Laser Spectroscopy of radioactive isotopes in an MR-ToF Device

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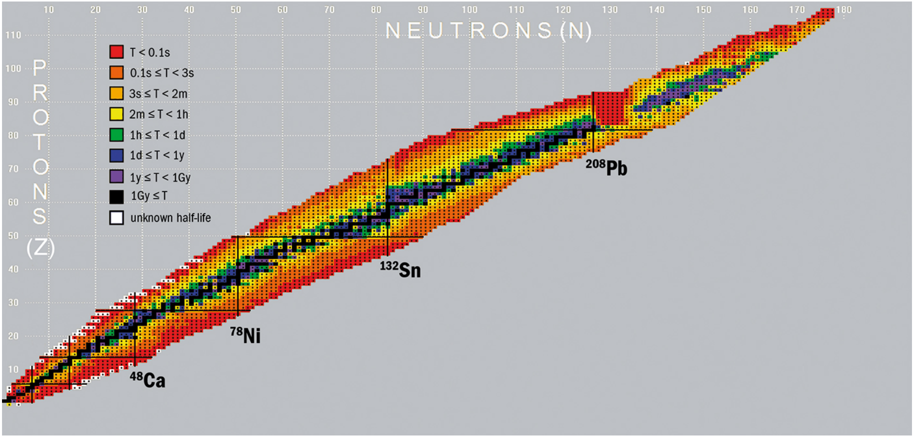
Outline - In two parts

1. Intro to MIRACLS
    - Motivation
    - The MIRACLS technique
2. Latest experimental results

Nuclear chart - The nuclear physicist's playground



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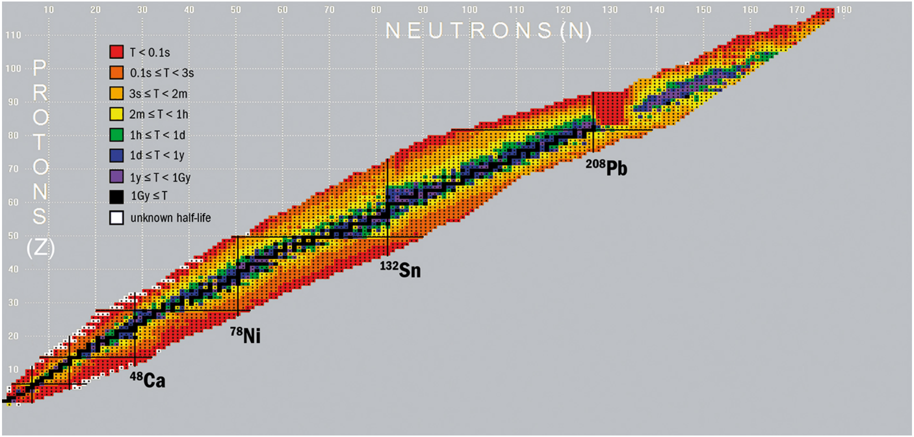
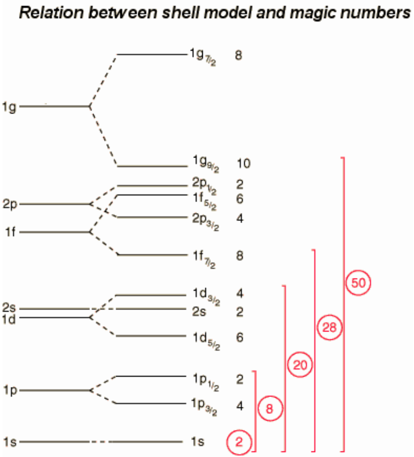


- ISOLDE is a facility at CERN to produce rare and short-lived radioactive isotopes

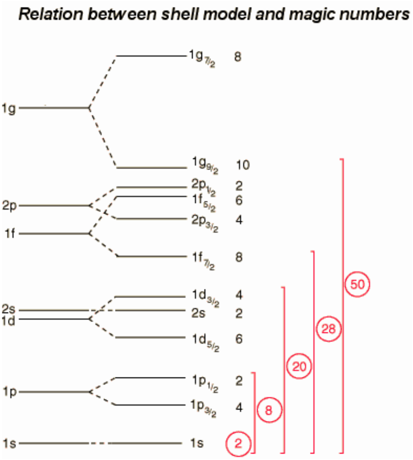
Nuclear Shell Model

- Nucleons organized into shells
  - increased stability at shell closures corresponding to magic numbers



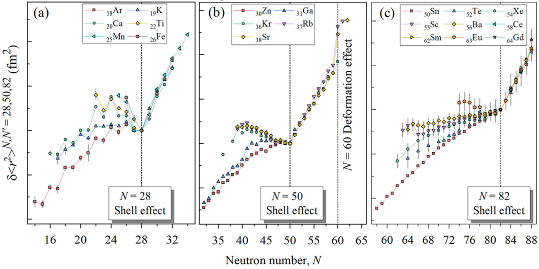
Nuclear Shell Model

- Nucleons organized into shells
  - increased stability at shell closures corresponding to magic numbers
- 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., Progress in Particle and Nuclear Physics 129, 104005 (2023)

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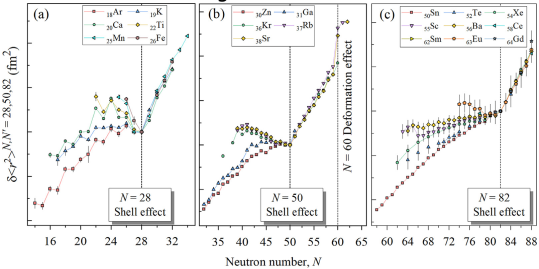
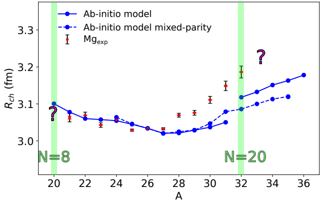


disappearance of shell closure at N = 20:
island of inversion



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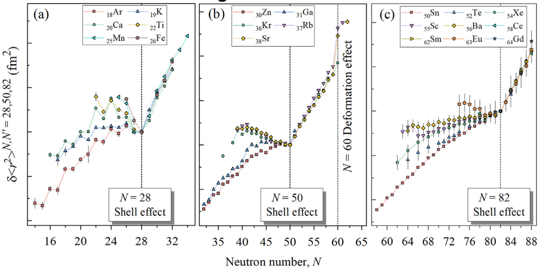

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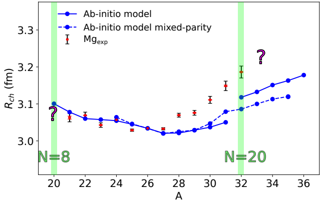

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- $N = 20$ shell closure disappears for magnesium: highly interesting for testing nuclear theories

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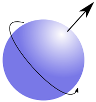
- We want to measure the charge radii of exotic magnesium isotopes, such as ^{20}Mg, ^{33}Mg and ^{34}Mg using Collinear Laser Spectroscopy
- Challenge: yields as low as $\sim\ 10 - 100$ ions / second and half lives $T_{1/2} \sim 10$ ms

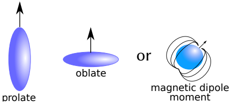
Laser Spectroscopy in Nuclear Physics

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

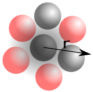
- nuclear spin



- electromagnetic moments

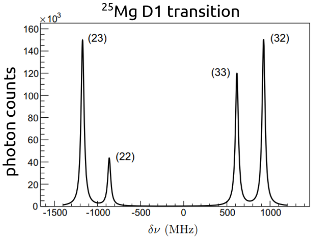


- charge radii

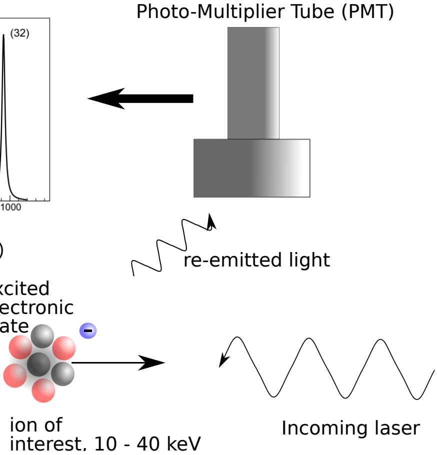


Many observables become accessible with only one measurement!

Collinear Laser Spectroscopy



D. Yordanov, PhD Thesis. (2007)



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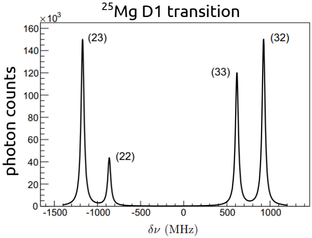

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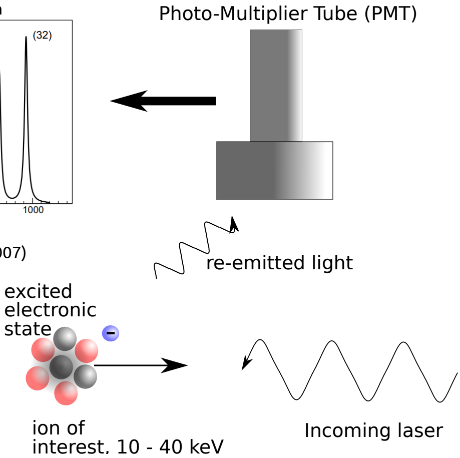
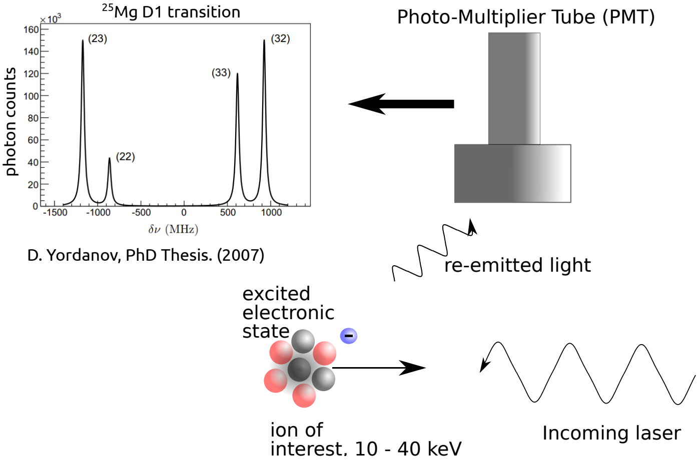


- Collinear geometry minimizes Doppler broadening:

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

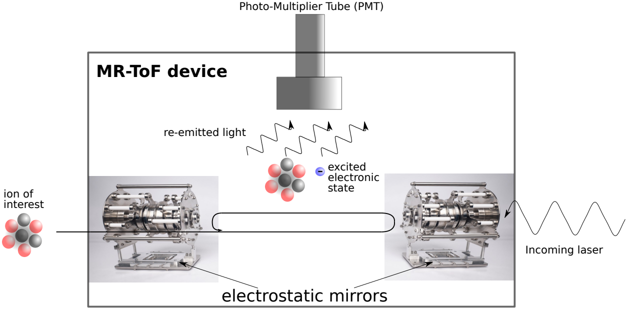
Collinear Laser Spectroscopy



- Problem: Measurement cycle $\sim 10\ \mu s$, but $T_{1/2} \sim 10$ ms

Our solution: MIRACLS

Multi-Reflection Time-of-Flight (MR-ToF) device “recycles” ions



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

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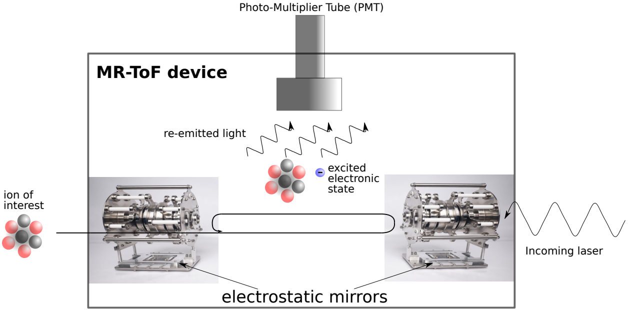


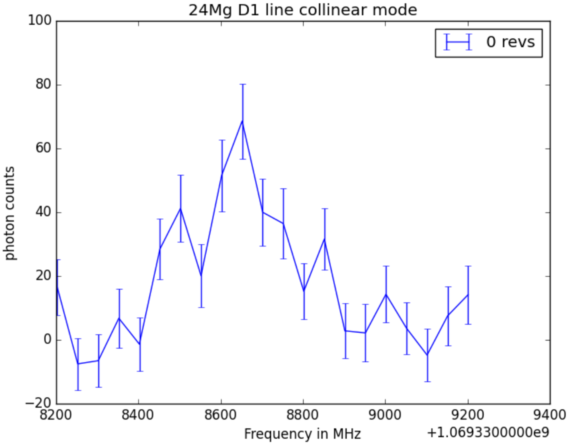
- signal-to-noise ratio improvement: $\frac{S}{N} = \frac{S_0}{N_0}\sqrt{r}$
- More exotic radionuclides with low production yields can be probed

MIRACLS method

A short animation

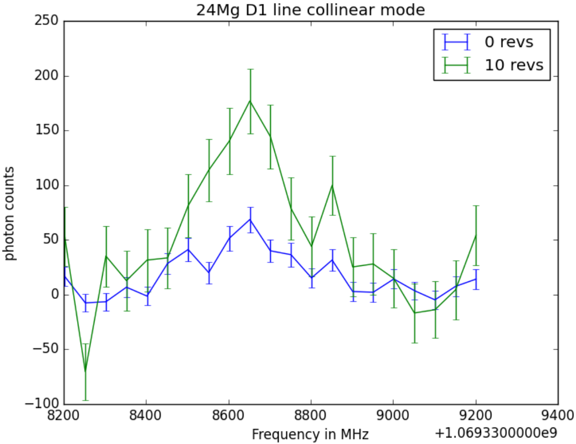
Improvement Factor

- Single-passage mode:



Improvement Factor

- Multi-Reflection improvement:



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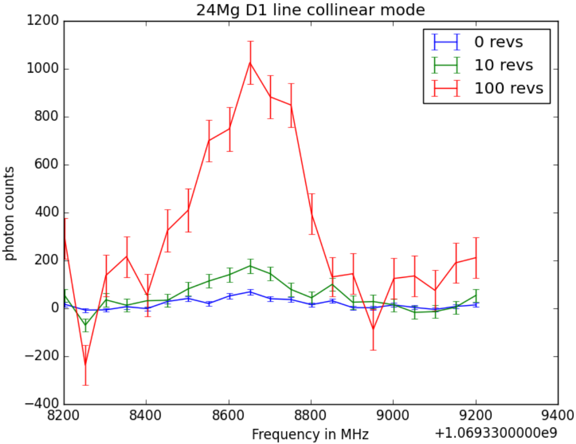

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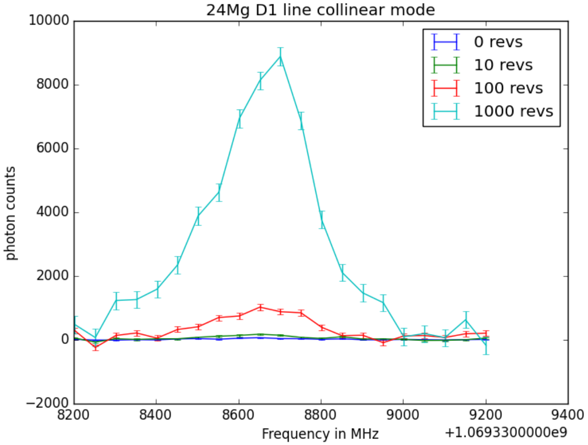

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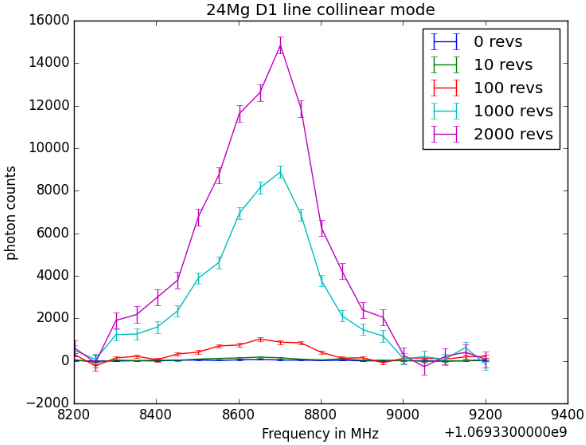
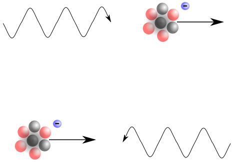


Collinear-Anticollinear measurements

Knowing the beam energy exactly is difficult in an MR-ToF device.



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- Collinear:
  $\nu_0 = \nu_c \frac{1-\beta}{\sqrt{1-\beta^2}}$

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- Removes the need for knowing beam energy for the determination of ν_0

Latest experimental results

First measurement performed using radioactive ISOLDE beam on June 30th, 2024 (11 days ago)

Beamtime: Isotope shift measurements

Measured the collinear and anticollinear D1 and D2 transitions for even magnesium isotopes $^{24-32}$Mg

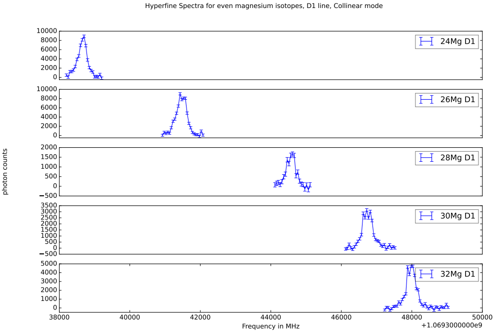

Figure: Preliminary

Beamtime: Isotope shift measurements

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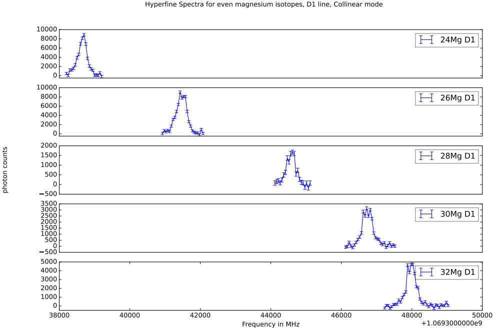

Figure: Preliminary

- Charge radius can be extracted as a function of isotope shift:

$$\delta < r^2 >^{AA'} = \frac{1}{F}\left(\delta\nu^{AA'} - K\frac{m_{A'} - m_A}{m_{A'} m_A}\right)$$

Beamtime: Isotope shift measurements

Isotope shift for D2 line (New measurement!) – should yield roughly same isotope shifts as D1 line

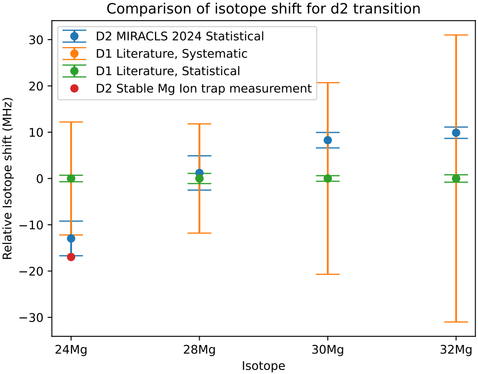

Figure: Preliminary.

COLLAPS: D. T. Yordanov, et al., Phys. Rev. Lett., 108:042504, (2012)
Stable Mg: V. Batteiger, et al., Phys. Rev. A, 80:022503, (2009)

Sensitivity limit for first measurement: 30 ions / s

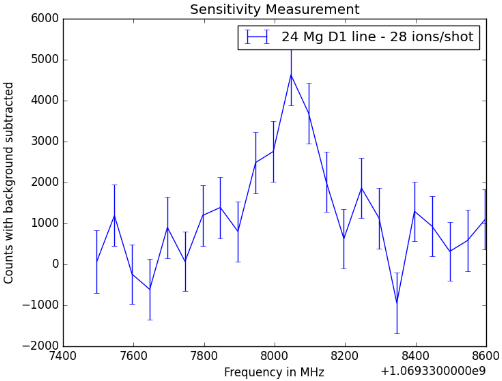

Figure: Preliminary

- ^{34}Mg yield very low due to old target: $5 - 15$ ions / s compared to nominal value: 150 ions / s

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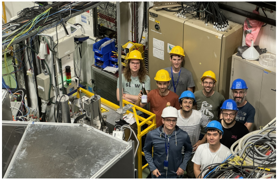
- ^{34}Mg charge radius measurement planned for later this year

Acknowledgements



Collaboration:

Sponsors:

Team Members:
L. Bartels, I. Belosevic, L. Croquette, L. Fischer, P. Fischer, E. Ganzke, C. Kanitz, F. Hummer, H. Heylen, E. Leistenschneider, V. Lagaki, S. Lechner, F. Maier, L. Nies, P. Plattner, M. Rosenbusch, S. Sels, F. Wienholtz, M. Vilen, R. Wolf, F. Buchinger, W. Nörtershäuser, L. Schweikhard, S. Malbrunot-Ettenauer

Beamtime Participants:
P. Giesel, K. Koenig, D. Lange, S. Lechner, S. Malbrunot, L. Nies, J. Palmes, P. Plattner, V. Repo, J. Wilson, Z. Yue

Charge radius from isotope shift

- Difference in mean square charge radius from isotope shift between isotopes A' and A:

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- Field and mass shift F and K determined from stable isotopes ^{24,25,26}Mg or from atomic theory.