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Nuclear resonance spectroscopy at X-ray free electron lasers

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Probing resonances in Mössbauer nuclei with x-rays or γ -rays is widely used to study structure and dynamics of matter with a remarkably high energy resolution. So far, most experiments use radioactive or synchrotron radiation sources. In the past few years, self-seeded X-ray free electron lasers have become available, which provide qualitatively new conditions for studying interactions of the nuclei with the intense x-ray radiation.

In this talk, I will review our recent theoretical and experimental progress in exploring the new capabilities for nuclear resonance scattering offered by the XFELs. These can broadly be classified into methods relying on the exceptionally high number of nuclear-resonant photons per second (average flux), or per x-ray pulse (peak flux).

As an example for the high average flux per second, I will briefly discuss the recent direct resonant X-ray excitation of the Mössbauer clock transition in ^{45}Sc [1].

The high peak flux leads to a disruptive change in experimental conditions, from less than one resonant photon per pulse at synchrotrons to several hundreds at XFELs. To explore these capabilities, the ^{57}Fe EuXFEL collaboration (led by R. Röhlberger and J. Evers) has established nuclear resonance scattering on ^{57}Fe in a series of experiments at the European X-ray free electron laser. As a first result, I will discuss an experiment which demonstrates the possibility to record entire Mössbauer datasets with single XFEL pulses. This new “single-shot” capability opens perspectives for the exploration of nonequilibrium phenomena using the Mössbauer effect, by disentangling different possible system evolution pathways from out-of-equilibrium back to equilibrium on the level of individual x-ray pulses [2].

Finally, I will revisit the old question if it is possible to fully invert an ensemble of nuclei using electromagnetic fields, in light of the new XFEL conditions and recent developments in nuclear quantum optics. In particular, I will discuss the interaction of strongly focused x-ray pulses with ensembles of nuclei embedded in an x-ray waveguide [3].

[1] Y. Shvyd'ko et al., “Resonant x-ray excitation of the nuclear clock isomer ^{45}Sc ”, *Nature* 622 (2023) 471.

[2] M. Gerharz et al., “Single-shot sorting of Mössbauer time-domain data at X-ray free electron lasers”, submitted

[3] D. Lentrodt, C. H. Keitel, and J. Evers, “Towards nonlinear optics with Mössbauer nuclei using x-ray cavities”, *Phys. Rev. Lett.* in print (2025)

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