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].

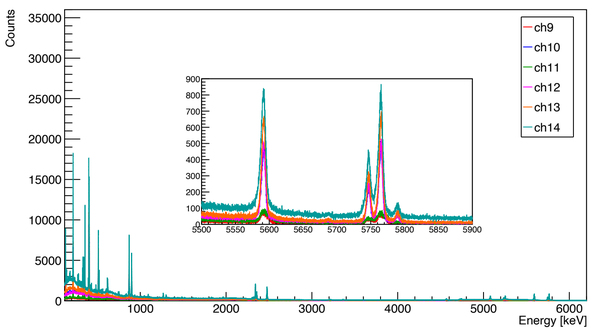
[1] PSI Center for Neutron and Muon Sciences CNM, 5232 Villigen PSI, Switzerland.
***Issa.briki@psi.ch**

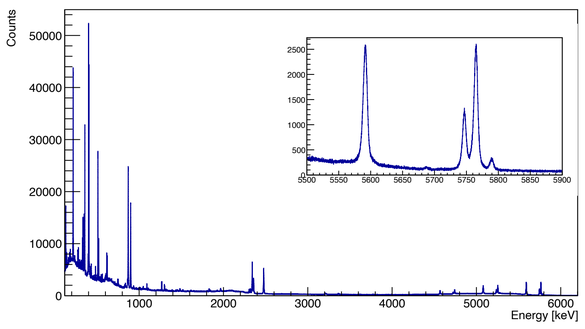
Abstract

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.

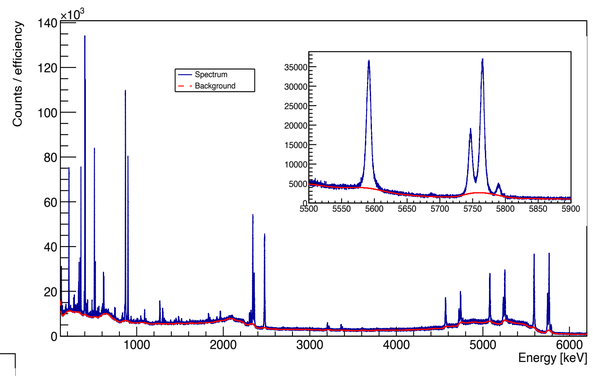
Experimental Approach

- 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.

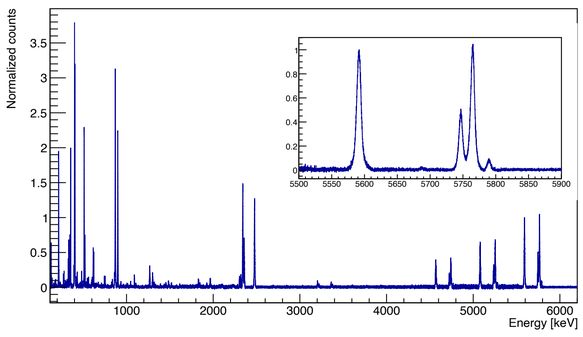




- A final timing window of −50 ns to +50 ns was applied uniformly to all detectors.
- The calibrated and time-aligned signals from all HPGe detectors are combined to construct the summed energy spectrum.



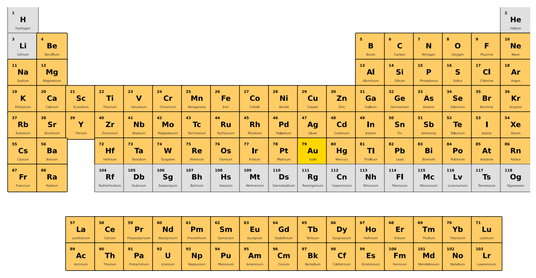
- The summed energy spectrum is constructed from efficiency-calibrated detectors.
- The background is modeled and subtracted using the TSpectrum class.

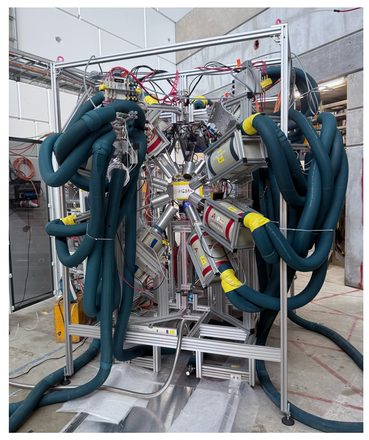


- The summed energy spectrum is normalized to the kα1 peak.
- Muonic X-ray transitions are observed up to principal quantum number n ≈ 8

Method

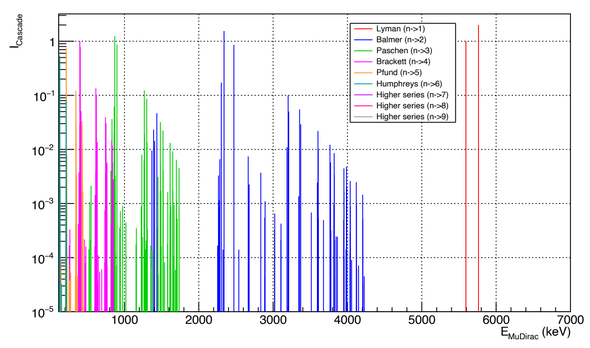
- Transition intensities computed for Z = 4–103 (up to n = 20).
- Good agreement with experiment for dipole transitions; discrepancies remain for some quadrupole transitions.
- New C++ cascade code under validation.
- Muonic X-ray energies obtained with MuDirac for all elements and stable isotopes.
-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

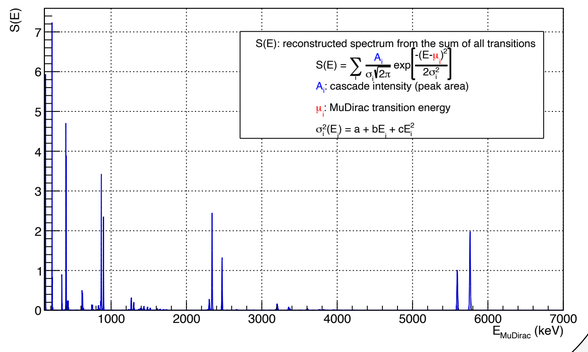




Computational Approach

- 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.



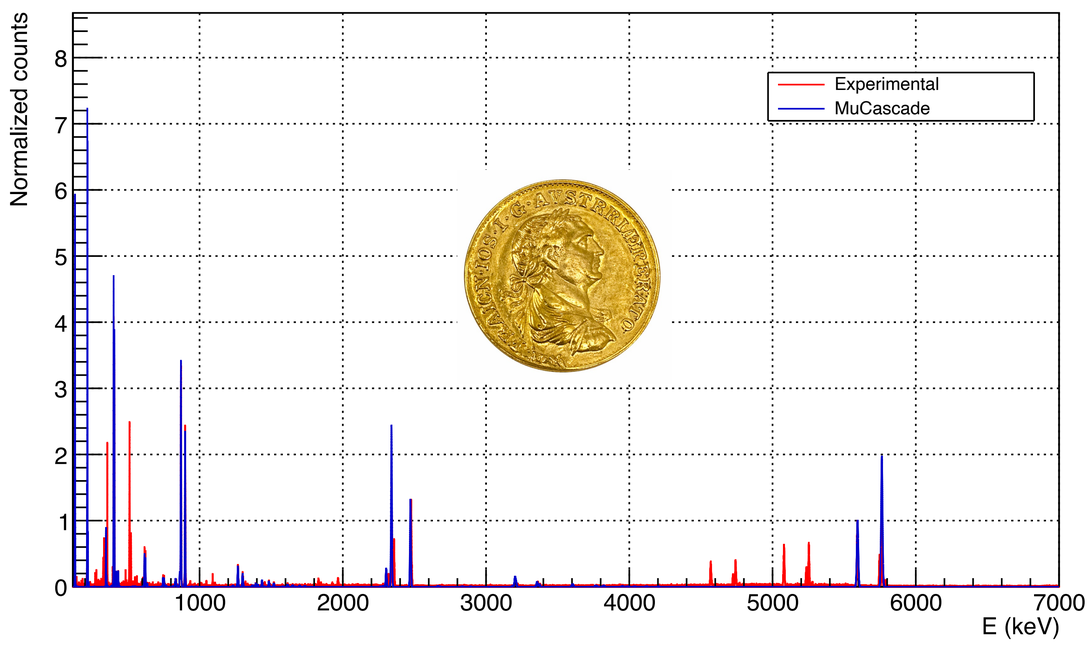


Conclusion

- 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).