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Muons from mobile accelerators in large-scale environmental analysis

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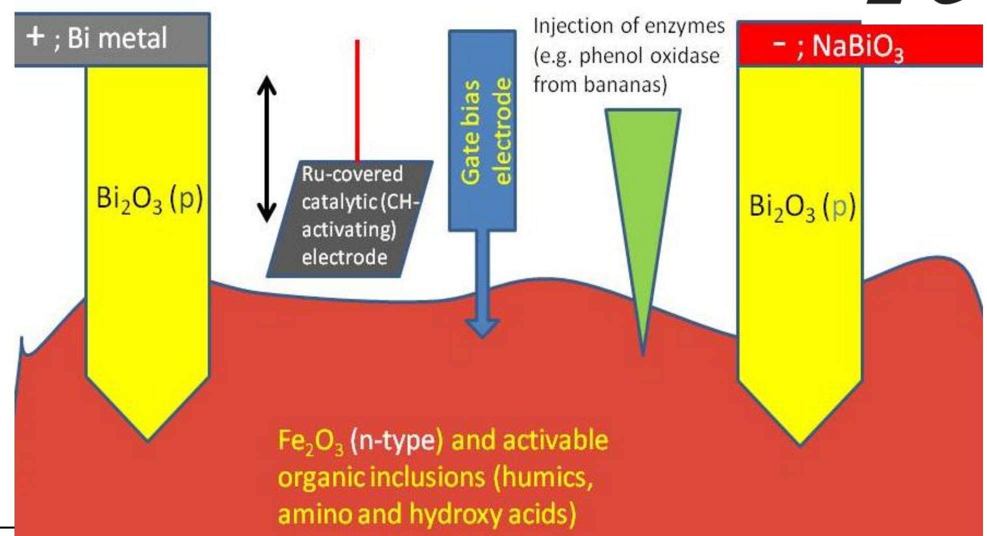
Where we start from

- IHI Zittau; Dresden Tech (TUD)
- Site of old lignite pits → man-made lake land-scape, strongly mixed, chemically still active topsoils
- Background in environ-mental and technical analytical chemistry, electrochemistry; interested in „more physi-cal methods“ to cover larger areas by one screening, rather than analyzing samples from (n + 1,001) bore-holes
- Which kinds of data do natural (soil, bio-mass) samples reveal without prior impact of chemicals or ionizing radiation? → activation by cosmic radiation **muons**

Lake Olbers-dorf, residual matter mound

Fe(III) oxide precipitations from aq. Fe^{2+} trickling to the surface from a per-turbed soil arrangement; (**down right**): I am **not** going to speak about this today: making signal amplification right from soil heterogeneity, Fe richness, SC properties!

Zittau and N part of Lusatian Mountains (D/Cz.R.); back centre: Lake Olbersdorf inundated lignite pit, residue heaps

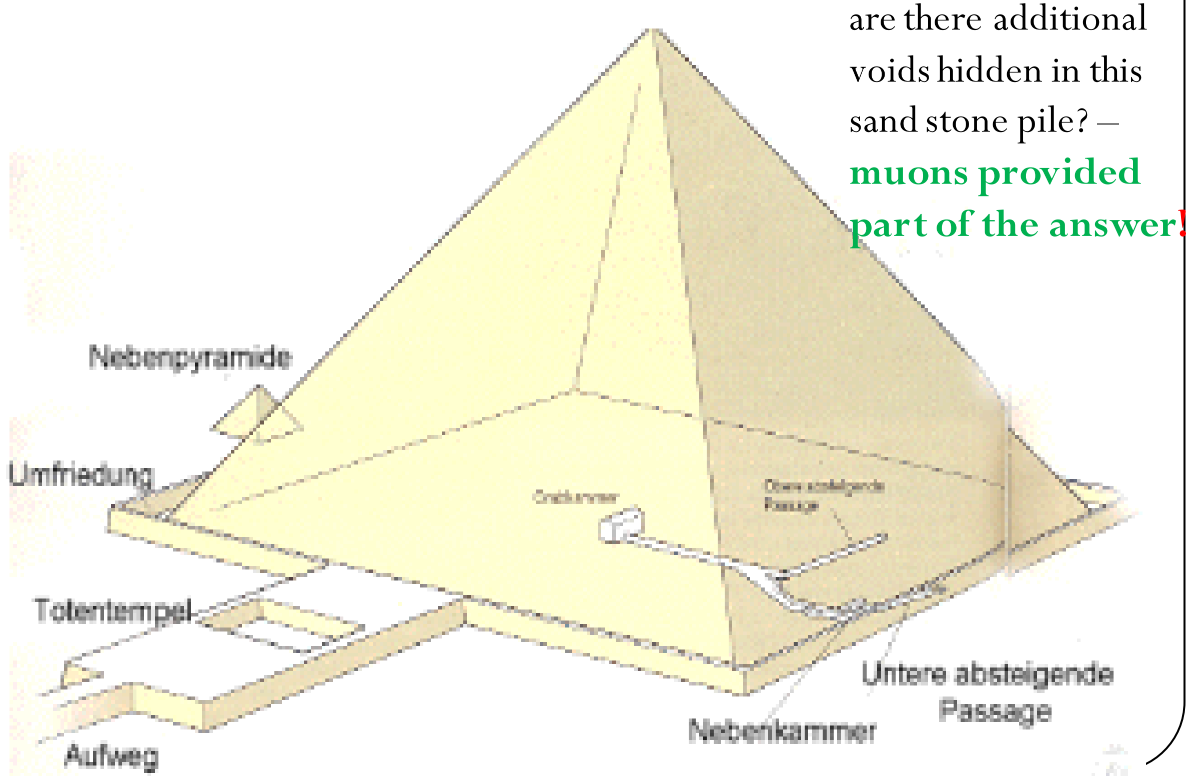


Why muons, and which ones?

- Muons can penetrate thick samples but are suitable to detect fairly small cavities therein
- μ^+ almost behave like protons in condensed media, forming chemical bonds (e.g. (μ-OH; muonic water) and get accessible to ESR during the μs before they decay
- μ^- are kind of „heavier electrons“ (lepton universality), get trapped by cations or neutral molecules after cooled down to some 40 eV ($v \approx 260$ km/s) interacting with heavy atoms, > 75 eV for very light ones, only then take part in chemical binding –

  but that´s **not** the entire story!

Pharaoh Chephren´s large pyramid: was he ever buried there, and are there additional voids hidden in this sand stone pile? – **muons provided part of the answer!**



Inverse β decay: electron capture (comparison)

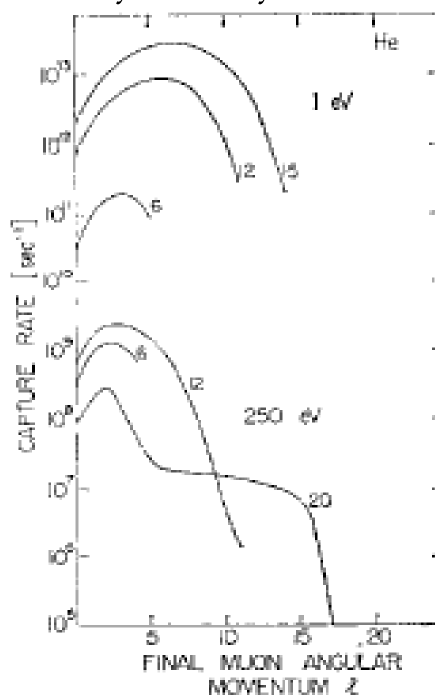
- Electrons (single or pairs [e.g. with ^{78}Kr, ^{130}Ba, ^{152}Gd – besides of α decay in latter: 10^{14} a]) can be trapped by protons (**up** quarks therein) by way of weak interaction, but
- For xs orbitals even, **electron** probability to be inside the nucleus at a given time is small
- Muons are 207 times heavier than electrons → average muon/nucleon [μ^-/u quark]-distance 207 times smaller than size of electronic K, L orbitals → muon density in nucleus $(207)^3 \approx 10^7$ times larger than with electrons, moreover: what would take 10 s with inv. β decay, will be done wihin << 1 μs by μ^- because
- much more energy is to be gained/released by muon capture hence probability of corresponding weak interaction per period of time is much larger

→ once negative muons were trapped to a single atom, they are likely to react with the nucleus although short-lived

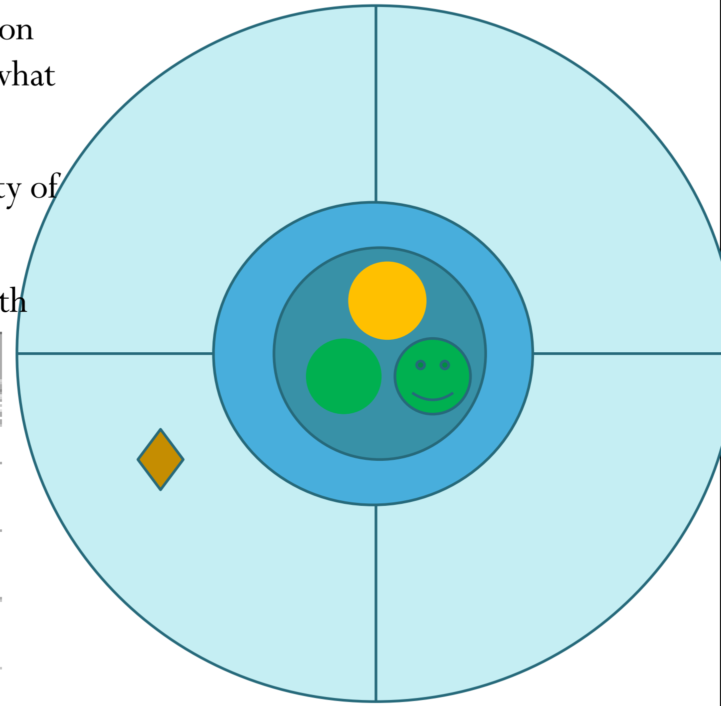
This reaction as a rule produces **radionuclides**

$(\text{lepton})^- + \textbf{u}\ \text{q.} \rightarrow \nu + \textbf{d}\ \text{q.} = (\text{lepton})^- + p \rightarrow \nu_{(L)} + n\ (\lambda^0)$;

always exothermic for L = μ or τ



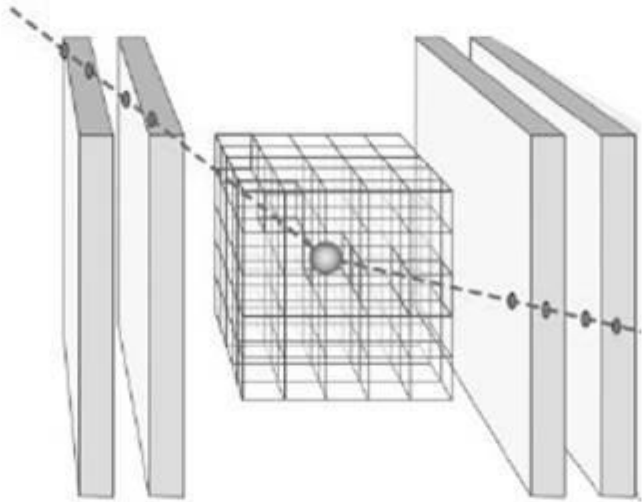
Quench, capture energy and final angular momentum distribution for muon quenching by ^4He; subsequent nuclear reaction likely only for L = 0, 2, 4… (best: L = 0 [s orbitals, right picture])



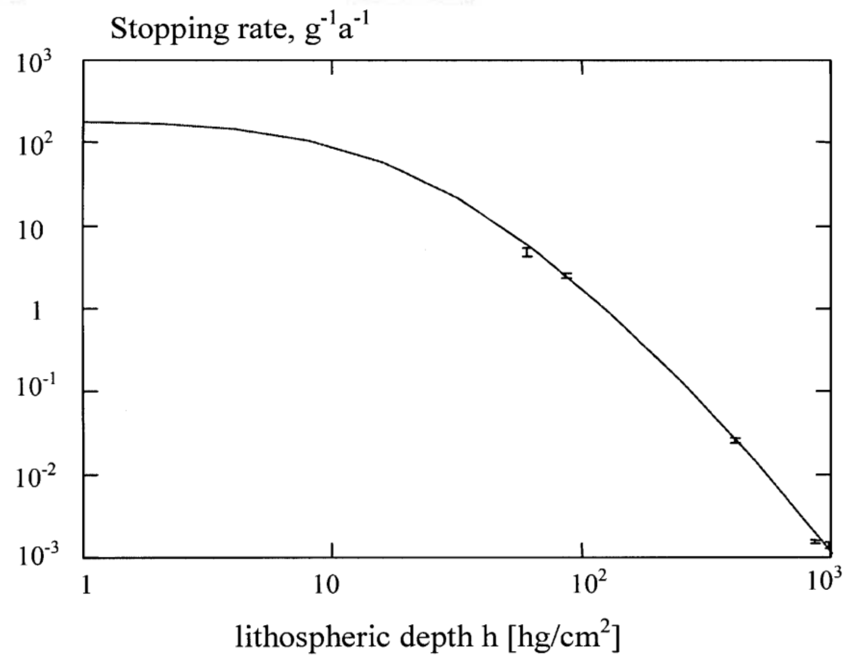
The probability to find a muon (brown crystal) in 1s or 2s…, states somewhere increases from outside when approaching the nucleus (quarks shown) [light to dark blue shades]

Make muons, pass them to the ground

- Size, kind of μ source: GeV protons, about car-sized
- Electromagnetic deflection
- Range of muons, range of secondary γ photons → measurements must be made parallel to some surface (grass-roots level, along a cliff or around a borehole)
- Lifetime of, penetration by „moderately relativistic" muons → beam will pass several 100 m ($\tau_0 * c \approx 660$ m) → an area of several times 50 m in diameter can be sampled from a single point of muon injection → rapid analysis at high spatial resolution
- Activation of U, Pu by simple capture producing the typical prompt Moseley-type γ radiation rather than causing nuclear reactions which give away hidden nuclear materials



A muon beam may be deflected at both voids and sites where exceptionally light or heavy atoms „gather" (e.g. organic inclusions)



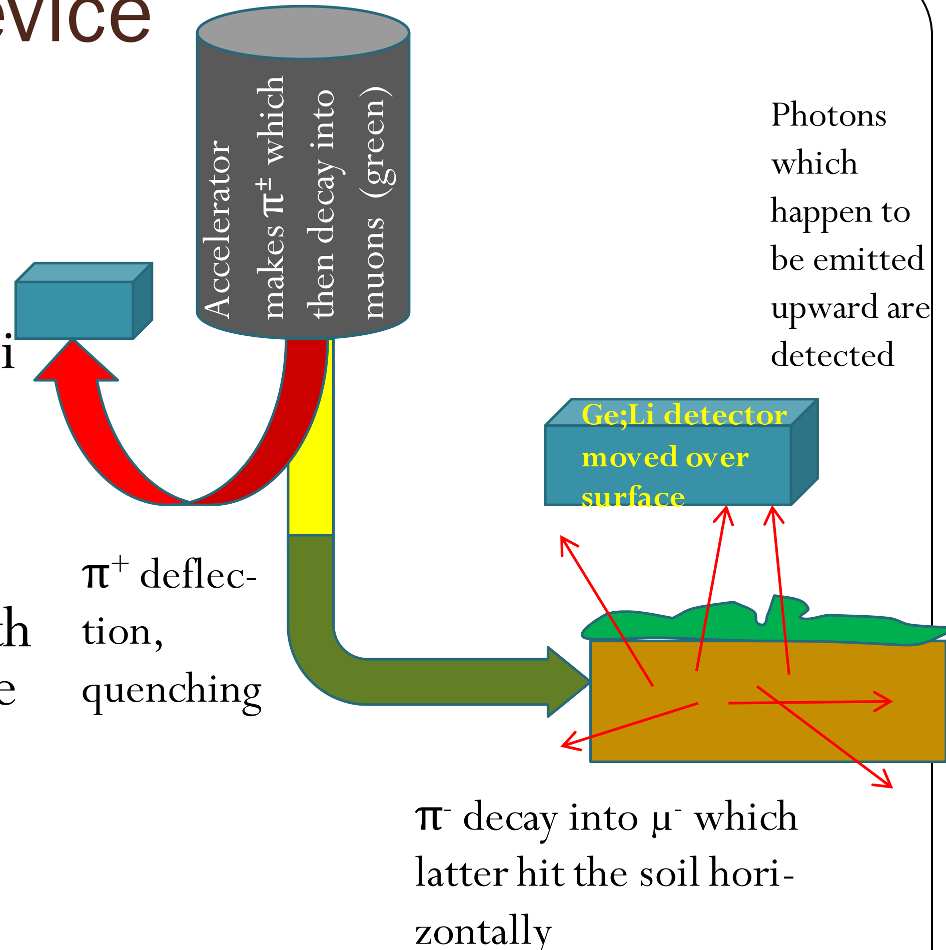
Range, capture rate of cosmic rad. μ^- vs. amount of overlying sediment matter, rocks: decline starts at ≈ 1 kg/cm^2 ≈ 4.5 m layer,, reasonable yields still at 20 kg/cm^2 ≈ 75 – 80 m layer; average primary energy higher than in soilborne irradiation

Size, construction of device

- Table-top electron- or proton accelerator with loop system (e some 300 MeV, p about 1 GeV)

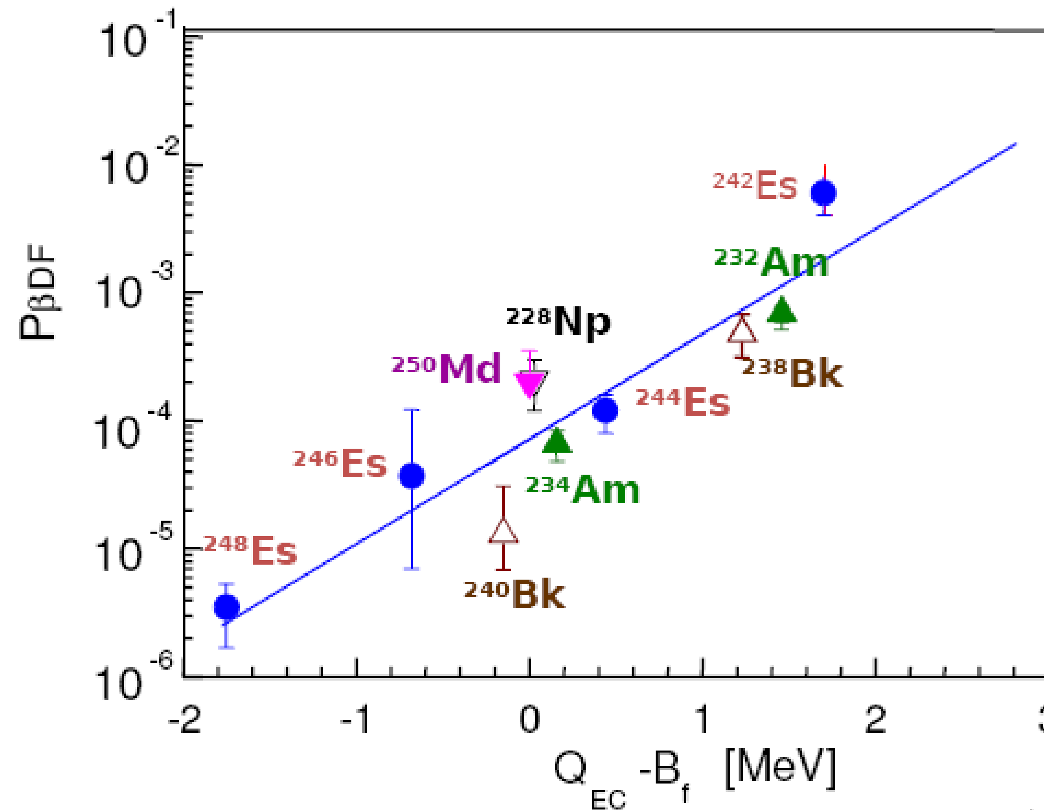
First, $\pi^{\pm}$ are formed/kicked out of nuclei which

- decay into μ on some 1 m way-length
- electromagnetic separation of μ and π mesons (remaining π rapidly react with matter in a very thin layer, while μ^{+} are discarded), then the
- μ^{-} beam is directed parallel to the surface
- γ detector is moved around on the surface, looking „downward“
- Classical translation of γ spectra into element compositions, like in INAA



Kinds of nuclear reactions secondary to (delay due to) μ^- capture by nuclei (w.i.)

- Pure **γ emission** (daughter nuclide is stable but formed in an excited state), to be distinguished from Auger-Moseley emissions shifted into γ by muon mass
- **n-** or p **emission**
- **Fission** (cp. βdF, disc. at Dubna on ^{232}Am; βdF may occur rarely if energy gain < fission barrier)
- Fission is also possible by a closely orbiting muon (1s- or 2s states) pulling opposite (proton) charges in nucleus forth and back periodically, making the nucleus vibrate (lepton, purely electromagnetic effect)
- n emission prevails in moderately heavy nuclei, commonly just one neutron is detached (excitation energy ≈ 10 MeV; $\rightarrow {}^{m}E^{Z} \rightarrow {}^{m-1}E'^{Z-1}$, e.g. ^{68}Zn → ^{67}Cu ($T_{½}$ = 62 h; γ = 185 or 93 keV); pattern of products from common topsoil, sand, pig iron, carbonate etc. minerals (that is, C, N, O, Si, S, Ti, Ca, Mg or Fe isotopes)



Beta-delayed fission yields vs. energy excess during decay: a rather rare event which suggests most heavy nuclei will behave well during μ^- capture, rather than undergo fission and make „atypical“ daughter nuclides (for comparison only)

- Chances for detection of trace components

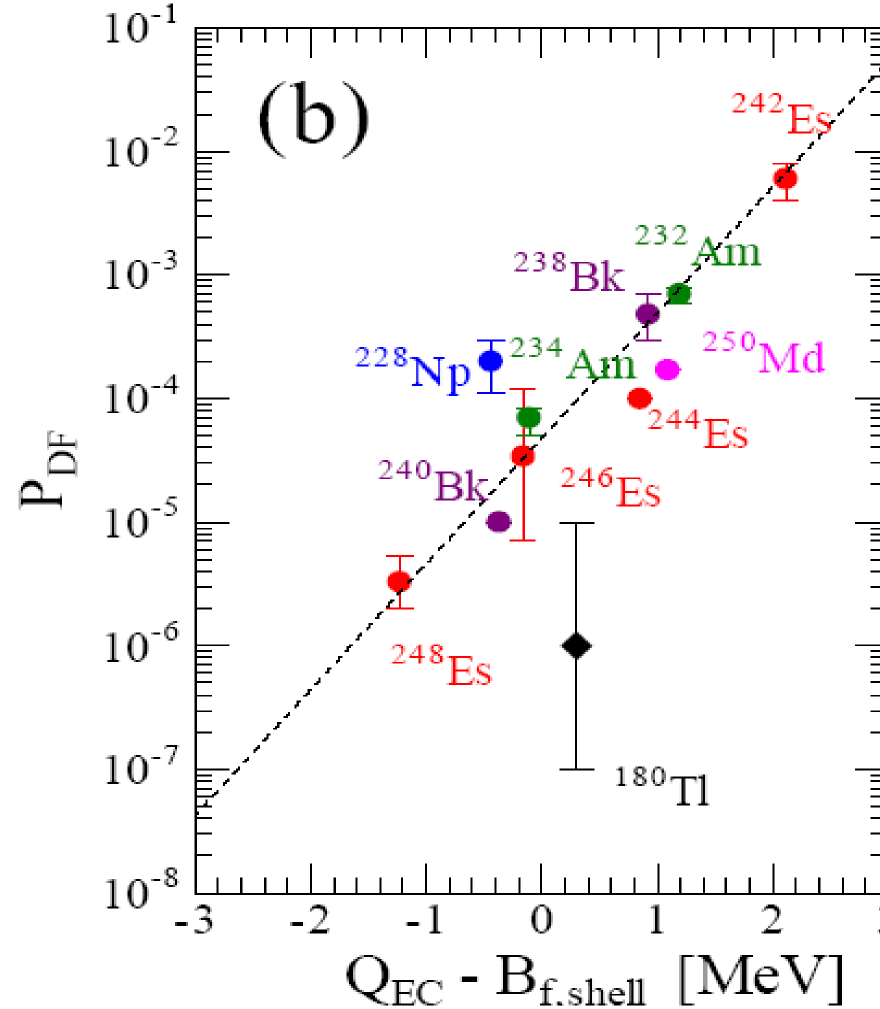
Examples of emitting nuclides

- Available from most elements by one pathway or another
- Positron emitters, annihilation γ from Cd, Sn, Ba, Ce, Nd, and Hg → γ (341; 511 keV) useful for summarizing toxicological indica-tions (Cd, Hg, Ba)! [table]
- Fission products
- „common" β^- emitters even from very light elements

element	Short-lived isotopes of (Z – 1); half-life	Natural abundance of M	Natural abundance of (M + 1; M + 2)	β^+ emission, nuclide
Cd	^{105}Ag 41.3 h; ^{106}Ag 24 min		$^{106;108}$Cd about 1% each	β^+ in ^{105}Ag, ^{106m}Ag; extremely hard γ in ^{112}Ag (3.1 h; 1387 keV) and ^{115}Ag (20 min; 2156 keV)
Sn	^{110}In 4.9 h; ^{110m}In 69 min; ^{111m}In 7.7 min; ^{114}In 72 s;…		^{112}Sn 1.0%	^{110}In β^+
Ba	^{129}Cs 32.06 h; ^{130}Cs 29.2 min; ^{134m}Cs 2.9 h; ^{135m}Cs 53 min		$^{130;132}$Ba about 0.1% each	Almost purely β^+ in $^{129;130}$Cs ($^{131;132}$Cs but too long-lived for efficient detection)
Ce	^{135}La 19.5 h; ^{136}La 9.9 min; ^{140}La 40.2 h; ^{141}La 3.9 h; ^{142}La 91 min		^{136}Ce 0.19%	$^{135;136}$La (100% each)
Nd	^{140}Pr 3.4 min; ^{142}Pr 19.1 h; ^{142m}Pr 14.6 min		^{142}Nd 27.1%	^{140}Pr β^+ 100%
Hg	^{196m}Au 8.1 s; ^{197m}Au 7.73 s; ^{200}Au 48.4 min; ^{201}Au 26 min; ^{202}Au 28.8 s; ^{203}Au 53 s; ^{204}Au 40 s	^{196}Hg 0.15%	^{198}Hg 10.1%	γ deexcitation daughter ^{196}Au (6.17 h): β^+ = 92.8%; plus fission products

„Good“ vs. „poor“ absorbers

- Water content of sample and muon moderation efficiency
- Production of β^+ emitters from certain p-rich nuclides (precursors …) → annihilation radiation among the γ spectrum
- Particularly hard γ radiation emitters in spectrum
- C-, N-, S- vs. O capture efficiency → how is the chance to detect oxidation state of sample, or even content of organic matter?
- μdF of heavy nuclei, mainly Pb: an analytical nuisance or a chance to enhance sensitivity? (rate of μdF [cp. βdF: always << 1% except for ^{242}Es]?); exper. muonogenic fission yield: 13±5 % in ^{238}U, some 45% in ^{239}Pu, < 2% for ^{232}Th (cp. thermal neutrons)
- Typical traces of Hg, Tl, Bi and lighter Pb isotopes are detected only due to fission (look to right!)



βdF yields increase by **factor 10 with every MeV $\Delta\varepsilon B_f$** → about 3% at + 3MeV; efficient excess some 5 MeV at Pb (M ≠ 208), → $y_{\mu dF}$ > 50%; Tl, Bi…, $(M/Z)_{prod}$ ≈ 2.6 in μdF products with Z_{start} ≥ 80 → few s to min; no perturbation of Sn, Ba, REE detection, but fission-less detection of Pb only as ^{206}Tl (4.2 min, γ = 803 keV)

Safety considerations: where can it be done?

- We do not do anything else than is caused by cosmic radiation anyhow though at elevated rates
- Control of beam: loss of electromagnetic deflection means directing beam perpendicularly downward into massive bedrock
- Life-times, amounts of radionuclides formed (few GBq along 100m/20 cm diameter flux tube for minutes to weeks)
- Effects on local biota?! - **μSR with low energy μ^+ is used** for making pictures [μ-RT], not destroying tumour cells, even **in human brain tissue**!

Slightly rough forest terrain in which such measurements may be made (for illustration only, displaying biogenic Fe oxide deposits above a reducing bottom environment)

Oxidizing vs. reducing soil conditions: muons feel and tell the difference!

Accelerator makes $\pi^{\pm}$ which then decay into muons (blue)

Removal of μ^+ (to left)

Fe_2O_3, sulfates, carbonates

^{16}**N** prevails, besides residues of alkaline earths

Accelerator makes $\pi^{\pm}$ which then decay into muons (blue)

Removal of μ^+ (to left)

Sulfides, thiometallates, Fe_3O_4, $FeCO_3$, organic matter

Heavy **P-** and **Si** isotopes, ^{15}**C**

Estimating analytical sensitivities

- Several γ/min at given energy readily detectable by Ge;Li detector, < 10% of photons directed into upward segment, some 70 - 80% absorption in thicker soil layers $\rightarrow$ about 2 Bq must be produced ($\approx$ 0.1 Bq/kg in 30*30*20 cm activated volume)
- 10^5 muons/s back in 2002, today some 10^7; equal-intensity pathway some 10 m, high relative yields in abundant isotopes, but annihilation γ from rare ones ($\leq$ 1% except for ^{198}Hg) only, average radionuclide lifetime several times 10^3 s means
- Saturation activation after some min by $\approx 10^9$ μ^- total dose in column (some 10^7 in sampling segment of flux tube)
- ppm or upper-ppb determination levels should be reached for elements which produce min- to hour-lifetime nuclides from fairly abundant isotopes
- **$\rightarrow$ competes with ICP-OES, inferior to ICP-MS but you need no drilling and no preparation/digestion of hundreds or thousands of individual samples, and you won´t destroy information on local structures, redox conditions, organic contents!!**

Thank you for your kind attention – spassiba!