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A. Amato :: Paul Scherrer Institute :: NUM Division

Use of muons to investigate materials:

Not only µSR…., but also the Muon-Induced X-ray Emission (MIXE) Technique

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Swiss National Science Foundation

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- B. Hoffmann, Bern
- K. Ninomiya and A. Sato, Osaka University
- and (part of the muX Collaboration)

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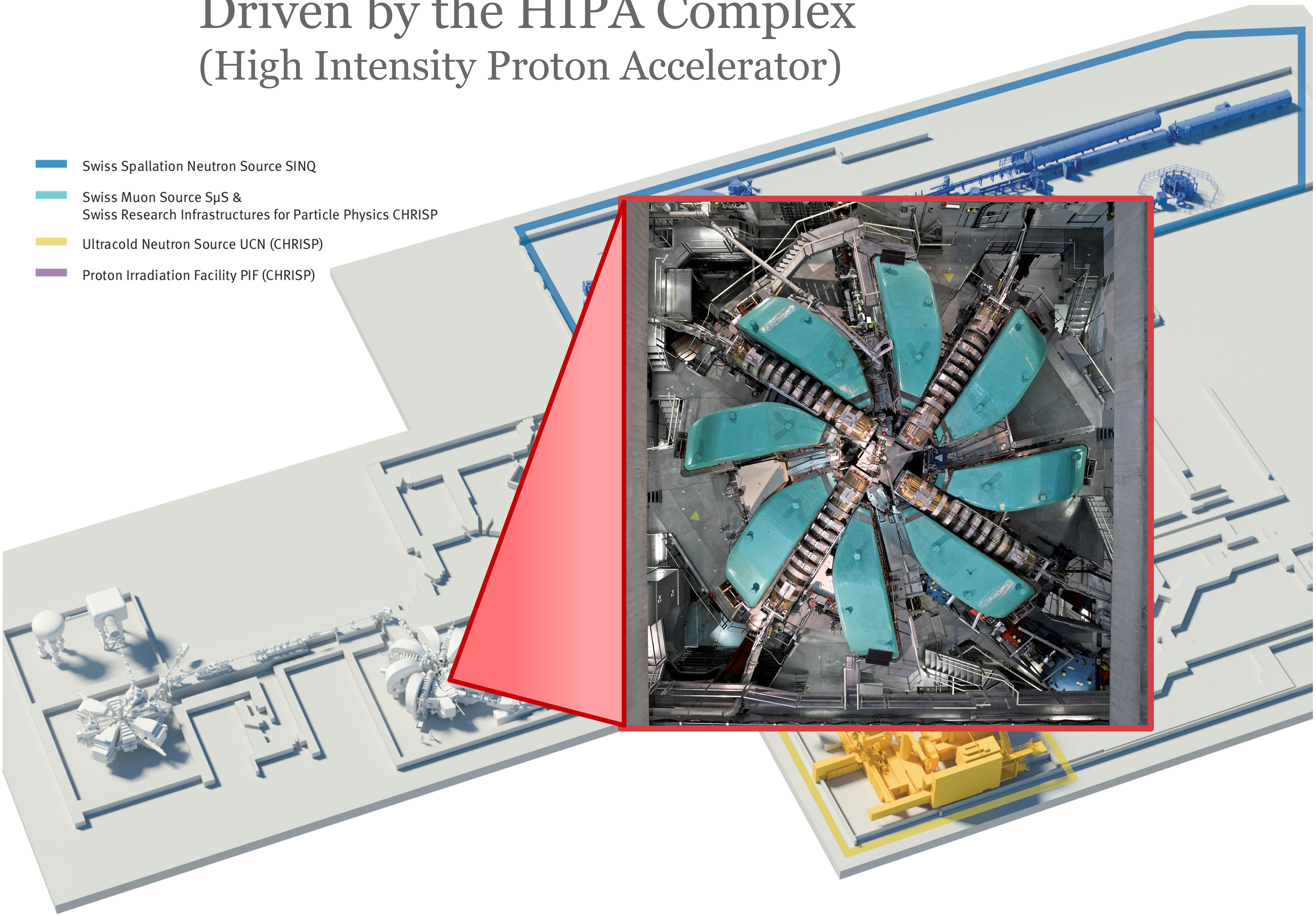
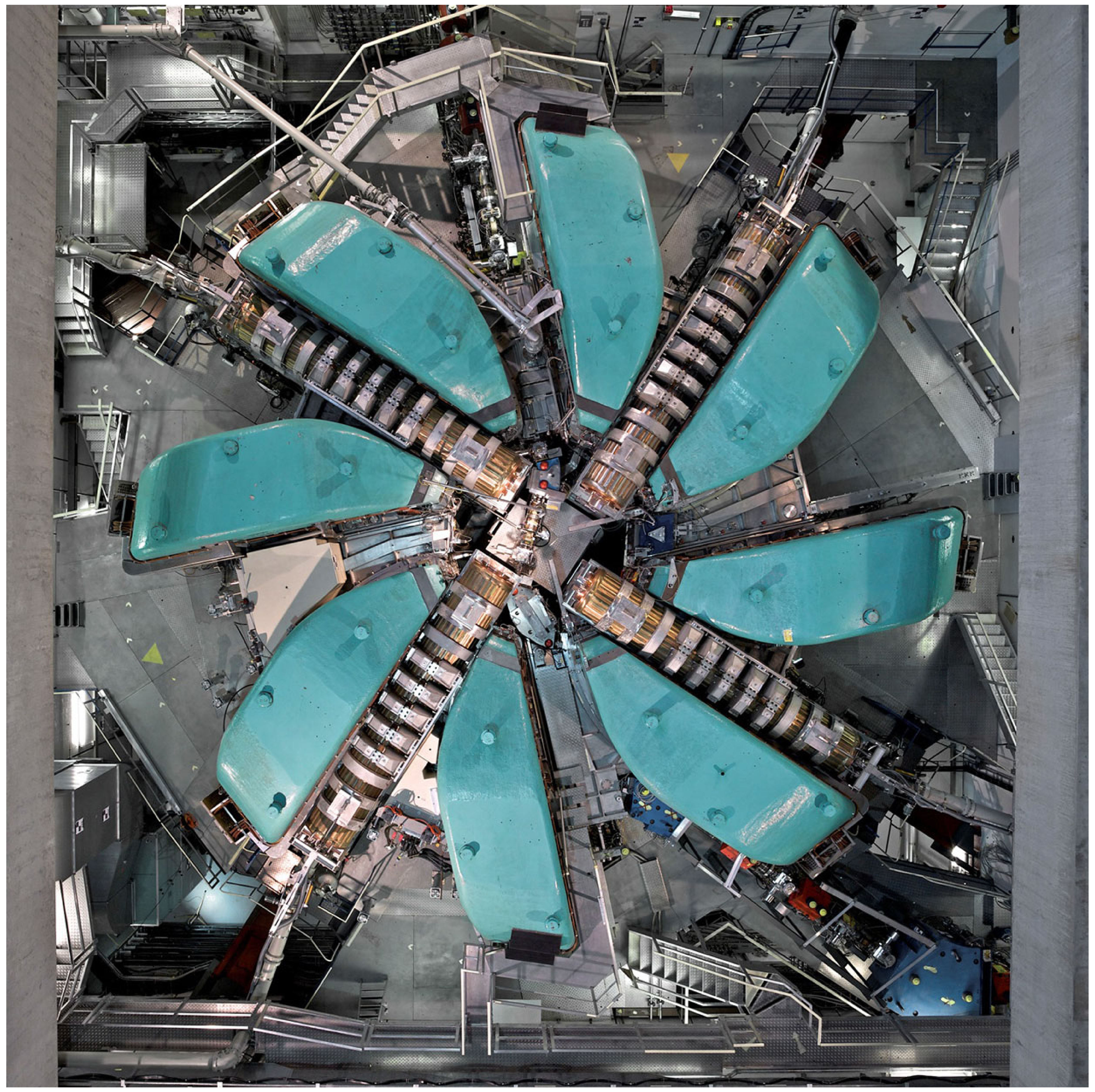
Large Research Facilities at PSI Driven by the HIPA Complex

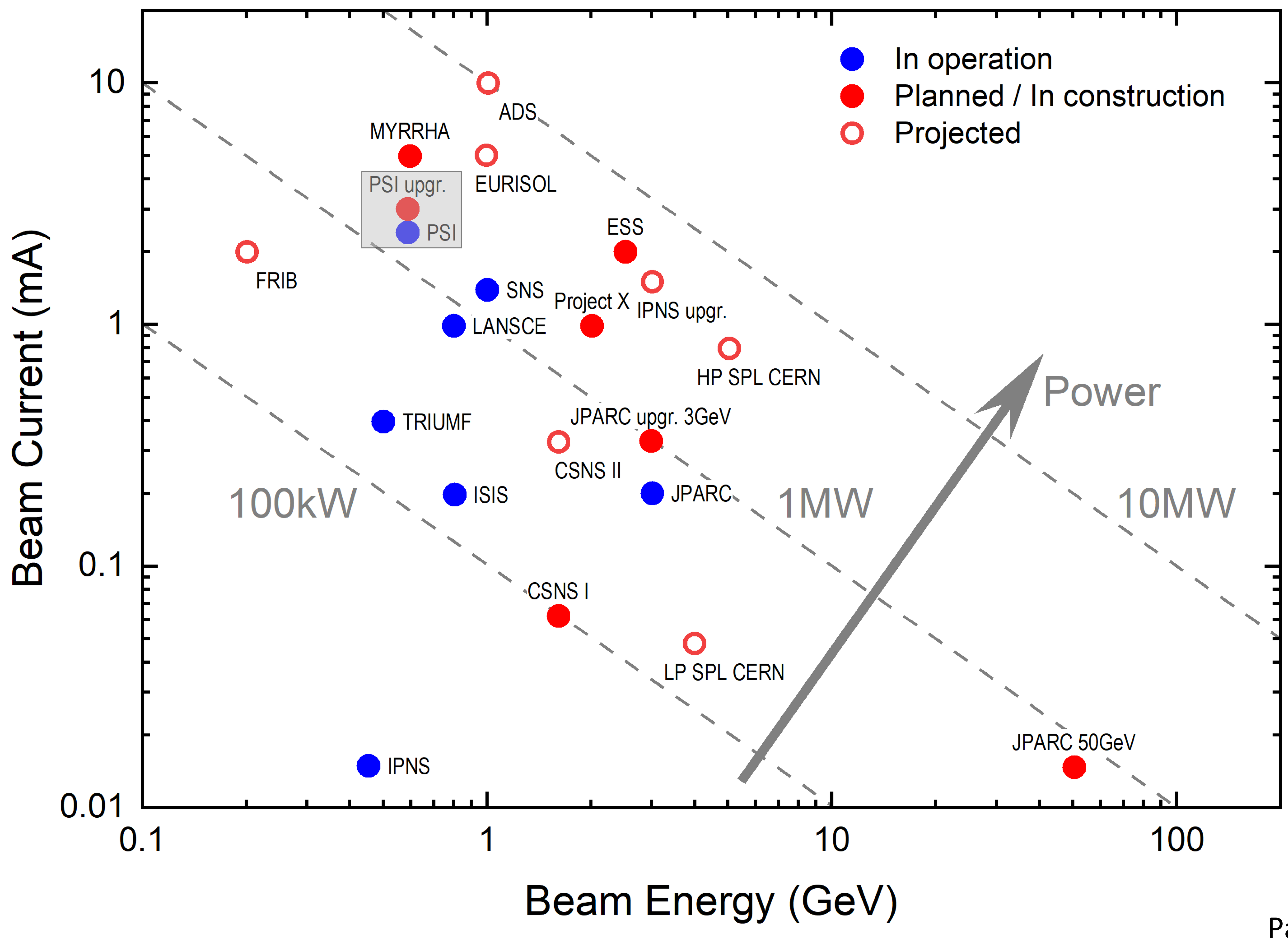
(High Intensity Proton Accelerator)



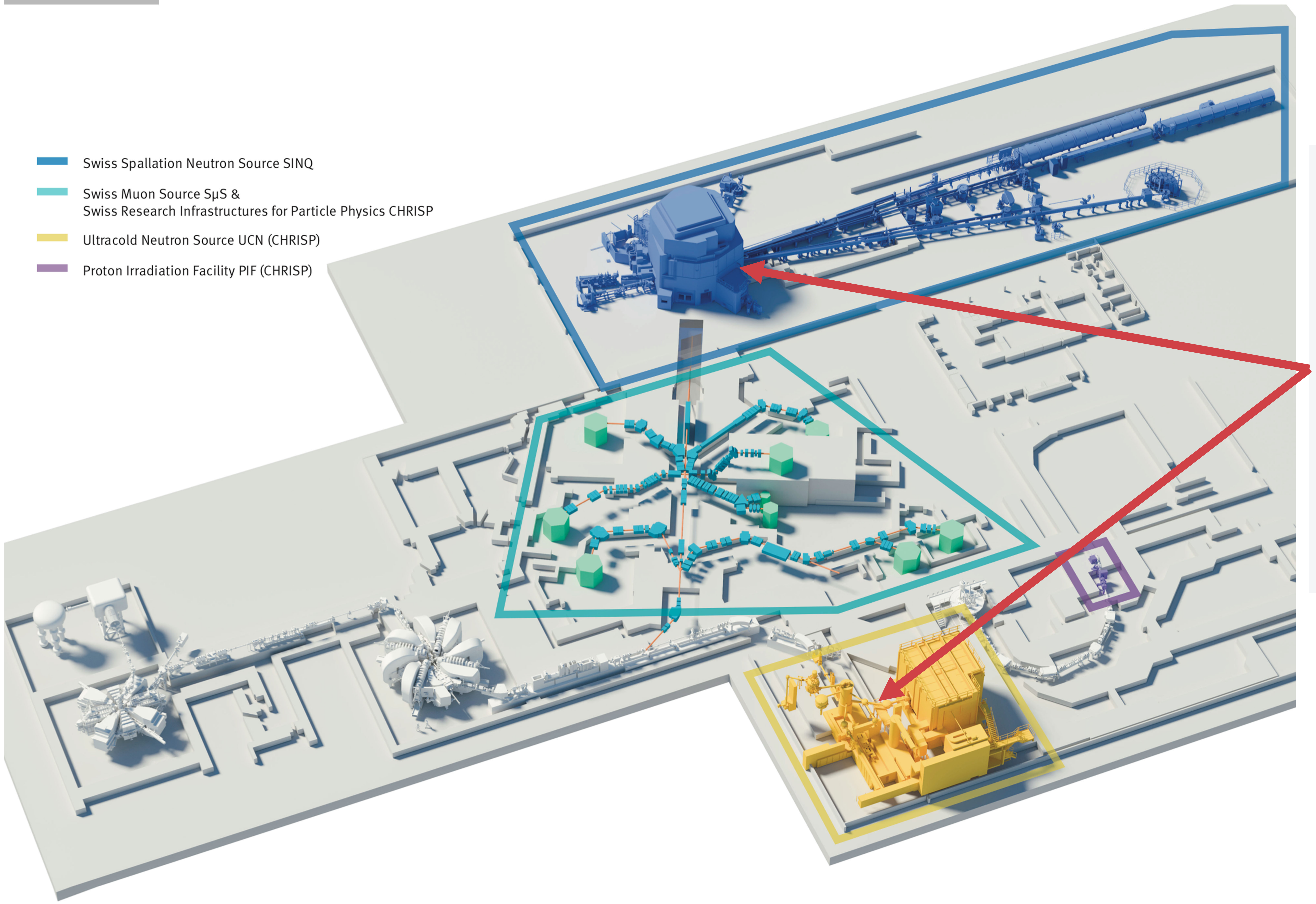
HIPA Proton Accelerator (Overview)

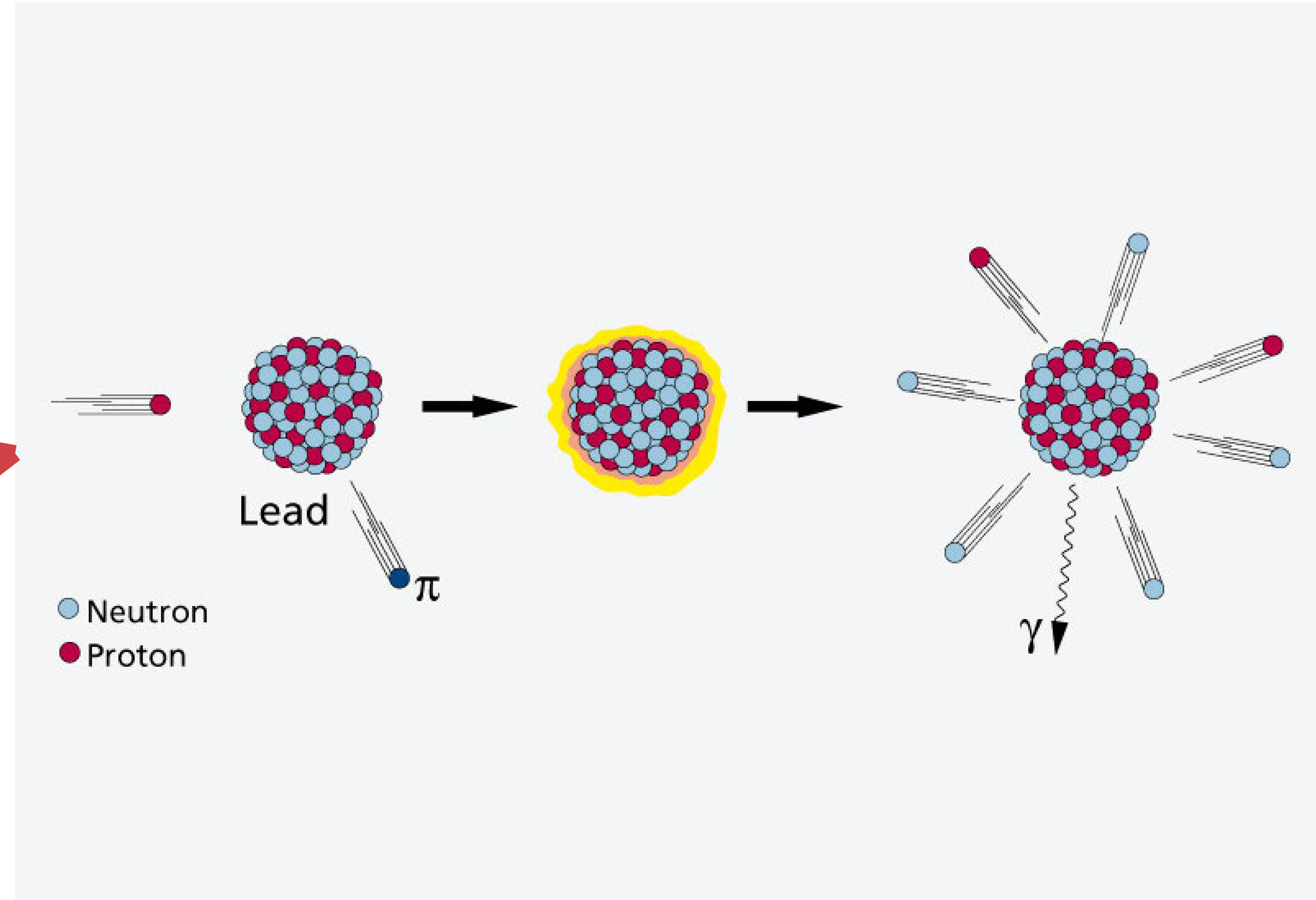


Injection Energy	72 MeV
Extraction Energy	590 MeV
Extraction Momentum	1.2 Gev/c
Energy spread (FWHM)	ca. 0.2 %
Beam Emittance	ca. 2 pi mm x mrad
Beam Current	2.2 mA DC
Accelerator Frequency	50.63 MHz
Time Between Pulses	19.75 ns
Bunch Width	ca. 0.3 ns
Extraction Losses	ca. 0.03 %



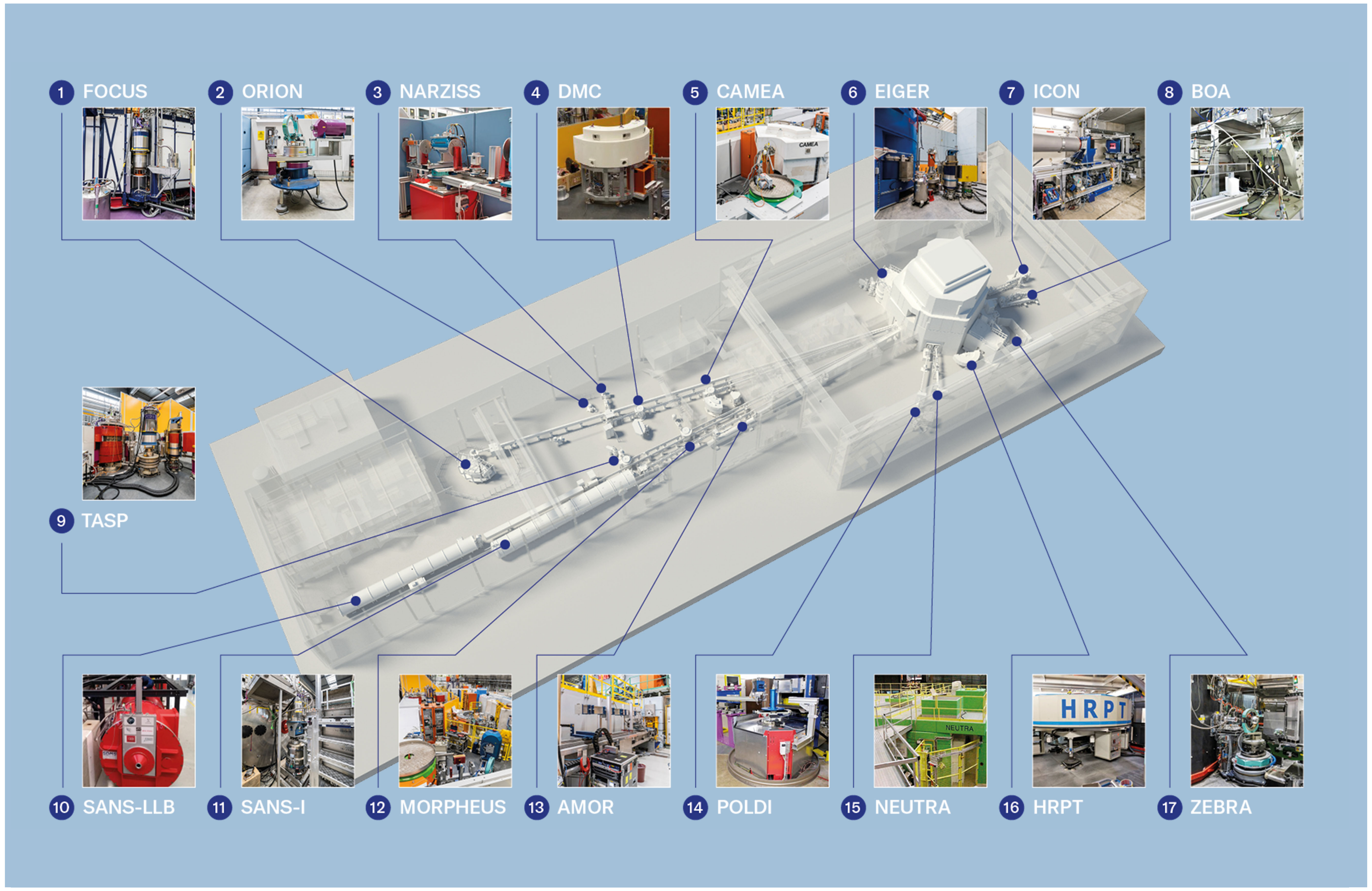
Production of neutrons





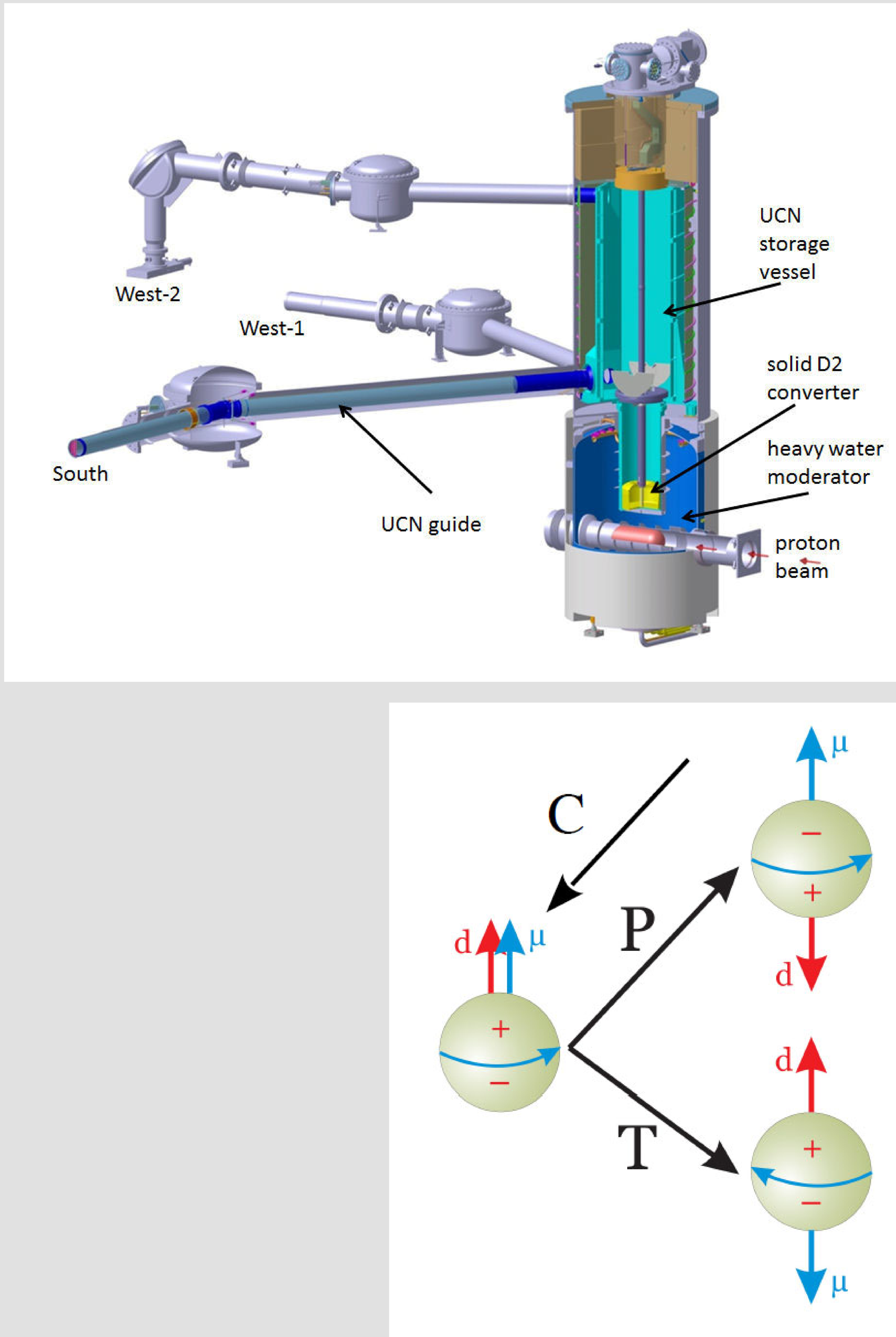
Spallation reactions

Neutrons for Condensed Matter and Particle Physics

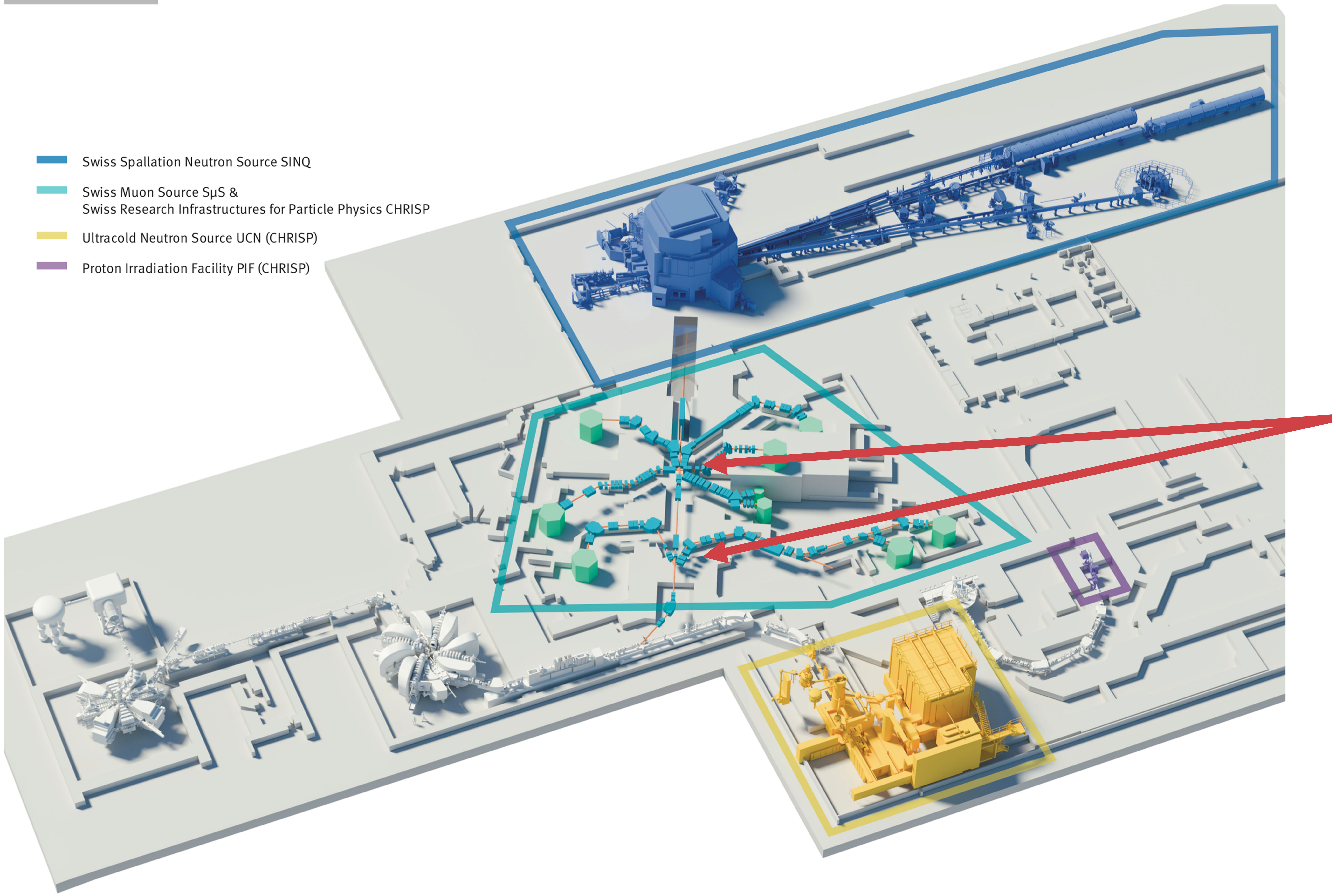


SINQ

n-EDM (neutron – Electrical Dipole Moment)



Production of muons



$$p + p \rightarrow p + n + \pi^+$$

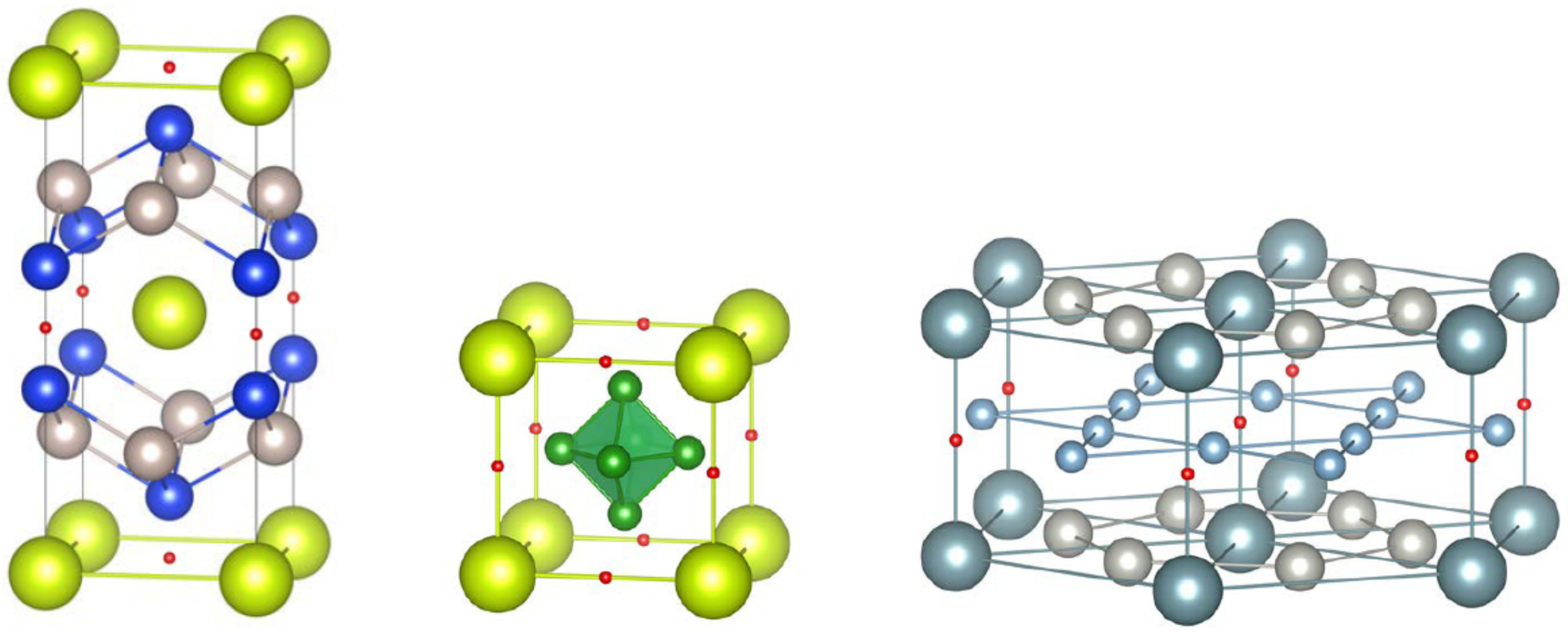
$$p + n \rightarrow n + n + \pi^+$$

$$p + n \rightarrow d + \pi^+$$

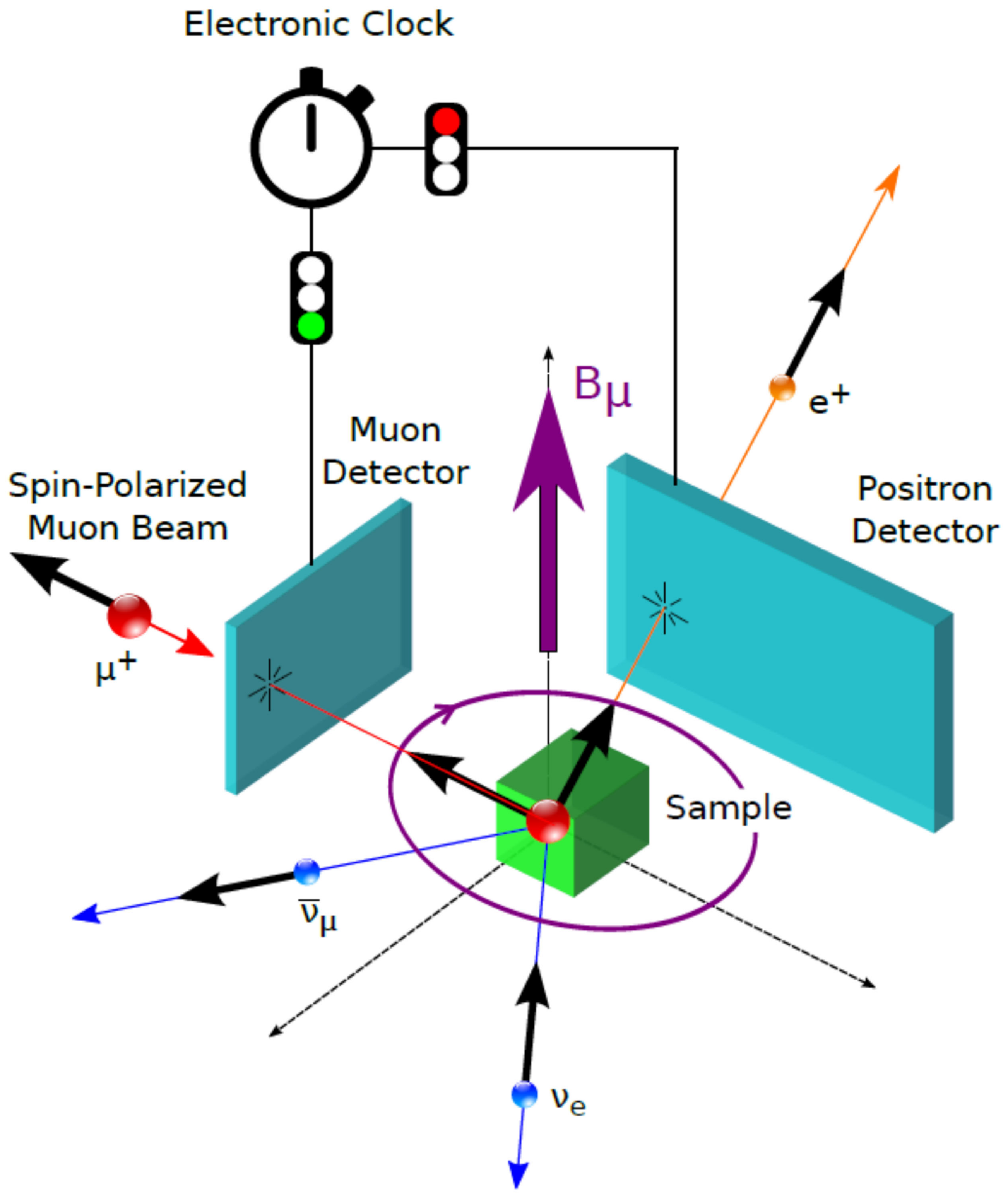
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

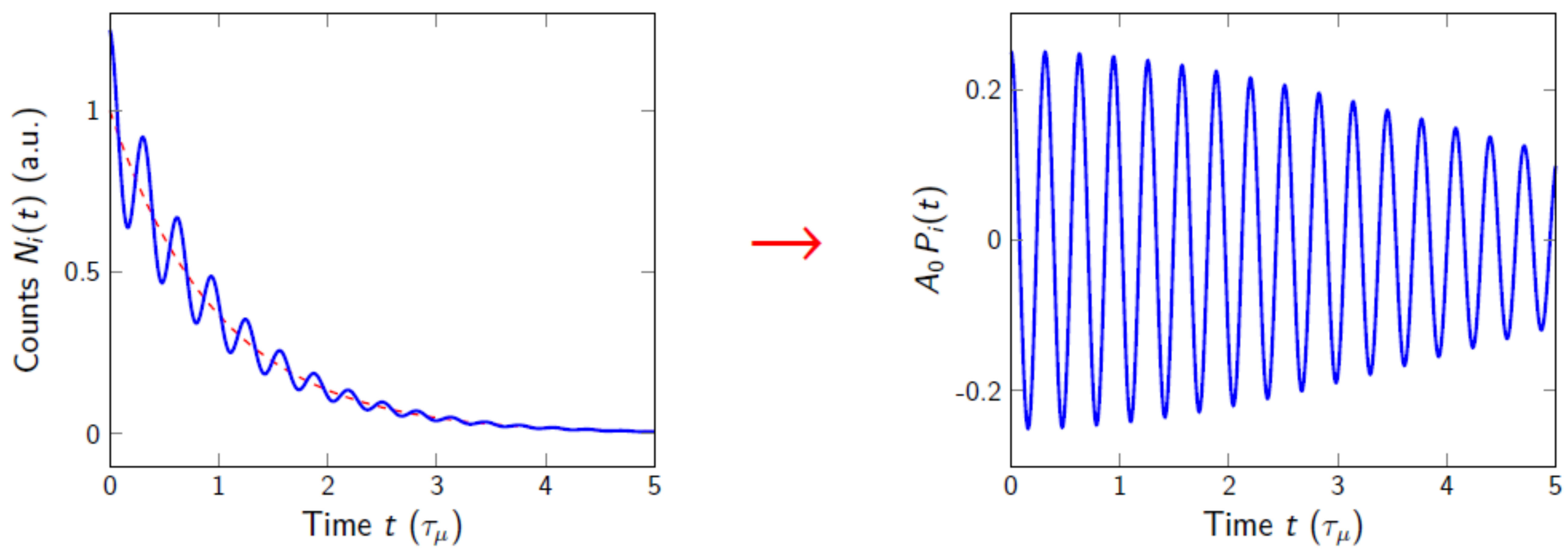
Positive Muons - μSR Technique

- Implant positive muons into a target
  → Muon stays polarized
  → interstitial sites (minimum of electrostatic potential)



- Observe the behaviour of the muon spin (through the positron emmission)





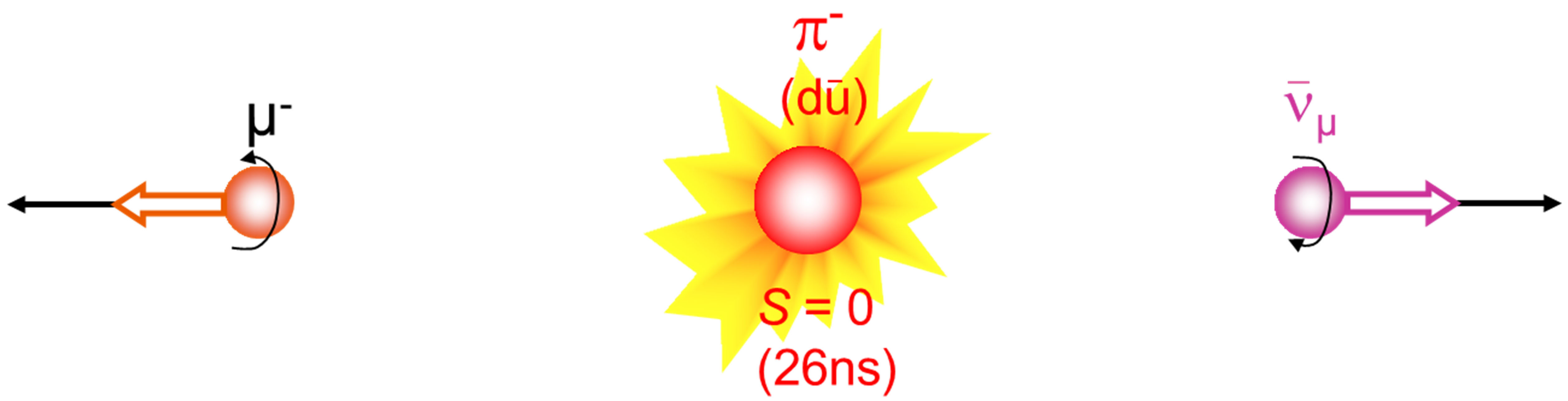
Frequency is a direct measure of the internal field
→ magnetism, SC, diffusion, etc
https://www.psi.ch/de/lmu/lectures

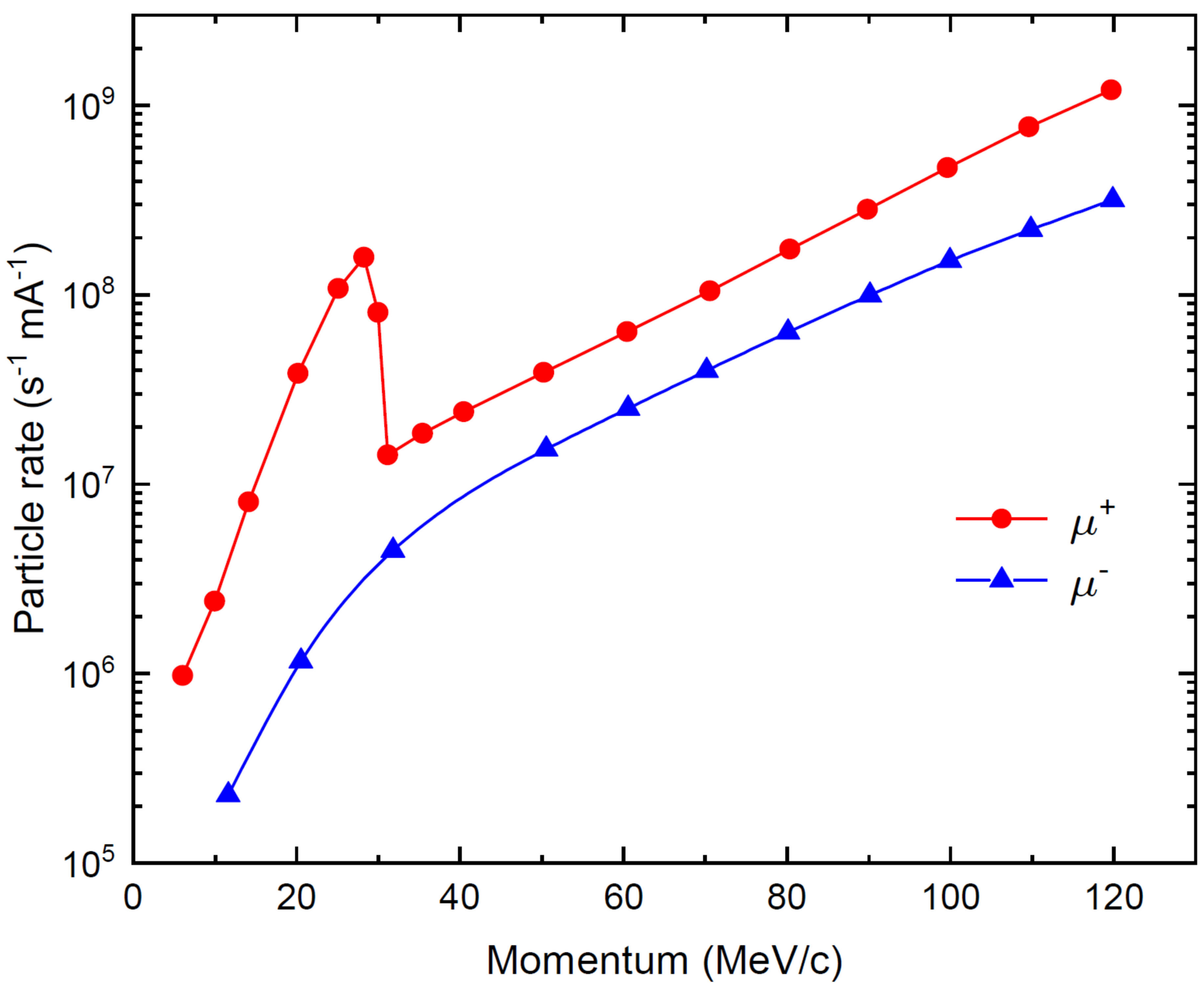
What about negative muons

Negative pions also produced in the production target, e.g.: $p + n \rightarrow p + p + \pi^-$

The negative pion decay into a negative muon:

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$





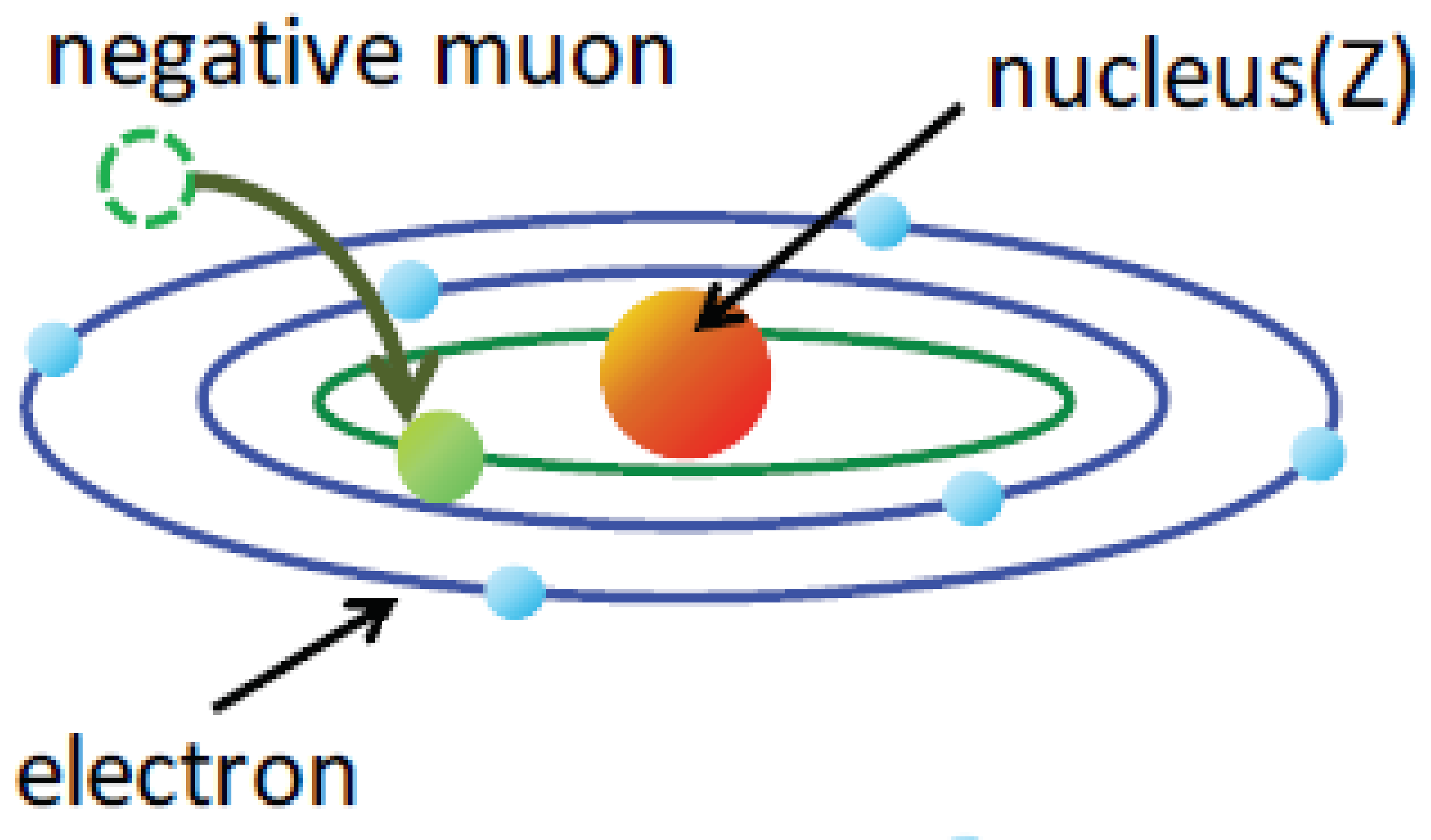
What about negative muons

Subsequently, can be sent into a sample (similar to positive muons).

Negative muons are **captured** by an atom of the sample (do not stop at an interstitial site)

→ **Two captures…**

First Capture: the negative muon is captured by the atom
Capture in a «muonic» orbital
(associated with the emission of
Auger electrons)



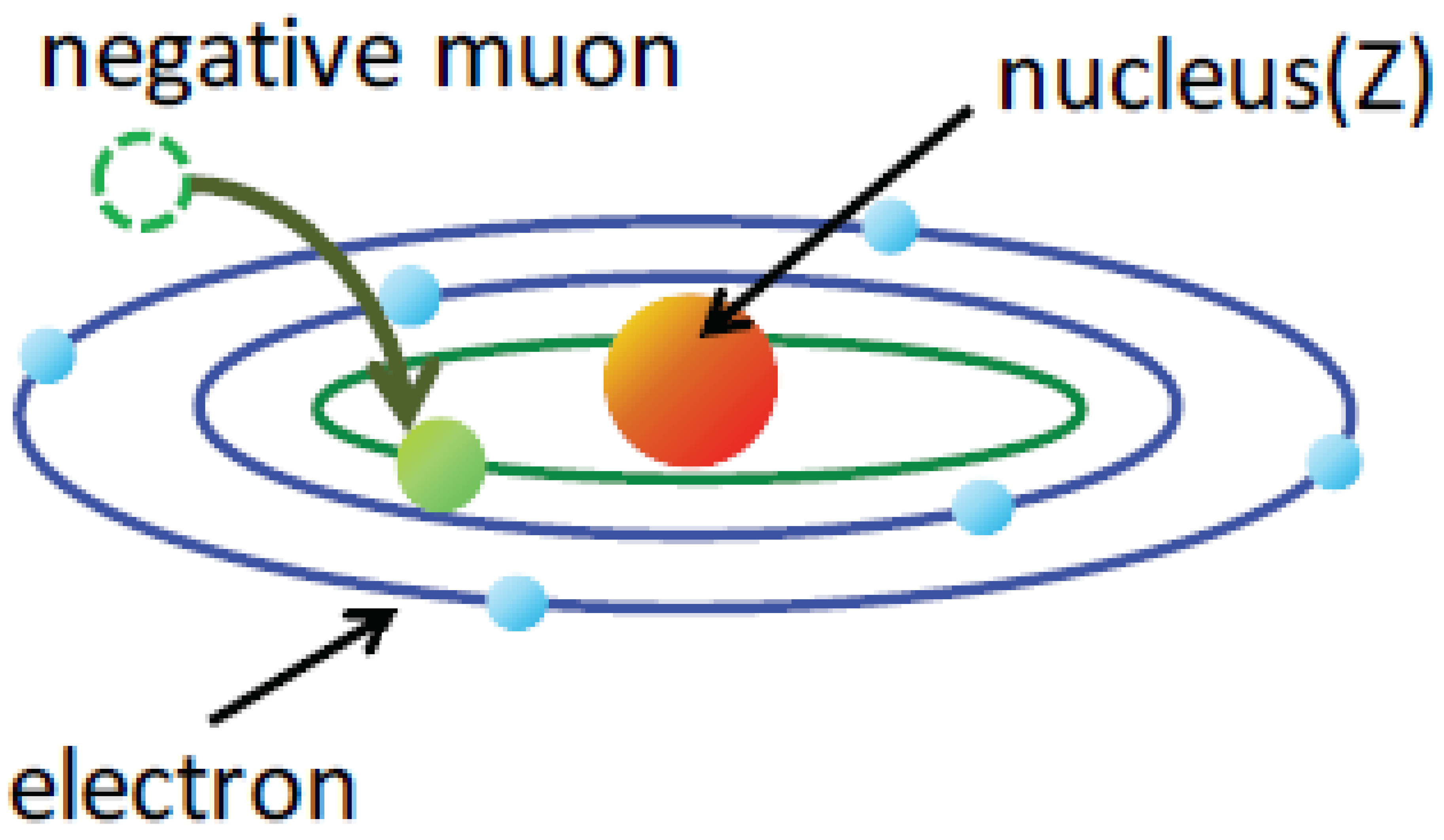
Very close to nuclei…
Since the muon has a mass about 207 times higher that the one of the electron, its orbits will be a factor 207 closer to the nucleus than the respective ones of the electron.

$$r_{n,\mu} = \frac{4\pi\varepsilon_0\hbar^2\, n^2}{\bar{M}_\mu Z e^2} = \frac{\hbar n^2}{\bar{M}_\mu Z c\alpha}$$

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$ fine structure constant

What about negative muons – Level energy

The muon cascades down to its 1*s* ground state



Energy of the levels:

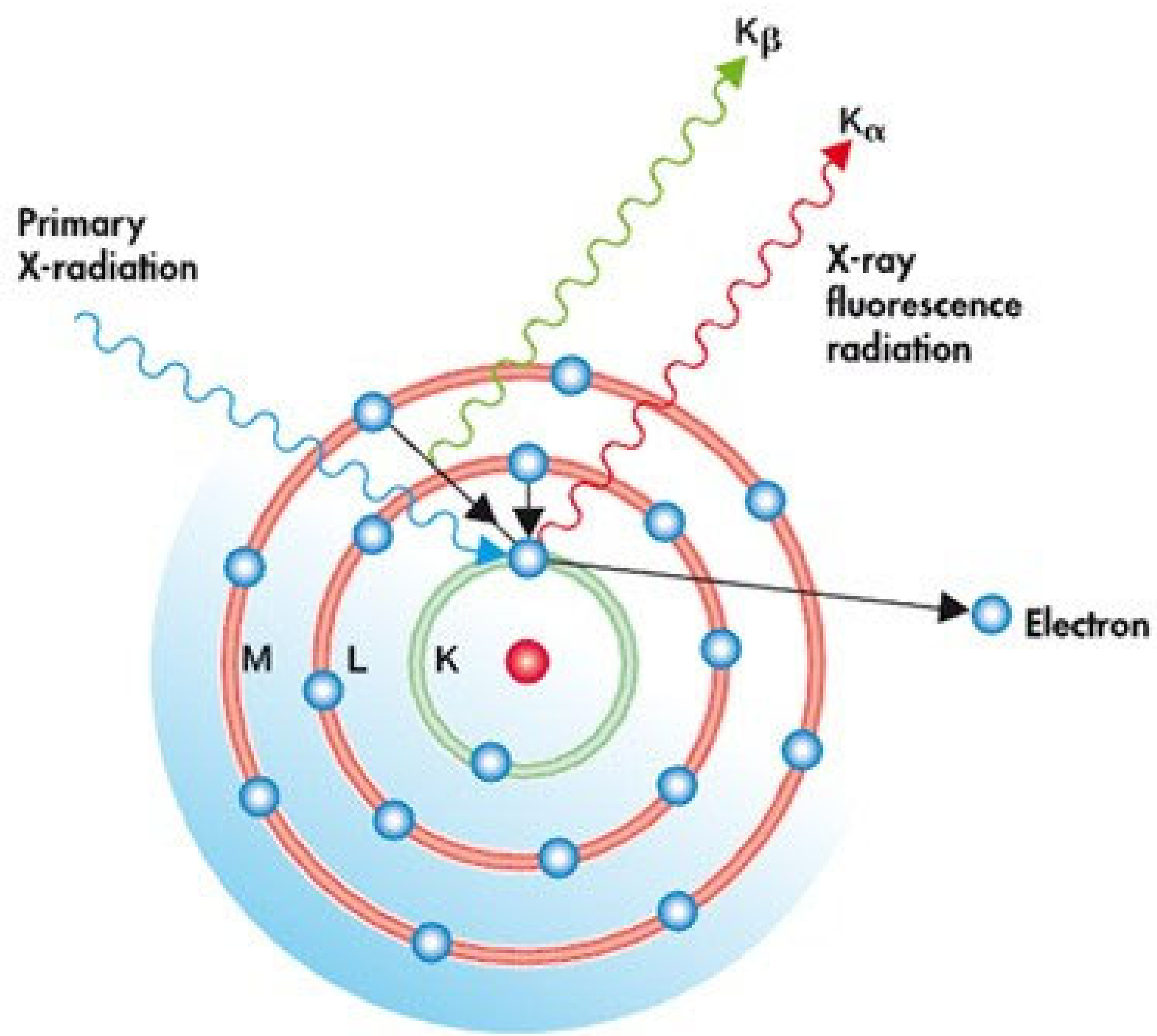
$$E_n = -\frac{\bar{M}_\mu\, Z^2 e^4}{(4\pi\varepsilon_0)^2 2n^2\hbar^2}$$

A bit more precisely:

$$E_n = -\frac{1}{2}\frac{(Z\alpha)^2\bar{M}_\mu c^2}{n^2} - \frac{\bar{M}_\mu c^2}{2n^4}\left(\frac{n}{j+\frac{1}{2}} - \frac{3}{4}\right)(Z\alpha)^4 + \ldots$$

What about negative muons – X-ray energy

As for the XRF (X-ray fluorescence) technique, X-rays are emitted during the muon cascade



- Remember for the electrons (Moseley law)

$$E_{i\to f,e} = \frac{\bar{M}_e}{M_e} R_y (Z - S_{\mathrm{scr},e})^2 \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

$$Z_{\mathrm{eff}} = (Z - S_{\mathrm{scr},e})$$

$$R_y = \frac{M_e e^4}{8\varepsilon_0^2 h^2}$$

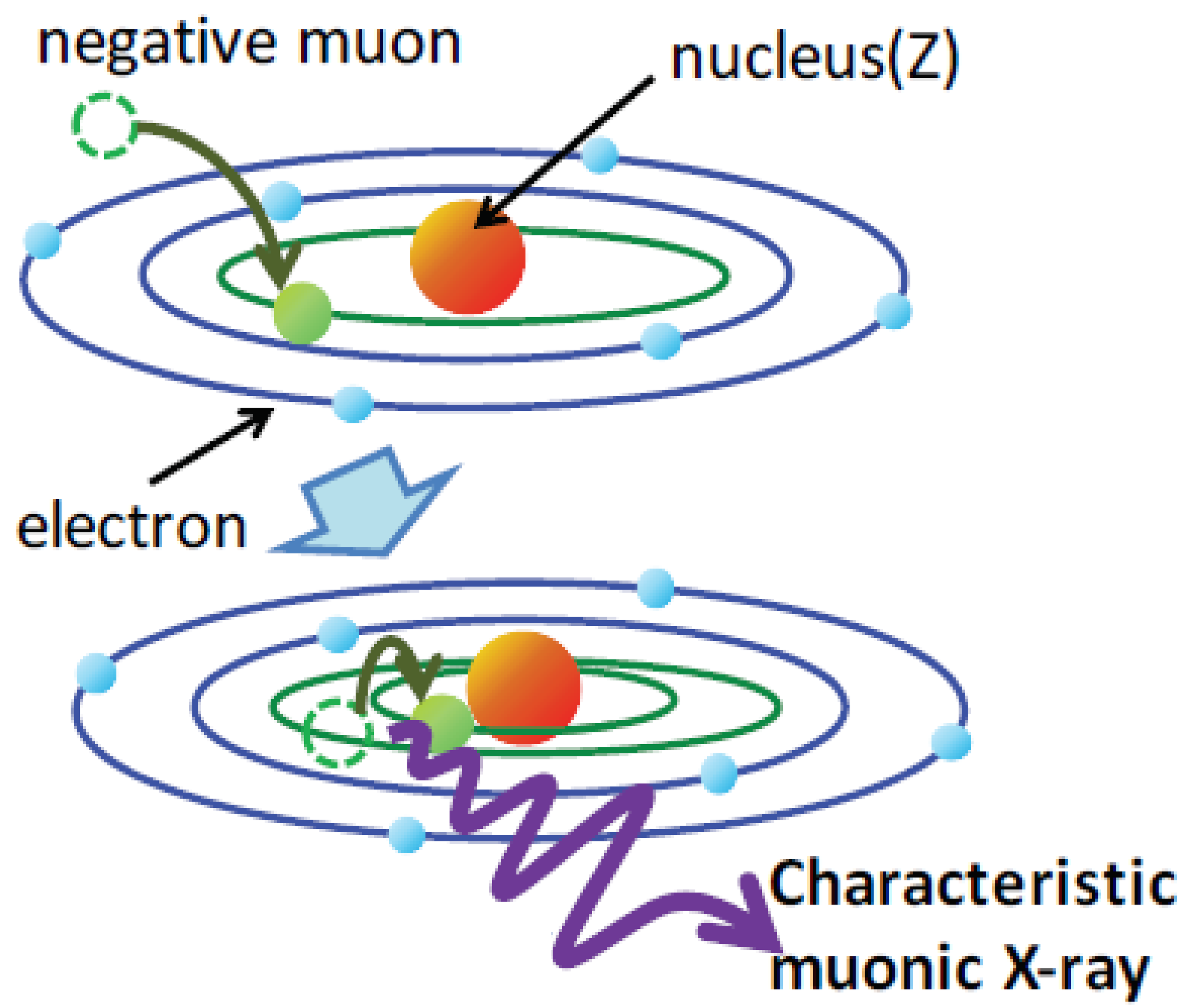
- **For the muon:….**

Energy of the Muonic X-rays:

$$E_{i\to f,\mu} = \frac{\bar{M}_\mu}{M_e} R_y (Z - S_{\mathrm{scr},\mu})^2 \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$

$$\simeq \frac{\bar{M}_\mu}{\bar{M}_e} \times E_{i\to f,e}$$

$$\simeq 207 \times E_{i\to f,e} \quad .$$



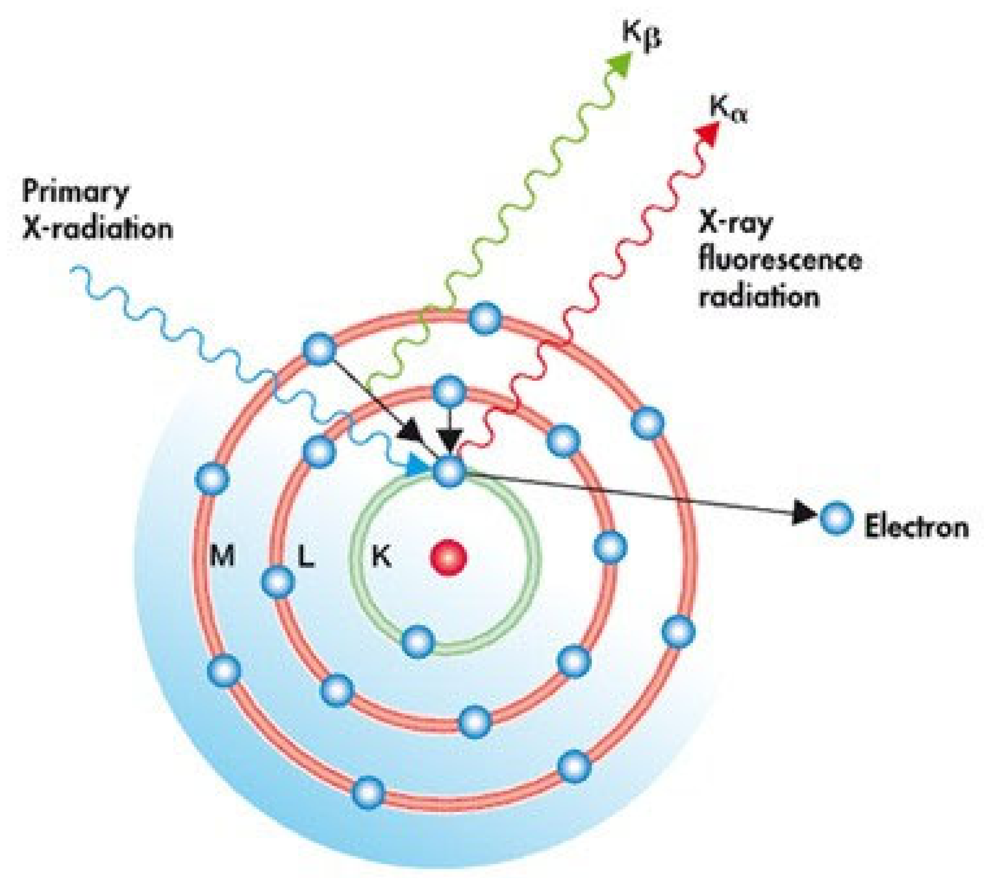
What about negative muons – X-ray energy

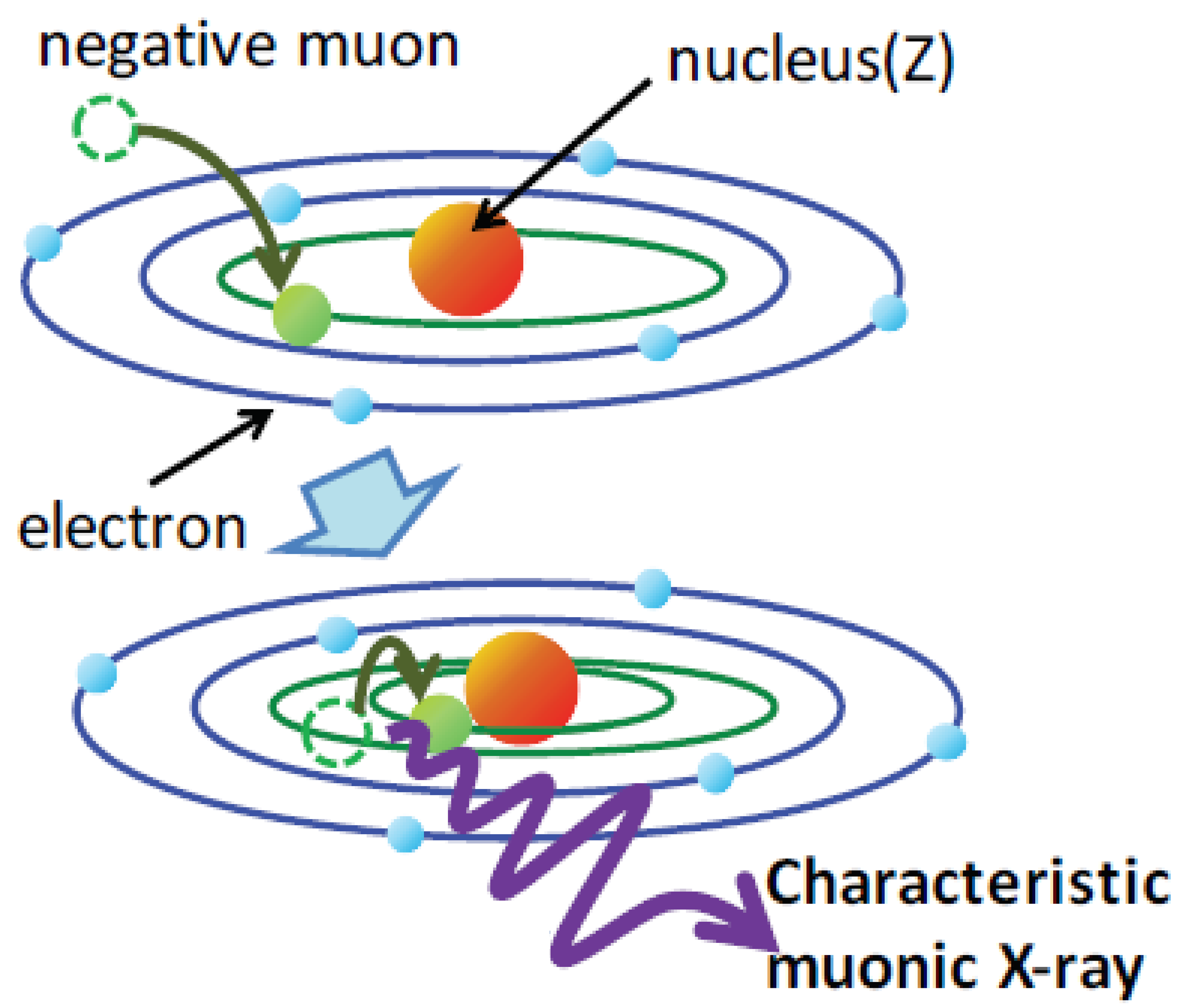
Energy of the X-rays:

$2p_{1/2} \longrightarrow 1s_{1/2}$

$$E_{i\to f,e} = \frac{\bar{M}_e}{M_e} R_y (Z - S_{\text{scr},e})^2 \left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

$$E_{i\to f,\mu} = \frac{\bar{M}_\mu}{M_e} R_y (Z - S_{\text{scr},\mu})^2 \left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

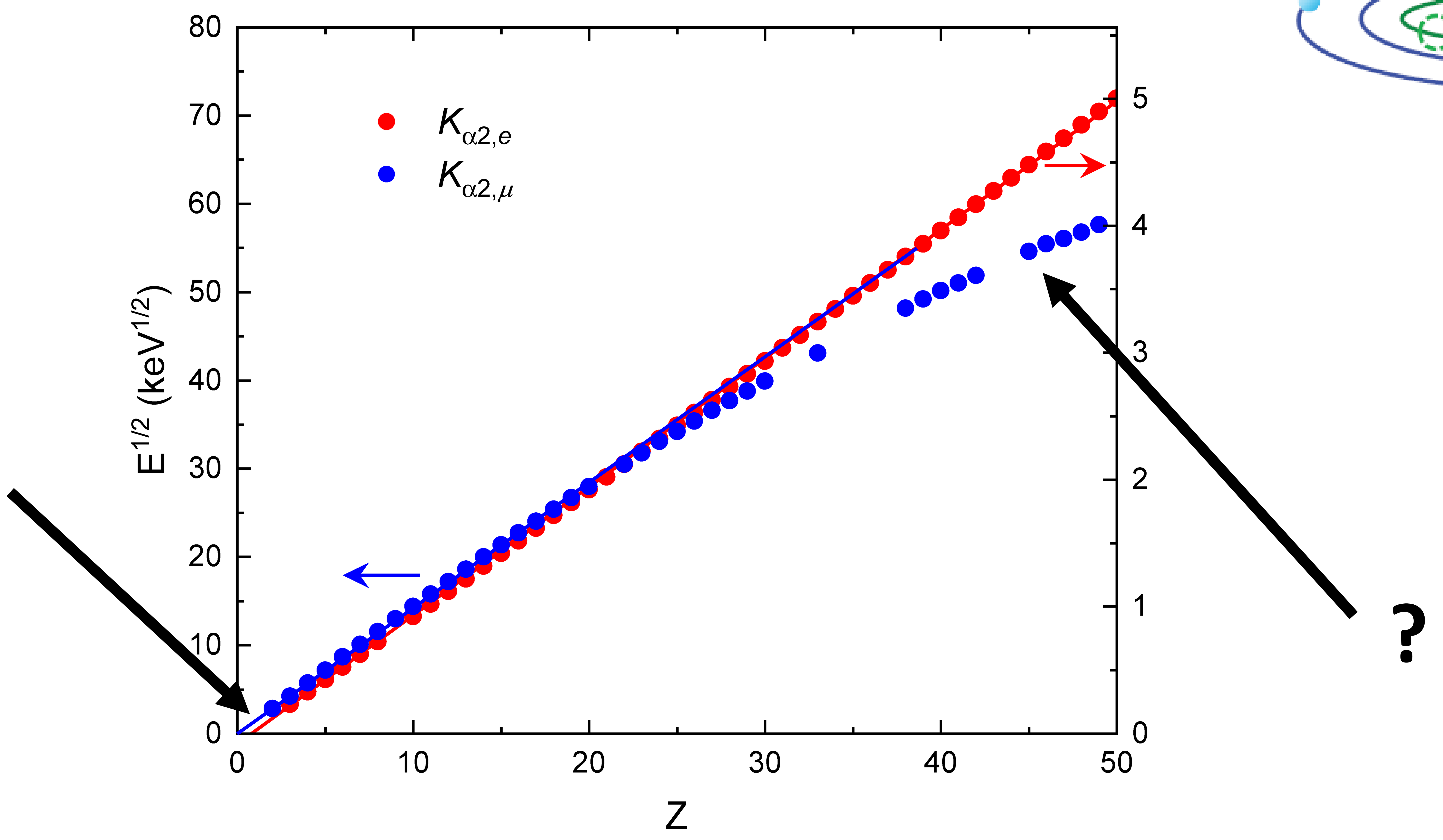




Note:

$S_{scr,\mu} = 0$

$S_{scr,e} = 1$

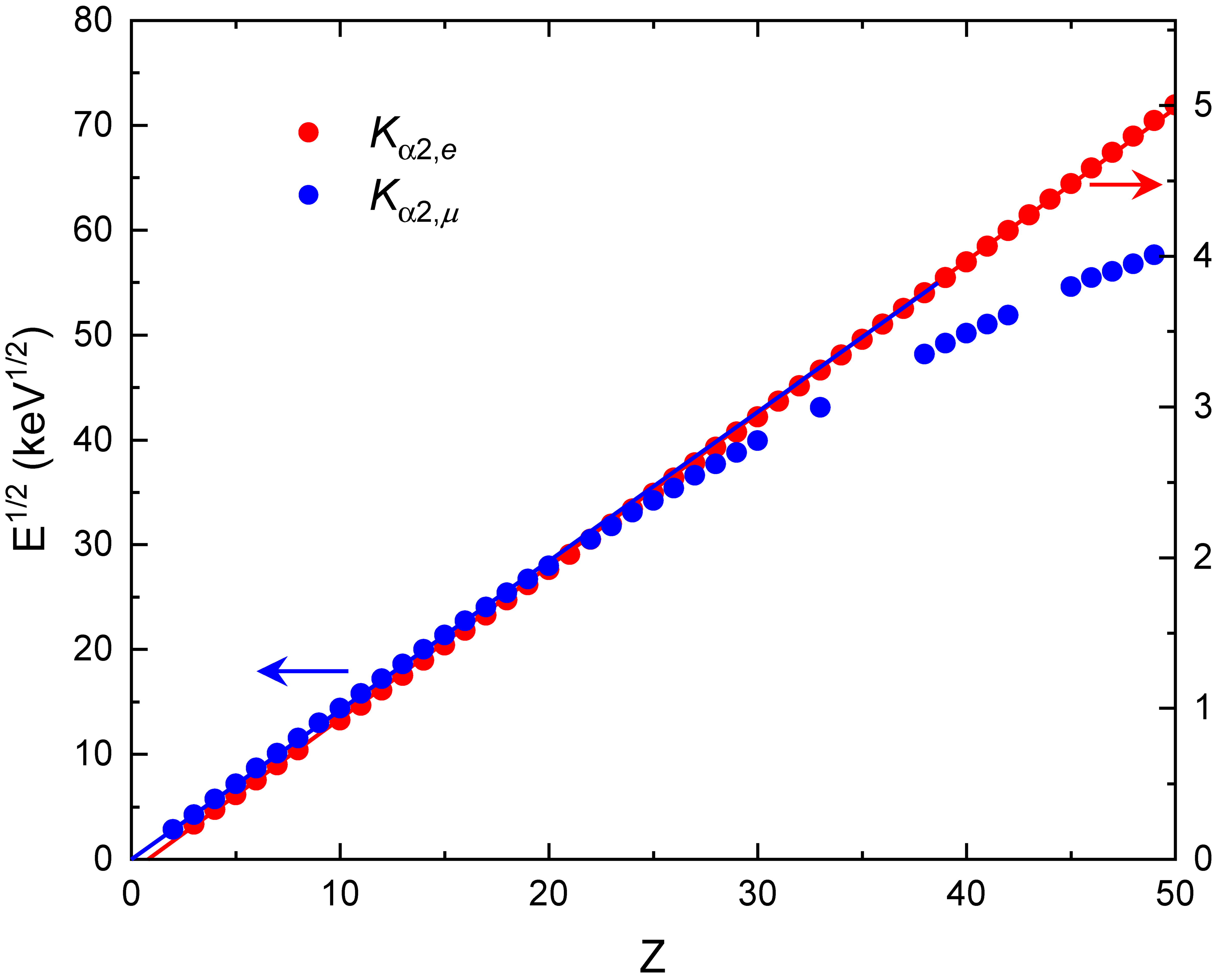


What about negative muons – X-ray energy

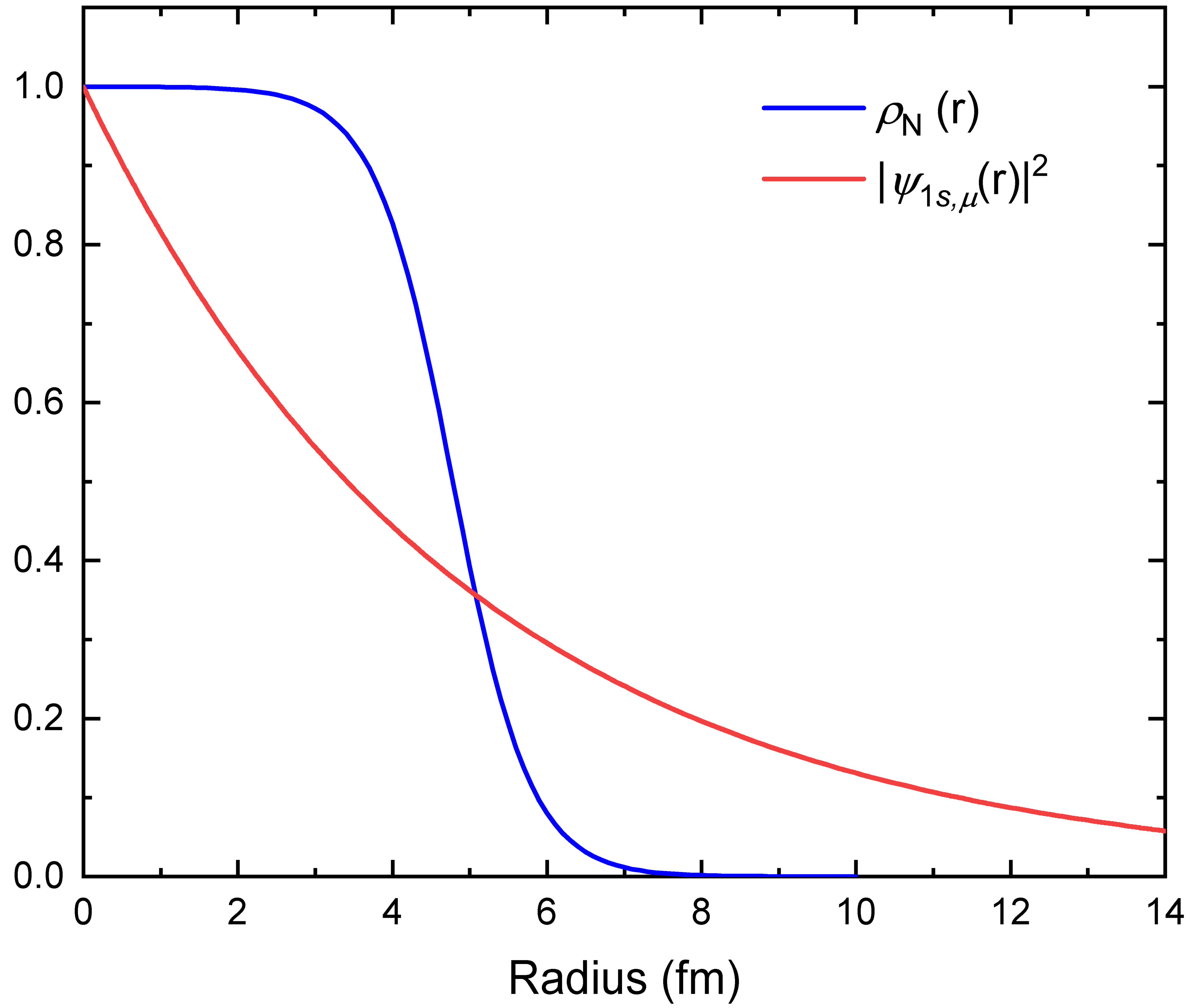
Energy of the X-rays: **Size effects**

For large Z atoms, the muons is so close to the nucleus (radius proportional to $1/Z$) that the nucleus can no more be considered as point-like → **size effects**
Can be used to determined the charge radius of nuclei.

This effect decreases for final levels in the *d* of *f* shell…



Example Iron (Z = 26)

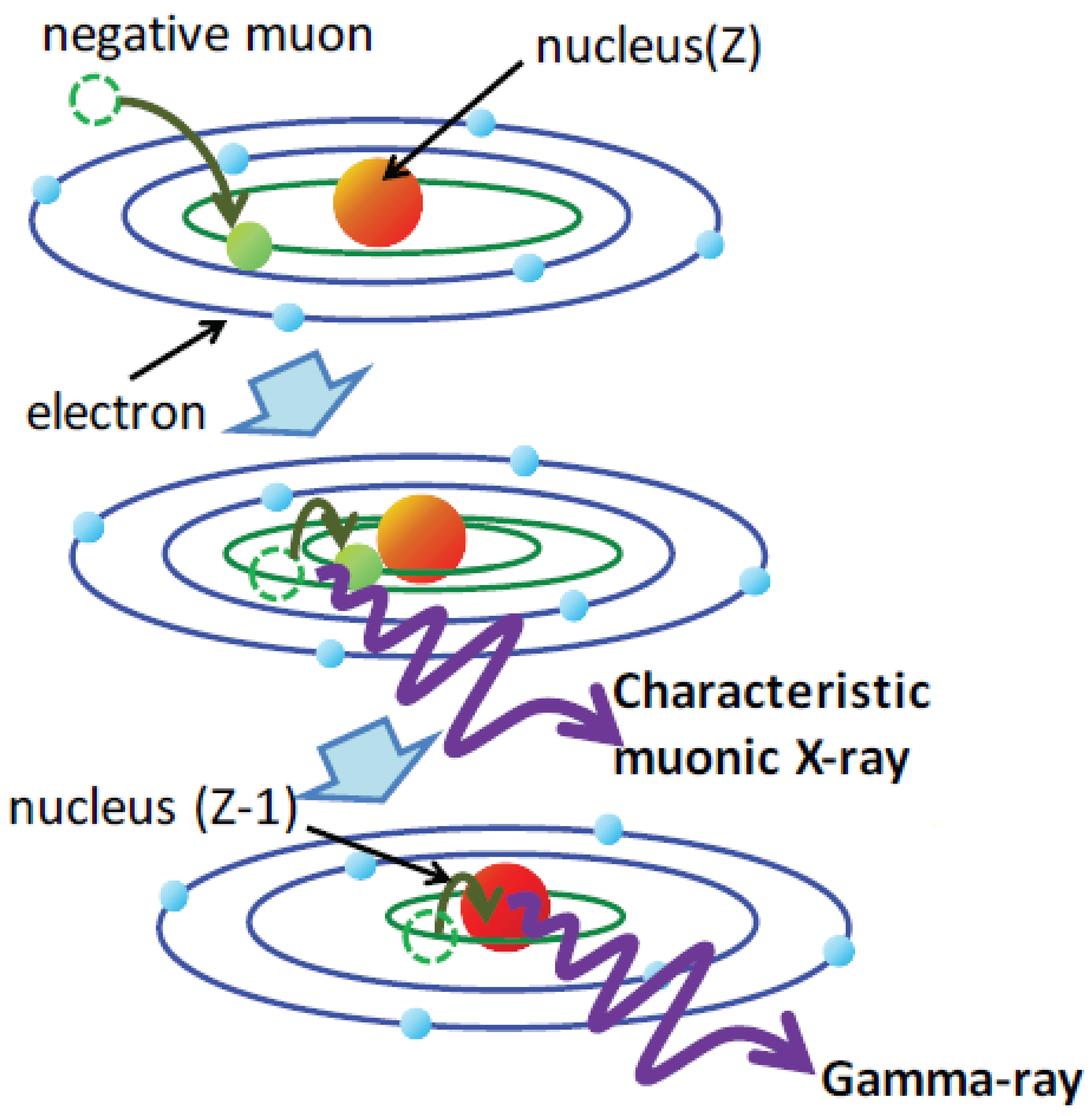


$$\rho_N(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)} \qquad a \simeq 0.5 \text{ fm}, \quad R = r_0 A^{1/3}$$

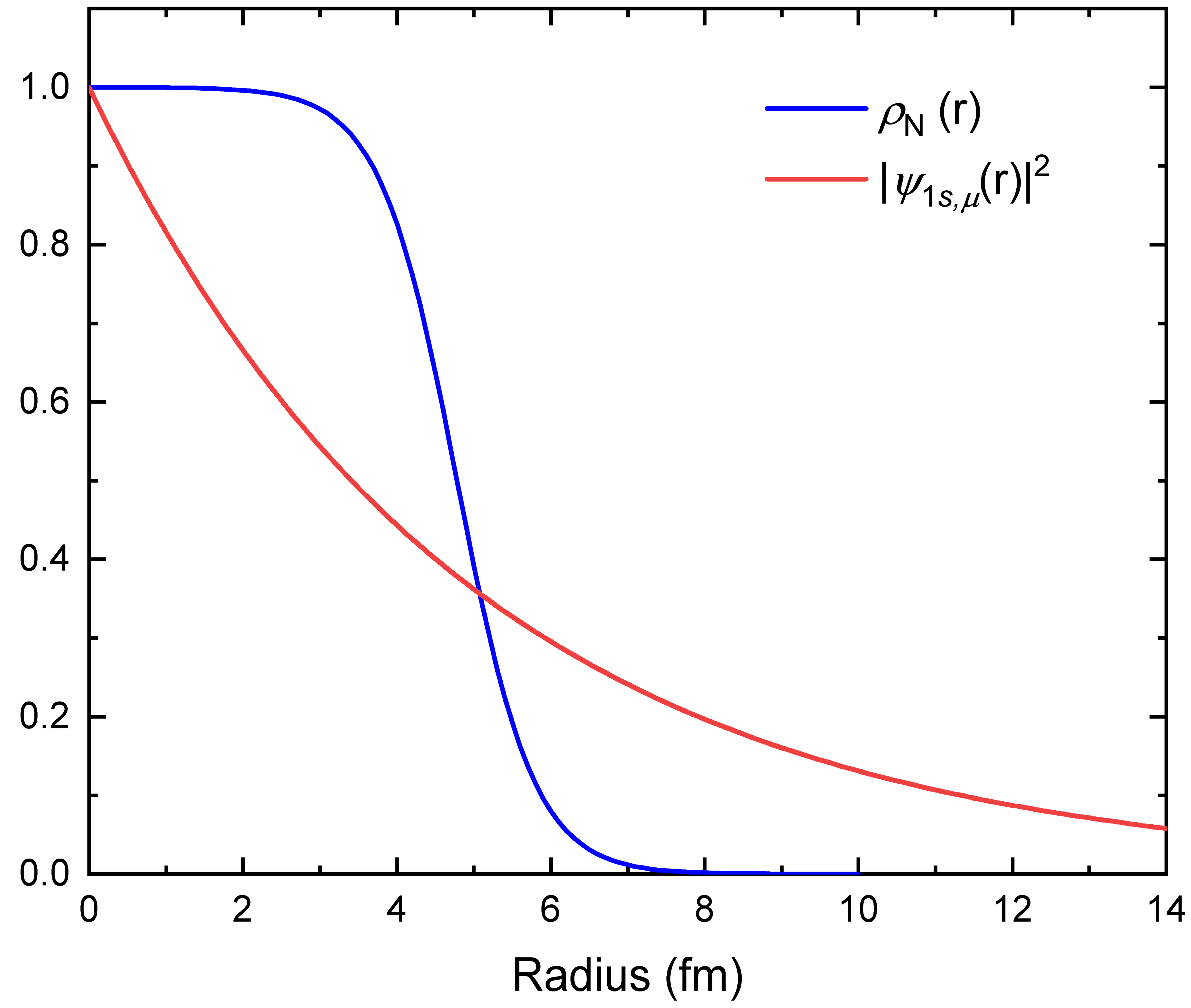
$$|\psi_{1s,\mu}(r)|^2 = \frac{1}{\pi a_{0,\mu}^3} \exp\left(-\frac{2r}{a_{0,\mu}}\right)$$

What about negative muons – Nucleus capture

Second Capture:



$$\mu^- + p \rightarrow n + \nu_\mu$$



Example of Iron:

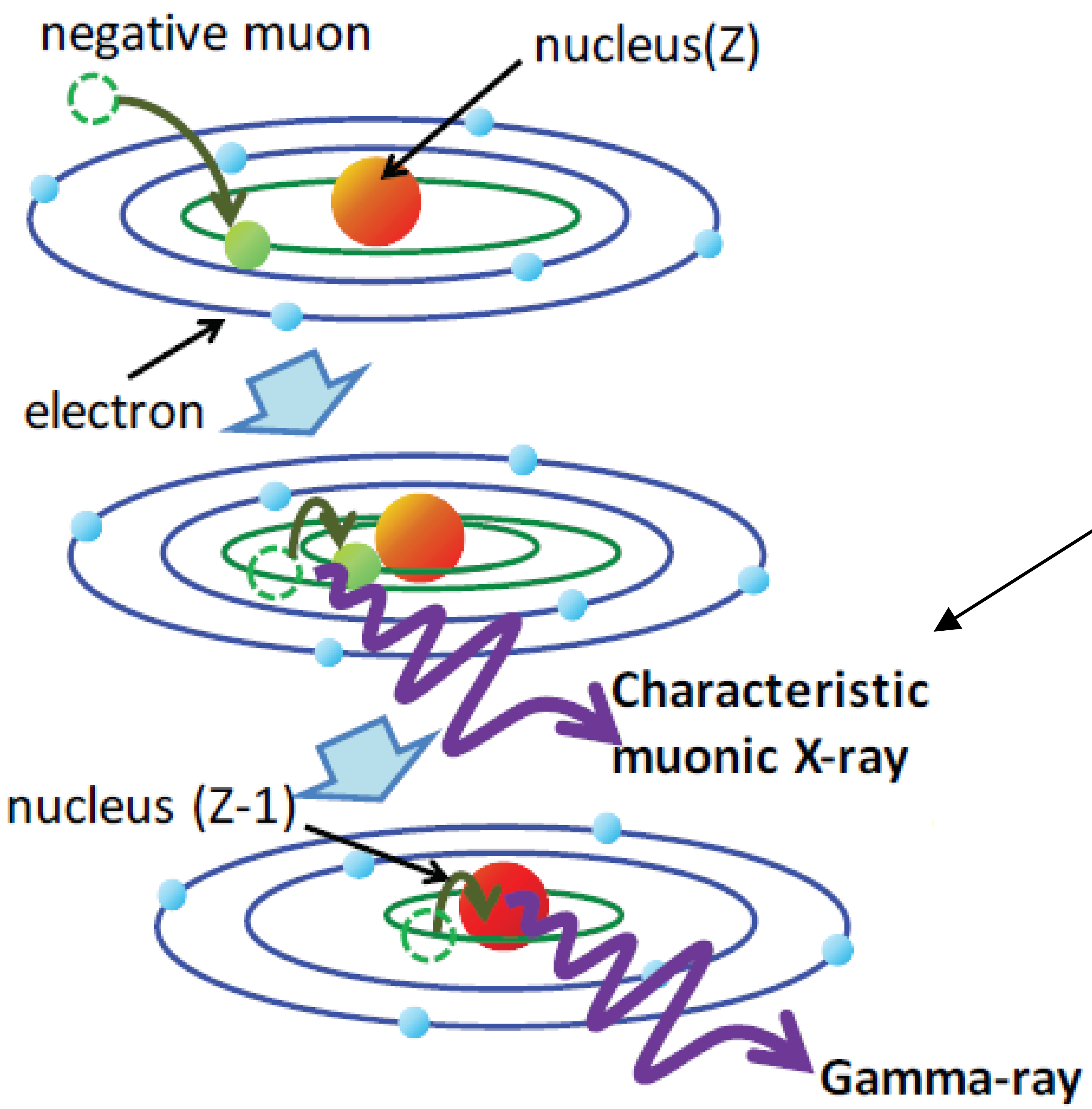
$$\mu^- + {}^{56}_{26}\mathrm{Fe} \rightarrow {}^{56}_{25}\mathrm{Mn}^* + \nu_\mu$$

The excited Manganese nucleus will emit Gamma-rays.
Or one or more neutrons (and later Gamma-rays) can be emitted:

$$\mu^- + {}^{56}_{26}\mathrm{Fe} \rightarrow {}^{55}_{25}\mathrm{Mn}^* + n + \nu_\mu$$

$$\mu^- + {}^{56}_{26}\mathrm{Fe} \rightarrow {}^{54}_{25}\mathrm{Mn}^* + n + n + \nu_\mu$$

What about negative muons – Nucleus capture



$$\mu^- + p \rightarrow n + \nu_\mu$$

«Prompt» X-rays
(i.e. few picosec. after muon arrival)

«Prompt» and «delayed»
Gamma rays characterized by

$$\frac{1}{\tau_{\mu,\text{ Nucl. capt}}(Z)}$$

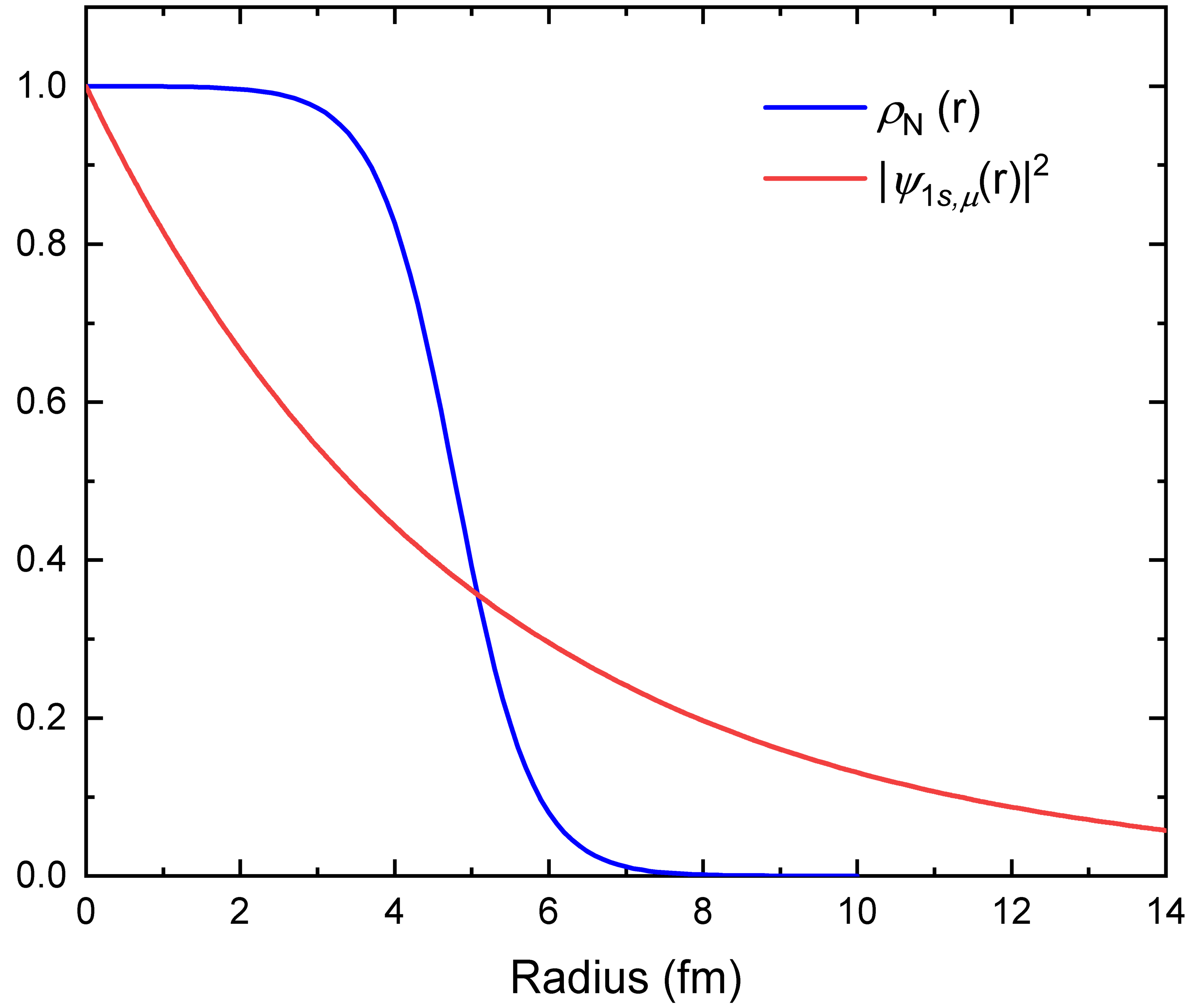
What about negative muons – Lifetime

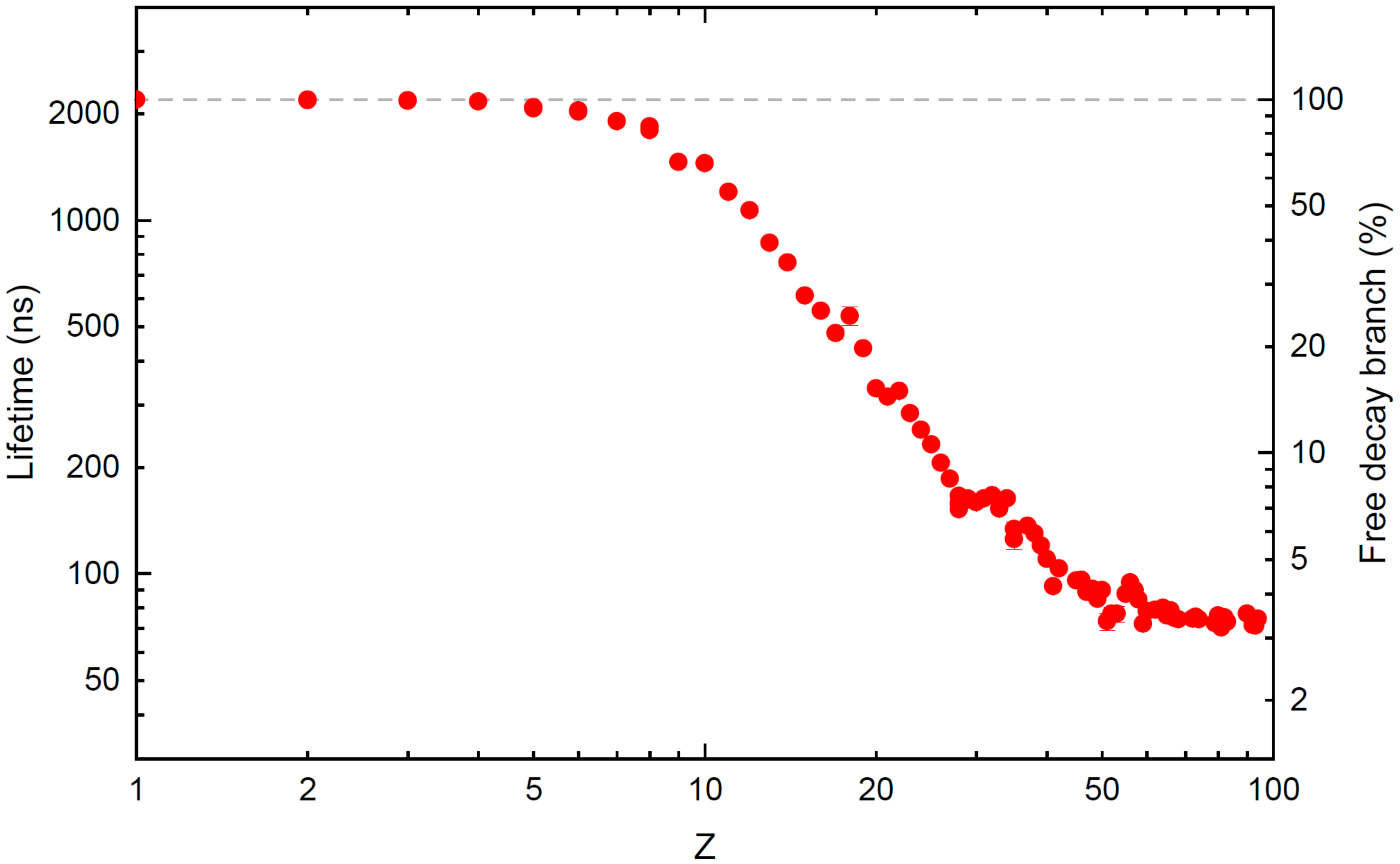
Free negative muon:

$\tau_{\mu,\,\text{free}} = 2.1969811(22) \times 10^{-6}$ sec.

For captured muons:

$$\frac{1}{\tau_\mu(Z)} = \frac{1}{\tau_{\mu,\,\text{free}}} + \frac{1}{\tau_{\mu,\,\text{Nucl. capt}}(Z)}$$

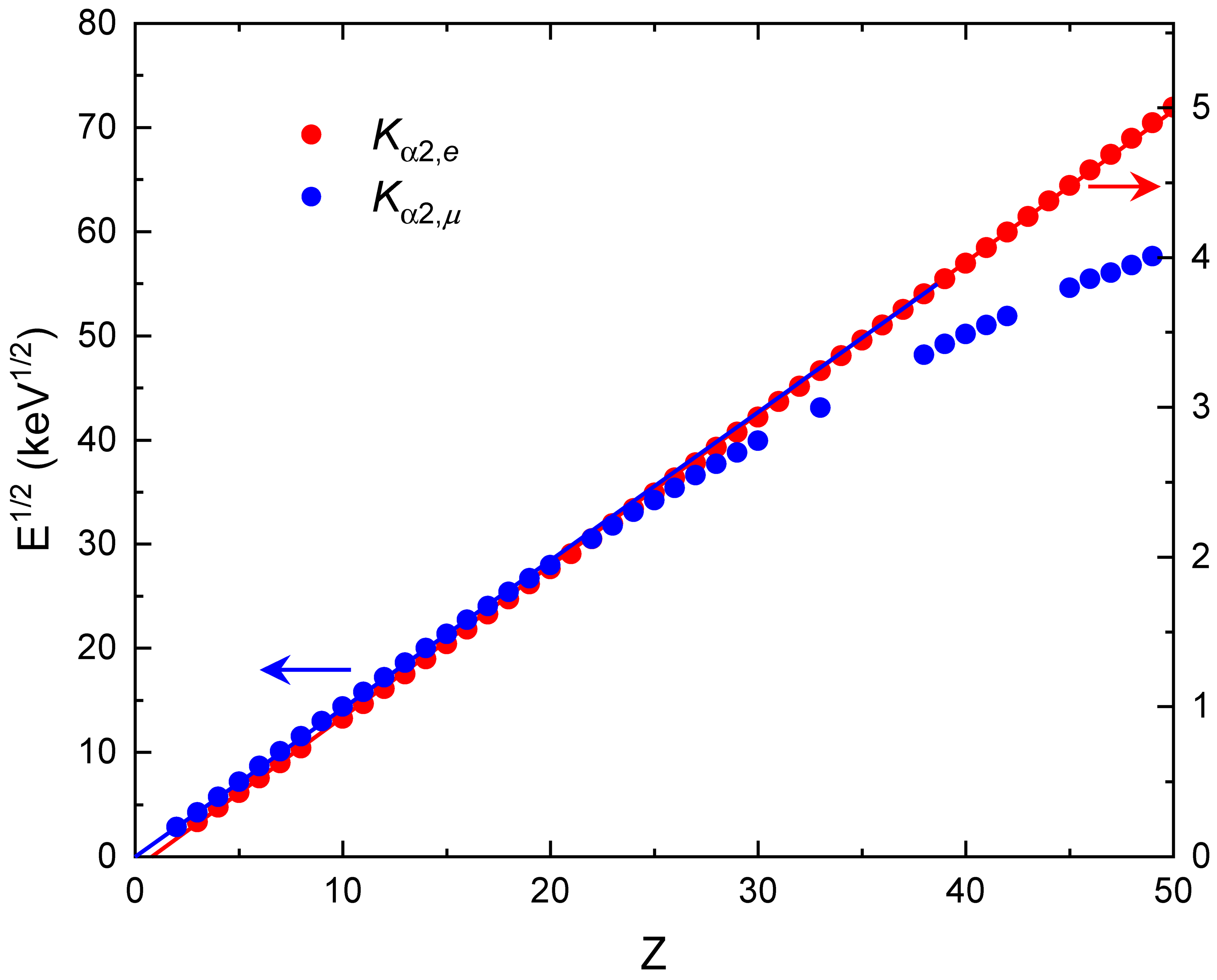


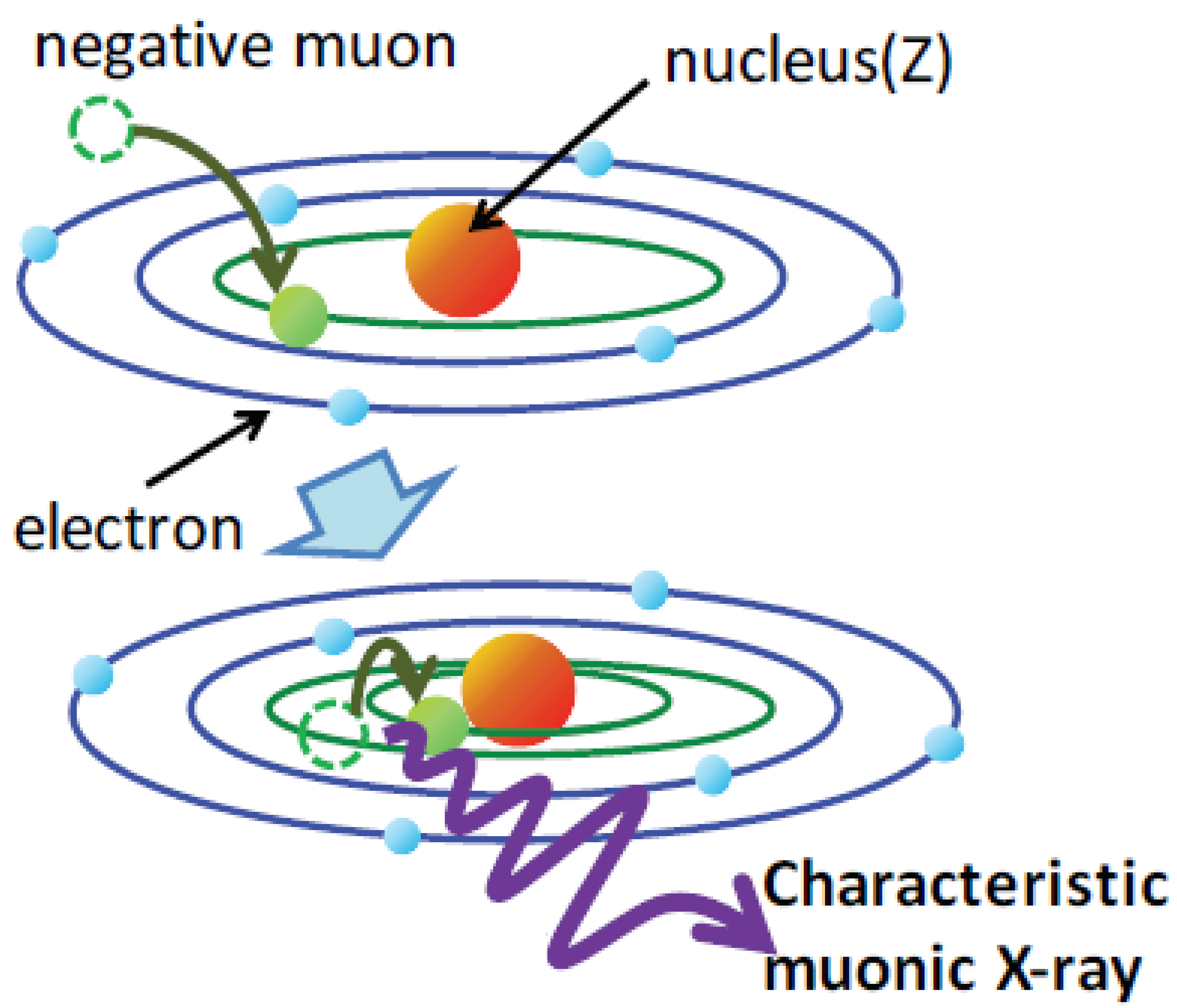


→ **Different lifetimes depending on the atom capturing the muon**

→ **Additional difficulty to perform µSR with negative muons**

What about negative muons – Elemental Analysis





- Possibility to implant the muons at a controlled depth (by changing the muon momentum)
- Characteristic muonic X-rays high energy and can escape from the sample

→ **μ^- : Non-destructive, depth-sensitive probes of elemental composition**

New Technique?

Nuclear Instruments and Methods 187 (1981) 563–568 563
North-Holland Publishing Company

APPLICATION OF MUONIC X-RAY TECHNIQUES TO THE ELEMENTAL ANALYSIS OF ARCHEOLOGICAL OBJECTS

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Physics Department, Technische Universität München, D 8046 Garching, Germany

Received 27 February 1981

The use of muonic X-rays as a tool for elemental analysis is described. Bulk analyses of modern and archeological fired clay samples are presented. Comparison with chemical and neutron activation analyses supplies standards for future measurements. Scanning techniques are also described.

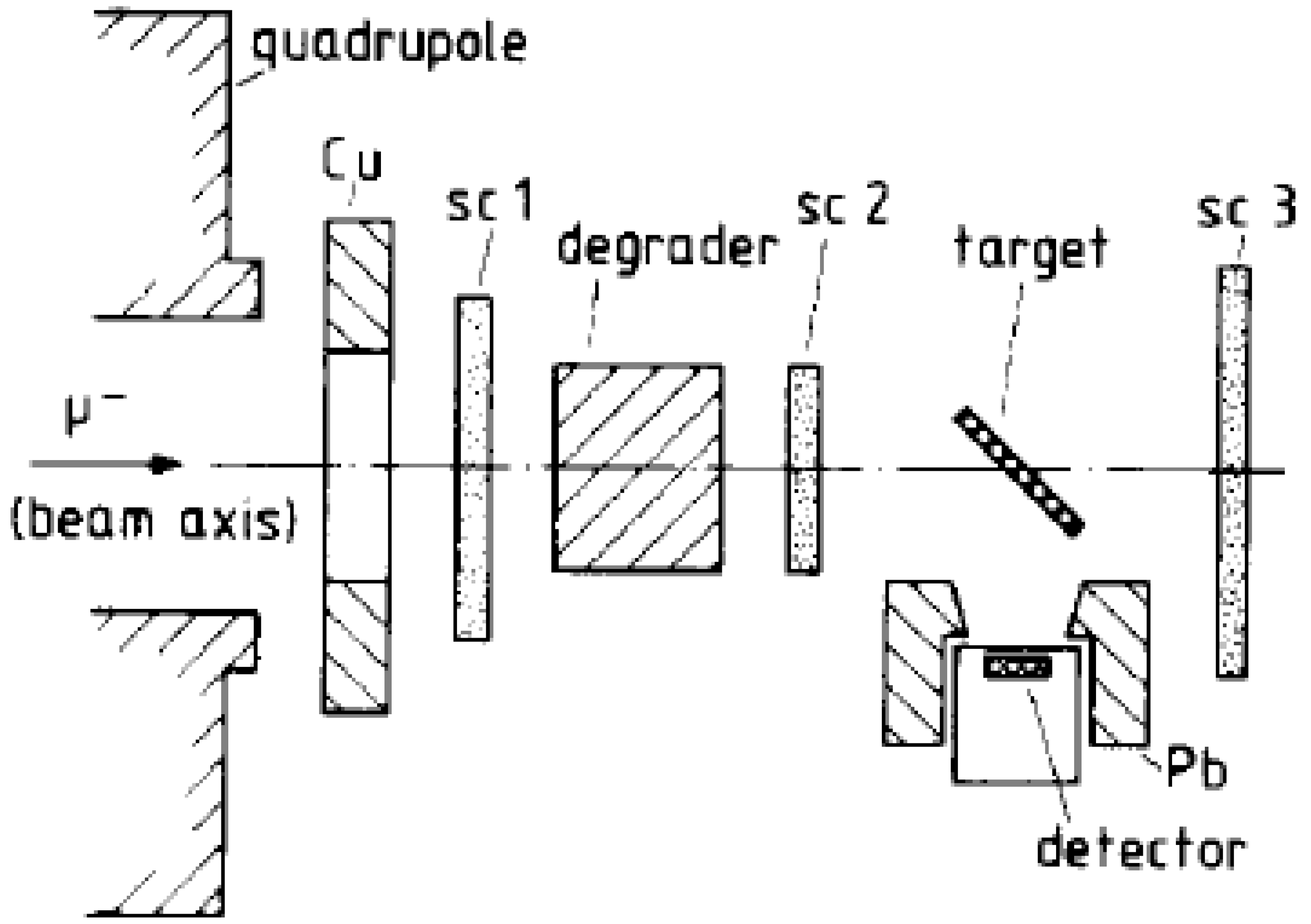

Fig. 1. Experimental setup: Cu–copper shielding, detector–Ge(Li) detector, Pb–lead shielding for detector, sc1, sc2, sc3–scintillation counters forming a telescope.

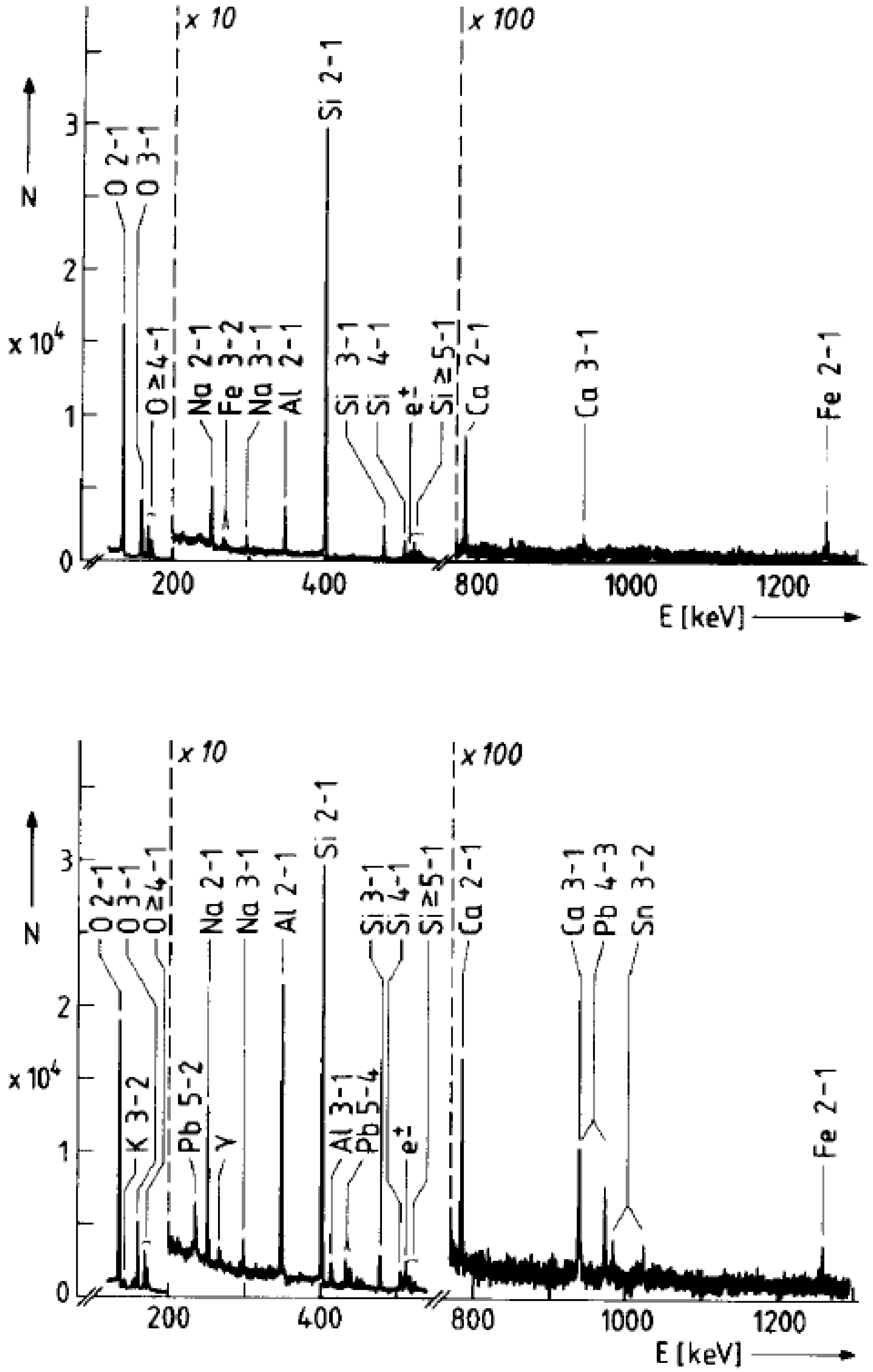

Fig. 2. Spectra of Islamic tile. Above: base material (fired clay); below: glaze.

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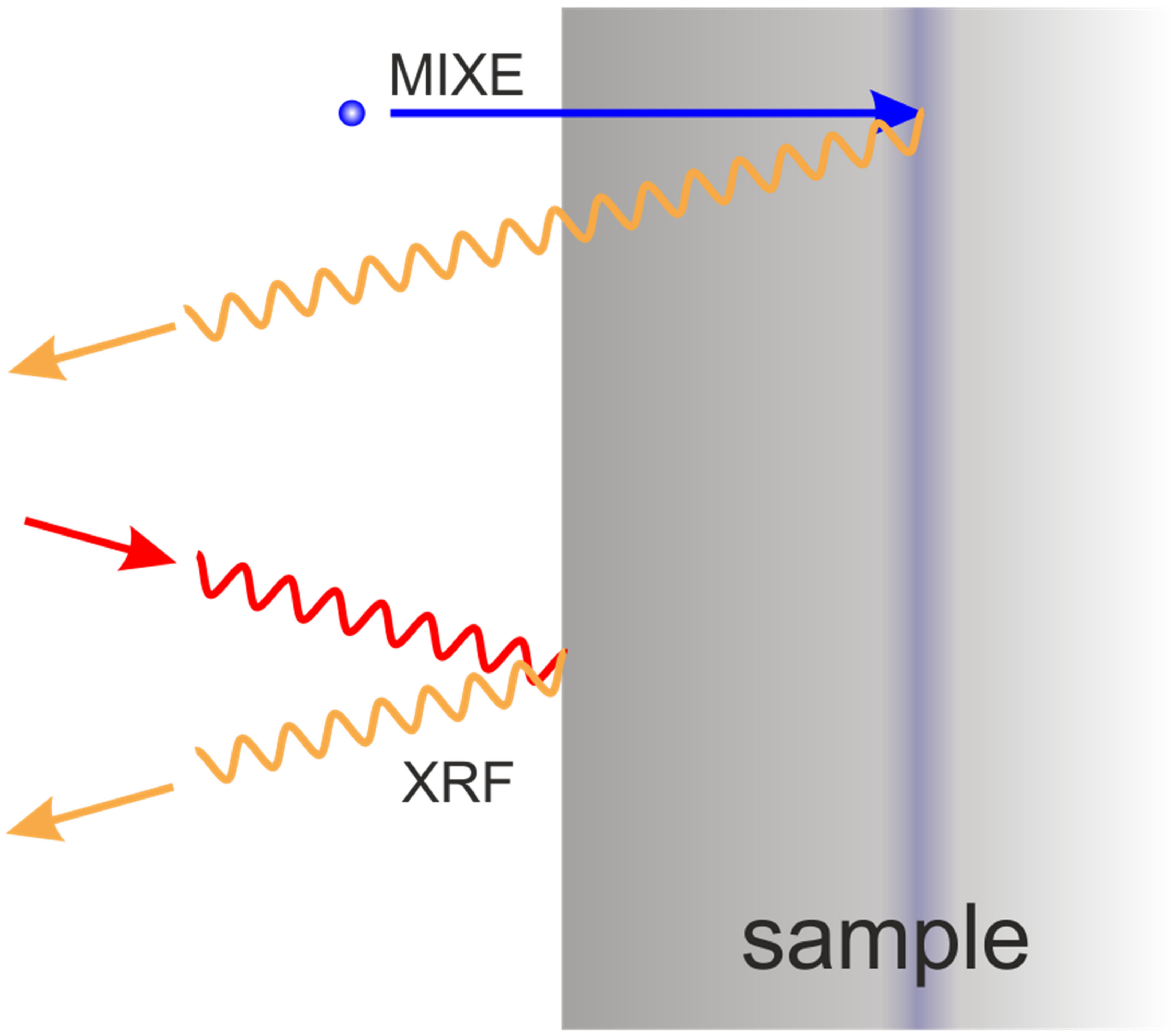
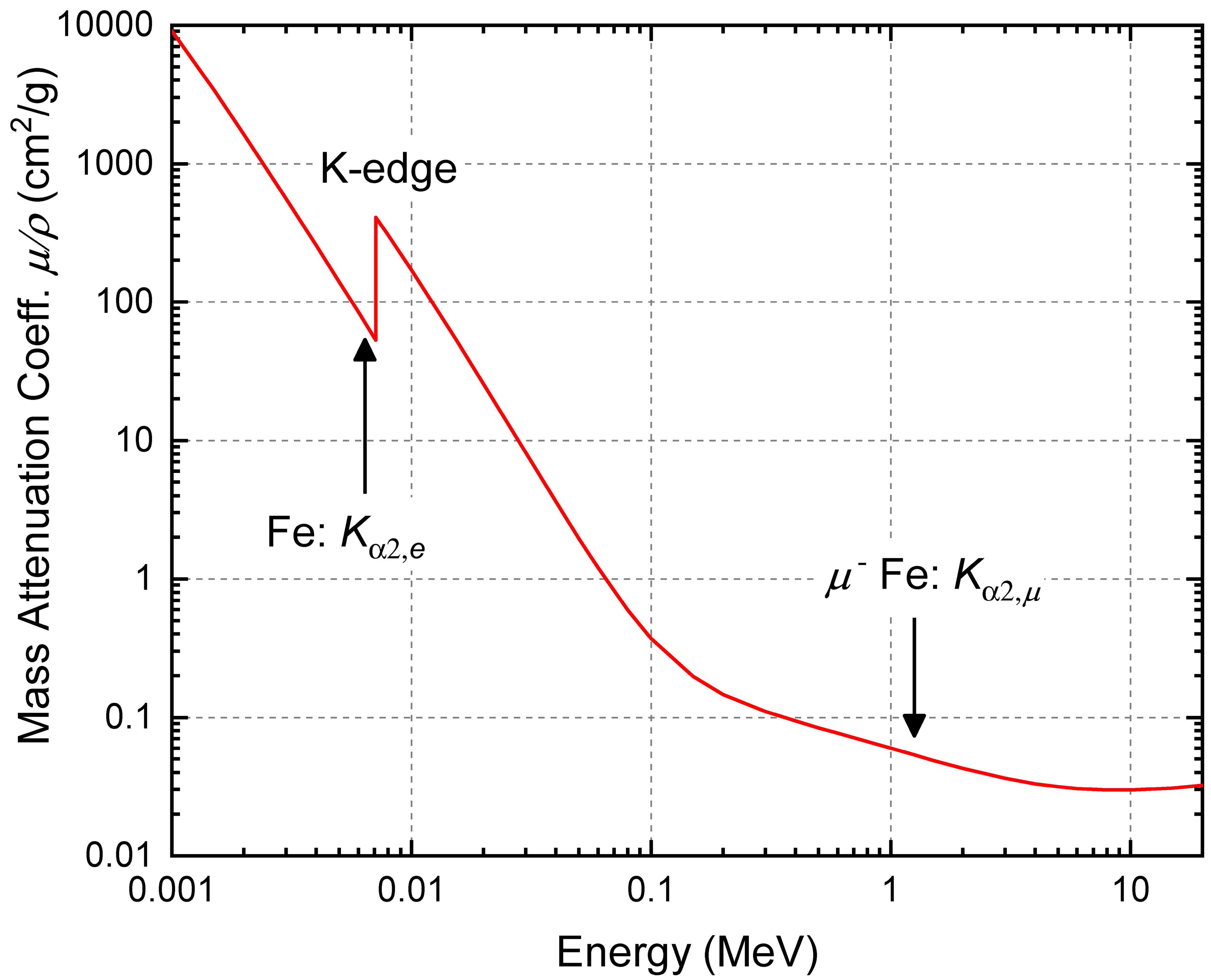
MIXE vs XRF





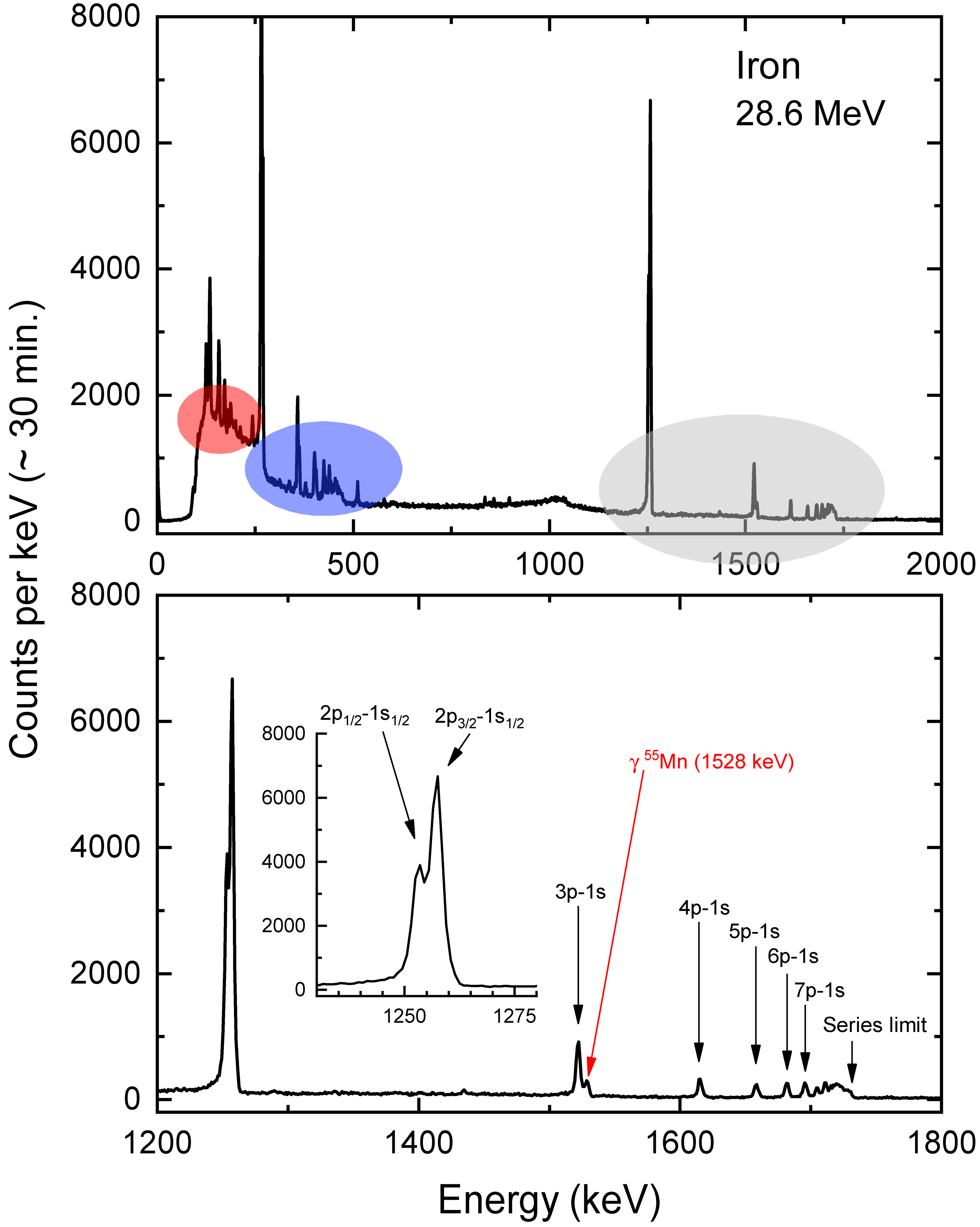
Attenuation of X-rays into a material:

$$I(\ell) = I_0 \ \exp[-(\mu/\rho)\rho\ell]$$

Example of iron

- **Electronic X-ray:** $K_{\alpha 2} = 6.39 \text{ keV} \longrightarrow$ attenuation by a factor *e* after **25 µm**
- **Muonic X-ray:** $K_{\alpha 2} = 1255 \text{ keV} \longrightarrow$ attenuation by a factor *e* after **2.5 cm**

MIXE – Example

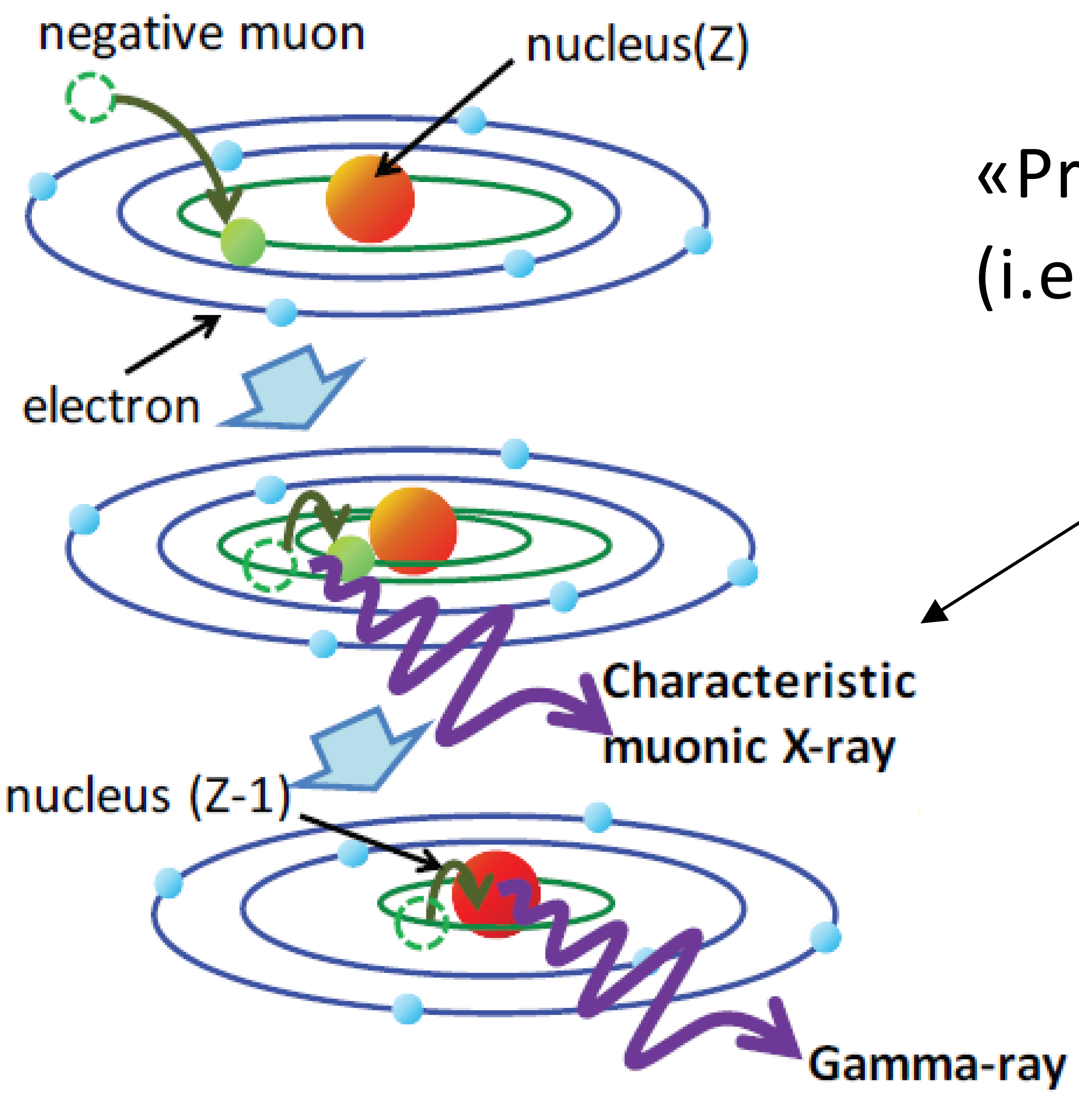


- Muon momentum 28.6 MeV/c.
- Penetration about 200 µm.
- Signals from muonic series
  - Lyman (n_f = 1, grey region),
  - Balmer (n_f = 2, blue region) and
  - Paschen (n_f = 3, red region)
- Data were recorded with one HPGe detector for about 30 minutes.

- Note the signal at 1528 keV

$$\mu^- + {}^{56}_{26}\mathrm{Fe} \rightarrow {}^{55}_{25}\mathrm{Mn}^* + n + \nu_\mu$$

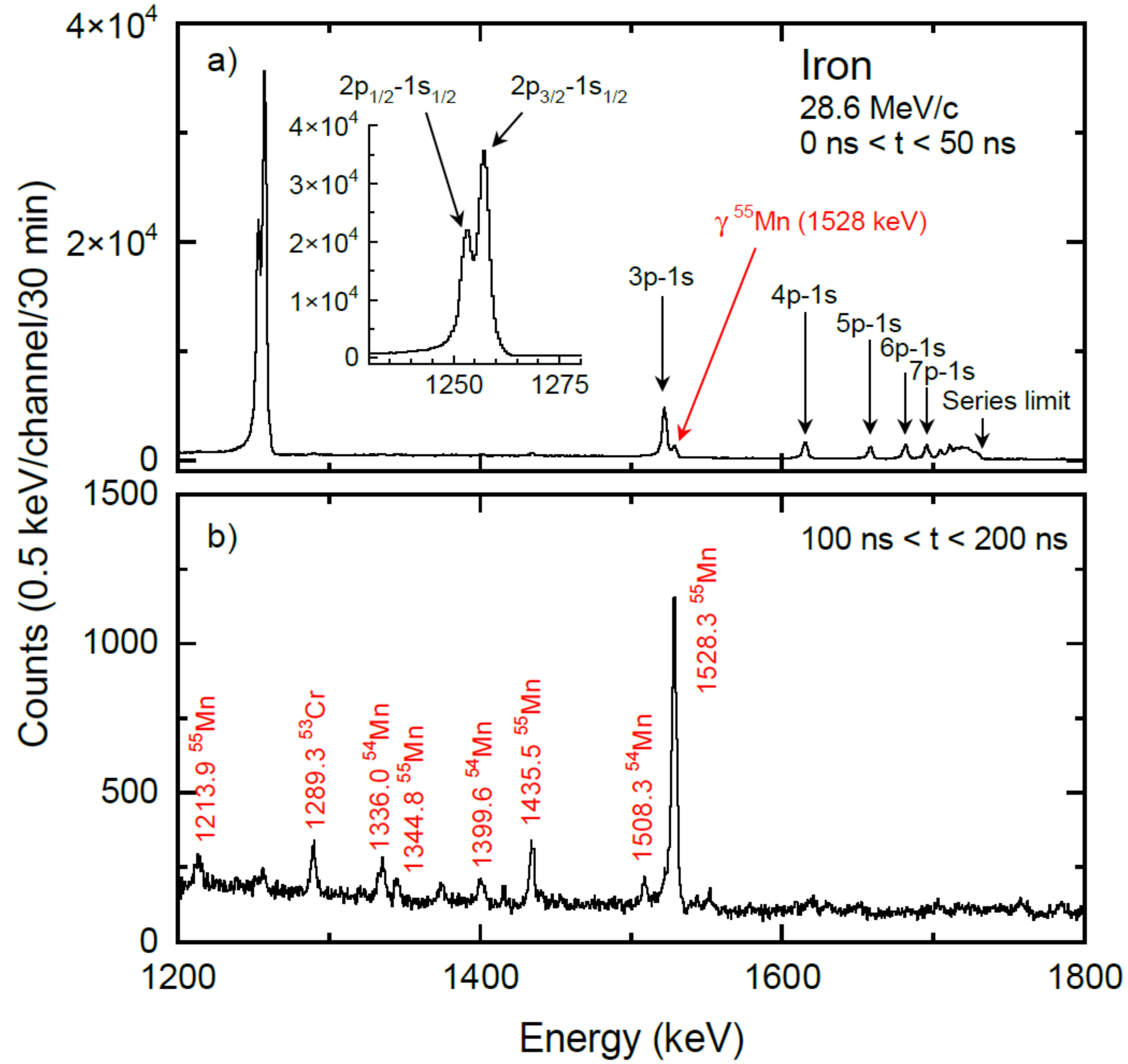
MIXE – Differentiate X-rays from Gamma-rays



$$\mu^- + p \rightarrow n + \nu_\mu$$

«Prompt» X-rays
(i.e. few picosec. after muon arrival)

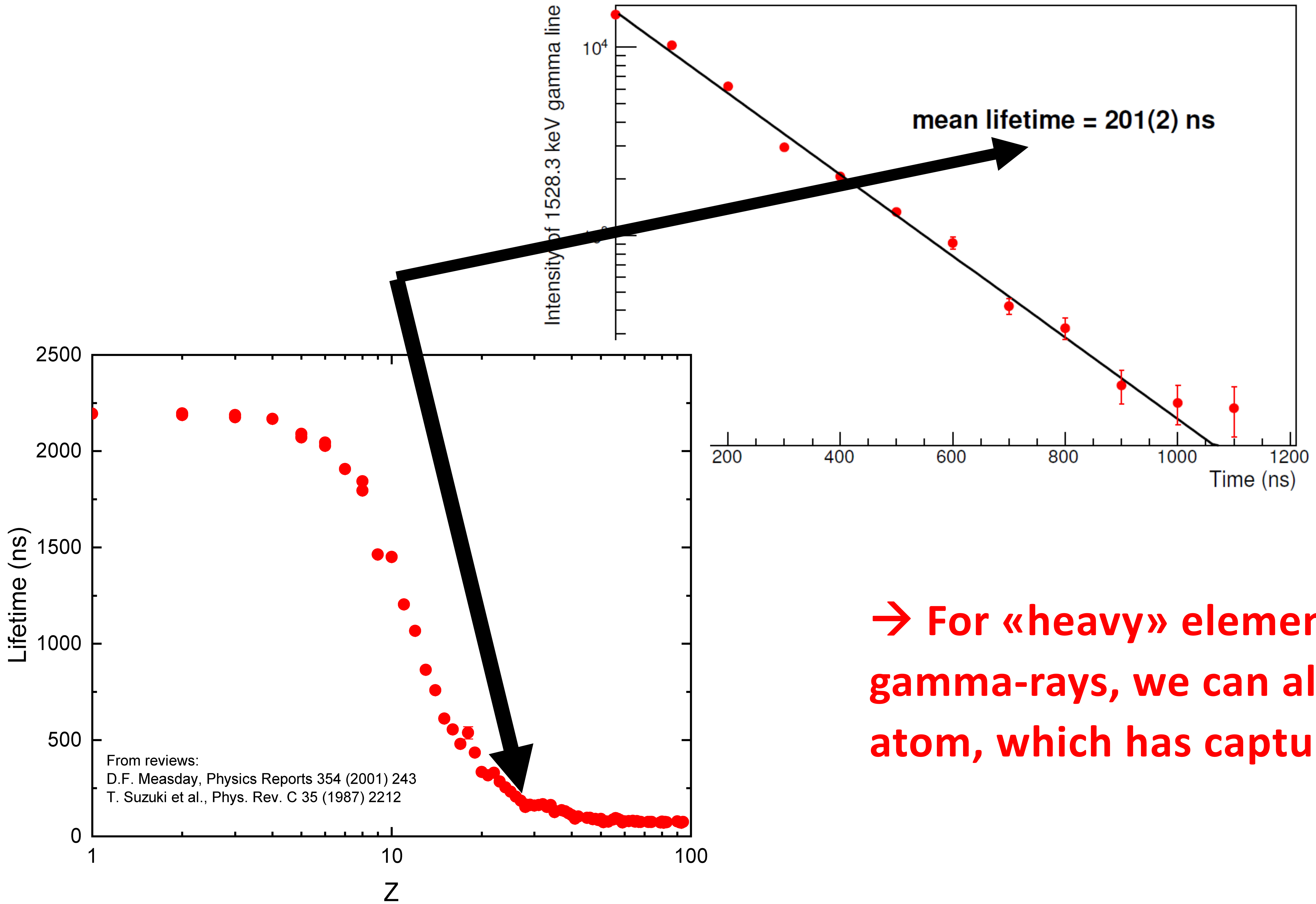
«Prompt» and «delayed»
Gamma rays characterized by $\frac{1}{\tau_{\mu,\,\mathrm{Nucl.\,capt}}(Z)}$



MIXE – Gamma rays

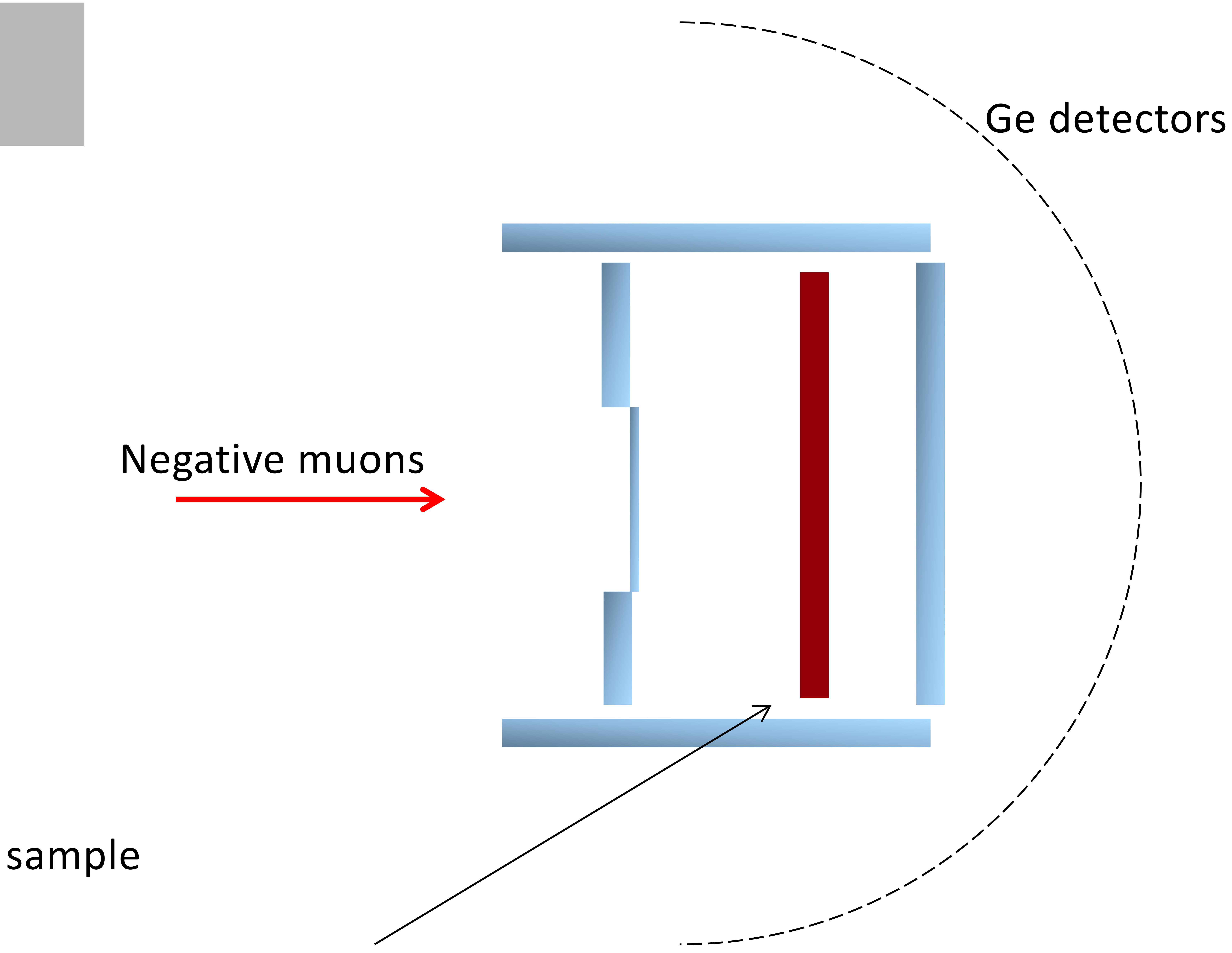
Example: $\mu^- + {}^{56}_{26}\text{Fe} \rightarrow {}^{55}_{25}\text{Mn}^* + n + \nu_\mu$

Emmission of gamma-rays → one gamma-ray with energy 1528.3 keV

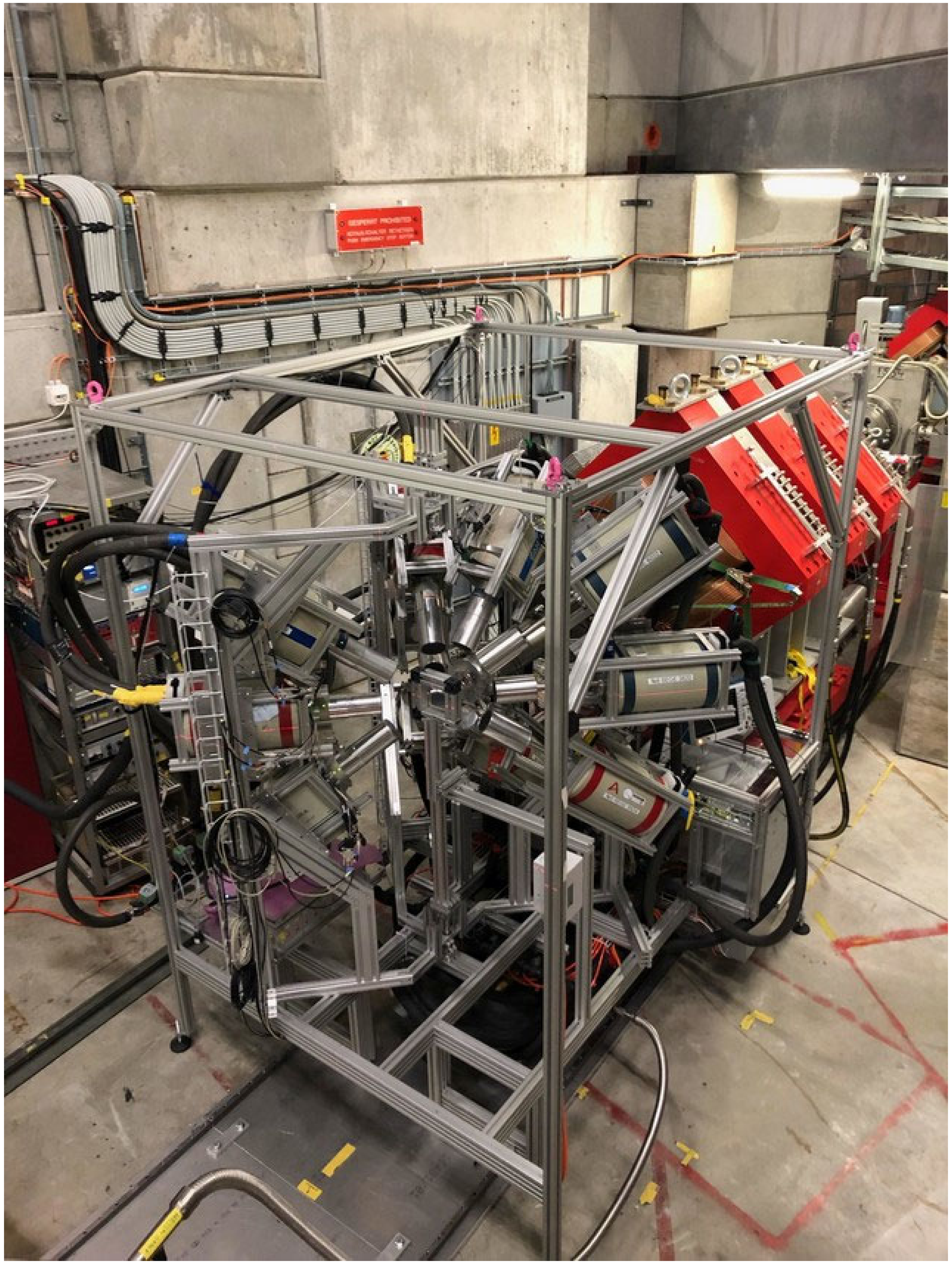


→ For «heavy» elements, by looking at the gamma-rays, we can also identify the primary atom, which has captured the muon

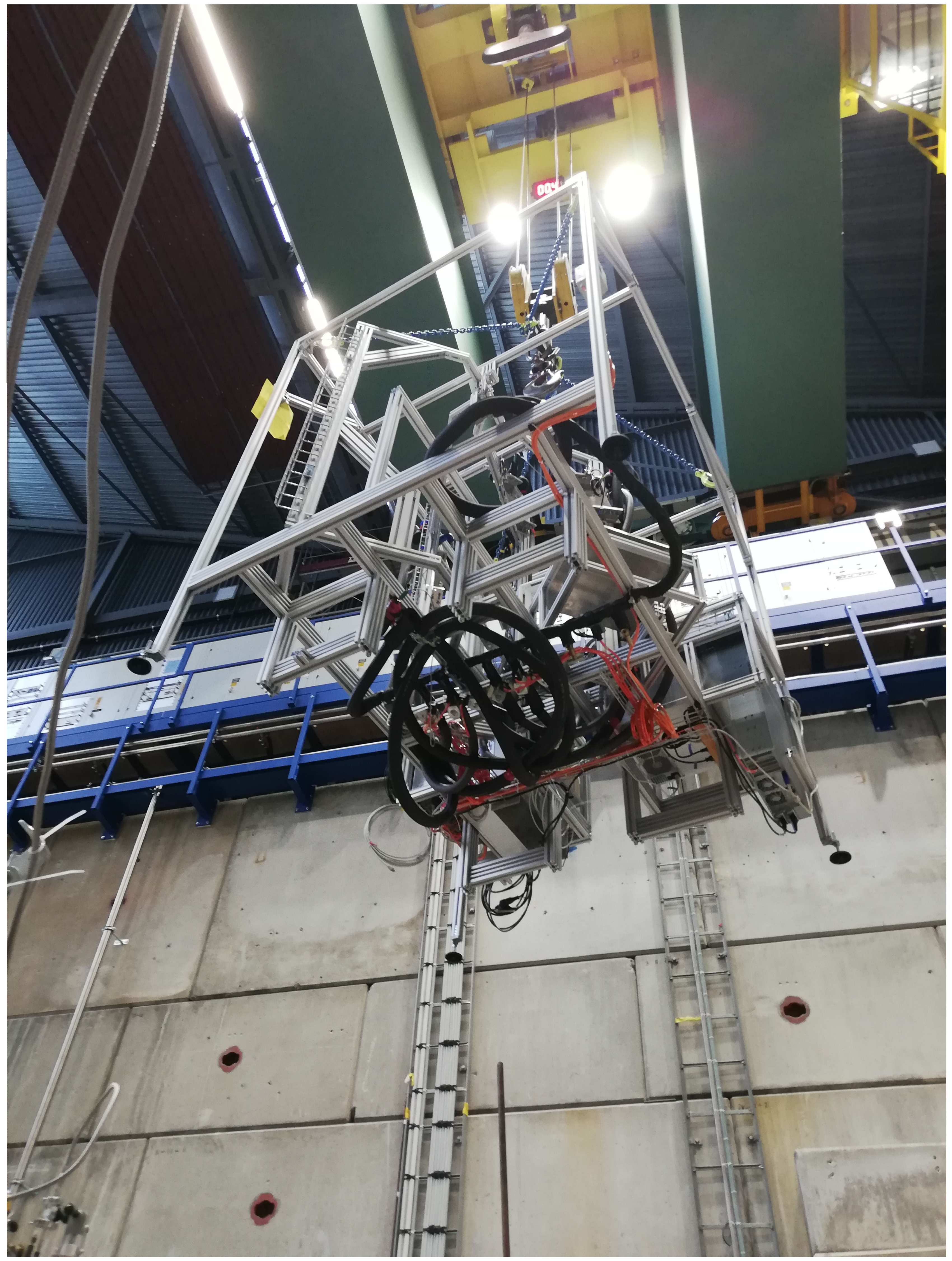
MIXE -- setup

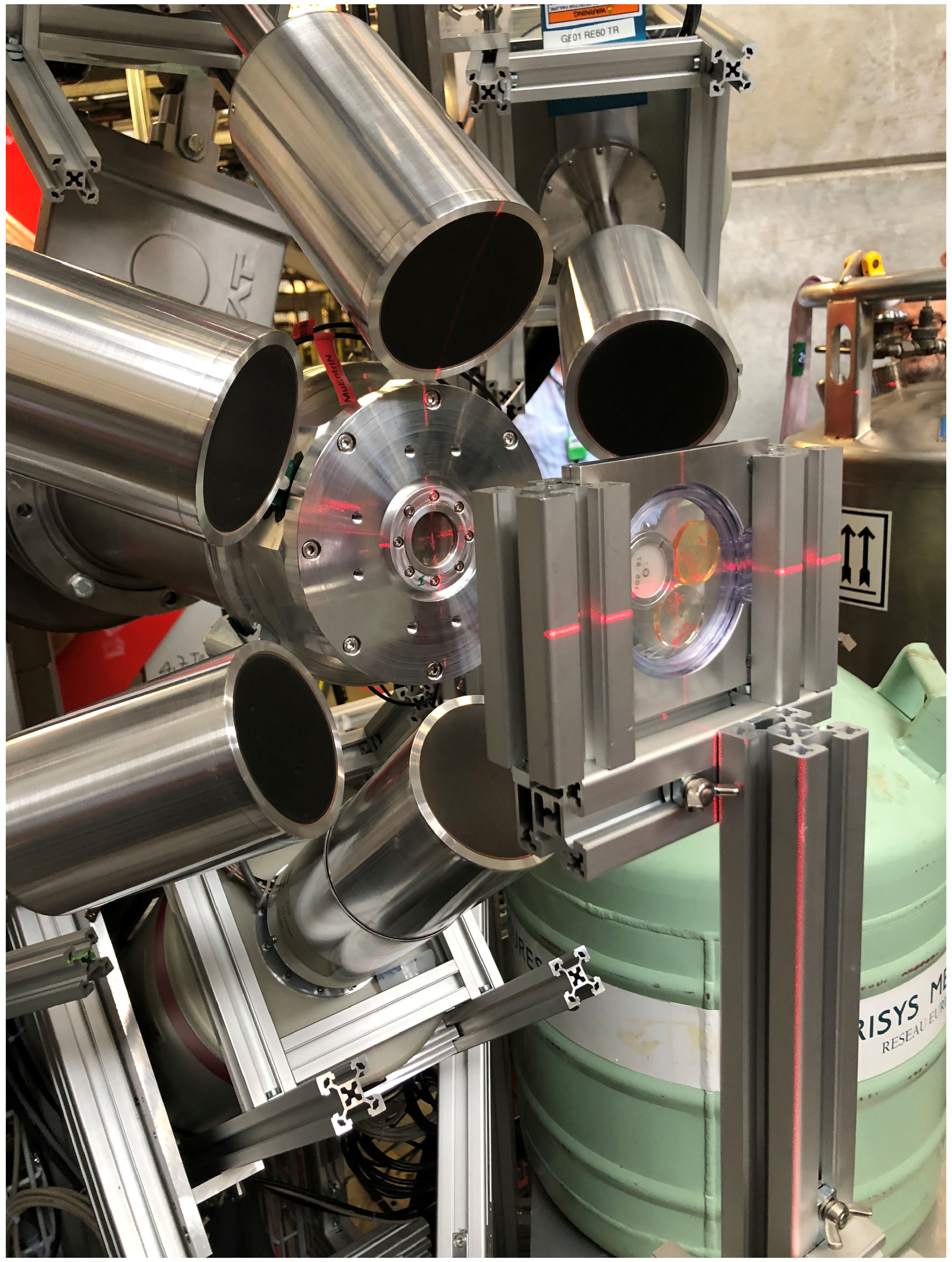


MIXE – Campaign 2021 (piE1)

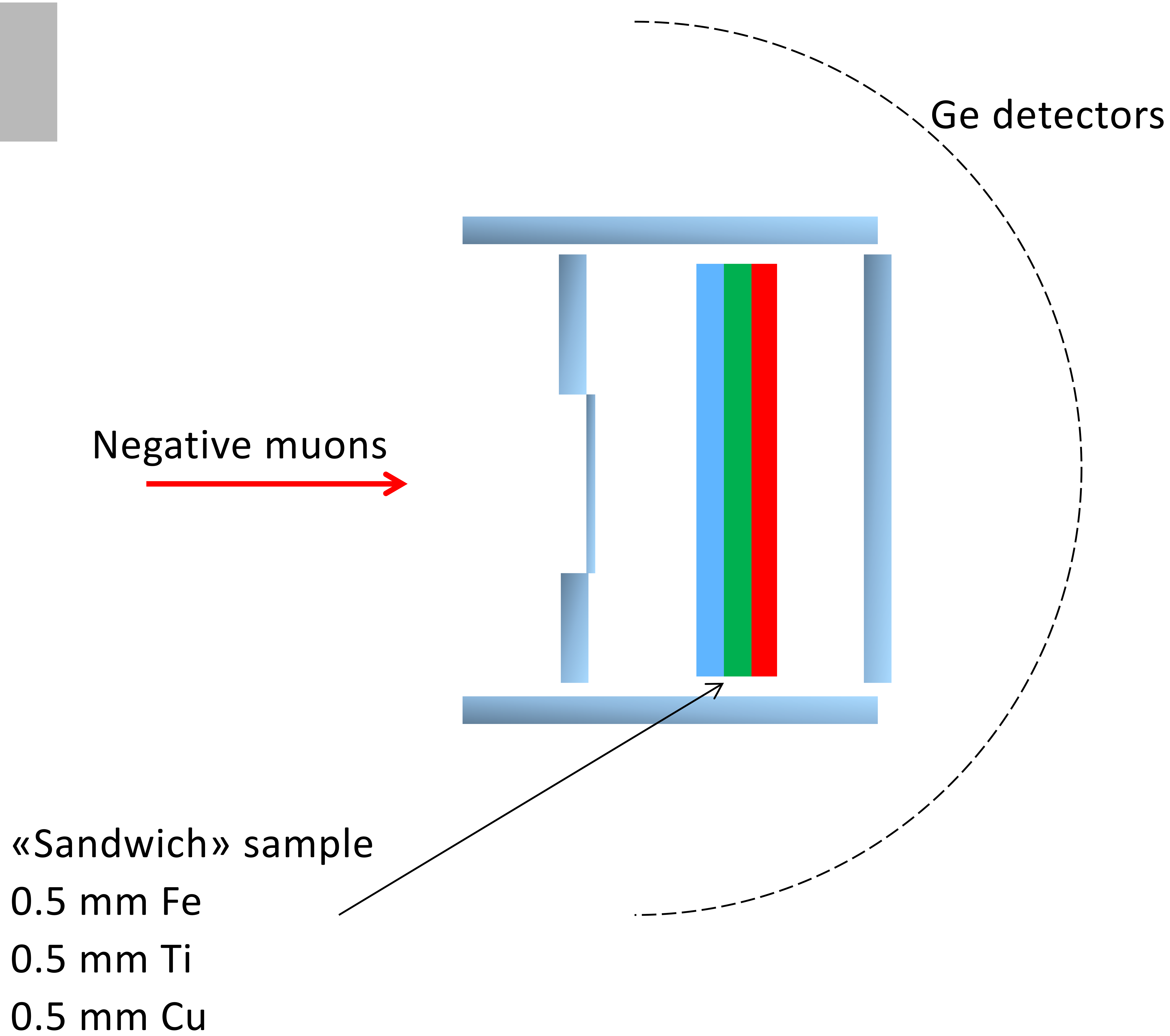


MIXE – Campaign 2021 (piE1)

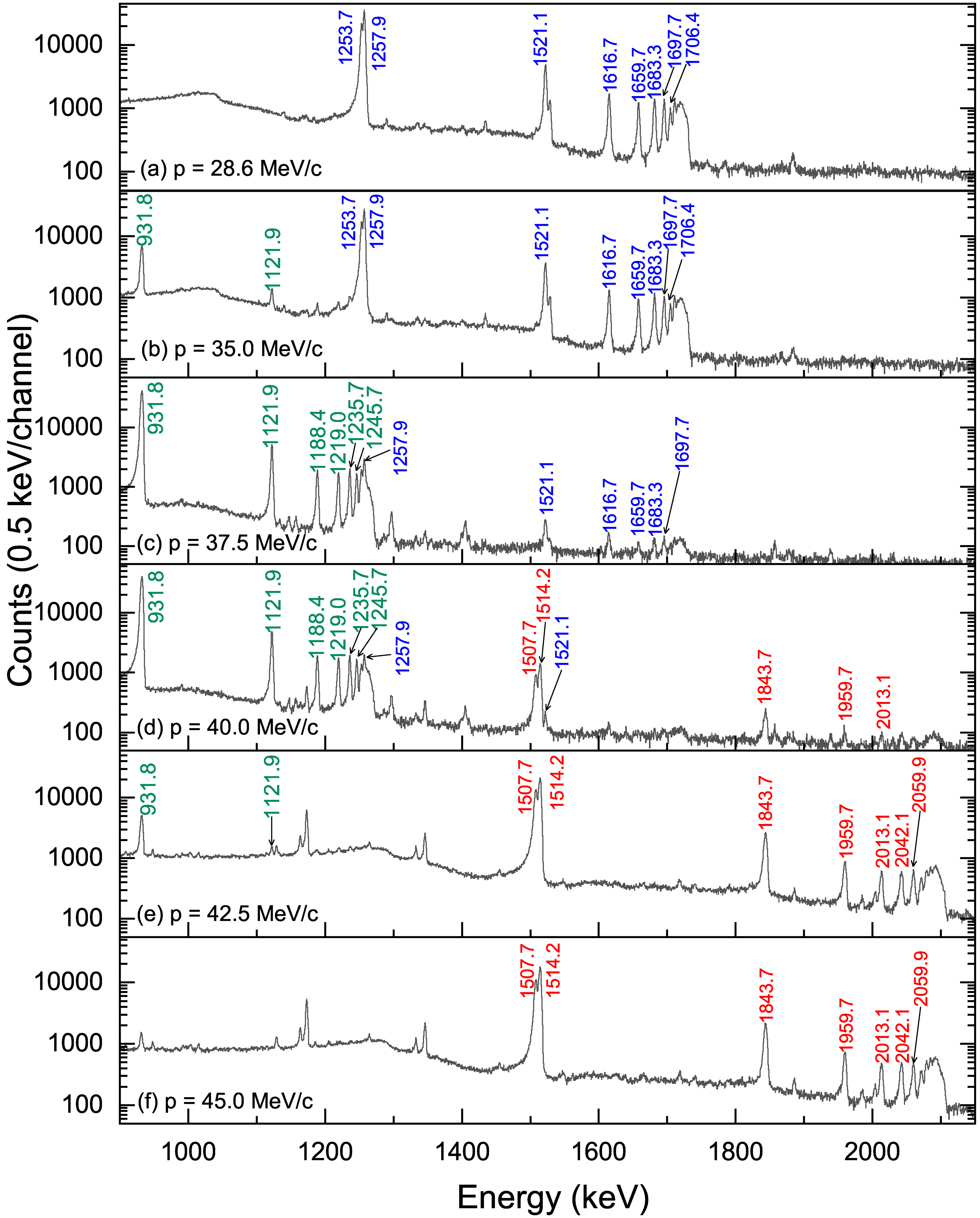




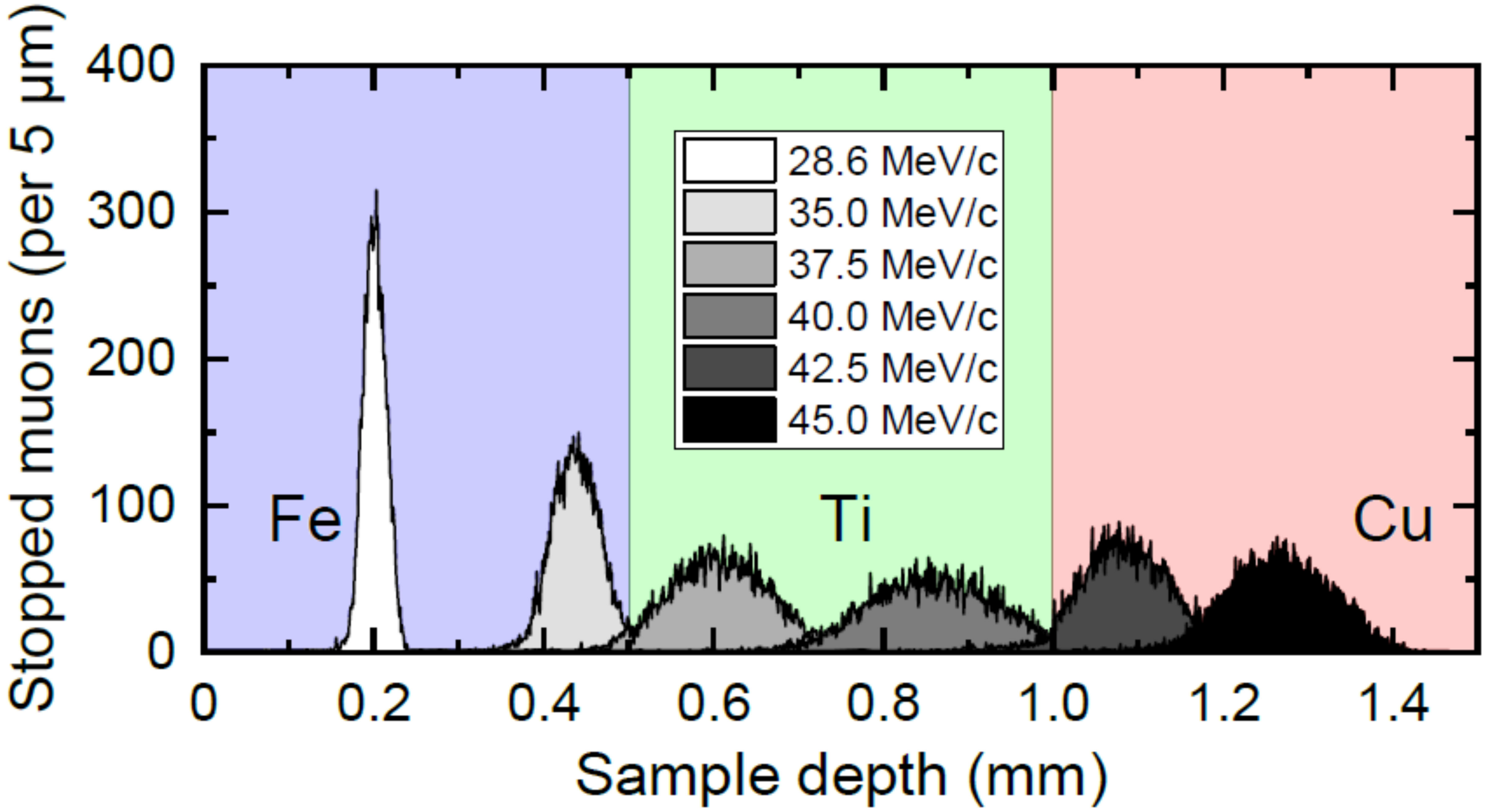
MIXE -- test

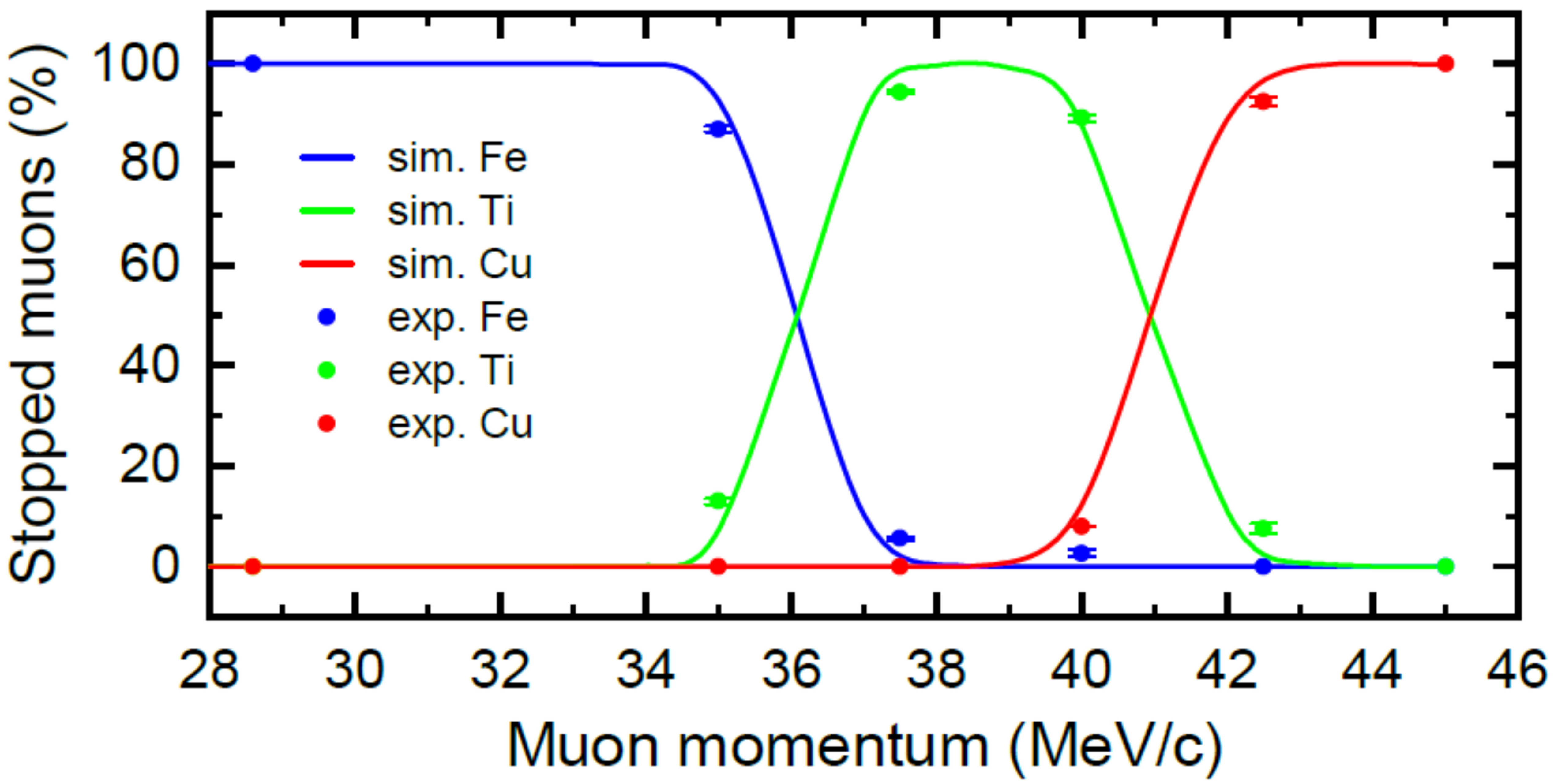

Ge detectors
Negative muons
«Sandwich» sample
0.5 mm Fe
0.5 mm Ti
0.5 mm Cu

MIXE -- test


(a) p = 28.6 MeV/c
(b) p = 35.0 MeV/c
(c) p = 37.5 MeV/c
(d) p = 40.0 MeV/c
(e) p = 42.5 MeV/c
(f) p = 45.0 MeV/c
1253.7
1257.9
1521.1
1616.7
1659.7
1683.3
1697.7
1706.4
931.8
1121.9
1188.4
1219.0
1235.7
1245.7
1507.7
1514.2
1843.7
1959.7
2013.1
2042.1
2059.9
Counts (0.5 keV/channel)
Energy (keV)

MIXE -- test





This is an easy test as a muon will only see one type of atom.

What about an alloy?

MIXE in alloys

Binary alloy $Z_k Z'_{k'}$

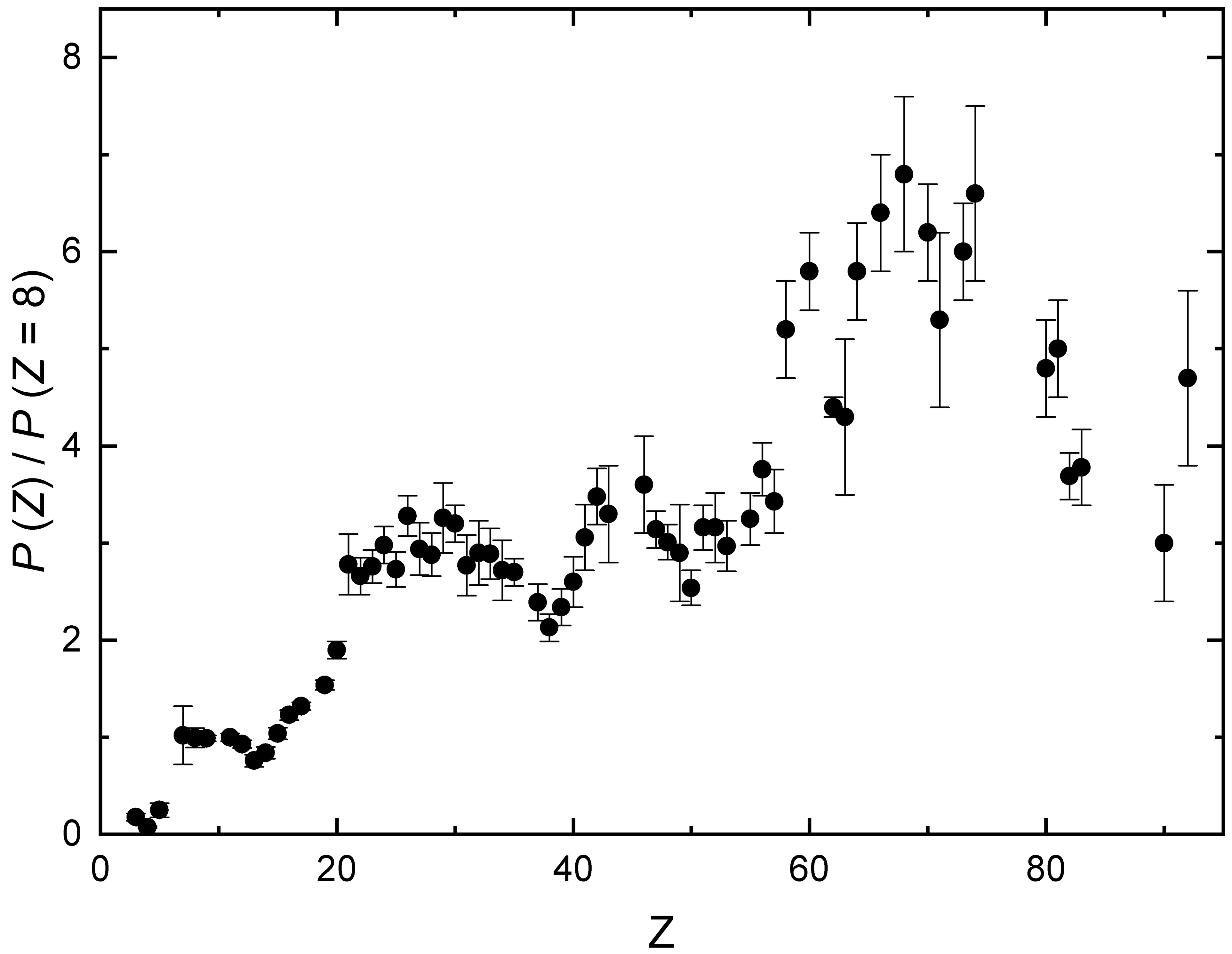
$$R(Z,Z',k,k') = A(Z,Z')\frac{k}{k'}$$

MIXE intensity ratio (including corrections)

Capture ratio between the 2 elements

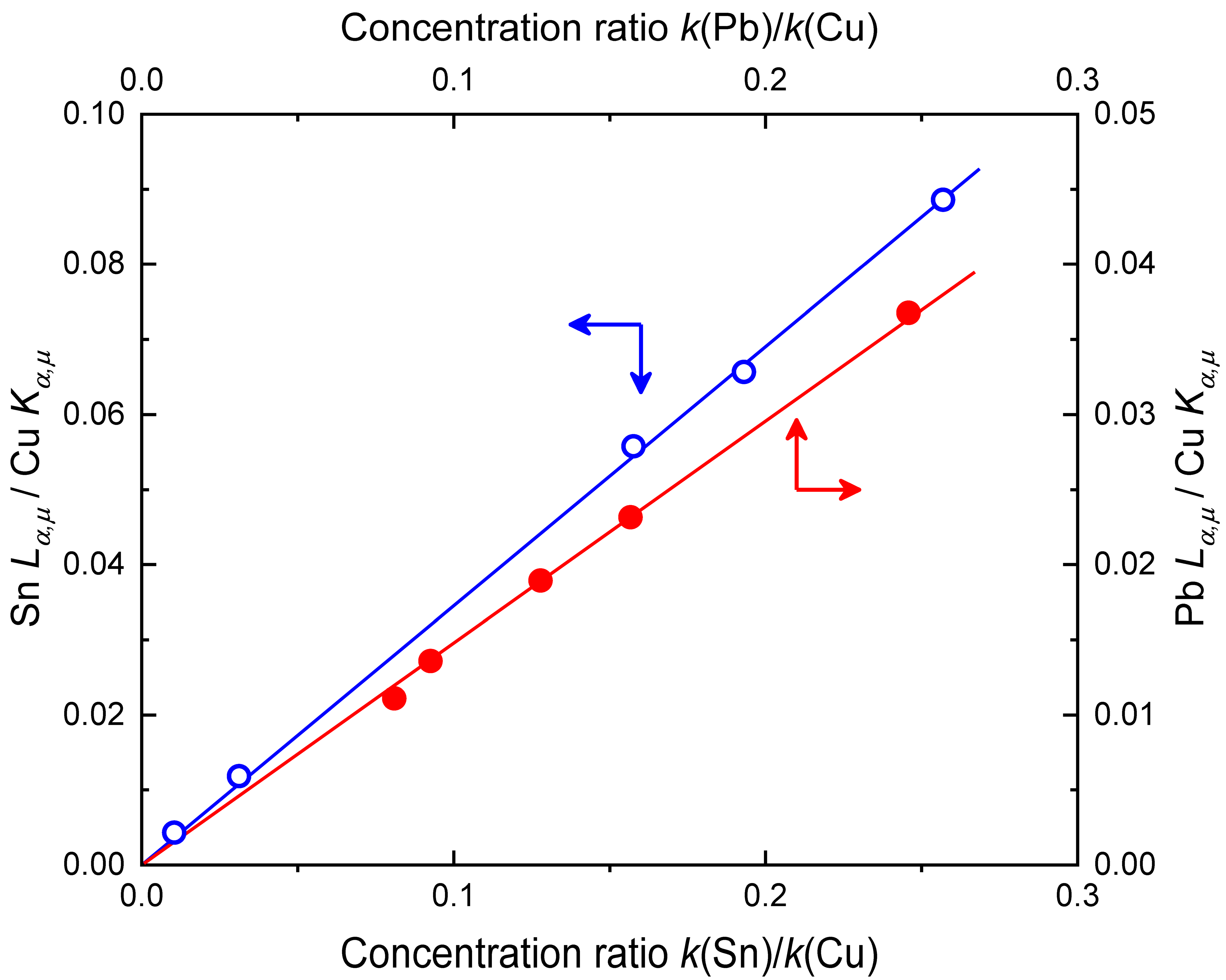
$$A(Z,Z') = \frac{P(Z)}{P(Z')}$$

capture probability: depends on the quantum numbers n and l of the electron involved in the Auger emission during the capture and the atomic number Z



MIXE in alloys

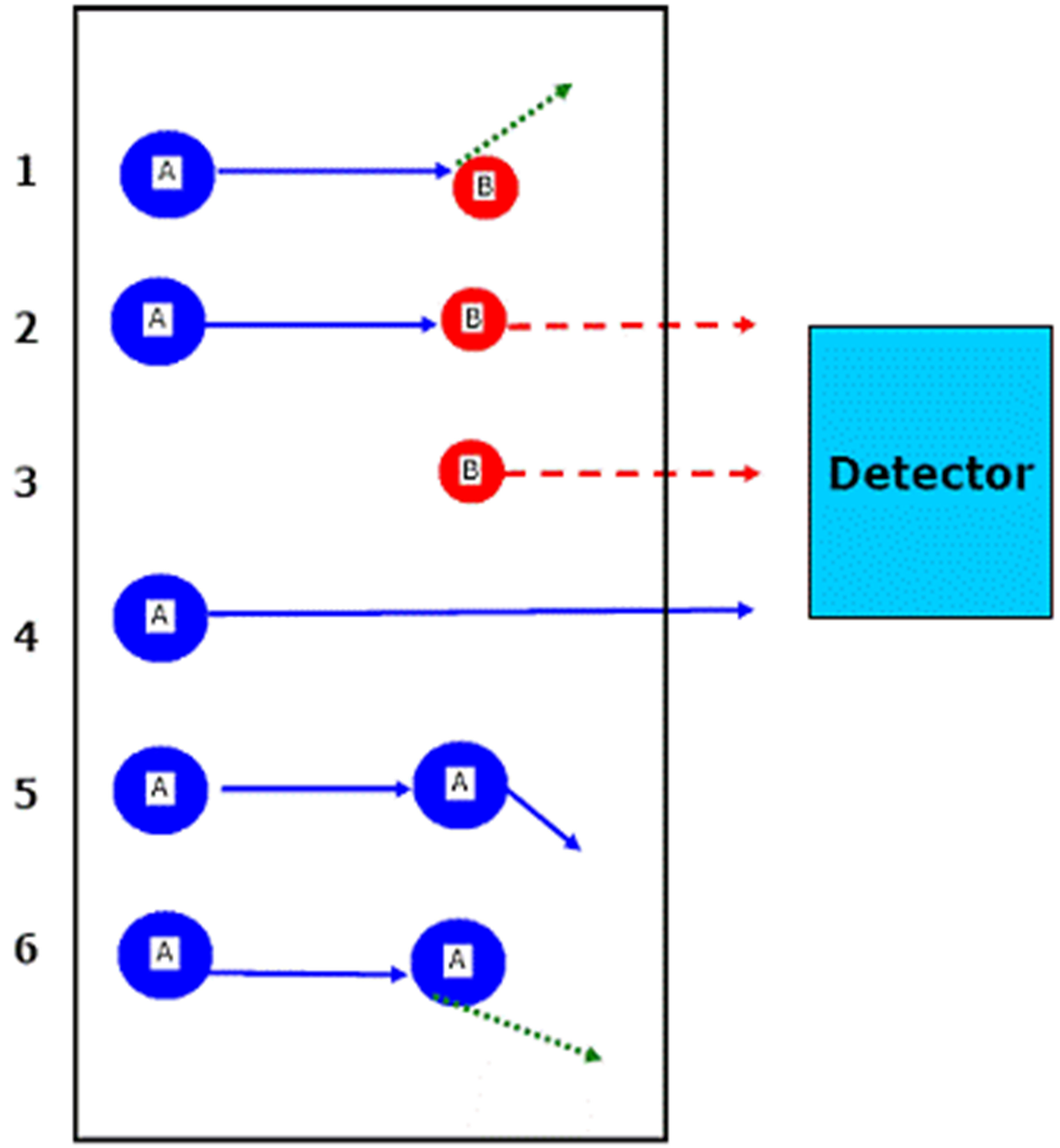
Also for ternary alloys: example $Cu_{k(Cu)}Sn_{k(Sn)}Pb_{k(Pb)}$



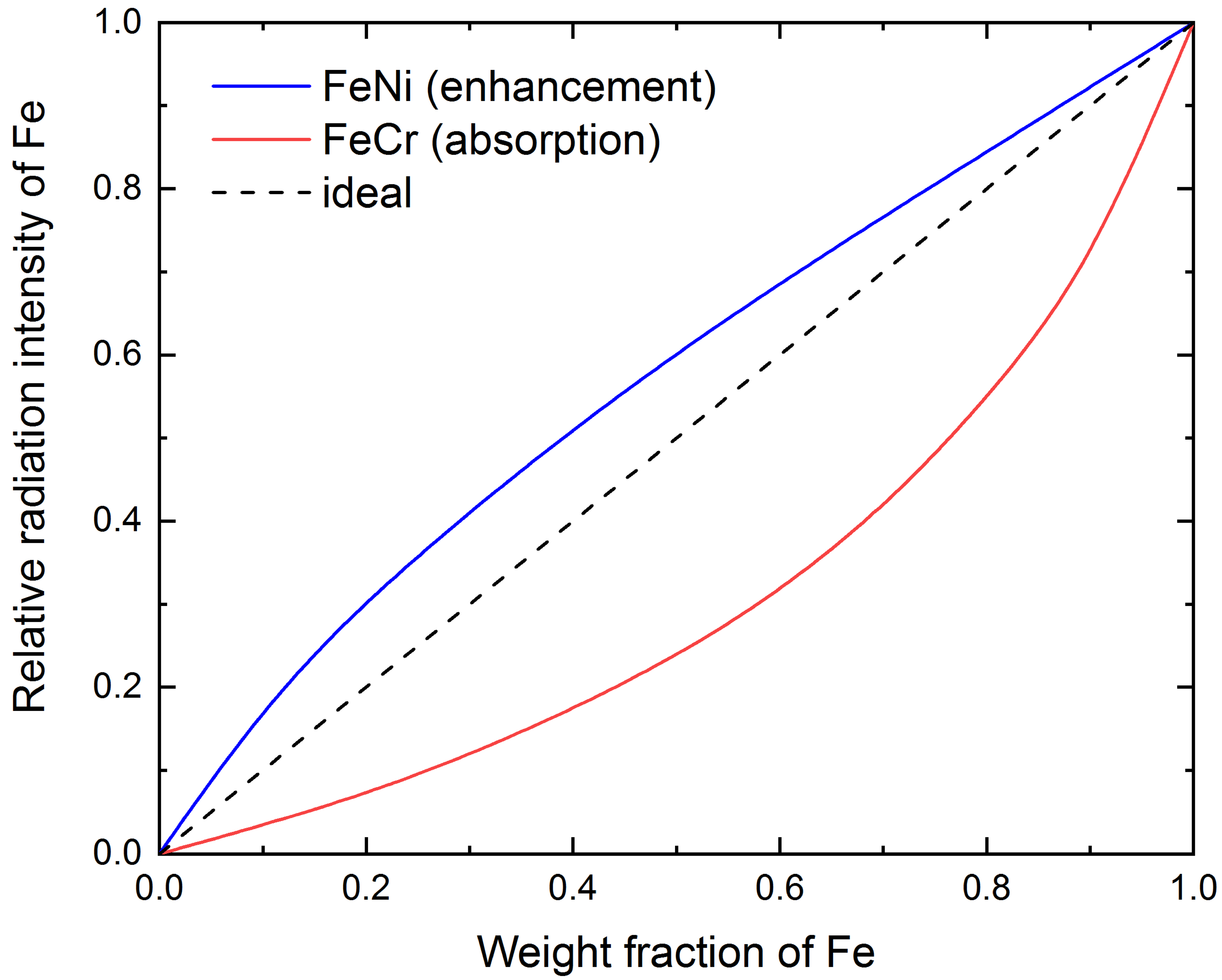
$$R(Z,Z',k,k') = A(Z,Z')\frac{k}{k'}$$

Matrix effects in X-ray Fluorescence

- Absorption
- Enhancement



F.G. Banica, 09-03-20



"Quantification in X-Ray Fluorescence Spectrometry"
Rafał Sitko and Beata Zawisza
https://doi.org/10.5772/29367

Main characteristics

	Muon-Induced X-ray Emission
Abbreviation	MIXE
Primary Excitation	Negative Muon
Detected Secondary	X-ray
Elemental Range	3-92
Lateral Resolution	1 mm
Detected Depth	Up to several cm
Detection Limit	0.1% at least
Depth Profile	Yes
Destructive	No

Ideal for:

- Large objects
- Valuable objects

Examples:

- Rare objects (archeological artefacts, meteorites, return samples,…)
- Operando devices (batteries)
- …

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Also: Absence of enhancement and absorbtion !

Thank you very much!