PSI Center for Neutron and Muon Sciences

Muonic atom spectroscopy at PSI and the development of the MIXE technique

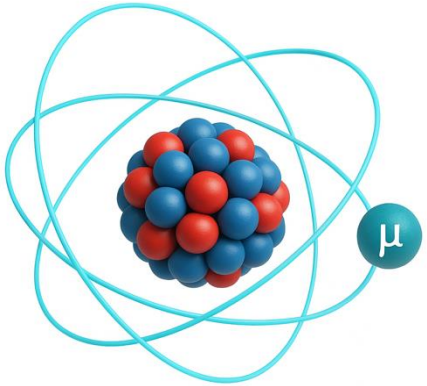
Issa Briki (on behalf of the **MIXE** team)
Laboratory for Muon Spin Spectroscopy (LEM group)

Huizhou, China 25-27 April 2026

1

Muonic atoms

Introduction



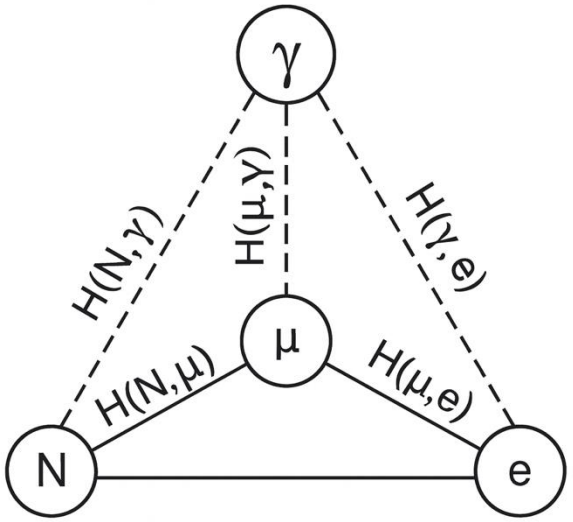
- Single negative muon bound to a single atomic nucleus.
- The physics of the muonic atom happens in a time interval of about 10^{-14} s.

Model Hamiltonian

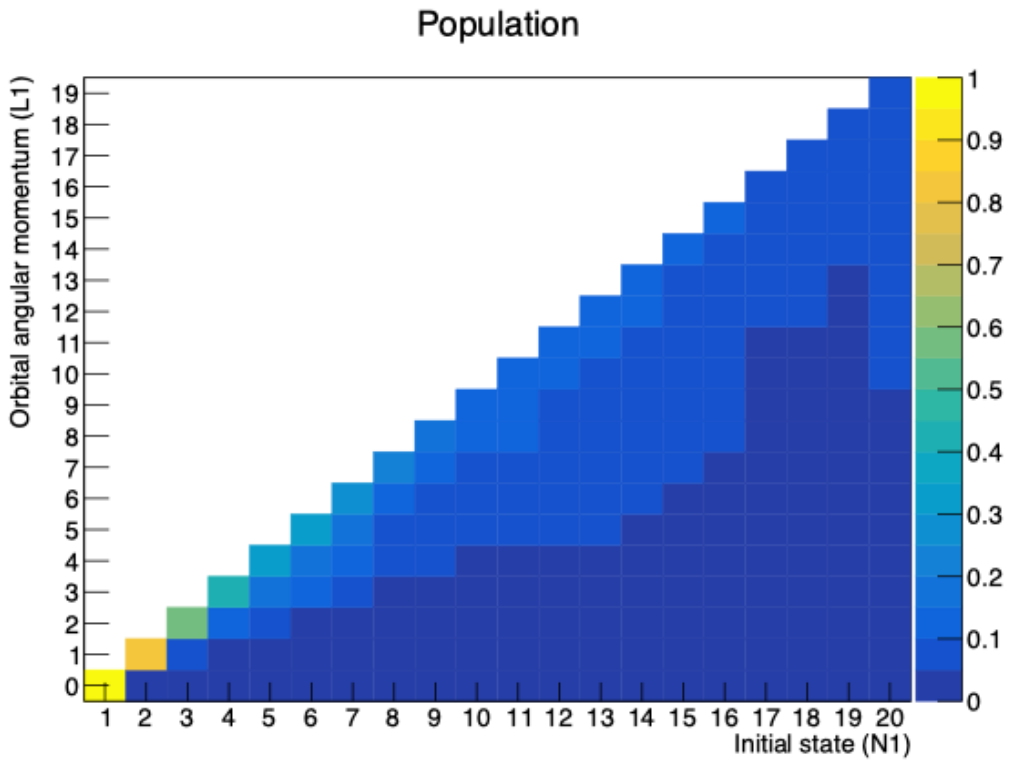
The electromagnetic interactions are treated in the Coulomb gauge:

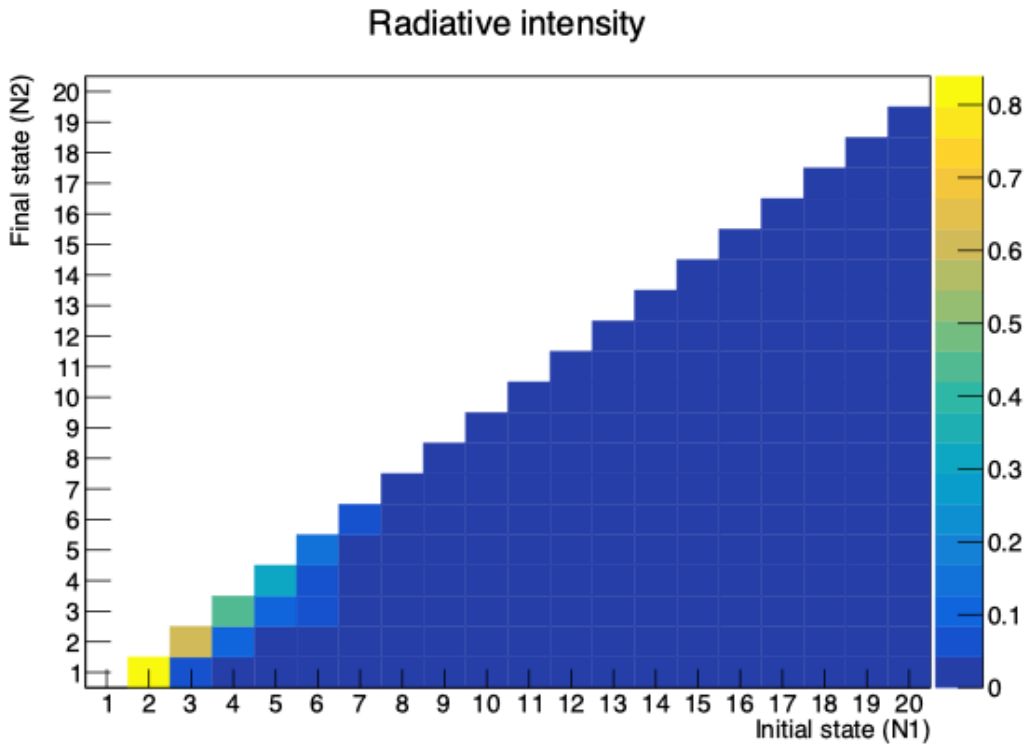
- The μ, e-, and N interact via the static Coulomb interaction:
  H(μ)=H(free μ) + H(μ, N) + H(μ, e-)

- The μ, e-, and N interact with the transverse photon field:
  These interactions give rise to magnetic interactions between N and μ, the emission (absorption) of gamma rays.



Muonic cascade





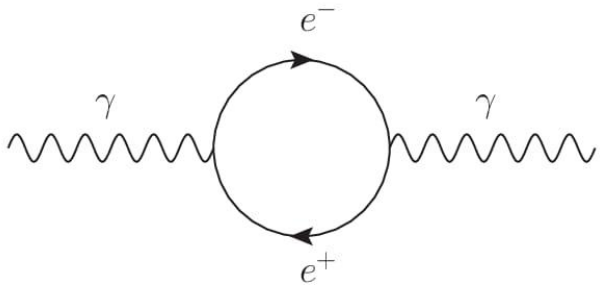
- The highest orbits (n>5) overlap with the electronic cloud -> Auger transitions dominate
- The lowest orbits (n<4) are close to the nucleus -> Radiative transitions dominate
- The refilling of holes depends on the chemical or physical environment.
- This refilling mechanism leads to observable effects on the muonic cascade.

Muonic energy

Finite size effect: at proximity to the nucleus, the nuclear potential undergoes an extreme change which end in the energy shift. (reduction of about 50 % in case of 75Re, Abu Saleh et al.)

QED effects:

- Vacuum polarization: the emission of virtual e-e+ pairs changes the nuclear potential; thus, the muon feels a larger effective charge (binding energy increases by a few 10 of keV).



- Self-energy: the reduction of the muon's binding energy is due to its interaction with the electromagnetic field it produces (binding energy increases by a few keV)

Other corrections:

- Electron screening: the presence of the e- decreases the effective charge experienced by the muon and thus reduce its binding energy by few eV (n>5).
- Recoil effect, Orbital collapse, isotope and isomer shifts, ...

The resonance excitation

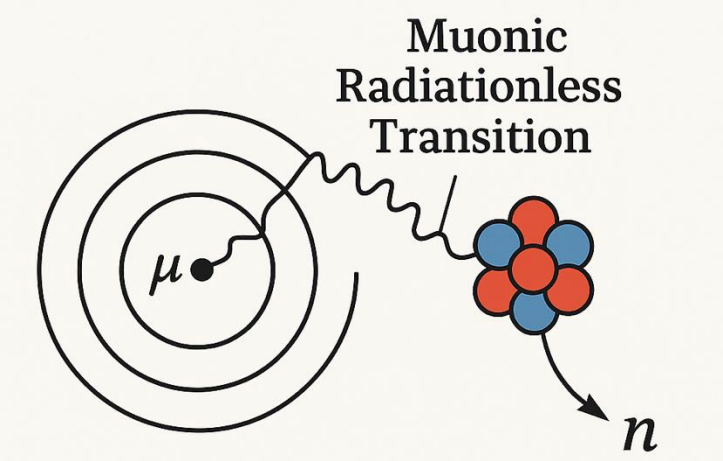
When the energy difference between muonic levels is close to, or nearly degenerate with, a nuclear excitation energy, the muon can lead to resonance excitation of the nucleus.

- Anomalous lines of significant intensity have been observed in 76Os and 70Yb and are interpreted as 3d-2p muonic-nuclear resonance (M. V. Hoehm et al).
- This resonance may occur frequently in heavy muonic atoms (L. Wilets et al.).
- This resonance could result in the excitation of low-lying and high-lying nuclear states in certain deformed nucleus and nucleus near 82Pb respectively.

- (M. Y. Chen et al.) resonance excitation in 81Tl
- (W. Y. Lee et al. 1972) (J. HUFNER) resonance excitation in 83Bi
- (W. Y. Lee et al. 1971) (J. HUFNER) resonance excitation in 53I
- (WILLIAM B. ROLNICK) resonance excitation in Tl, Pb, and Bi

Nuclear Auger Effect

- The nuclear Auger transitions resemble the internal conversion process for nuclear gamma-rays, except that the roles of the nucleus and the atom are swapped.

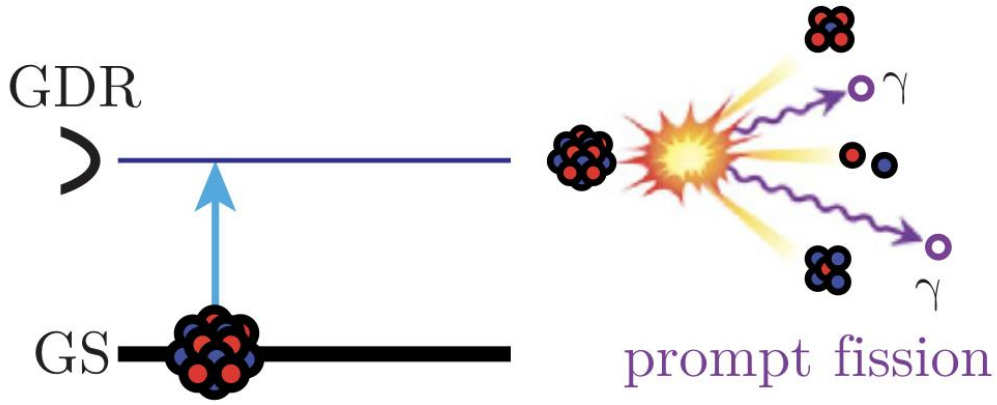


- This effect occurs (when the muonic transition energy is higher than the binding energy of the neutron) predominantly for the lowest transitions (e.g. E1, E2) and in heavy nucleus.
- The neutron is ejected at the same time scale of the muonic X-rays (both transition are electromagnetic)
- Neuron rate per stopped muon: 5% to 10% (Zaretskii et al); 7% (Hargrove et al)

Muon-induced fission

- Prompt fission: immediate breakup of the nucleus after absorbs radaitionless energy ($10^{-20}\ s$)
- Excited muonic atoms in the actinide region (Z>88) may induce prompt fission (Y. E. Oberacker et al.)
- The E2 muonic transition energy is close to the ISGOR peak of the isoscaler giant quadrupole resonance in actinide nucleus which exhibits a large fission width.

ISGOR: is a collective vibration of the nucleus where all the protons and neutrons oscillate together forming a quadrupole or a “rugby ball” Shape.



MuCascade

PSI Center for Neutron and Muon Sciences

MuCascade: A Database of Muonic X-ray Transition Energies and Intensities.

Authors: Issa Briki[1*], Michael W. Heiss[1], Xiao Zhao[1], Maxime Lamotte[1], Gianluca Janka[1], and Thomas Prokscha[1].

[1] PSI Center for Neutron and Muon Sciences CNM, 5232 Villigen PSI, Switzerland.

*issa.briki@psi.ch

Abstract

Muonic atoms are powerful probes of atomic and nuclear structure through their characteristic X-ray transitions. Accurate modeling of these spectra requires reliable transition energies and intensities. **Cascade calculations [1]** are used to determine the transition intensities, accounting for the main physical processes governing the muonic cascade. To improve the description of transition energies, **MuDirac [2]** is used, which solves the Dirac equation including nuclear size, vacuum polarization, and electronic screening.

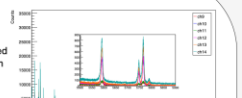
Using these two complementary approaches, we construct a database containing cascade transition intensities and MuDirac-calculated energies for muonic atoms across a wide range of elements. The calculated transition energies and relative intensities are compared with available experimental muonic X-ray measurements.

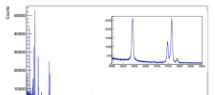
Method

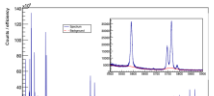
- Transition intensities computed for Z = 4–103 (up to n = 20).
- Good agreement with experiment for dipole transitions; discrepancies remain for some quadrupole transitions.
- New C++ cascade code under validation.
- Muonic X-ray energies obtained with MuDirac for all elements and stable isotopes.
- Experiments are performed using the **GIANT** setup (Germanium Array for Non-destructive Testing) **[3].**

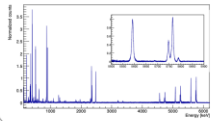
Experimental Approach

- Full spectrum of muonic X-rays from gold, measured using the GIANT setup.
- Each HPGe detector is energy-calibrated using standard radioactive sources with well-known gamma-ray lines.
- Event-by-event ELET correction was applied to the HPGe timing relative to the tag detector.
- A final timing window of −50 ns to +50 ns was applied uniformly to all detectors.
- The calibrated and time-aligned signals from all HPGe detectors are combined to construct the summed energy spectrum.
- The summed energy spectrum is constructed from efficiency-calibrated detectors.
- The background is modeled and subtracted using the TSpectrum class.
- The summed energy spectrum is normalized to the kα1 peak.
- Muonic X-ray transitions are observed up to principal quantum number n ≈ 8



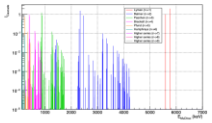


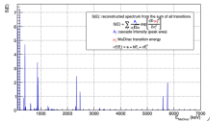


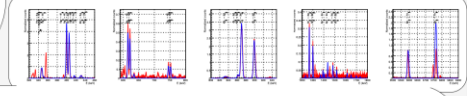


Computational Approach

- Each transition is represented by an analytical response function centered at the MuDirac energy.
- The area of each peak is fixed by the normalized cascade intensity.
- The detector resolution is introduced through an energy-dependent width.
- All individual response functions are summed to build the reconstructed spectrum.
- The summed spectrum is normalized to kα1 for direct comparison with experiment.





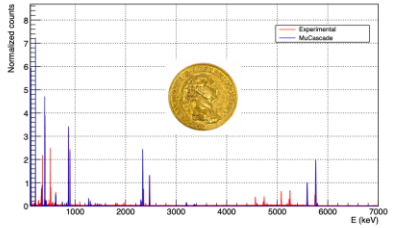


Conclusion

- The combined MuCascade approach provides a reliable description of muonic X-ray spectra.
- Current limitations (HF splitting, self-absorption, cascade refinements) define the next development steps.
- A validated, comprehensive database covering all the periodic table is in preparation and will be released upon completion of systematic benchmarking.

Results

- The summed Au energy spectrum is compared with MuCascade (cascade + MuDirac).
- Good agreement is observed for the dominant transitions in both energy and relative intensity.
- Discrepancies in some weaker lines and selected transitions.
- Missing hyperfine structure (HF) and self-absorption effects are not yet included and are likely sources of the residual discrepancies.



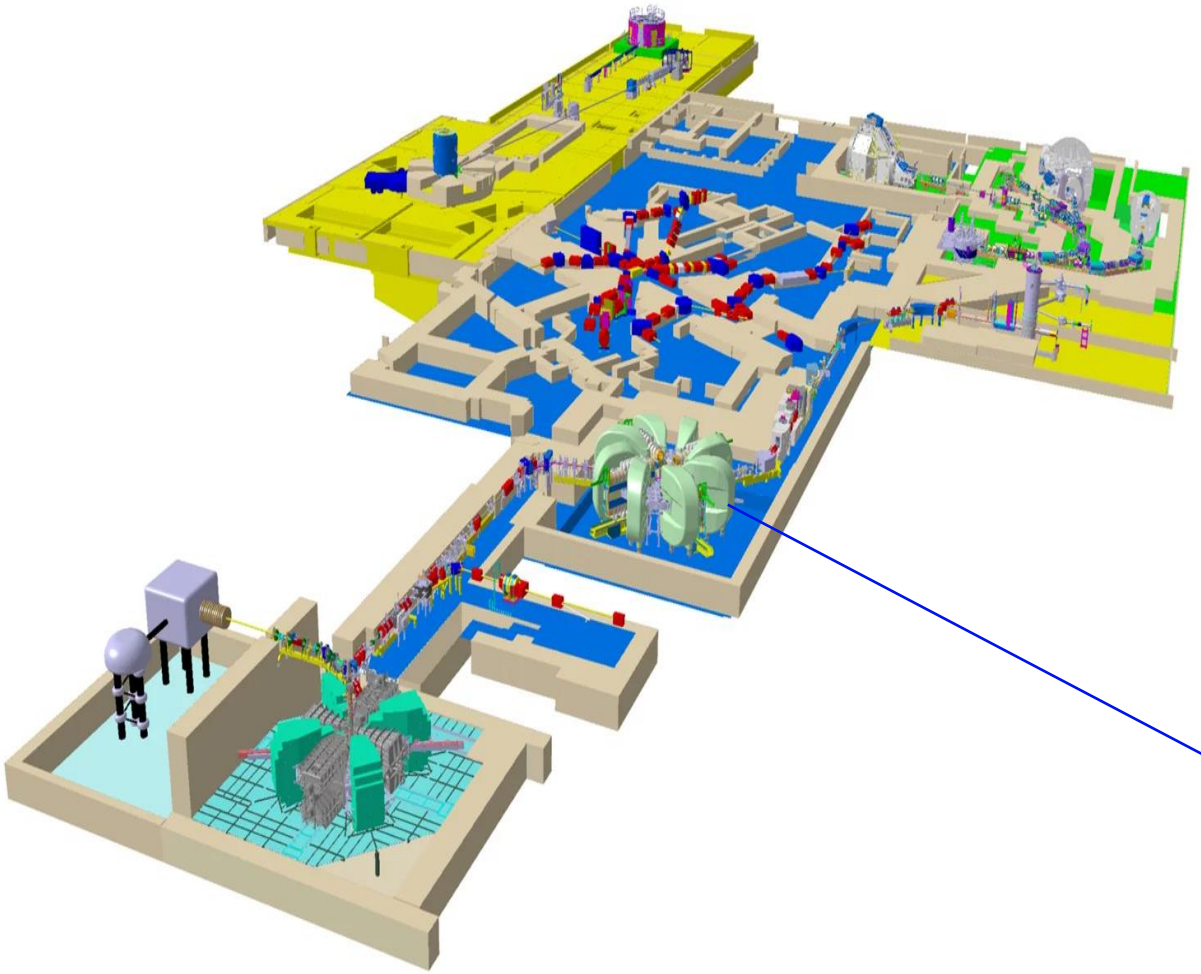
References

[1] V. Akylas, Comput. Phys. Commun 15, (1978).
[2] S. Sturniolo, X-Ray Spectrometry 50, 180 (2021).
[3] L. Gerchow, Review of Scientific Instruments 94, (2023).

2

Facility & Instrument

PSI-HIPA



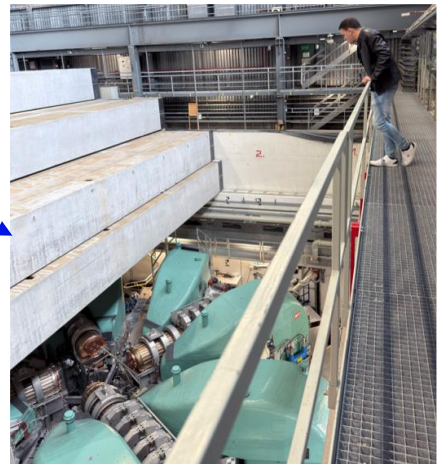
HIPA : High Intensity Proton Accelerator

- HIPA provides 10^{16} protons per second (1.4 MW).
- The proton beam is used to produce muons:

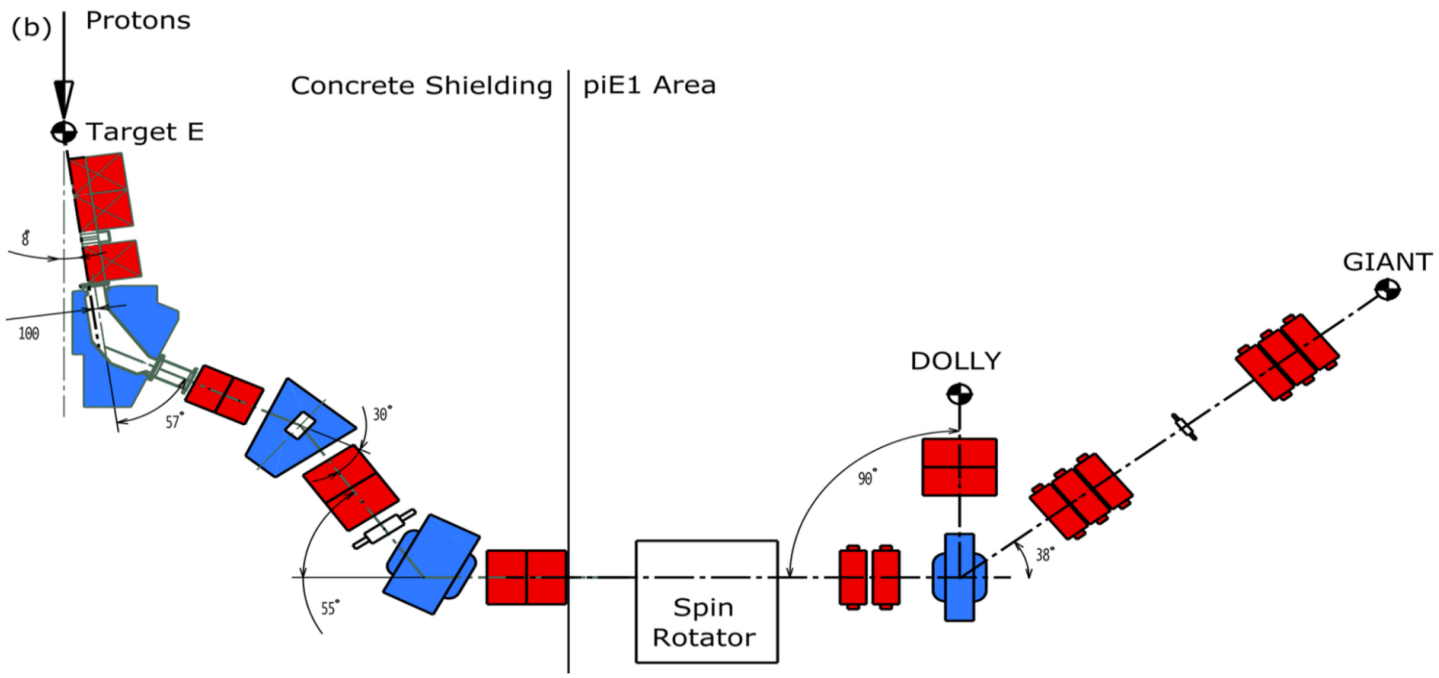
$$p + n \rightarrow p + p + \pi^-$$

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

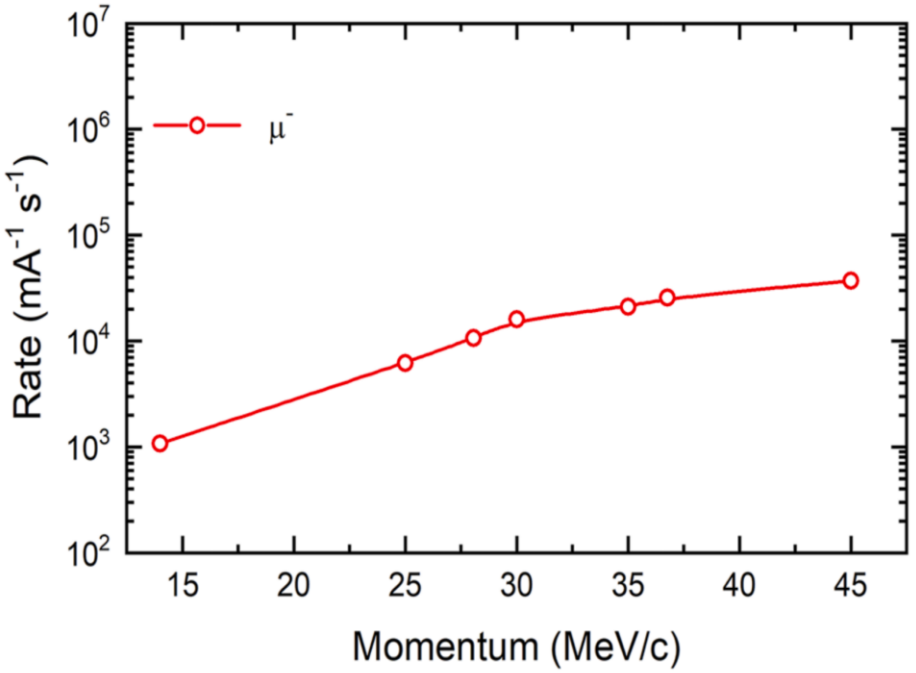
- The rest of the proton beam (60 %) is transported to a neutron spallation source (SINQ).



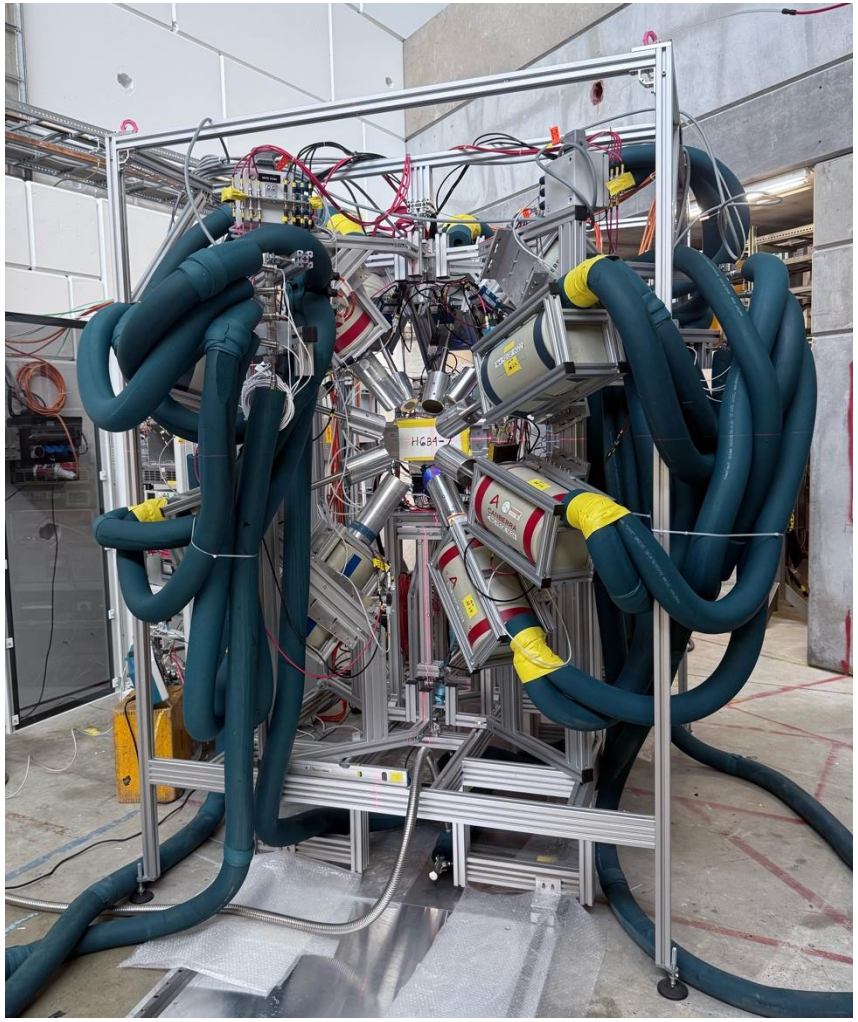
PiE1 Beamline



- Typical μ^- momenta : 15-60 MeV/c.
- Rates range from 10^3 to 10^5 μ^- per second on target.



GIANT



L. Gerchow, et al., Germanium Array for Non-destructive Testing (GIANT) setup for muon-induced X-ray emission (MIXE) at the Paul Scherrer Institute, Rev. Sci. Instrum. 94 (4) (2023) 045106.

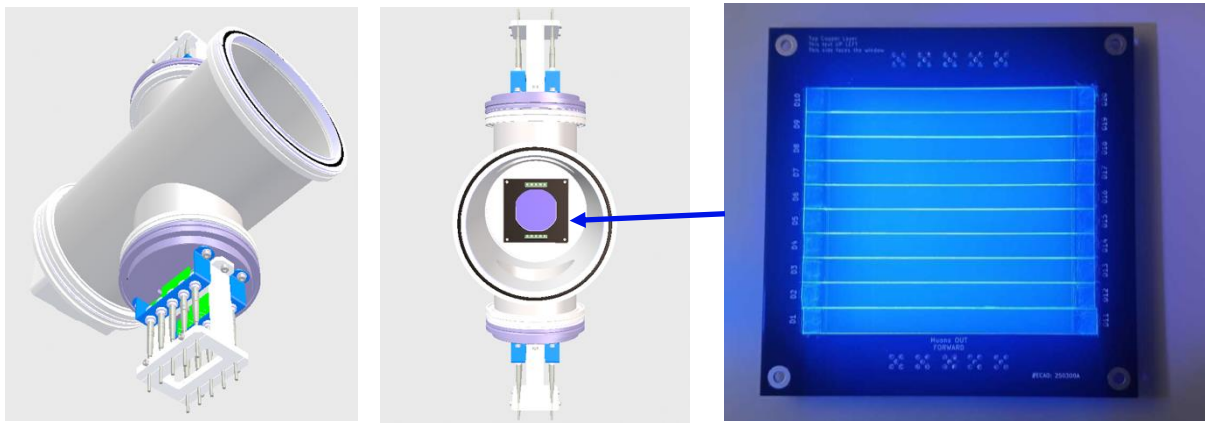
GIANT: GermanIum Array for Non-destructive Testing

- **Mechanical Structure:**
  - Aluminum Frame.
  - Fully Movable as a Unit.
- **Detector Configuration:**
  - 8 Freely Rotating Arms *(Currently 5 installed)*.
  - 4 BigMac HPGe Detectors per Arm.
  - 30 HPGe Detectors Total (Currently ~12 Installed).
  - Reproducible positions and angles.
  - HPGe detectors shared with multiple experiments.
- **Cryogenics & Automation:**
  - Fully Automatic Liquid Nitrogen (LN_2) Refill System
- **Sample Holder:**
  - A central target/sample position ensures symmetrical detector geometry for optimized detection efficiency and angular coverage.

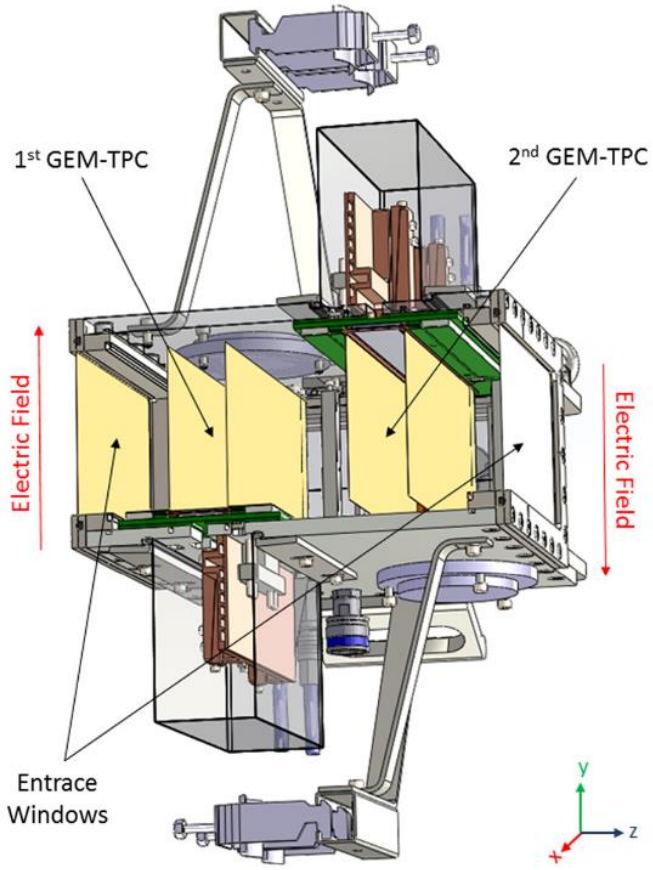
Tagging and Tracking

Tagger detector:

- BC-400 plastic scintillators: striped design (10 individual channels).
- Active area (~7x7cm^2).
- Allows for discrimination of nuclear capture events.
- Reduces uncorrelated background
- Beamport: 50 µm Mylar



Tracker detector:



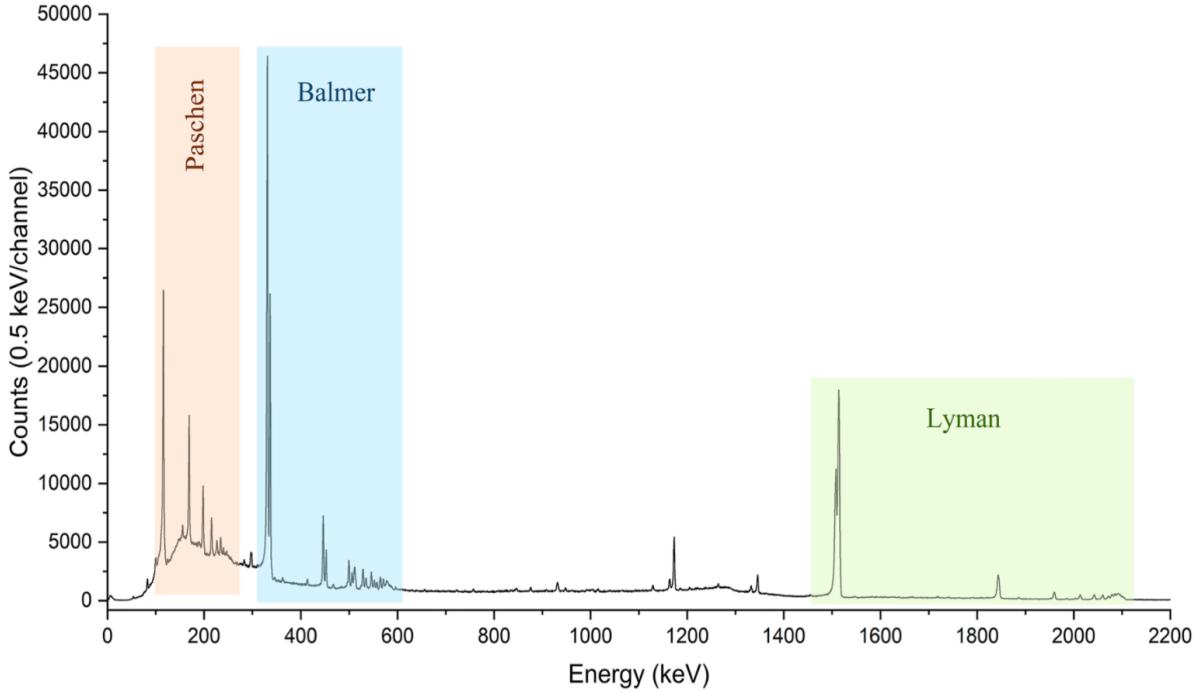
3

MIXE

Elemental Analysis

- X-ray Spectrum from Muon-Irradiated Iron Sample:
- Single HPGe detector.
- Beam momentum: 28.6 MeV/c.
- Acquisition time: 0.5 h

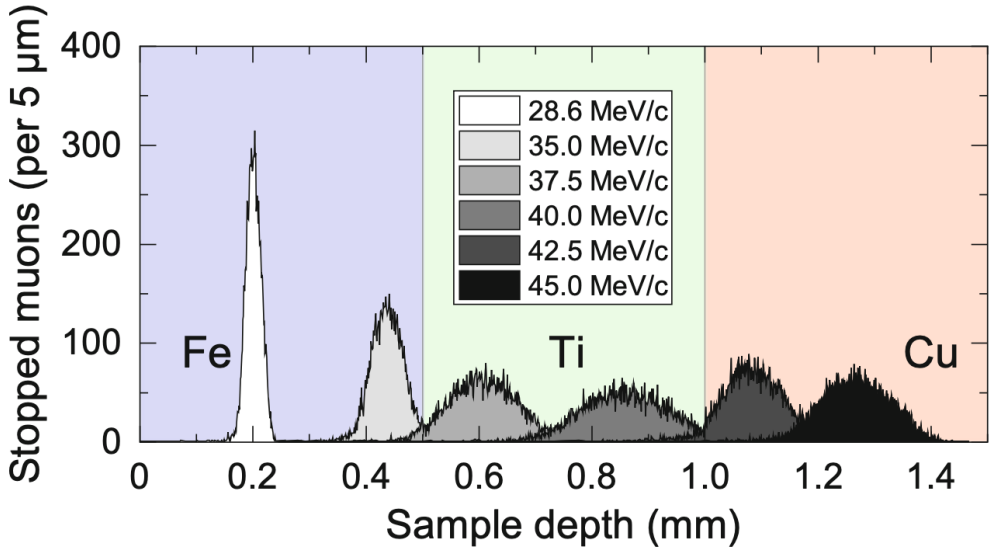
- Series lines are clearly visible in the X-ray spectrum.
- MIXE produces high-energy X-rays that travel much farther in the material.

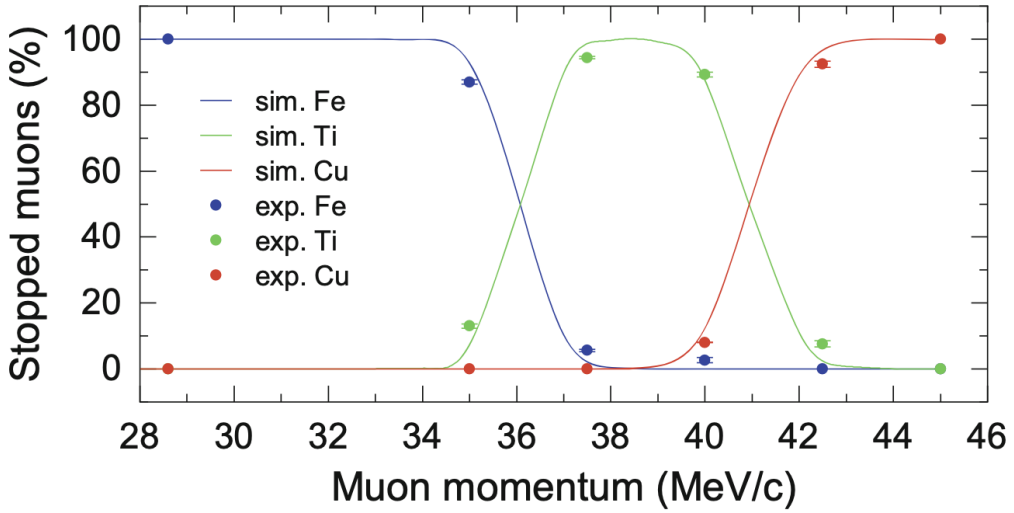


- Compared to XRF or PIXE, MIXE's higher-energy X-rays penetrate deeper with less attenuation, enabling bulk rather than surface-only analysis.

Depth Dependence

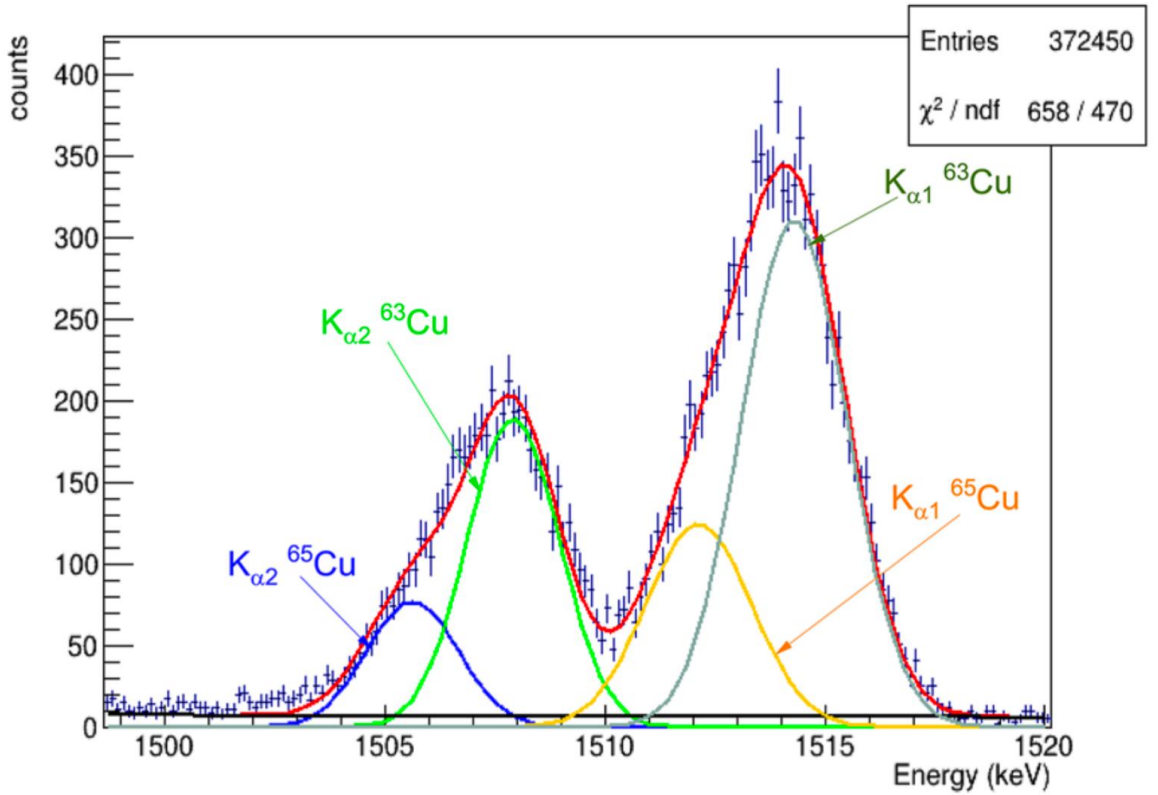
- Simulation of the capture profiles of μ^- in Tri-layer (thickness of each layer 500 µm).
- Muon momentum tuning allows scanning of element occurrence as a function of penetration depth.
- Comparison between simulation and measured K_α line intensities shows good agreement.
- Implantation depths :~ µm to ~ cm.





Isotopic composition

- The nuclear radius of isotopes of an element follows an $A^{1/3}$ dependence.
- Nuclear polarization causes additional isotope-dependent energy shifts.
- These shifts open the possibility of determining isotopic ratios by MIXE (For Z≳20).
- Spectrum showing the $K_{\alpha 1}$ and $K_{\alpha 2}$ lines for a copper sample.



- MIXE doesn't just tell us what element is present, it can also tell us which isotope, and it can do so non-destructively and deep inside the sample.

4

Conclusion

Conclusion

- **Why MIXE:**
- MIXE is non-destructive.
- Elemental analysis, depth dependence, isotopic. composition, and tomography.
- Not only archaeology, but we can also explore other samples.
- The MIXE call for proposals has been open since the beginning of this year (no cost for users).

  https://www.psi.ch/en/smus/calls

  issa.briki@psi.ch

- **Acknowledgement:**

5

Backup