MIRACLS

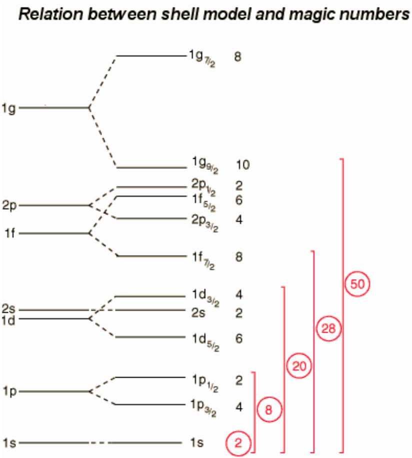
Laser Spectroscopy in an MR-ToF Device

Anthony Roitman

McGill University (Canada), CERN (France/Switzerland)

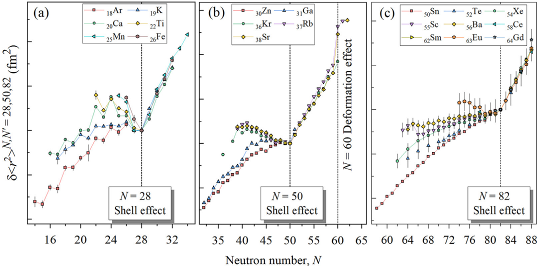
Nuclear Shell Model

- Major area of nuclear research: stability at shell closures
  - Reflected in many observables, such as binding energy or charge radius



Nuclear Shell Model

kink in charge radii at shell closures



X. Yang et al., Prog. Part. Nuc. Phys. 129, 104005 (2023)

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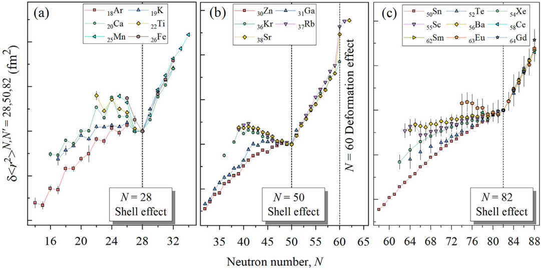
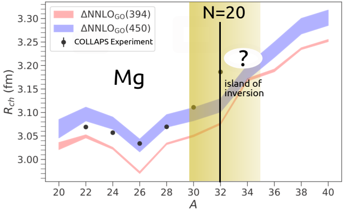


disappearance of shell closure at N=20: island of inversion



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S. J. Novario et al., Phys. Rev. C 102, 051303 (2020)
D. T. Yordanov et al., PRL, 108:042504 (2012)

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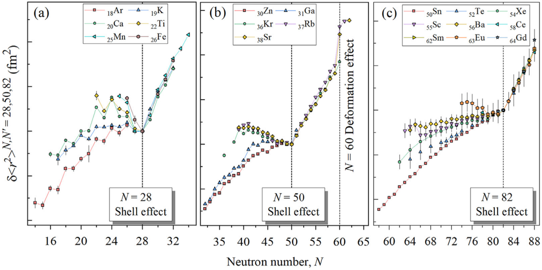

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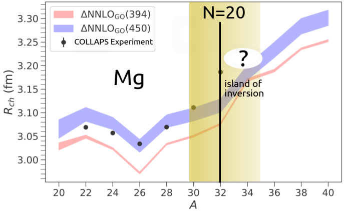
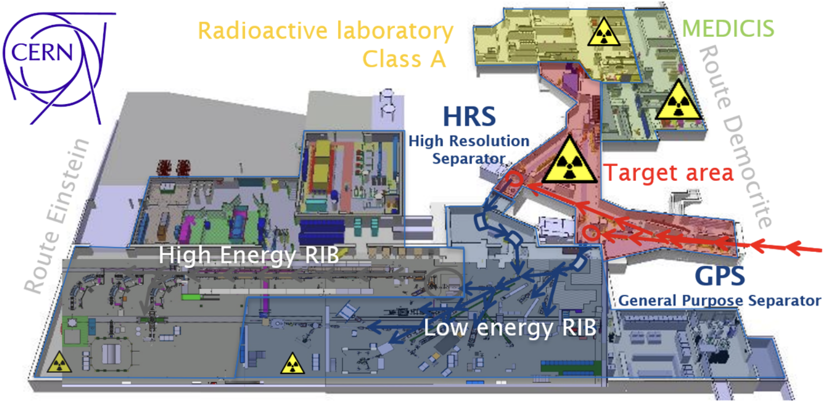


S. J. Novario et al., Phys. Rev. C 102, 051303 (2020)
D. T. Yordanov et al., PRL, 108:042504 (2012)

- $N = 20$ shell closure disappears for magnesium: charge radii for ^{33,34}Mg would provide a powerful benchmark for nuclear theory

ISOLDE facility



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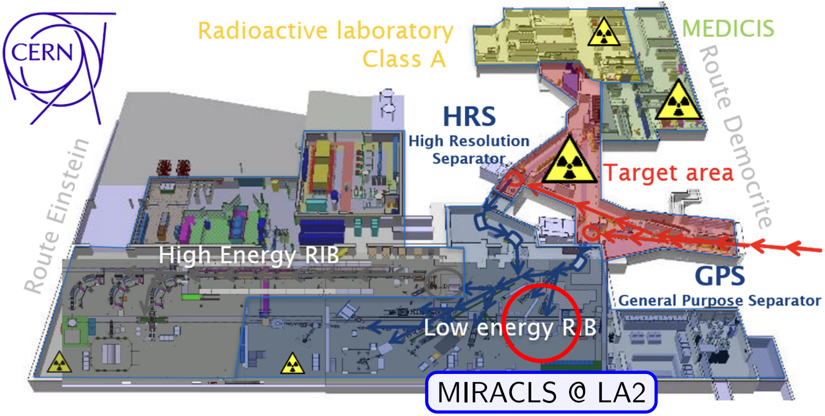
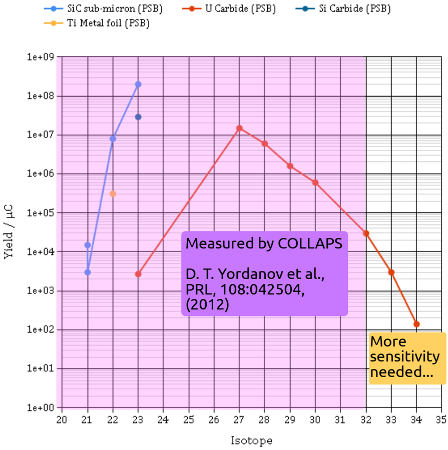


- Challenge: yields down to 100 ions / second and half lives down to 40 ms



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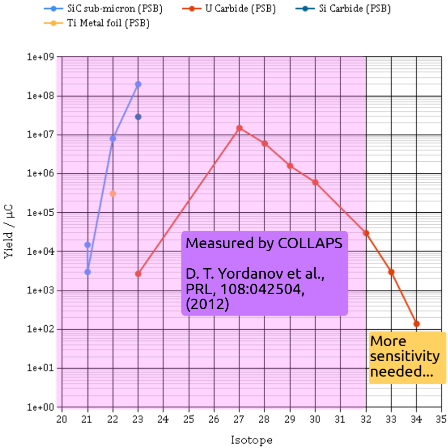
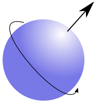


Need highly sensitive laser spectroscopy techniques to probe charge radii of exotic nuclei

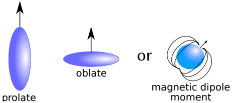
Laser Spectroscopy in Nuclear Physics

By probing an atom's electronic hyperfine structure, we can determine the properties of its nucleus, such as:

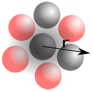
- nuclear spin



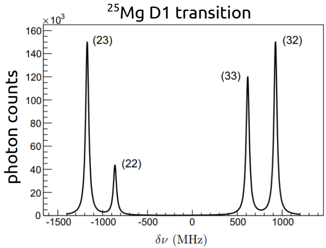
- electromagnetic moments



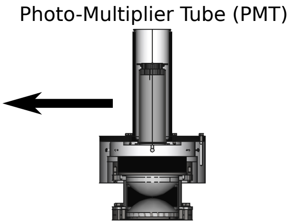
- charge radii

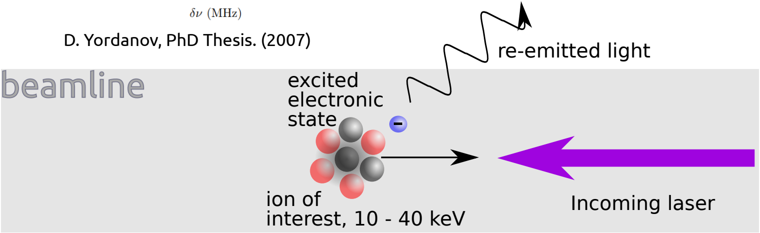


Collinear Laser Spectroscopy (CLS)



D. Yordanov, PhD Thesis. (2007)





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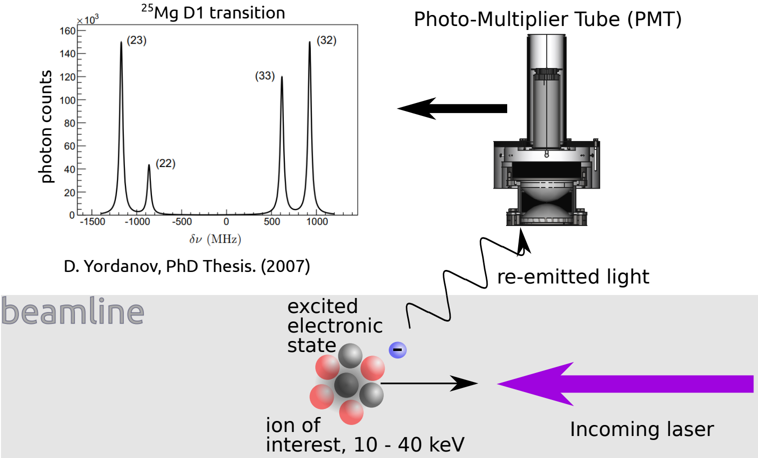

- Collinear geometry minimizes Doppler broadening:

$$\delta\nu \propto \frac{\delta E}{\sqrt{E}}$$

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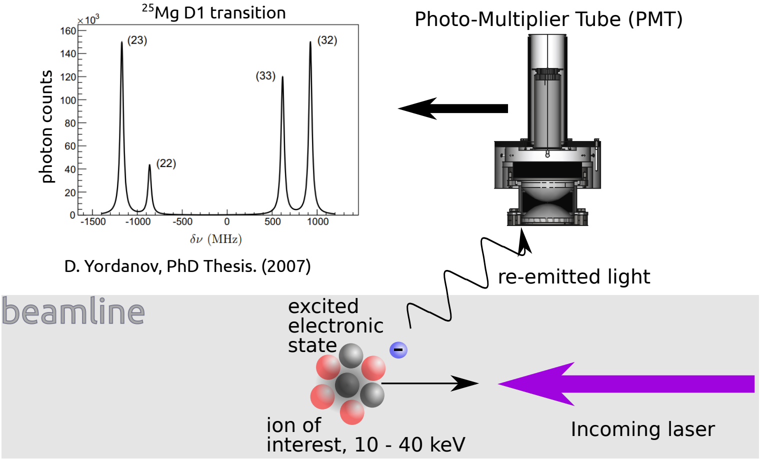

- Limitation: Measurement time $\boxed{\sim 5\ \mu s}$, but $\boxed{T_{1/2} > 10\text{ ms}}$

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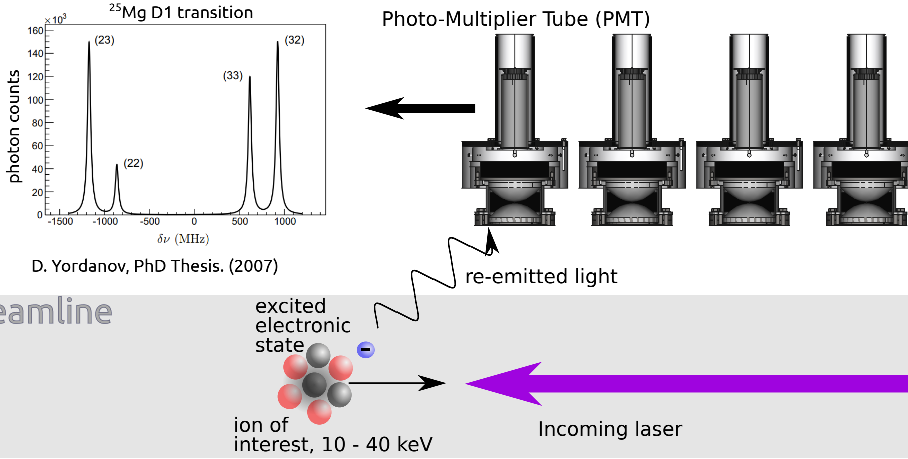
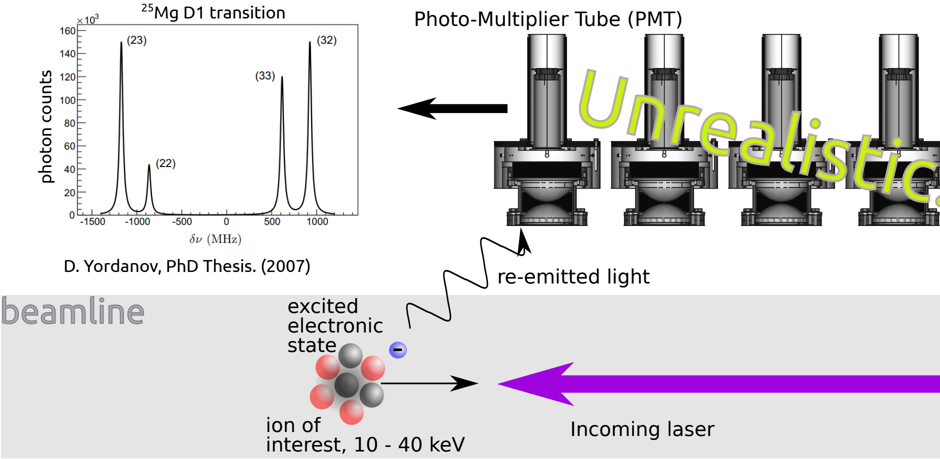


- Solution?

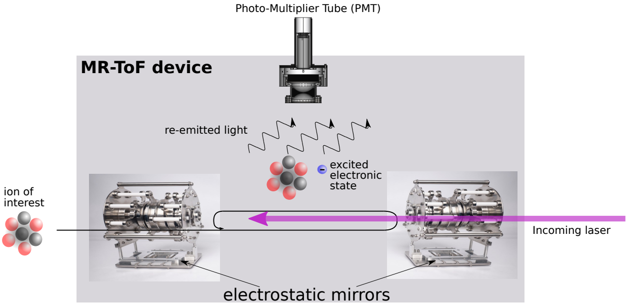
Collinear Laser Spectroscopy (CLS)



- Solution?

Multi-Ion Reflection Apparatus for CLS (MIRACLS)

Multi-Reflection Time-of-Flight (MR-ToF) device increases effective beampath to “recycle” ions



- signal-to-noise ratio improvement: $\frac{S}{N} = \frac{S_0}{N_0}\sqrt{r}$

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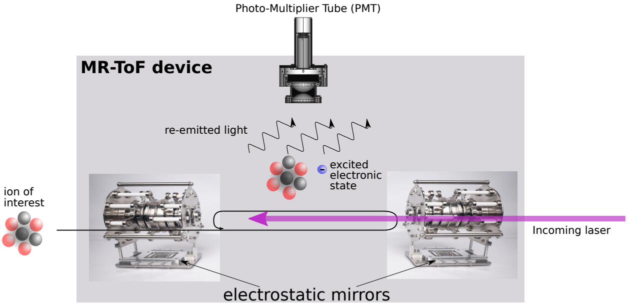
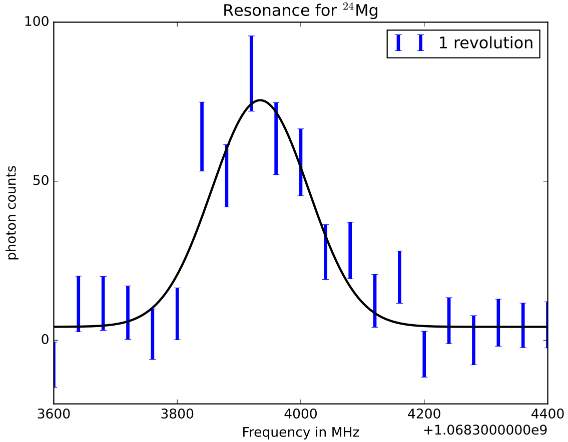


- signal-to-noise ratio improvement: $\frac{S}{N} = \frac{S_0}{N_0}\sqrt{r}$
- More exotic radionuclides with low production yields can be probed

Improvement Factor

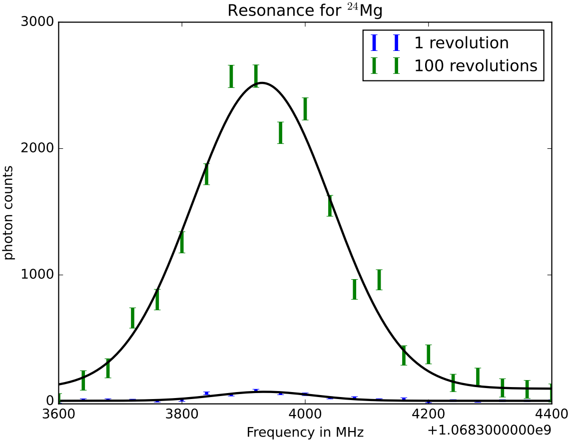
- Single-passage mode (experimental data):



Preliminary

Improvement Factor

- Multi-reflection improvement (experimental data):



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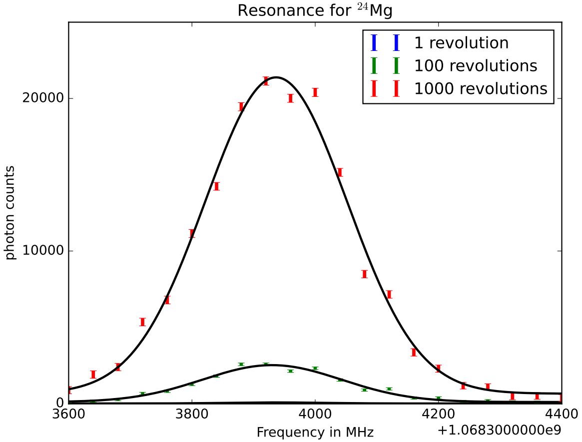

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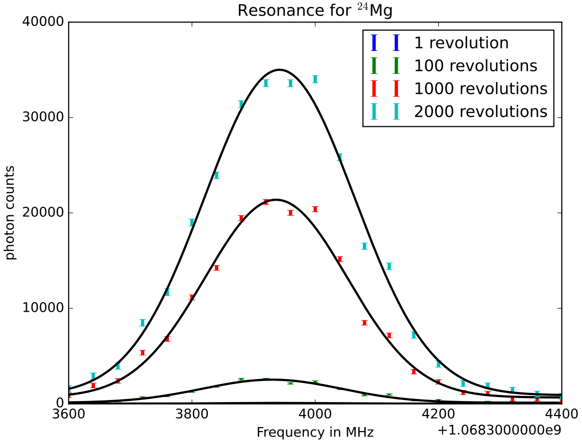
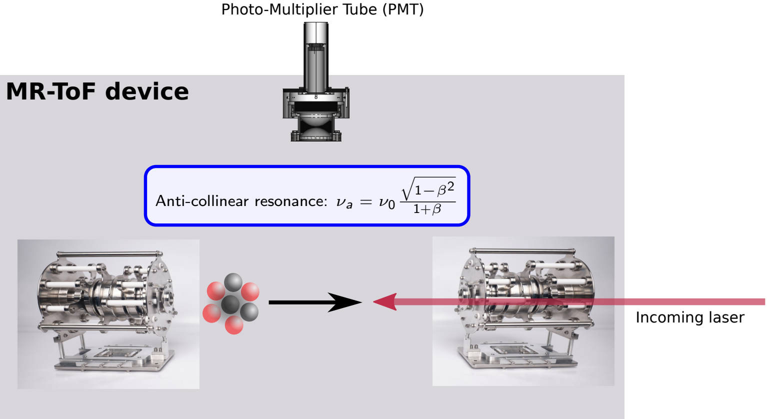


Preliminary

Collinear-Anticollinear measurements at MIRACLS

Beam energy: large source of uncertainty in CLS



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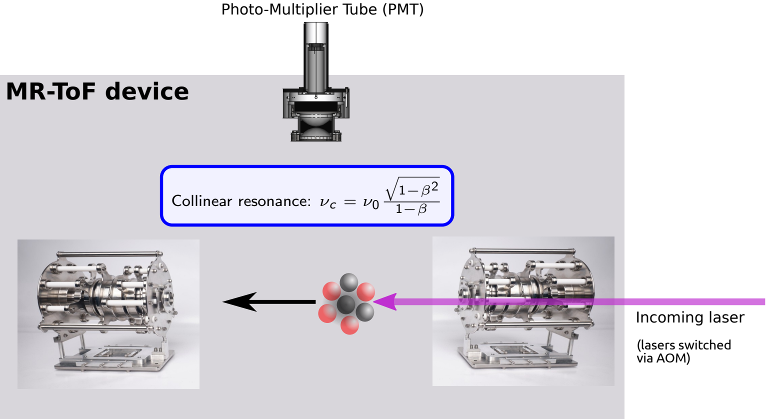

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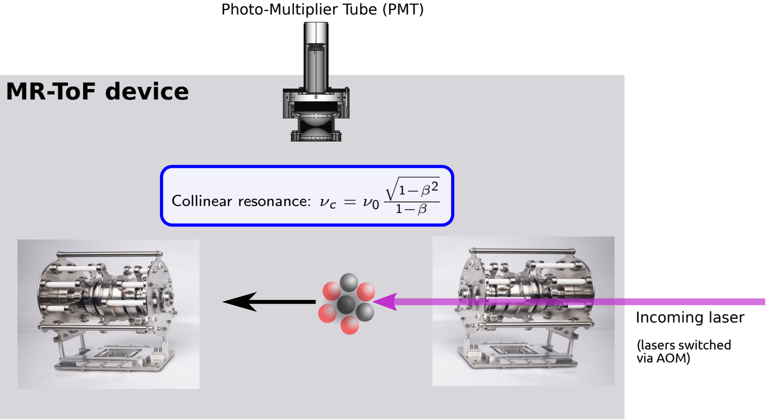

$\Rightarrow \nu_0 = \sqrt{\nu_c \cdot \nu_a}$, independent of beam energy!

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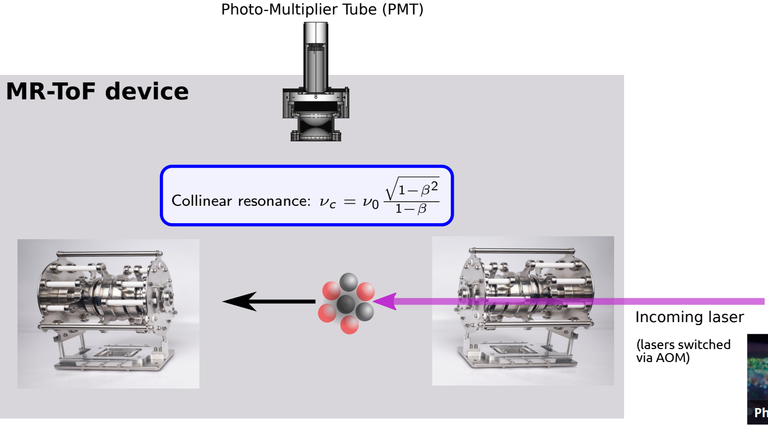

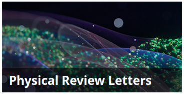

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Nuclear Charge Radii of ^{7,9,10}Be and the One-Neutron Halo Nucleus ^{11}Be

W. Nörtershäuser[1,2], D. Tiedemann[2], M. Žáková[2], Z. Andjelkovic[2], K. Blaum[3], M. L. Bissell[4], R. Cazan[2], G. W. F. Drake[5], and Ch. Geppert[1,6] *et al.*

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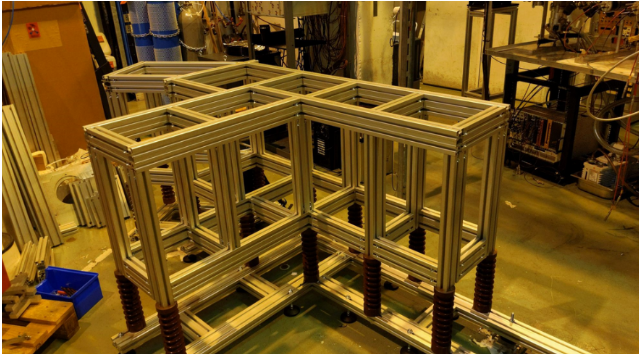
MIRACLS method

A short animation

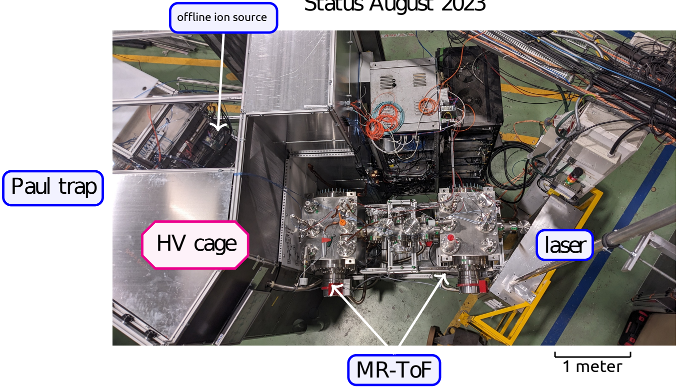
Online Apparatus Progress:

Status January 2022



Online Apparatus Progress:

Status August 2023



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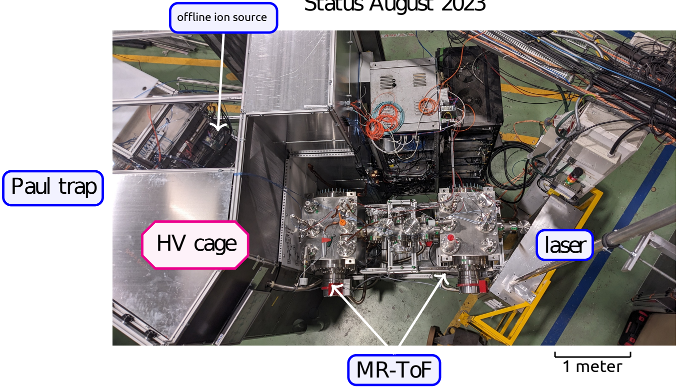

Highest energy MR-ToF device ever built! ($>$ 10 kV)

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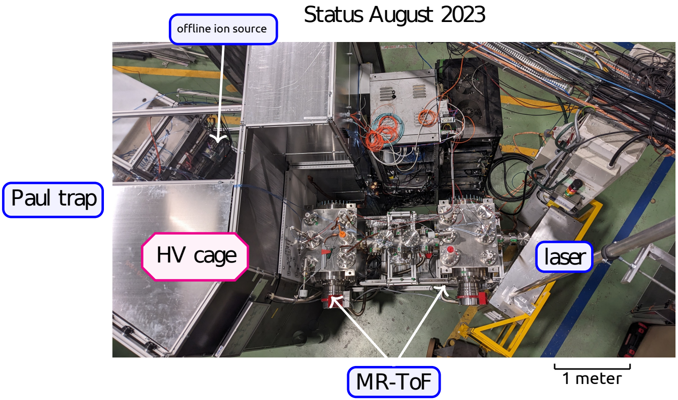
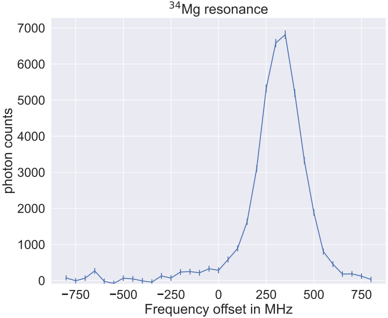


Highest energy MR-ToF device ever built! (> 10 kV)
Advantages for mass separation: see F. M. Maier et al., NIMA A., 1048, (2023)

November 2024: Mg Beamtime

Measured our first physics case: ^{34}Mg

Preliminary



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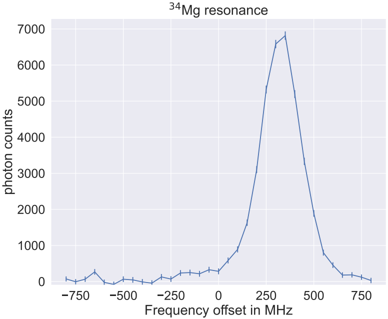

- ^{34}Mg measurement with down to 10 ions in MR-ToF device per bunch

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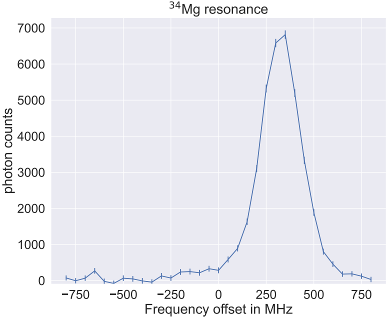
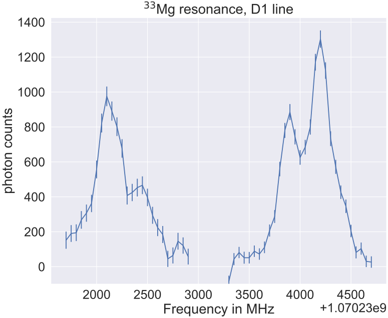
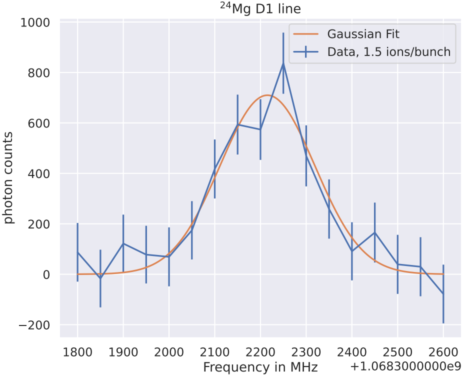




- ^{34}Mg measurement with down to 10 ions in MR-ToF device per bunch
- ^{33}Mg measurement also performed with repumping scheme.

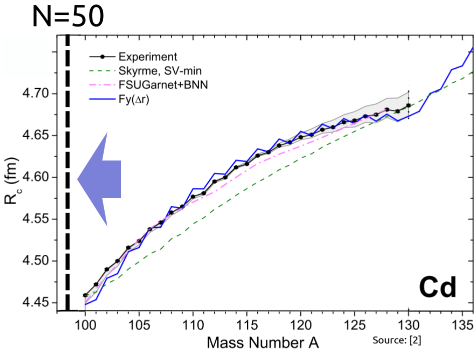
Sensitivity Limit

Performed measurements with down to 0.7 ions / measurement cycle in MR-ToF device



New in August 2025: Cd Beamtime

Goal: Extend previous measurements by the COLLAPS experiment to ^{98,99}Cd ($N = 50$ shell closure)

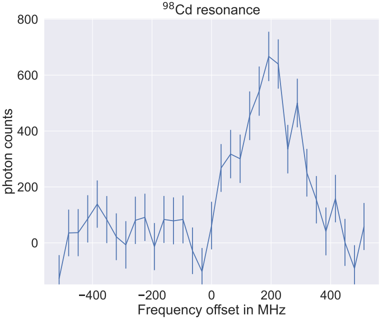


M. Hammen, et al., PRL, 121:102501, (2018)

New in August 2025: Cd Beamtime

Results:

Preliminary



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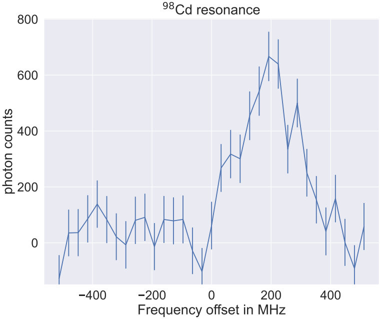

- Also 10 ions in MR-ToF per bunch, but with much lower laser power.

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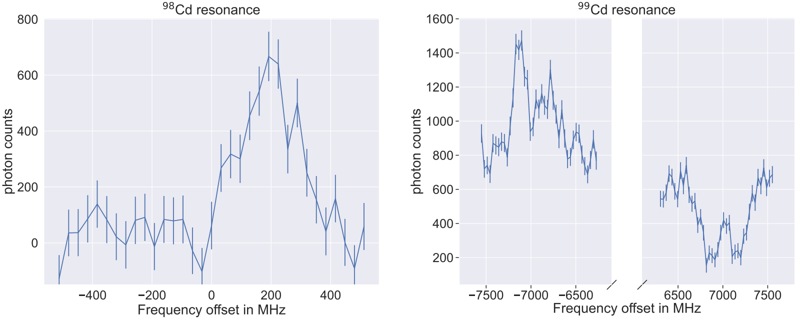

- Also 10 ions in MR-ToF per bunch, but with much lower laser power.
- Pump & probe scheme used for ^{99,101,103}Cd

Summary

- MIRACLS has demonstrated its effectiveness as a new technique for CLS

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- **Magnesium:** charge radii measured for even-even isotopes $^{24-34}$Mg and odd-even ^{33}Mg

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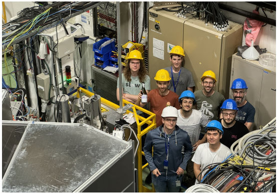
- **Magnesium:** charge radii measured for even-even isotopes $^{24-34}$Mg and odd-even ^{33}Mg
- **Cadmium:** charge radii measured for even-even isotopes $^{\mathbf{98}-116}$Cd, charge radii and moments for odd-even $^{\mathbf{99},101,103}$Cd

Acknowledgements



Collaboration:

CERN, Universität Greifswald – Wissen lockt. Seit 1456, Technische Universität Darmstadt, McGill, TRIUMF, University of Toronto

Funding:

European Research Council (erc), ATTRACT, CERN Medical Applications Funds, NSERC CRSNG

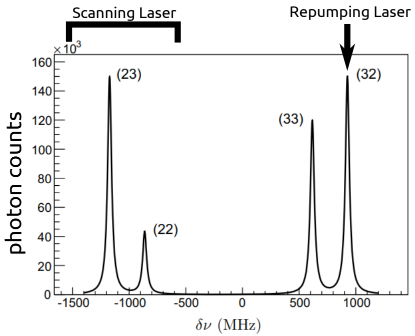
MIRACLS team and participants:

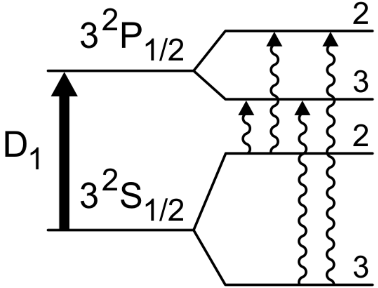
L. Croquette, H. Heylen, E. Leistenschneider, S. Lechner, F. Maier, L. Nies, P. Plattner, M. Rosenbusch, F. Wienholtz, M. Vilen, R. Wolf, F. Buchinger, W. Nörtershäuser, L. Schweikhard, S. Malbrunot-Ettenauer O. Ahmad, T. Fabritz, P. Giesel, R. Hernandez, H. Heylen, J. Hughes, F. Koehler, K. Koenig, D. Lange, L. Lalanne, T. Lellinger, E. Matthews, A. Mcglone, K. Mohr, J. Palmes, V. Repo, L. Rodriguez, C. Shweiger, J. Spahn, J. Warbinek, J. Wilson, Z. Yue, C. Zambrano

Odd-even scheme for magnesium

=

- Repurposing Lasers: One for repumping, one for scanning





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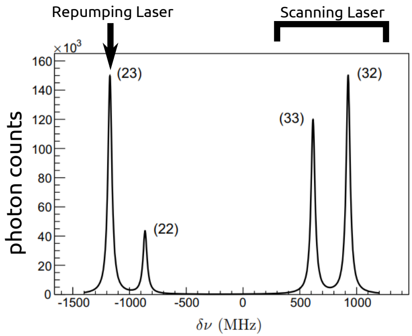

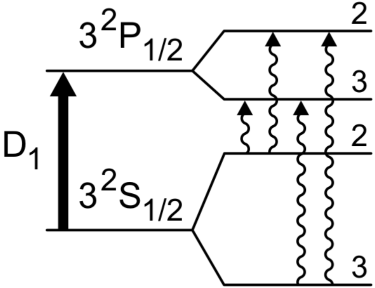

Odd-even scheme for cadmium