The nuclear charge radius of ^{26m}Al and its implication for V_{ud} in the quark mixing matrix

UW Nuclear Physics Seminar

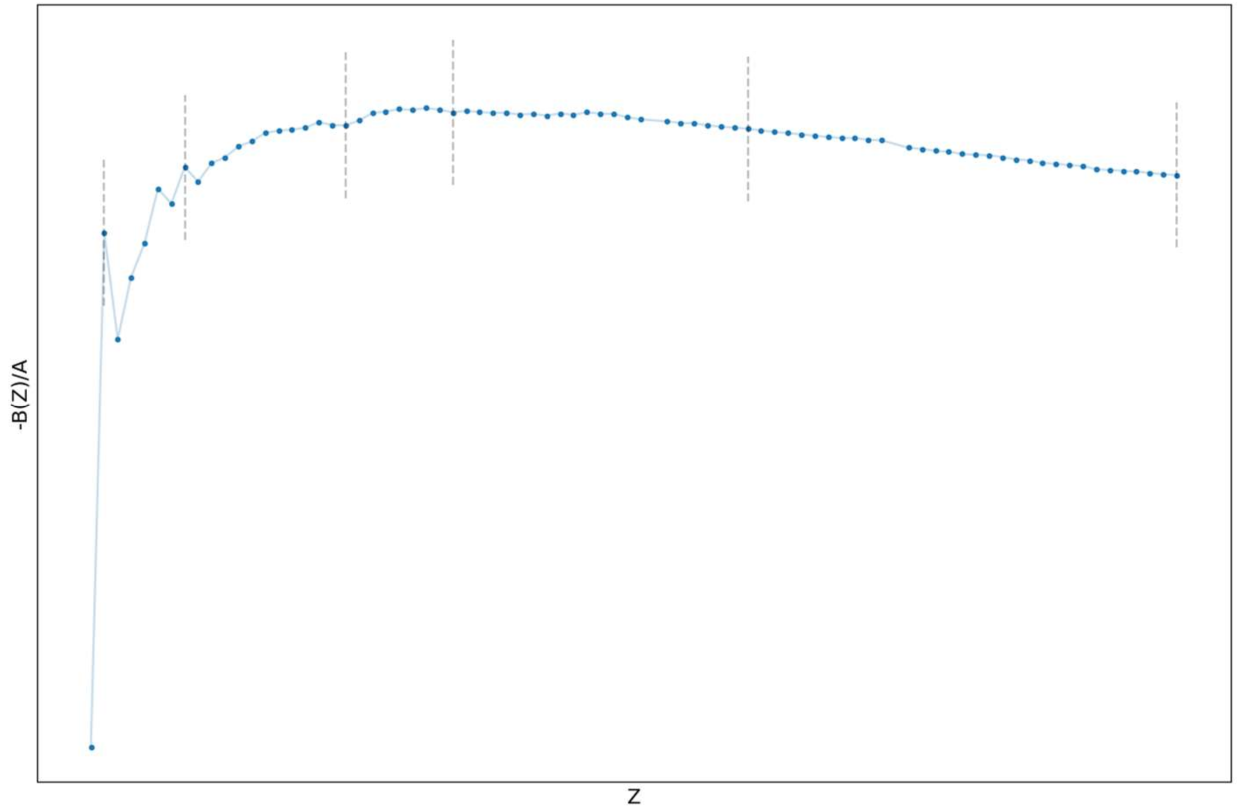
Peter Plattner

Outline

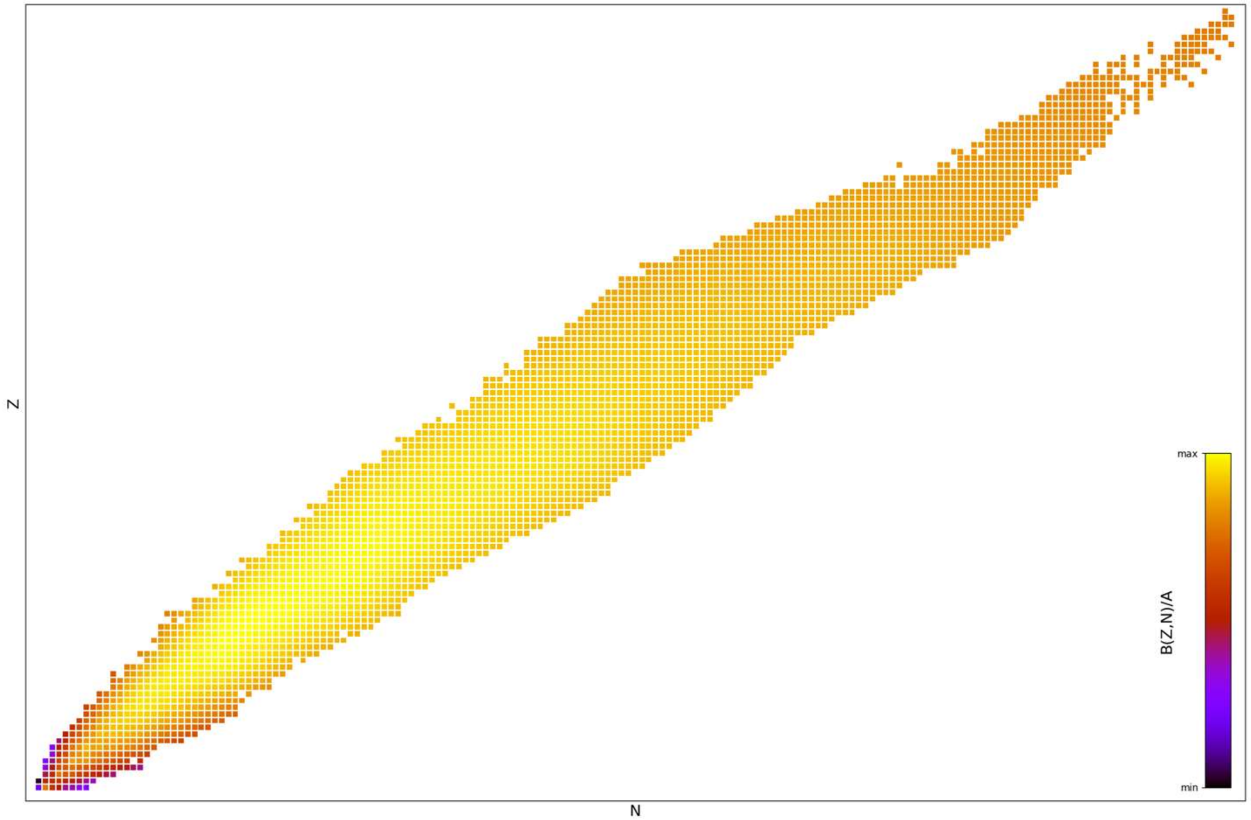
- Motivation
- Determination of V_{ud}
- Introduction to laser spectroscopy and isotope production
- Results of measurements
- Outlook and conclusion

Binding Energy

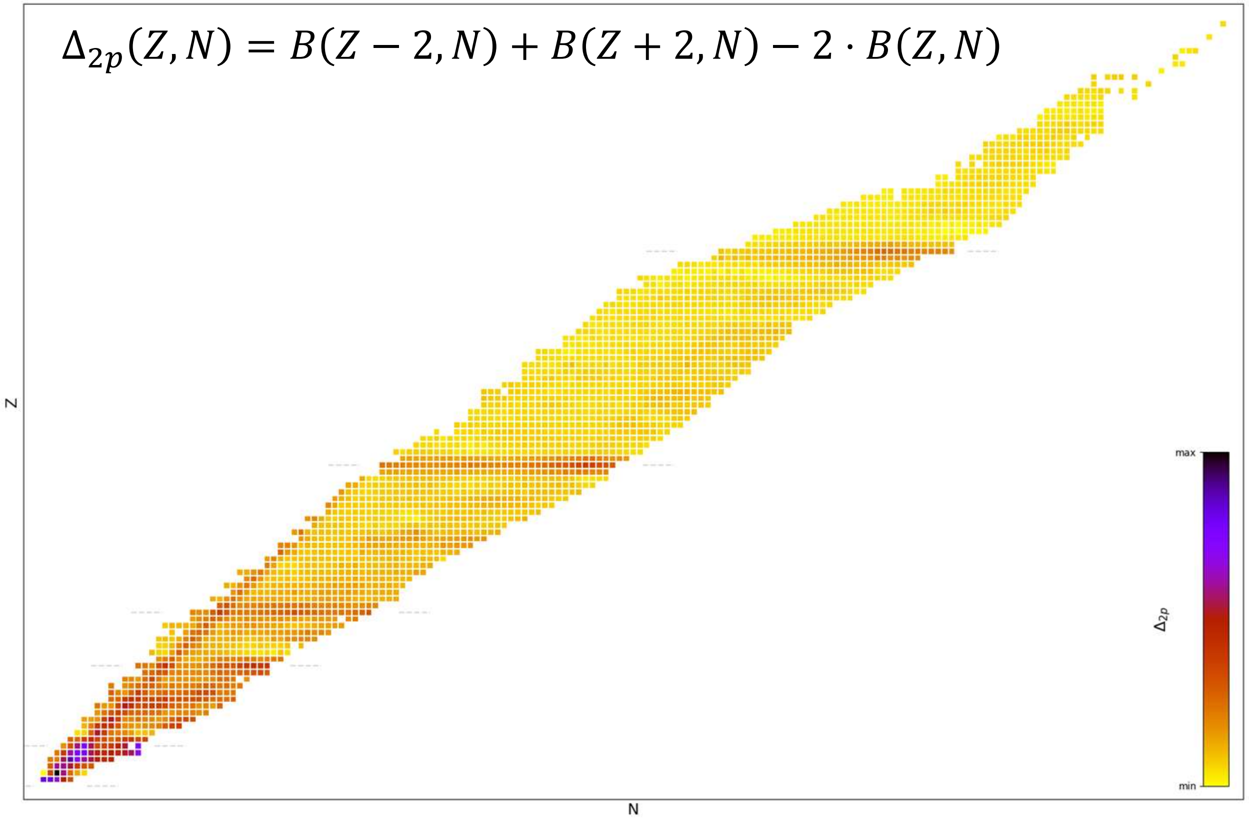
- Binding energy per nucleon for most abundant stable isotopes of each element
- Certain elements show enhanced stability compared to immediate neighbours



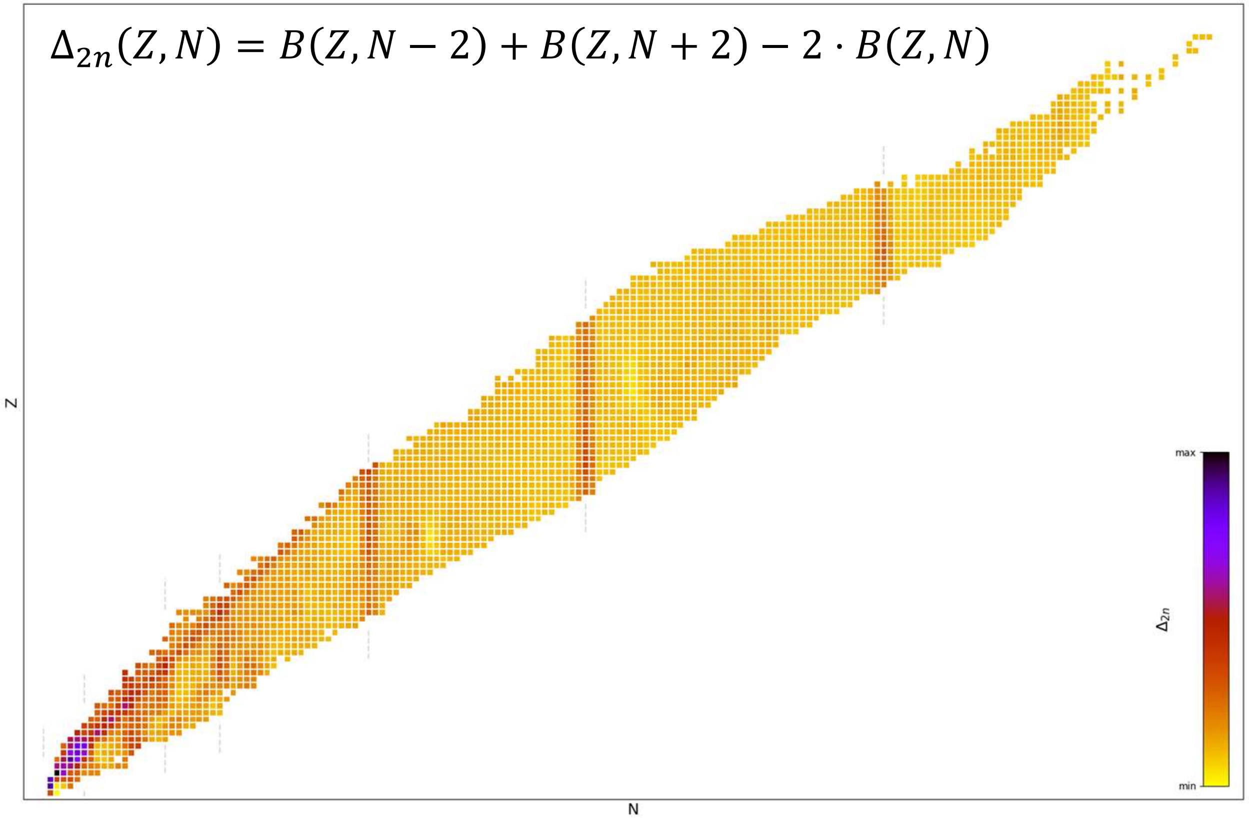
Binding Energy over Nuclear Chart

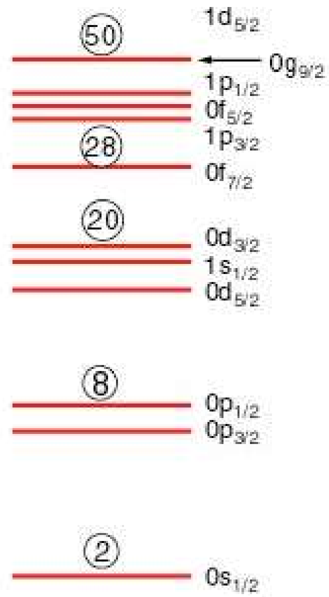


Empirical Proton Shell Gap



Empirical Neutron Shell Gap

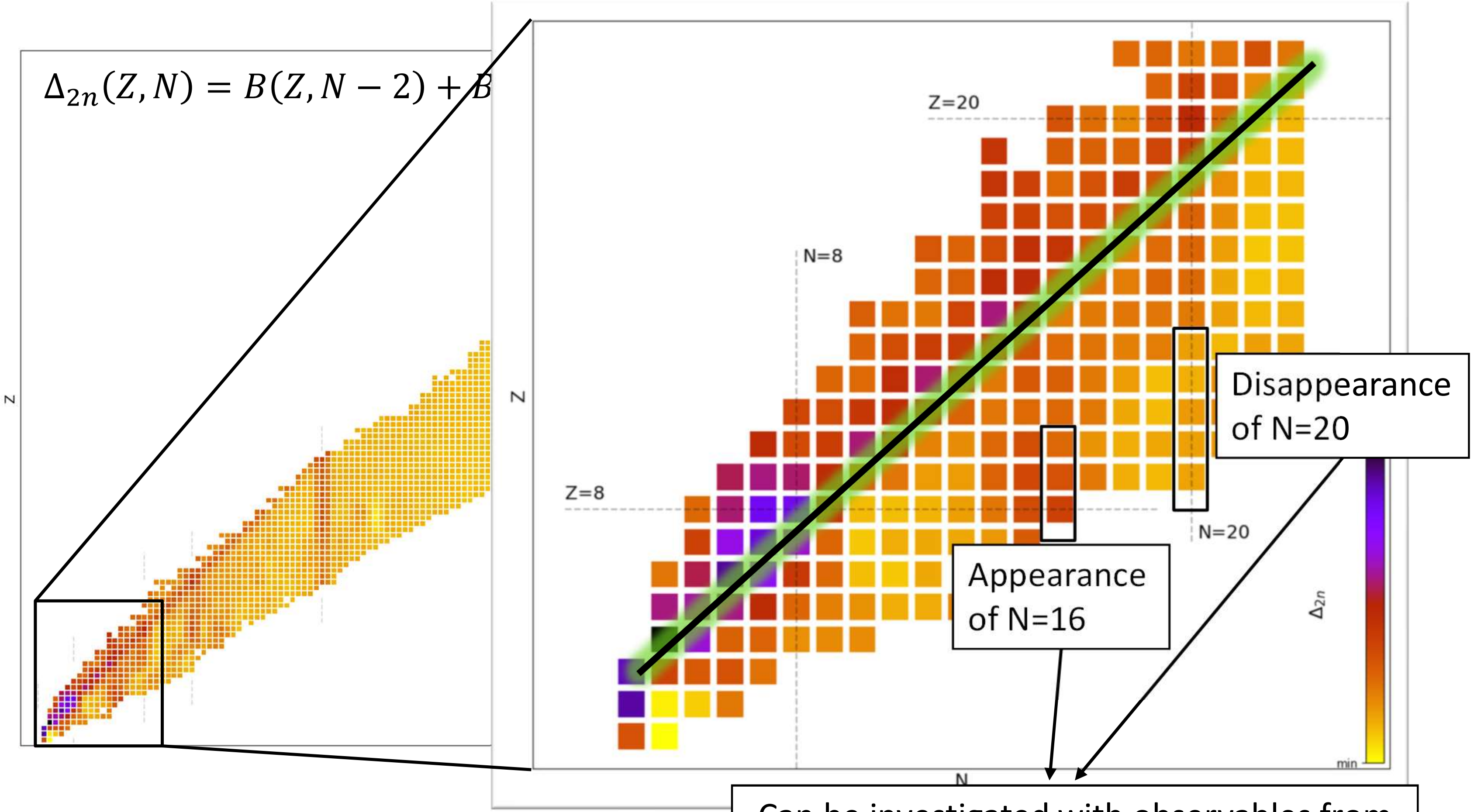




Shell Model of Nuclei

Maria Goeppert-Mayer
J. Hans D. Jensen
Nobel prize 1963

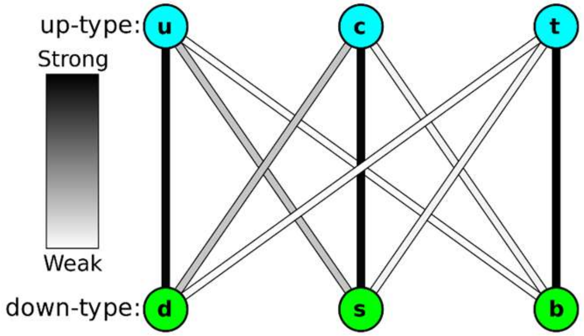
Empirical Neutron Shell Gap



Can be investigated with observables from Collinear Laser Spectroscopy, such as mean square charge radius

Standard Model of Particle Physics

- Standard Model of particle physics
  - very successful theory 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

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

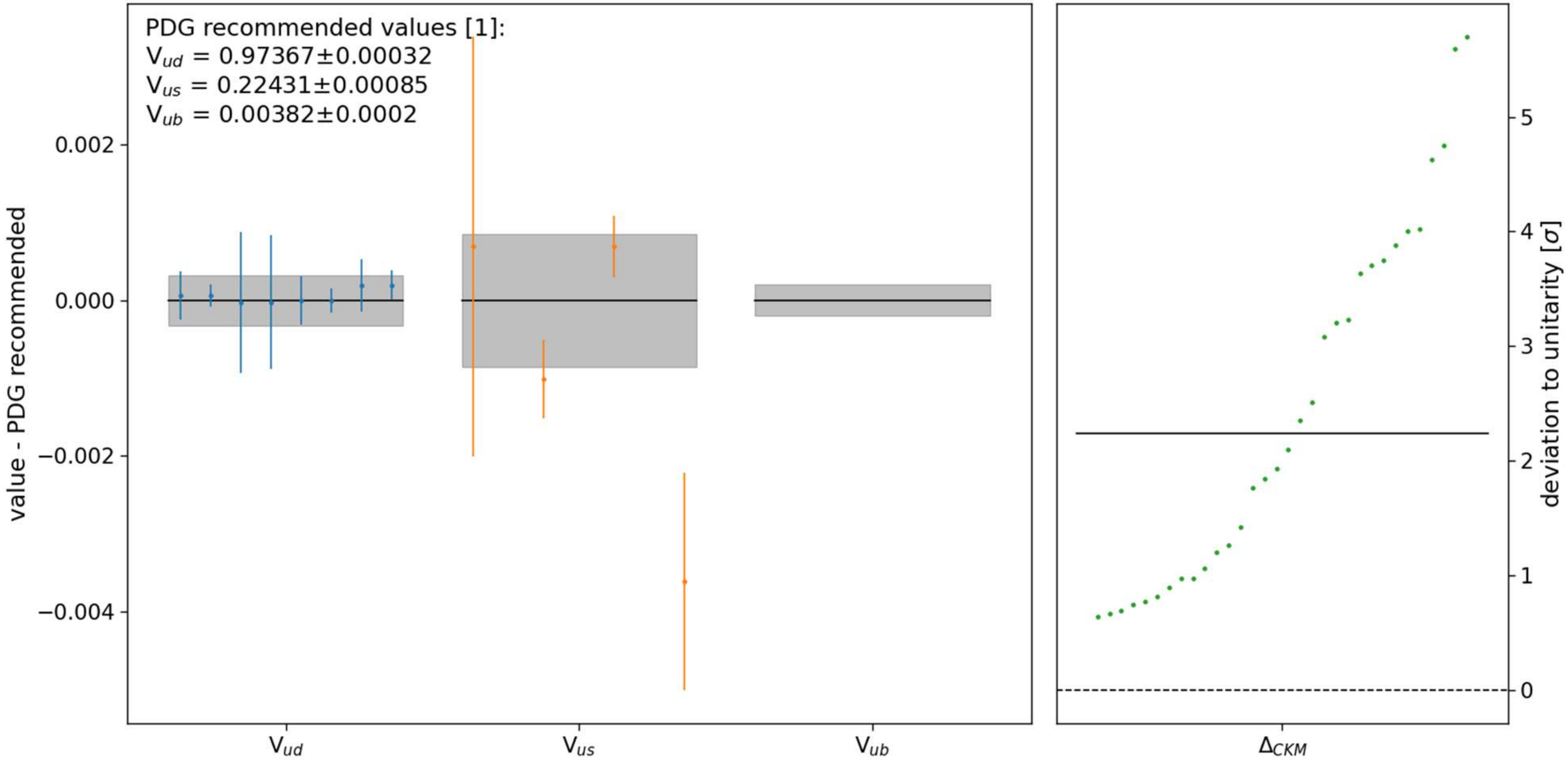
- Absolute square (i.e. $\left|V_{ij}\right|^2$) of each CKM-entry is probability of weak decay of j-type quark into i-type quark
- Standard Model of particle physics predicts unitarity of CKM matrix
- Deviation from unitarity would imply incomplete picture of Standard model

- Unitarity: $V_{CKM} \cdot {V_{CKM}}^T = I_3$
- In particular: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- Deviation from unitarity: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta_{CKM}$

[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.

Tension to Unitarity

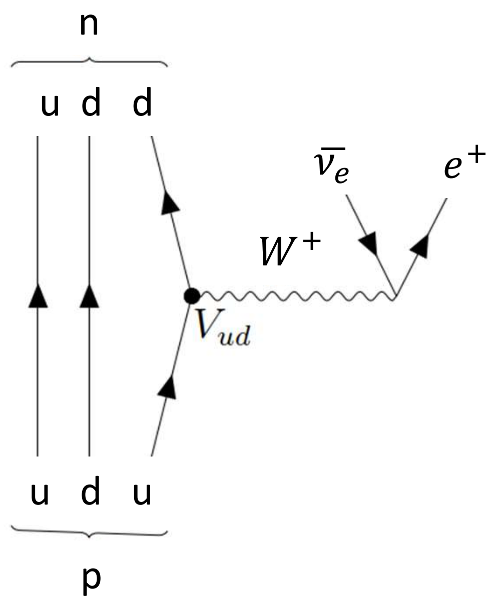
- Currently recommended values by PDG:



[1] S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)
[2] J. C. Hardy, I. S. Towner, Physical Review C 2020, 102.

CKM Unitarity (2)

- Determination of couplings for:
- V_{us}
  - Kaon decays
  - Hyperon decays
  - Tau decays
- V_{ud}
  - Neutron decay
  - Pion decay
  - Mirror decays (e.g. $^{21}Na \rightarrow ^{21}Ne$)
  - **Superallowed $0^+ \rightarrow 0^+$ β decays**



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!)

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

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

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

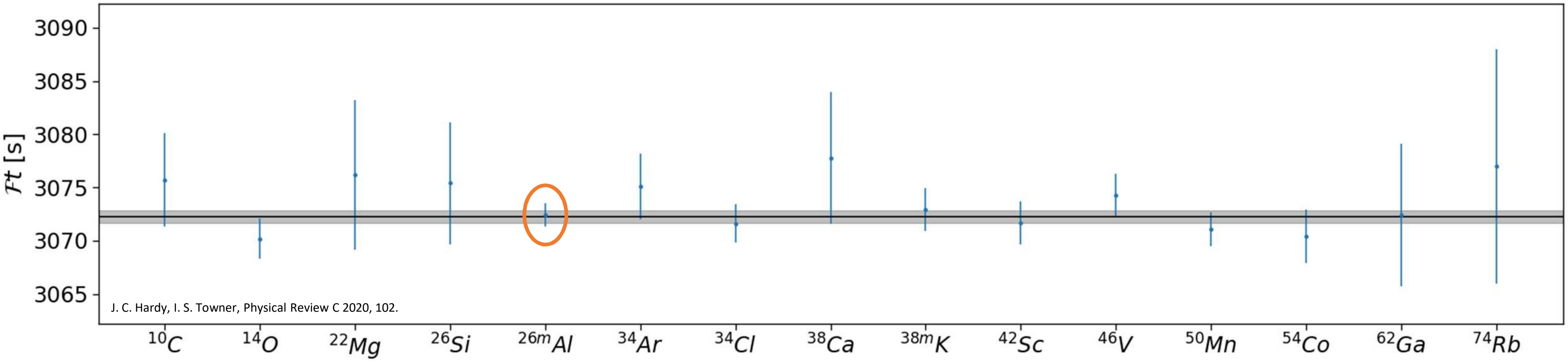
J. C. Hardy, I. S. Towner, Physical Review C 2020, 102.

Importance of charge radius of ^{26m}Al

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

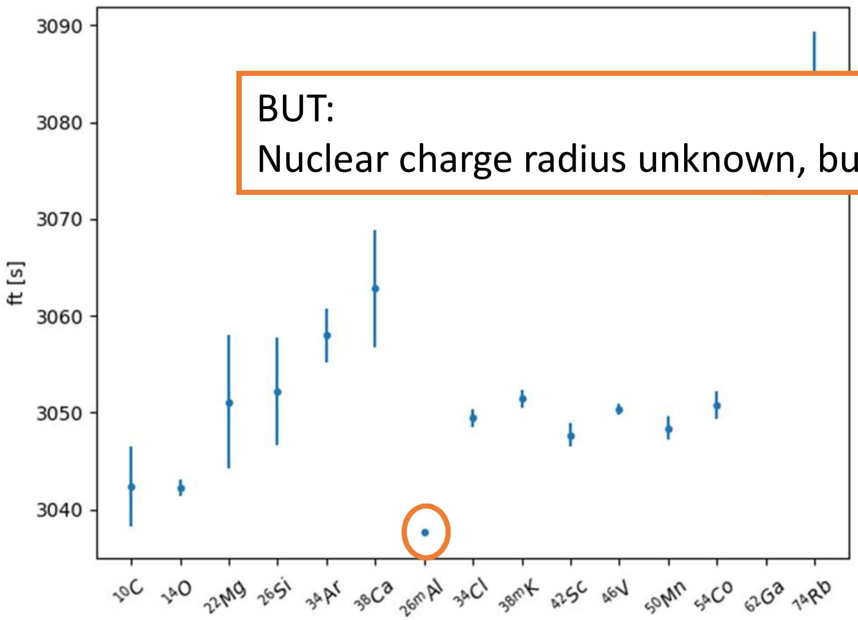
$$|V_{ud}|^2 = \frac{K}{2G_F^2(1+\Delta_R^V)\overline{\mathcal{F}t}}$$

- $\mathcal{F}t$ value of ^{26m}Al
  - Most accurately known of 15 isotopes used to calculate $\overline{\mathcal{F}t}$

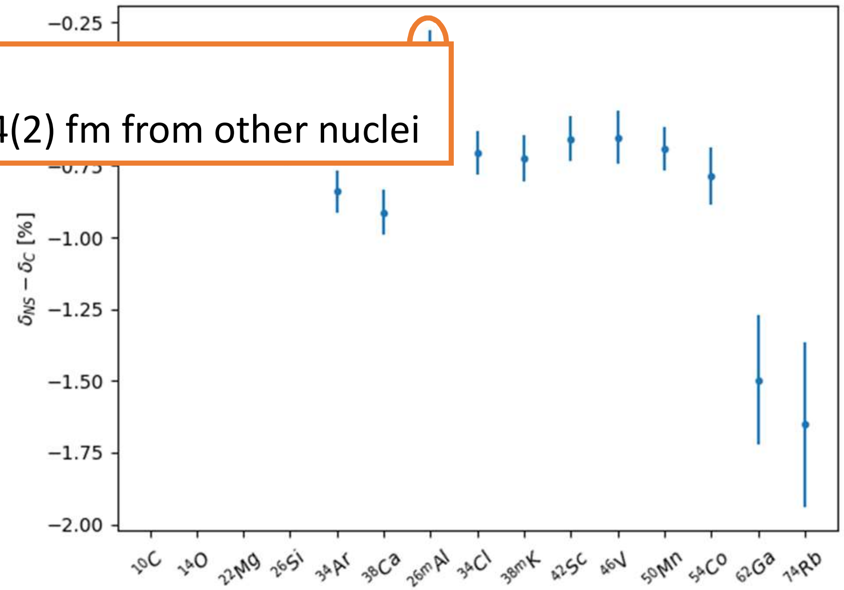


Importance of charge radius of ^{26m}Al

- Accuracy of $\mathcal{F}t$ value of ^{26m}Al coming from
  - Small uncertainty on ft
  - Small uncertainty on nuclear structure and isospin-symmetry breaking corrections
  - Lowest numerical correction on combined $\delta_{NS} - \delta_c$

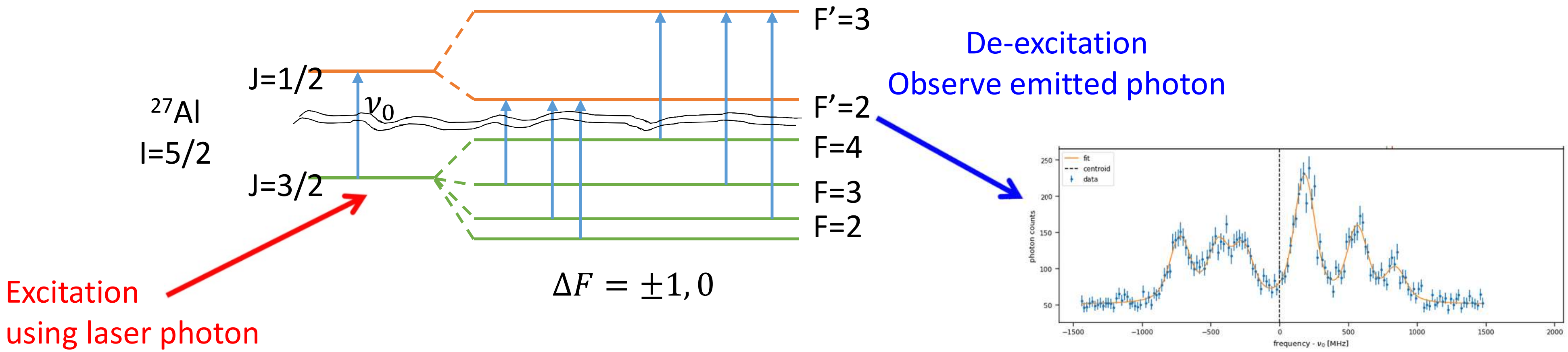


BUT:
Nuclear charge radius unknown, but extrapolated as 3.04(2) fm from other nuclei



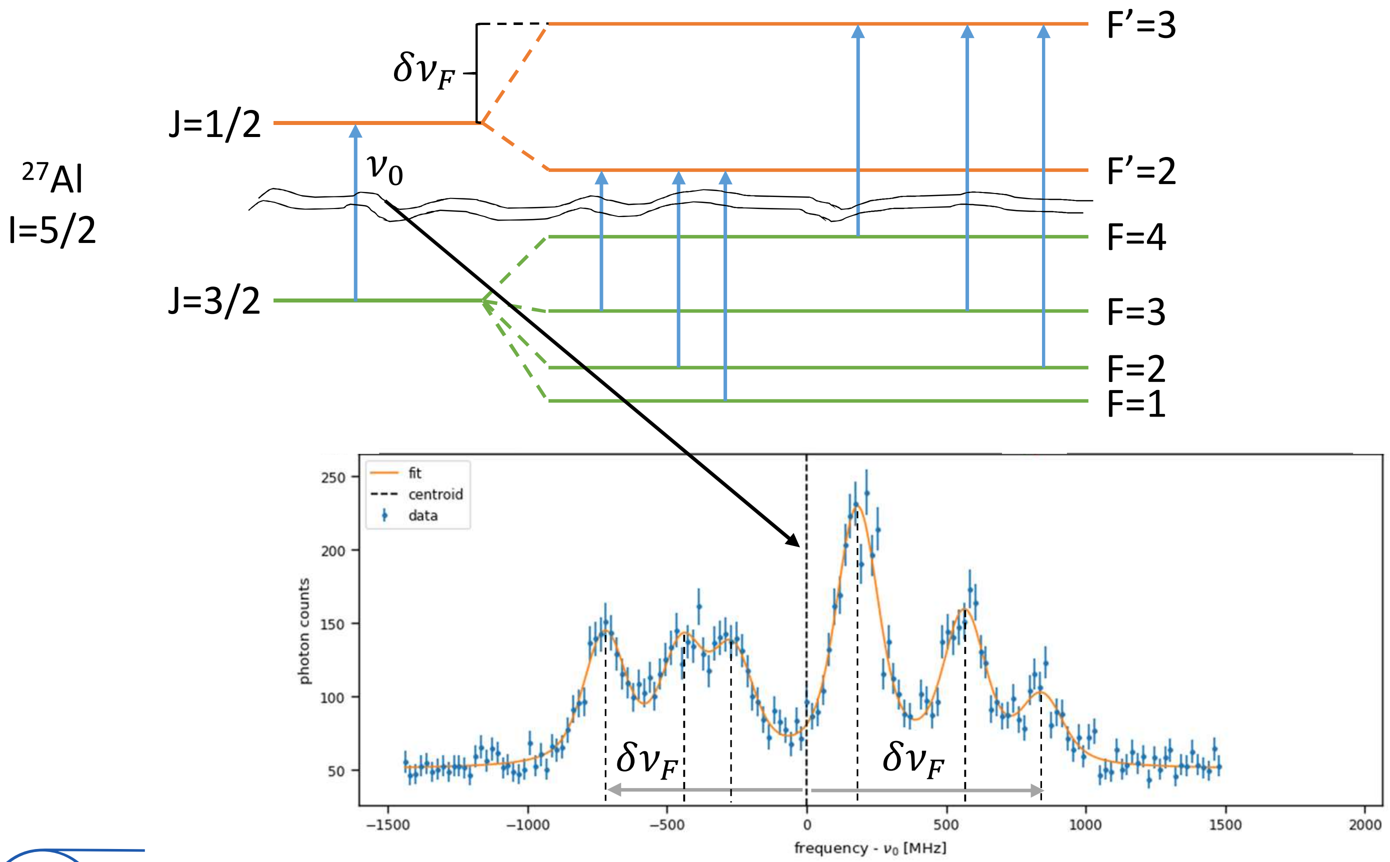
Laser Spectroscopy

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



- 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



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

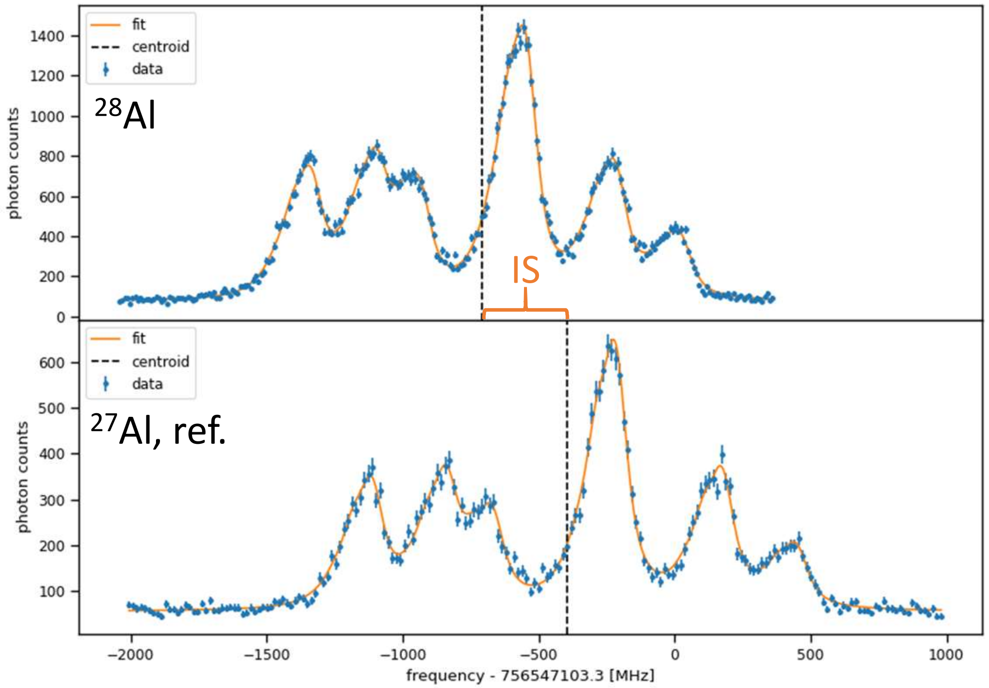
$$C = F(F+1) - I(I+1) - J(J+1)$$

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

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

$$\delta\nu = \nu_0 + \delta\nu^{F'} - \delta\nu^{F}$$

Isotope Shift

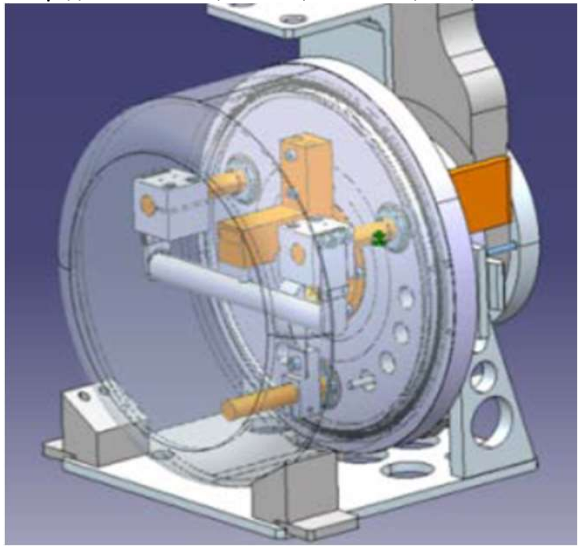


- Isotope shift IS = difference of centroid frequencies for different isotopes
- Used to calculate difference in mean square charge radii between isotopes

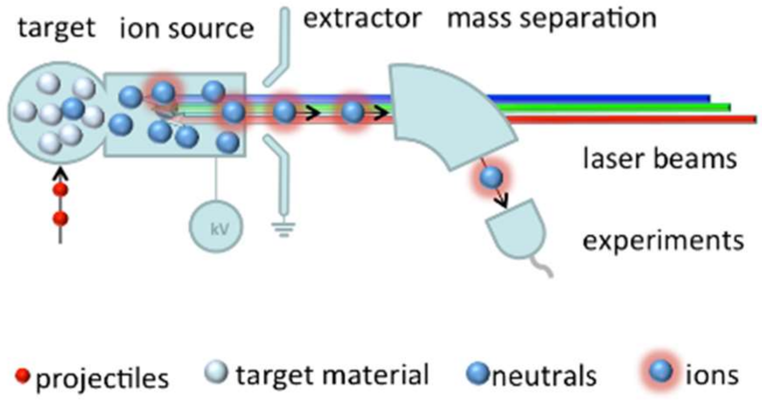
ISOLDE

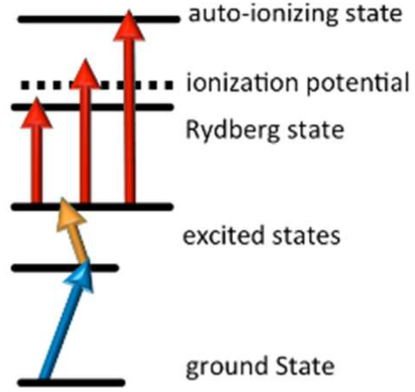
- Located at CERN
- Two target stations can be irradiated with up to 2 uA of 1.4 GeV protons from proton synchrotron booster (PSB)
- Isotopes produced via nuclear reactions in target material
- Then ionised and transported to experimental setup

Source: http://cds.cern.ch/record/1693046/files/arXiv:1404.0515.pdf



Ionisation





- Resonance ionisation laser ion source (RILIS)
- Electron exited through several resonant transition steps until ionization
- Very element specific
- Ionisation efficiency enhancement of factor ~10-100 (varies for different schemes for different elements)

Isotope Selection and Bunching

- Mass selection via High Resolution Separator (HRS) by two dipole magnets
- Offers mass resolving power of ~5000
- Injected into helium buffer gas filled Paul trap (ISCOOL)
- Used as cooler-buncher to accumulate isotopes before transporting bunches to experiment

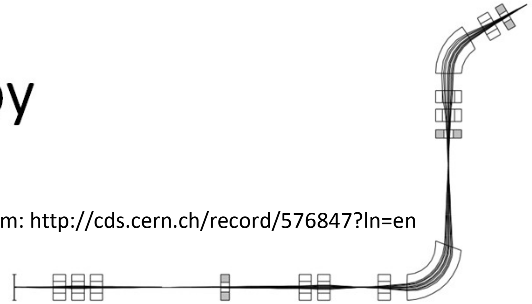
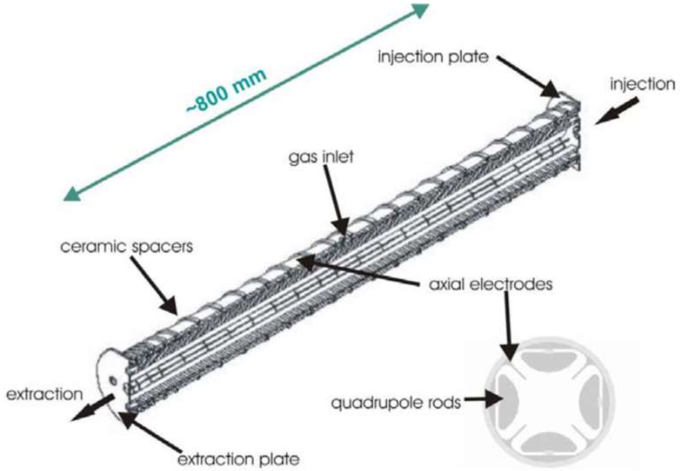
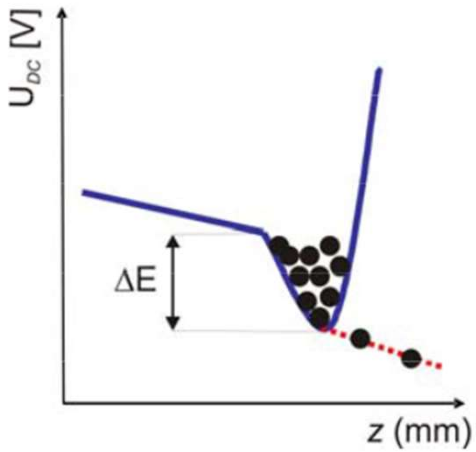


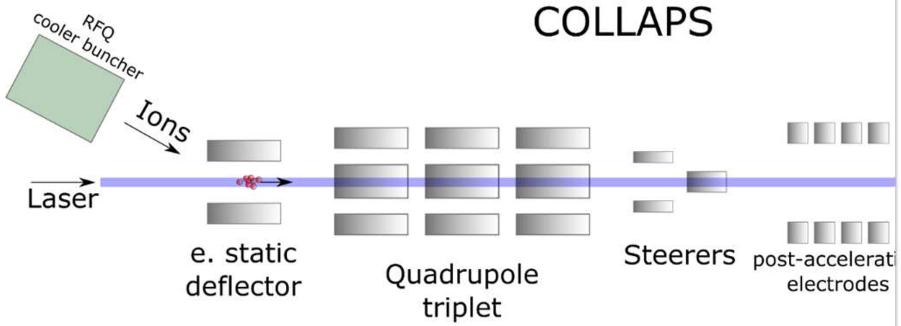
Image from: http://cds.cern.ch/record/576847?ln=en

Images from: http://cds.cern.ch/record/1058103/files/p57.pdf

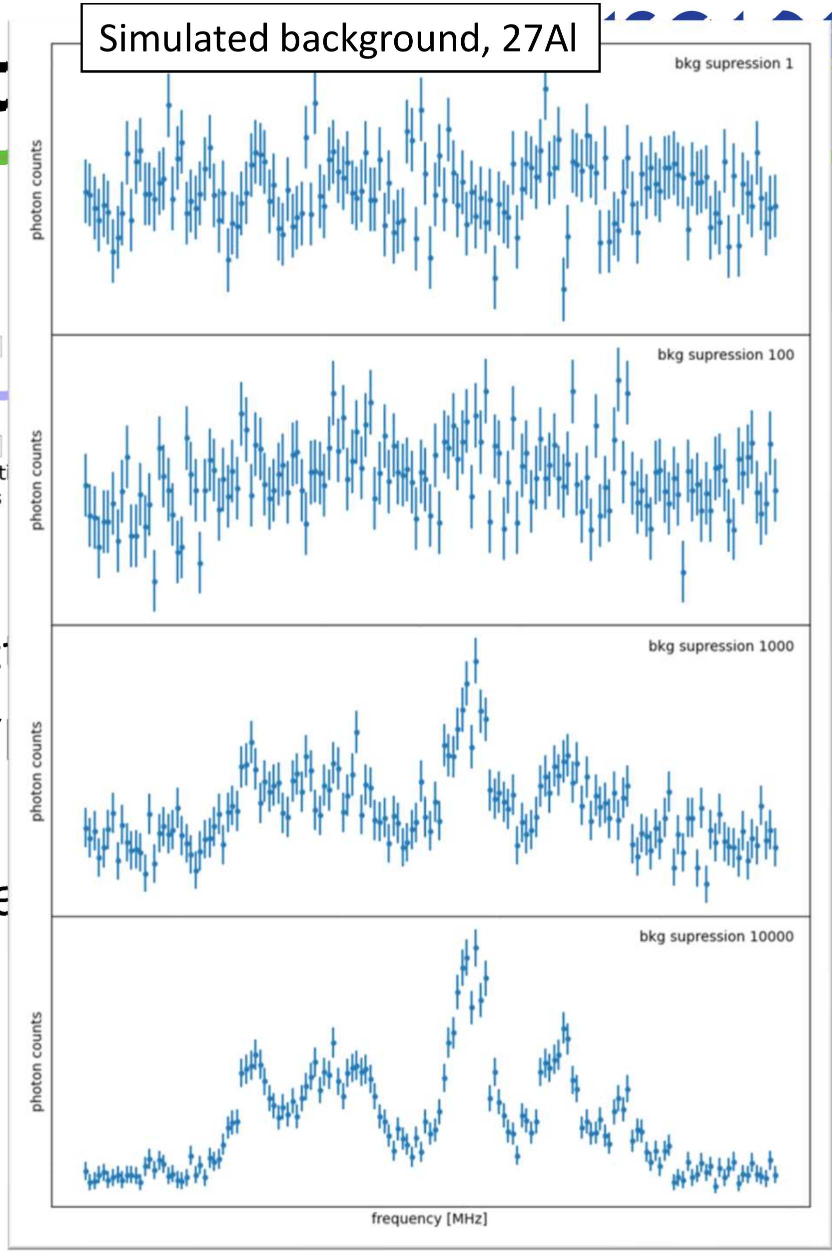




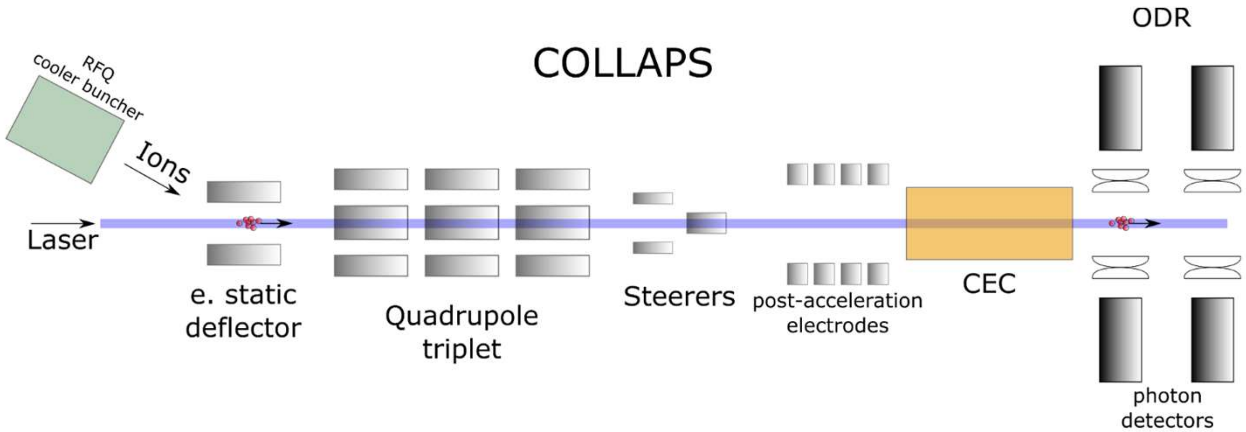
Collinear Laser Spect



- Ions and laser collinearly overlapped via elec
- Reduced doppler spread (<100MHz) due to "
30keV
- Bunched beam allows for time gating to incre
background by factor of ~10 000

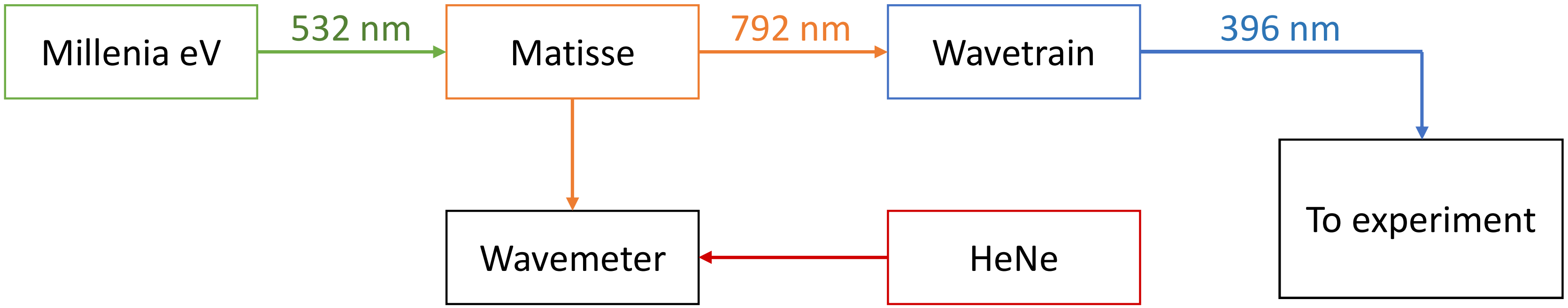


Collinear Laser Spectroscopy

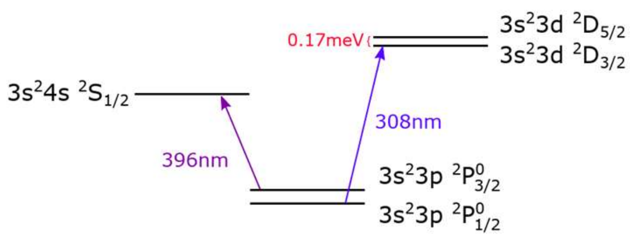


- Post-acceleration leads to frequency shift in ion rest frame
- Charge exchange with sodium to neutralize ions
- Measure fluorescence photons of resonant transitions

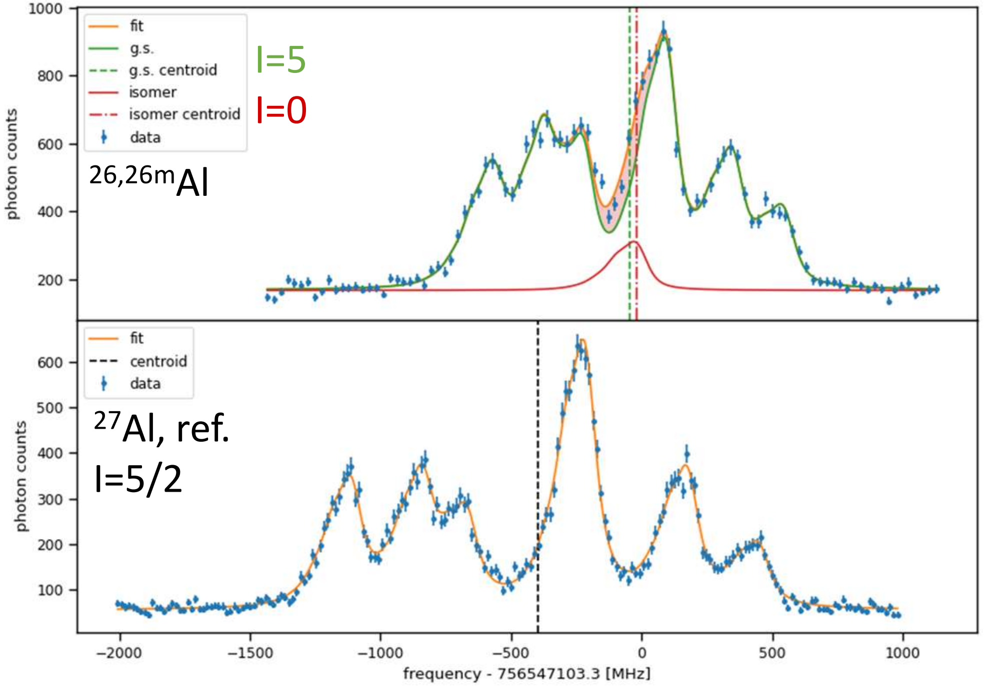
Laser System

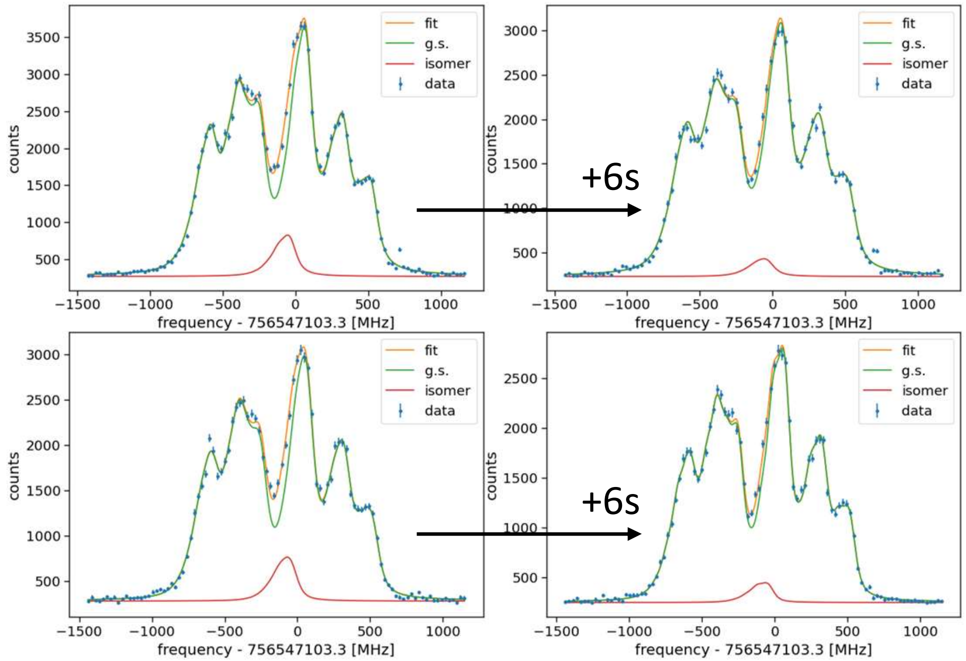


- Used transition: $3s^2 3p\ ^2P^\circ_{3/2} \rightarrow 3s^2 4s\ ^2S_{1/2}$ provided by frequency doubled Matisse Ti:Sa ring cavity laser
- Frequency stabilised by WSU-10 wavemeter
- Regularly calibrated by HeNe laser



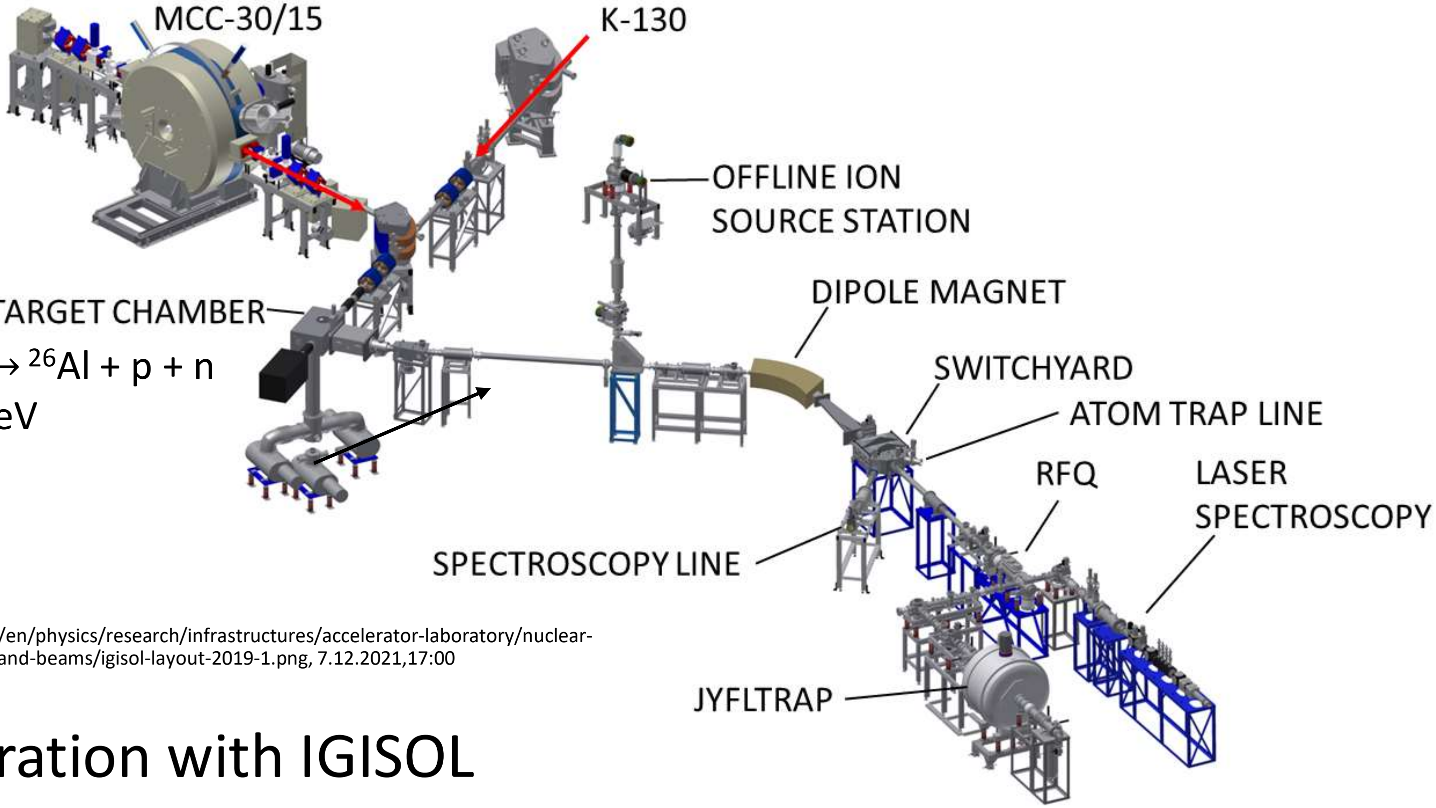
Hyperfine Spectra





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

IGISOL

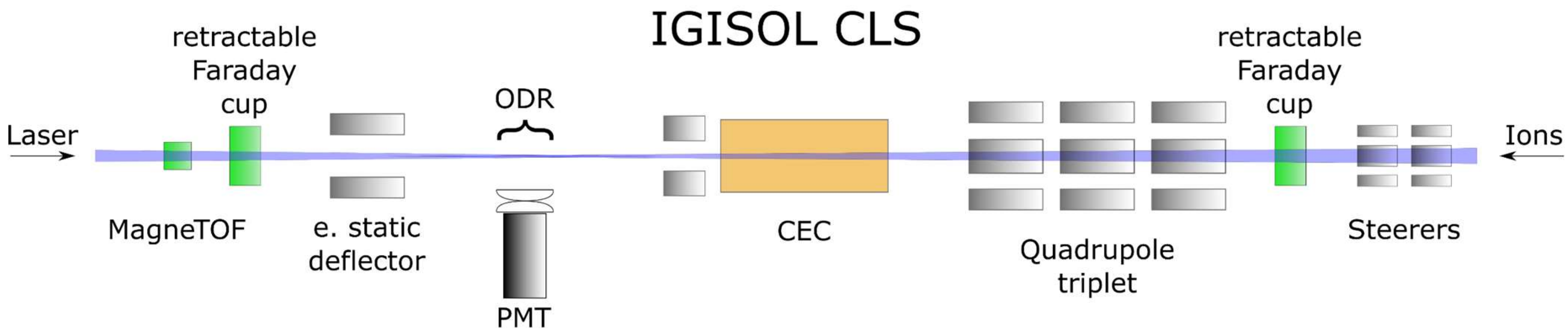


$^{27}Al + p \rightarrow {}^{26}Al + p + n$
at 25 MeV

Source: https://www.jyu.fi/science/en/physics/research/infrastructures/accelerator-laboratory/nuclear-physics-facilities/the-exotic-nuclei-and-beams/igisol-layout-2019-1.png, 7.12.2021,17:00

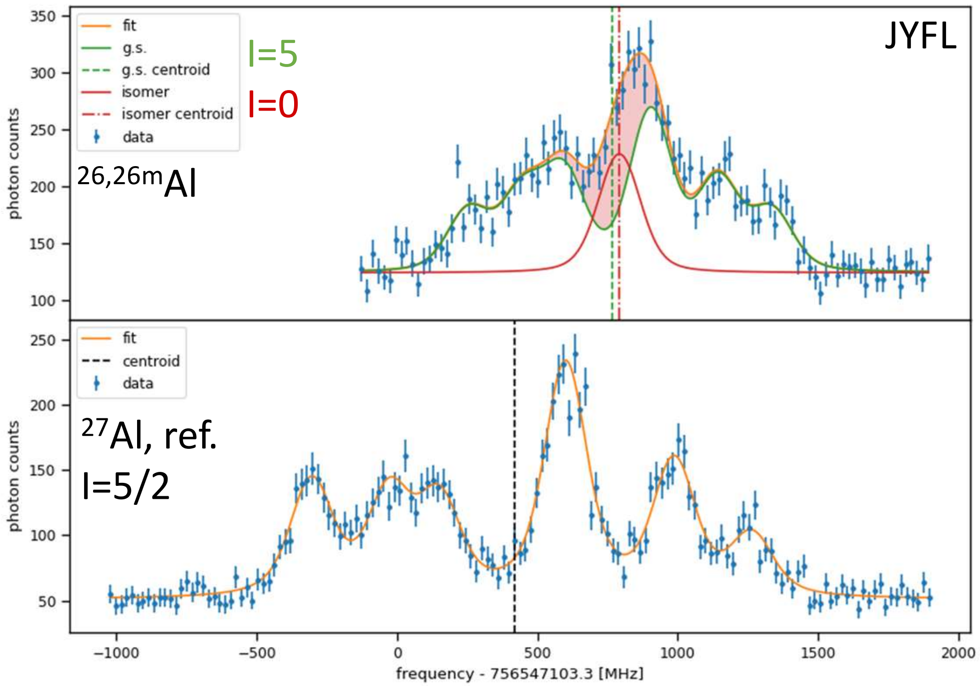
- Collaboration with IGISOL
- Second set of measurements performed at IGISOL, Jyväskylä
- Known to have more favorable isomer : ground state ratio for $^{26,26m}Al$

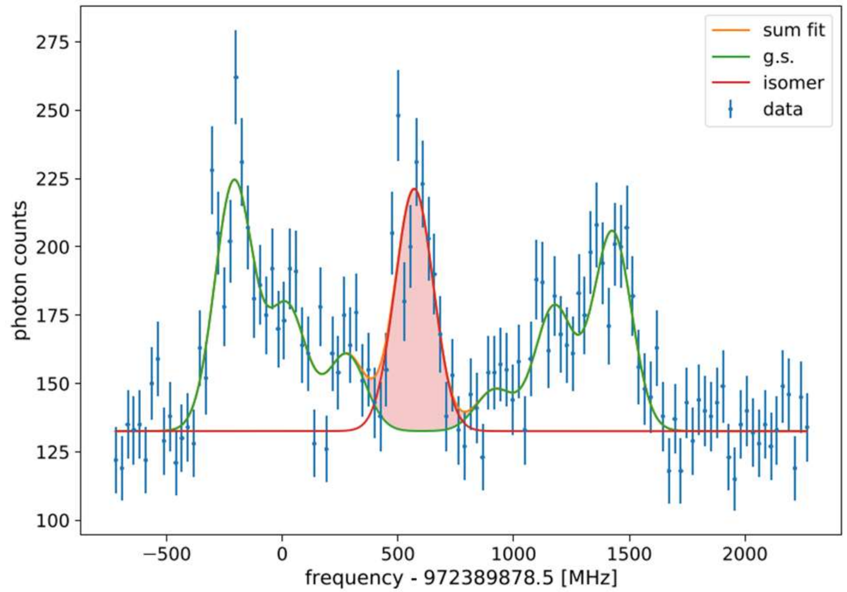
Collinear Laser Spectroscopy at IGISOL



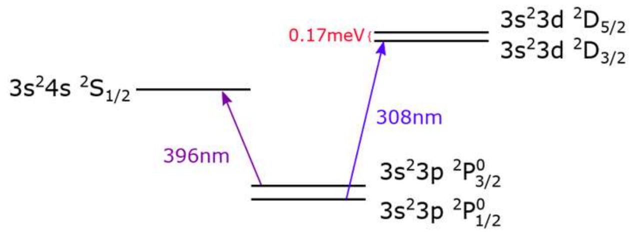
- Similar overall configuration as COLLAPS
- Laser and ions injected anti-collinearly
- CEC also filled with sodium
- Single photomultiplier compared to quad configuration at COLLAPS

Hyperfine Spectra

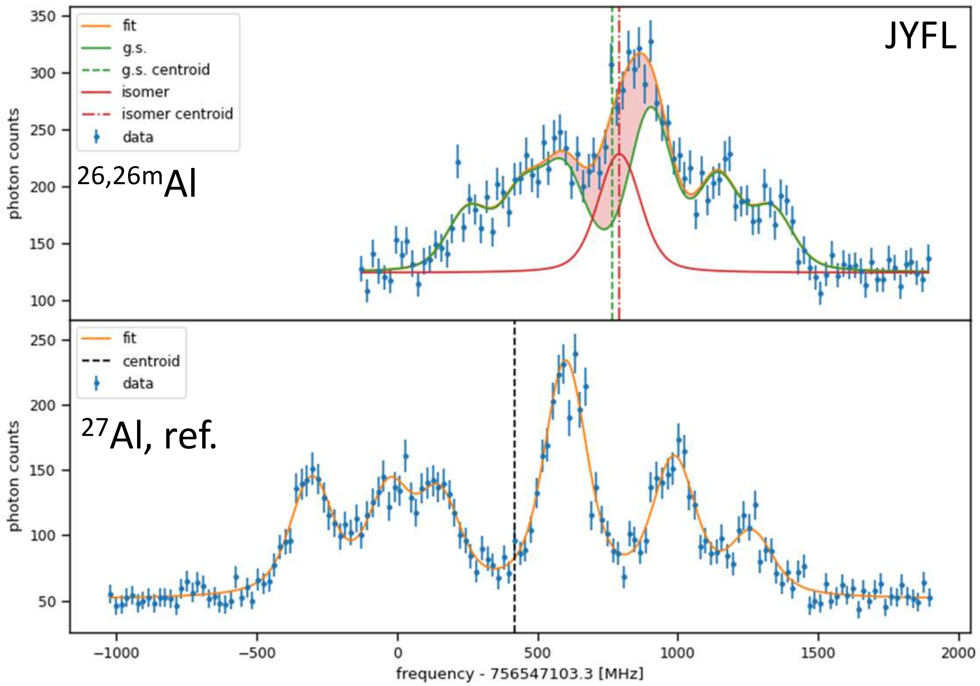


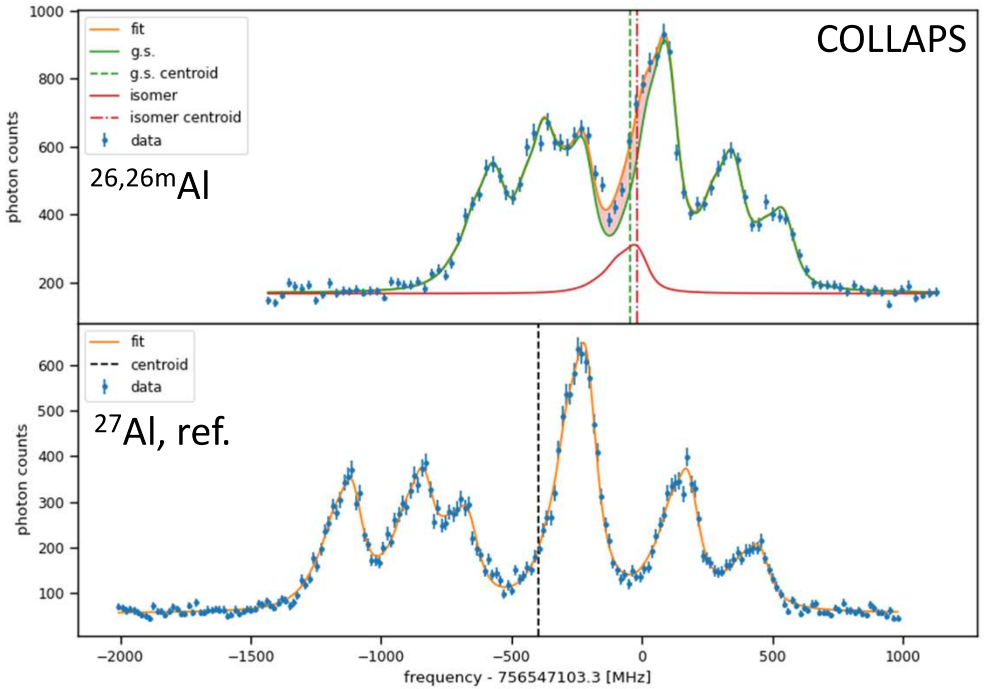


- Clear presence of isomer in Al I $P_{1/2} \rightarrow D_{3/2}$ transition



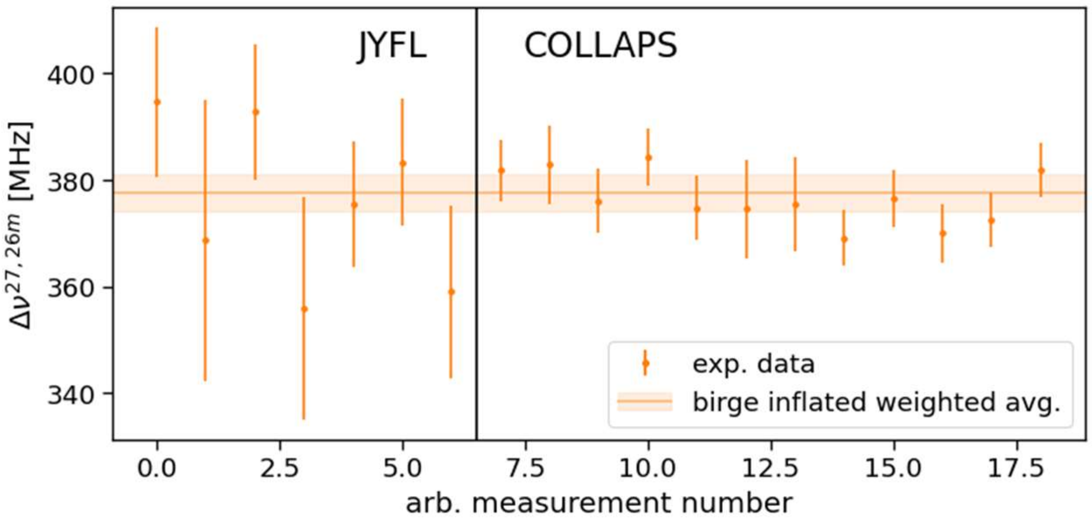
Hyperfine Spectra





Isotope Shift

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



Isotope Shift [MHz]	
IGISOL	379.7{5.5}[2.2]
COLLAPS	376.5{1.7}[3.7]
weighted avg.	377.5(3.4)

- Statistical and systematic uncertainties combined in quadrature for each experiment
- Combination of both datasets as weighted average

Mean Square Charge Radius

- 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 reference

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

- Depends on
  - Respective nuclear masses m_A, electron mass m_e
  - Atomic mass shift factor M
  - Field shift factor F

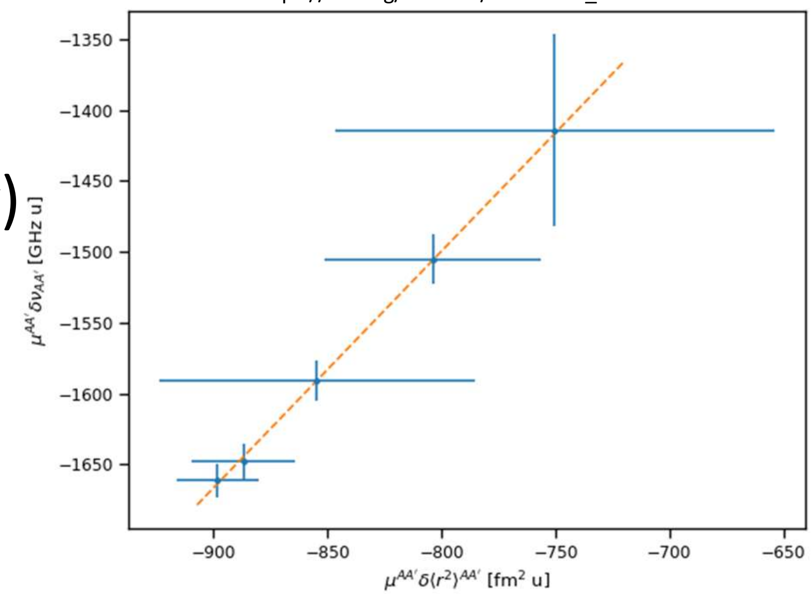
King plot

- If enough (>=3) stable isotopes with absolute charge radii are known
- Transformation of previous equation leads to linear relation $\mu_{27,A} \cdot \delta\nu^{27,A} = F \cdot \mu_{27,A} \cdot \delta\langle r^2\rangle^{2\ ,A} + M$

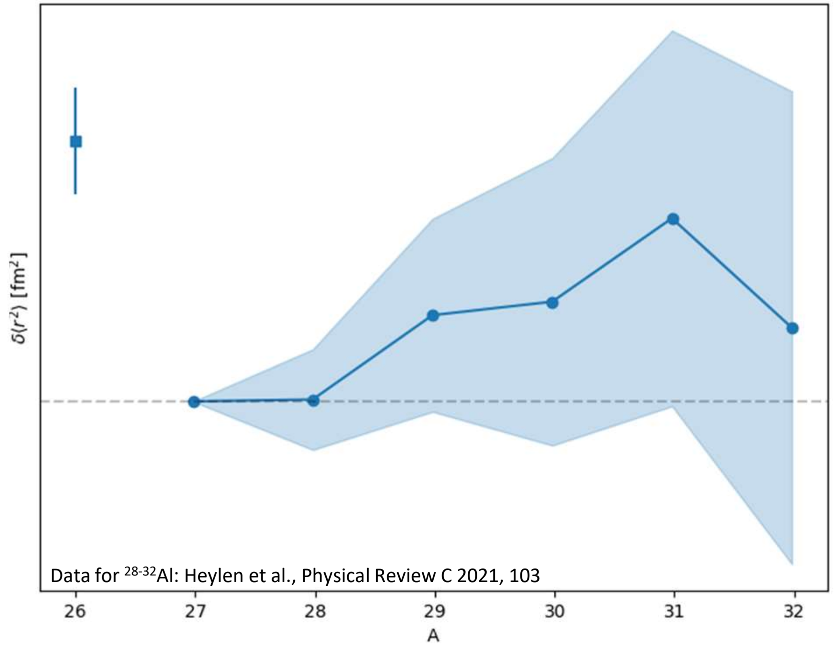
$$\mu_{27,A} := \frac{m_{27} \cdot (m_A + m_e)}{m_A - m_{27}}$$

Example: isotopes of tin
Source IS: PRL 122, 192502 (2019)
Source radii: https://doi.org/10.1007/10856314_1

- Aluminium: only 1 stable isotope
- Determination of F and M through atomic calculations necessary (higher uncertainty)



RMS Charge Radii of aluminium isotopes



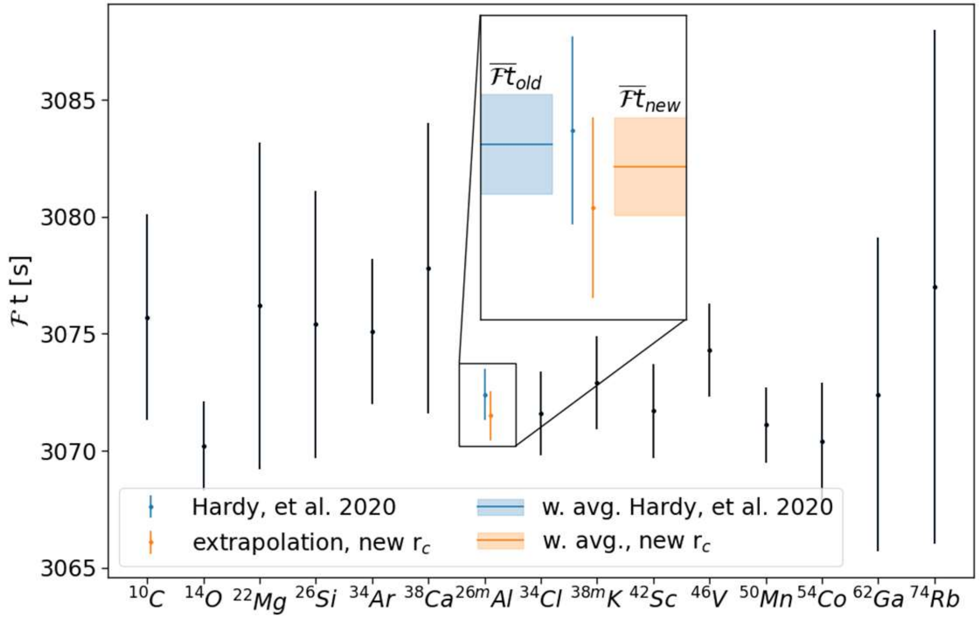
- Absolute charge radius of ^{27}Al from Barrett equivalent radius obtained by muonic spectroscopy and charge density from electron scattering measurements

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

Nuclear Charge Radius and $\mathcal{F}t$

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

	Old values from [1]	New Values
^{26m}Al nuclear charge radius	3.04(2) fm	3.130(15) fm
$\mathcal{F}t$ of ^{26m}Al	3072.4(1.1) s	3071.4(1.0) s
$\overline{\mathcal{F}t}$	3072.24(1.85) s	3071.96(1.85) s



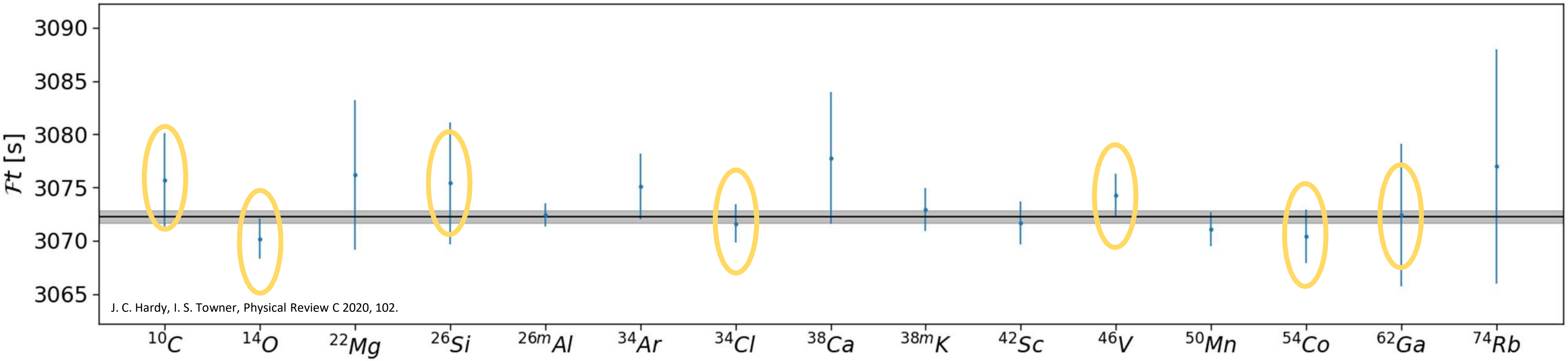
[1] J. C. Hardy, I. S. Towner, Physical Review C 2020, 102.

Implications for CKM unitarity

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

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = \cancel{0.99848(70)} \rightarrow 0.99856(70)$$

- Motivates further studies of nuclear charge radii in other superallowed β emitters with so-far unknown charge radii:



Outlook

- Current status: charge radii of 7/15 superallowed beta emitters still unknown
- Ongoing efforts to determine ^{54}Co at IGISOL

- Further effect of charge radius of ^{26m}Al on Fermi function leading to necessary correction of ft-value
- → Might result in another shift of average $\mathcal{F}t$ depending on magnitude of correction

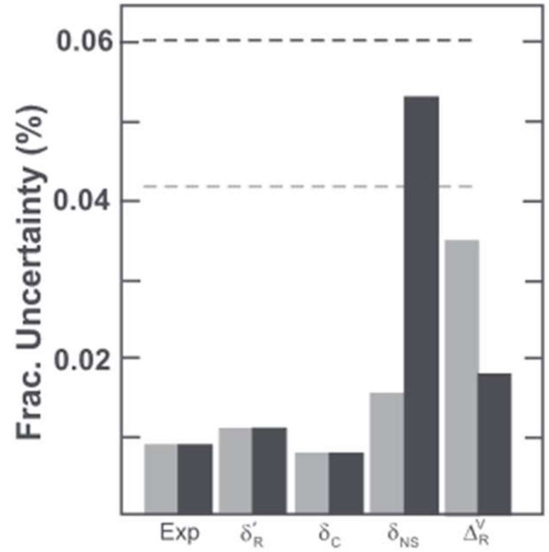
[1] https://arxiv.org/abs/2309.16893

Outlook

- Uncertainty of $|V_{ud}|^2$ currently dominated by systematic theoretical uncertainties on δ_{NS}
- If δ_{NS} were reduced to being non-dominant contribution, result of unitarity test would shift to ≈3σ

- New calculations for δ_{NS} correction (with ab-initio methods) are being explored by TRIUMF's theory department
- Currently limited to lightest superallowed β emitters

Grey: 2015
Black: 2020



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

[1] https://arxiv.org/abs/2405.19281

Summary and Conclusion

- The charge radius of ^{26m}Al has 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
- Extrapolation points towards slight shift towards CKM unitarity
- For more information:
  PRL 131, 222502 (2023) (DOI:10.1103/PhysRevLett.131.222502)

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 Ruzíz[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*

Thanks to COLLAPS, IGISOL, ISOLDE