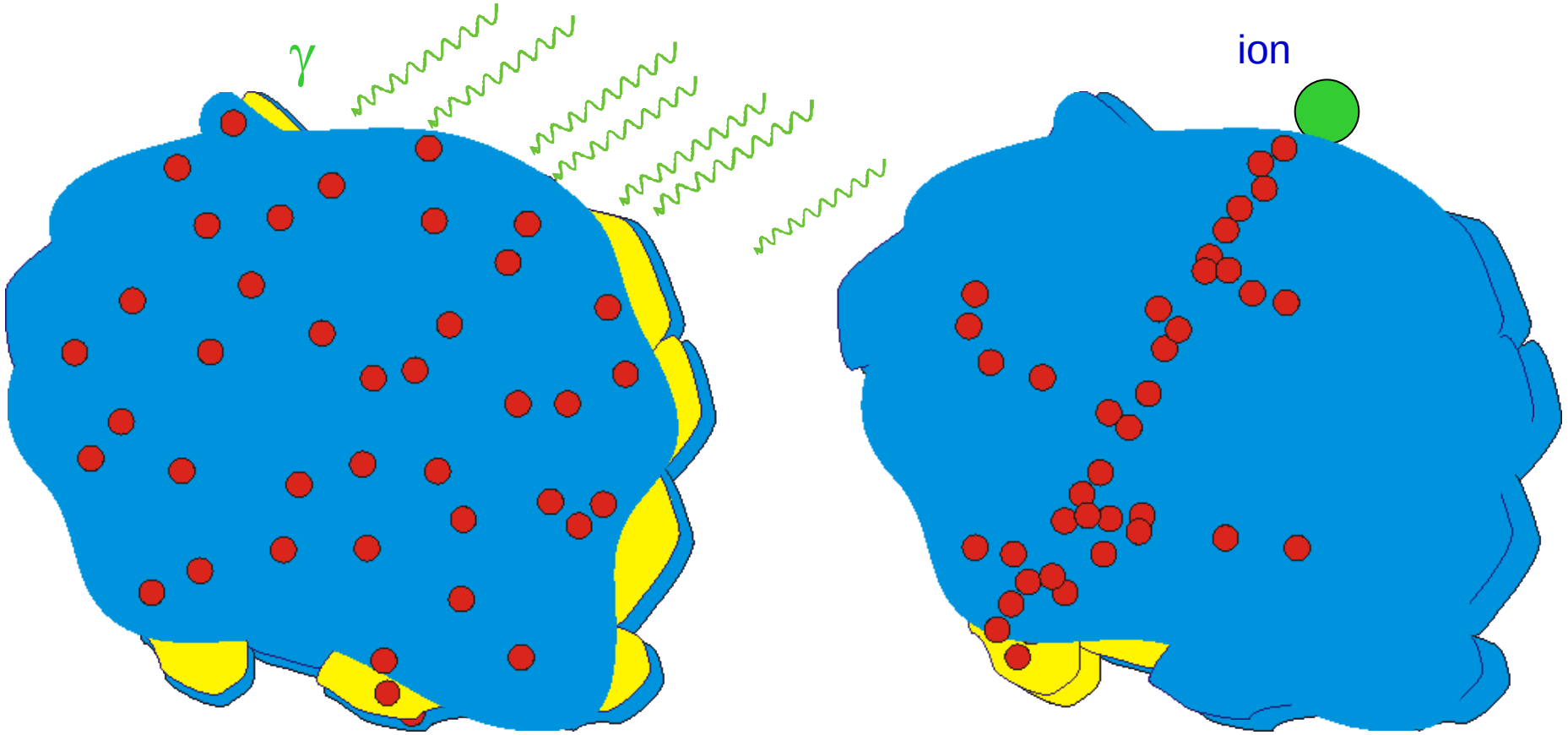
INTRODUCTION I (QUOTING FROM ICRP 103)

- Deterministic effects: due to the killing/malfunction of cells following high doses.
  - → they are generally characterized by threshold doses. The reason for the presence of this threshold dose is that radiation damage (serious malfunction or death) of a critical population of cells in a given tissue needs to be sustained before injury is expressed in a clinically relevant form. Above the threshold dose the severity of the injury, including impairment of the capacity for tissue recovery, increases with dose.
  - → in the absorbed dose range up to around 100 mGy (low LET or high LET) no tissues are judged to express clinically relevant functional impairment. This judgement applies to both single acute doses and to situations where these low doses are experienced in a protracted form as repeated annual exposures.
- Stochastic effects: cancer and heritable effects involving either cancer development in exposed individuals owing to mutation of somatic cells or heritable disease in their offspring owing to mutation of reproductive (germ) cells (no threshold).
  - → In the case of cancer, epidemiological and experimental studies provide evidence of radiation risk albeit with uncertainties at doses about 100 mSv or less. In the case of heritable diseases, even though there is no direct evidence of radiation risks to humans, experimental observations argue convincingly that such risks for future generations should be included in the system of protection.

INTRODUCTION (II)

- The absorbed dose does not give information about the risk caused by exposure to ionizing radiation:
  - → risk indicators (RP quantities) were introduced for correlating the dose quantities and stochastic effects;

INTRODUCTION



Courtesy of Paolo Colautti

RP QUANTITIES – ICRP 26

- ICRP 26 (1997) accounted for the different qualities of ionizing radiation through the quality factor Q;
- The dose equivalent H was defined as:

$$H = DQN$$

  - → D is the absorbed dose;
  - → N included any factor which could modify the risk from radiation dose.

- ICRP 26 did not specify any factor N and the dose equivalent was later changed to (e.g. ICRU 51):

$$H = QD$$

- The unit of dose equivalent is the sievert (Sv) (1 Sv = 1 J kg^{-1})

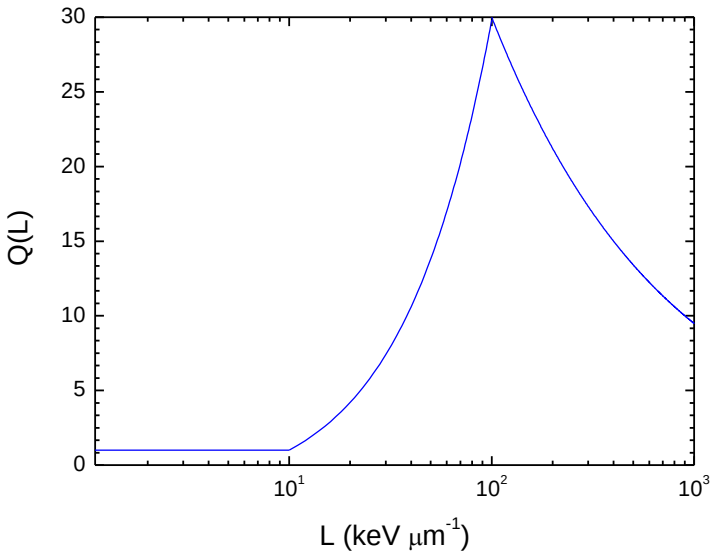
QUALITY FACTOR

- A dependence of Q on LET (L) was given by ICRP;
- The quality factor Q at a point in tissue is:

$$Q = \frac{1}{D}\int_L Q(L) D_L \, dL$$

- ICRP 60 (1991) specified the following Q(L) relation in water (overkilling effect accounted for):

$$Q(L) = \begin{cases} 1 & L \geq 10 \text{ kev } \mu\text{m}^{-1} \\ 0.32L - 2.2 & 10 \leq L \leq 100 \\ \dfrac{300}{\sqrt{L}} & L \geq 100 \end{cases}$$



QUALITY FACTOR

- When the D(L) relation cannot be assessed, $\overline{Q}$ were recommended as the ratio of the maximum value of H in depth in tissue and D at the corresponding maximum depth.

Radiation	$\overline{Q}$
X, γ, electrons	1
Neutrons, protons, single charged particles with mass > 1 amu	10
Alphas, multiple charged particles	20

QUANTITIES BASED ON THE DOSE EQUIVALENT

- Dose equivalent rate:
  - ✓ Units: J kg^{-1} s^{-1}; special unit: Sv s^{-1};

$$\dot{H} = \frac{dH}{dt}$$

- Mean absorbed dose in a specified tissue or organ:
  - ✓ m_T mass of the organ or tissue;
  - ✓ D absorbed dose in the mass element dm

$$D_T = \frac{1}{m_T} \int_{m_T} D dm$$

- Mean quality factor:
  - ✓ Q quality factor in the mass element dm

$$Q_T = \frac{1}{m_T D_T} \int_{m_T} Q D dm = \frac{1}{m_T D_T} \int_{m_T} \int_{L} Q(L) D_L dL dm$$

QUANTITIES BASED ON THE DOSE EQUIVALENT

- Effective dose equivalent :
  - ✓ w_T tissue weighting factors

$$H_E = \sum_T w_T D_T Q_T$$

$$\sum_T w_T = 1$$

ICRP 103

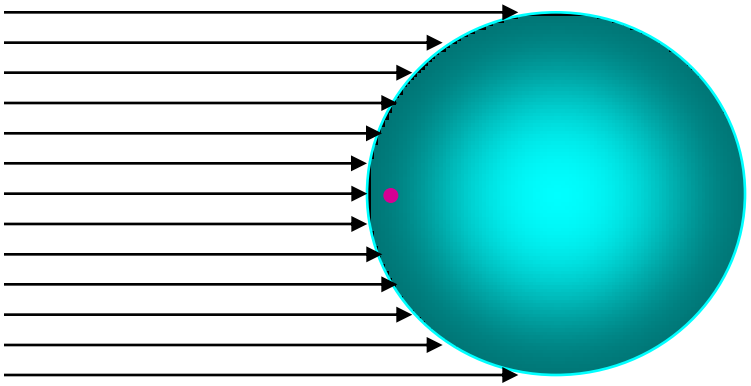
Table B.1. ICRP Recommendations for tissue weighting factors in *Publication 26* (1977) and *Publication 60* (1991b).

Tissue	Tissue weighting factor, w_T	
	1977 *Publication 26*	1991 *Publication 60*[2,3]
Bone surfaces	0.03	0.01
Bladder		0.05
Breast	0.15	0.05
Colon		0.12
Gonads	0.25	0.20
Liver		0.05
Lungs	0.12	0.12
Oesophagus		0.05
Red bone marrow	0.12	0.12
Skin		0.01
Stomach		0.12
Thyroid	0.03	0.05
Remainder	0.30[1]	0.05
TOTAL	1.0	1.0

OPERATIONAL QUANTITIES

- The operational quantities defined by ICRU 51 are:
  - ✓ the ambient dose equivalent, $H^*(d)$;
  - ✓ the directional dose equivalent, $H'(d,\Omega)$;
  - ✓ the personal dose equivalent $H_p(d)$.

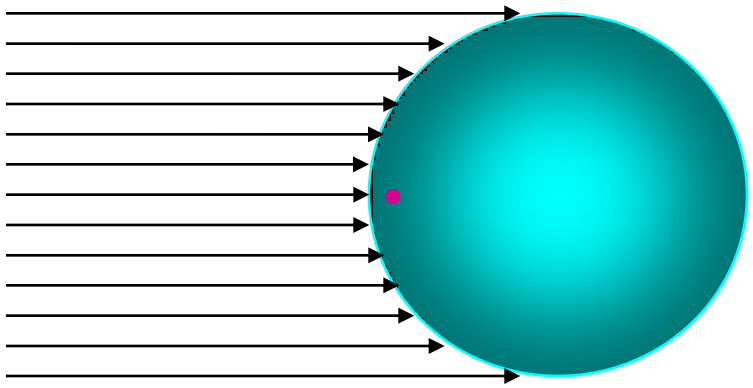
- Their values are "taken as sufficiently precise assessments of effective dose or skin dose, respectively, especially if their values are below the protection limits"(ICRP 103).
- They should give a reasonable conservative estimate of the RP quantities.
- Area monitoring: $H^*(d)$ and $H'(d,\Omega)$;
- Individual monitoring: $Hp(d)$.



- ICRU sphere:
  - ✓ Tissue-equivalent;
  - ✓ Mass composition: oxygen 76.2%, 11.1% carbon, 10.1% hydrogen; 2.6% nitrogen.
  - ✓ 30 cm in diameter;
  - ✓ Density = 1 g cm^{-2};

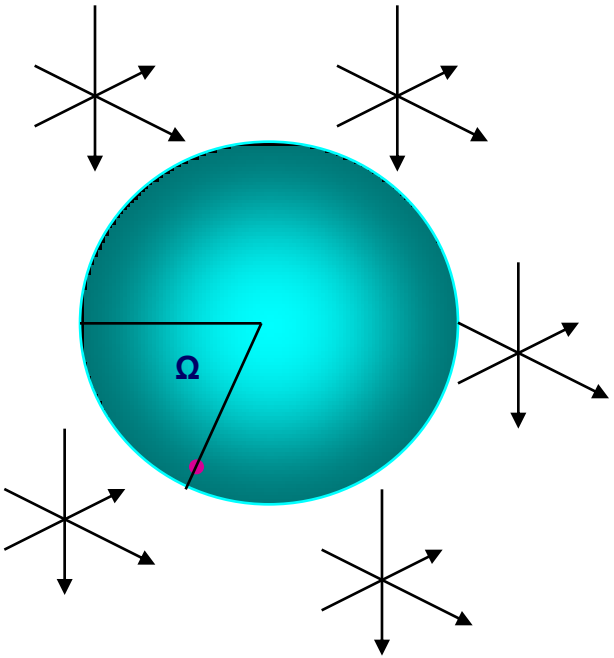
AMBIENT DOSE EQUIVALENT

- 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(ICRU 51).
  - ✓ currently recommended *d*=10 mm, *H*(10)*;
  - ✓ weekly penetrating radiation:
    - → skin *d*=0.07 mm;
    - → eye *d*= 3 mm.

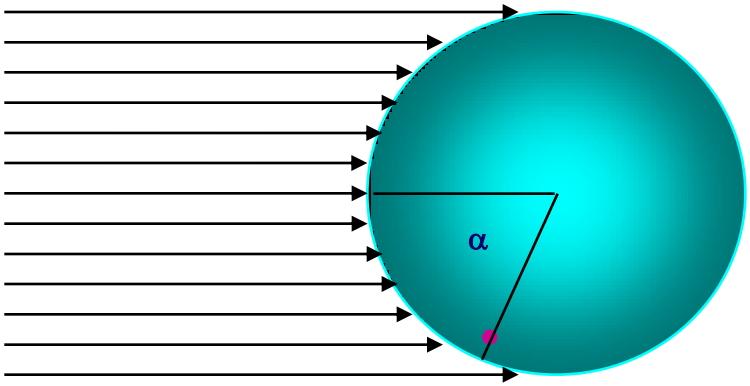


DIRECTIONAL DOSE EQUIVALENT

- 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 the radius in a specified direction Ω (ICRU 51).
  - ✓ strongly penetrating radiation, currently recommended d=10 mm;
  - ✓ weekly penetrating radiation:
    - → skin d=0.07 mm;
    - → eye d= 3 mm.



Unidirectional field: $\Omega \rightarrow \alpha$, when α=0, $H'(d,0)=H'(d)=H^*(d)$.



PERSONAL DOSE EQUIVALENT

- The directional dose equivalent, $H_p(d)$, is the dose equivalent in soft tissue, at an appropriate depth *d,* below a specified point in the body(ICRU 51).
  - ✓ Strongly penetrating radiation *d*=10 mm;
  - ✓ weekly penetrating radiation:
    - → skin *d*=0.07 mm;
    - → eye *d*= 3 mm.
- $H_p(d)$ can measured with a detector worn on the surface of the body and covered with an appropriate thickness of TE material;
- The calibration of a dosimeter is generally performed under simplified conditions and on an appropriate phantom:
  - ✓ ISO phantom: slab phantom (30×30×15 cm^3) filled with water, PMMA walls 10 mm in thickness, excluding the front wall which is 2.5 mm in thickness.

ICRP 60 & ICRP 103

- The mean absorbed dose in the region of an organ or tissue T is:

$$\overline{D}_T = \frac{\int_T D(x,y,z)\rho(x,y,z)dV}{\int_T \rho(x,y,z)dV}$$

  - where:
    - ✓ V is the volume of the tissue region T;
    - ✓ D is the absorbed dose at a point (x,y,z) in that region;
    - ✓ ρ is the density at this point.

EQUIVALENT DOSE

- The equivalent dose in an organ or tissue T is:

$$H_T = \sum_R w_R D_{T,R}$$

- where:
  - ✓ w_R is the radiation weighting factor for radiation R.
- Unit: sievert (Sv)

RADIATION WEIGHTING FACTORS

ICRP Publication 103

Table B.3. Radiation weighting factors[1] (ICRP 1991b).

Type and energy range[2]	Radiation weighting factors, w_R
Photons, all energies	1
Electrons and muons, all energies[3]	1
Neutrons, energy < 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, energy>2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

[1] All values relate to the radiation incident on the body or, for internal sources, emitted from the source.

[2] The choice of values for other radiations is discussed in paragraph A14 in ICRP (1991b).

[3] Excluding Auger electrons emitted from nuclei bound to DNA (see paragraph A13 in ICRP 1991b).

Table B.4. Radiation weighting factors[1] in the 2007 Recommendations.

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous curve as a function of neutron energy (see Fig. B.4 and Eqn. B.3.16)

[1] All values relate to the radiation incident on the body or, for internal sources, emitted from the source.

RADIATION WEIGHTING FACTORS - NEUTRONS

$$w_R = \begin{cases} 2.5 + 18.2\, e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0\, e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leqslant E_n \leqslant 50 \text{ MeV} \\ 2.5 + 3.25\, e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases} \qquad \text{(B.3.16)}$$

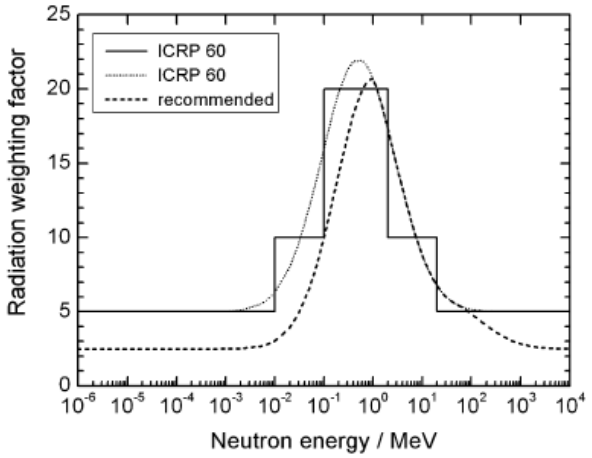


Fig. B.4. Radiation weighting factor, w_R, for neutrons versus neutron energy. Step function and continuous function given in *Publication 60* (ICRP 1991b) and function adopted in the 2007 Recommendations.

EFFECTIVE DOSE

- The equivalent dose in an organ or tissue T is:

$$E = \sum_T w_T \sum_R w_R D_{T,R} = \sum_T w_T H_T$$

- where:
  - ✓ w_R is the radiation weighting factor for radiation R;
  - ✓ w_T is the the tissue weighting factor for tissue T.
- Unit: sievert (Sv)

Table B.2. Tissue weighting factors, w_T, in the 2007 Recommendations.

Organ/Tissue	Number of tissues	w_T	Total Contribution
Lung, stomach, colon, bone marrow, breast, remainder	6	0.12	0.72
Gonads	1	0.08	0.08
Thyroid, oesophagus, bladder, liver	4	0.04	0.16
Bone surface, skin, brain, salivary glands	4	0.01	0.04

ESTIMATE OF RP QUANTITIES

- As discussed by Stadtmann (Radiat. Prot. Dosim. 96 (2001) 21-26), the quantities of interest for RP against external irradiation (defined by ICRU and ICRP) can be subdivided into:
  - ✓ basic physical quantities (fluence, absorbed dose, kerma);
  - ✓ protection quantities (effective dose, equivalent dose, dose equivalent);
  - ✓ operational quantities (ambient dose equivalent, directional dose equivalent, personal dose equivalent).

PHYSICAL QUANTITIES

- They can be defined at any point of a radiation field;
- They are measurable;
- The reference value is held by Primary Metrology Laboratories;
- Reference radiation fields, meeting the recommendations of the ISO are available at Secondary Metrology Labs. for calibration;
  - ✓ these secondary reference fields are traced against the Primary Laboratory ones in terms of physical quantities.

PHYSICAL QUANTITIES: FLUENCE

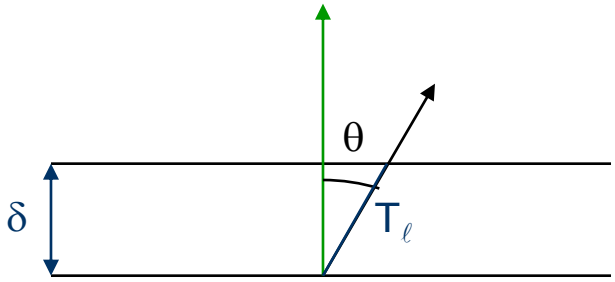
- The contribution to the fluence of one particle crossing a surface S is:

$$\Phi = \frac{1}{S\left|\cos\theta\right|}$$

  - ✓ for a collimated mono-directional beam of charged particle it can be measured with a Faraday cup. Only in the case of a mono-directional beam impinging normally on the cup, the fluence can be determined by dividing the measured charge by the unitary charge and by the cross-sectional area of the beam.

- Usually the assessment of the neutron fluence is based on the measurement of the rate R of reactions induced by neutrons on some elements:

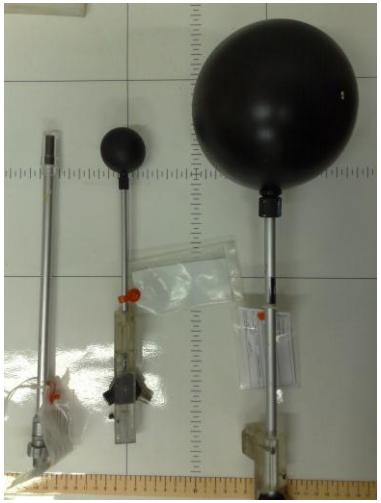
$$R = N_T \sigma \frac{d\Phi}{dt}$$



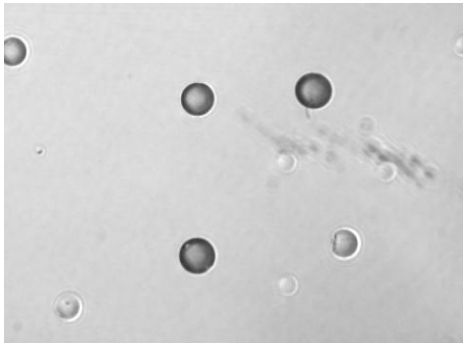
A Faraday cup

PHYSICAL QUANTITIES: ABSORBED DOSE

- Absolute techniques for its measurement:
  - ✓ calorimetry (direct measurement of the temperature increase in an irradiated sample);
  - ✓ chemical dosimetry (e.g Fricke, the number of chemical species induced by radiation per unit deposited energy should be known a-priori);
  - ✓ ionization (the W value should be known a-priori).
- All the other techniques (TLDs, track detectors, photographic films, etc.) require inter-calibration with an absolute instrument (relative dosemeters).



Ionization chambers



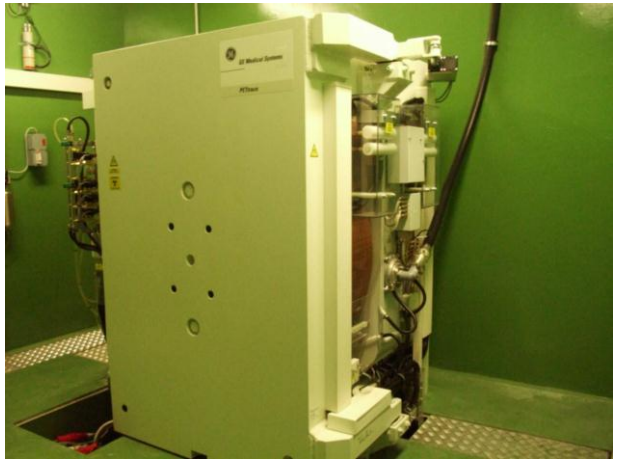
Tracks from α-particles in a CR-39 detector

RP QUANTITIES

- The radiation protection quantities at the basis of dose limitation are not directly measurable:
  - ✓ a quantity defined through a relation with a non measurable quantity/parameter is not measurable;
  - ✓ a quantity defined through measurable quantities is in turn measurable. For example:
    - the activity of a radionuclide generated by a proton beam (mono-energetic and mono-directional impinging normally on the target) striking a thin target is:

$$A = N_T \sigma \varphi \left[1 - \exp(-\lambda t_{irr})\right] \exp(-\lambda t_W)$$

N_T, σ, φ, λ, t_{irr} and t_W are directly measurable, as well as the activity which can be measured directly with an ionization chamber, a scintillator, etc.



Courtesy of F. Colombo, M. Zito, Policlinico di Milano

RP QUANTITIES

- The equivalent dose H_T and the effective dose E introduced by ICRP 60 and maintained in ICRP 103 are defined via w_R and w_T which:
  - ✓ account for "different types of radiation and of stochastic effects in different organs and tissues of the body"(ICRP103);
  - ✓ moreover: "these weighting factors are selected for application in radiological protection by judgement and include acceptable simplifications. Therefore the definition and the value of effective dose are not based on physical properties only. For example, the tissue weighting factors, w_T, are based on epidemiological studies of cancer induction as well as on experimental genetic data after radiation exposure, and on judgements. Furthermore they represent mean values for humans, averaged over both sexes and all ages"(ICRP103).
- Therefore H_T and E are not directly measurable:
  - ✓ they rely on a physical quantity (the absorbed dose), but
    - → non-physical and relative parameters are introduced to take into account the stochastic effects of radiation in the human body.

RP QUANTITIES

- The w_R values are based on experimental data of the RBE and are relative to photon irradiation;
- The w_T values are normalised to their sum.
- These factors allow to employ a single quantity (*E*) for dose limitation, independent of the type of radiation and of the irradiated tissue/organ.
- Other physical quantities (fluence) are not linked directly to the radiation stochastic effects and cannot be used as single quantities for dose limitation.

- The mean absorbed dose $D_{T,R}$ in the volume of a specified organ or tissue is a measurable quantity:
  - ✓ in-vivo dosimetry is a challenging task for radiation therapy;
  - ✓ for RP it is not practicable;
  - ✓ dosimetry with TE detectors (microdosimetry);
  - ✓ it can be calculated by employing computational phantoms.

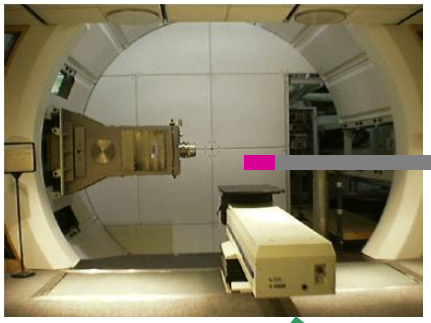
RP QUANTITIES

- The selection of the w_R and of the w_T values "by judgement" is not the only reason for the non-measurability of E;
- For example the

$$RBE = \frac{D_{ref}}{D}$$

is not assessed by judgement, but it is not a physical quantity and it is not measurable directly.

- A "quantity" defined through the RBE (e.g. the "cobalt equivalent gray"=$RBE_{Co\text{-}60}D$) cannot be measured directly, but requires an "a-priori" estimate of the RBE, by specifying the particular cellular system and irradiation conditions (dose rate, etc.) which were adopted.



Hadron-therapy

Measurement

Dose

×RBE

CE-gray
Not a physical quantity!!
Impossible to be measured directly

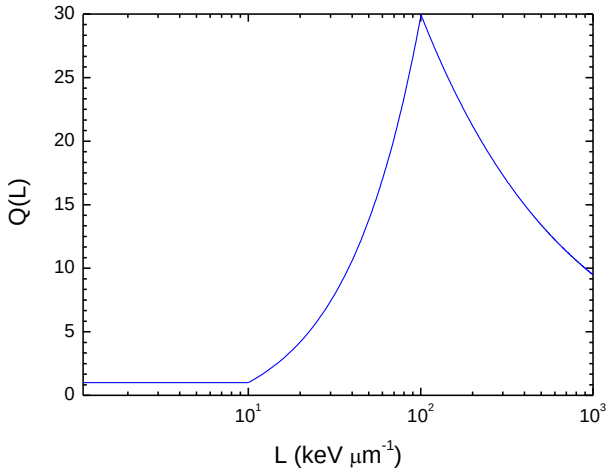
It represents the dose which should be prescribed with X rays to obtain the same effect observed with hadron-therapy

Conventional X-ray therapy

RP QUANTITIES

- Also the RP quantities introduced in the past by ICRP 26 (dose equivalent and effective dose equivalent) are not directly measurable;
- The ICRP 60 defined the Q(*L*) function, where *L* (L_∞) is the unrestricted LET of charged particles in water:
  - ✓ The Q(*L*) function is "the outcome of judgements taking account of results of radiobiological investigations on cellular and molecular systems as well as on the results of animal experiments"(ICRP103). Therefore the dose equivalent is not measurable directly, even when it is assessed as:

$$H = \int_{L\min}^{L\max} Q(L)D(L)dL$$



RP QUANTITIES

- To summarize, the RP quantities are not measurable because:
  - ✓ their definition is based on non-measurable weighting (or quality) factors;

- Anyway:
  - ✓ the respect of dose limits should be controlled routinely by measurements;
  - ✓ there exist radiation monitors which respond against the RP quantities.

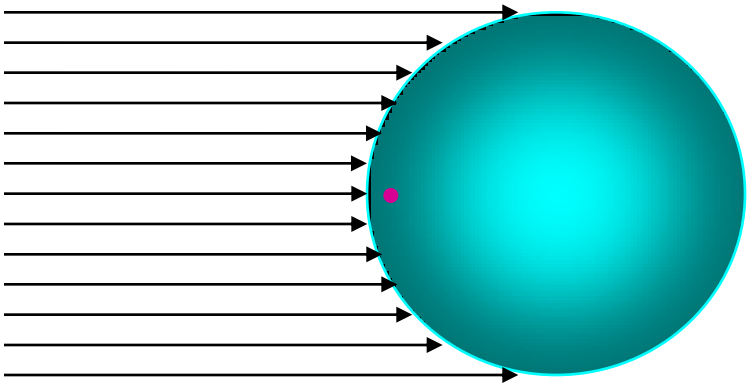
- To overcome the problem of the non direct measurability of the RP quantities, the ICRU introduced operational quantities for the assessment of the RP quantities with respect to external exposure.

OPERATIONAL QUANTITIES

- The operational quantities defined by ICRU 51 are:
  - ✓ the ambient dose equivalent, $H^*(d)$;
  - ✓ the directional dose equivalent, $H'(d,\Omega)$;
  - ✓ the personal dose equivalent $H_p(d)$.

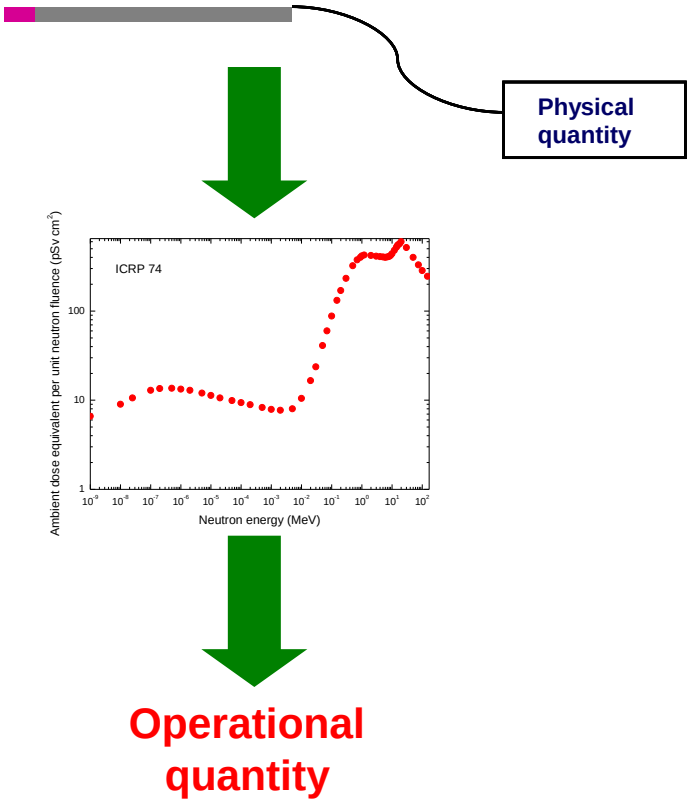
- Their values are "taken as sufficiently precise assessments of effective dose or skin dose, respectively, especially if their values are below the protection limits"(ICRP 103).
- They should give a reasonable conservative estimate of the RP quantities.

- Since they are defined through the dose equivalent which is not measurable directly:
  - → they are not directly measurable.
  - ✓ they allow to express the response of an instrument without ambiguity since they refer to well-defined phantoms and well-defined irradiation conditions.



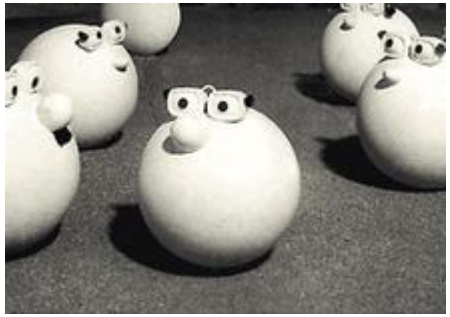
CONVERSION COEFFICIENTS

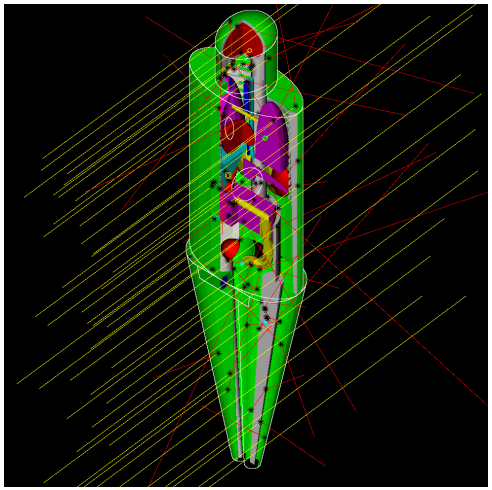
- The connection between physical/measurable and operational quantities is given by the conversion coefficients, calculated by an ICRP-ICRU joint group (ICRP 74, ICRU 57).
- The conversion coefficients allow calibrating an instrument in reference radiation fields:
  - ✓ the basic physical quantity is measured in the reference field;
  - ✓ the operational quantity can be assessed through the conversion coefficients
    - → and taken as the conventional true value.
- An instrument for area monitoring can be designed by calculating its response against the *H**(10):
  - ✓ the instrument responds in terms of *H**(10);
  - ✓ anyway it does not measure directly the *H**(10), but a physical quantity (e.g. the fluence).



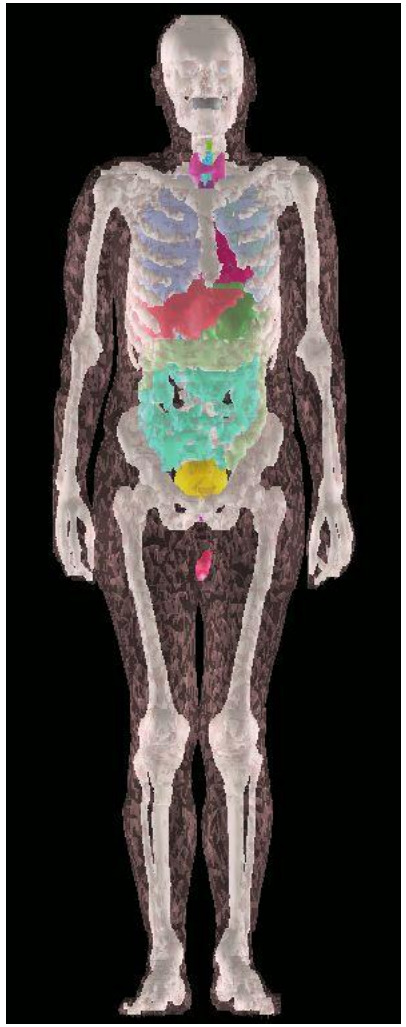
CONVERSION COEFFICIENTS

- An extensive critical discussion about the limits of the operational quantities is given by D. Bartlett (Radiat. Meas. 43 (2008) 133-138):
  - ✓ the set of conversion coefficients (CC) published by ICRP74/ICRU57 is incomplete (the $h^*(10)$ and $h_p(10)$ for neutrons extend up to 200 and 20 MeV, respectively);
    - → for HE applications a comprehensive set of CC was calculated by Pelliccioni;
    - → the ICRP DOCAL task-group is calculating a new set of CC by using anthropomorphic voxel phantoms;
  - ✓ the ICRU 4-element tissue cannot be fabricated;
  - ✓ generally the CC were calculated in vacuo with the kerma approximation (i.e charged particle equilibrium).



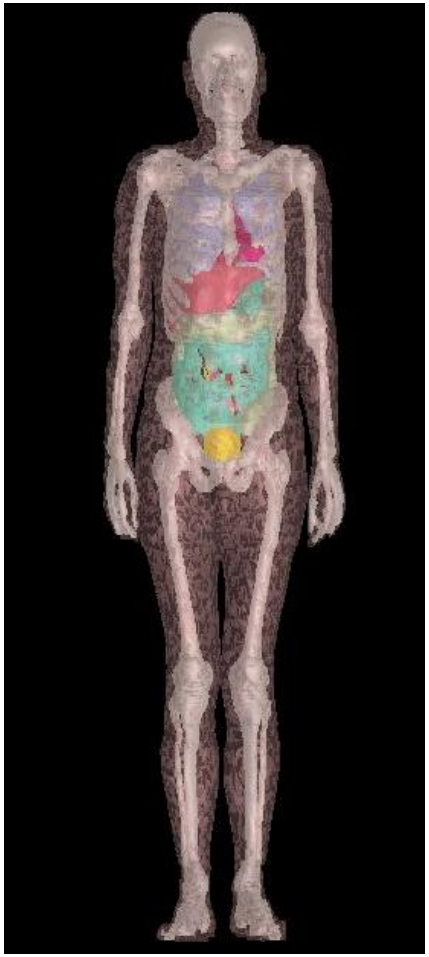


ADAM, courtesy of G. Gualdrini, ENEA, Italy



Adult male voxel model "Golem" (Zankl & Wittmann, 2001)
Courtesy of M. Zankl, Helmholtz Zentrum, Munich

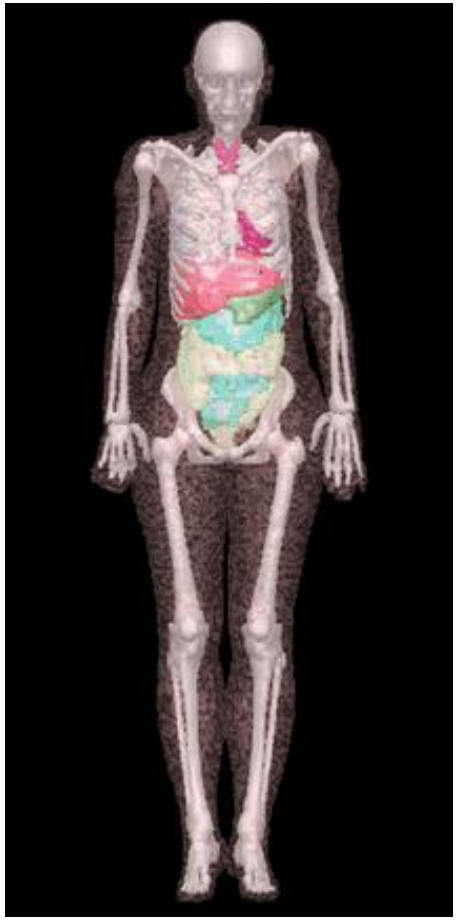
MAIN CHARACTERISTICS OF THE ADULT ICRP/ICRU REFERENCE COMPUTATIONAL PHANTOMS (courtesy of M. Zankl, Helmholtz Zentrum, Munich)



Adult Male Computational Phantom
176 cm, 73 kg
1.9 million voxels
Voxel size: 36.5 mm^3
Slice thickness: 8 mm
In-plane resolution: 2.137 mm

140 Organ identification numbers

Adult Female Computational Phantom
163 cm, 60 kg
3.9 million voxels
Voxel size: 15.2 mm^3
Slice thickness: 4.84 mm
In-plane resolution: 1.775 mm

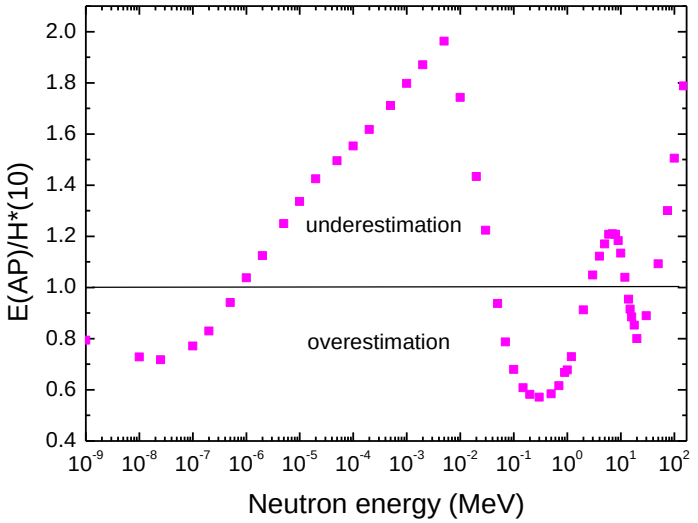


Golem: Zankl, M., Wittmann, A.: The adult male voxel model "Golem" segmented from whole body CT patient data. Radiat. Environ. Biophys. 40 (2001) 153-162

Adult reference computational phantoms. ICRP Publication 108 (in press)

OPERATIONAL QUANTITIES

- The operational quantities should give a conservative estimate of the radiation protection quantities (effective dose). This requirement is not always satisfied:
  - ✓ for HE fields around particle accelerators or for cosmic rays, the operational quantities underestimate *E*;
  - ✓ for very HE particles, the depth of 10 mm in tissue is not sufficient to complete the charged particle build-up.



MICRODOSIMETRY (introductory remarks)

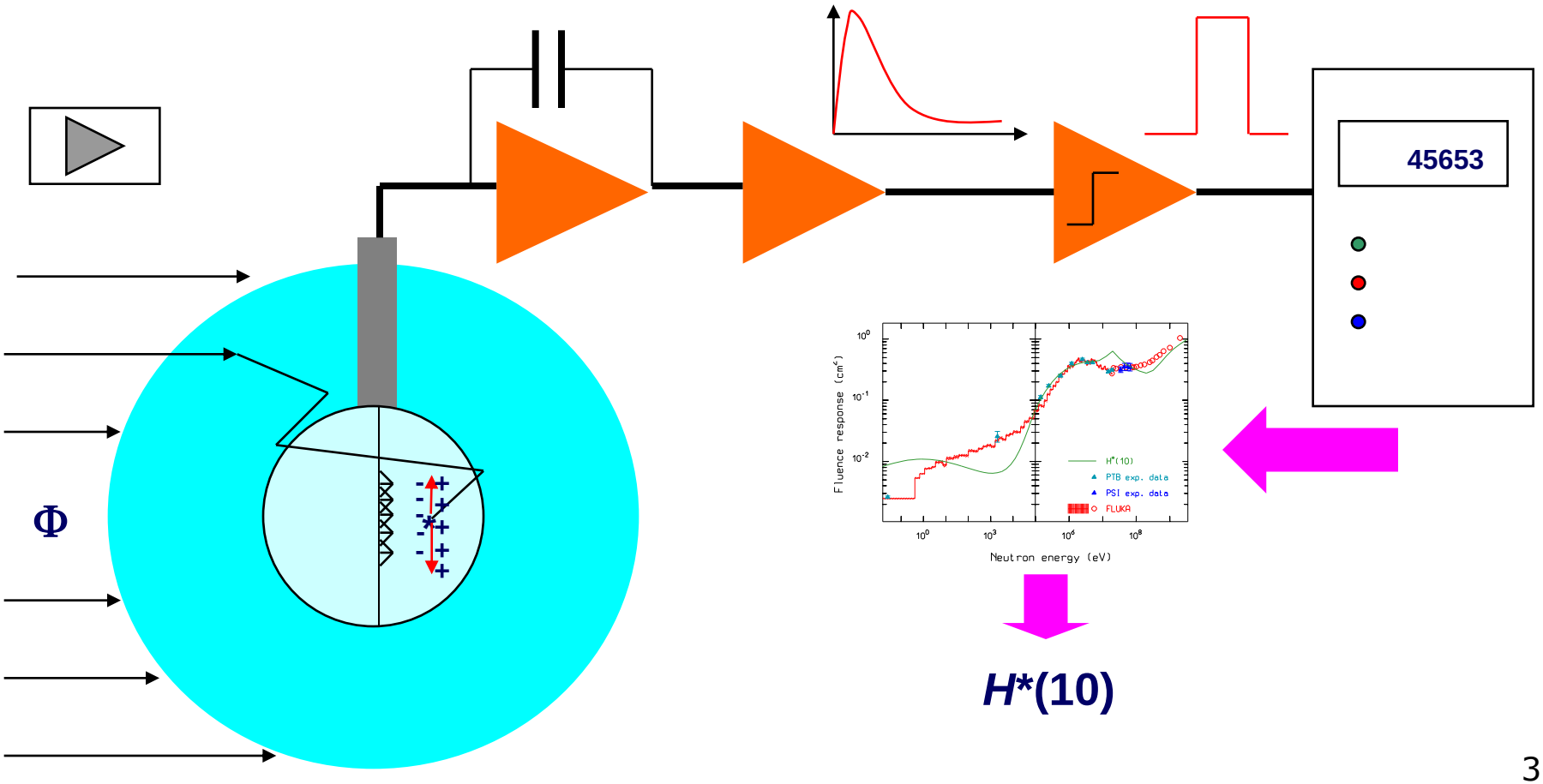
- "The fluctuations of energy deposited in individual cells and sub cellular structures and the microscopic tracks of charged particles are the subject of *microdosimetry*" (ICRP103).
- "Experimental microdosimetry is the study and the interpretation of single-event energy deposition spectra measured using low pressure proportional counters to simulate microscopic sites of tissue" (A. Waker RPD 61 (1995) 297-308).
  - → Its basic quantities *z* and *y* (ICRU 36) are physical (and stochastic) quantities. They are directly measurable.

RP QUANTITY ESTIMATE: MAIN APPROACHES

- Since neutrons are the main component of stray fields, only the main approaches for estimating the neutron $H^*(10)$ (or H) will be discussed:
  - ✓ the use of an instrument with a response to $H^*(10)$ quasi-independent of energy;
  - ✓ neutron spectrometry;
  - ✓ microdosimetry.

RP QUANTITY ESTIMATE: MAIN APPROACHES

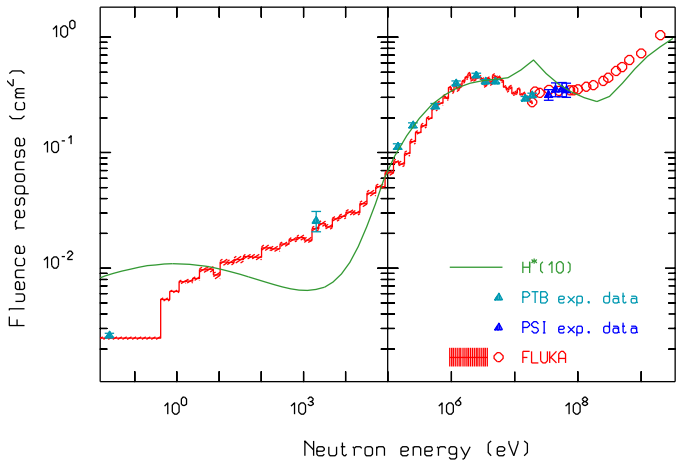
- Since the RP quantities are not directly measurable, their estimate involves the measurement of a physical quantity.

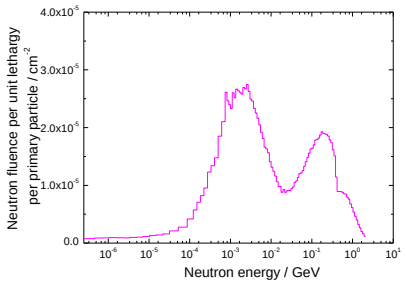


H**(10)

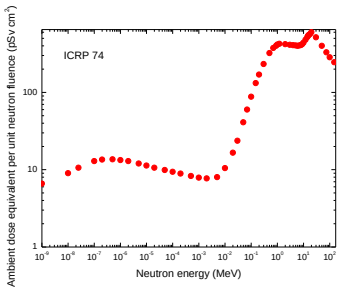
RP QUANTITY ESTIMATE: MAIN APPROACHES

- The subsequent step is to relate the fluence to the protection quantity ($H^*(10)$):
  - ✓ this is achieved through the conversion coefficients;
    1. by designing an instrument whose response varies with energy as the conversion coefficients (the ratio of the response to the conversion coefficient is constant for each energy of the impinging neutrons);
    2. by assessing the neutron spectral fluence and by folding it with the conversion coefficients.





⊗



= $H^*(10)$

RP QUANTITY ESTIMATE: MAIN APPROACHES

- The first approach is at the basis of rem-meters.
  - ✓ The $H^*(10)$ can be evaluated as:

$$H^*(10) = \int h_E^*(10)\Phi_E dE$$

  - ✓ if:

$$k = \frac{h_E^*(10)}{R_E} = \text{constant}$$

  - ✓ then:

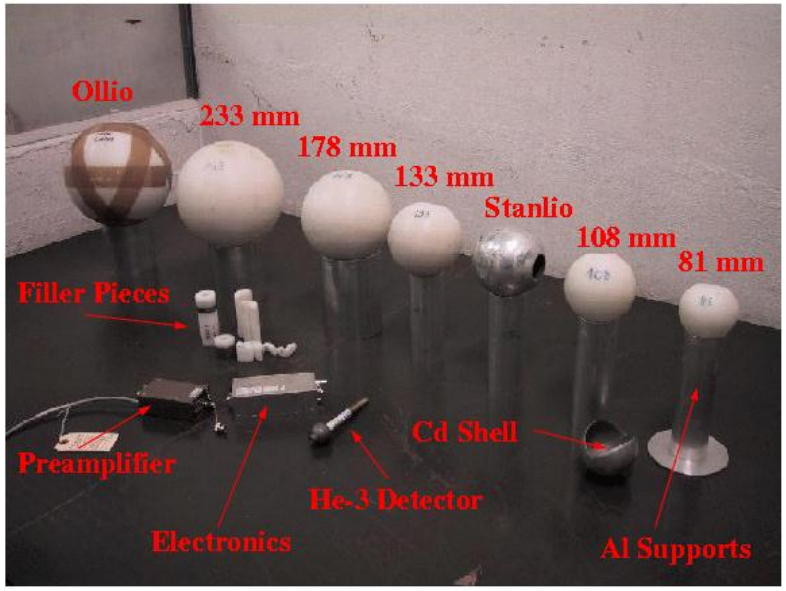
$$H^*(10) = \int kR_E\Phi_E dE = kM$$

- Therefore if *k* is known, the $H^*(10)$ can be assessed from the instrument reading *M*.
- *k* (calibration constant) can be assessed in a calibration field.

RP QUANTITY ESTIMATE: MAIN APPROACHES

- The second approach consists in measuring the energy distribution of the particle fluence and in folding it with the conversion coefficients.

$$H^*(10) = \int h_E^*(10)\Phi_E dE$$



RP QUANTITY ESTIMATE: MAIN APPROACHES

- Microdosimetry allows to estimate the dose equivalent H through the measurement of the dose probability density d(y):

$$d(y) = \frac{yf(y)}{\int_0^\infty yf(y)dy}$$

- By assuming a spherical detector and a single particle of a given LET producing a lineal energy distribution of ideal triangular shape:

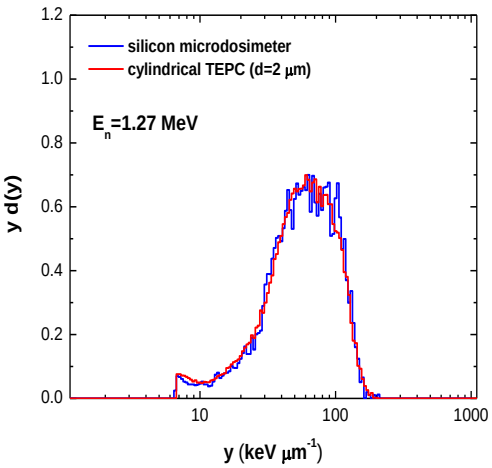
$$d(y) = \frac{8y^2}{9}\int_{2y/3}^{L\,max} \frac{d(L)}{L^3}dL$$

- d(L) can be derived by differentiating the previous expression and:

$$H = D\int_0^\infty Q(L)d(L)dL = \overline{Q}D$$

$$y = \frac{\varepsilon}{\bar{\ell}}$$

- ε energy imparted to the matter in a volume by a single energy deposition event. $\bar{\ell}$ mean chord length.
- for a convex body $\bar{\ell} = \frac{4V}{S}$



RP QUANTITY ESTIMATE: MAIN APPROACHES

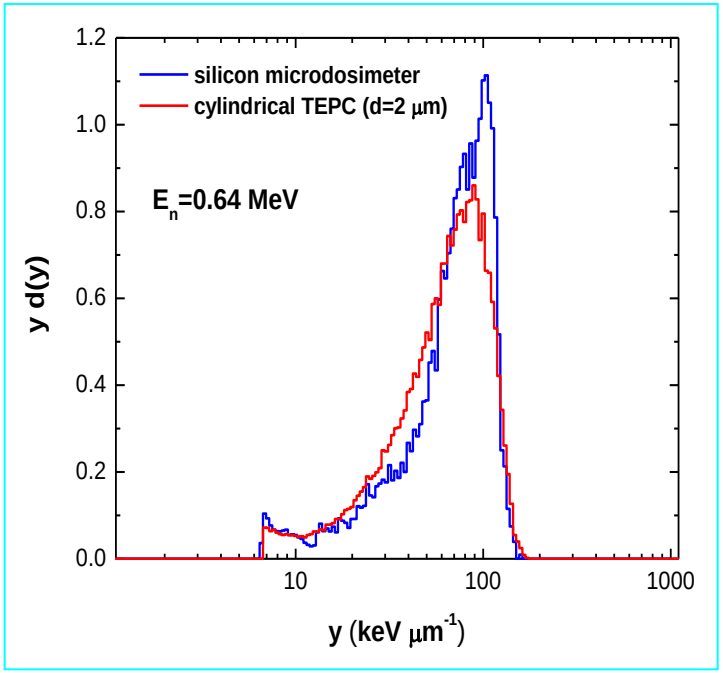
- An alternative procedure is based on the assumption:

$$\overline{Q} = \int_0^\infty Q(L)d(L)dL \cong \int_0^\infty Q(y)d(y)dy$$

- An approximation of the Q(y) relation (determined in a spherical volume of tissue 1μm in diameter) is given by (ICRU 40):

$$Q(y) = \frac{a_1}{y}\left[1 - \exp(-a_2 y^2 - a_3 y^3)\right]$$

- where a_1=5510 keV μm^{-1}; a_2=5×10^{-5} μm^2 keV^{-2} and a_3=2×10^{-7} μm^3 keV^{-3}.



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Additional Slides

Lethargy plots

- Conservative in terms of area for semi-logarithmic plots

$$\int_{E1}^{E2} f(E)dE = \int_{E1}^{E2} E\, f(E)dE/E = \int_{E1}^{E2} E\, f(E)d(\ln E) = \ln 10 \int_{E1}^{E2} E\, f(E)\, d(\log\ E)$$

- Therefore:

$$f(E)dE = Ef(E)d(\ln E) \quad \text{and:}\ Ef(E) = \frac{f(E)dE}{d(\ln E)}$$

- Histogram:

$$E_i f_i(E) = \frac{f_i(E) \times (E_{i+1} - E_i)}{\ln E_{i+1} - \ln E_i} = \frac{f_i(E)\Delta E}{\ln(E_{i+1}/E_i)}$$

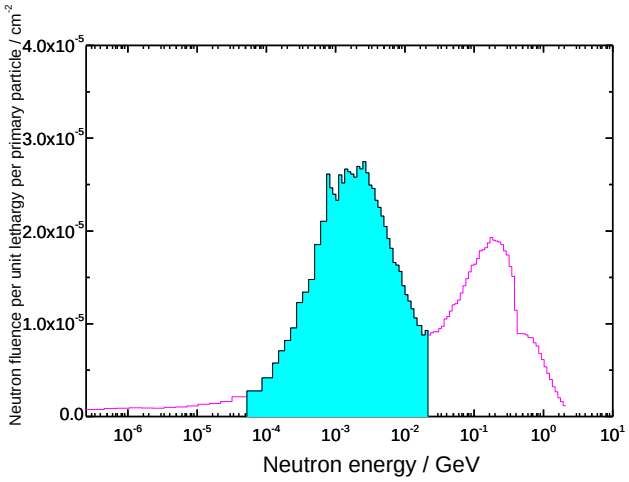
- Lethargy (definition):

$$u = \ln \frac{E_0}{E} = \ln E_0 - \ln E$$

$$du = -\frac{dE}{E}$$

$$F(u)du = -F(E)dE$$

$$F(u) = EF(E)$$



PARTICLE FLUENCE: COSINE-WEIGHTED BOUNDARY CROSSING

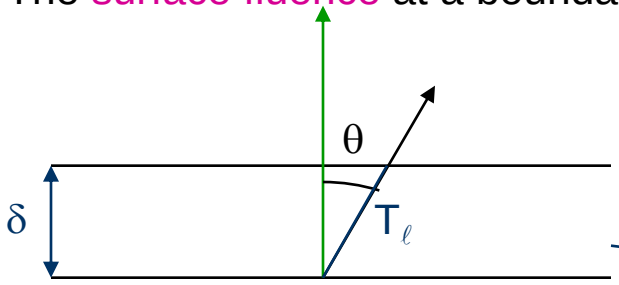
- The spectral distribution of particle radiance is defined as:

$$p_E = \frac{d^4N}{da\, d\Omega\, dE\, dt} = vn(\vec{r},\Omega,E)$$

  - ✓ v=particle velocity;
  - ✓ n=particle density (number of particles N per unit volume).
- The particle fluence averaged over a region of volume V can be estimated as:

$$\Phi = \int_V\int_\Omega\int_E\int_t vn(\vec{r},\Omega,E)dtdEd\Omega\frac{dV}{V} = \frac{\int\int nvdtdV}{V} = \frac{\int ndsdV}{V} = \frac{T_\ell}{V}$$

  - ✓ nds is a “track-length density”;
  - ✓ T_ℓ sum of track lengths.
- The surface fluence at a boundary crossing is, for one particle of weight w:



$$\Phi_S = \lim_{\delta\to 0} w\frac{T_\ell}{V} = w\frac{\delta/|\cos\theta|}{S\delta} = \frac{w}{S|\cos\theta|}$$

Infinitely thin region of volume Sδ

RP QUANTITY ESTIMATE: MAIN APPROACHES

- Since the RP quantities are not directly measurable, their estimate involves the measurement of a physical quantity.