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Radiation Protection and Safety – Part 1

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Electrostatic Accelerator Technologies
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Radiological Protection is dealing with what?

Radiological Protection: discipline applied to the protection, of man and the environment, from the possible harmful effects of ionizing radiations

Principles of Radiological Protection system

- ***Justification of a practice***
- ***Optimization of protection:*** (ALARA)
- ***Individual Dose limits***

Main problem in RP

Define Quantities to quantify the Exposure Risks to the different types of Ionizing Radiation. Quantities which therefore serve as indicators of radiation risk and allow a satisfactory preventive structure to be given.



Quantities

Quantities used in Radiological Protection

- *Physical Quantities* - are defined at any point of the radiation field and they can be measured directly from a primary standard
- *Radiation Protection Quantities* – ICRP defined – non directly measurable / average values
- *Operational Quantities* – ICRU defined – they are used for environmental and personal monitoring. They give an estimate of the dosimetric quantities and refer to a specific point.



Physical Quantities

Quantities of radiation field

Radiation Field a certain region of space in which radiations of any kind are propagated. The radiation fields of interest to us concern only ionizing radiation.

The Radiation Field can be characterized through the following quantities:

Particle fluence in a certain material at SI: m^{-2}

$$\Phi = \frac{dN}{da}$$

Rate SI: $\text{m}^{-2} \cdot \text{s}^{-1}$

$$\varphi = \frac{d\Phi}{dt} = \frac{d^2N}{dt da}$$

Absorbed Dose

Absorbed dose: the ratio between the average energy transferred by the radiation to the matter contained in a certain element of volume and the mass of matter in this volume element

.

Unit at SI: **Gray (Gy)**;

$$1 \text{ Gy} = 1 \text{ J/kg}$$

$$1 \text{ Gy} = 100 \text{ rad}$$

$$D = \frac{d\bar{\varepsilon}}{dm}$$

Absorbed dose rate: unit at SI: **Gy·s⁻¹**.

$$\dot{D} = \frac{dD}{dt}$$

Kerma

Kinetic energy released in the matter: the quotient between the sum of the initial kinetic energies of all the charged particles produced by indirectly ionizing particles in a certain volume element of specified material and mass dm .

Unit of measurement in SI: **Gray (Gy)**;

$$1 \text{ Gy} = 1 \text{ J/kg}$$

$$1 \text{ Gy} = 100 \text{ rad}$$

$$K = \frac{dE_{tr}}{dm}$$

Rate of Kerma: unit at SI: **Gy·s⁻¹**.

$$\dot{K} = \frac{dK}{dt}$$



Radiation Protection Quantities

Average absorbed dose by body organ T

Average absorbed dose at organ T:

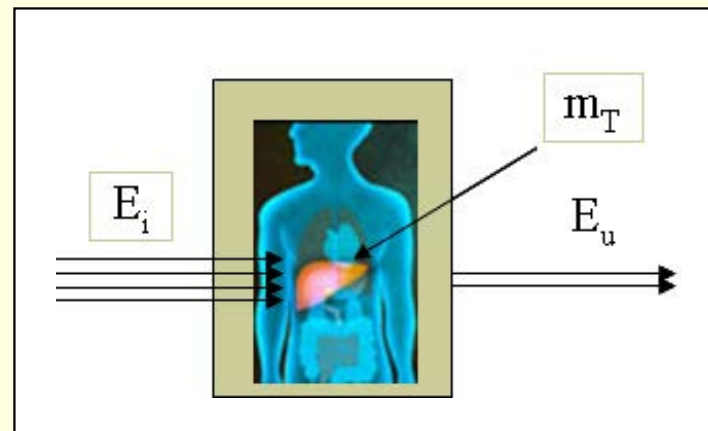
Unit at SI: **Gray (Gy)**

1Gy = 1 J/kg=100 rad \approx 6 keV/ μm^3

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

The average absorbed dose in the T organ due to the R radiation is indicated with **$D_{T,R}$**

Therefore, for every organ or tissue T, the potential biological damage is proportional to the average absorbed dose



Equivalent Dose

To take into account the dependence of biological damage on the type of radiation absorbed, the concept of Equivalent Dose has been introduced which provides a measure of the risk associated with exposure to a particular radiation and also allows to compare the risks deriving from exposure to types of different radiation.

The different dangerousness of incident radiations is explained by the radiation weighting factor, w_R which takes into account the biological effectiveness of the particular radiation with respect to the reference radiation (photons), to which a value equal to 1 is assigned by definition.

Equivalent Dose $H_{T,R}$: tissue or organ T due to radiation R:

$$H_{T,R} = w_R D_{T,R}$$

Unit at SI: **Sievert (Sv)**

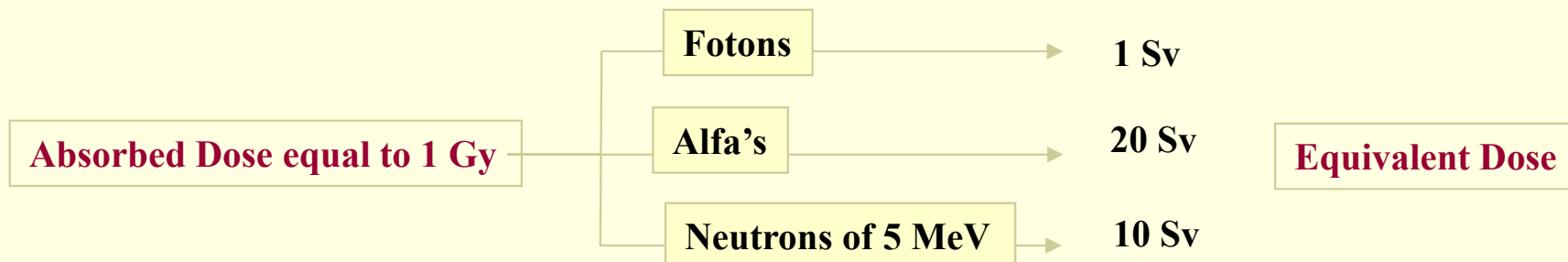
Rate of Equivalent Dose: Unit at SI: **Svs⁻¹** or **μSv/h**

Total Dose Equivalent H_T : if field is composed with different types of radiations with different w_R

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

Weighting factors for radiation

Radiation		W_R
Fotons (X, gamma's)		1
Electrons		1
Alfa's		20
Protons		5
Neutrons	$E < 10\text{keV}$	5
	$10\text{ keV} < E < 100\text{ keV}$	10
	$100\text{ keV} < E < 2\text{ MeV}$	20
	$2\text{ MeV} < E < 20\text{ MeV}$	10
	$E > 20\text{ MeV}$	5



Effective dose

The radio-induced damage also depends on the response of the various irradiated organs or tissues.

To take into account the radiosensitivity of the different organs and tissues of the human body due to the stochastic effects, the concept of **effective dose E** was introduced as the sum of the average equivalent doses in the different organs and tissues each multiplied by the **weighting factor w_T** .

Effective Dose: it is the sum of the equivalent doses weighted in the tissues and organs of the body caused by internal and external radiation; unit at SI: **Sievert (Sv)**;

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

Effective Dose rate: unit at SI: **Svs⁻¹** or better mSv/h, µSv/h

Weighting factors for organs and tissues

Organo	W_T	Risk estimation (cases 10^{-2} Sv^{-1})
Gonads	0.20	0.92
Bone marrow (red)	0.12	0.83
Colon	0.12	0.82
Lung	0.12	0.64
Stomach	0.12	0.8
Bladder	0.05	0.24
Breast	0.05	0.29
Fegato	0.05	0.13
Esofago	0.05	0.19
Tiroide	0.05	0.12
Skin	0.01	0.003
Bone surface	0.01	0.06
Remainders - organs or tissues	0.05	0.47
Total body	1.00	5.6

Exposed workers [ICRP60]

New Values W_T

Organi o Tessuto	W_T ICRP60	W_T ICRP103
Gonadi	0.20	0.05
Midollo osseo (emopoietico)	0.12	0.12
Colon	0.12	0.12
Polmone (vie respiratorie toraciche)	0.12	0.12
Stomaco	0.12	0.12
Vescica	0.05	0.05
Mammelle	0.05	0.05
Fegato	0.05	0.05
Esofago	0.05	0.05
Tiroide	0.05	0.05
Pelle	0.01	0.01
Superficie ossea	0.01	0.01
Cervello	Rimanenti org.	0.01
Rene	Rimanenti org.	0.01
Ghiandole salivari	Rimanenti org.	0.01
Rimanenti organi o tessuti	0.05	0.10
Totale complessivo	1.00	1.00

Comparison ICRP60 and ICRP103

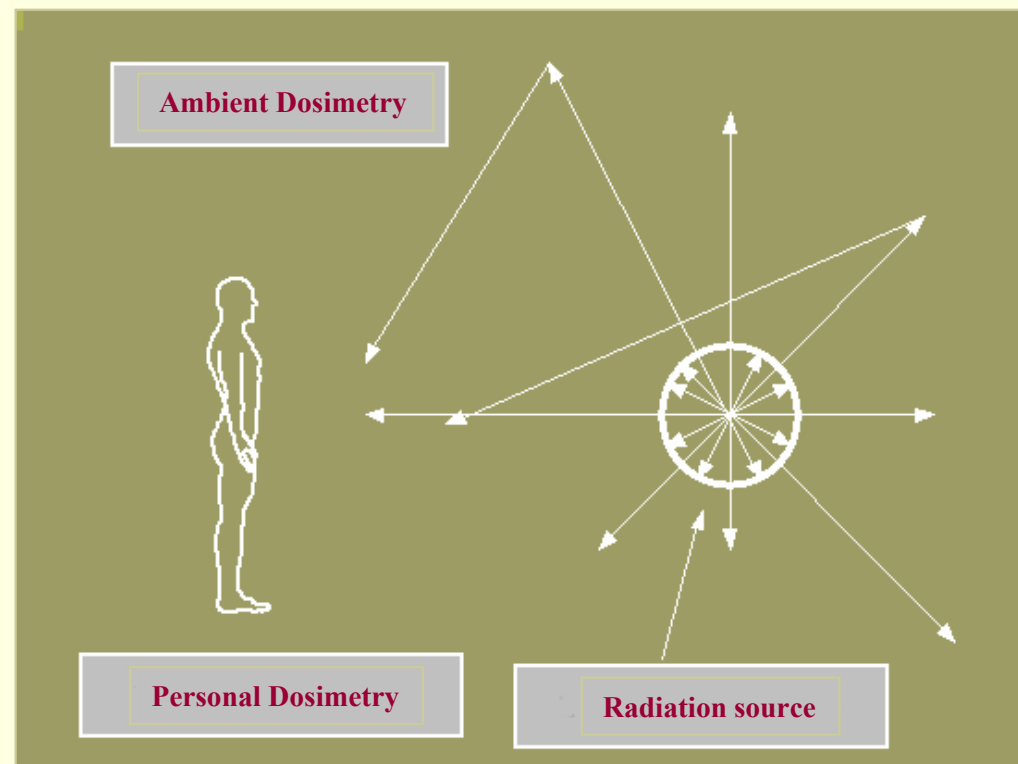


Operational Quantities

In the presence of a radiation source the dosimetry in the field of radiation protection must be carried out through two basic operations:

Environmental Monitoring → **Ambient Dosimetry**

Individual Monitoring → **Personal Dosimetry**



The Ambient and Personal Monitoring operations are carried out with the use respectively of active electronic instruments and passive personal dosimeters.

The two quantities used for Environmental and Personal Dosimetry are:

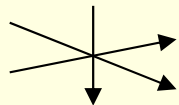
➤ *Ambient dose equivalent $H^*(d)$*

➤ *Personal dose equivalent $H_p(d)$*

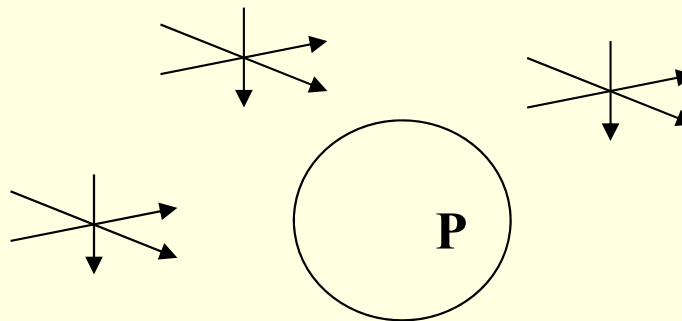
Campo di Radiazione Espanso

Expanded Field: field derived from the real radiation field in which fluence, directional distribution and energy distribution, in all the volume of interest, have values equal to those of the real field at the point of interest.

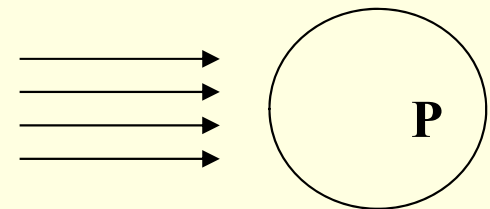
Expanded and Unidirectional Field: field in which the fluence and the distribution of energy are equal to those of the expanded field, but the fluency is unidirectional.



Real Field



Expanded Field

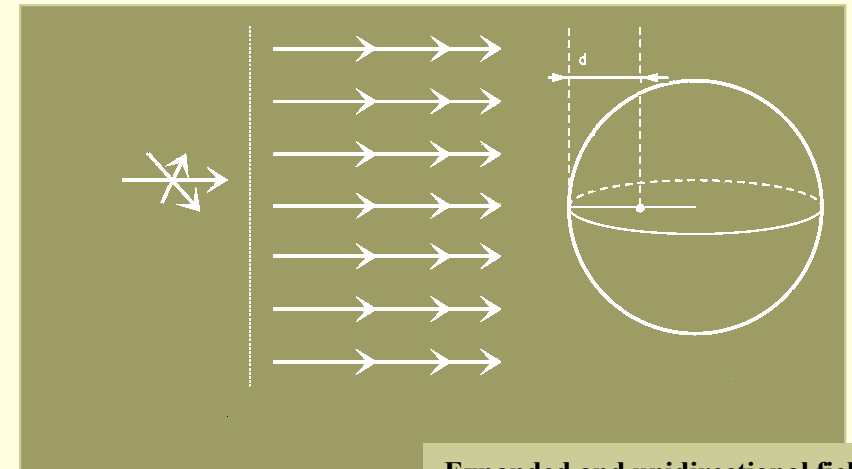


Unidirectional and expanded field

Ambient Dosimetry

Ambient dose equivalent $H^*(d)$: it is the dose equivalent in a point of a radiation field that would be produced by the corresponding expanded and unidirectional field in the ICRU sphere at a depth d , on the radius opposite to the direction of the unidirectional field.

It is suitable for the measurement of strongly penetrating radiation fields and gives an estimate of the effective dose: recommended distance $d = 10 \text{ mm}$

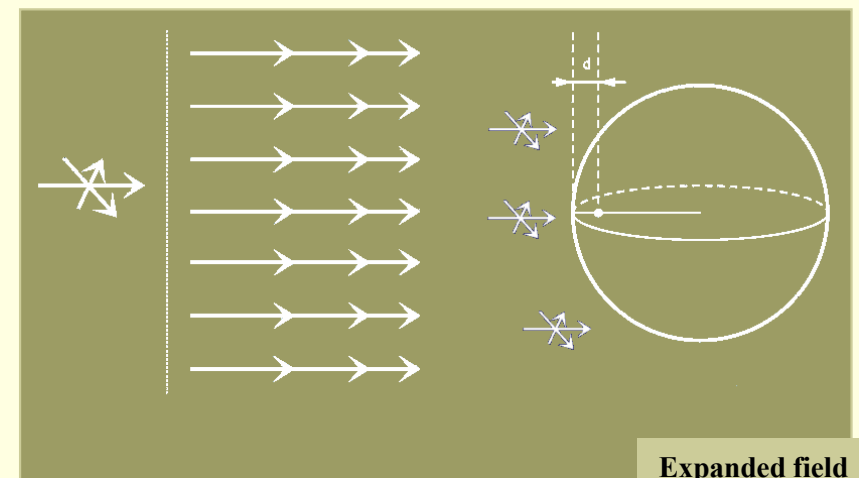


Expanded and unidirectional field

Directional Equivalent Dose $H'(d, \Omega)$: is the equivalent dose at a point of a radiation field that would be produced by the corresponding expanded field, in the ICRU sphere, at a depth d , on a radius in a given W direction.

It is suitable for the measurement of weakly penetrating radiation fields: recommended depth $d = 0.07 \text{ mm}$ and 3 mm .

Provides an estimate of the dose to the skin and lens



Expanded field

Individual Dosimetry

Personal dose equivalent $H_p(d)$: dose equivalent in soft tissue, at an appropriate depth d , below a certain point on the body; provides an estimate of the effective dose

The depth d varies according to the type of radiation:

- for strong penetration radiation a depth of 10 mm is recommended;
- for radiation with low penetration, a depth of 0.07 mm is recommended for the skin and 3 mm for the eyes.

Internal radiation and Effective Dose

Internal irradiation → the source of radiation is located inside the body following inhalation of contaminated air or ingestion of contaminated food, etc. In this case the irradiation will continue until the introduced radionuclide is present in the body. For this discussion the concepts of committed equivalent dose received by a certain organ or tissue must be introduced, in this period it is called **the equivalent dose committed** and **of committed effective dose**.

Committed equivalent dose: integral with respect to time of equivalent dose intensity in a tissue or organ T that will be received by an individual, in that tissue or organ for the introduction of one or more radionuclides

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t) dt$$

Committed effective dose: sum of the equivalent doses committed in the different $H_T(t)$ organs or tissues resulting from the introduction of one or more radionuclides, each multiplied by the weighting factor of the w_T tissue

$$E(\tau) = \sum_T w_T H_T(\tau)$$

In the case of workers, the calculation of the doses involved is carried out cautiously over a period of 50 years starting from the introduction of the radioactive material

Main Limits of dose for exposed workers, non exposed workers and members of public

	Exposed workers	Non exposed workers and Members of public
<i>Effective dose E</i>	20 mSv/y	1 mSv/y
<i>Equivalent Dose H</i> Lens of the eye	150 mSv/y	15 mSv/y
<i>Equivalent Dose H</i> Arms, legs	500 mSv/y	50 mSv/y
<i>Equivalent Dose H</i> Tissue (average dose over 1cm ² of surface)	500 mSv/y	50 mSv/y

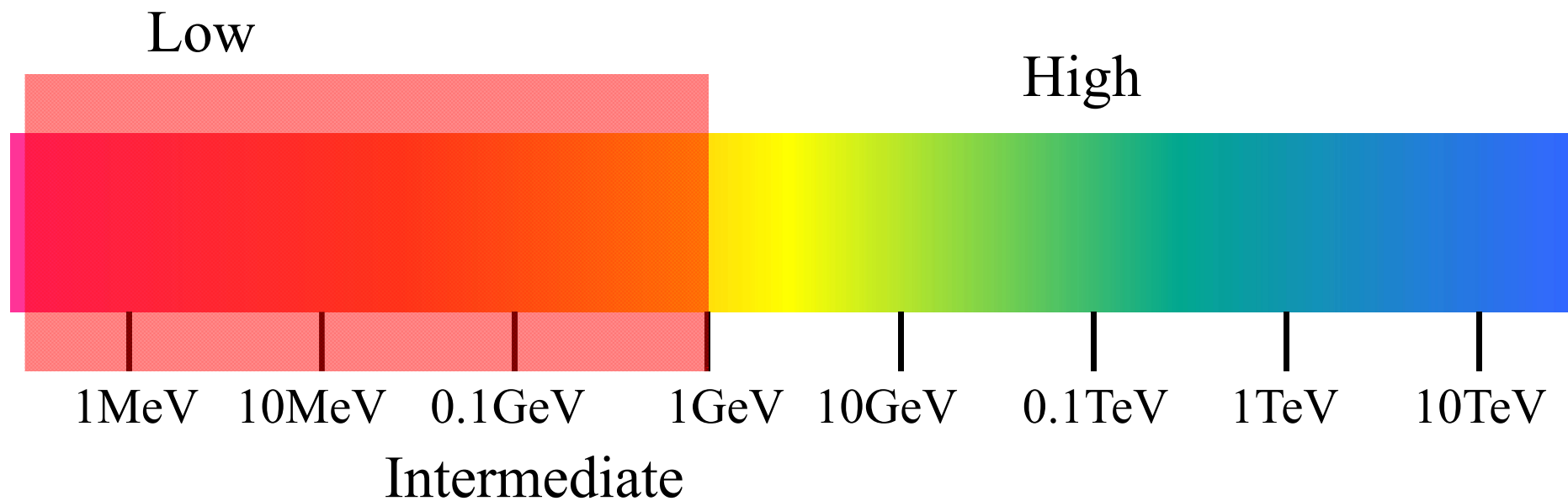
Radiation Protection at Low-energy Proton Accelerators

Overview

- Introduction
- Generation of prompt radiation
 - Interaction of protons with matter
 - Nuclear interactions
 - Characteristics of prompt radiation field
 - Attenuation of the prompt radiation field
- Induced radioactivity production
 - Magnitude of induced radioactivity
 - Prediction of residual radiation field
- Environmental Impact
 - Neutron skyshine
 - Some aspects of emission of radioactive effluents
- Summary

Introduction

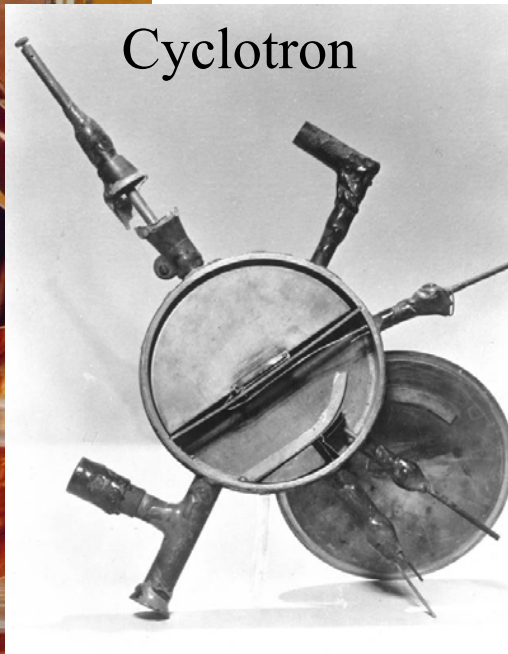
Energy scale for proton accelerators:



Many acceleration schemes are available:



RFQ



Cyclotron



Ballista



Cyclotron



Cyclotron



Van de Graaff



DTL

Many applications:

- Research
- Radiotherapy
 - protons
 - neutrons
 - heavy ions
 - π -mesons
- Industrial and medical radioisotope production
- Waste transmutation
- Contraband detection

Example: Contraband detector:

‘Contraband’ detector:

$^{13}\text{C}(\text{p},\gamma)^{14}\text{N}$ reaction
produces gamma rays
precisely tuned for
absorption by nitrogen



Generation of prompt radiation

- Interactions of protons with matter
 - Low energies: energy loss by ionization
 - Higher energies: energy loss by nuclear interactions
- Nuclear Interactions
 - Direct interactions
 - Pre-equilibrium
 - Equilibrium → evaporation
- Characteristics of the prompt radiation field

Interaction of protons with matter

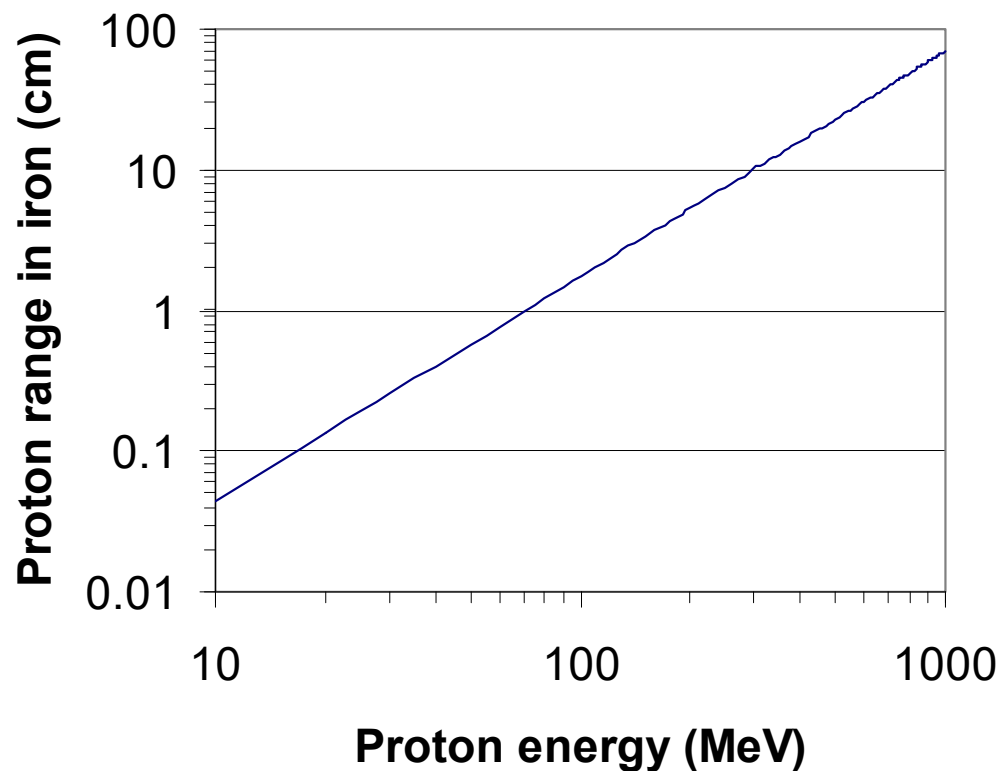
Low-energy protons have a definite range, however, at high energies “range” not meaningful

Range in iron:

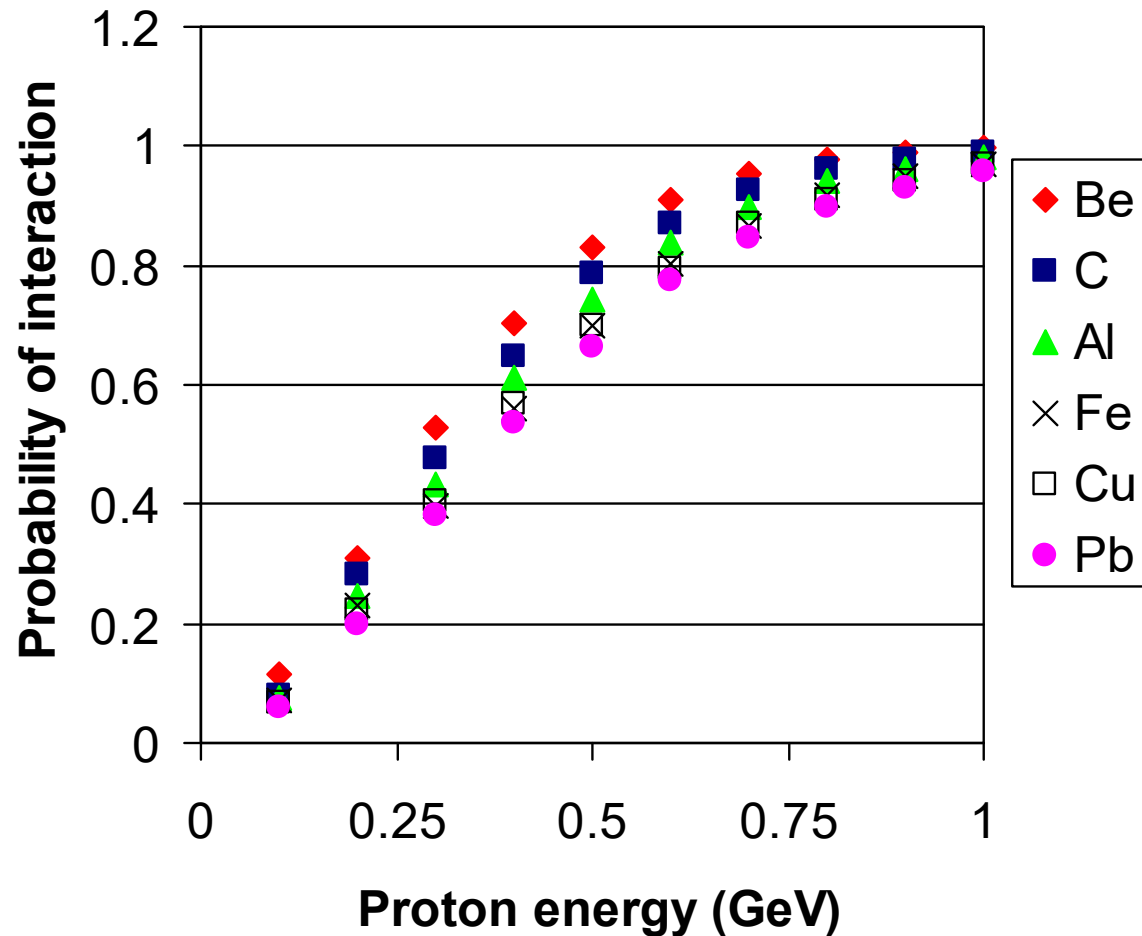
$$R = 1.1 \times 10^{-3} E_p^{1.6}$$

For other materials:

$$R = R_{Fe} \frac{\rho_{Fe}}{\rho} \frac{\sqrt{A}}{\sqrt{A_{Fe}}}$$



Nuclear interaction probability $f_n(E_p)$

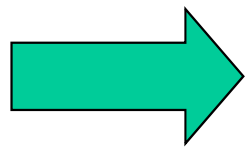


At high energies
attenuation characterized
by nuclear interaction
length

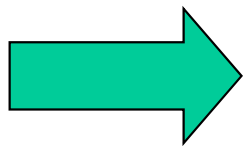
At high energies *every* proton undergoes nuclear interaction if target thick enough

Interaction of protons with matter

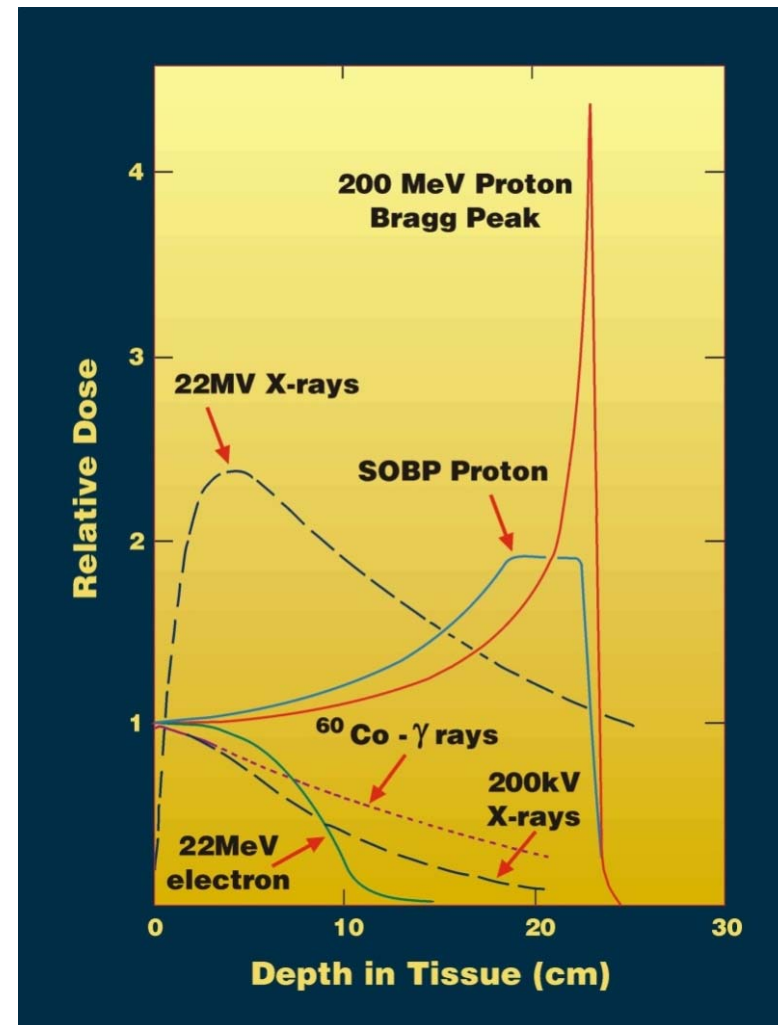
Specific ionization is greatest for low-energy protons:



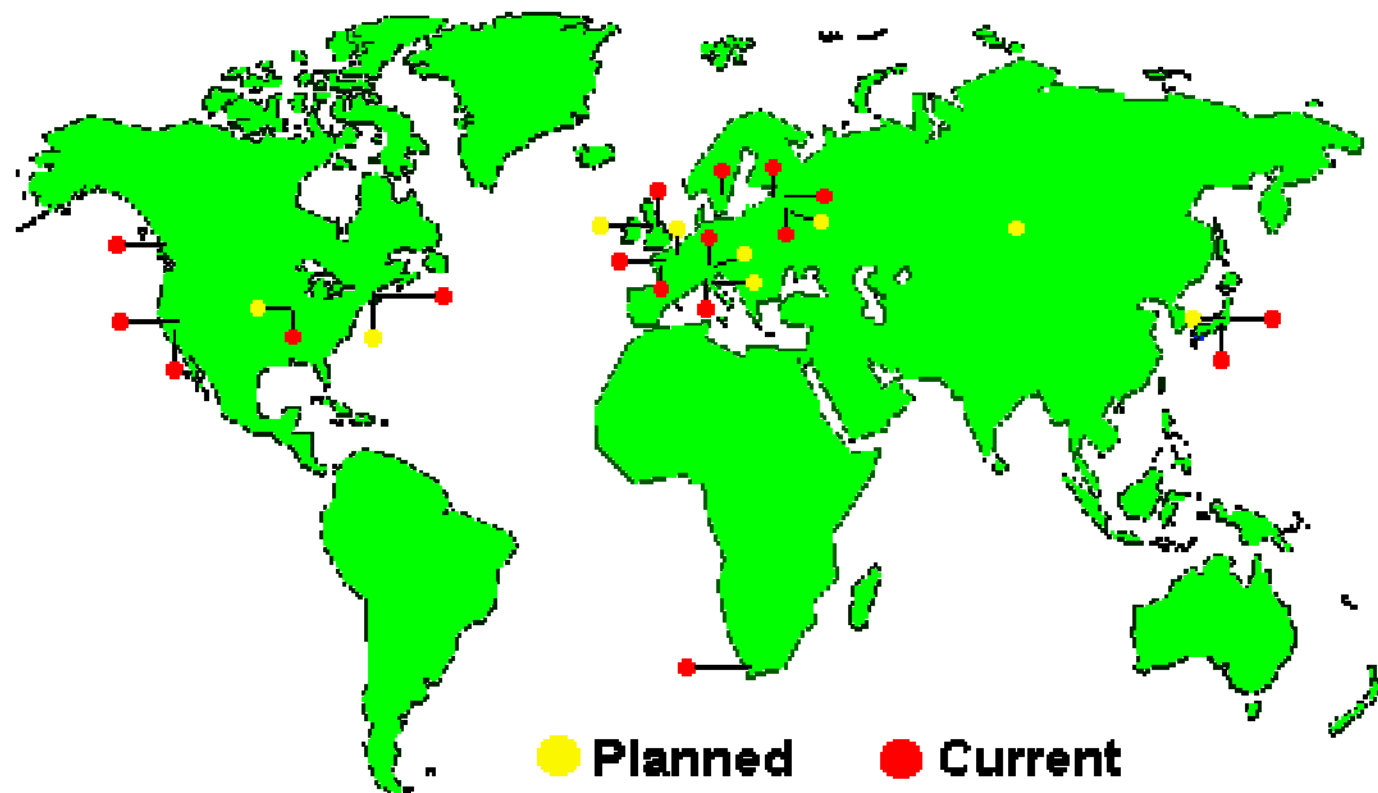
Bragg peak
at the end of proton
range



Application to
Proton therapy

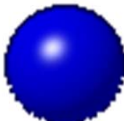
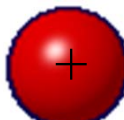







Proton therapy facilities



Characteristics of prompt radiation field

Secondary Particles
Produced:

Above pion threshold (~430 MeV): {	n		Neutrons
	p		Protons
	π		Pions
	μ		Muons
	e		Electrons
	ν		Neutrinos
	γ		Gamma rays

Nuclear interactions

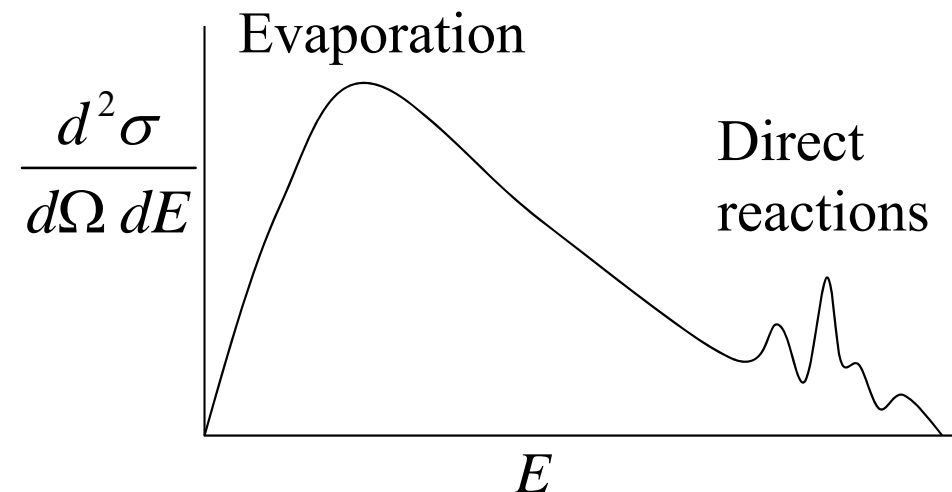
Direct reactions:

- $\Delta A = 0$

- Elastic scattering
- Inelastic scattering
- Charge exchange reaction

- $\Delta A \neq 0$

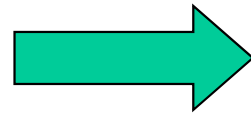
- Transfer reactions
- Knockout reactions



Schematic spectrum of emitted particles

Angular distribution of emitted particles

- Multi-step direct: “memory” of initial direction is preserved



Anisotropic angular distribution

- Multi-step compound: phase relations preserved



Angular distribution not symmetric about 90°

- Evaporation: all memory of initial direction destroyed

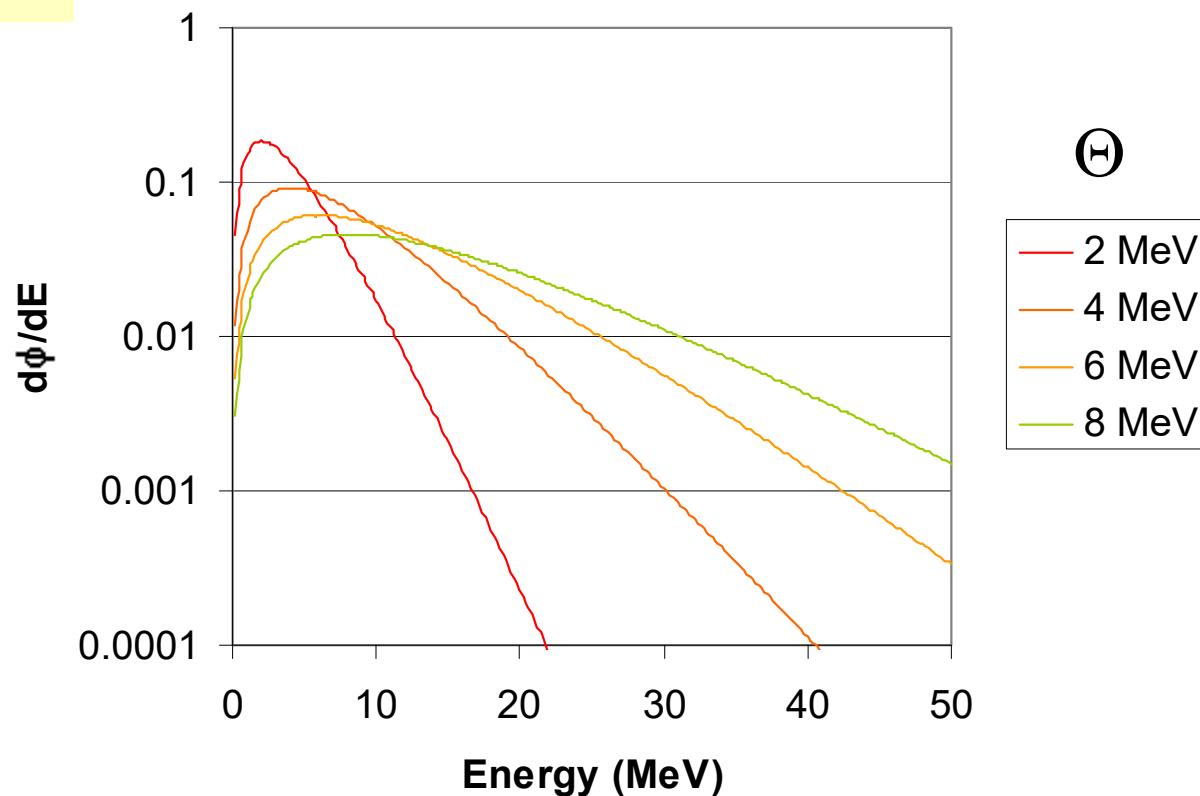
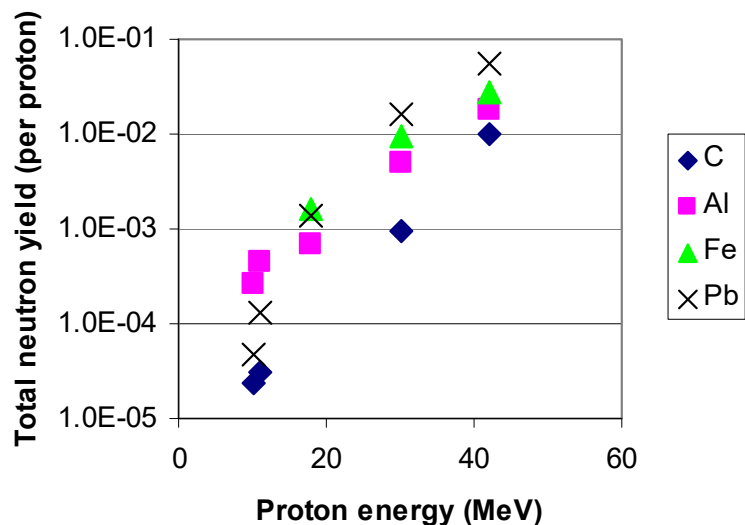


Isotropic angular distribution

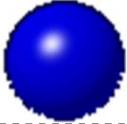
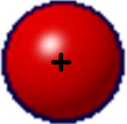





Energy spectrum of evaporated particles

$$d\phi(E_n) \propto \frac{E_n}{\Theta^2} \exp\left(-\frac{E_n}{\Theta}\right) dE_n$$

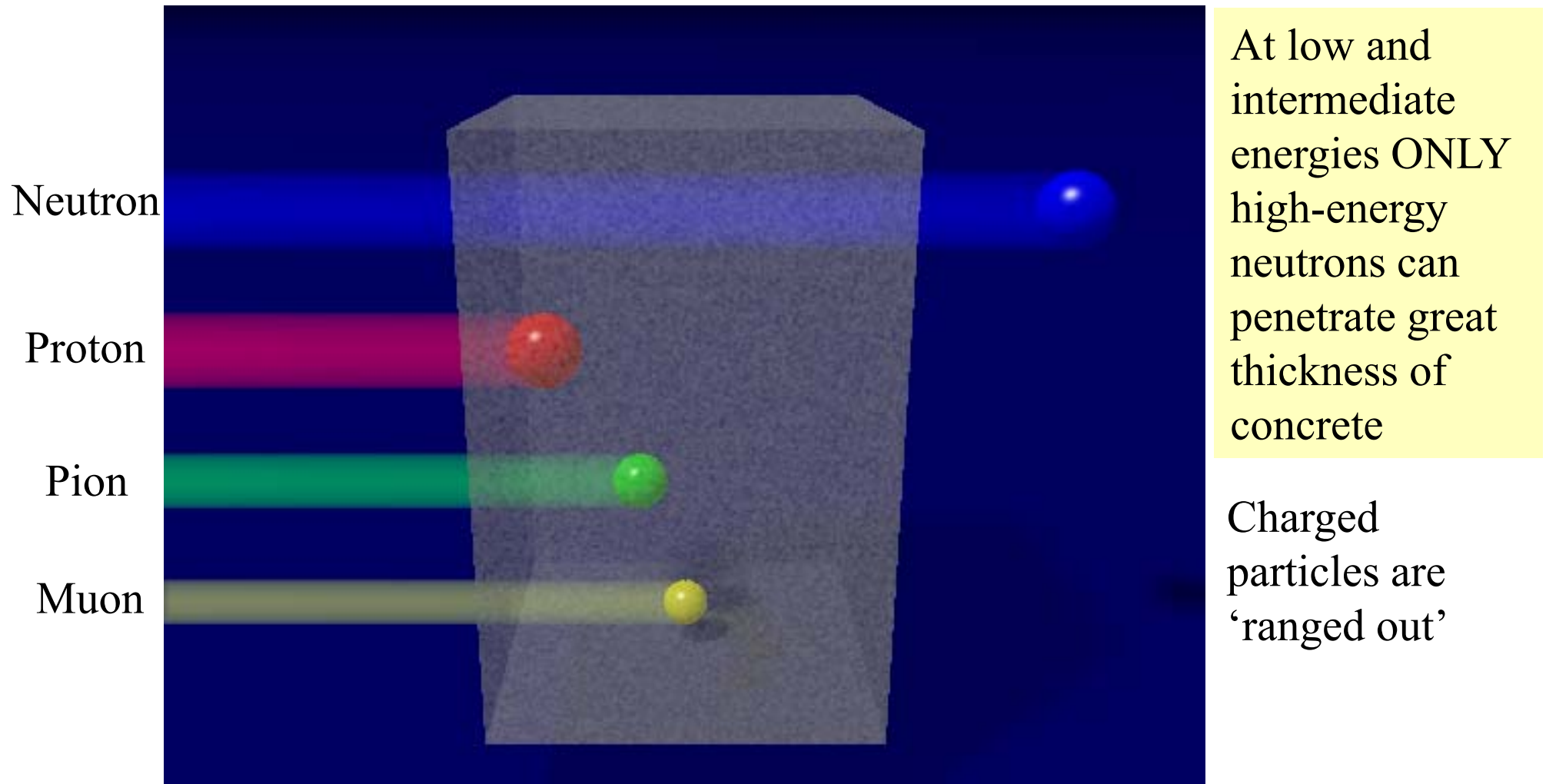
Θ is the “nuclear temperature”




Interaction of prompt radiation with matter

n 	ONLY nuclear reactions
p  π  μ 	Energy loss by ionization, Coulomb scattering and nuclear reactions, decay
e  γ 	Energy loss by ionization Energy loss by photo- electric, Compton scattering & pair production
ν 	Practically no interaction

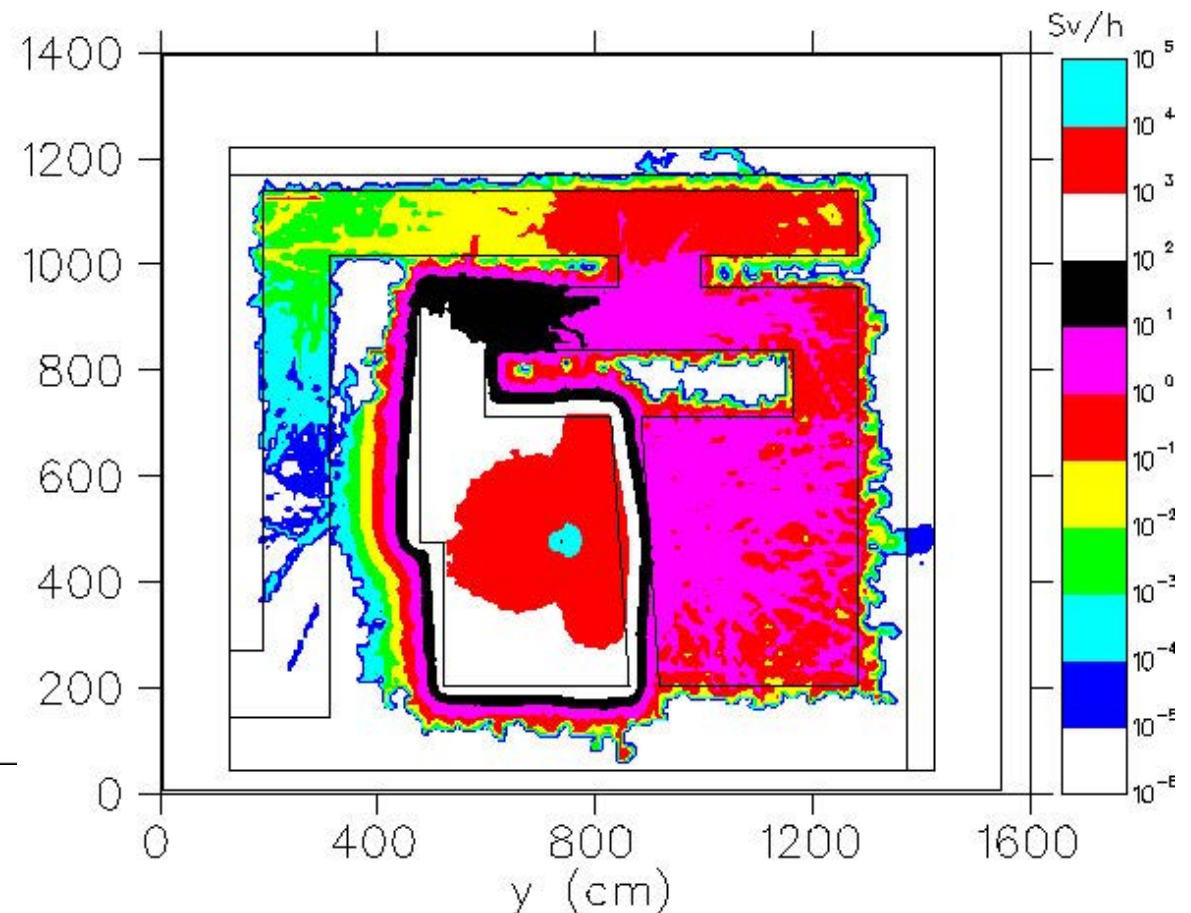
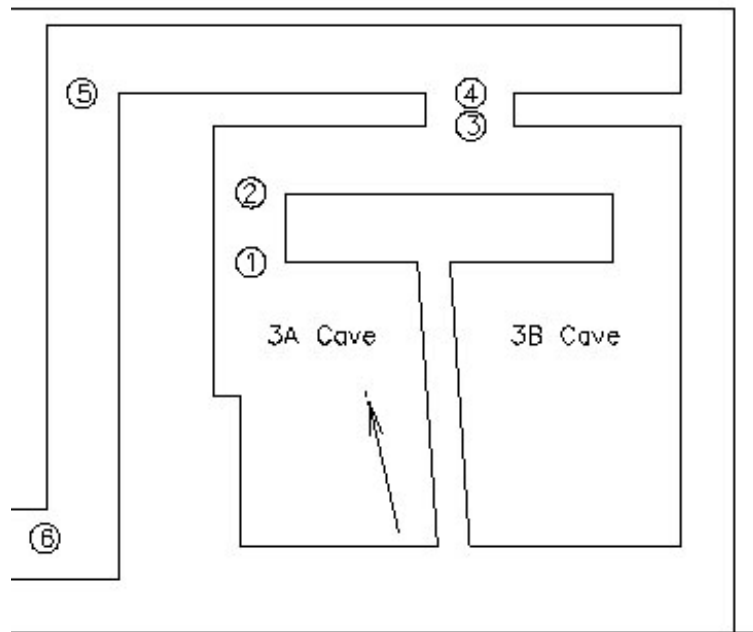
Interaction of prompt radiation with matter



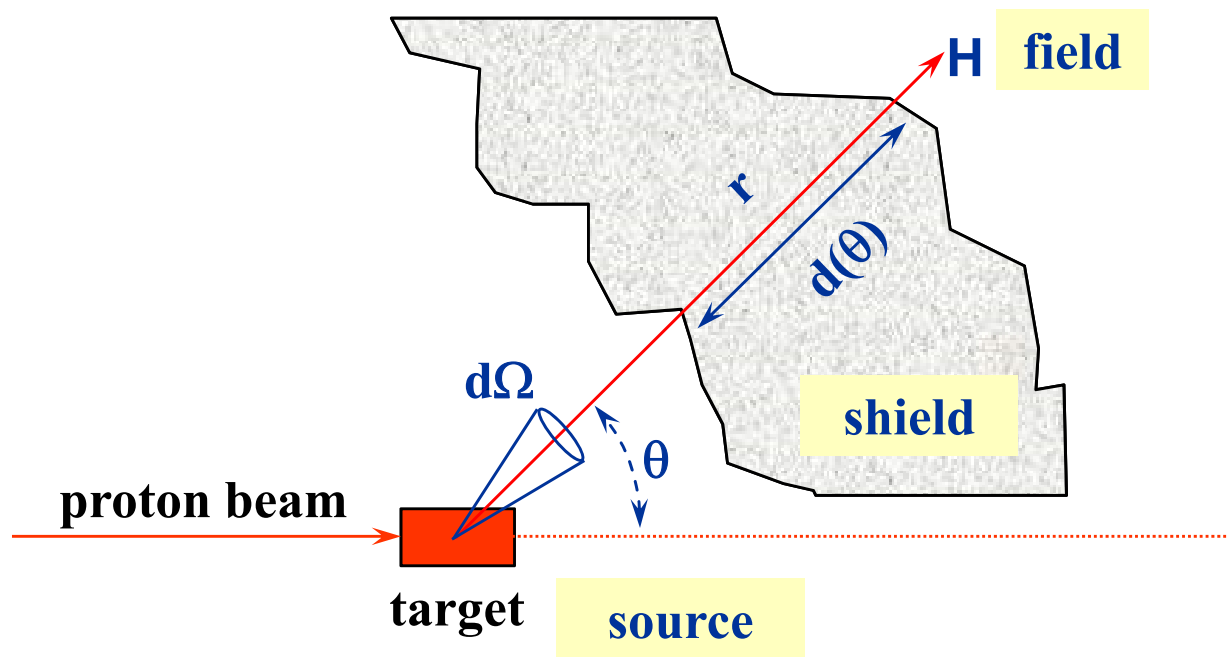
Most complete description of interactions available in simulation codes

- MCNP
 - LAHET
 - FLUKA
 - MARS
 - Etc.
- 
- Not discussed in this presentation

One example: 30 MeV radioisotope production cyclotron target caves

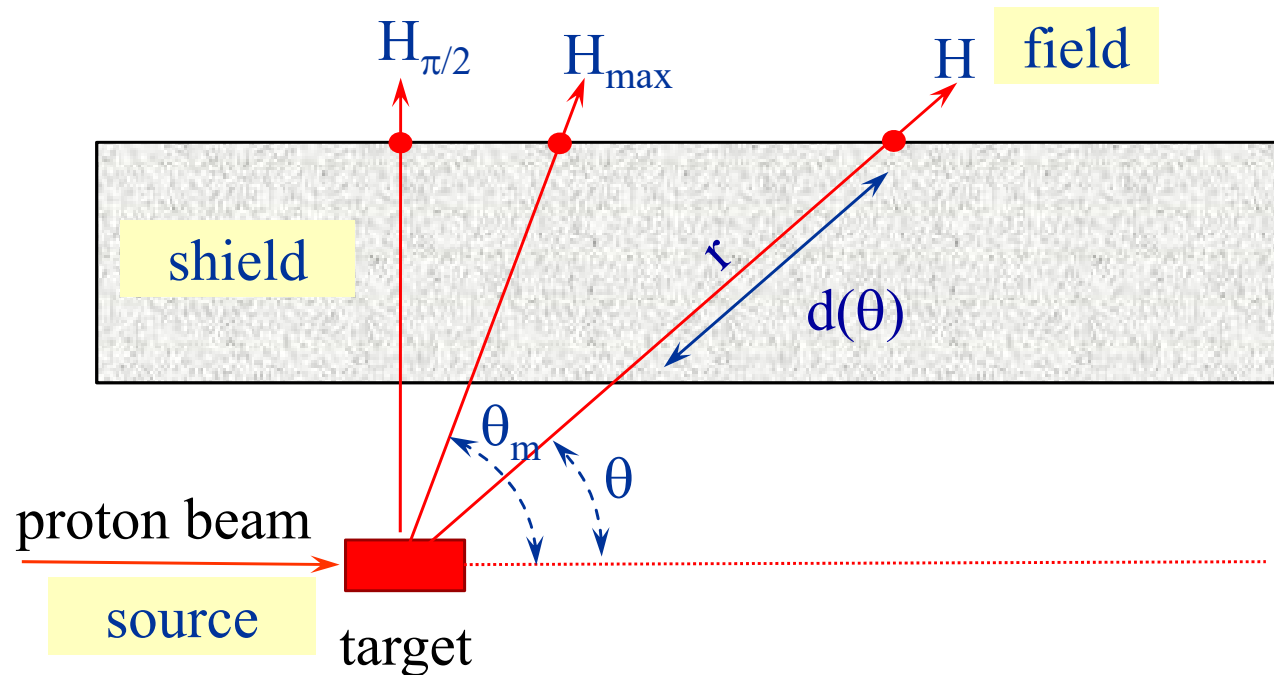


Geometry for generalized shielding problem



Would like: $H(E_p, \theta, d/\lambda) = H_0(E_p, \theta) \exp[-d/\lambda(\theta)] / r^2$

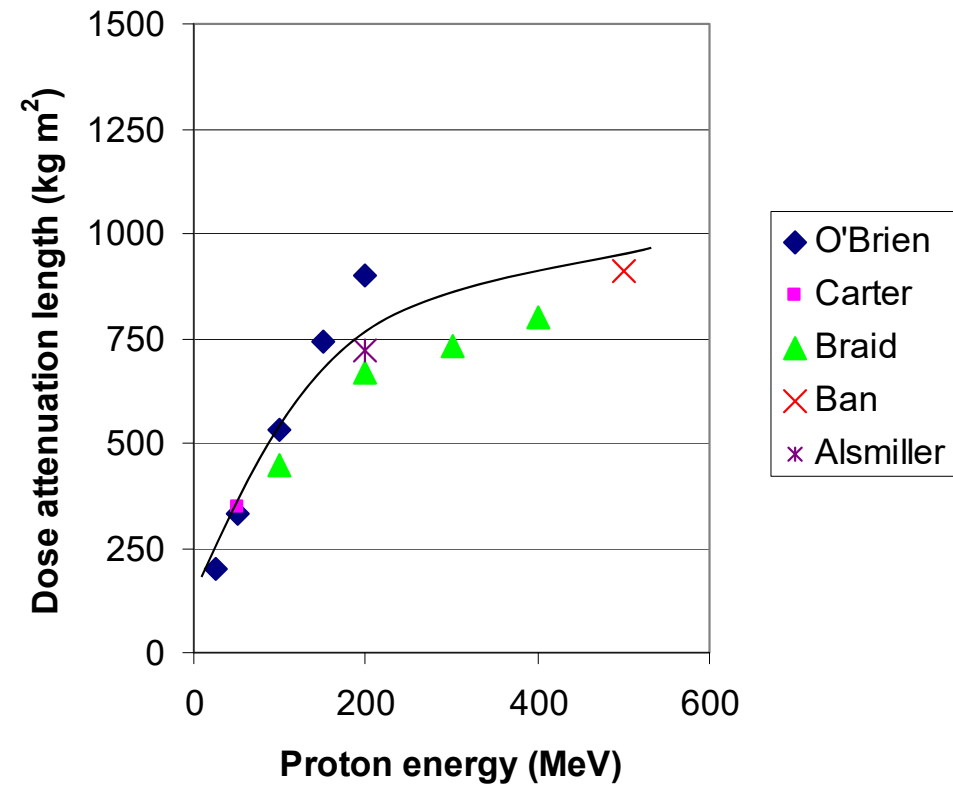
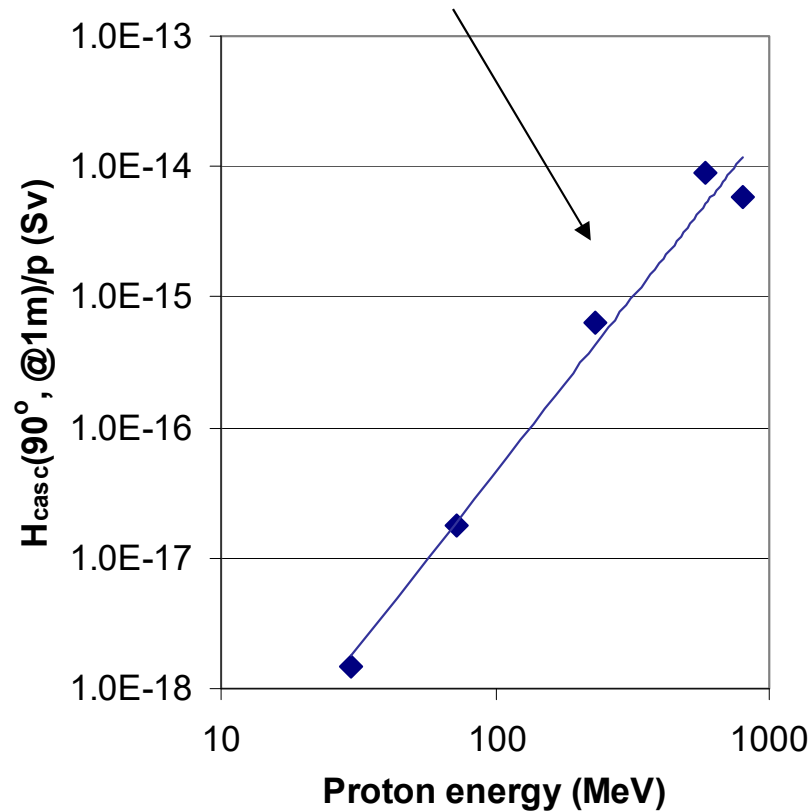
Restricted, lateral shielding problem



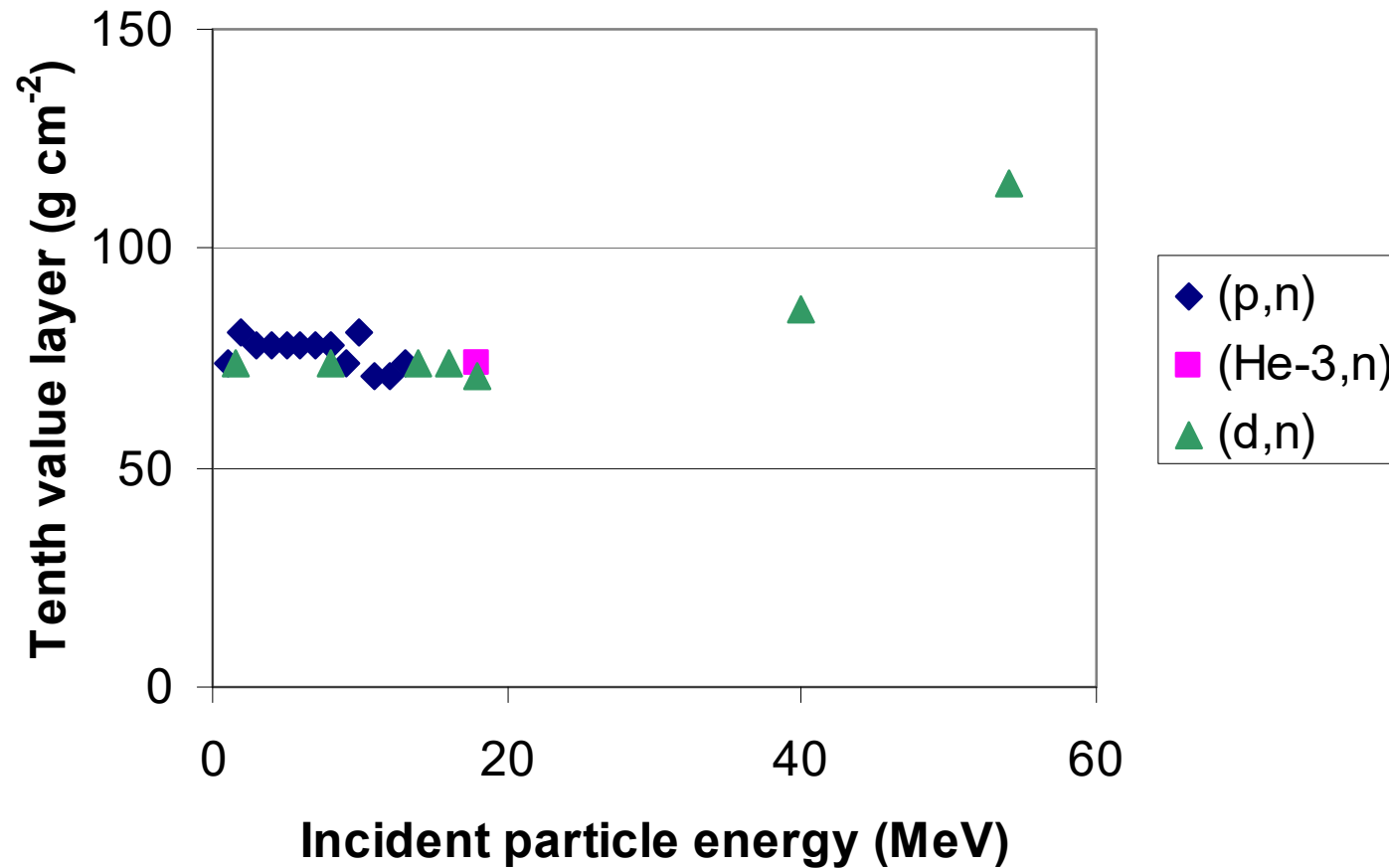
Tesch:
$$H(\pi / 2) = H_{casc} \exp(-d/\lambda) / r^2$$

Values of parameters H_{casc} , $\rho\lambda_h$ (concrete)

Based on neutron yield with $E_n > 8$ MeV



Neutron tenth-value layer, $\rho\lambda_{10}$, in concrete (NCRP Report No. 51)



Equivalent formulations of dose attenuation

$$\frac{H}{H_0} = e^{-d/\lambda} = 2^{-d/\lambda_2} = 10^{-d/\lambda_{10}}$$

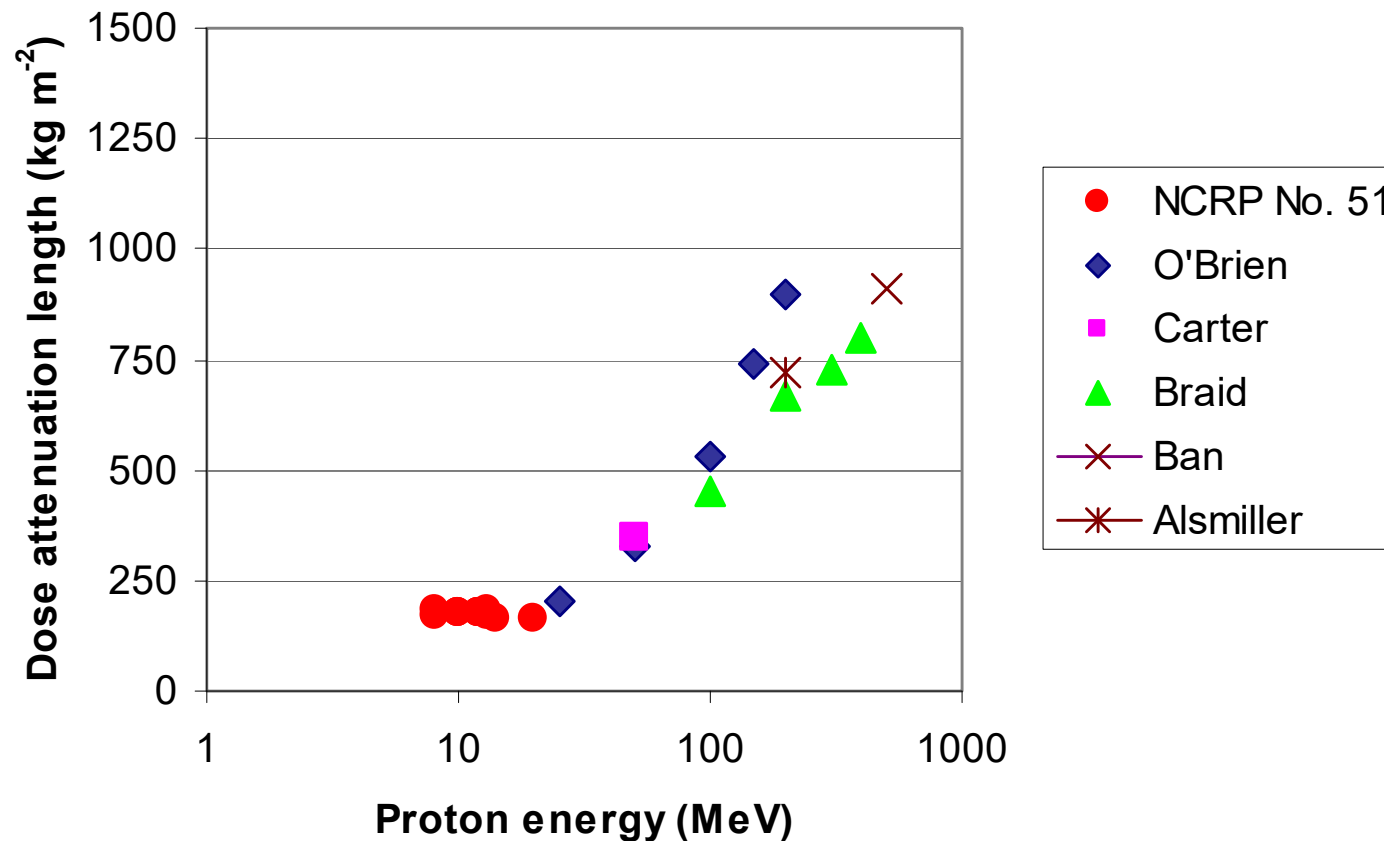
λ = attenuation length

λ_2 = half-value layer

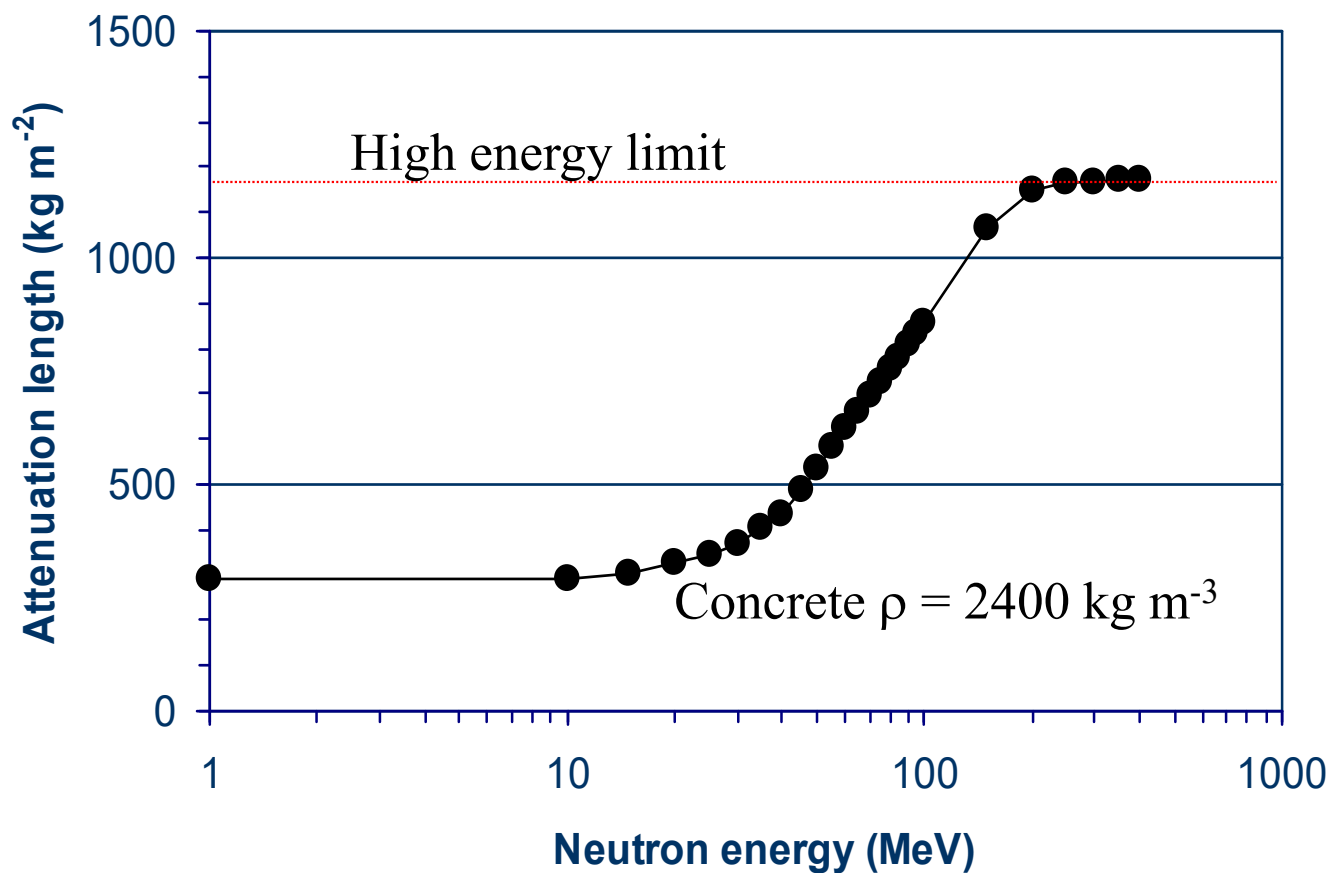
λ_{10} = tenth-value layer

$$\lambda = \frac{\lambda_2}{\ln 2} = \frac{\lambda_2}{0.693} = \frac{\lambda_{10}}{\ln 10} = \frac{\lambda_{10}}{2.30}$$

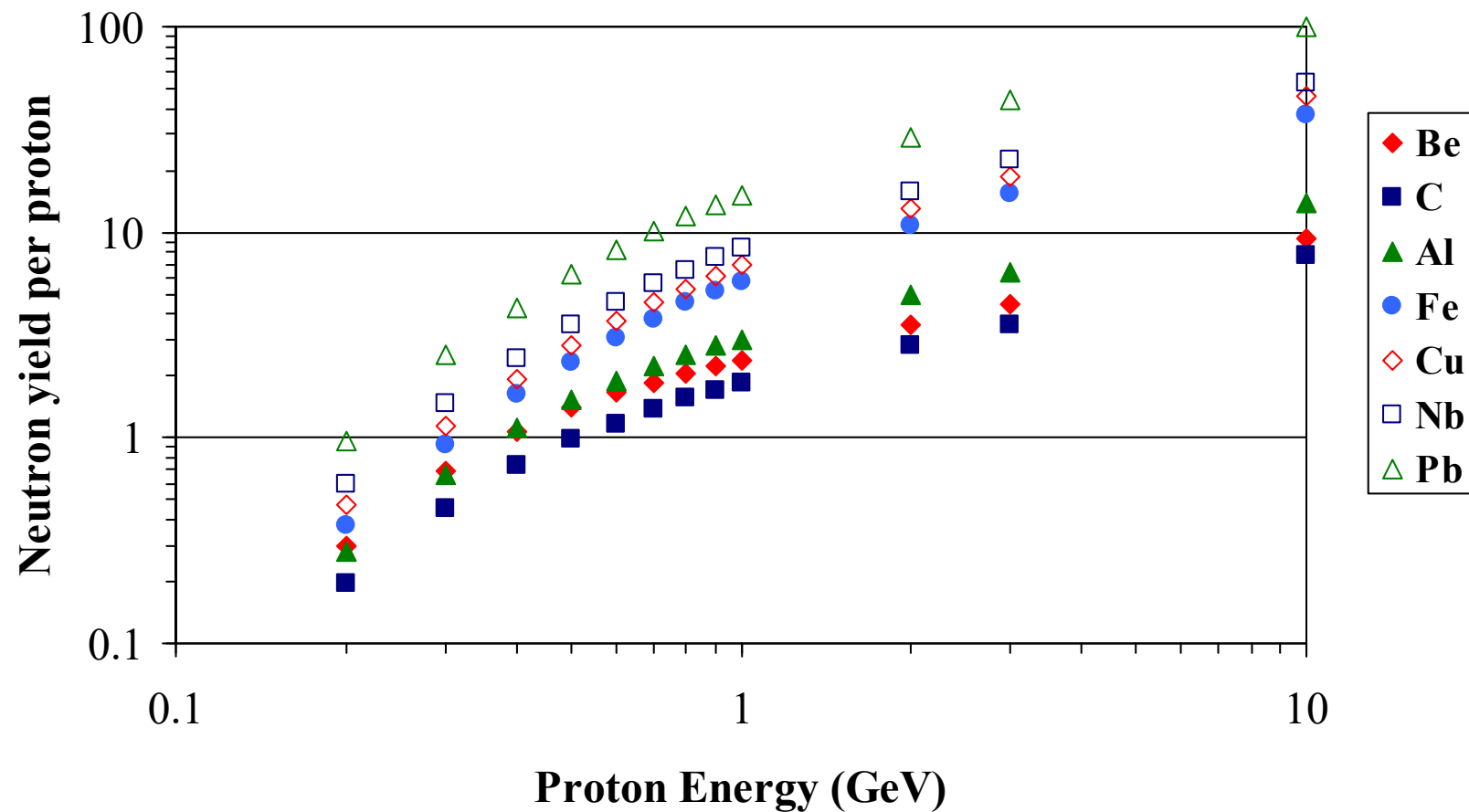
Dose attenuation length $\rho\lambda_h$ (concrete)



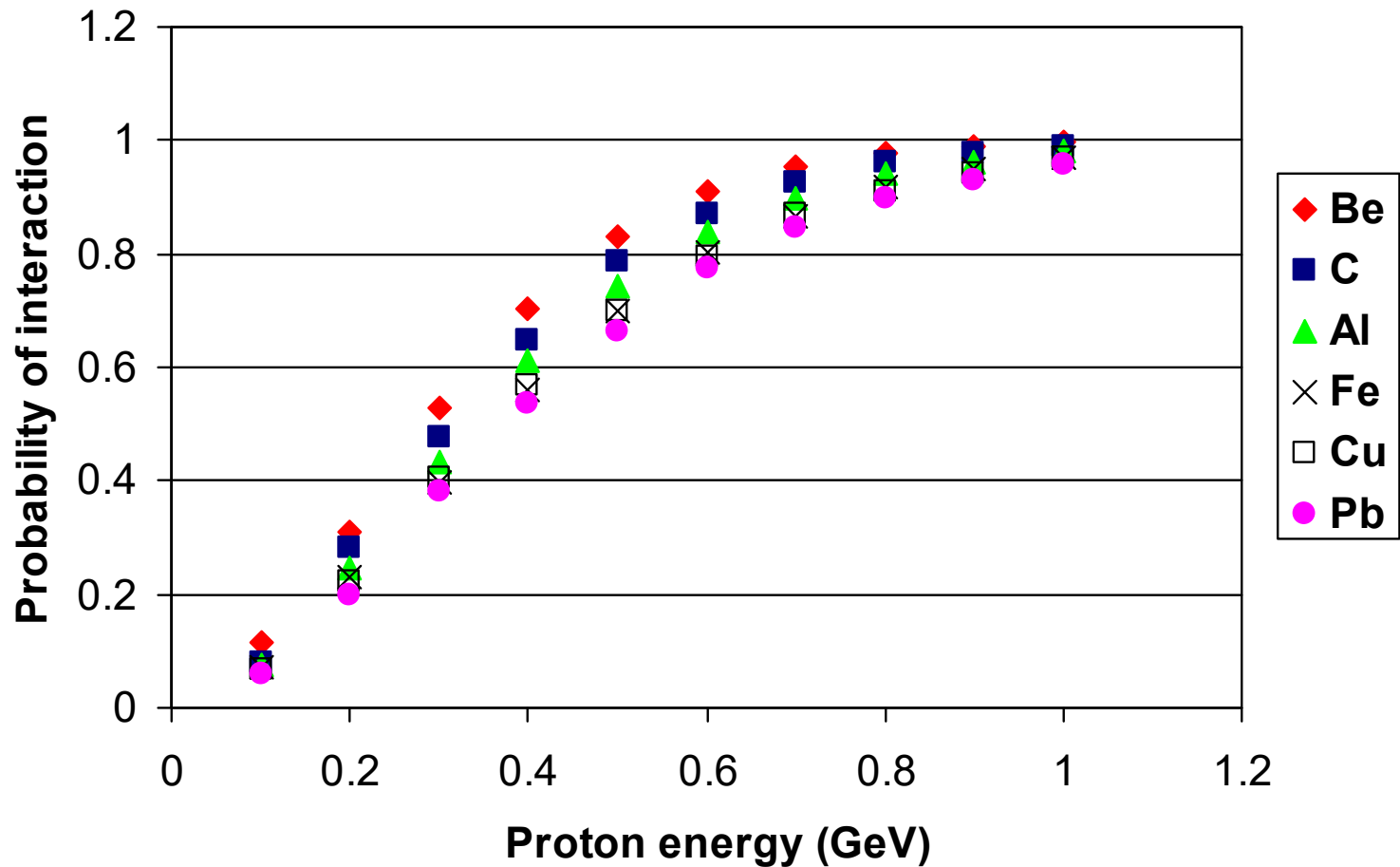
Neutron attenuation length, $\rho\lambda_n$ (concrete)



Thick target neutron yield per *incident* proton ($E_n > 100$ MeV) (FLUKA)

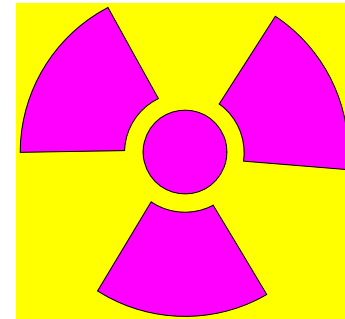
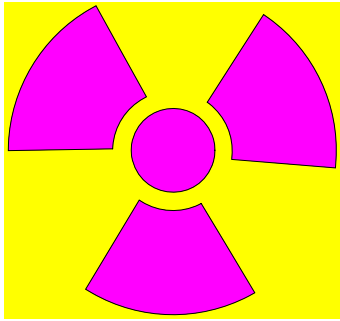


Nuclear interaction probability $f_n(E_p)$



At high energies *every* proton undergoes nuclear interaction if target thick enough

Radioactivity induced in targets and structures



Induced total radioactivity production in perspective

Accelerator

Rule of thumb:

$$A_{\text{sat}} \sim 6 \text{ TBq/kW}$$

0.1 – 1.0 MW



10^3 - 10^4 TBq

Fission reactor

Rule of thumb:

$$A_{\text{sat}} \sim 50 \text{ TBq/kW}$$

2000 MW




10^8 TBq

Residual fields of components (targets)

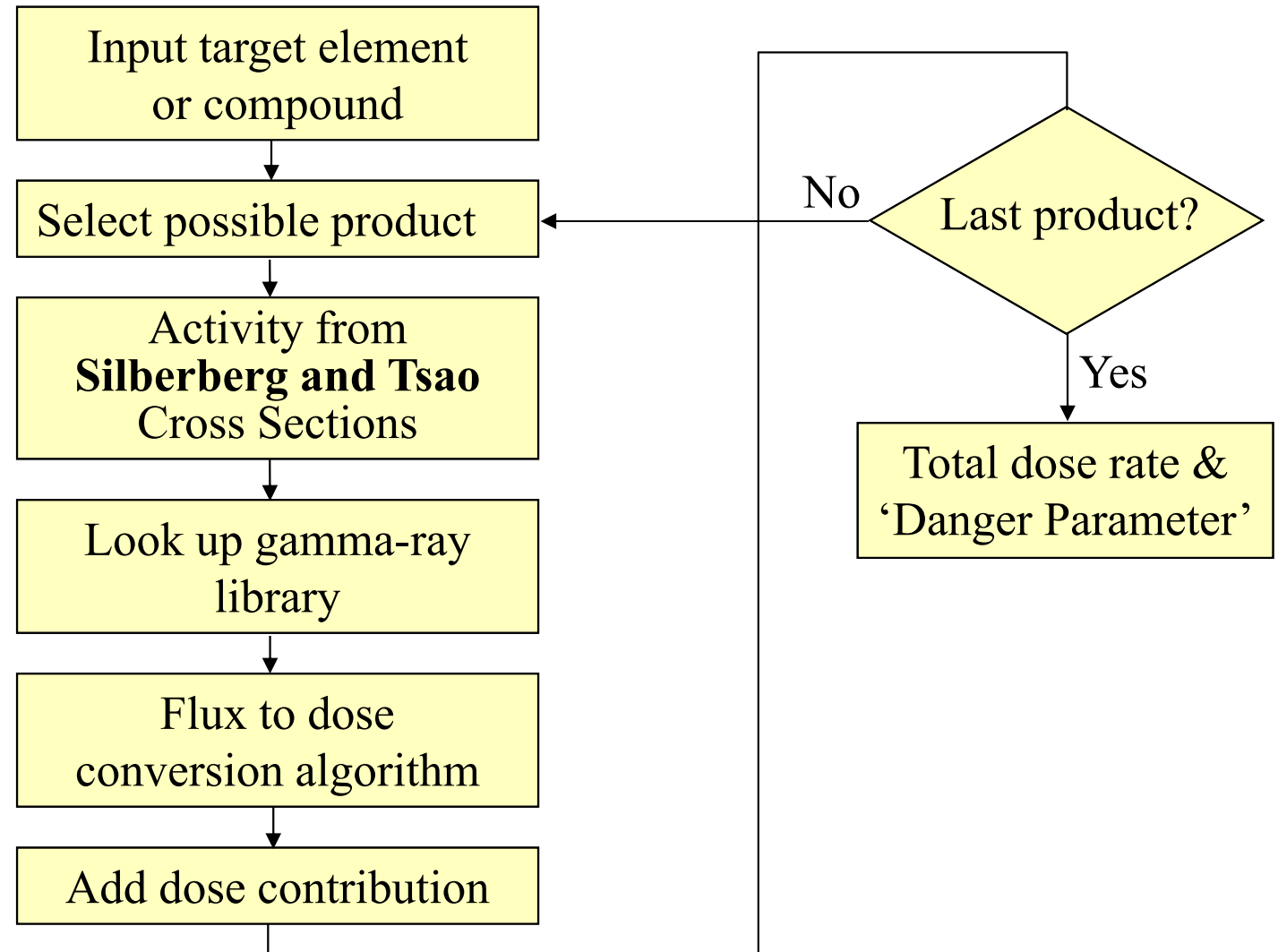
Total radioactivity produced in thin targets of medium A per unit proton beam current I_p (μA):

$$\begin{aligned} A_S &\approx 1.5 \times 10^9 I_p \text{ Bq per g cm}^{-2} \\ &\approx 3 \times 10^{-4} I_p \text{ Sv h}^{-1} @ 1\text{m per g cm}^{-2} \\ &= 3 \times 10^{-2} I_p \text{ Sv h}^{-1} @ 1\text{m per 100 g cm}^{-2} \end{aligned}$$

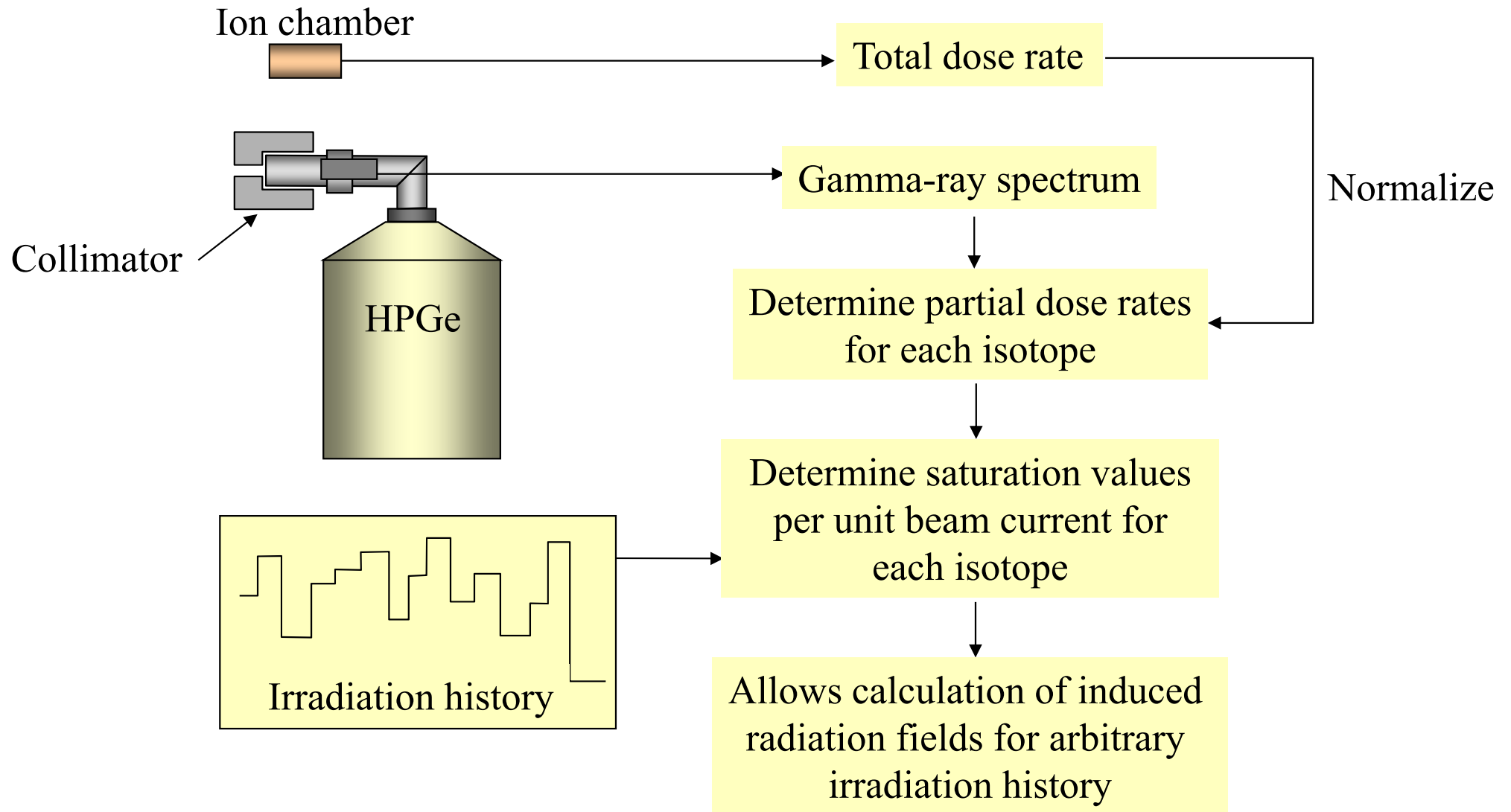
For $I_p \gtrsim 1\text{-}10 \mu\text{A}$  Remote handling

Determining induced radiation fields (I)

Method due to
Barbier, using
semi-empirical
cross sections



Determining induced radiation fields (II)



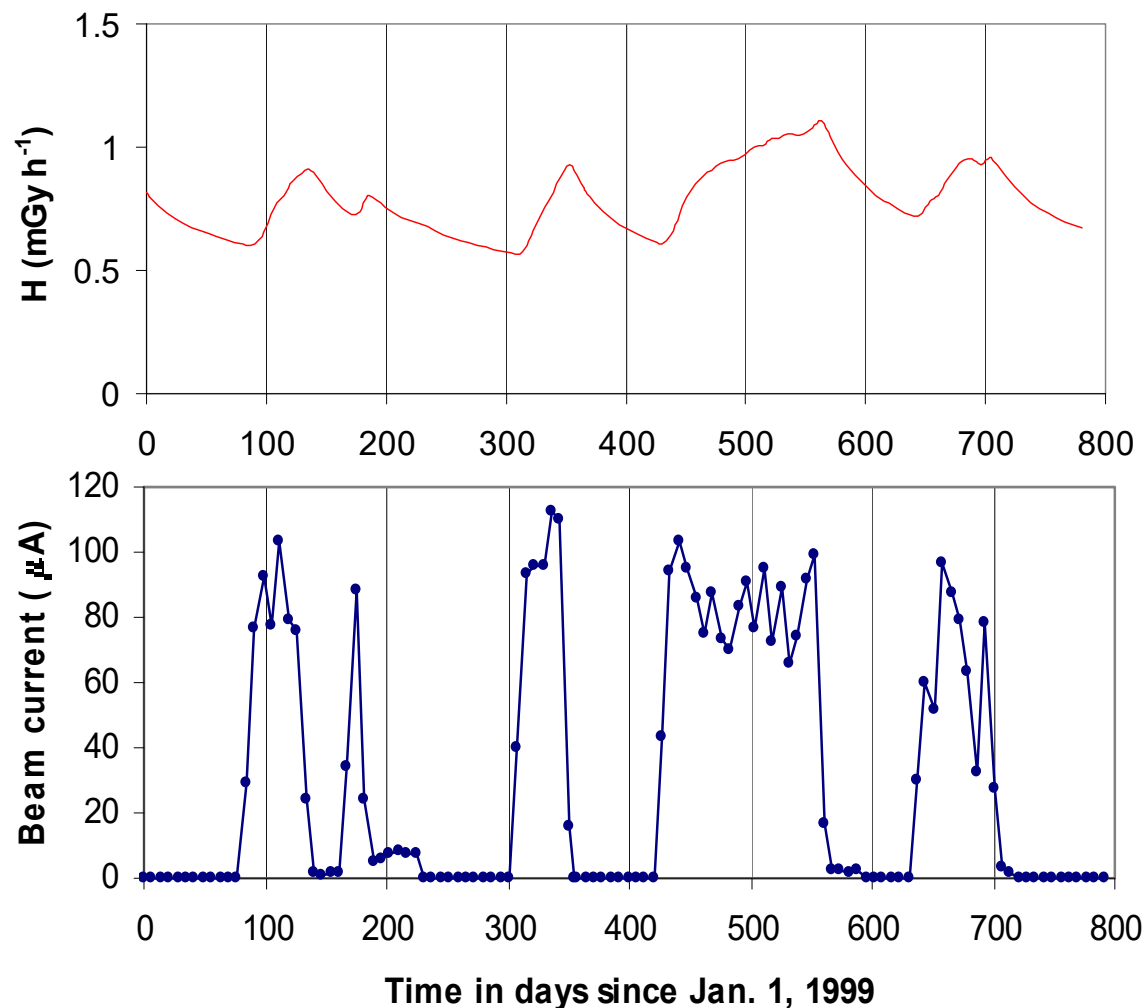
Determining induced radiation fields (II)

Useful for:

Shutdown and maintenance planning

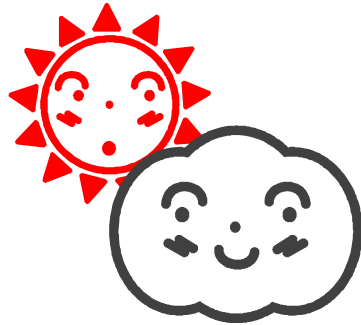
Decommissioning planning

Example: build-up and decay of induced radiation field in a 500 MeV cyclotron



Environmental Impact

Skyshine



Release of effluents

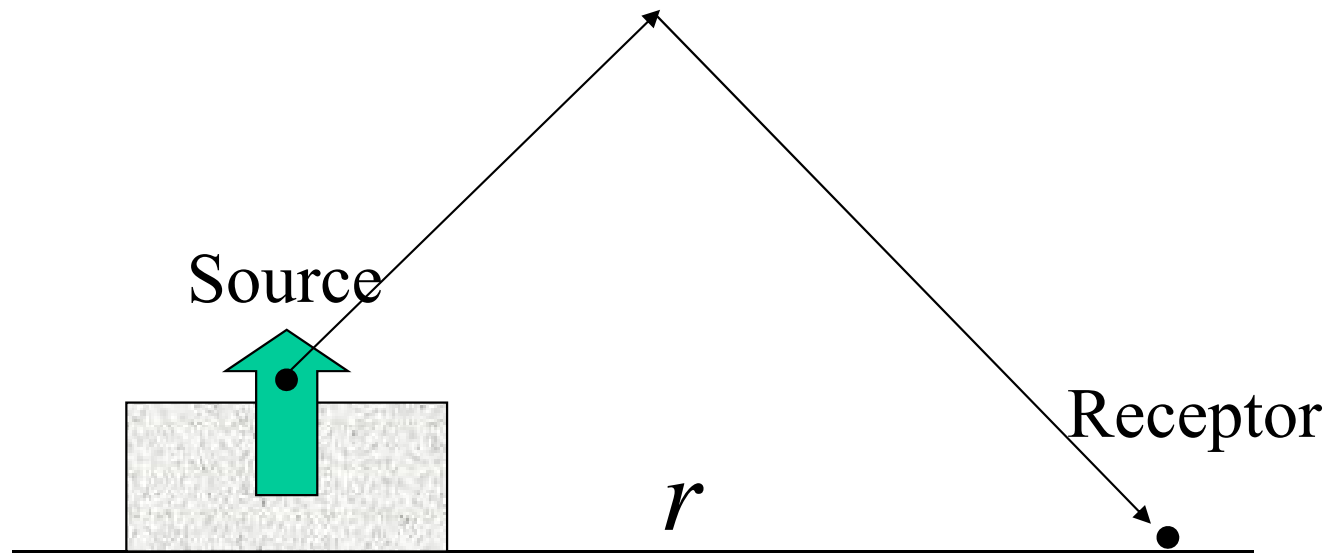


Air

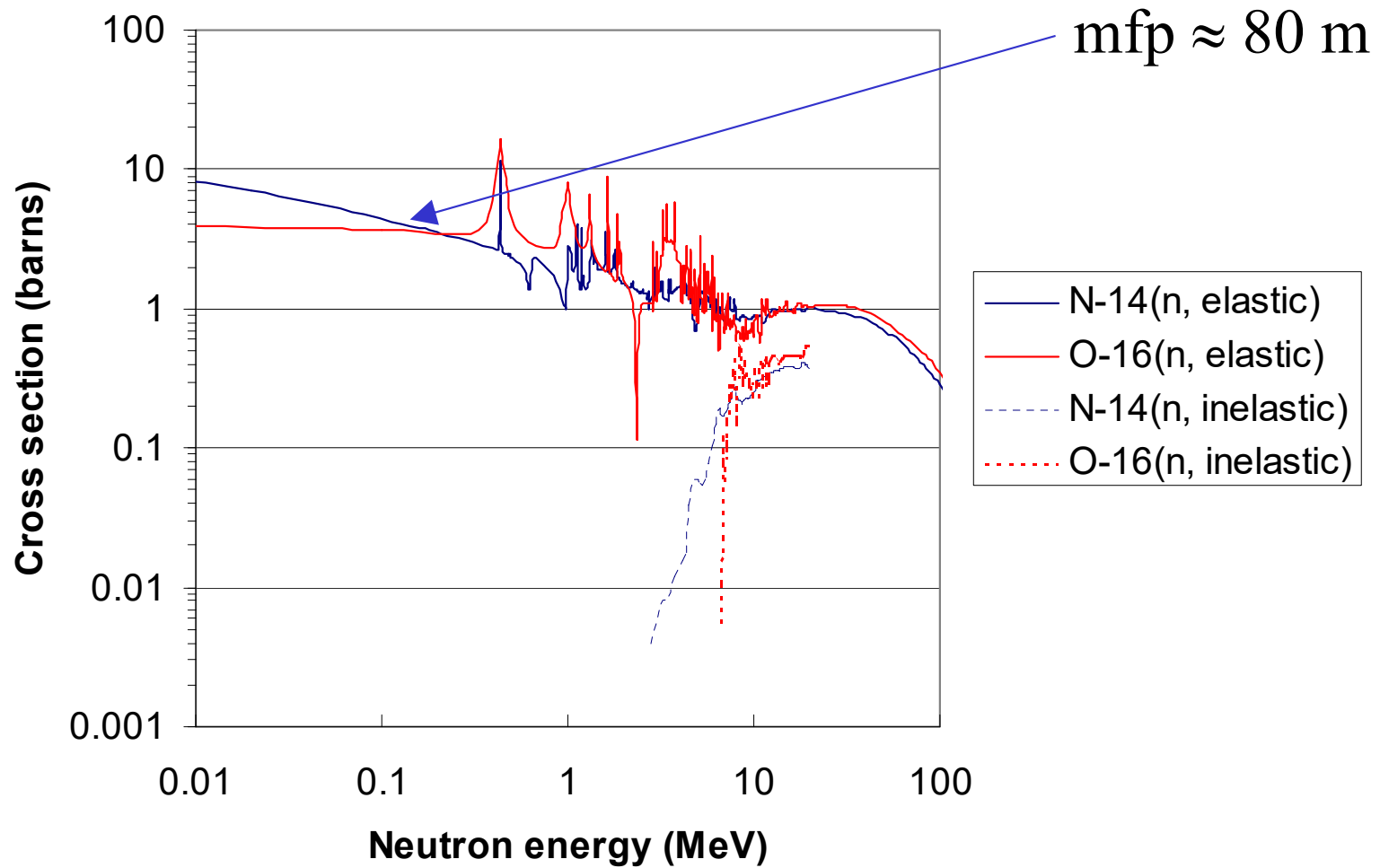


Water

Skyshine



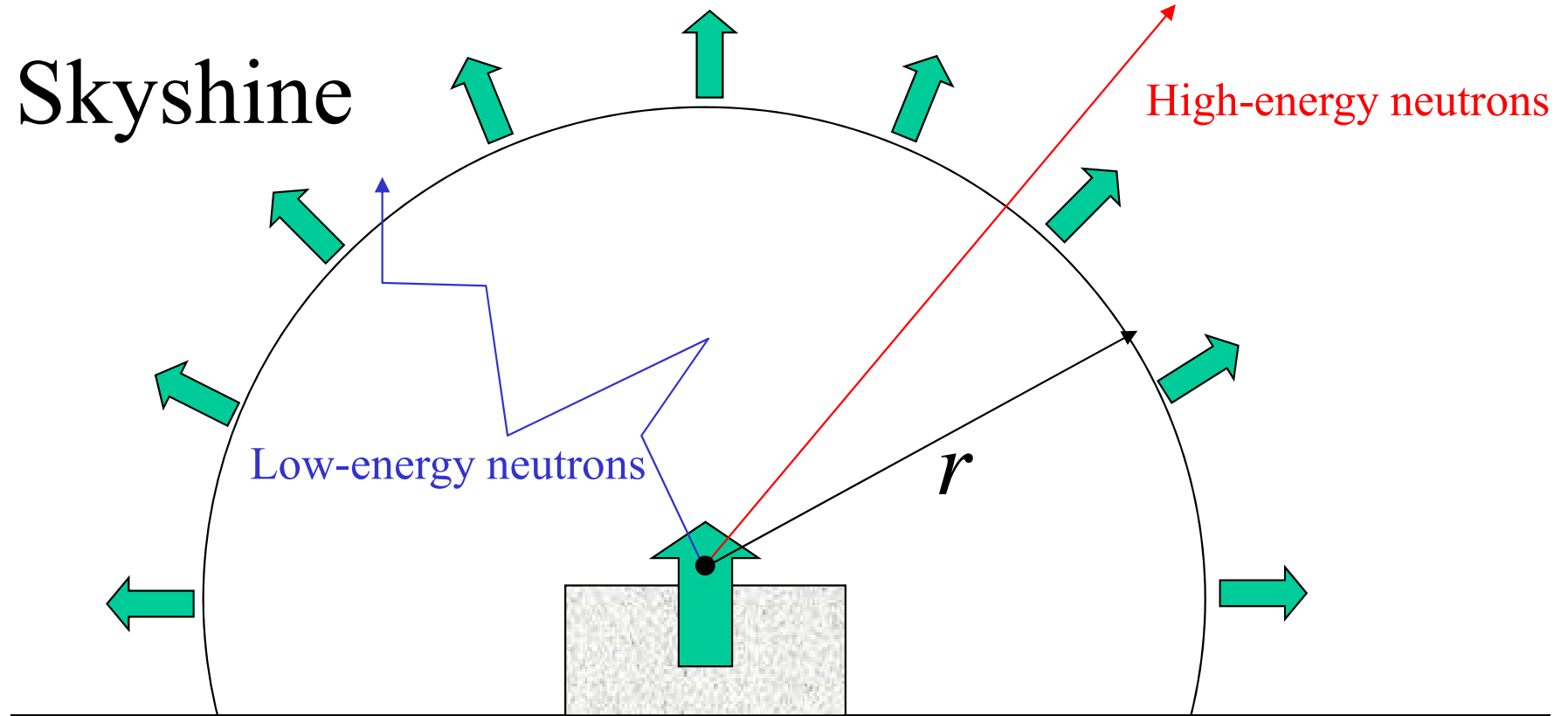
Neutron interactions with air



Maximum energy loss of neutron by elastic scattering

$$\frac{\Delta E_n}{E_n} = \left[1 - \left(\frac{M - m}{M + m} \right)^2 \right]$$

$$\begin{array}{lcl} \text{Nitrogen:} & = \left[1 - \left(\frac{14 - 1}{14 + 1} \right)^2 \right] = 0.24 & \left. \vphantom{\begin{array}{l} \text{Nitrogen:} \\ \text{Oxygen:} \end{array}} \right\} \text{Many} \\ \text{Oxygen:} & = \left[1 - \left(\frac{16 - 1}{16 + 1} \right)^2 \right] = 0.22 & \text{collisions} \end{array}$$



First approximation
(geometric effect only):

$$H = \frac{Q}{4\pi r^2}$$

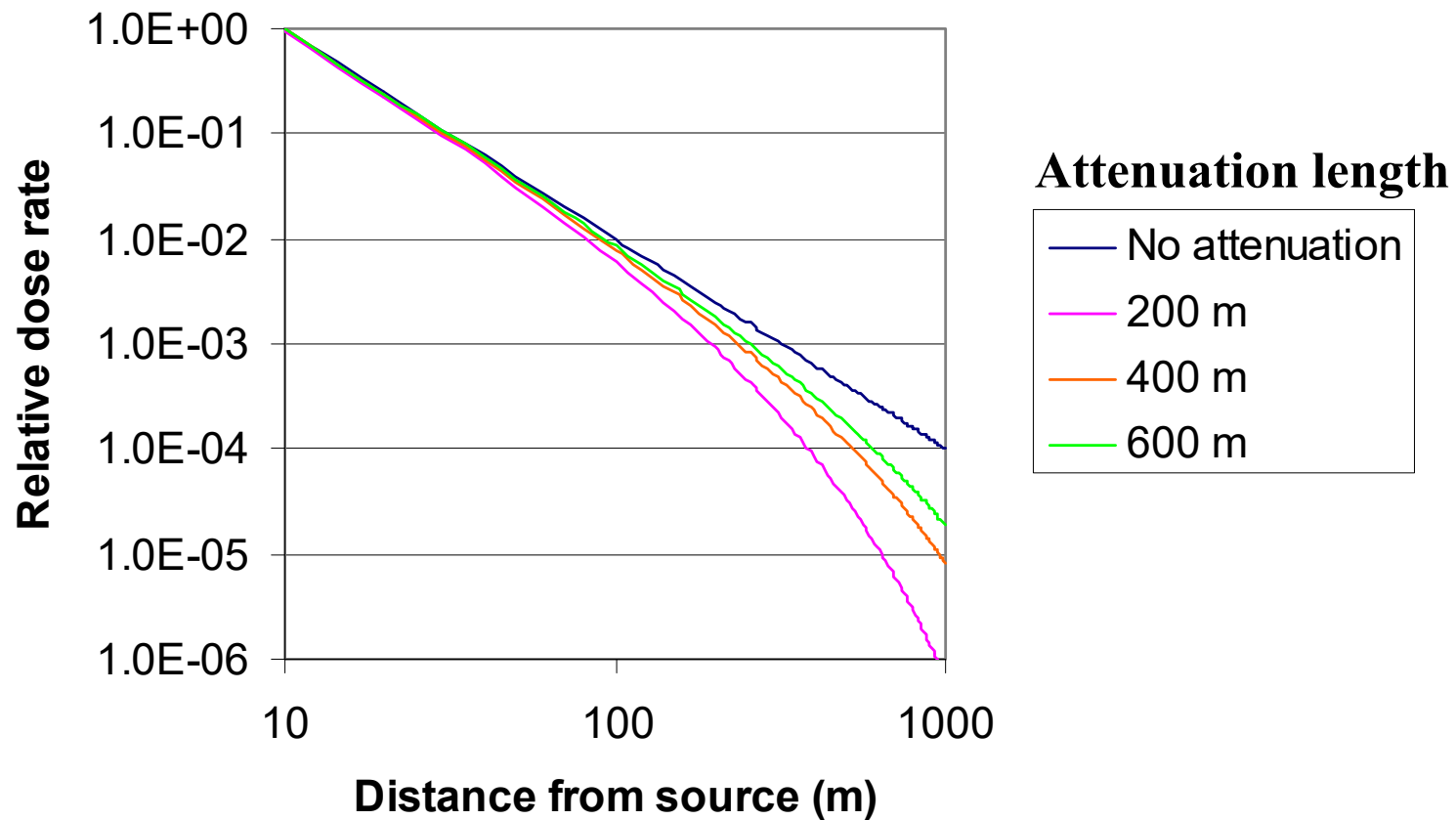
Some attenuation for large distances



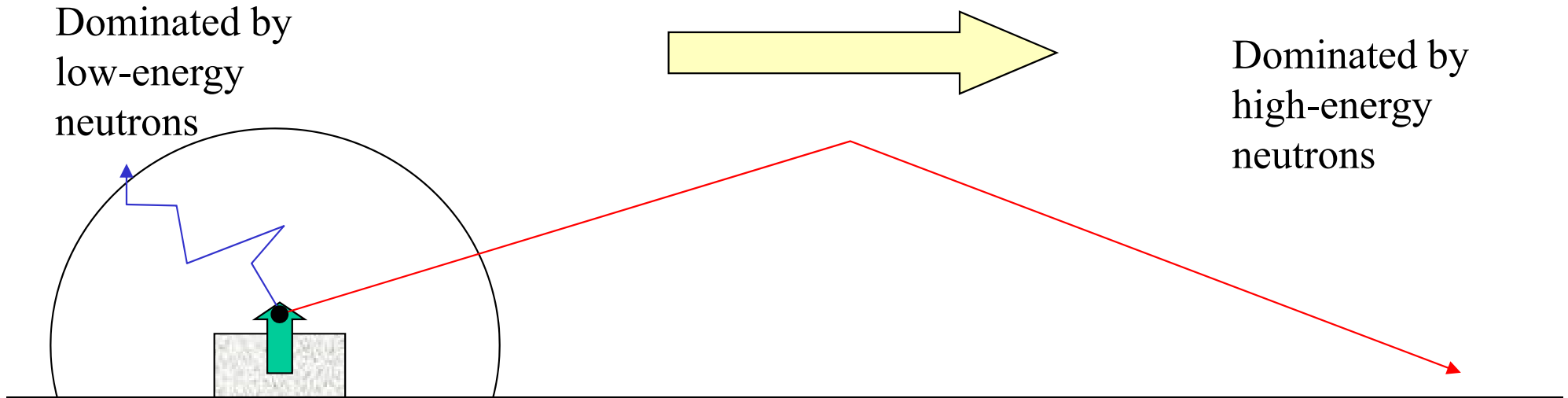
$$H(r) = \frac{Q}{4\pi r^2} \exp(-r / \lambda)$$

With λ of order a few hundred m

Effect of attenuation in air



Spectrum hardens with distance



Emission of radioactive effluents

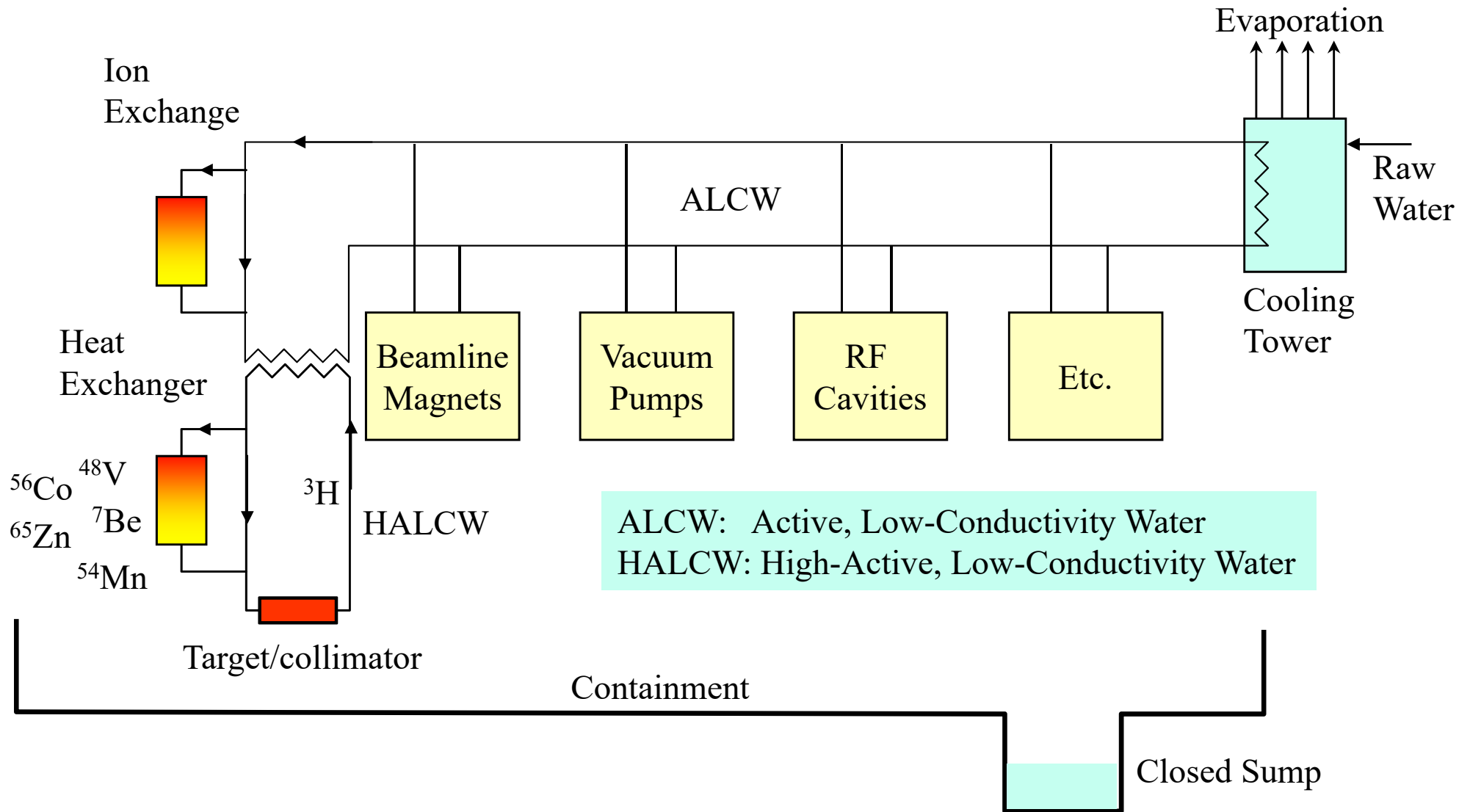


Air: difficult to hold up except
for vacuum system exhaust,
but higher release limits

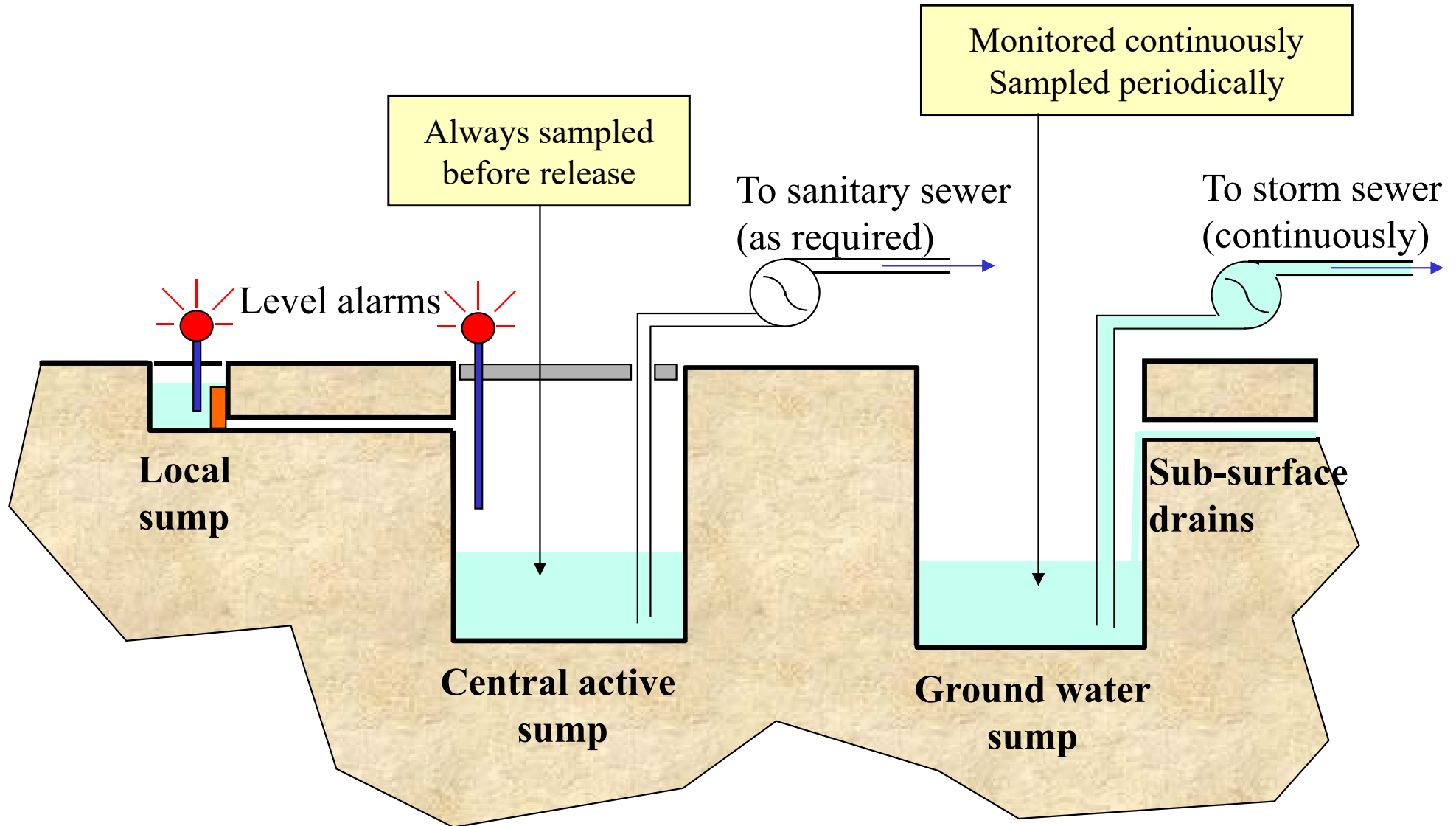


Water: easier to control
(re-circulation, hold-up)

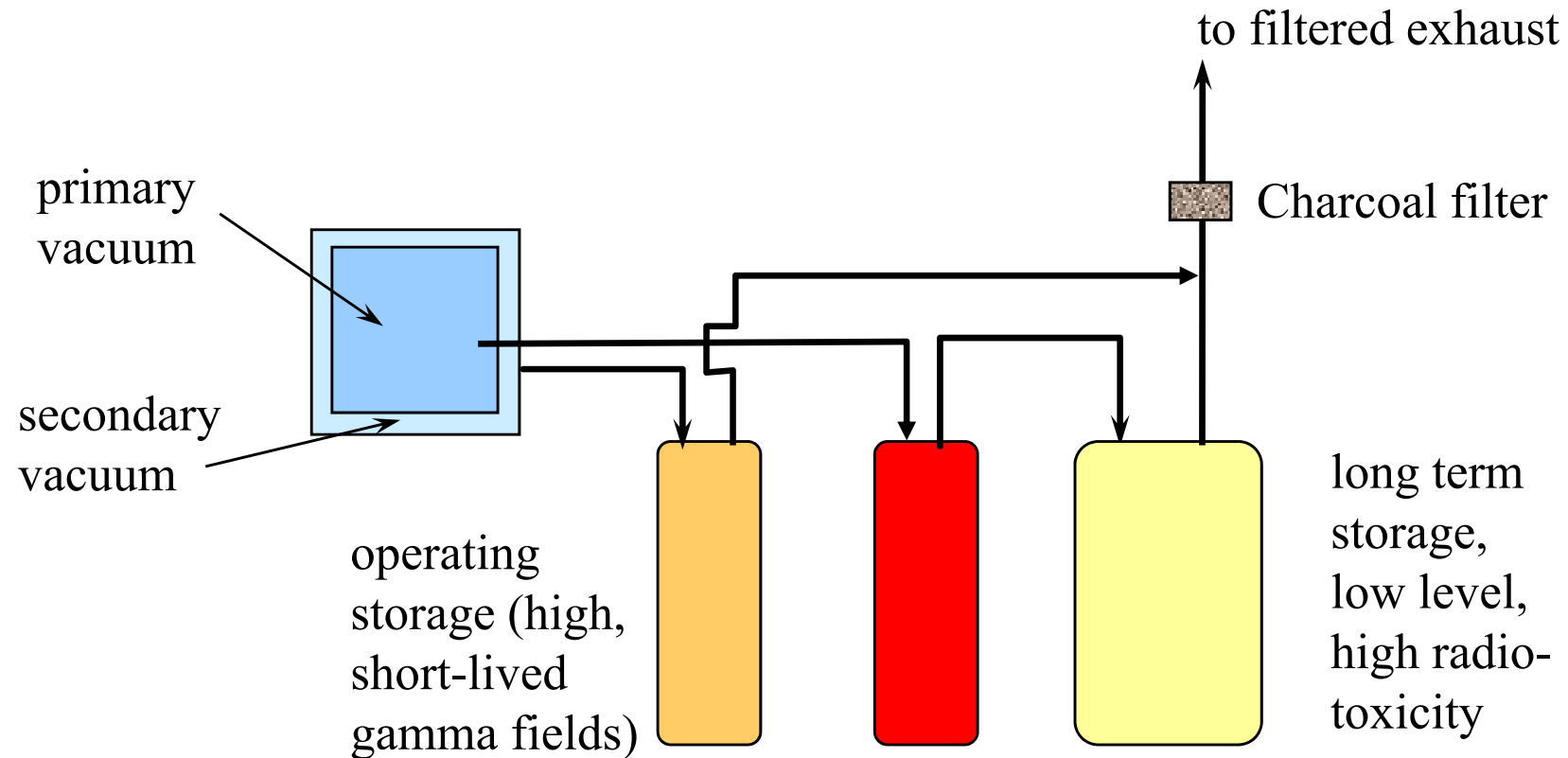
Typical active cooling water systems



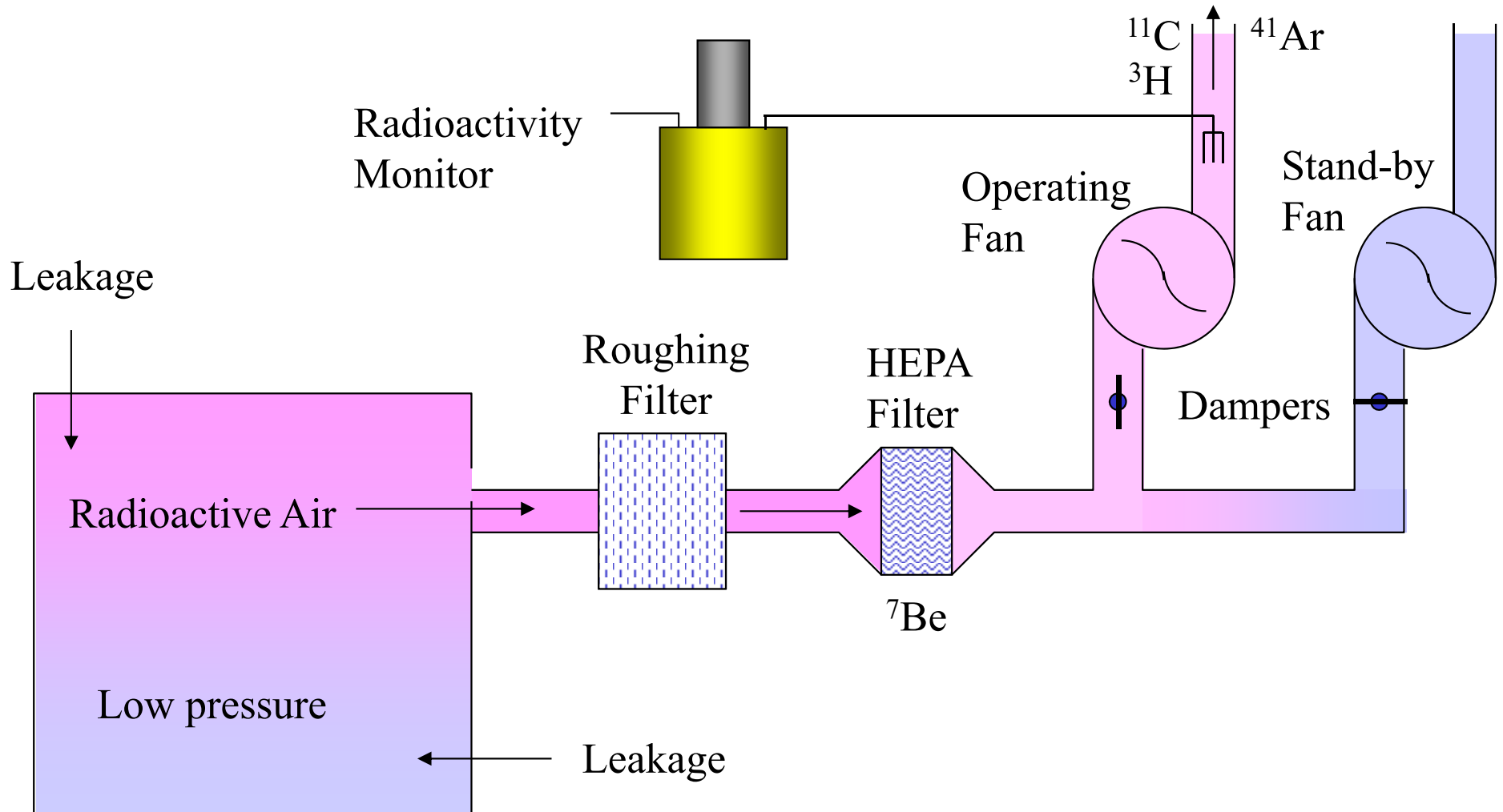
Design of typical drainage system



Hold-up of vacuum exhaust (RIB facilities, e.g. ISOLDE, ISAC)

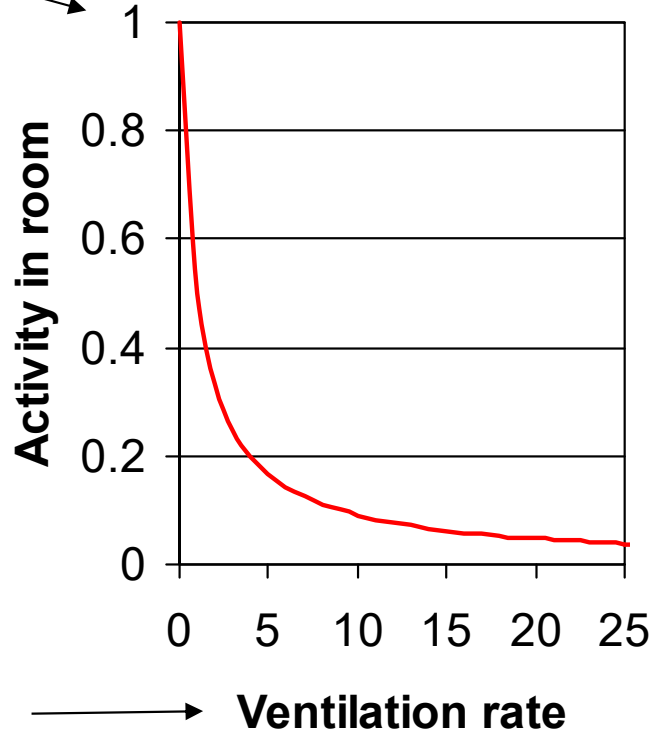
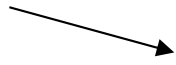


Design of typical ventilation system

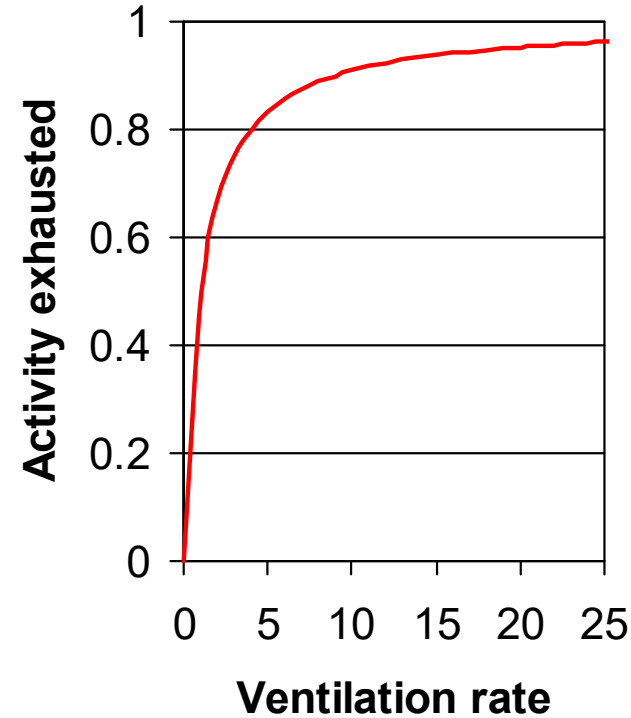
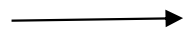


Effect of ventilation rate

Saturation Activity

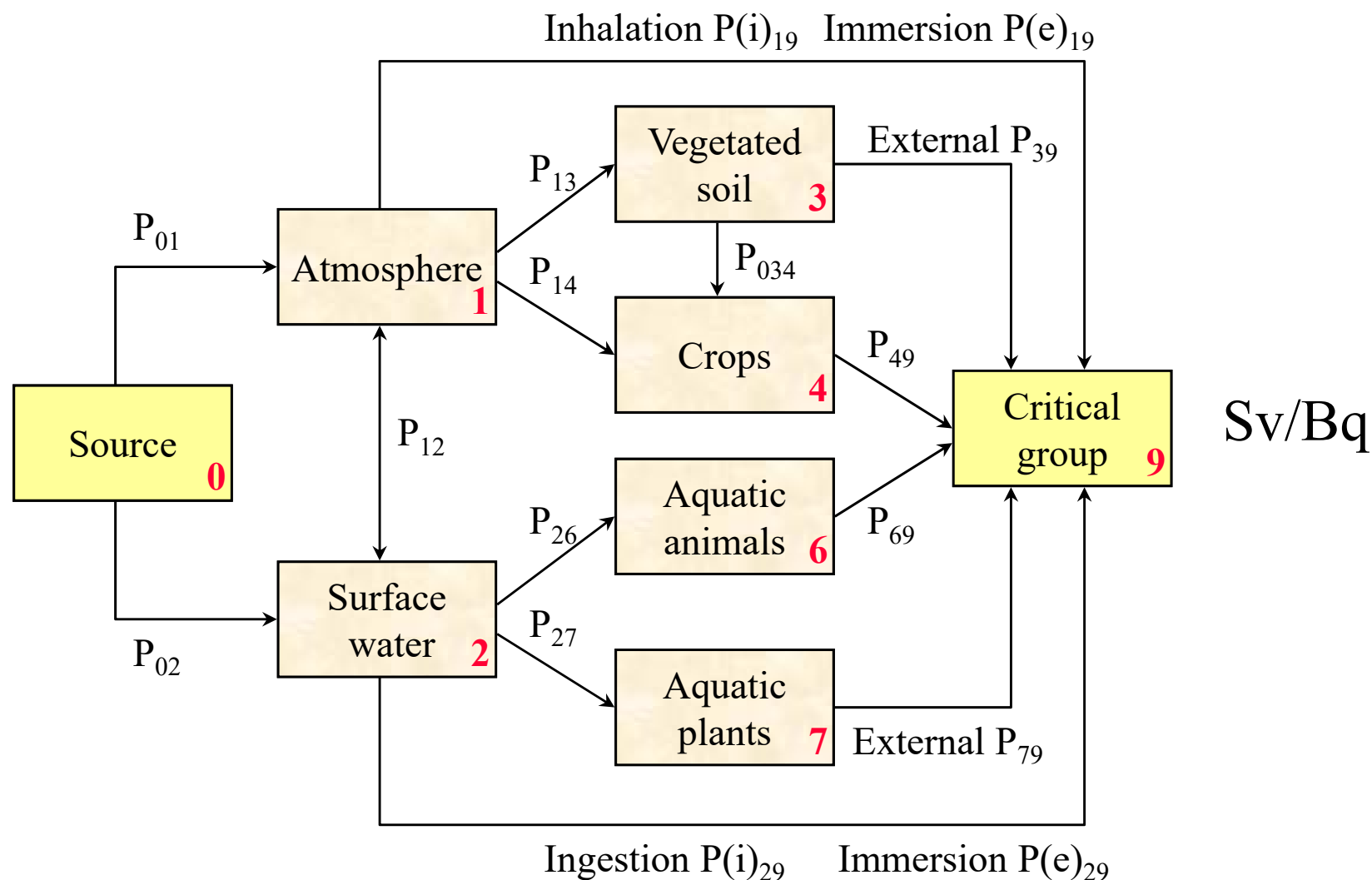


Number of air
changes per
half-life



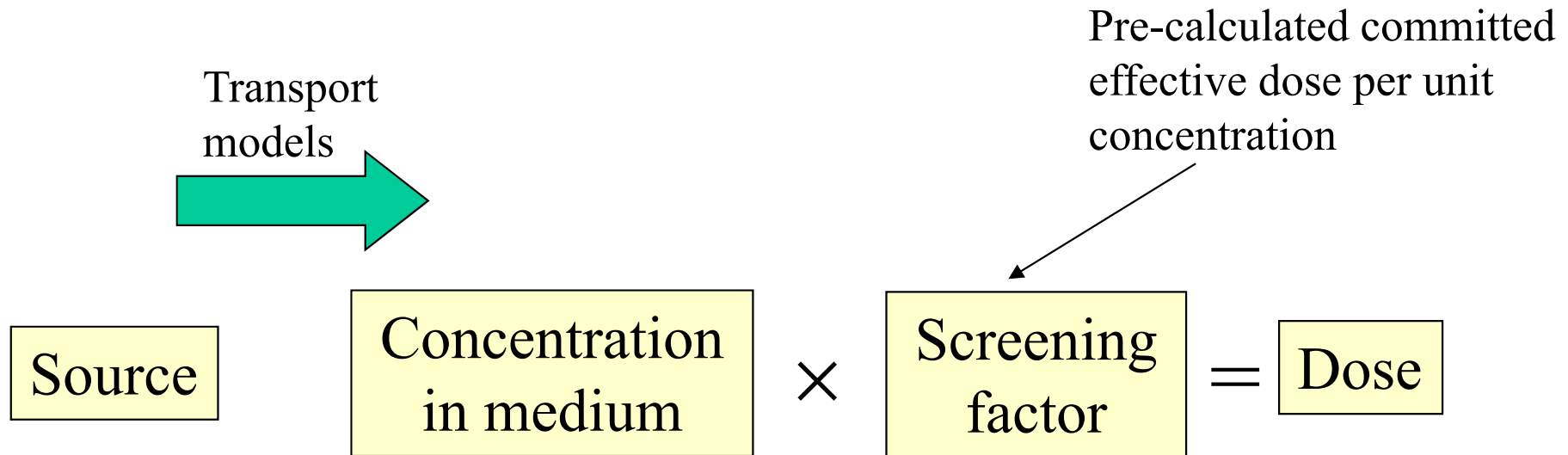
Higher ventilation rates reduce the radioactivity level in the irradiation room but increase the amount of radioactivity exhausted

Dose From Effluents Released



Screening Models

(NCRP Report No. 123)



Three levels of screening:

Level I: assume radionuclide concentration
at point of emission

if $\text{Dose} < \text{Dose Limit}$ then no further calculation

Level II: dispersion in atmosphere or
surface water

if $\text{Dose} < \text{Dose Limit}$ then no further calculation

Level III: more definitive pathway analysis
(air only)

Increasing
sophistication



Summary

Have described:

- Some specific application:
 - proton therapy
- Generation of prompt radiation
 - direct interactions, evaporation
- Need for point-source model
 - shielding at intermediate energies
- Generation of induced radioactivity
 - semi-empirical recipes, measurements
- Environmental impact
 - skyshine, emission of radioactive effluents

THANK YOU

For Your Attention!