Nuclear Quantum Dynamics at X-Ray Free-Electron Lasers

M Gerharz[1] and J Evers[1]

[1] *Theoretical Quantum Dynamics and Quantum Electrodynamics, Max Planck Institute for Nuclear Physics, Heidelberg, Germany*

Contact Email: miriam.gerharz@mpi-hd.mpg.de

Mössbauer spectroscopy is well established across the natural sciences. The exceptionally narrow linewidths of Mössbauer nuclei also make them a promising platform for X-ray quantum optics. These narrow transitions feature long lifetimes, but on the other hand also allowed to only study single excitations for decades. This limitation changed with the advent of X-ray free-electron lasers (XFELs), which deliver orders of magnitude more resonant photons than synchrotrons. As a result, pulses containing multiple resonant photons occur frequently and the average resonant photon flux is increased, enabling experiments previously not possible. For example, multiple photon excitations and the subsequent dynamics [1,2] as well as nuclear clock transitions [3,4] can be studied. In addition, finite size effects in small samples can be explored and further progress of x-ray light sources, *e.g.* an X-ray free-electron laser oscillator, would enable a non-linear time evolution of the nuclei after the full excitation of a nuclear ensemble [5].

In this talk I will focus on the experimental progress related to the higher peak resonant photon flux. So far for Mössbauer spectroscopy extensive averaging was always necessary thereby limiting the applications. With up to 1000 resonant photons per shot, we demonstrate a data-driven single-shot sorting of Mössbauer data [1], which opens up new applications for Mössbauer spectroscopy, *e.g.* fast time scales or different decay paths. In addition, I will present our results of interacting many-body simulations [5]. These consist of finite size effects already measurable in the low-excitation regime at XFELs and an excitation-dependent dipole-phase evolution, which is a clear signature of non-linear nuclear dynamics at higher excitation.

References

[1] M Gerharz, W Hippler, B Marx-Glowna, *et al.*, arXiv:2509.15833 (2025)

[2] A I Chumakov, A Q R Baron, I Sergueev, *et al.*, Nat. Phys. **14**, 261 (2018)

[3] Yu Shvyd'ko, R Röhlsberger, O Kocharovskaya, *et al.*, Nature **622**, 471 (2023)

[4] P Liu, M Gerharz, B Marx-Glowna, *et al.*, arXiv:2508.17538 (2025)

[5] M Gerharz and J Evers, arXiv:2510.00970 (2025)