The Charge Radii of $^{26,26m}Al$

Peter Plattner

ISOLDE Workshop and User‘s Meeting

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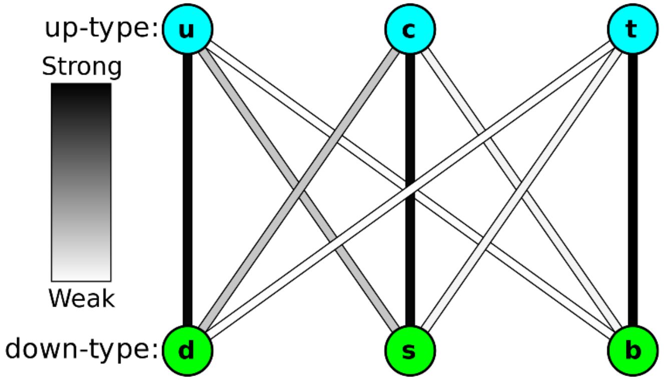
Standard Model of Particle Physics

- Standard Model of particle physics
  - One of the most comprehensive theories in physics
  - predicts sub-atomic particles further comprised of 3 generations of quarks



  - Cabibbo-Kobayashi-Maskawa (CKM) matrix describes mixing of quarks via weak interaction

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

https://en.wikipedia.org/wiki/Cabibbo%E2%80%93Kobayashi%E2%80%93Maskawa_matrix#/media/File:Quark_weak_interactions.svg

CKM Unitarity

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Absolute square (i.e. $|V_{ij}|^2$) of each CKM-entry is probability of weak decay of j-type quark into i-type quark
- Standard Model of particle physics predicts unitarity of CKM matrix
- Deviation from unitarity would imply incomplete picture of Standard model

- Unitarity: $V_{CKM} \cdot {V_{CKM}}^T = I_3$
- In particular: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- Recent values in [1], [2]: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99848(70)$

[1] R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)
[2] J. C. Hardy, I. S. Towner, Physical Review C 2020, 102.

Determination of V_{ud}

- V_{ud} can be determined via $\mathcal{F}t$ value of superallowed $0^+ \rightarrow 0^+$ β decays

$$|V_{ud}|^2 = \frac{K}{2G_F^2(1+\Delta_R^V)\overline{\mathcal{F}t}}$$

Partial half life

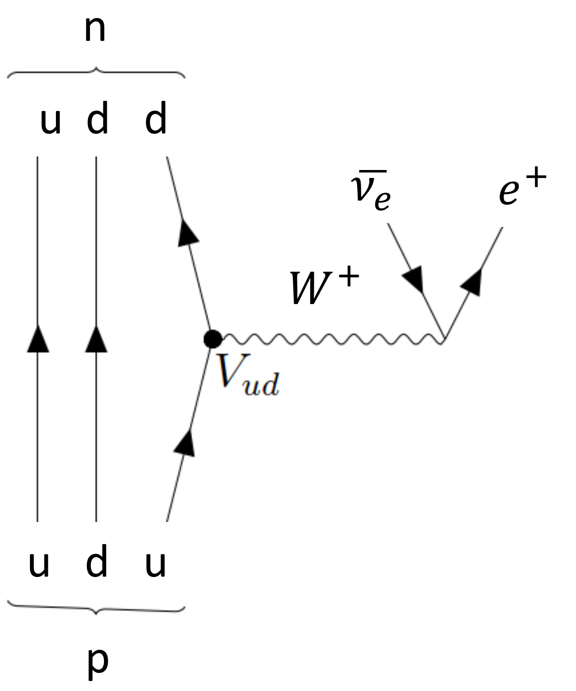
Energy difference

Small theoretical corrections (leading uncertainty!)

$$\mathcal{F}t = ft \cdot (1+\delta'_R)(1+\delta_{NS}-\delta_C)$$

- Nuclear charge radius r_c important experimental input into theoretical calculation of isospin-symmetry-breaking corrections

$$\delta_c \coloneqq f(r_c, \dots)$$

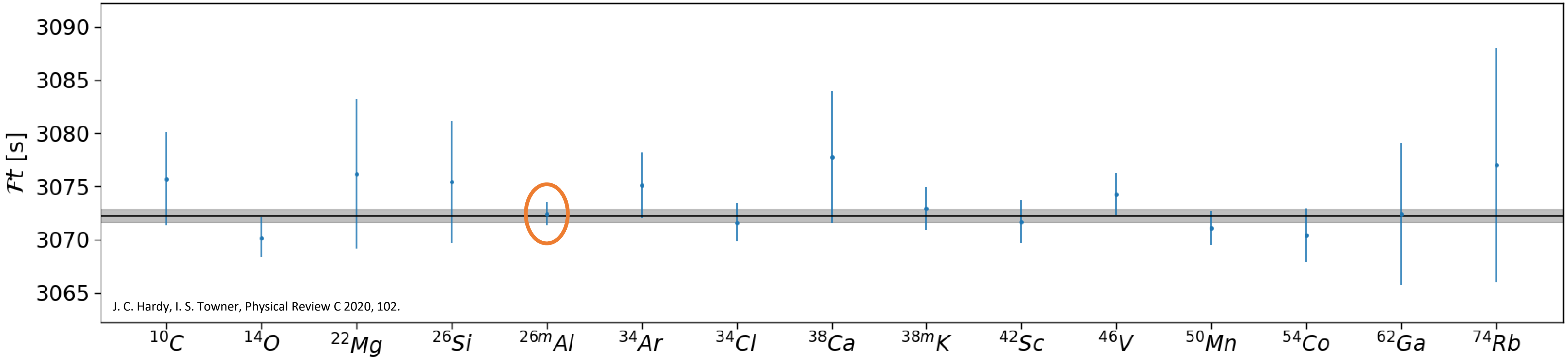


Importance of charge radius of ^{26m}Al

- Weighted mean $\overline{\mathcal{F}t}$ of 15 precision cases used to calculate V_{ud}

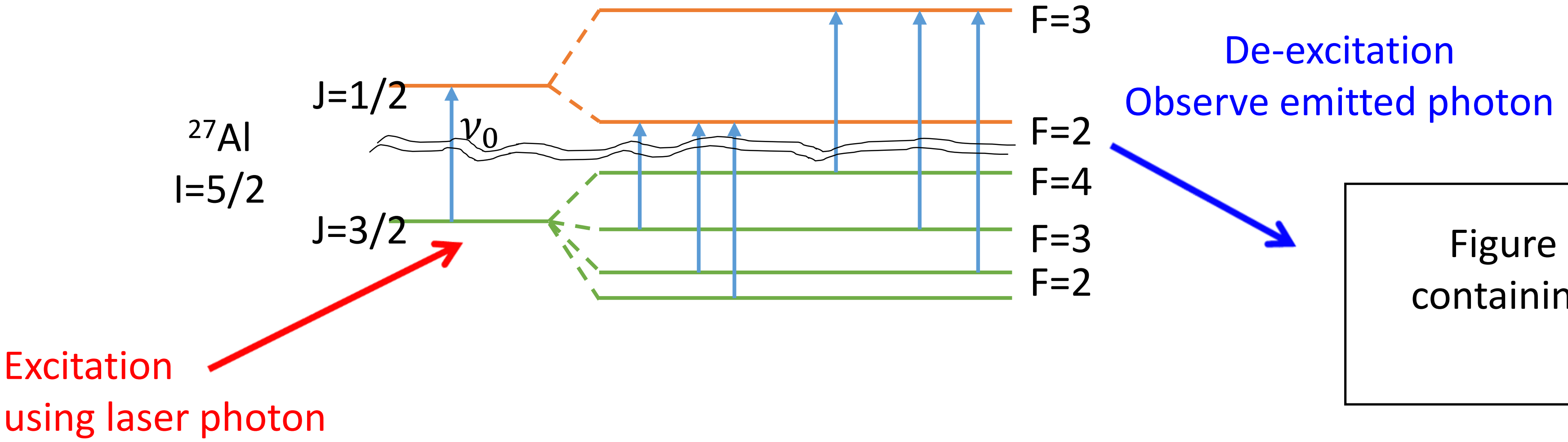
$$|V_{ud}|^2 = \frac{K}{2G_F^2(1+\Delta_R^V)\overline{\mathcal{F}t}}$$

- $\mathcal{F}t$ value of ^{26m}Al
  - Most accurately known of 15 isotopes used to calculate $\overline{\mathcal{F}t}$
  - Nuclear charge radius unknown, but extrapolated as 3.04(2) fm from other nuclei



Laser Spectroscopy

$$\vec{F} = \vec{I} + \vec{J}$$



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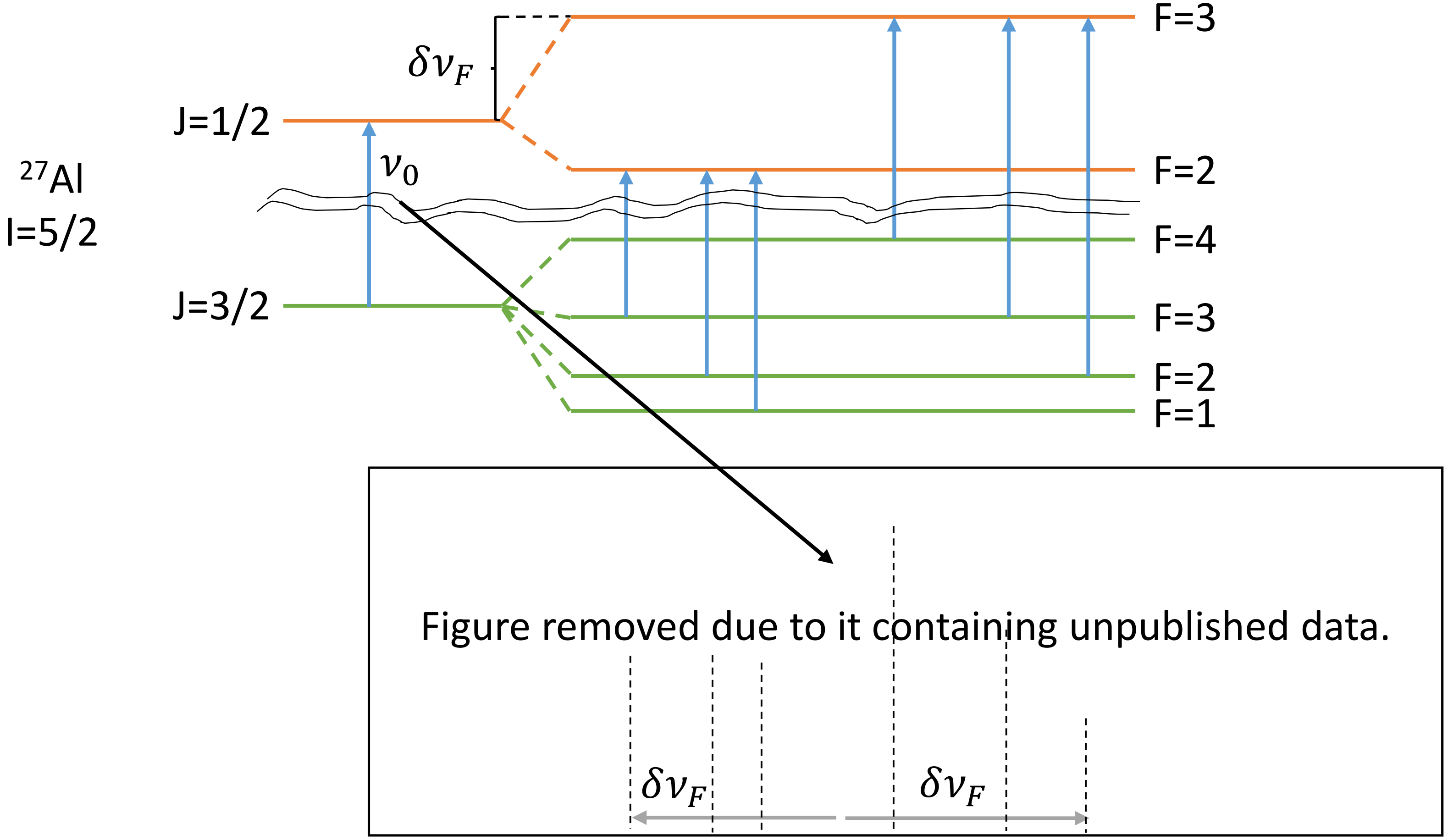
- Hyperfine transitions in atoms or ions yield information about
  - Nuclear spin
  - Magnetic dipole and electric quadrupole moments of nuclei
  - **Isotope shifts and nuclear charge radii**

Hyperfine Spectrum



$$\delta\nu_F = A_J \frac{C}{2} + B_J \frac{3C(C+1) - 4I(I+1)J(J+1)}{8I(2I-1)J(2J-1)}$$

$$C = F(F+1) - I(I+1) - J(J+1)$$

electric quadrupole moment $Q = \frac{B_J}{eV_{JJ}}$

magnetic dipole moment $\mu = \frac{A_J \cdot I\, J}{B_0}$

Isotope Shift

^{28}Al

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IS

^{27}Al, ref.

- Isotope shift IS = difference of centroid frequencies for different isotopes
- Used to calculate difference in mean square charge radii between isotopes

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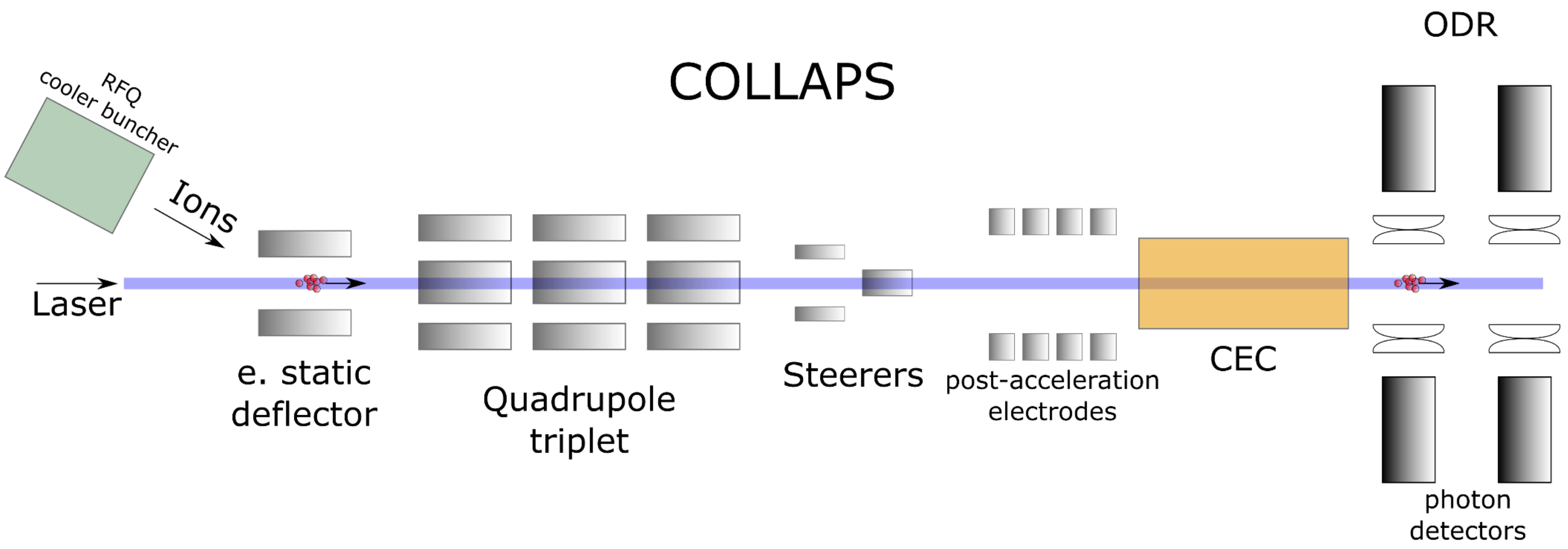
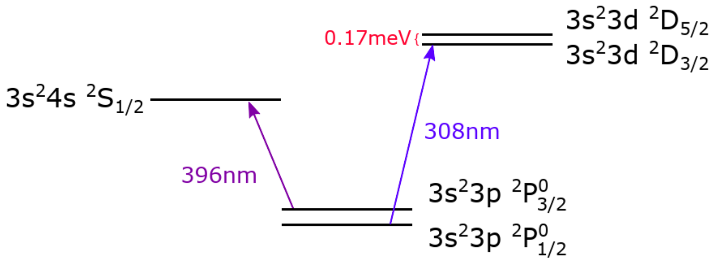
Collinear Laser Spectroscopy



- Measurements performed at COLLAPS
- Charge exchange with sodium
- Measure fluorescence photons of resonant transitions



Hyperfine Spectra

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- Ion extraction 0 and 6s after proton trigger
- Decrease in isomer intensity in fit consistent with half-life
  - $N_2 = N_1 \cdot \left(\frac{1}{2}\right)^{\frac{6s}{t_{1/2}}}$

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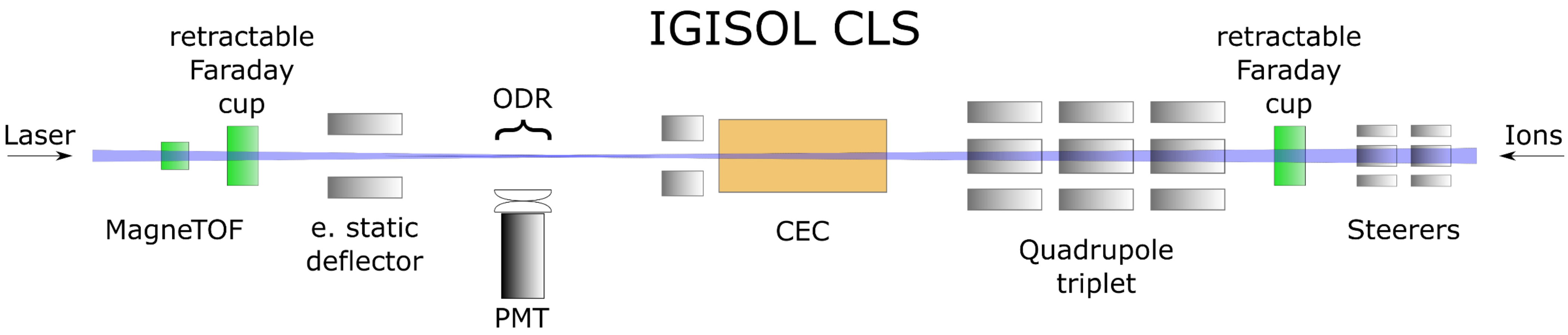
Collinear Laser Spectroscopy at IGISOL



- Collaboration with IGISOL
- Second set of measurements performed at IGISOL, Jyväskylä
- Known to have more favorable isomer : ground state ratio for $^{26,26m}Al$

Hyperfine Spectra

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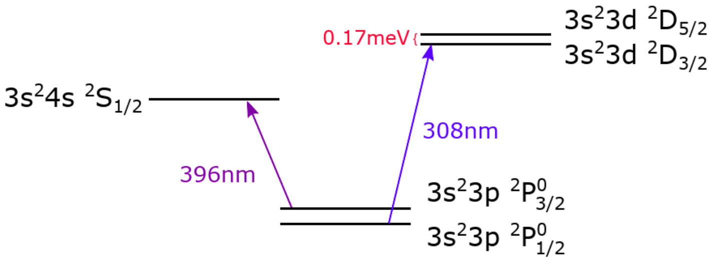
- Clear presence of isomer in Al I $P_{1/2} \rightarrow D_{3/2}$ transition



Hyperfine Spectra

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Isotope Shift

Isotope shift to ^{26}Al **ground state**

Isotope shift to ^{26}Al **isomer**

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- Isotope shifts $\delta\nu^{27,26}$, $\delta\nu^{27,26m}$ used to calculate difference in mean square nuclear charge radii $\delta\langle r^2\rangle^{27,A}$ between ^{26,26m}Al and ^{27}Al
- Nuclear charge radius of ^{27}Al, F, M from [1]

$$\delta\langle r^2\rangle^{27,A} = \frac{\delta\nu^{27,A}}{F} - \frac{M}{F}\frac{m_A - m_{27}}{m_{27}\cdot(m_A + m_e)}$$

[1] Heylen et al., Physical Review C 2021, 103.

Nuclear Charge Radii

- Nuclear charge radius of ^{26}Al: 3.080(19) fm
- Nuclear charge radius of ^{26m}Al: 3.130(15) fm
- 4.5 statistical standard deviations from extrapolated value
- Preliminary extrapolation by same number of standard deviations for radial overlap correction of ISB correction

	Old values from [1]	Removed due to it containing unpublished data.
^{26m}Al nuclear charge radius	3.04(2) fm	
$\mathcal{F}t$ of ^{26m}Al	3072.4(11) s	
$\overline{\mathcal{F}t}$	3072.24(185) s	

Figure removed due to it containing unpublished data.

[1] J. C. Hardy, I. S. Towner, Physical Review C 2020, 102.

Implications for CKM unitarity

- Shifts the result of unitarity test closer towards unitarity by ~1/10 standard deviations

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = \sout{0.99848(70)} \rightarrow$$

prel.:

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- Motivates further studies of nuclear charge radii in other superallowed β emitters

Summary and Conclusion

- The charge radii of $^{26,26m}Al$ have been determined by Collinear Laser spectroscopy
- 4.5 standard deviations difference to extrapolated value used in isospin-symmetry-breaking corrections for V_{ud} of CKM matrix
- Prelim. extrapolation hints at slight shift towards CKM unitarity

Thank you for your attention!

P. Plattner[1], E. Wood[2], L. Al Ayoubi[3], O. Beliuskina[3], M. L. Bissell[4,5], K. Blaum[1], P. Campbell[4], B. Cheal[2], R. de Groote[6], C. Devlin[2], T. Eronen[3], L. Filippin[7], R. F. García Ruíz[8], Z. Ge[3], S. Geldhof[6], W. Gins[3], M. Godefroid[7], H. Heylen[5], M. Hukkanen[3], J. D. Holt[9,10], P. Imgram[11], A. Jaries[3], A. Jokinen[3], A. Kanellakopoulos[6], A. Kankainen[3], S. Kaufmann[11], K. König[11], Á. Koszorús[5], S. Kujanpää[3], S. Lechner[5], S. Malbrunot-Ettenauer[5], R. Mathieson[2], T. Miyagi[11], I. Moore[3], P. Müller[11], D. Nesterenko[3], R. Neugart[1,12], G. Neyens[6], W. Nörtershäuser[11], A. Ortiz-Cortes[3], H. Penttilä[3], I. Pohjalainen[3], A. Raggio[3], M. Reponen[3], S. Rinta-Antila[3], L. V. Rodríguez[5,1], J. Romero[3], R. Sánchez[13], F. Sommer[11], M. Stryjczyk[3], V. Virtanen[3], L. Xie[4], Z. Y. Xu[6], X. F. Yang[6,14], and D. T. Yordanov[15]

[1] *Max Planck Institute for Nuclear Physics, Heidelberg, Germany*
[2] *University of Liverpool Department of Physics, Liverpool, United Kingdom*
[3] *Department of Physics, University of Jyväskylä, Jyväskylä, Finland*
[4] *Department of Physics Astronomy, University of Manchester, Manchester, United Kingdom*
[5] *ISOLDE, CERN Experimental Physics Department, Switzerland*
[6] *Institute for Nuclear and Radiation Physics, KU Leuven, Leuven, Belgium*
[7] *Spectroscopy, Quantum Chemistry and Atmospheric Remote Sensing (SQUARES), Université libre de Bruxelles, Brussels, Belgium*
[8] *Massachusetts Institute of Technology, Cambridge, MA, USA*
[9] *TRIUMF, Vancouver, Canada*
[10] *Department of Physics, McGill University, Montréal, Canada*
[11] *Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany*
[12] *Institut für Kernchemie, Universität Mainz, Mainz, Germany.*
[13] *GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany*
[14] *School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[15] *Institut de Physique Nucléaire, Université Paris-Sud, Université Paris-Saclay, Orsay, France*

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TECHNISCHE UNIVERSITÄT DARMSTADT
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Max-Planck-Institut für Kernphysik Heidelberg

Backup

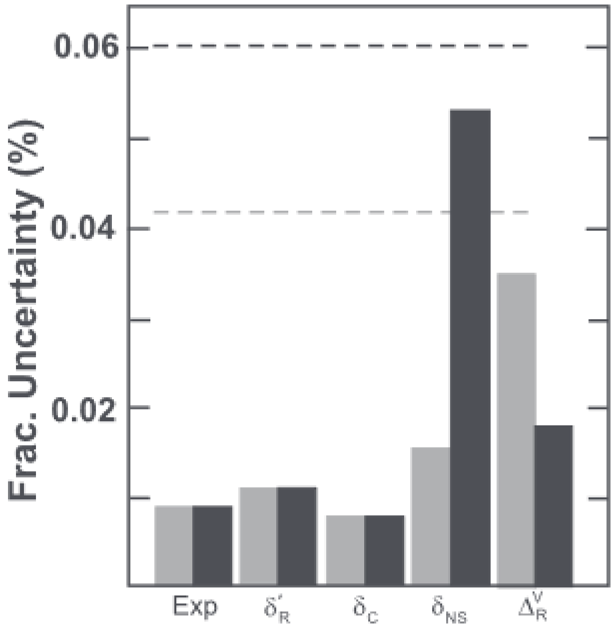
Formulas

$$\mathcal{F}t = ft \cdot (1 + \delta'_R)(1 + \delta_{NS} - \delta_C)$$

$$|V_{ud}|^2 = \frac{K}{2G_F^2(1 + \Delta_R^V)\overline{\mathcal{F}t}}$$

J. C. Hardy, I. S. Towner, Physical Review C 2020, 102.

V_{ud} Uncertainties



Grey: 2015
Black: 2020

J. C. Hardy, I. S. Towner, Physical Review C 2020, 102.

Unknown Charge Radii for V_{ud}

known			
Z	iso	Ele	Ref
22		Mg	ISOLDE, Yordanov
34		Ar	ISOLDE, Klein
38		Ca	NSCL, Miller
38	m	K	ISOLDE, Bissell
42		Sc	JYFL, Koszorus
50		Mn	JYFL, Charlwood
74		Rb	TRIUMF, Mane
unknown			
10		C	
14		O	
26		Si	
26	m	Al	
34		Cl	
46		V	
54		Co	
62		Ga	