

Introducing ^{181}Ta nuclear resonance for precision metrology applications

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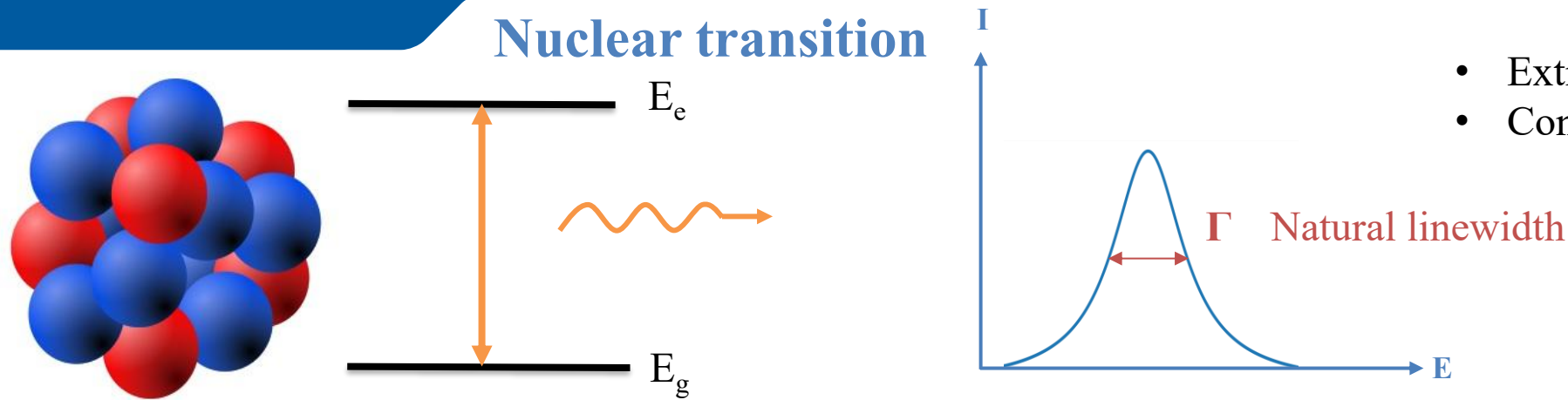
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Outline

- **Nuclear resonance for precision metrology**
- **How to observe narrow nuclear transition?**
 - Mössbauer spectroscopy
 - Nuclear excitation with synchrotron radiation
- **^{181}Ta nuclear resonance**
- **From first synchrotron excitation to recent developments**
- **Experimental setup for polarization-resolved ^{181}Ta NFS**
 - Steps prior to the NFS measurement
- **Controlling the nuclear Zeeman splitting with an external magnetic field**
 - Time resolved ^{181}Ta nuclear frequency comb
- **Conclusion and Outlook**

Nuclear resonance for precision metrology



High precision resonant isotopes relative to ^{57}Fe

Isotope	E_0 (keV)	Γ_0 (eV)	Γ_0/E_0
^{57}Fe	14.412	$4.66 \cdot 10^{-9}$	$3.2 \cdot 10^{-13}$
^{181}Ta	6.214	$75 \cdot 10^{-12}$	$1.2 \cdot 10^{-14}$
^{67}Zn	93.312	$49.8 \cdot 10^{-12}$	$5.3 \cdot 10^{-16}$
^{45}Sc	12.389	$1.4 \cdot 10^{-15}$	$1.1 \cdot 10^{-19}$
^{109}Ag	88	$1.2 \cdot 10^{-17}$	$1.3 \cdot 10^{-22}$
^{229}Th	$8.4 \cdot 10^{-3}$	$1.0 \cdot 10^{-18}$	$1.1 \cdot 10^{-16}$



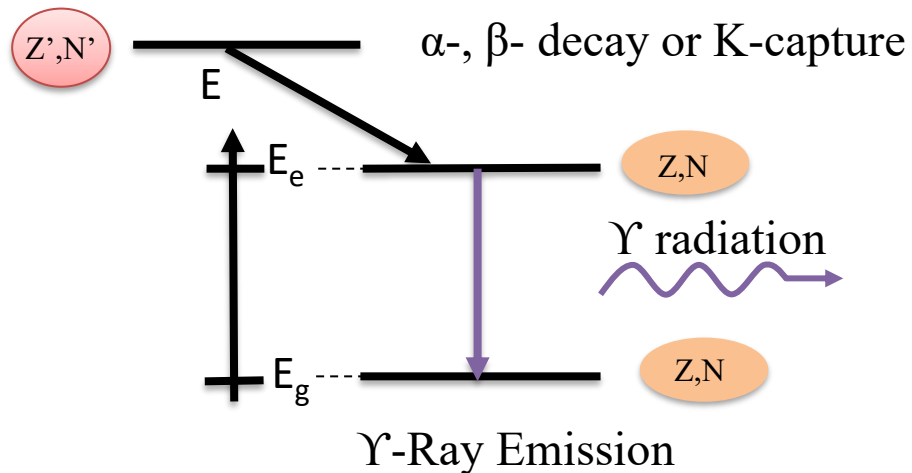
Interesting for
Metrology, Quantum optics, Sensing
and Material science

How to observe narrow nuclear transition?

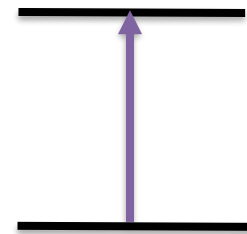
Mössbauer Effect

Rudolf L Mössbauer
Nobel prize in Physics (1961)

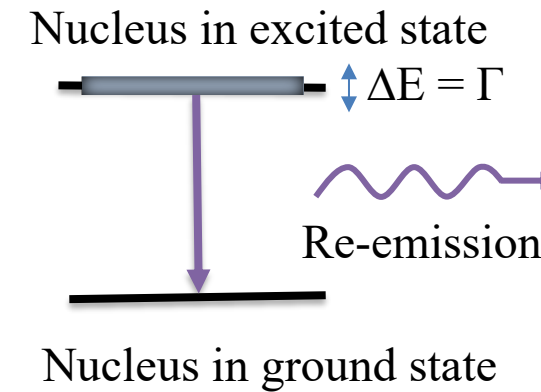
Radioactive Source Isotope



Recoilless emission and absorption of γ -rays by nuclei embedded in a solid lattice.



Resonant Absorption



Nucleus in ground state

- Spectroscopy is performed with radioactive γ - ray source.
- Provides the information on electric, magnetic and structural properties of the sample.

Gütlich, Philipp, Rainer Link, and Alfred Trautwein. Mössbauer spectroscopy and transition metal chemistry. Springer Science, 2013.

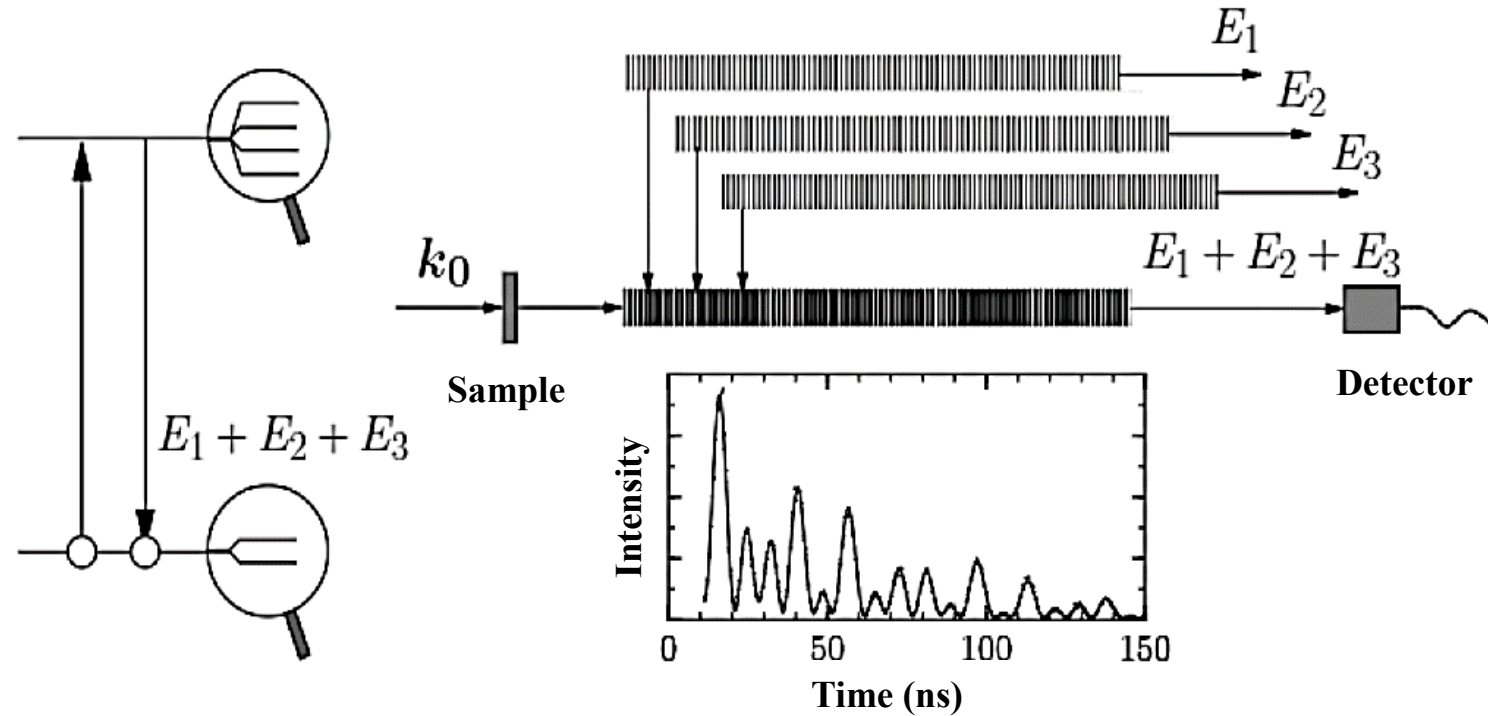
Nuclear excitation with synchrotron radiation

Nuclear Resonance Scattering (NRS)

S. L. Ruby (1974): Proposed to excite Mössbauer nuclei from ground state.

E. Gerdau (1985): First Experimental realization at DESY, Hamburg.

- Uses pulsed, highly monochromatic synchrotron x-ray beam.
- Time dependent coherent decay of excited nuclear states.
- Reveals quantum beats arising from the hyperfine interactions.



Advantages:

- No radioactive source required.
- Energy tunability to access other Mössbauer isotopes such as ^{181}Ta .

R. Röhlsberger, Nuclear Condensed Matter Physics with Synchrotron Radiation: Basic Principles, Methodology and Applications, Springer Tracts in Modern Physics Vol. 208 (Springer, Berlin, Heidelberg, 2004)

^{181}Ta nuclear resonance

^{181}Ta has a nuclear resonance at **6.214 keV** in hard X-ray regime.

Properties	^{57}Fe	^{181}Ta
Natural abundance	2.11 %	99.98%
Lamb Mössbauer factor	0.79	0.96
Natural linewidth	4.5 neV	75 peV
Quadrupole moment (Q_e , Q_g)	0.16, 0.0 barn	3.7, 3.2 barn
Magnetic moment (μ_e , μ_g)	-0.15, 0.09 μ_N	5.2, 2.3 μ_N

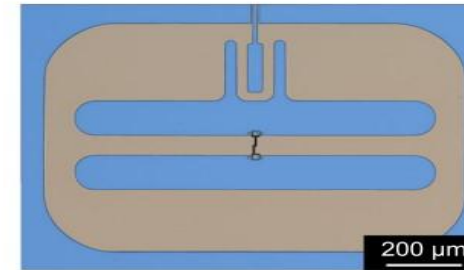
Over 25 times larger
nuclear moments than
 ^{57}Fe



Highly sensitive to small
magnetic, electric and
chemical perturbations.

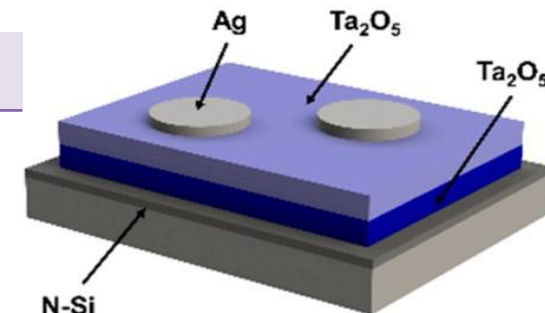
Gütlich, Philipp, Eckhard Bill, and Alfred X. Trautwein. *Mössbauer spectroscopy and transition metal chemistry: fundamentals and applications*. Springer Science & Business Media, 2010.

Applications



Tantalum based transmon
superconducting qubit.

Place, Alexander PM, et al. "New material platform for superconducting transmon qubits with coherence times exceeding 0.3 milliseconds." *Nature communications* 12.1 (2021): 1779.

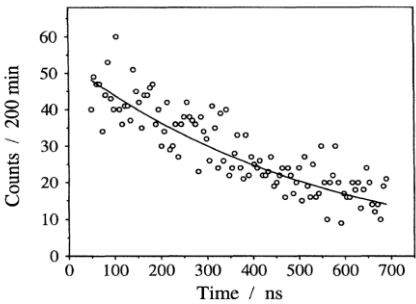


Ta_2O_5 based device
for photonic in
memory computing.

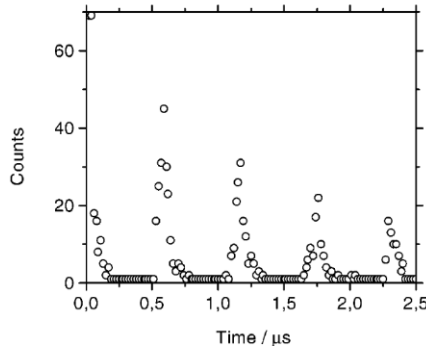
Wang, Wenxiao, et al. "Tantalum pentoxide (Ta_2O_5 and $\text{Ta}_2\text{O}_{5-x}$)-based memristor for photonic in-memory computing application." *Nano Energy* 106 (2023): 108072.

From first synchrotron excitation to recent developments

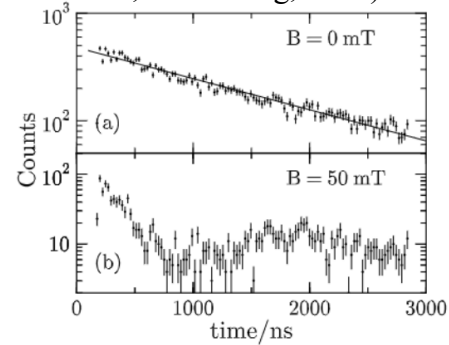
A. I. Chumakov et al., Phys. Rev. Lett. **75**, 549 (1995)



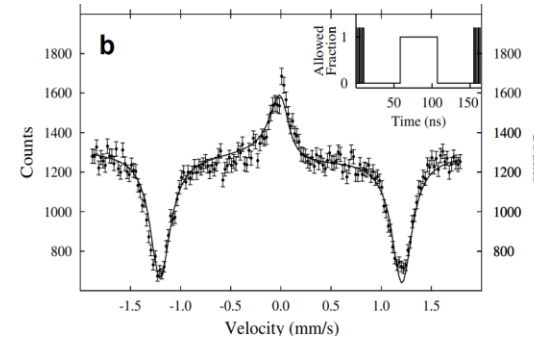
O. Leupold et al., Hyperfine Interact. **123/124**, 611 (1999)



R. Röhlberger, Springer tracts in modern Physics Vol.208 (Springer, Berlin, Heidelberg, 2004)



I. Serdons et al., Nucl. Instrum. Methods Phys. Res. B **251**, 297 (2006)



(2026)

The knowledge gap

First synchrotron radiation excitation of 6.214 keV Ta nuclear transition



Subsequent studies of Ta in external magnetic field



Bragg diffraction from a single crystal of Ta



Stroboscopic detection of Ta Mössbauer resonance

A systematic polarization-resolved study of magnetically splitted dynamics

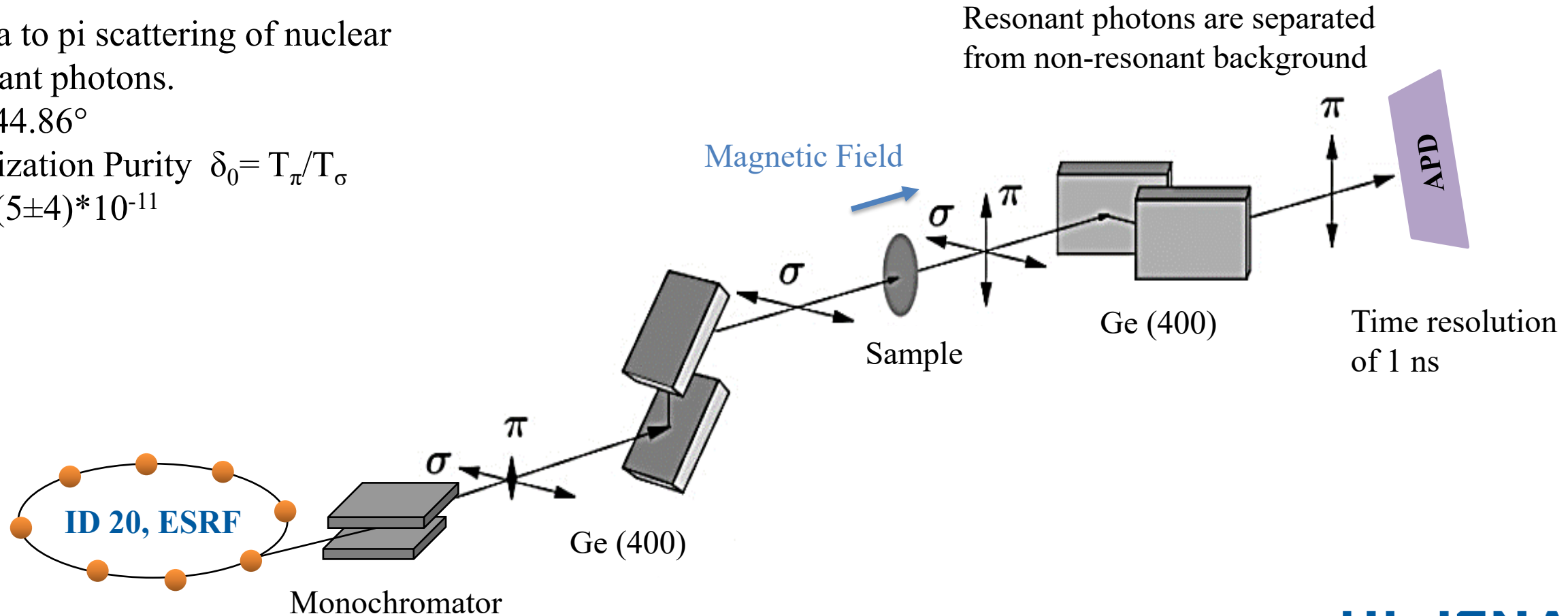
HI JENA
Helmholtz Institute Jena

www.hi-jena.de

Experimental setup for polarization-resolved ^{181}Ta NFS

Optical activity & Polarization Filtering

- Sigma to pi scattering of nuclear resonant photons.
- $\theta_B = 44.86^\circ$
- Polarization Purity $\delta_0 = T_\pi/T_\sigma$
 $\delta_0 = (5 \pm 4) \cdot 10^{-11}$



R. Röhlsberger, Nuclear Condensed Matter Physics with Synchrotron Radiation: Basic Principles, Methodology and Applications, Springer Tracts in Modern Physics Vol. 208 (Springer, Berlin, Heidelberg, 2004)

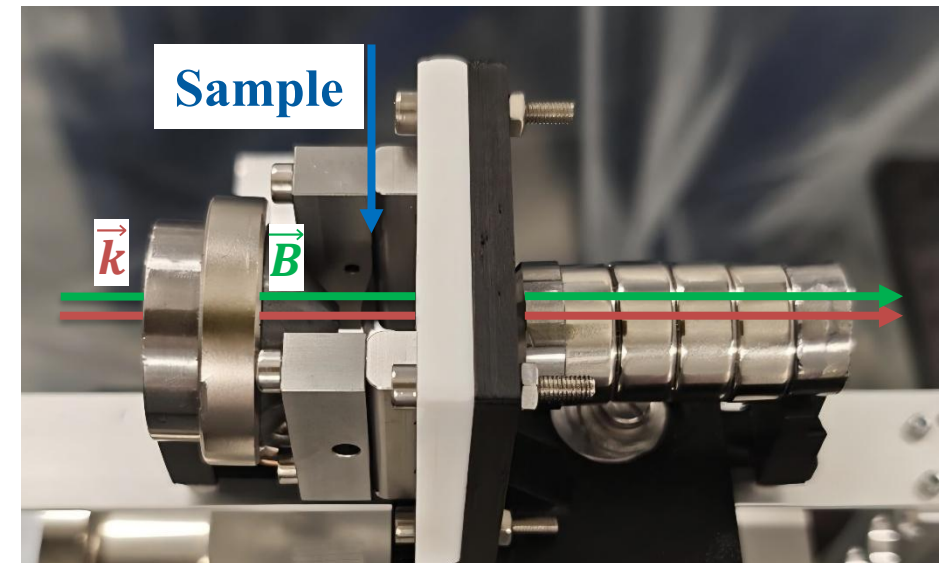
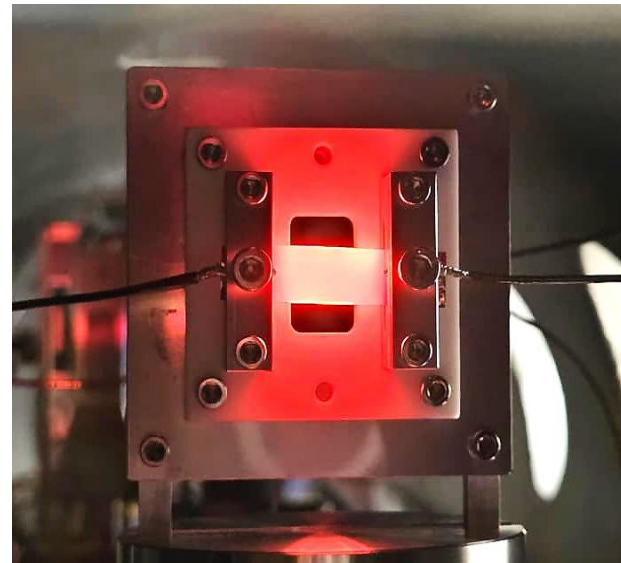
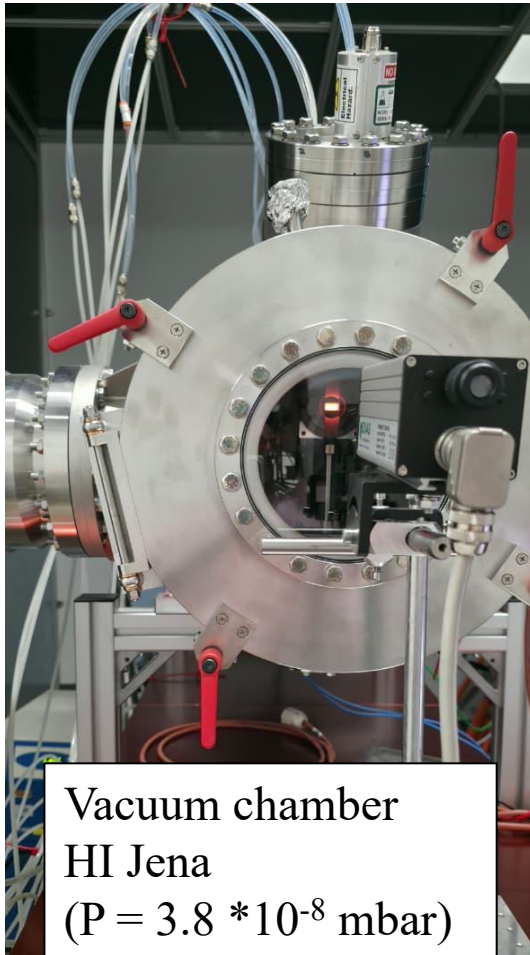
Steps prior to the NFS experiment

^{181}Ta nuclear resonance is sensitive to:

- Interstitial defects
- Local environment

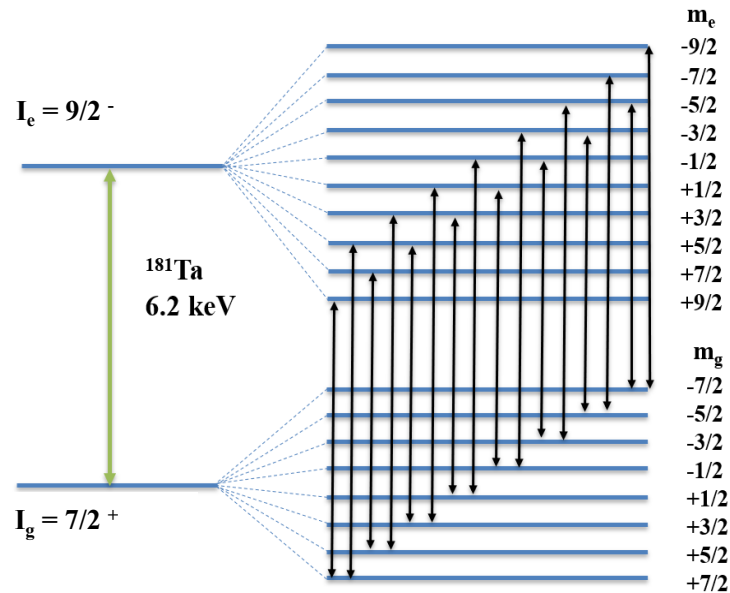
Annealed Ta foils via direct current heating:
➤ 3.8 μm 2500°C for 1hr

Foil in longitudinal magnetic field



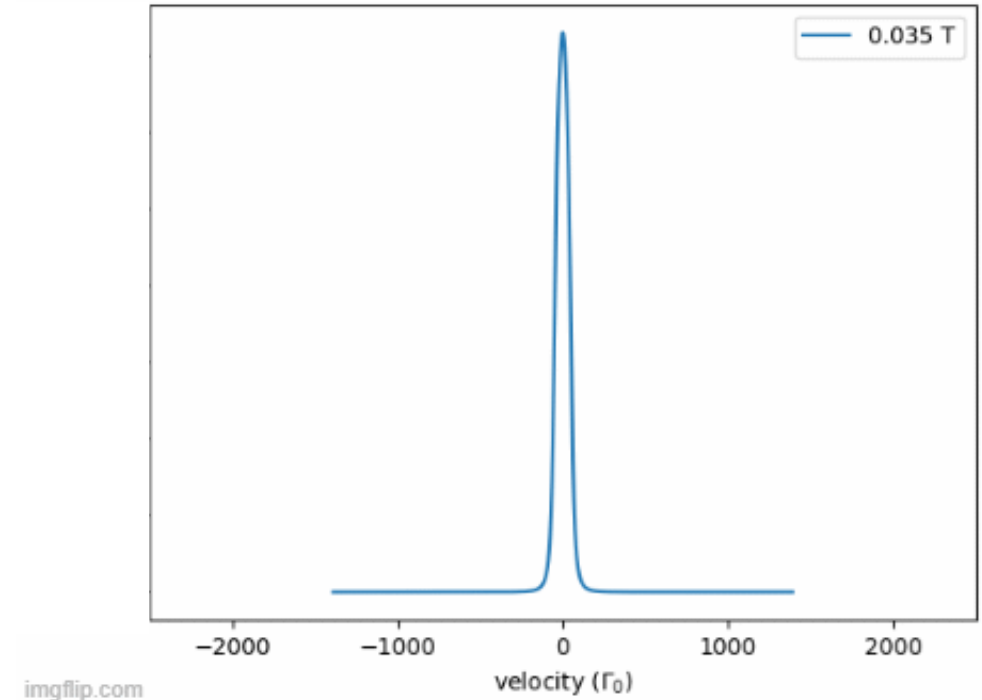
Controlling the nuclear Zeeman splitting with an external magnetic field

Splitting of nuclear levels in external magnetic field, $B \parallel k$ -vector
 $\Delta m = \pm 1$ allowed transition



- External B lifts the degeneracy of nuclear sublevels.
- Zeeman splitting increases with B .

Tunable nuclear frequency comb

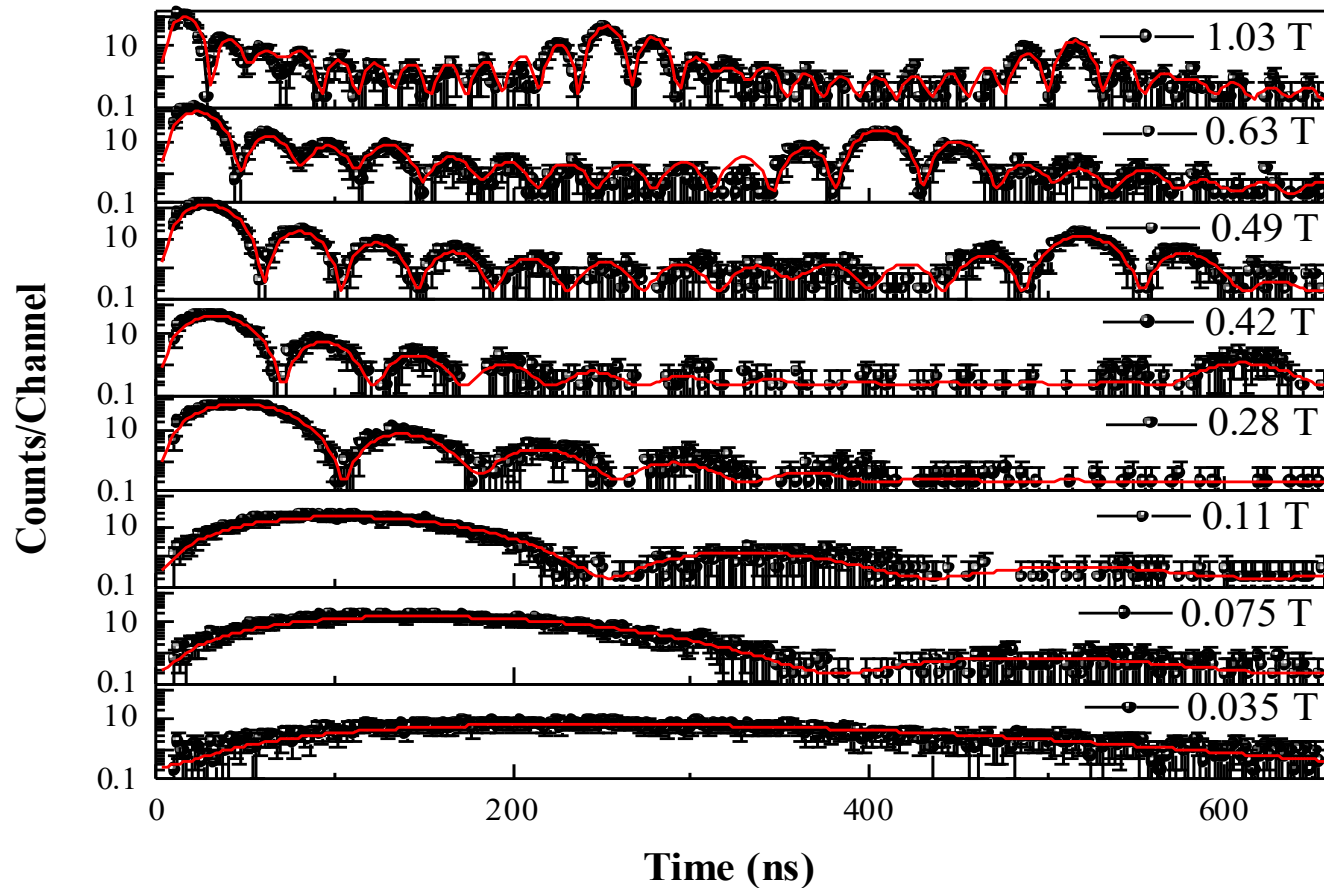


Can we actually observe this controlled nuclear dynamics experimentally?

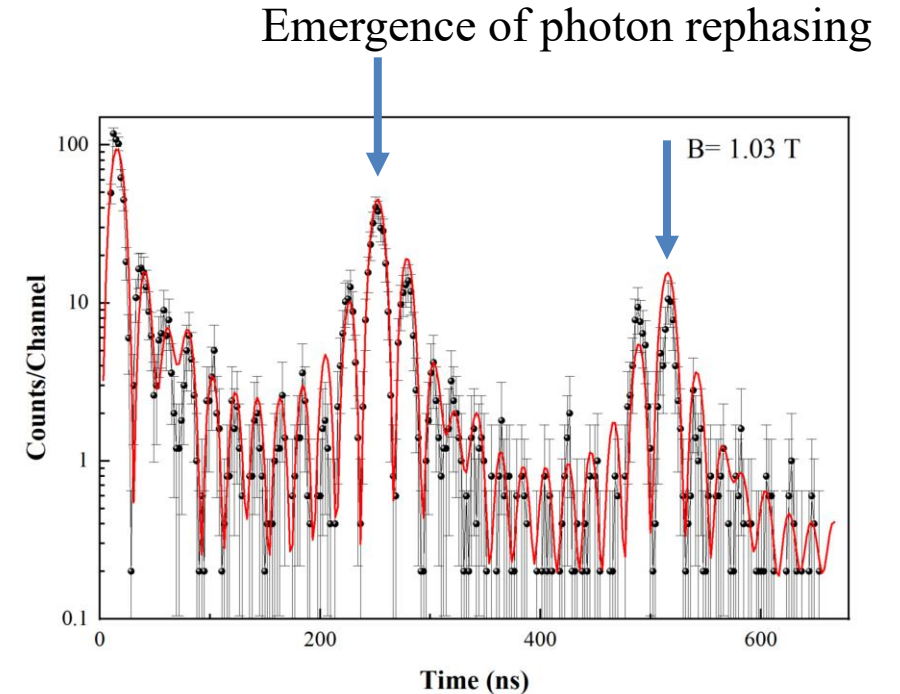
L. Bocklage, Programm package NEXUS (2021 - 2024). <https://doi.org/10.5281/zenodo.106864>

Time resolved ^{181}Ta nuclear frequency comb

(Performed at ID20, ESRF in 4 bunch mode, July 2026)

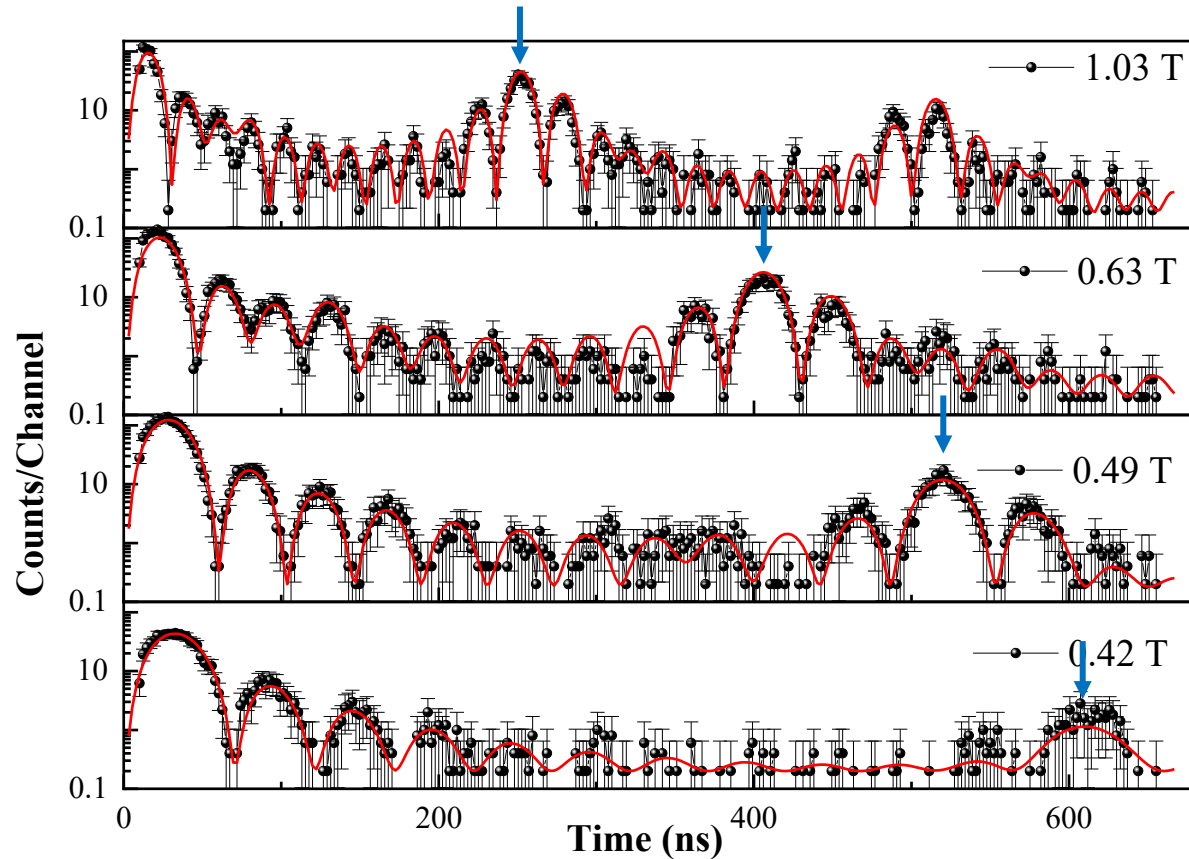


- Observed oscillation reflects the magnetic field induced splitting.



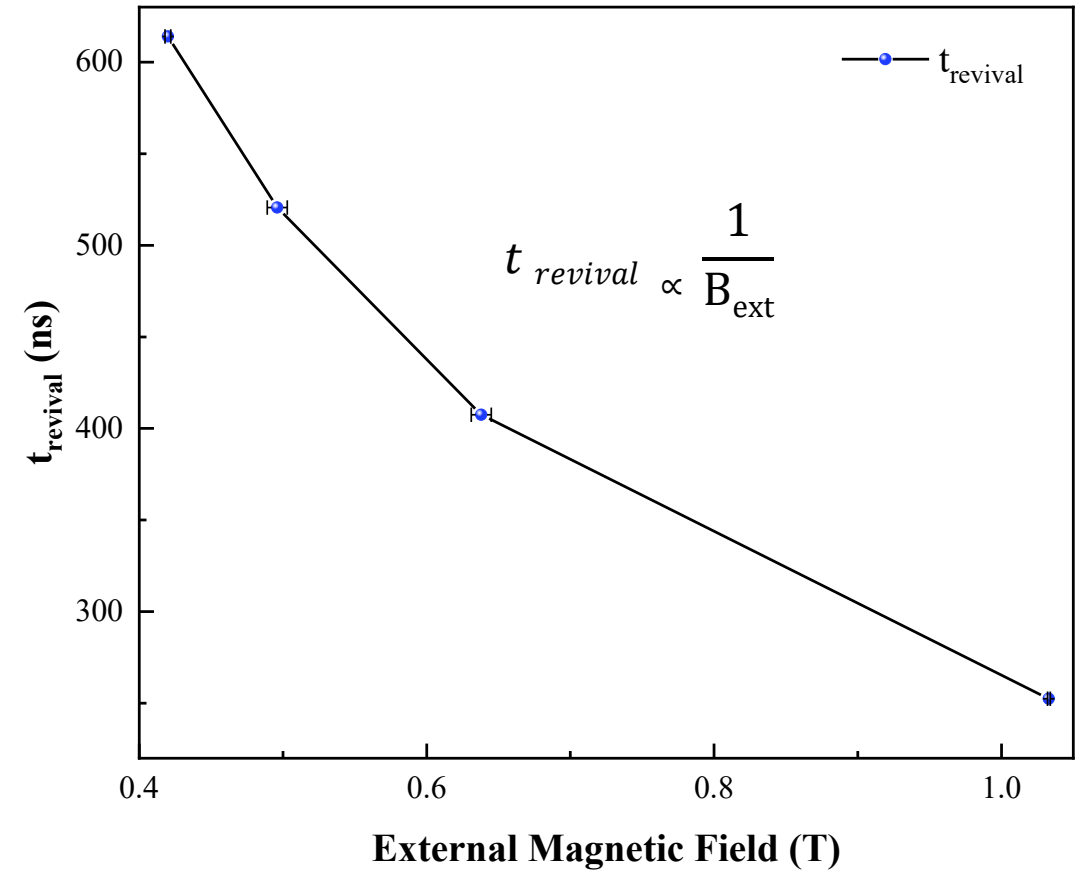
- Magnetic field induced splitting creates multiple nuclear transition frequencies.
- At well defined time, phases realign.
- Rephasing produces photon echo signal.

Time resolved ^{181}Ta nuclear frequency comb



Take-home message: The magnetic field provides direct control on the timescale of nuclear rephasing.

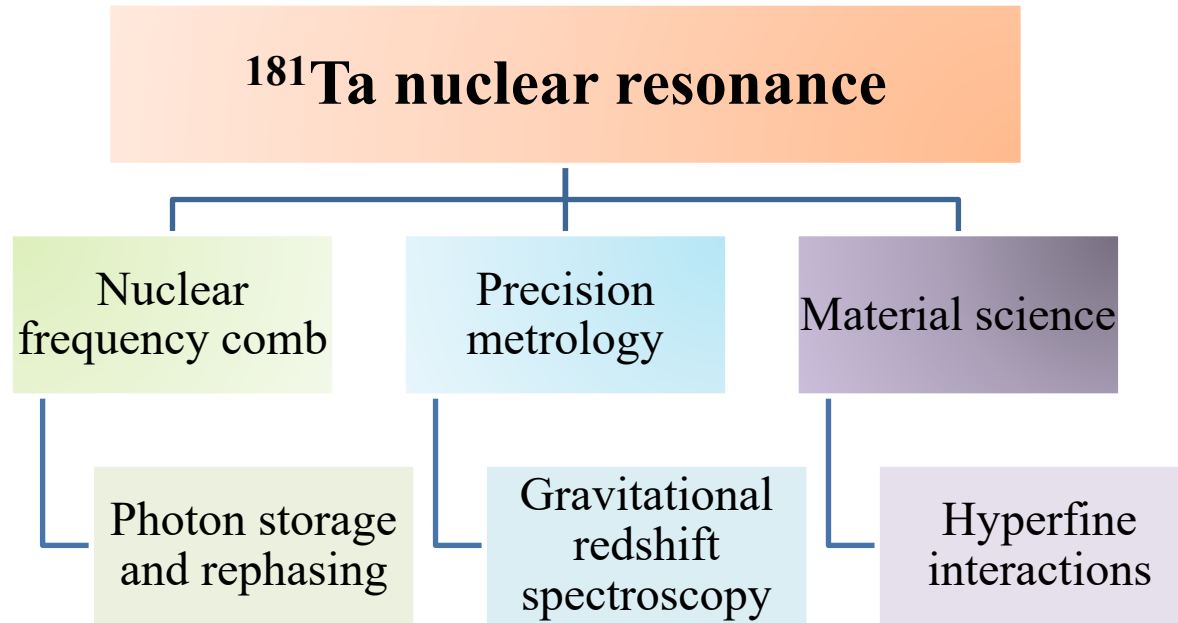
Rephasing time v/s External magnetic field



- Revival time follows an inverse magnetic field dependence.

Conclusion & Outlook

- Polarization-resolved ^{181}Ta nuclear resonant scattering is performed.
- Pronounced magnetic-field-tunable hyperfine rephasing is observed.
- Nuclear dynamics can be externally controlled via magnetic field.



Röhlsberger, Ralf. "Nuclear Heterodyne Interferometry for Gravitational Spectroscopy." *arXiv preprint arXiv:2604.17157* (2026).

Acknowledgements

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Thank you for your attention!

Beamline ID20, ESRF

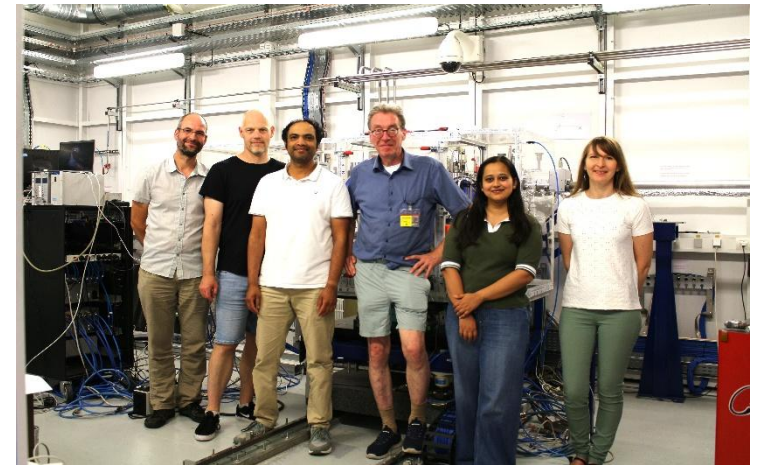
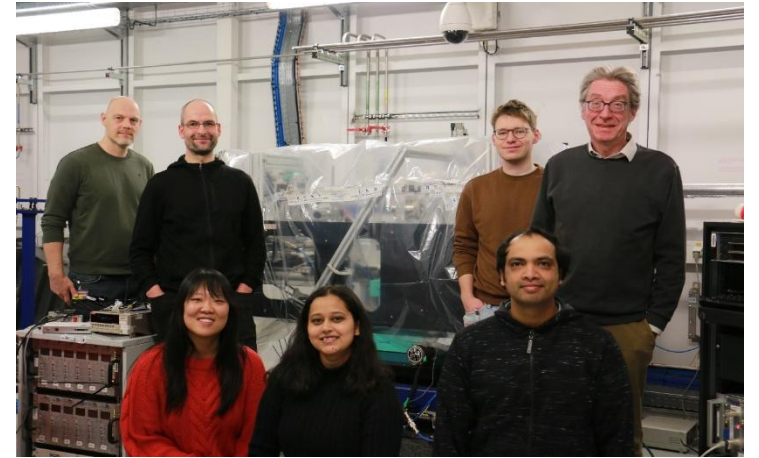
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