# RADON

discovered in 1900
by F. Dorn

**Inert,
colourless,
odourless,
radioactive
rare gas.**

**30 different isotopes, only two reaching non negligible concentrations in the atmosphere:**

$$^{238}_{92}U \rightarrow ^{234}_{90}Th \rightarrow ^{234}_{91}Pa \rightarrow ^{234}_{92}U \rightarrow ^{230}_{90}Th \rightarrow ^{226}_{88}Ra \rightarrow ^{222}_{86}Rn$$

$$^{232}_{90}Th \rightarrow ^{228}_{88}Ra \rightarrow ^{228}_{89}Ac \rightarrow ^{228}_{90}Th \rightarrow ^{224}_{88}Ra \rightarrow ^{220}_{86}Rn$$

**no chemical bond**

**no surface attachment (adsorption, except char coal)**

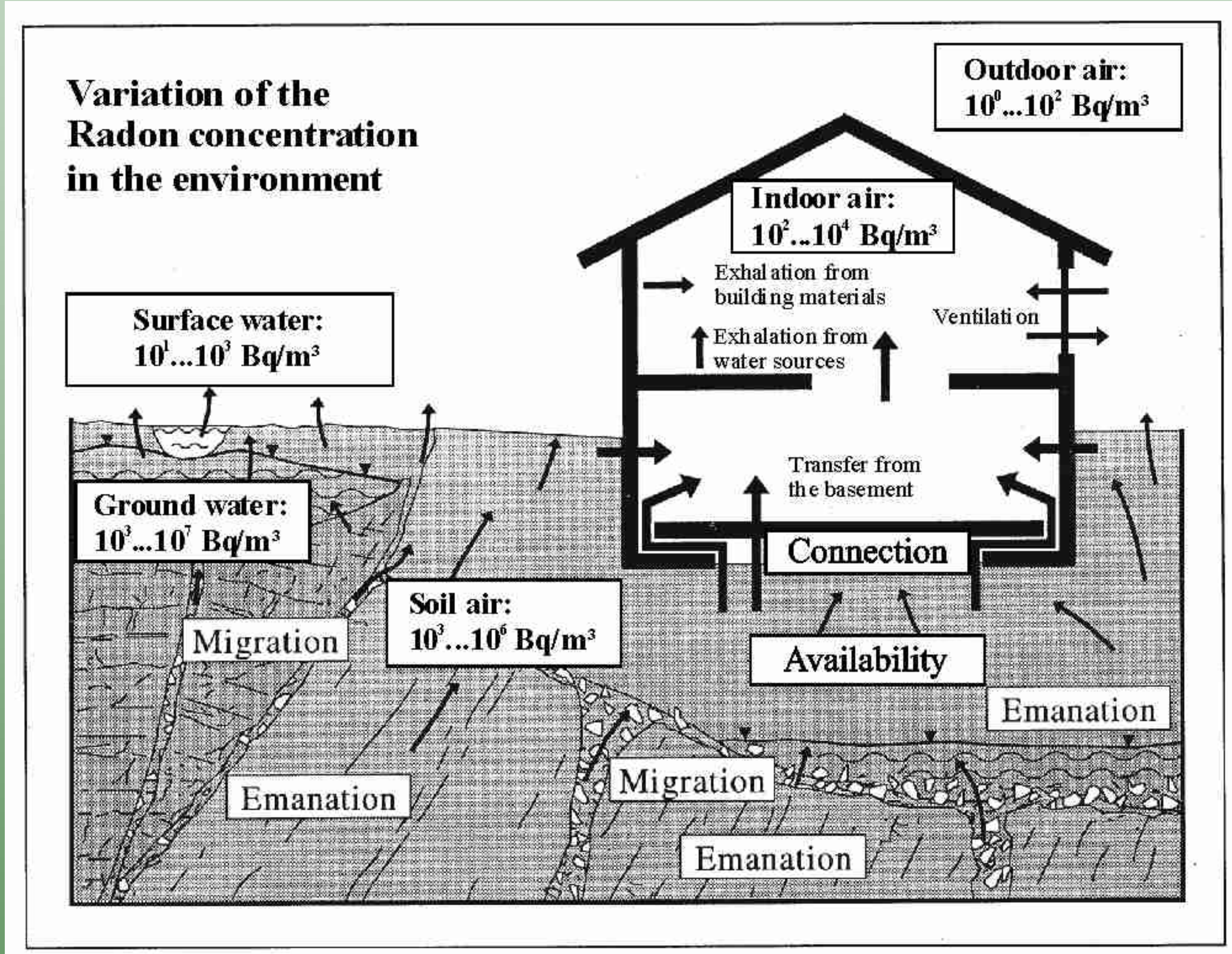
**can emanate from solids**

**will diffuse easily through the most materials**

**will fast disperse in air**

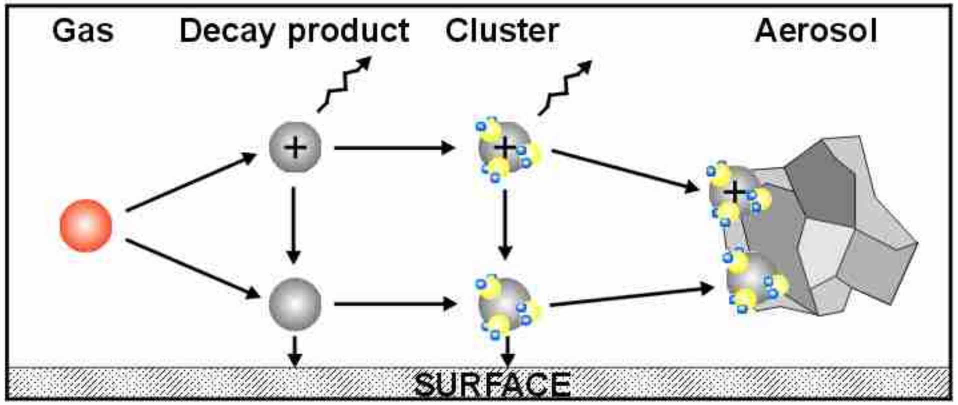
**generates a chain of radioactive decay products, all of them are heavy metals**

# Radon Origin and Distribution



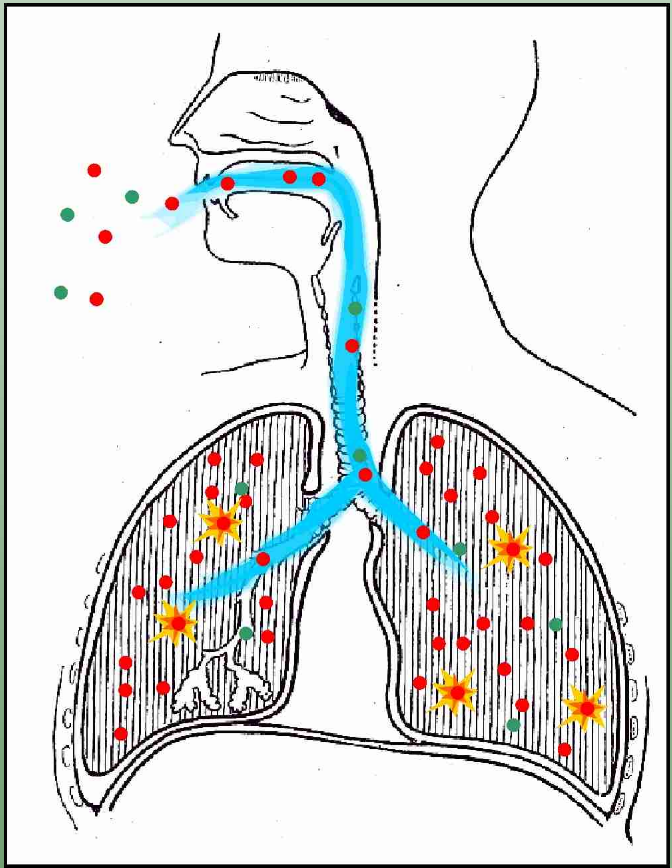
# Airborne Radon Decay Products

Rn-222 → Po-218 → Pb-214 → Bi-214 → Po-214 → Pb-210 → Bi-210 → Po-210 → Pb-206




**Radon generates aerosols carrying radioactive decay products within in the air**

# Dangerous Impact of Radon Daughters



**No impact by Radon gas**

**Deposition of daughter products within the lung**

**Decay directly at the surface of the epithelium**

**Emitted <u>Alpha</u> radiation damages cell nucleus and cause genetic defects**

## Goal:

**Assessment of the injurious impact of inhaled <u>Radon daughter products</u>!**

**<u>Radon is risk factor No. 2 for lung cancer - after smoking!</u>**

# Terms and Definitions

**We know:** some of the Radon daughters emitting dangerous Alpha radiation

↓

**Radon decay chain**

↓

**PAE (Potential Alpha Energy)**

↓

**PAEC (Potential Alpha Energy Concentration)**

↓

**PAEE (Potential Alpha Energy Exposure)**

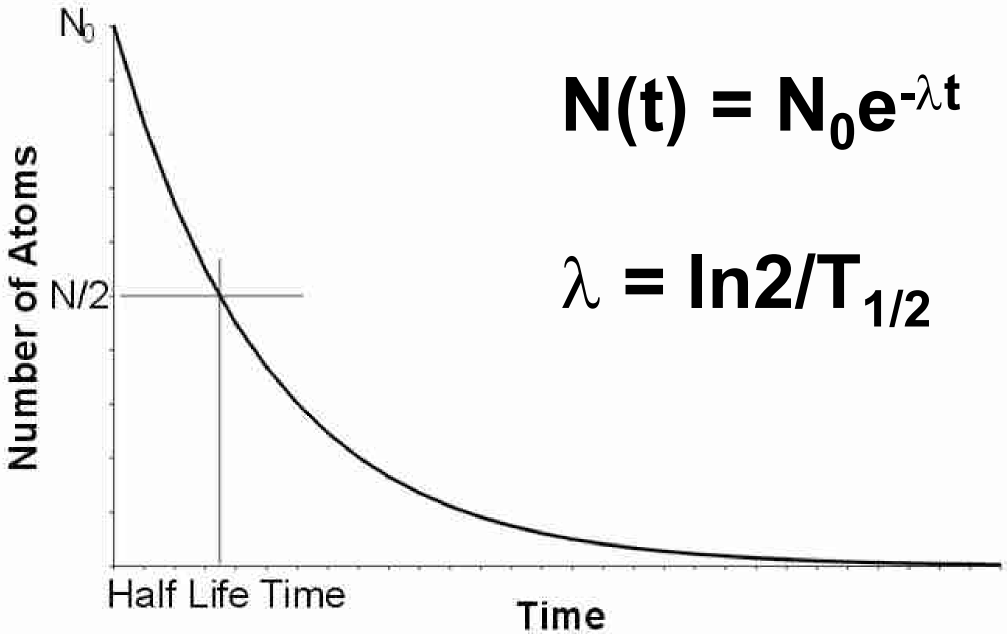
↓

**Equivalent Dose**

**=**

**We want:** a measure for the injurious impact to the human body

# Radioactive Decay and Activity




$$N(t) = N_0 e^{-\lambda t}$$

$$\lambda = \ln 2 / T_{1/2}$$

$$A = dN/dt = \lambda N = N^* \ln 2 / T_{1/2}$$

$$N = A^* T_{1/2} / \ln 2$$

# The radioactive Alpha Decay

**CARACTERISTICS**

Atoms with high mass number

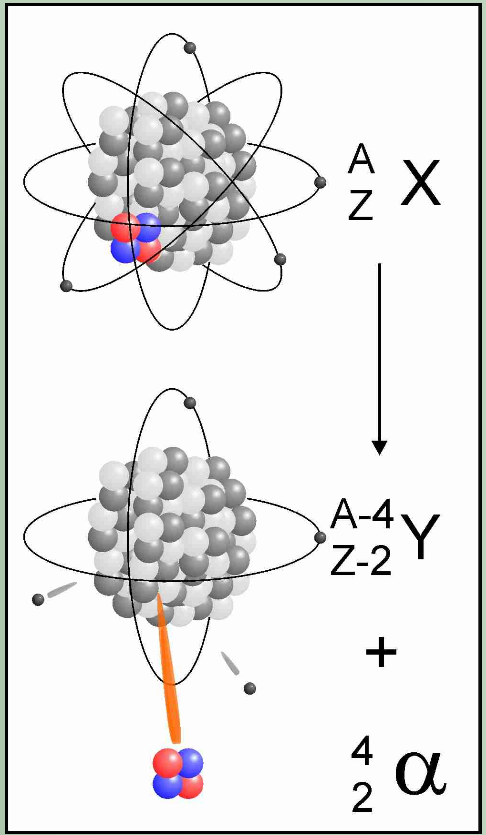
Electrostatic forces > nuclide gravitation

Emitting a He kernel (2 protons, 2 neutrons)

Nuclide specific monoenergetic emission

Alpha energy range from 4 to 9 MeV

Ionisation of remaining atom



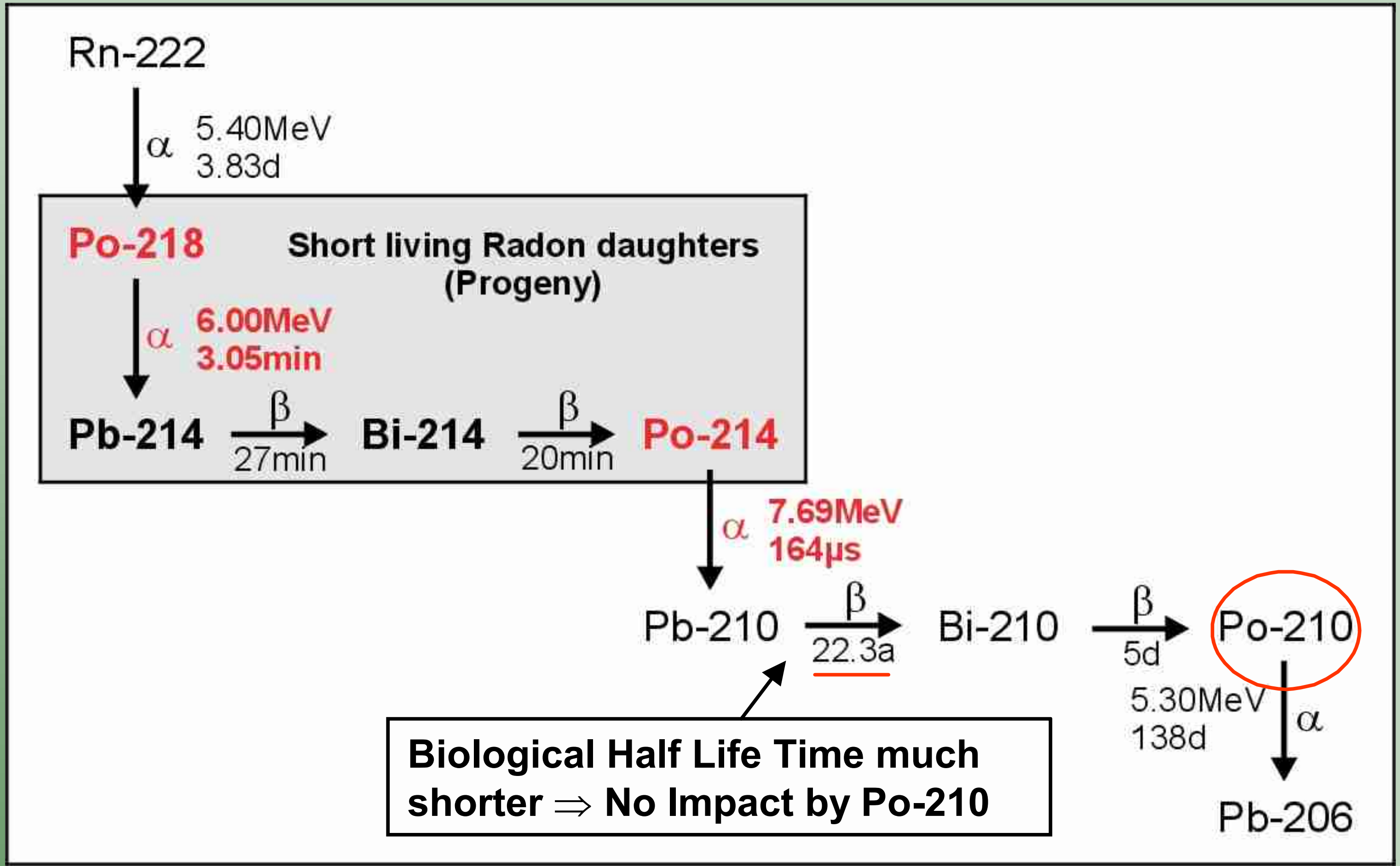

**EXAMPLES:**

Po-218 at 8.785 MeV

Am-241 at 5.485 MeV

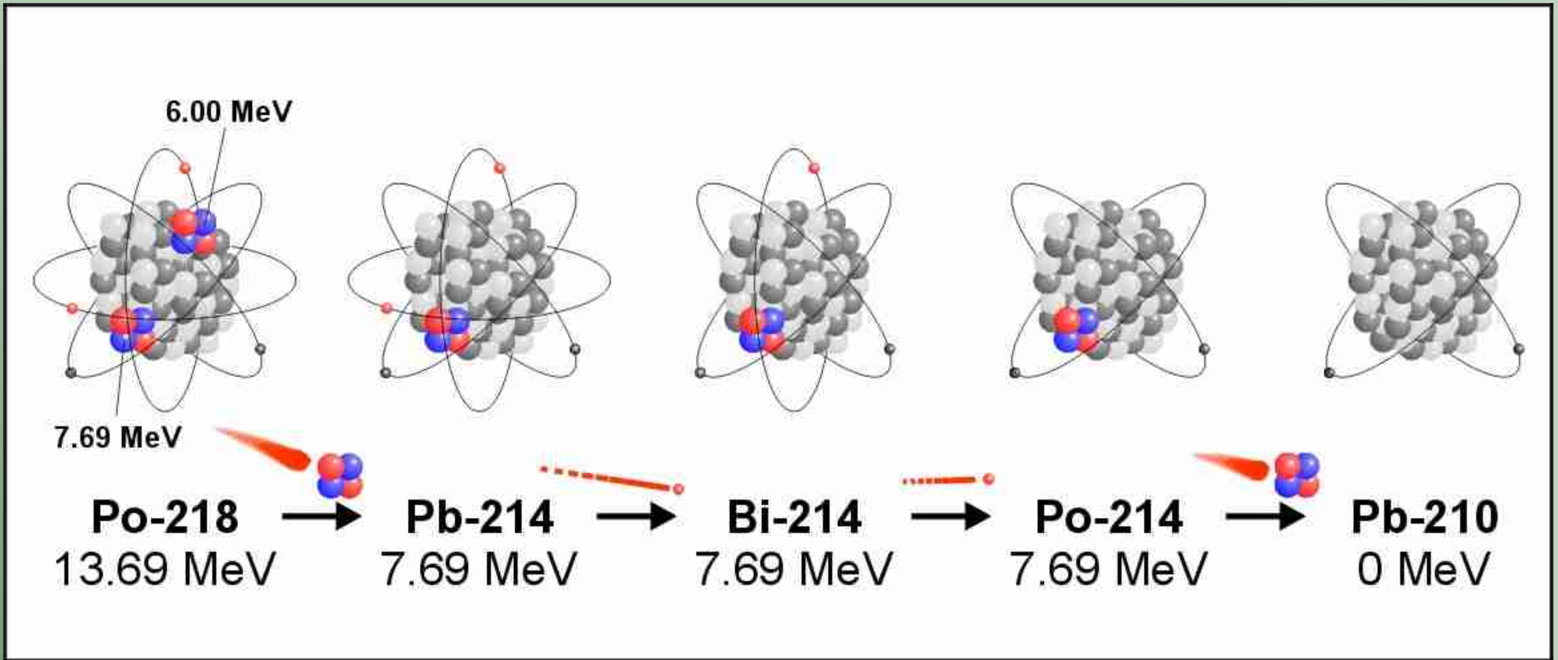
U-238 at 4.197 MeV (77%) and 4.147 MeV (23%)

# Radon (Rn-222) decay chain

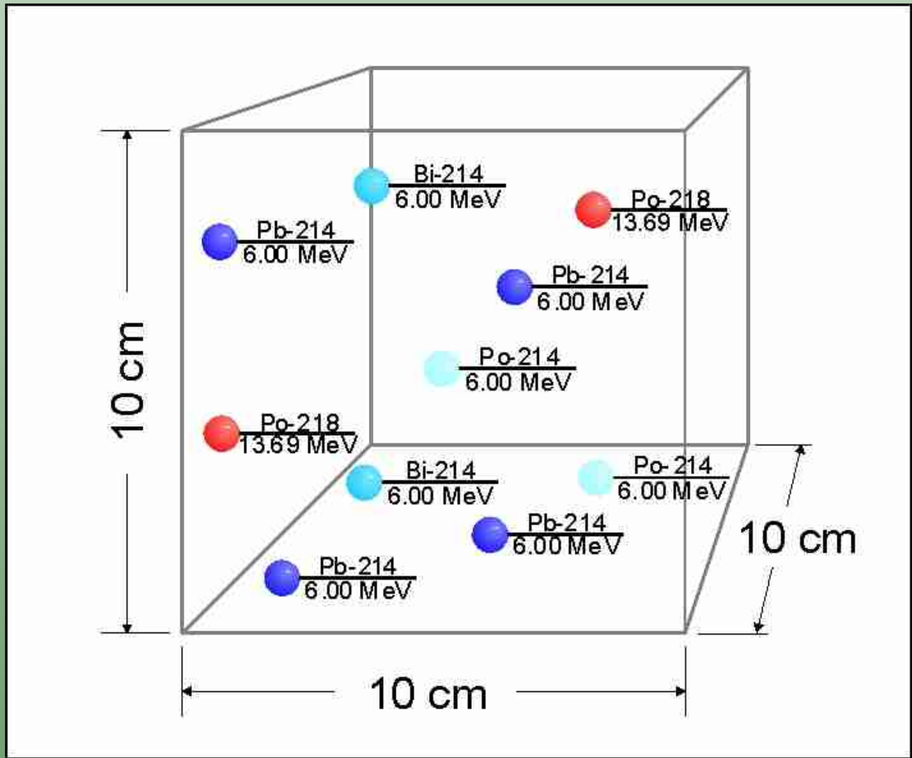


# Potential Alpha Energy - PAE

$$\sum E_{\alpha}(\text{any Radon daughter} \Rightarrow \text{Pb-210})$$



# Potential Alpha Energy Concentration of any Progeny mixture in the air - PAEC




$$\frac{\sum_{\text{Po-218, Pb-214}}^{\text{Bi-214, Po-214}} (\text{PAE})}{\text{AIR VOLUME}}$$

**PAEC = 75.38 MeV/Litre**

# Potential Alpha Energy Exposure - PAEE

**The amount of inhaled and deposited Radon progeny depends generally on:**

- **Potential Alpha Energy Concentration in the breathing air**
- **Time Interval during which a person is exposed to this PAEC**

**This connection is described by the term of PAEE :**

**PAEE = PAEC * TIME**

**PAEE takes not in account individual deposition process in the lung (breathing rates and particle size distribution) and also not the biological impact to the human body!**

# Dose Coefficient and Equivalent Dose

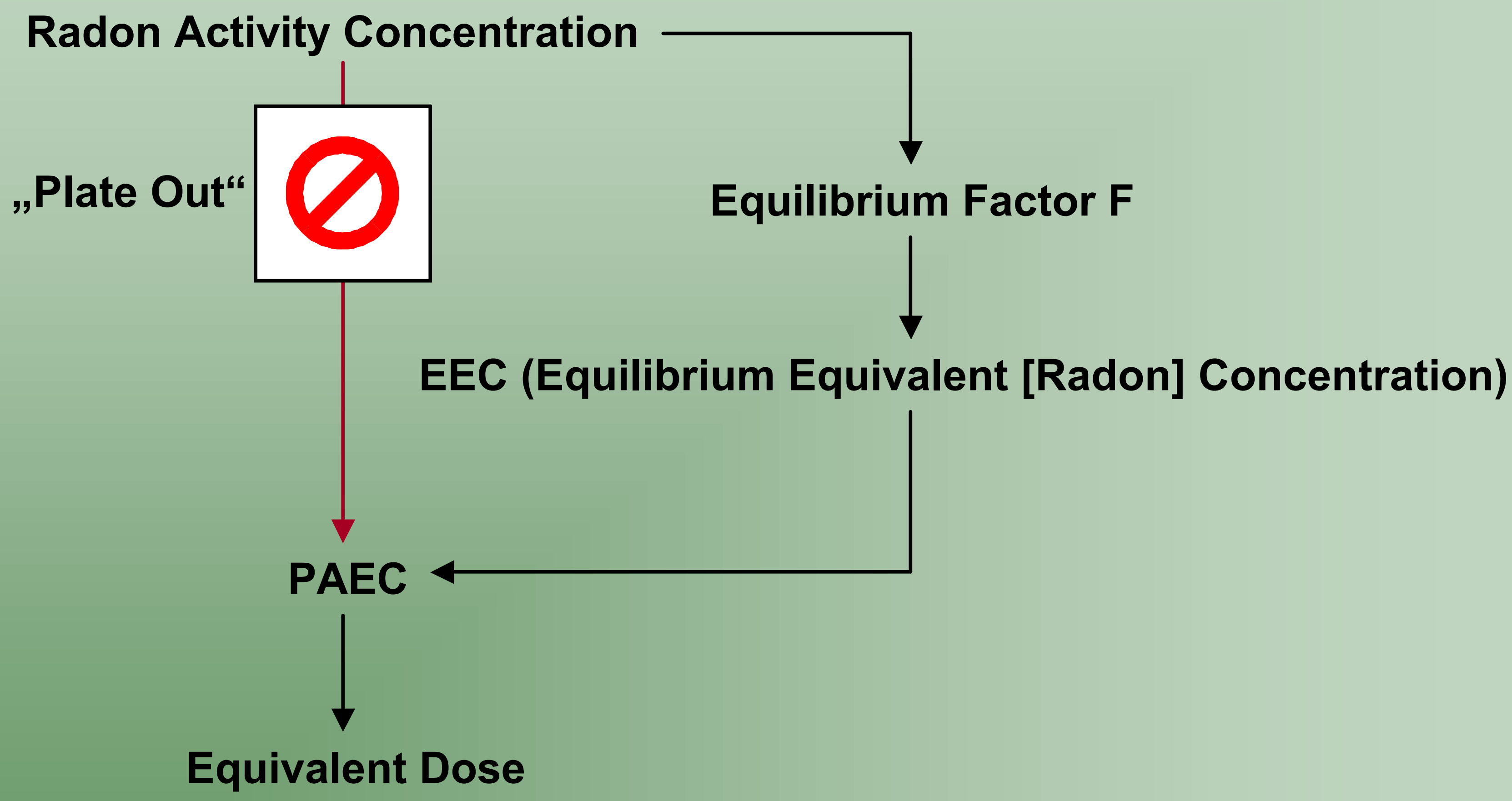
**To include the individual factors, the Dose Coefficient D was defined**

**D is the correlation factor between offered PAEE and biological impact specified by the Dose H**

$$H = PAEE * D$$

**Because of the individuality of Dose Coefficient the most limits are stated as Exposures and not as Dose**

# Radon Gas and Progeny



# Radioactive Equilibrium

Assumption: No „Plate Out" ⇒ Radioactive Equilibrium of Radon and Progeny

is given:

if the generated number is equal to the decayed number of atoms of any nuclide within the decay chain (all nuclides have the same activity A)

takes place:

after about 4...5 Half Live Times $T_{1/2}$ of the nuclide with the longest HLT

because of: $N = A*T_{1/2}/\ln 2$

particle number N of nuclides with longer live must growing compared with the shorter living ⇒ Different particle numbers

For an atmosphere where Radon Progeny are in equilibrium with the Radon the PAEC can be derived, because the number of atoms N of each nuclide can be calculated

# Equilibrium Factor F and EEC

**Radioactive Equilibrium never is given for Radon and it‘s Progeny in the air because of the “Plate Out” effect.**

**Need for a relation between Equilibrium and non equilibrium state**

$$C(Radon) \quad * \quad F \quad = \quad EEC$$

| C(Radon) | F | EEC |
|---|---|---|
| for the real Radon concentration C(Radon) of any non equilibrium atmosphere with a given PAEC | a factor F can found | to calculate a virtual Radon concentration (EEC) of an assumed atmosphere in equilibrium covering the same PAEC |

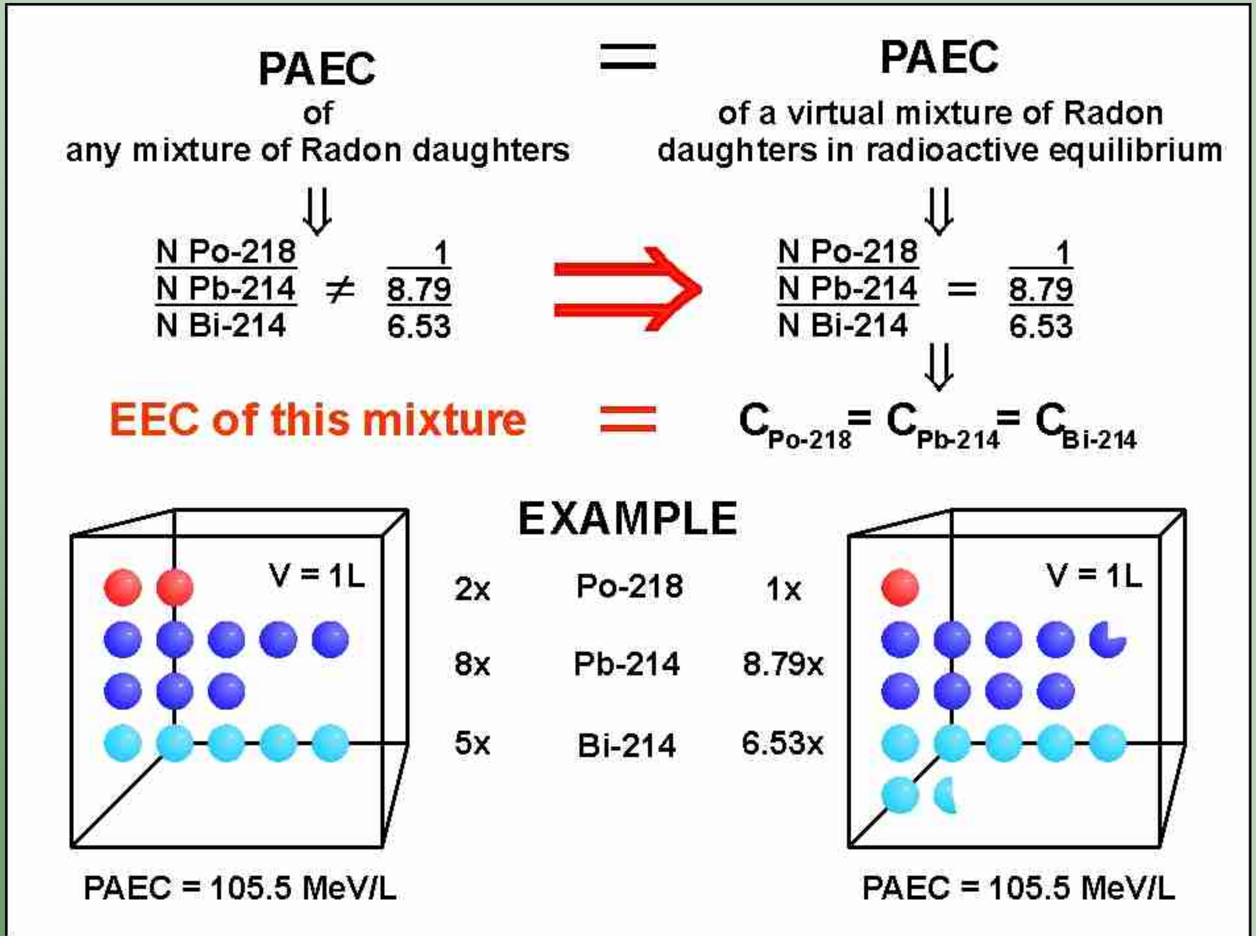
F characterises an atmosphere regarding the ratio Radon/Progeny

Range of F is 0...1

Typical values for F are

| | |
|---|---|
| Rooms with normal ventilation: | 0.3 ... 0.6 |
| Large rooms with dusty or smoky air: | 0.8 |
| Small volumes, moved air: | 0.1 |
| Outdoor air: | 0.7 |

# Equilibrium Equivalent (Radon) Concentration - EEC



# Dose Calculation by Radon or Progeny?

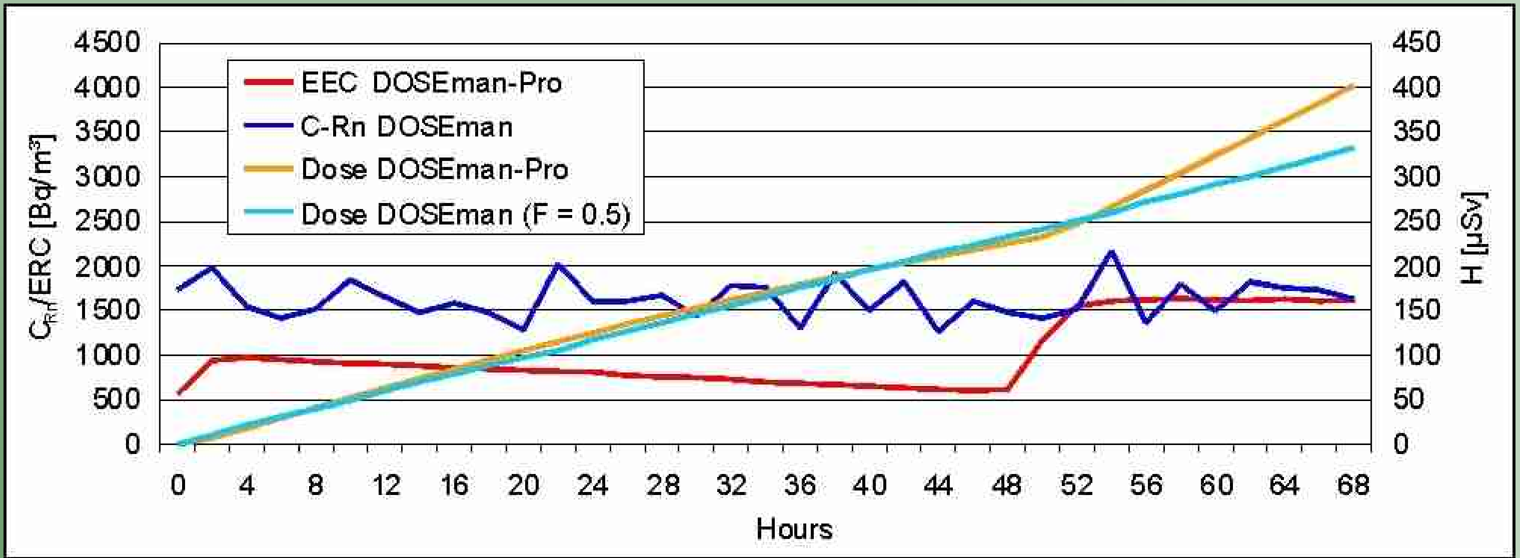
**Progeny measurement**

$$H = EEC * t * D$$

**Radon measurement**

$$H = C_{Rn} * t * F * D$$

**Variable!**



# Physical Units - SI and US

| | | |
|---|---|---|
| Activity | Bq (Bequerel) | Ci |
| Activity Concentration (C, EEC) | $Bq/m^3$ | pCi/L |
| PAEC | $J/m^3$ or $MeV/m^3$ | WL |
| Exposure | $Jh/m^3$ | WLM |
| Dose | Sv (Sievert) | rem (mrem) |
| Dose Coefficient | $Sv/(Jh/m^3)$ | rem/WLM |

**Unit conversion:**

1 Bq = 27 pCi

1 $Bq/m^3$ = 0.027 pCi/L

1 $J/m^3 = 6.24 \cdot 10^{12}$ $MeV/m^3 = 4.8 \cdot 10^4$ WL

1 $Jh/m^3 = 282.35 \cdot 10^{-6}$ WLM

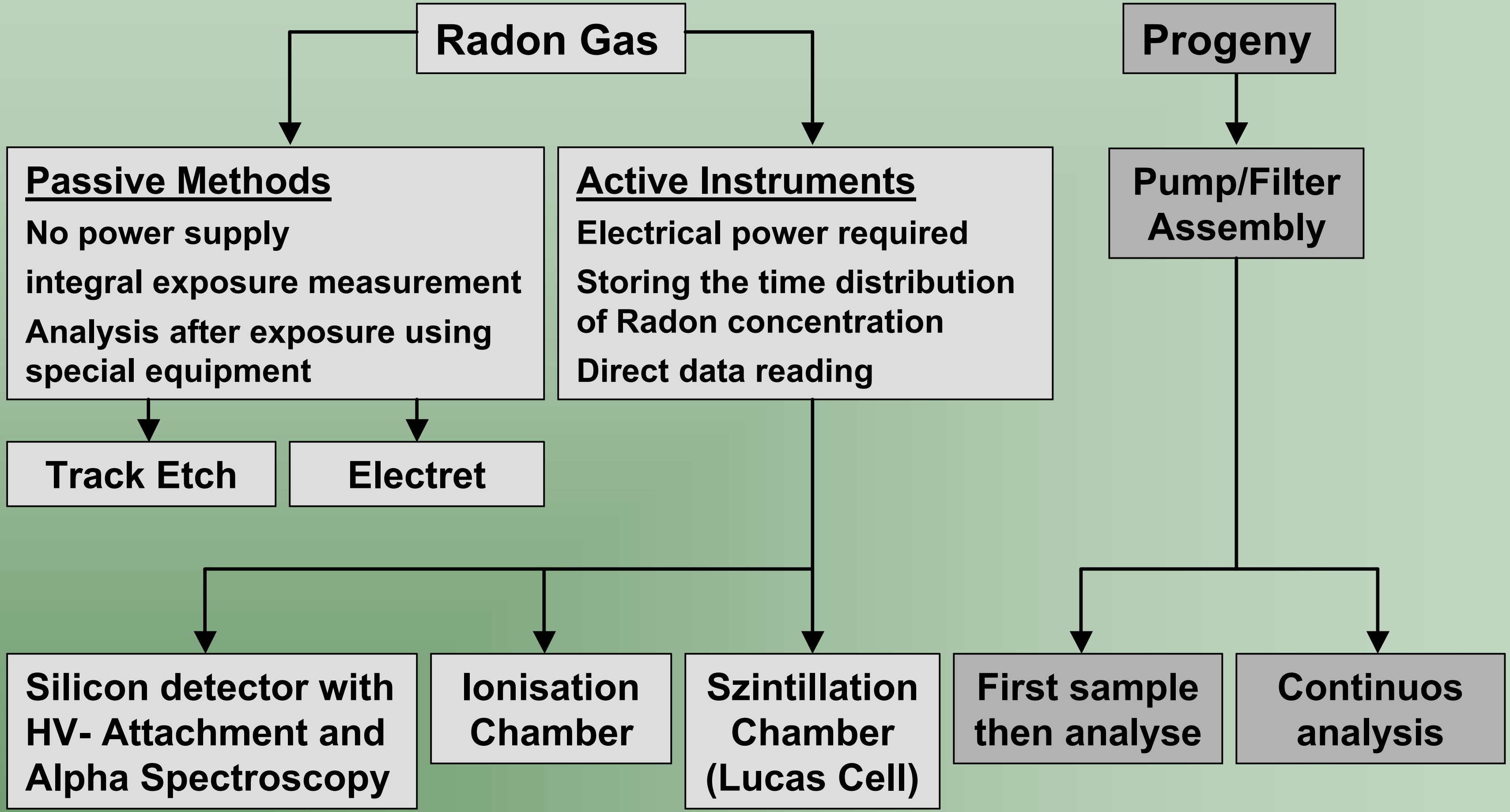
1 Sv = 100 rem

**Using EEC:** 1 $Bq/m^3$(EEC) = $5.4 \cdot 10^{-9}$ $J/m^3$ = $270.27 \cdot 10^{-6}$ WL

# International Limits for Radon Exposure (Examples)

| | Dwellings | Workplaces |
|---|---|---|
| EU | 200 Bq/m³ (buildings under construction)<br>400 Bq/m³ (existing buildings) | $6*10^6$ Bqh/m³ (WLM) |
| P.R. China | 200 Bq/m³ | |
| United States | 4 pCi/L = 150 Bq/m³ (EPA) | 4 WLM (DOE, EPA) |
| ICRP | 200...600 Bq/m³ (1993) | 4 WLM (1994) |

# Radon & Progeny Instrumentation



# Alpha spectroscopy - The most sophisticated way to measure Radon !

- ✓ High Radon sensitivity
- ✓ Radon can fully corrected against Thoron interference
- ✓ Simultaneous Thoron measurement possible
- ✓ Fast response to dynamic concentration changes
- ✓ No long term contamination by Po-210
- ✓ No background correction necessary, low detection limits
- ✓ 100% linearity by count mode over the whole range
- ✓ Transparent measurements and source level quality insurance by available alpha spectrum and count sums
- ✓ No EMI and vibration interference

# Detection of Alpha Rays

**Strong interaction with matter (mass, charge)**

**continuos energy lost over the track**

**100% energy absorption even in thin layers (80...100µm Silicon)**

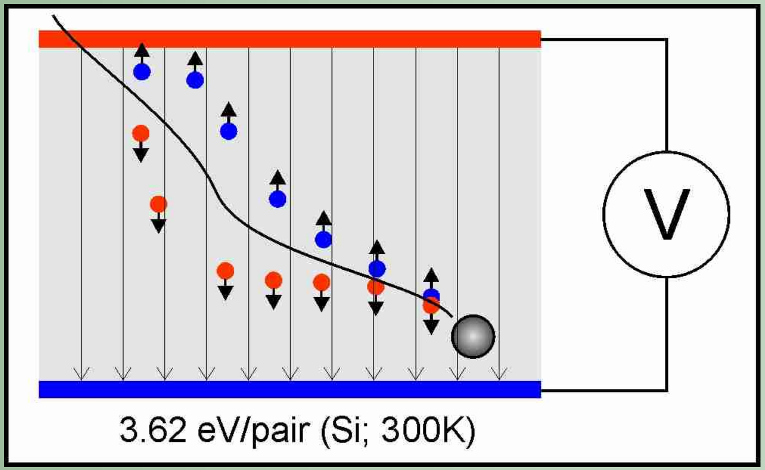
## Semiconductor Detector:

**Low band gap → low ionisation energy**

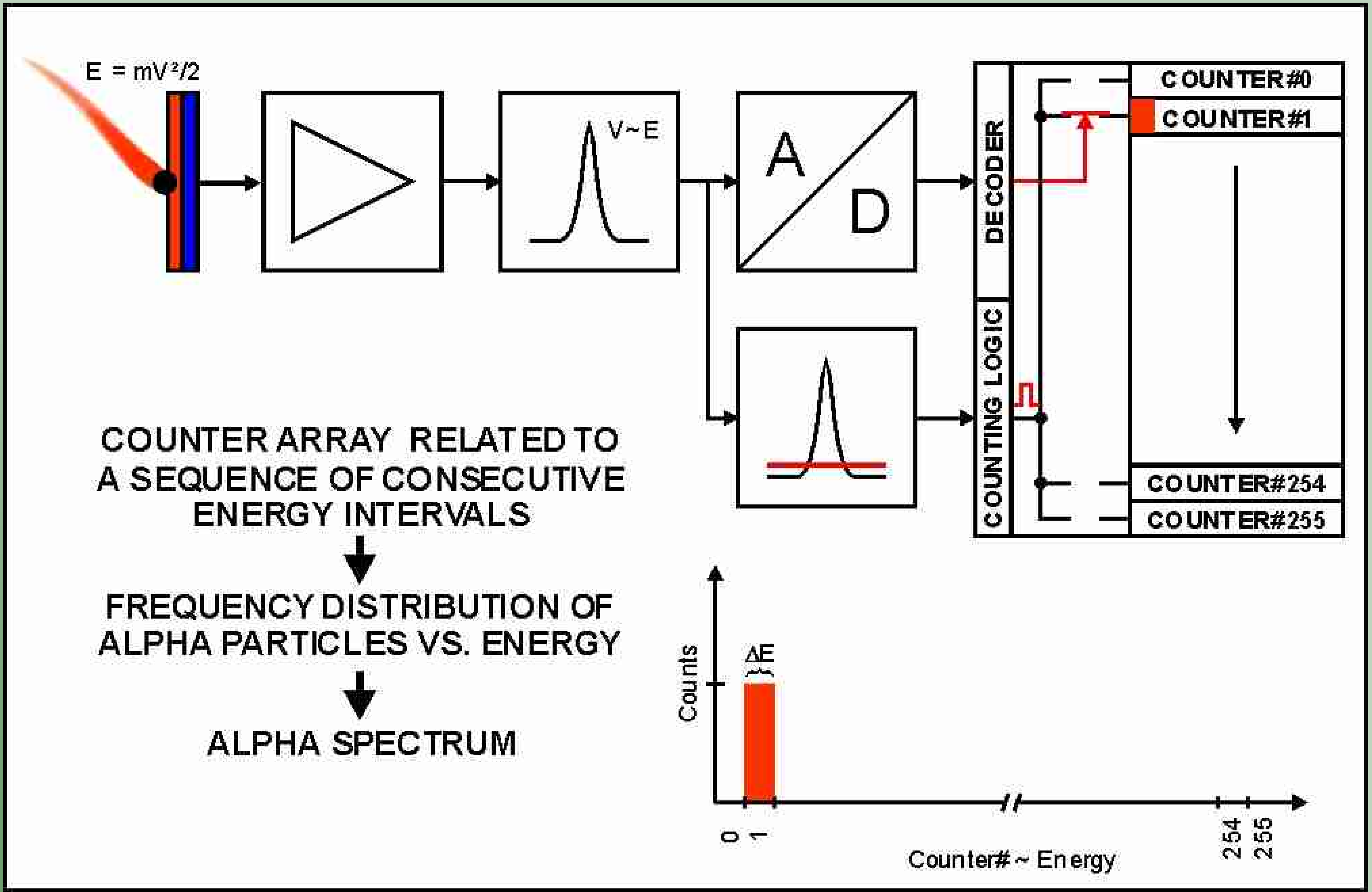
**Electrons shifted from valence into conduction band by electrostatic interaction with the Alpha particle**

**Number of generated electron/hole pairs ~ particle energy**

**Electrons/holes drifting to the electrodes by electrical field**



# Alpha Spectroscopy



# Ideal and real Spectrum

**PEAK:**

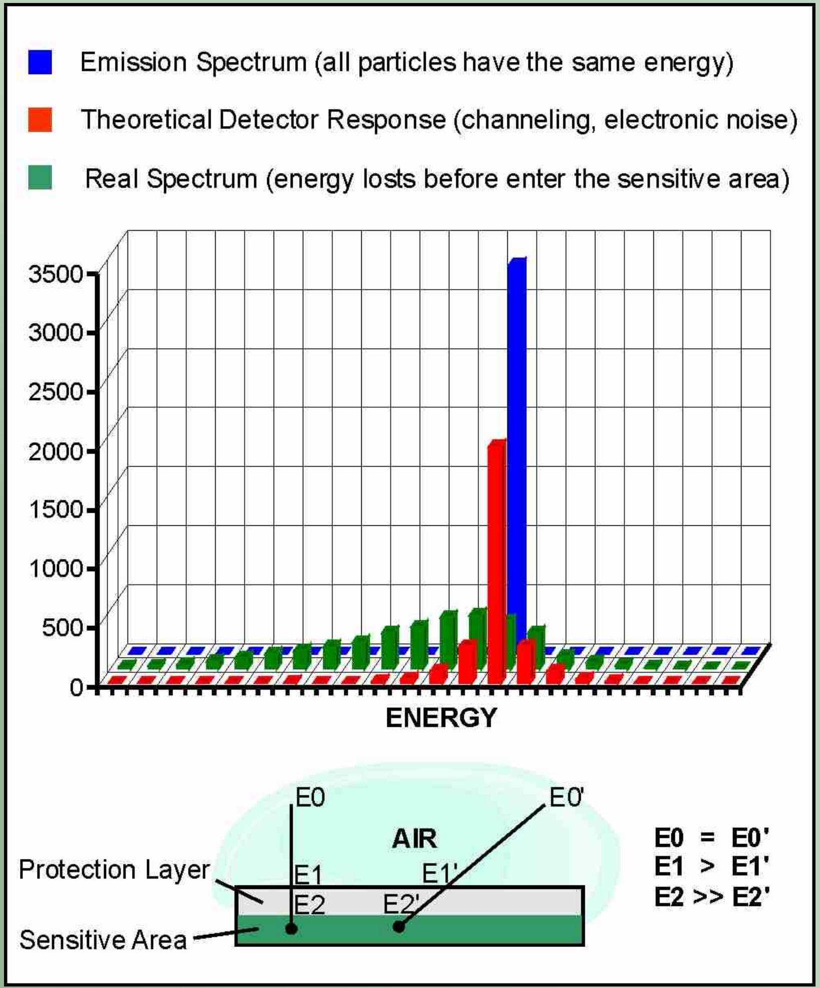
**Shape within the spectrum generated by a mono-energetic Alpha emission**

**PEAK AREA:**

**Number of counts within a peak (number of counts generated by this emission)**

**SPECTR. RESOLUTION**

**Increases with decreasing peak width (peak separation)**

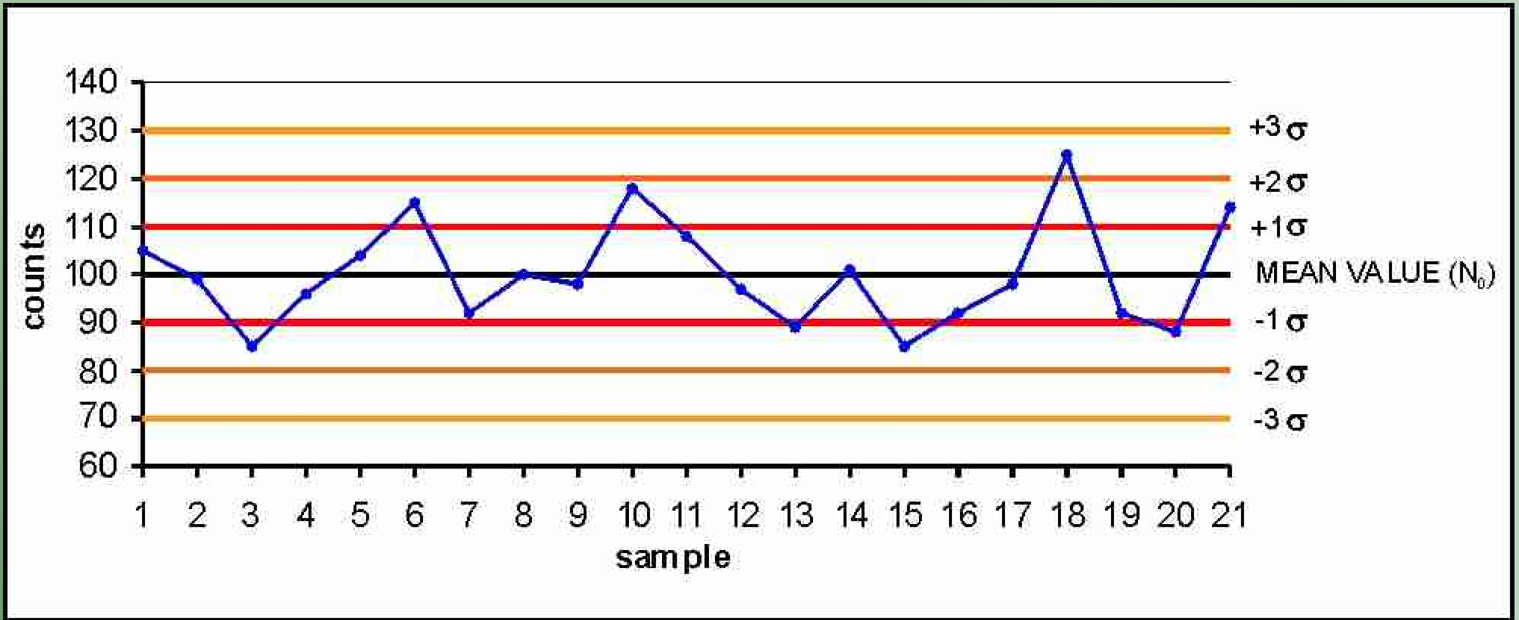


# Counting Statistics

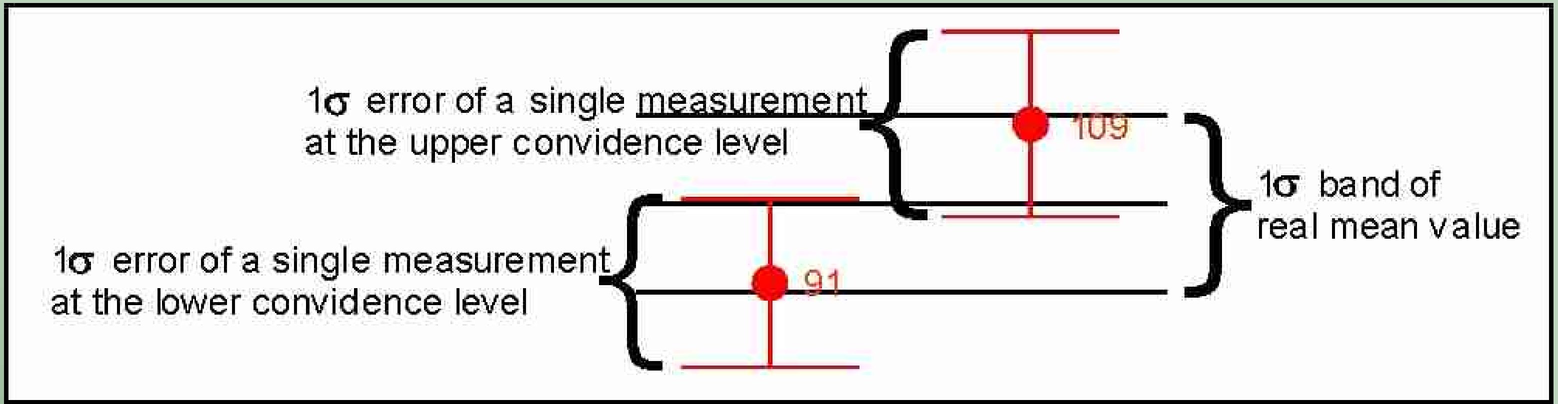
**Nuclear (Activity) Measurement → Counting Experiment**

**Number of counts detected within fixed time interval is a Poisson distributed random variable with $\overline{x} = N_0$; $\sigma = \sqrt{N_0}$**

**N: 68% within $N_0 \pm 1\sigma$, 95% within $N_0 \pm 2\sigma$; 99.7% within $N_0 \pm 3\sigma$**



# Error of a single Measurement

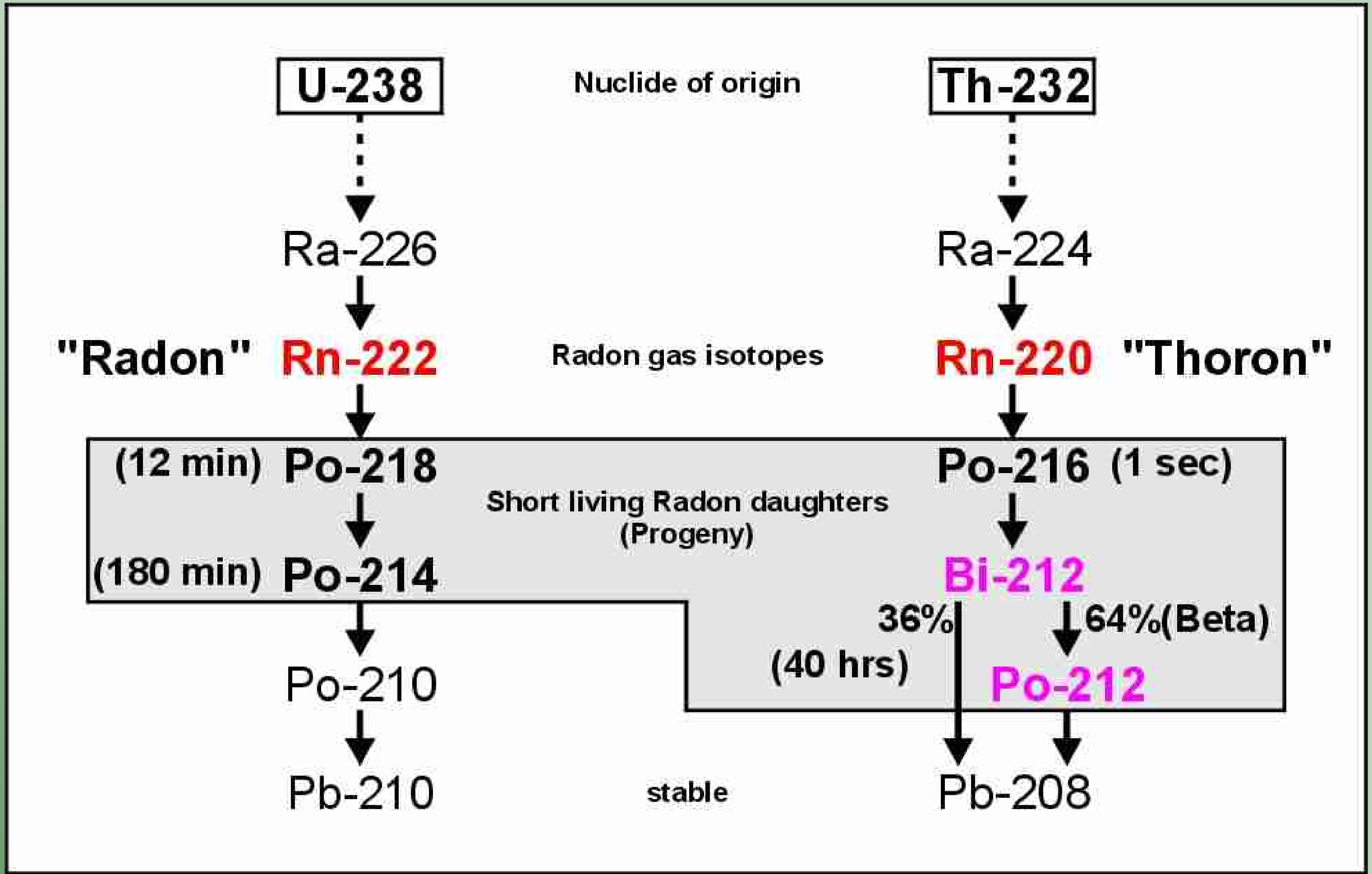



**The probability that the single measurement is placed within the 1σ band of the mean value is 68% ⇒ The probability that the real mean value is covered by the 1σ error of the single measurement is also 68% !**

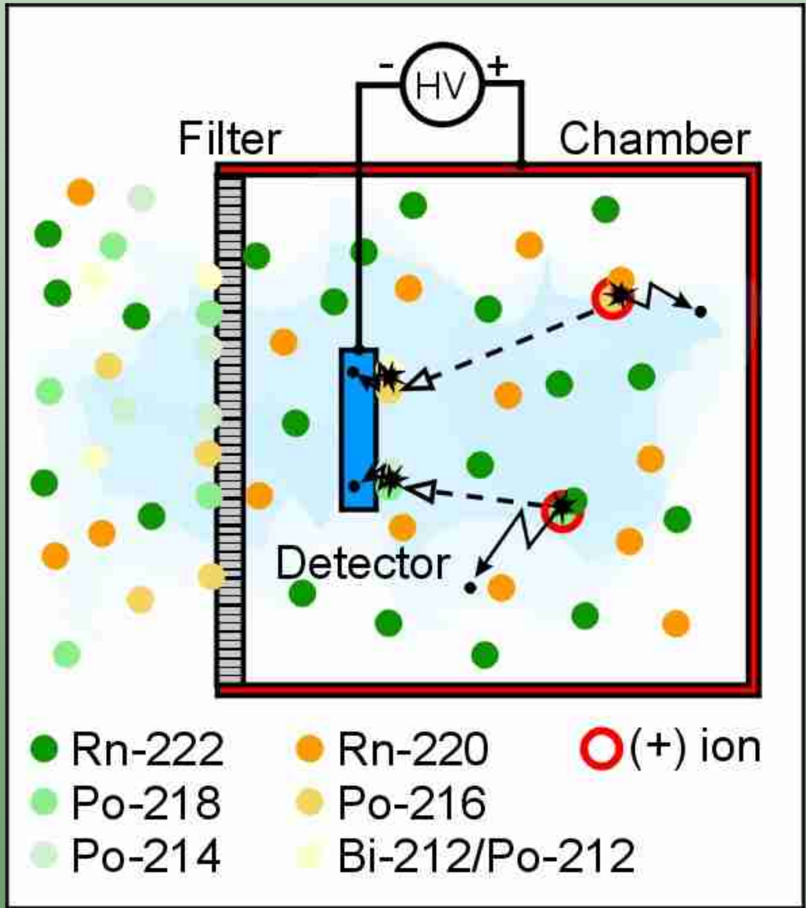
**For each measurement statistical error and confidence interval have to be stated!**

**Generally, nuclear instrumentation uses 1-Sigma confidence interval if not stated explicitly otherwise**

# Radon within the natural decay chains



# Radon chamber operation




Filter prevents progeny inlet from ambient air

Radon/Thoron decay generates positive charged Po-218/Po-216 ions

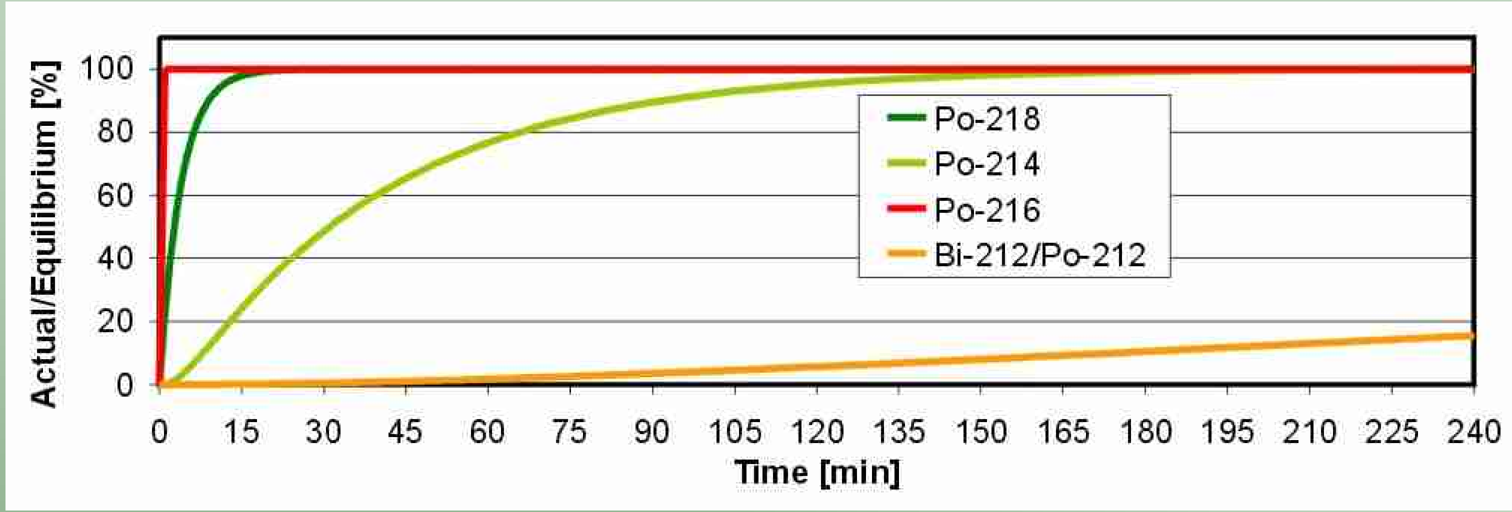
Ions are collected on detector by electrical field forces

Alpha particle emitted by the decay of Po-218/Po-216 and their daughters are detected with high probability

Equilibrium state between collection and decay process after about four half life times of each nuclide

Progeny activity on detector surface is proportional to the Radon/Thoron air concentration

# Radon chamber step response



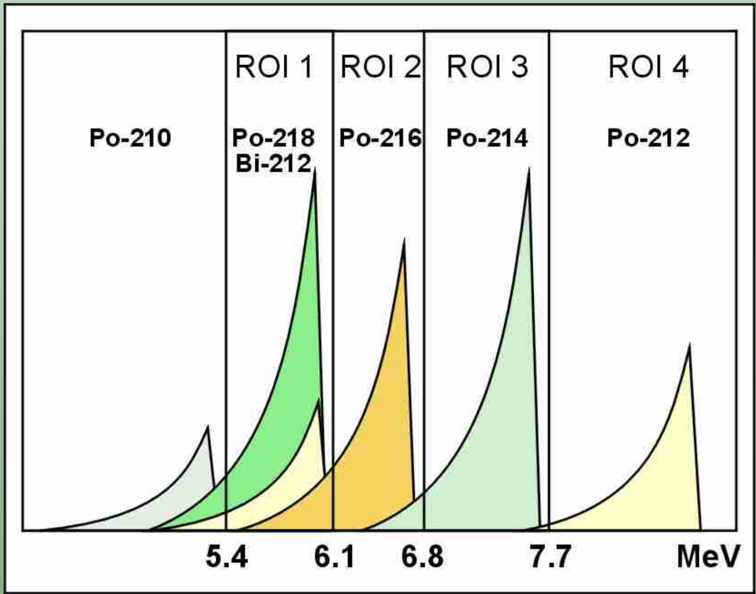

**Radon** calculation based either on **Po-218** only (***Fast Mode***) or on sum of **Po-218 and Po-214** (***Slow Mode***)

**Fast Mode: short response time**

**Slow Mode: increased response time but doubled count statistics**

**Thoron** calculation based on **Po-216** only because of the slow response of Bi-212/Po-212

# Nuclide separation by α spectroscopy




Acquisition of the alpha spectrum by a MCA connected to the detector

Definition of four ROI (region of interest) assigned to the several nuclides

Determination of ROI areas by addition of all counted events within a ROI

Count sum calculation for each nuclide taking into account the left peak slope (tailing) and the Bi-212 overlay in ROI1

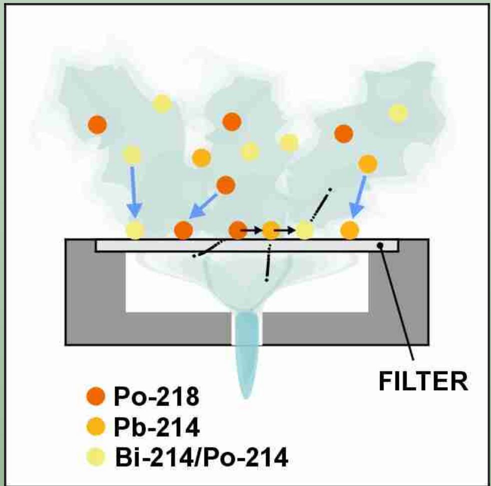
**Tailing:**

**Because tailings are detector constants a known percentage of the ROI area of the interfering peak will be subtracted from the affected ROI**

**Bi-212:**

**The Bi-212 count sum will be calculated by the unaffected Po-212 count sum within ROI4 and can subtracted from the peak area of ROI1 (ratio Po-212:Bi-212 is always 1:1.78).**

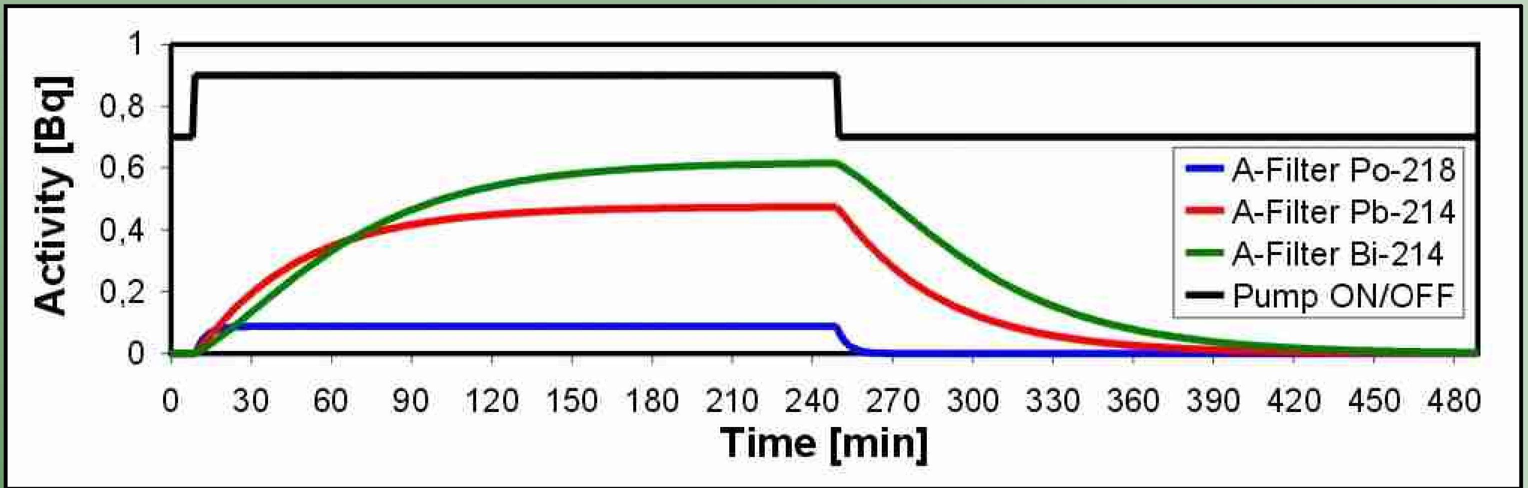
# Progeny Sampling Head Operation




**Collection of Radon progeny on a filter**

**Equilibrium between collection and decay after about 3 hours**

**Filter activity of Alpha emitters Po-218 and Po-214 proportional PAEC (collected Pb-214 and Bi-214 results in increased Po-214 activity)**



# Special Features of Progeny Sampling

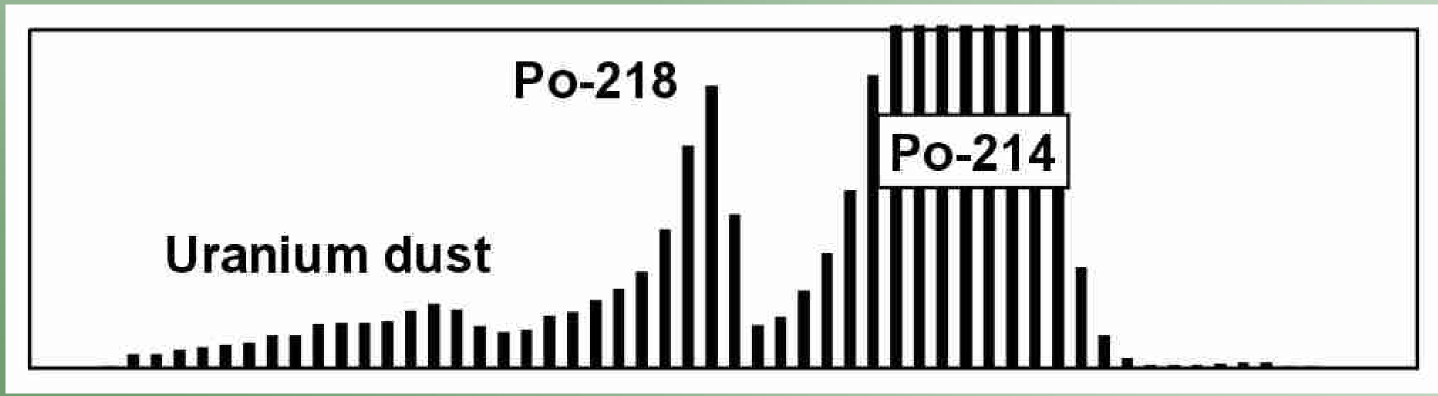
**Po-218 as a fast tracer**

Po-218 - after 12 min in equilibrium - indicates dangerous PAEC levels immediately

**Filter analysis after switch off the pump ...**

... ensures 100% accuracy by including all collected aerosols into the exposure calculation

**LLRD analysis using filter spectrum**



# Radon Measurements

| | |
|---|---|
| Radon in buildings (Risk assessment) | Passive methods, active Radon and Progeny monitors |
| Radon at Workplaces (Dosimetry) | Passive methods, active Radon and Progeny monitors |
| Air Quality Monitoring | Active Radon and Progeny monitors |
| Investigation of building ground | Active Radon Monitors |
| Special applications (Geological survey, tracer applications) | Active Radon Monitors |

# Radon in Buildings

## Problem:

**The Radon concentration is affected by external factors like ventilation, wheather or pressure conditions. Variations by a factor of 100 are possible!**

### „First Check“ (general survey) measurements

**to proof whether increased Radon exposure is expected or not**

**Snapshot sample at one selected (experience  based) place. One hour to one day sample time.**

### Radon Risk Assessment

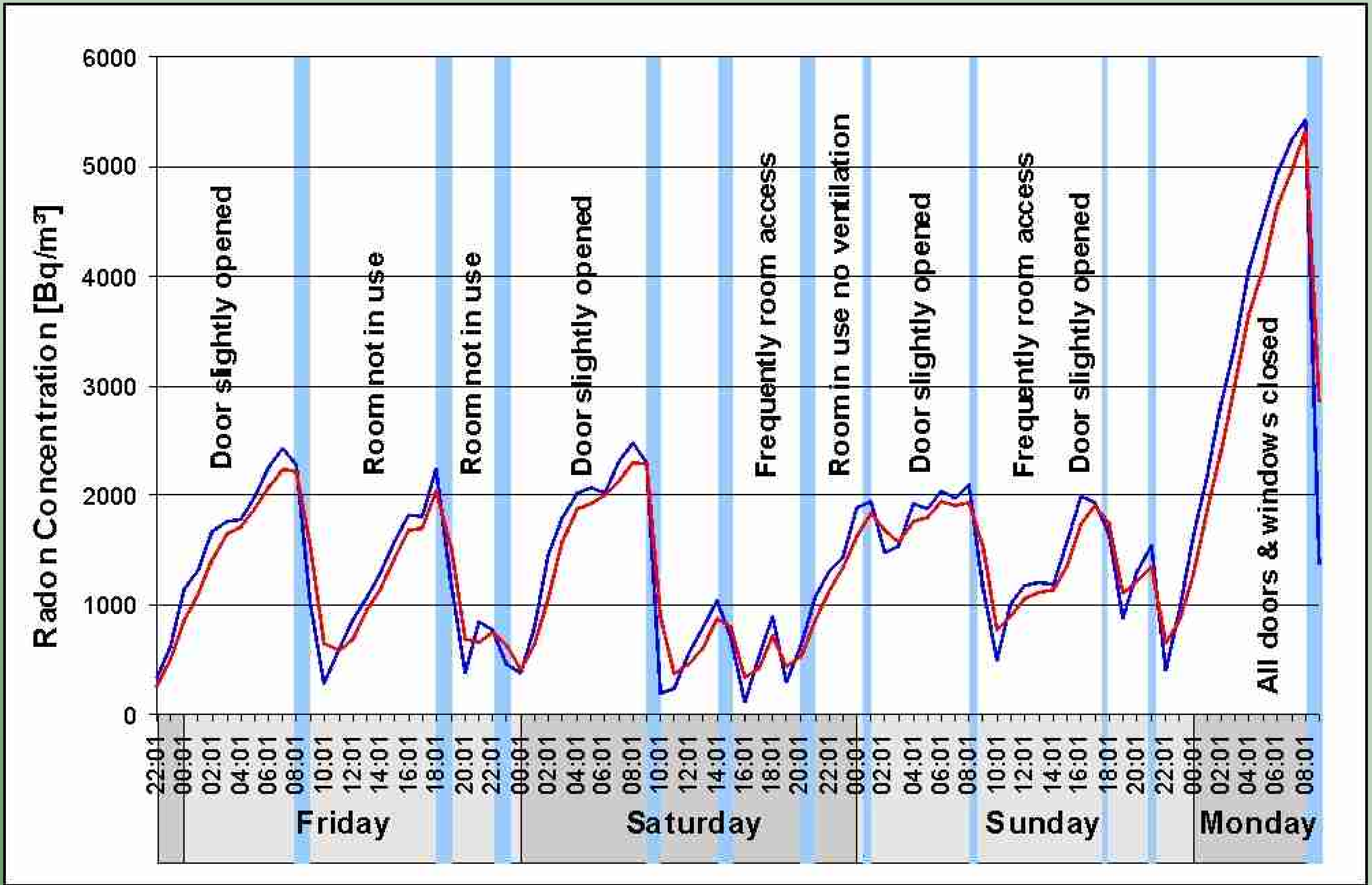
**to determine the real annual exposure including the external factors**

**to find out possibilities to decrease Radon levels**

**to optimise remedial action if necessary**

**Long period measurements at several locations accordant the habit of the owner**

# Example of a Radon affected Building



# Instrument Requirements

No disturbance of the people who living in the building

Reliable data without need for device access during measurement

Meaningful results with respect to remedial actions

Easy data access and handling to create protocols

- No noise emission (no or switched pump)
- Mains power independence
- Time distributed concentration available
- Protection against unintended manipulation
- Quality assurance features
- Small and lightweight (may sent by mail)
- Low price (simultaneous measurements)

# Radon affected Workplaces

**Mines, Shafts, Tunnels, Caves/Show Caves, Radon Spas, Waterworks**

**Dosimetry Concepts**

**Personal Dosimetry**

For people who working temporary at several places with undefined conditions

Unknown Radon Concentrations
Unknown Equilibrium Factor
Heavy short time exposure

**Radon Measurements**

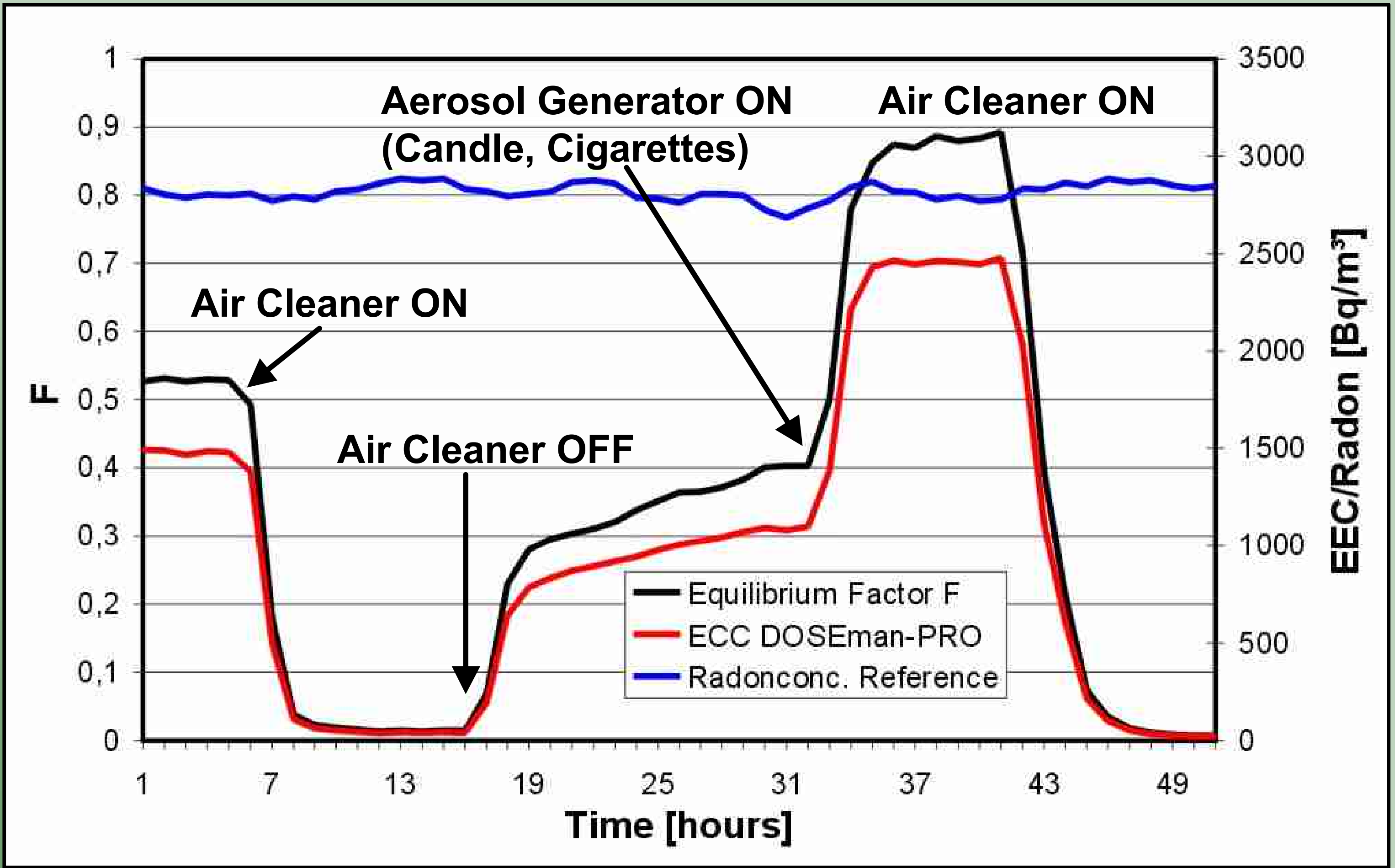
**Localised Dosimetry (tied to a certain place)**

For people who working continuos at defined places

Low Concentrations variations
Well known Equilibrium Factor
No hazardous Radon Levels

**Radon or Progeny Measurements**

# Workplace with changing conditions



# Assessment of Building Ground

Diffusion from foundation soil into the building is the most common source of increased indoor Radon concentrations. The Investigation helps to reduce costs - arrangements regarding Radon protection can made from begin.

A Grid of 1 to 2 m deep holes have to be drilled in the soil. After sealing the holes at the surface the Radon potential will be measured.

Requires a fast and easy to handle Monitor to carry out several measurements in a short time. An internal pump to take the samples is recommended.

Thoron is mostly available in soils. Don’t use instruments without Alpha spectroscopy.

# Who needs to measure Radon/Progeny