Laser spectroscopy of neutron-rich Ni with PI-LIST

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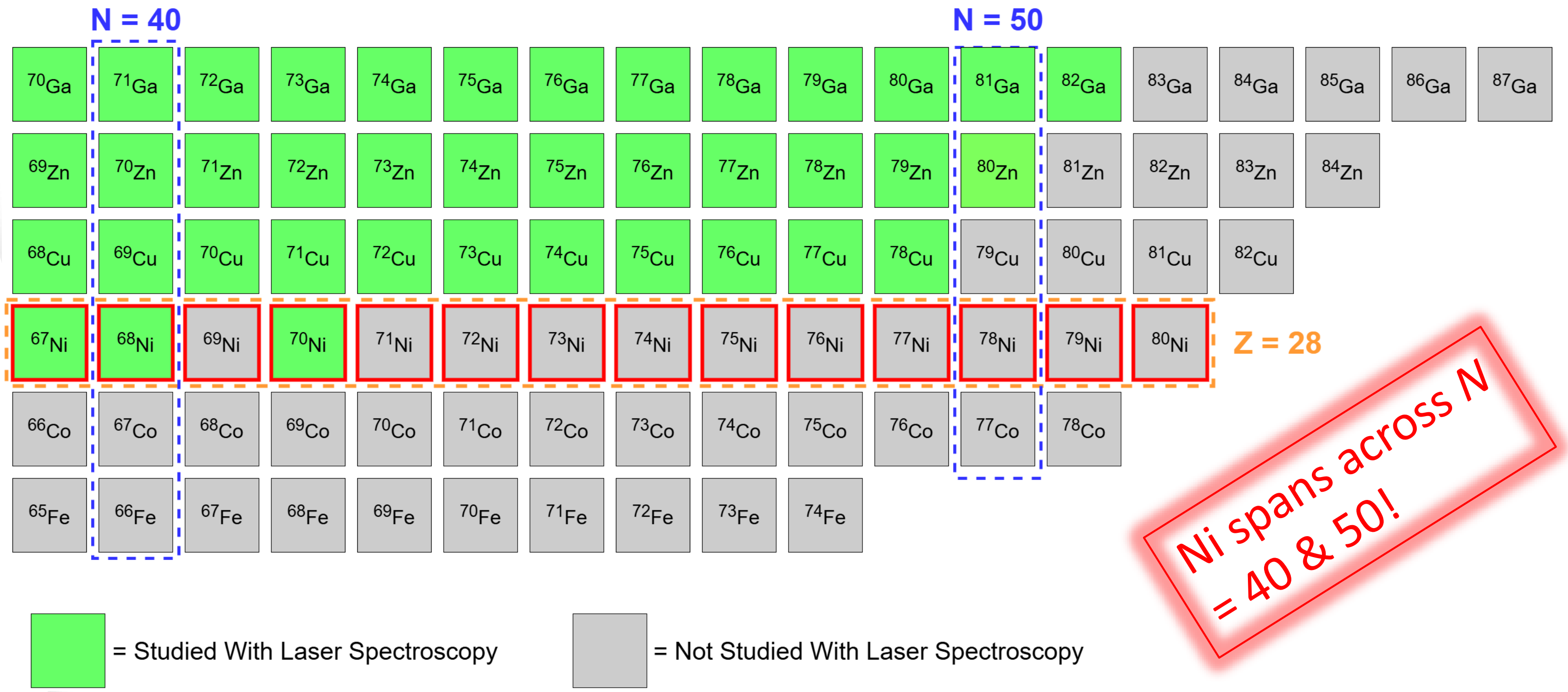
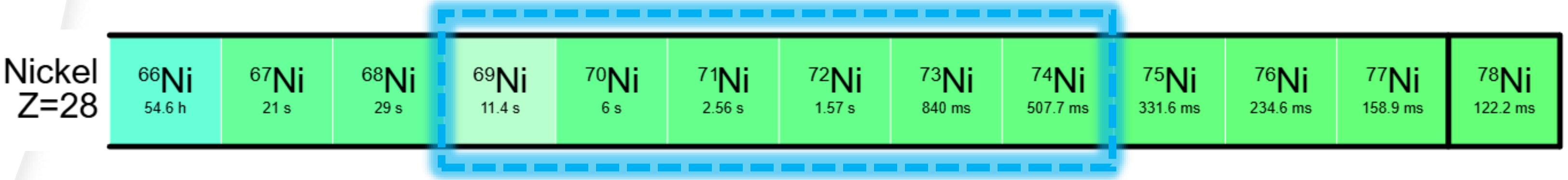
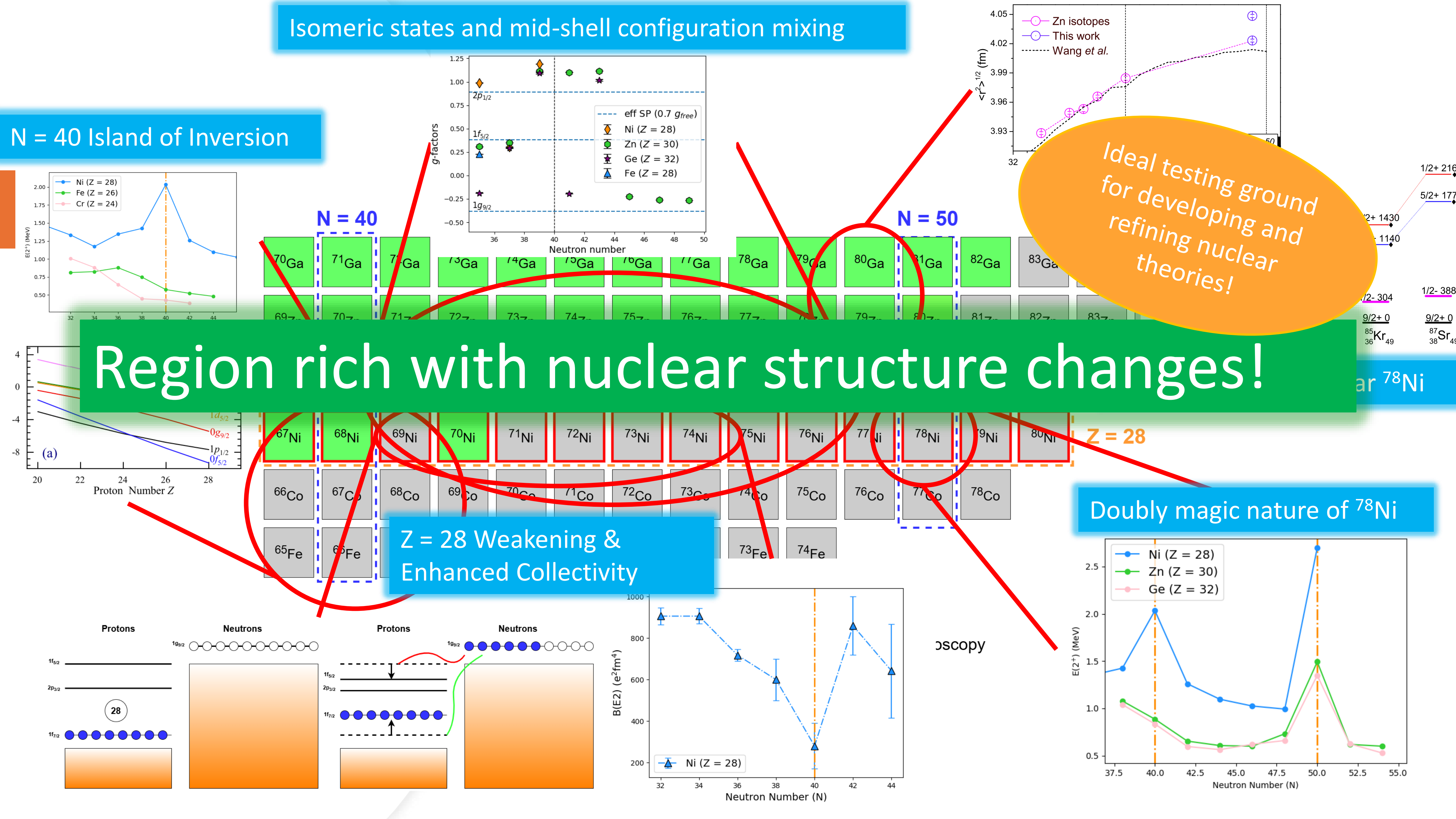
Introduction

- Closed proton shell (Z = 28)
- *Z* > 28 extensively studied with laser spectroscopy
- $^{54-68,70}$Ni studied previously
- Expand online PI-LIST into the medium-mass region





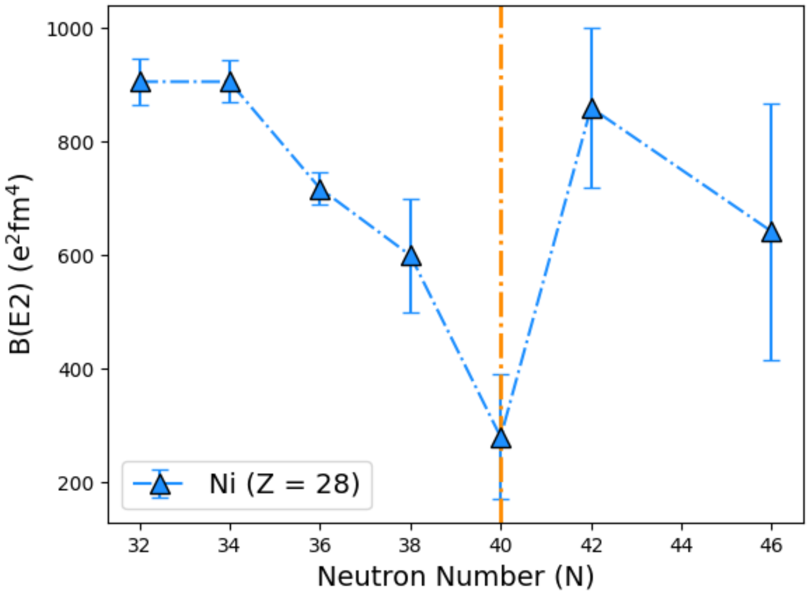


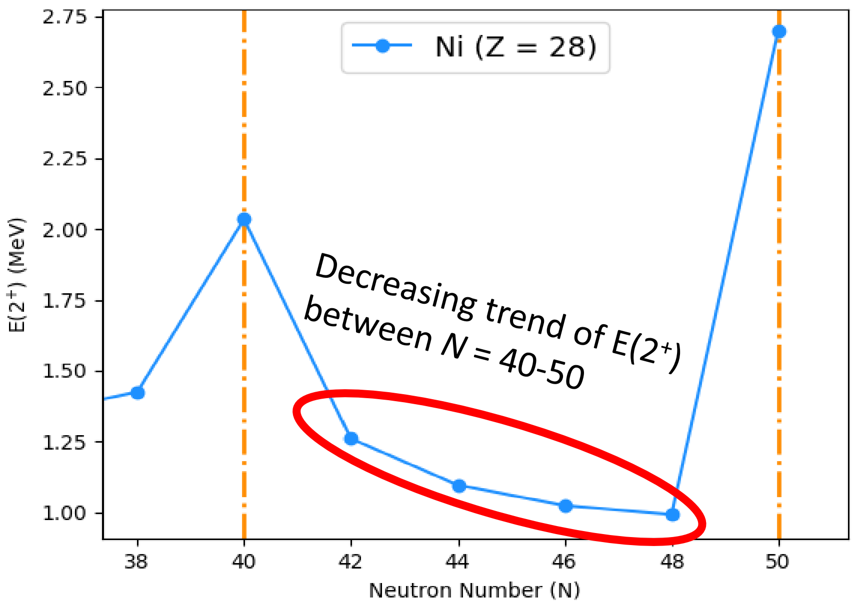
Isomeric states and mid-shell configuration mixing
N = 40 Island of Inversion
Ideal testing ground for developing and refining nuclear theories!
Region rich with nuclear structure changes!
N = 40
N = 50
Z = 28
Z = 28 Weakening & Enhanced Collectivity
Doubly magic nature of 78Ni
Zn isotopes
This work
Wang et al.
eff SP (0.7 gfree)
Ni (Z = 28)
Zn (Z = 30)
Ge (Z = 32)
Fe (Z = 28)
Cr (Z = 24)
g-factors
Neutron number
Proton Number Z
Protons
Neutrons
Neutron Number (N)
B(E2) (e2fm4)
E(2+) (MeV)

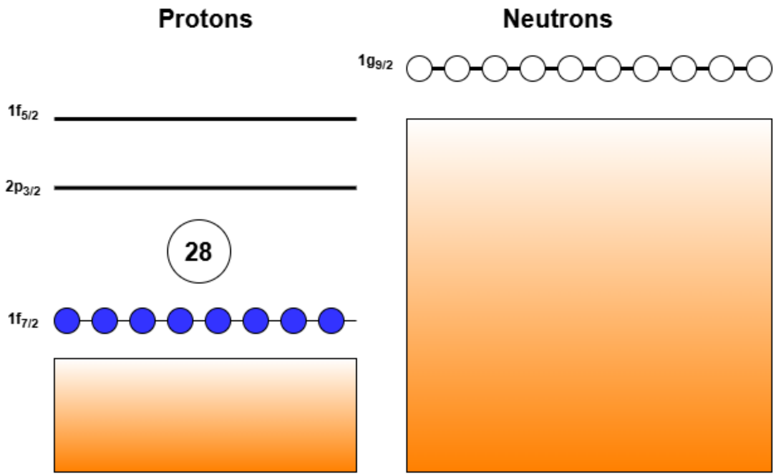
[1] N. Aoi et al., Enhanced collectivity in 74ni. Physics Letters B,692(5):302–306, September 2010.
[2] O. Perru et al., Enhanced core polarization in 70Ni and 74Zn.Phys. Rev. Lett., 96:232501, Jun 2006.
[3] T. Marchi et al., Quadrupole transition strength in the 74Ni nucleus and core polarization effects in the neutron-rich Ni isotopes. Phys. Rev. Lett., 113:182501, Oct 2014.

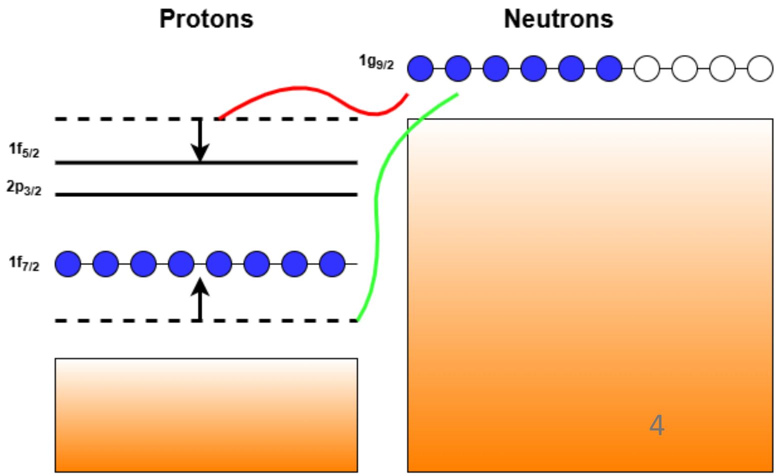
Motivation: possible weakening?

- Possible indicator of $Z = 28$ weakening as neutrons populate $g_{9/2}$
- Enhancement in collectivity in ^{74}Ni reported in [1]
- Increase in B(E2) between N = 40-42 [2]
- Prolate deformation in ^{74}Ni
- **$\mu, Q_s, \delta\langle r^2\rangle^{A,A'}$ measurements crucial in mid-shell region to understand development of collectivity**



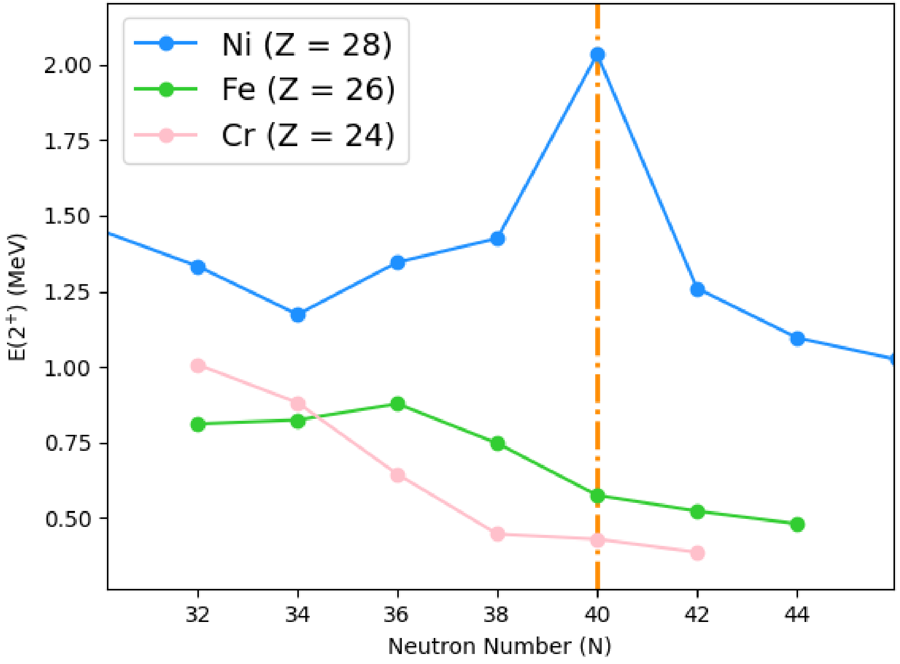






Motivation: N = 40 Island of inversion

- E(2^+) indicate re-emergence of N = 40 sub-shell closure in Ni
- ^{64}Cr marks the heart of the IoI, 4 protons from Ni [2]
- As $\pi 1f_{7/2}$ is populated, N = 40 energy gap narrows
- Promotes np-nh excitations, causing intruder-dominated configurations
- **Reflected in $\delta\langle r^2\rangle^{A,A'}$, Q_s and μ**
- To conclusively exclude Ni from N = 40 IoI, $\delta\langle r^2\rangle^{A,A'}$, μ and Q_s are required



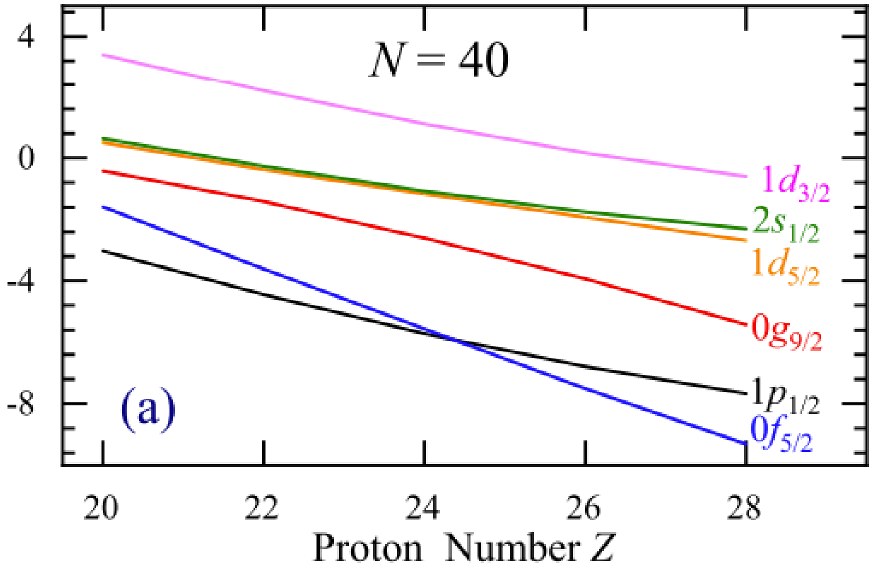


Fig from [1]

[1] J.G. Li. Merging of the island of inversion at n=40 and n=50. Physics Letters B,840:137893, 2023.
[2] L. Lalanne et al., ^{61}Cr as a door-way to the n = 40 island of inversion, 2024.

[1] P. Muller et al., electromagnetic moments of the odd-mass nickel isotopes 59-67ni. Physics Letters B, 854:138737, 2024.
[2] S. Malbrunot-Ettenauer et al., nuclear charge radii of the nickel isotopes 58–68,70Ni. Phys. Rev. Lett., 128:022502, Jan 2022.
[3] C. Wraith et al., Evolution of nuclear structure in neutron-rich odd-Zn isotopes and isomers. Physics Letters B, 771:385–391, 2017.

Previous measurements

- Laser spectroscopy of Ni previously performed @ COLLAPS [1, 2]
- $\delta\langle r^2\rangle^{A,A'}$ measured for **$^{58\text{-}68,70}$Ni** [2]
- μ and Q_s measured up to **^{67}Ni** [1]
- Neighbouring elements also studied: Fe, Zn, Ge
- **Zn deviates from the expected $1g_{9/2}$ SP *g*-factor at N = 41, 43** [3]
- Neutron hole in the $2p_{1/2}$ orbital at N = 41, 43
- Conventional shell filling resumes at N = 49 in Zn

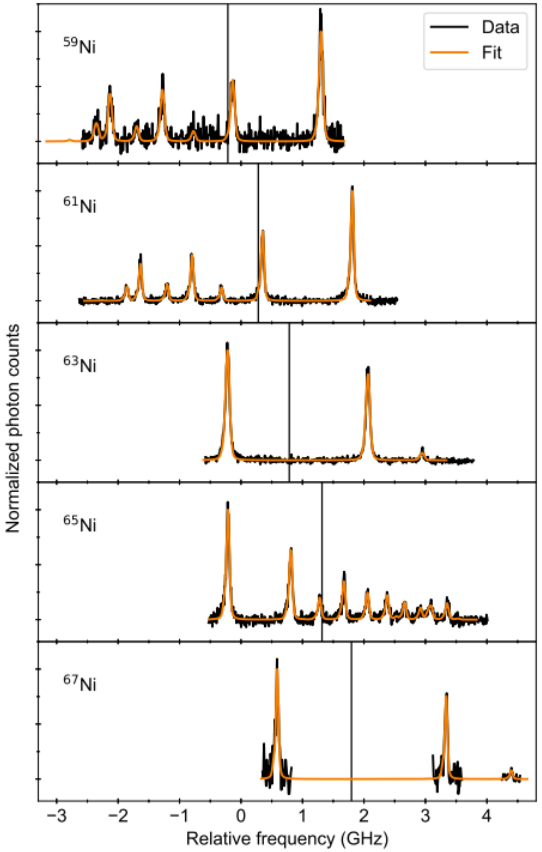
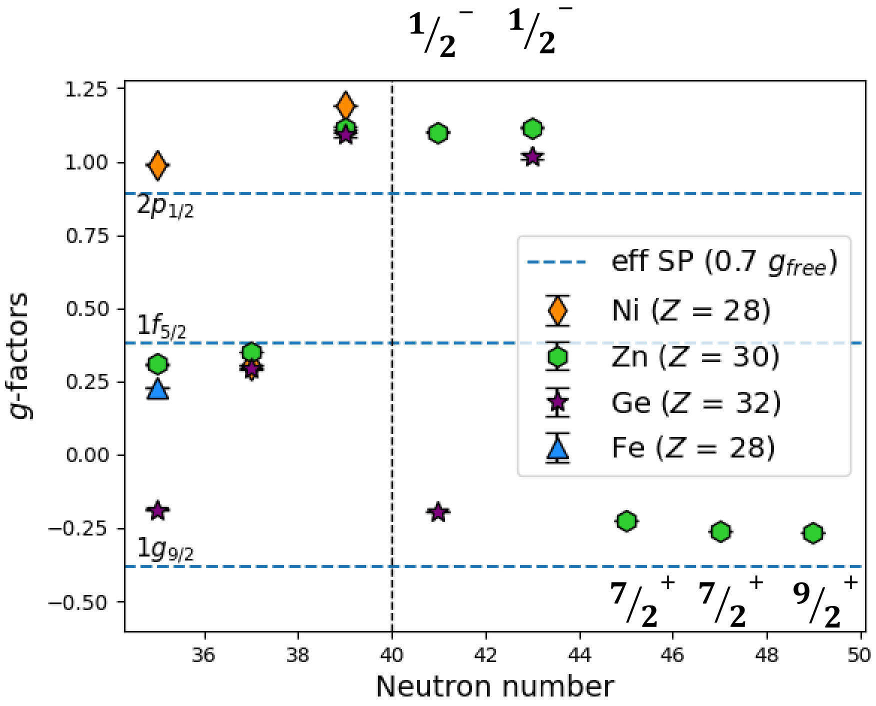
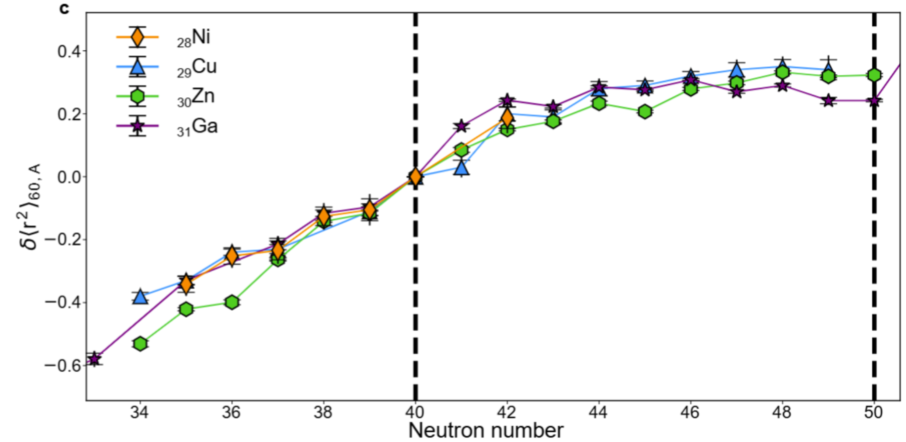
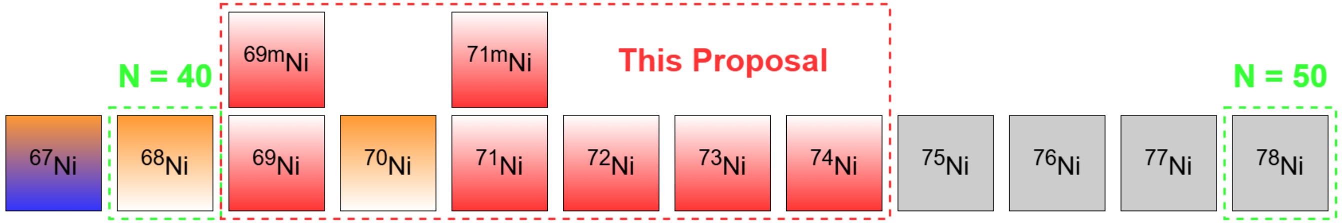


Fig from [1]

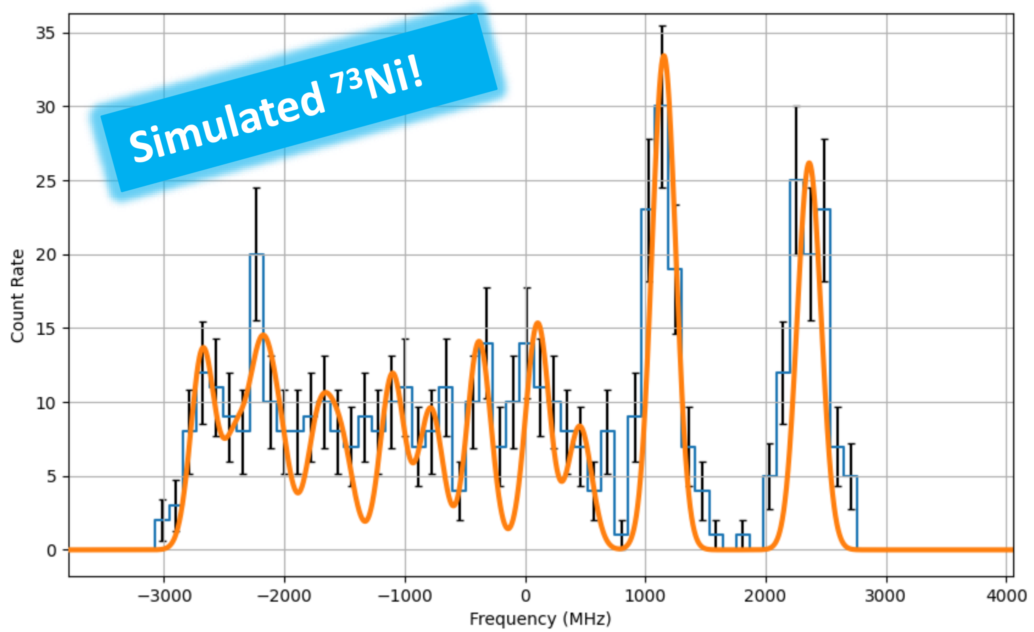






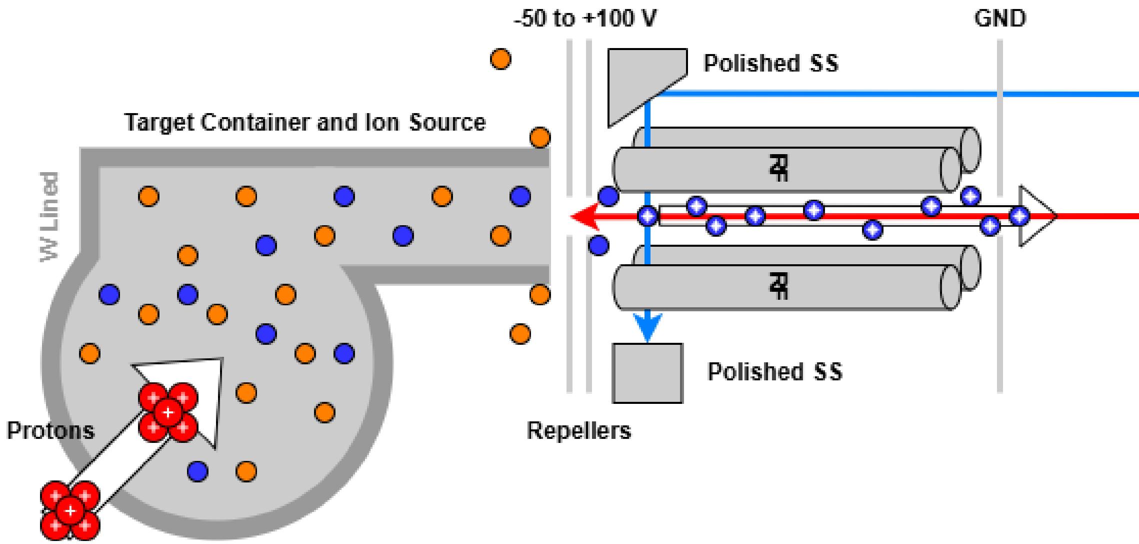
Proposal

- 24 shifts for high-resolution laser spectroscopy on $^{69-74}$Ni
- Lightest mass used online for PI-LIST
- Confirm tentative spins (I^{π}) of ^{69,71,73}Ni
- Confirm level ordering of ***I* = 9/2, 1/2** in ^{69,71}Ni with laser spectroscopy
- Benchmark PI-LIST against lit. values for ^{70}Ni
- Extend $\boldsymbol{\delta\langle r^2\rangle^{A,A'}}$ up to *N* = 46
- Extend $\boldsymbol{\mu}$ and $\boldsymbol{Q_s}$ up to *N* = 45
- Simultaneous decay data on ^{74}Ni at IDS
- Reaffirm mass measurements of ^{74}Ni at ISOLTRAP

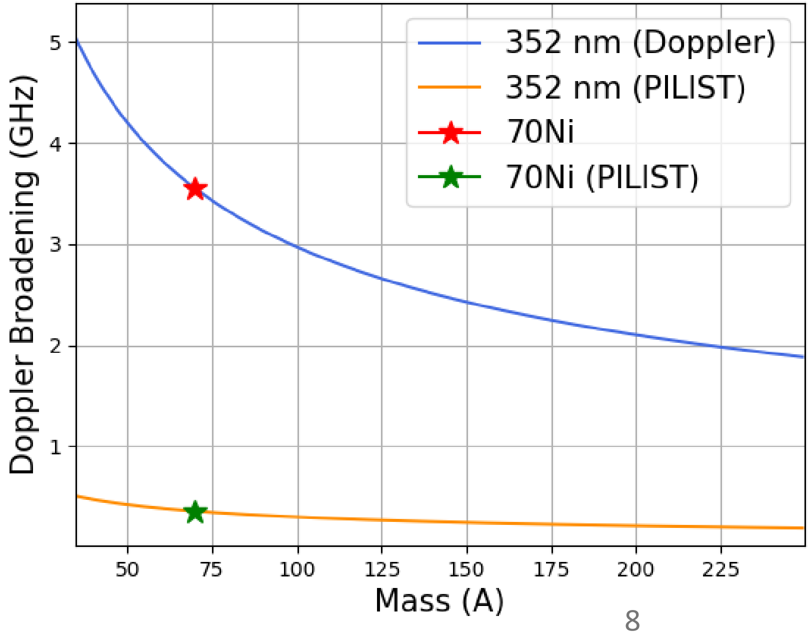


Isotope	$t_{1/2}$	Yields (ions/μC)	Shifts	New Measurements
^{66}Ni	54.6 hr	1×10^6 / 3×10^5	3	Ref. Measurement
^{69}Ni/^{69m}Ni*	11.4 s / 3.5 s	2×10^2 / 7×10^1 2×10^1 / 7*	2	$I, \delta\langle r^2\rangle^{A,A'} \mu, Q_s$
^{70}Ni	6.0 s	1×10^2 /3×10^1	1	Ref. Measurement
^{71}Ni/^{71m}Ni**	2.6 s / 2.3 s	4×10^1 /1×10^1 4 / 1**	4	$I, \delta\langle r^2\rangle^{A,A'} \mu, Q_s$
^{72}Ni	1.8 s	1×10^1 / 3	2	$\delta\langle r^2\rangle^{A,A'}$
^{73}Ni	0.8 s	0.5 / 0.1	6	$I, \delta\langle r^2\rangle^{A,A'} \mu, Q_s$
^{74}Ni	0.5 s	0.1	4	$\delta\langle r^2\rangle^{A,A'}$
Tuning/Optimization			2	
Total			**24**	

Technical Details: PI-LIST



- 10^4:1 ratio of ^{70}Ga:^{70}Ni, major obstacle in the past
- LIST → **x10^6** surface ion suppression, sacrifice **x10^2** ion of interest
- New 10-kHz fast-switching beam gates allow for laser-ion time-of-flight gating and further suppression
- **<u>TAC confirmed this is a well-established beam</u>**



Tab from [1]

Operation mode	Mode loss factor	Combined loss factor	Est. total efficiency (%)
Standard RILIS			10
LIST ion guide	3	3	3.3
LIST high purity	33	100	0.1
PI-LIST	2	200	0.05
PI-LIST opt.	10	2000	0.005

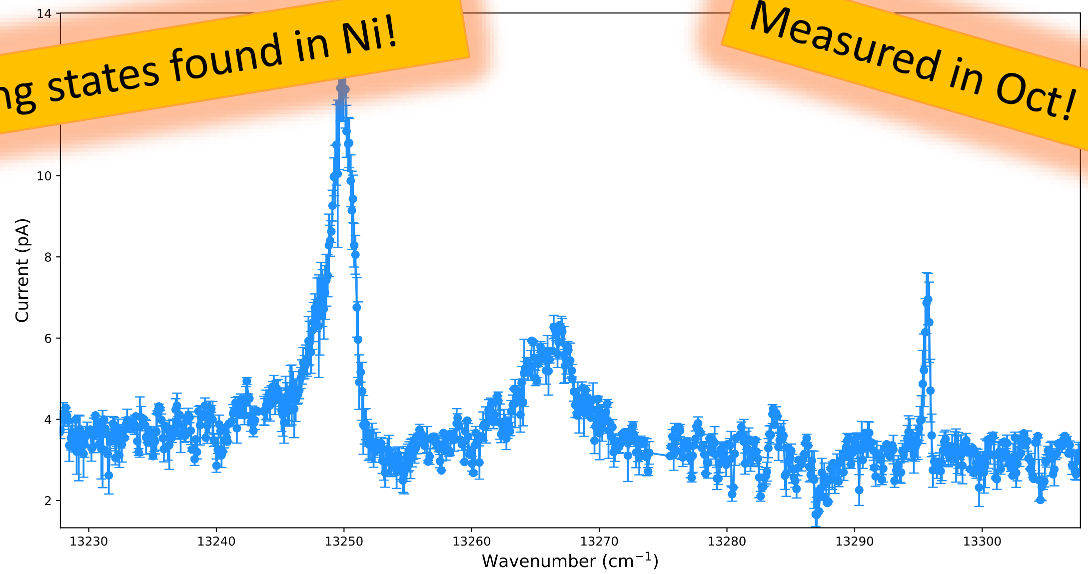
[1] R. Heinke et al., high-resolution in-source laser spectroscopy in perpendicular geometry: Development and application of the pi-list. Hyperfine Interactions, 238, 12 2016.

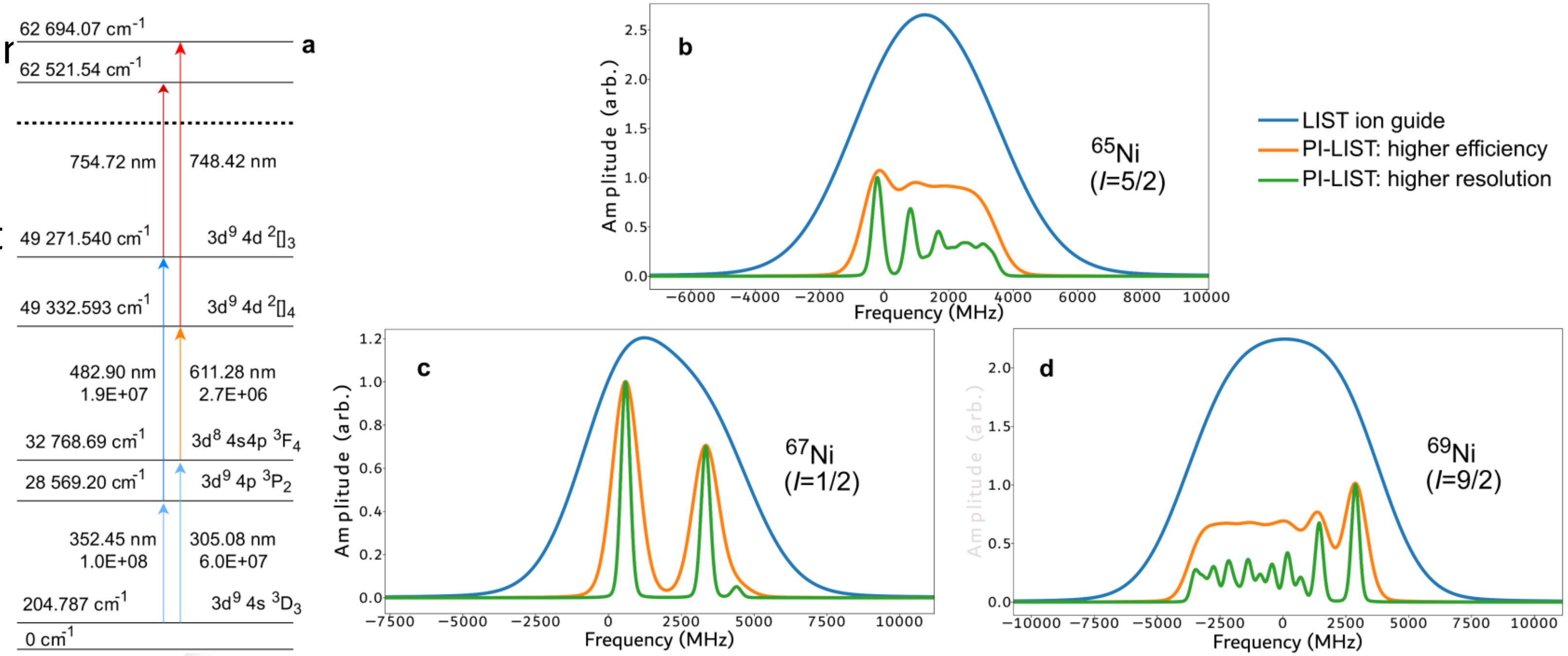
Technical Details: Laser Ionization Scheme

- Even-*A* isotopes can be converted back to **"higher production"** mode or even **Ion guide collinear LIST** mode
- This comes with a sacrifice in resolution
- Spectroscopy transition with known HFS parameters
- New laser ionization scheme is at least as efficient as the production scheme
- 1st step used previously in laser spectroscopy at ISOLDE

New autoionizing states found in Ni!

Measured in Oct!



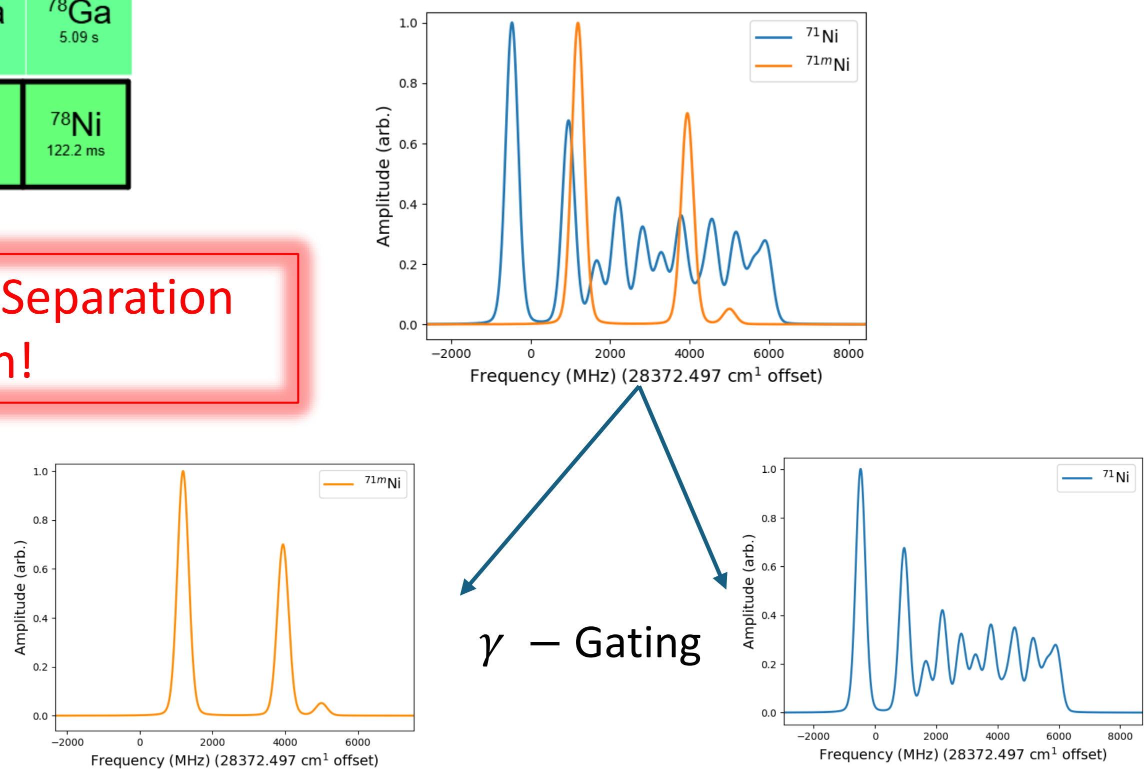


Gallium Z=31	^{66}Ga 9.304 h	^{67}Ga 78.2808 h	^{68}Ga 67.842 m	^{69}Ga Stable	^{70}Ga 21.14 m	^{71}Ga Stable	^{72}Ga 14.025 h	^{73}Ga 4.86 h	^{74}Ga 8.12 m	^{75}Ga 126 s	^{76}Ga 30.6 s	^{77}Ga 13.2 s	^{78}Ga 5.09 s
Nickel Z=28	^{66}Ni 54.6 h	^{67}Ni 21 s	^{68}Ni 29 s	^{69}Ni 11.4 s	^{70}Ni 6 s	^{71}Ni 2.56 s	^{72}Ni 1.57 s	^{73}Ni 840 ms	^{74}Ni 507.7 ms	^{75}Ni 331.6 ms	^{76}Ni 234.6 ms	^{77}Ni 158.9 ms	^{78}Ni 122.2 ms

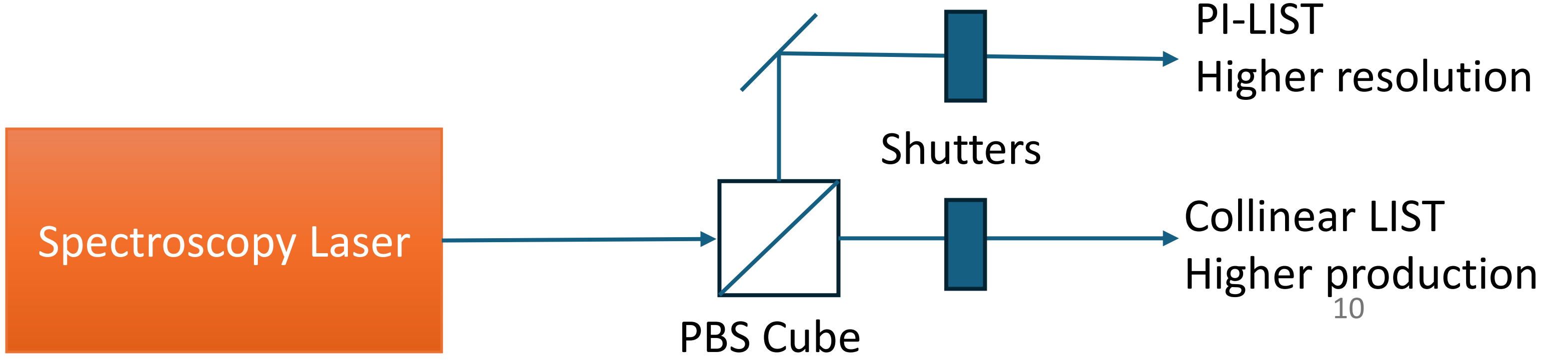
Technical Details: IDS and ISOLTRAP

- IDS: main element of detection
- $t_{1/2}$ **(Ga) >>** $t_{1/2}$ **(Ni)**, mostly filtered by tape movement
- Decay data on $^{69m, 71m}$Ni is sparse
- No decay data available for $A \geq {}^{74}$Ni
- Mass measurements of ^{74,75}Ni @ IGISOL (2022) – Reaffirm values
- Ion detection with ISOLTRAP MR-ToF
- Revert to high-production collinear LIST for decay or mass measurements
- Well-established method due to strong RILIS + IDS + ISOLTRAP technique!

Isomer & G.S. Separation in a single scan!



Instant Switching between **high production** and **high resolution!**



Conclusion

- The Z = 28, N = 40-50 region is rich with nuclear structure
- High-resolution laser spectroscopy performed with PI-LIST + IDS
- LIST is the ideal candidate to overcome the overwhelming Ga contamination
- New measurements on $\boldsymbol{\mu}$, $\boldsymbol{Q_s}$, $\boldsymbol{\delta\langle r^2\rangle^{A,A'}}$ and $\boldsymbol{I}$ on **$^{69,71\text{-}74}$Ni** and **^{69m,71m}Ni**.
- Measurement that will help clarify the evolution of nuclear structure leading to ^{78}Ni
- Free additional decay spectroscopy data on ^{74}Ni
- Instant switching between higher-resolution and higher-efficiency
- Lightest online medium mass measurements using PI-LIST, opening doors for other medium-mass elements

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Thank you!

Questions?

J. R. Reilly[1], M. Athanasakis-Kaklamanakis[2], M. Araszkiewicz[3], K. Chrysalidis[1],A. Ajayakumar[1], A. N. Andreyev[4], M. Au[1], C. Bernerd[1], J. G. Cubiss[4,5], L. M. Fraile[6], M. J. G. Borge[7], P. Garczynski[3], G. Georgiev[8], P. F. Giesel[9], R. de Groote[10],R. Grzywacz[11], R. Heinke[12,1], M. Karny[3], A. Koszorus[10], R. Kuczma[3], L. Lalanne[13], D. Lange[14], K. M. Lynch[12], D. McElroy[12], M. M lynarczyk[3], L. Nies[1], F. Nowacki[13],B. Olaizola[7], S. Rothe[1], C. Schweiger[14], A. I. Sison[6], K. Solak[3], K. Stoychev[15],R. Taniuchi[4], B. van den Borne[10], P. Wakuluk[3], J. Warbinek[16], J. Wessolek[1,12], J. Wilson[4], S. Zajda[3]

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Conclusion

- The Z = 28, N = 40-50 region is rich with nuclear structure
- High-resolution laser spectroscopy performed with PI-LIST + IDS
- LIST is the ideal candidate to overcome the overwhelming Ga contamination
- New measurements on $\boldsymbol{\mu}, \boldsymbol{Q_s}, \boldsymbol{\delta\langle r^2\rangle^{A,A'}}$ and $\boldsymbol{I}$ on **$^{69,71\text{-}74}$Ni** and **^{69m,71m}Ni**.
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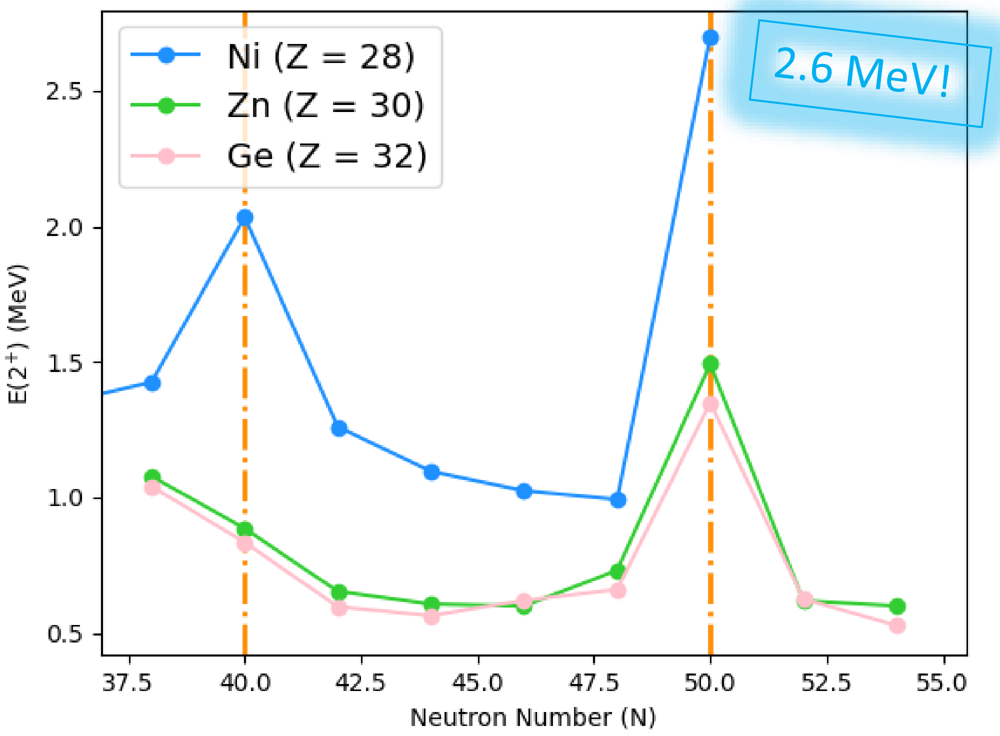
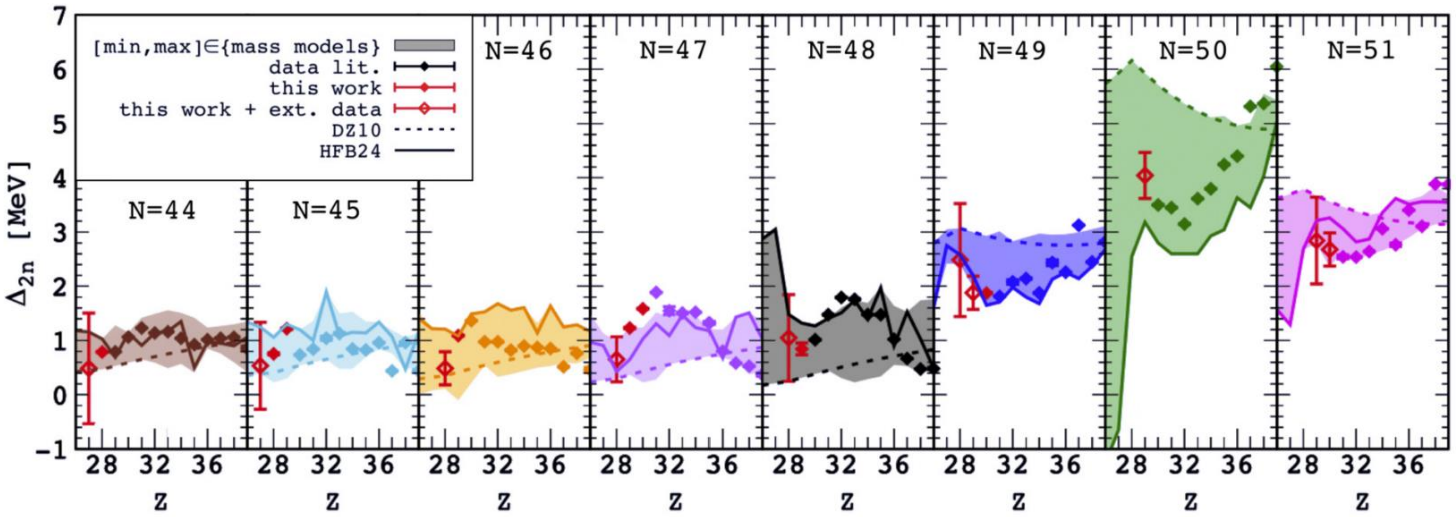


[1] S. Giraud Mass measurements towards doubly magic 78ni: Hydrodynamics versus nuclear mass contribution in core-collapse supernovae. Physics Letters B, 833:137309, 07 2022.



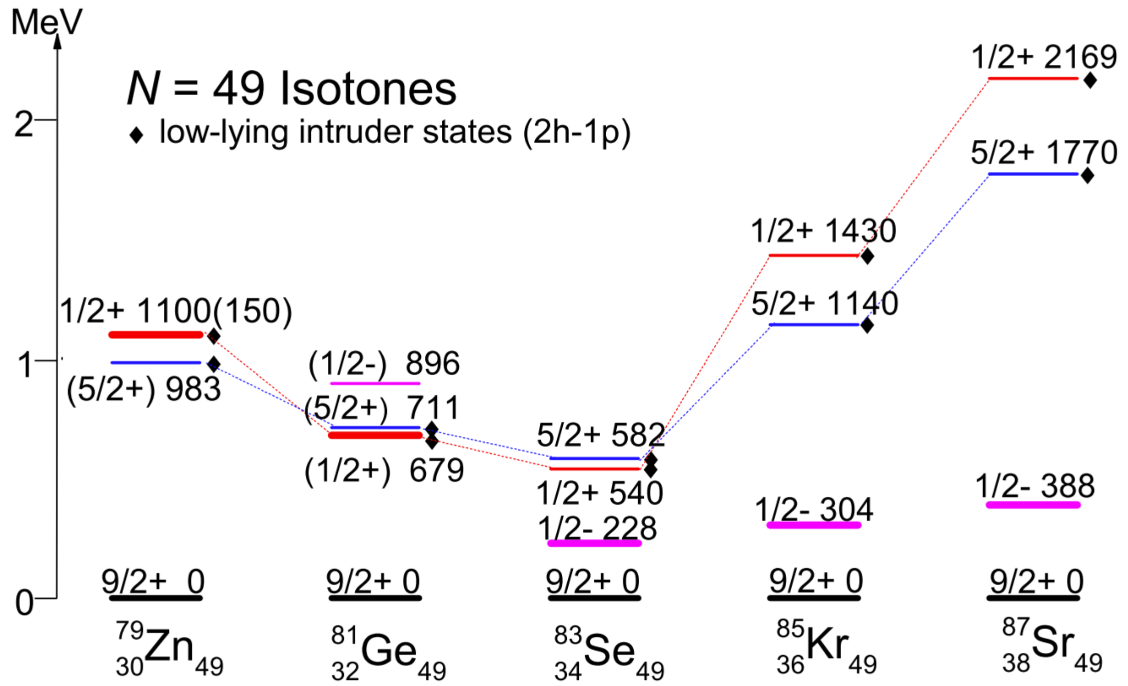
Back-up: Doubly magic ^{78}Ni

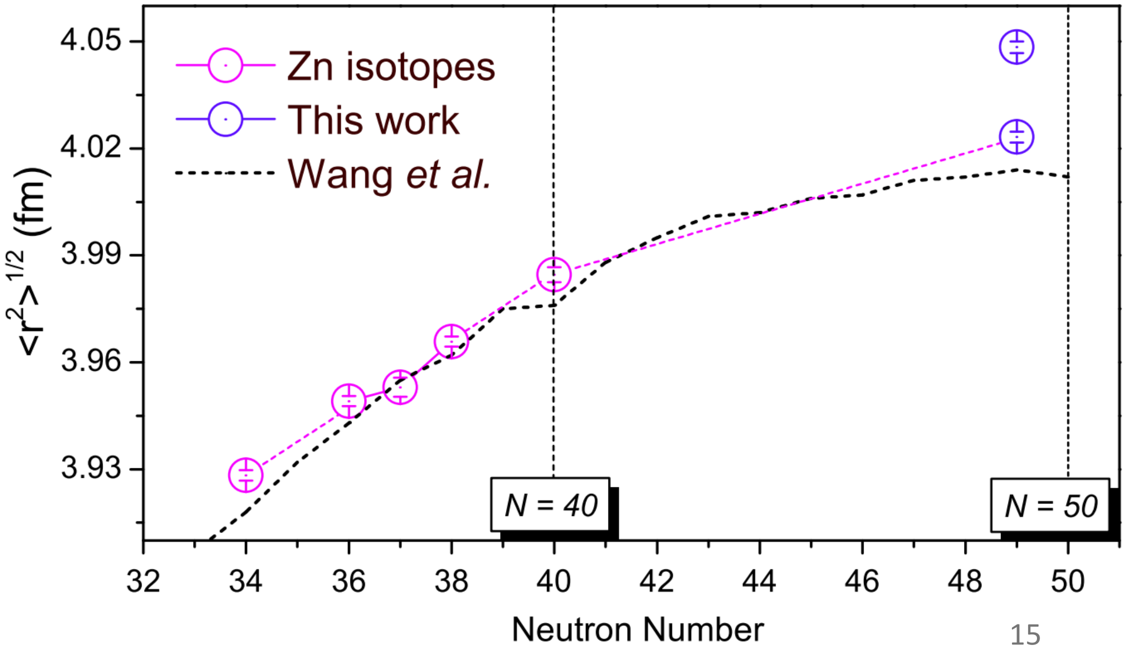
- E(2$^+$) values indicate strong shell closures at *N* = 40, 50
- Reinforced by Δ_{2n}, increasing trend towards *N* = 50 for *Z* = 28-38 [1]
- A kink in $t_{1/2}$ is also observed at ^{78}Ni: 122.2(51) ms
- Consistent with double magicity at *Z* = 28, *N* = 50
- Measurements of $\delta\langle r^2\rangle^{A,A'}$, μ and Q_s allow the study of the evolution of the single-particle nature between *N* = 40-50

Back-up: Shape Coexistence near ^{78}Ni

- Isomeric states in **^{79}Zn** [1] and **^{80}Ge** [2] question the doubly magic nature of **^{78}Ni**
- N = 50 weakening, minimum indicated at Z = 34
- $\nu(3s_{1/2})$ in 2p-2h excitations
- Zn: $\delta\langle r^2\rangle^{79,79m} =$ **0.204(6)** fm^2
- β_2 (^{79}Zn) = 0.15, β_2 (^{79m}Zn) = 0.22
- Prolate deformed 2$^+$ state in ^{78}Ni [3]
- Indicator of **shape coexistence** near ^{78}Ni

[1] X. F. Yang Isomer Shift andMagnetic Moment of the Long-Lived 1/2+ Isomer in 3079Zn49: Signature of ShapeCoexistence near 78Ni. Physical Review Letters, 116(18):182502, 5 2016.
[2] A. Gottardo irst Evidence of Shape Coexistence in the Ni 78 Region:Intruder 02+ State in Ge 80. Physical Review Letters, 116(18), 5 2016.
[3] R. Taniuchi et al., ^{78}Ni revealed as a doubly magic stronghold against nuclear deformation. Nature, 569(7754):53–58, 5 2019.





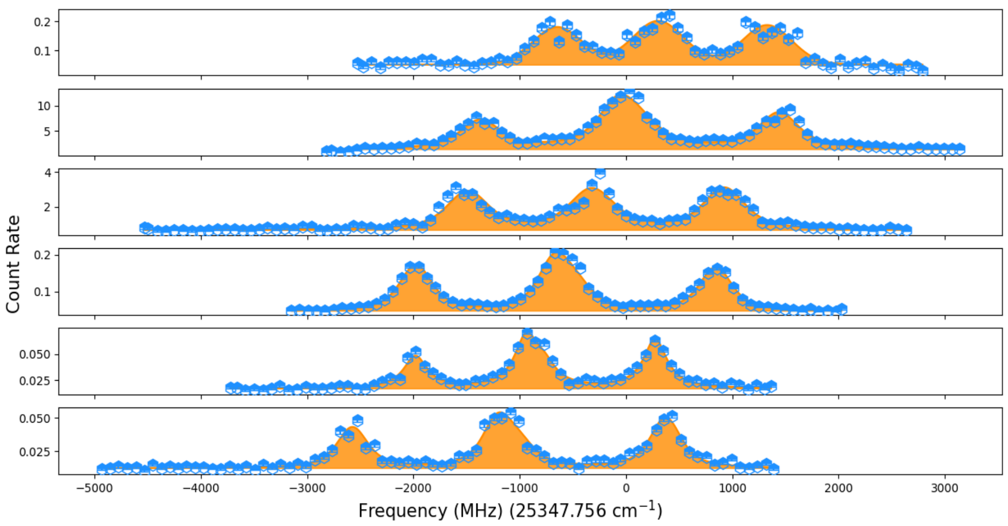
Back-up: Laser Spectroscopy

Laser spectroscopy provides access to:

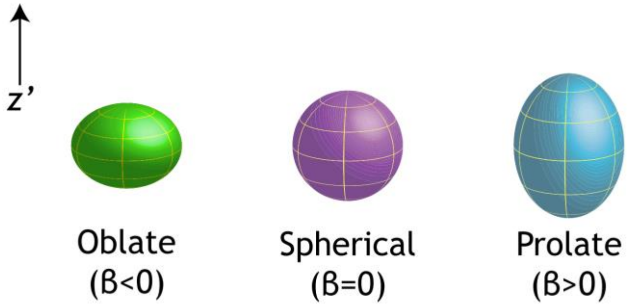
- Nuclear spin (I)
- Magnetic dipole moment (μ)
- Electric quadrupole moment (Q_s)
- Change in mean-square charge radii ($\delta\langle r^2\rangle^{A,A'}$)

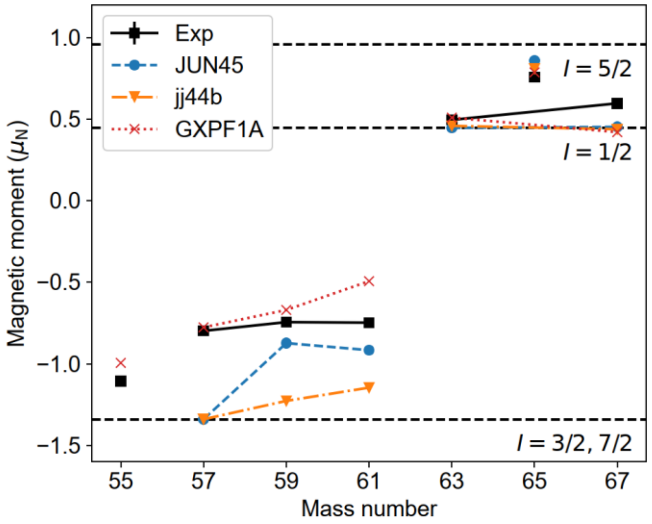
$$A_{\mathrm{HFS}} = \frac{\mu\, B_e(0)}{IJ}$$

$$B_{\mathrm{HFS}} = eQ_s \left\langle \frac{\delta^2 V_e}{\delta z^2} \right\rangle$$



$$\delta v^{A,A'} = F\delta\langle r^2\rangle^{A,A'} + \mu^{A,A'} M$$

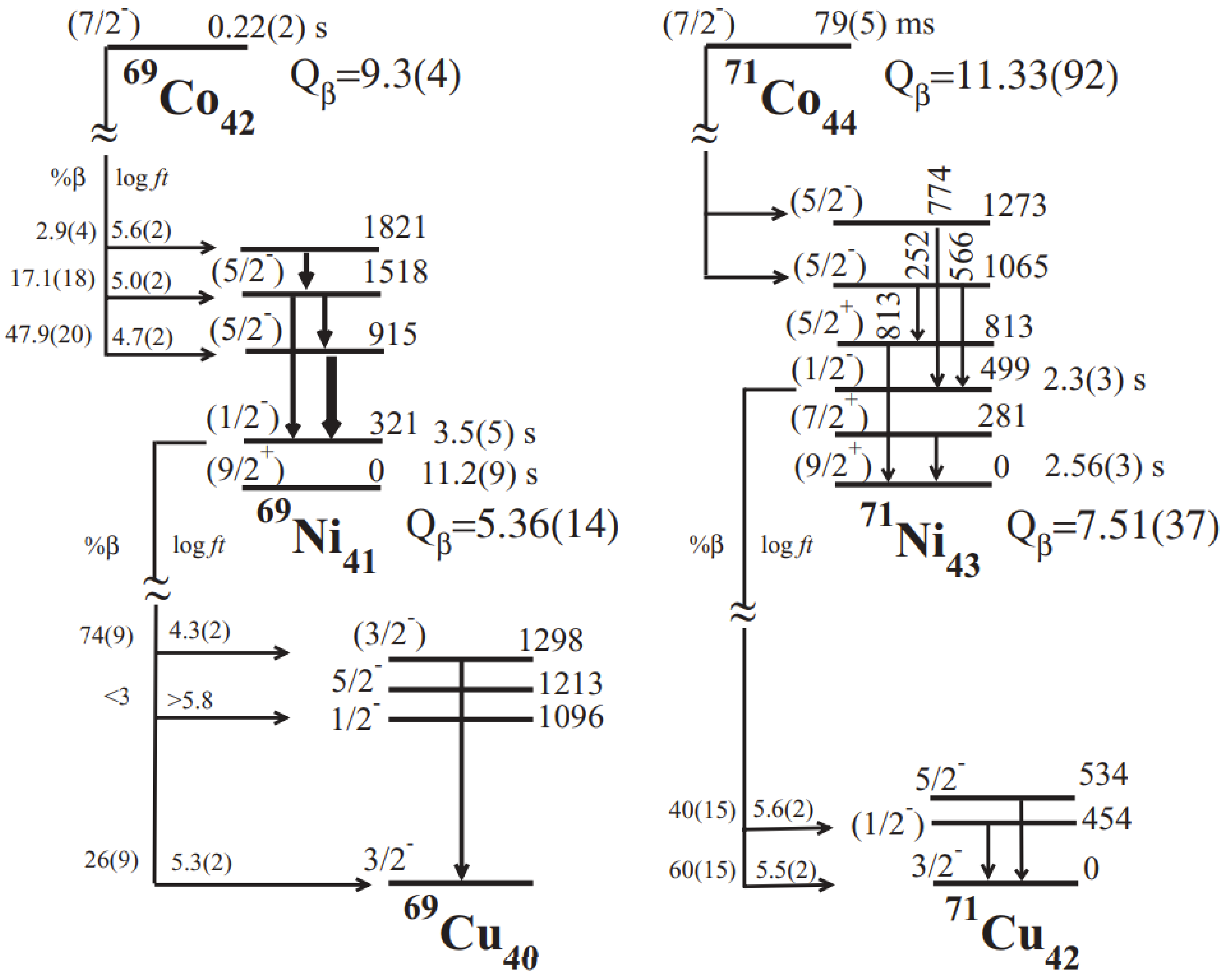




$$B_{\mathrm{HFS}} = eQ_s \left\langle \frac{\delta^2 V_e}{\delta z^2} \right\rangle$$

Back-up: ^{69m}Ni and ^{71m}Ni

- Discovery of $^{69m,\,71m}$Ni
- Decay paths in Cu populate states with varying characteristics
- 1298 keV transition in ^{69}Cu has a B(E2) value of 1.4 W.u
- 454 keV transition in ^{70}Cu has a B(E2) value of 20.4(22)
- Increasing population of the $g_{9/2}$ orbital
- $\delta\langle r^2\rangle^{A,A'}$ and μ would provide insight into the level of deformation compared to G.S. and make critical information about the configuration mixing



Back-up: $^9/_2{}^-$ and $^1/_2{}^-$ level inversion

- Occupation across the Z = 28 closure corresponds to an enhancement in the charge radii
- $I(^{71,\,73}\text{Zn}) = {}^1/_2{}^-$
- $I(^{71m}\text{Zn}) = {}^9/_2{}^-$

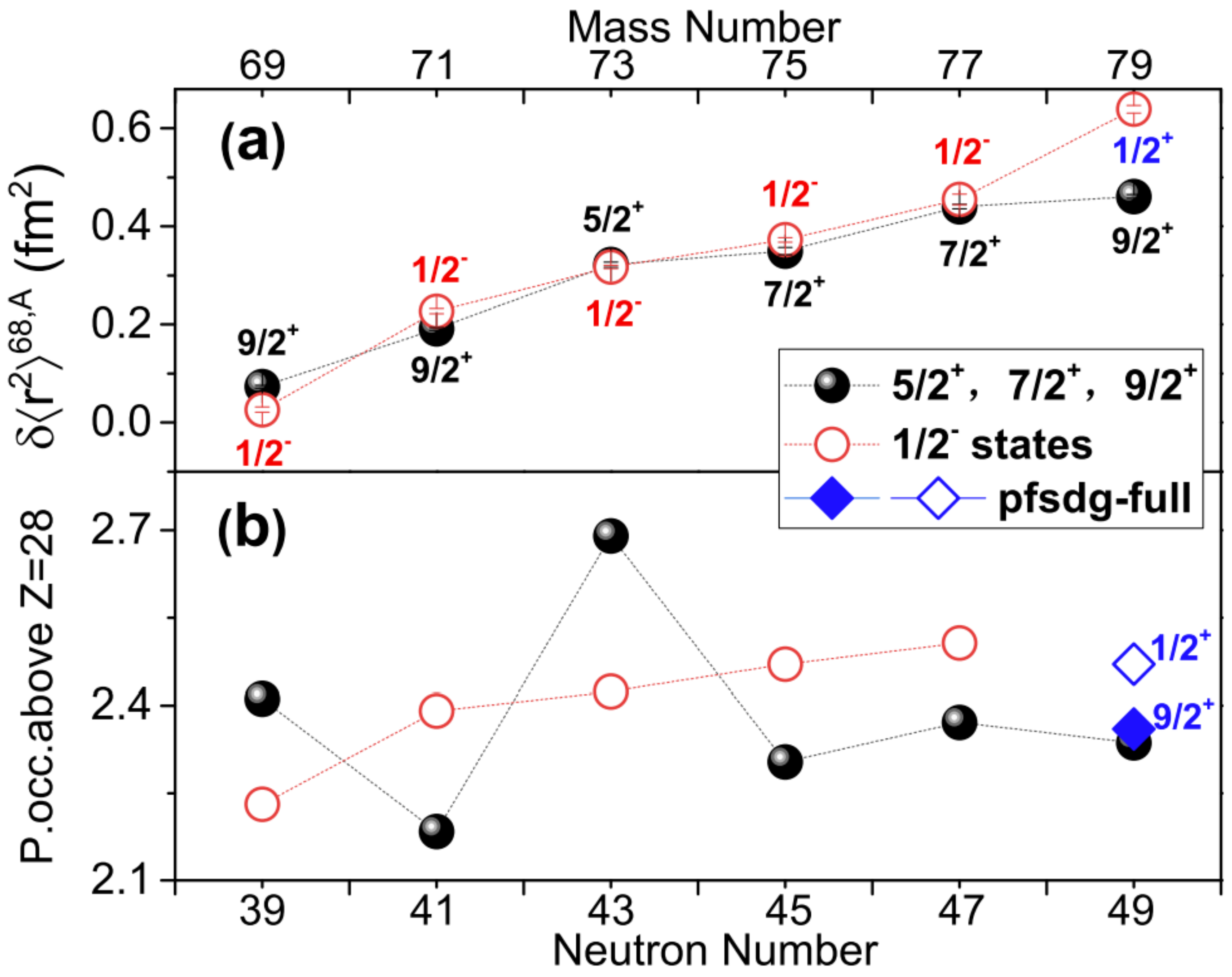
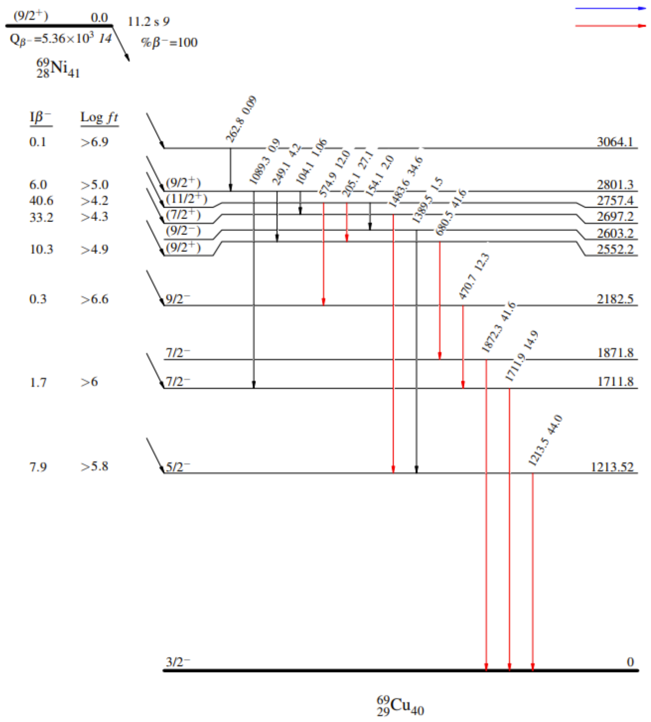


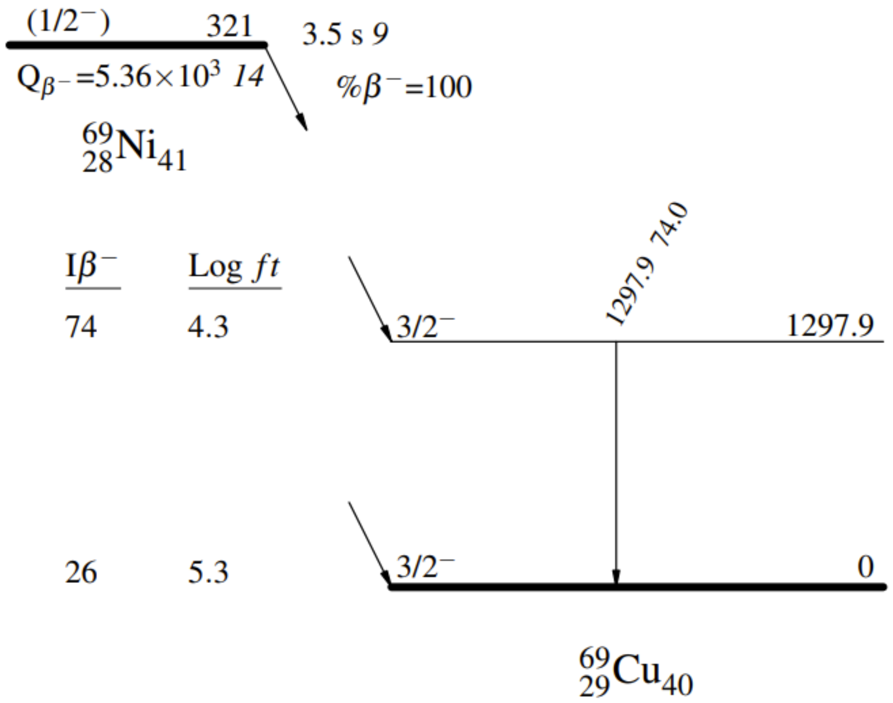
Fig from [1]

[1] L. Xie et al., Nuclear charge radii of 62-80zn and their dependence on cross-shell protonexcitations. Physics Letters B, 797:134805, 2019.

Back-up Slides

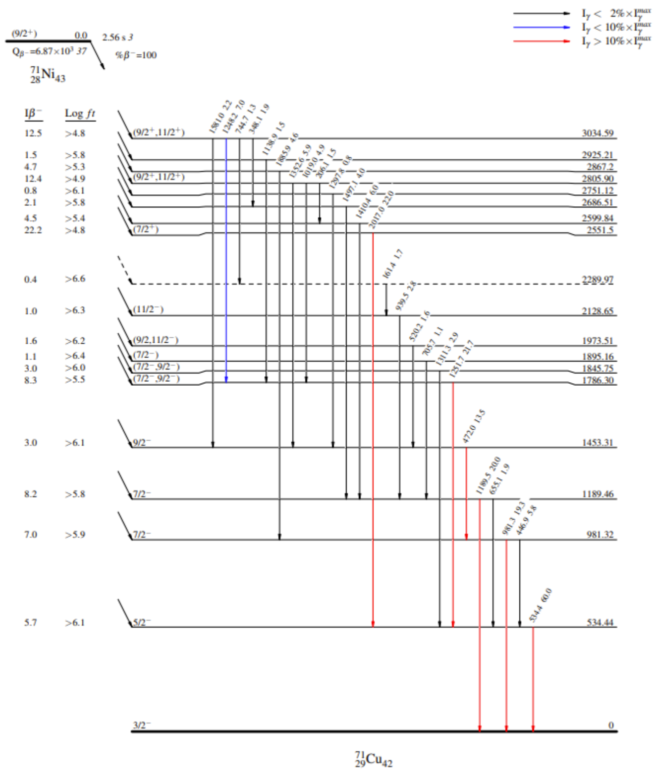
- LEFT: ^{69}Ni
- RIGHT: ^{69m}Ni

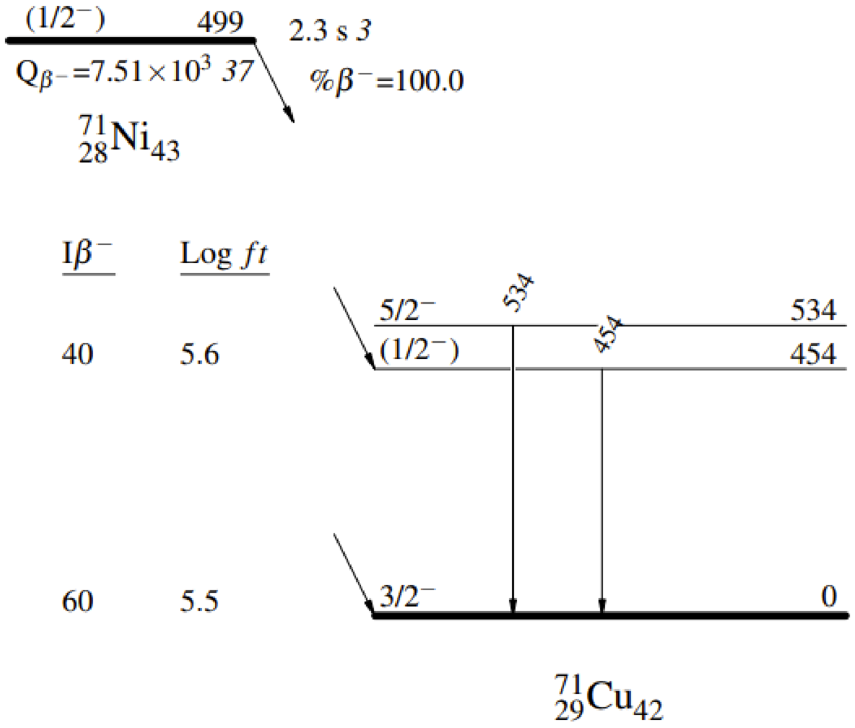




Back-up Slides

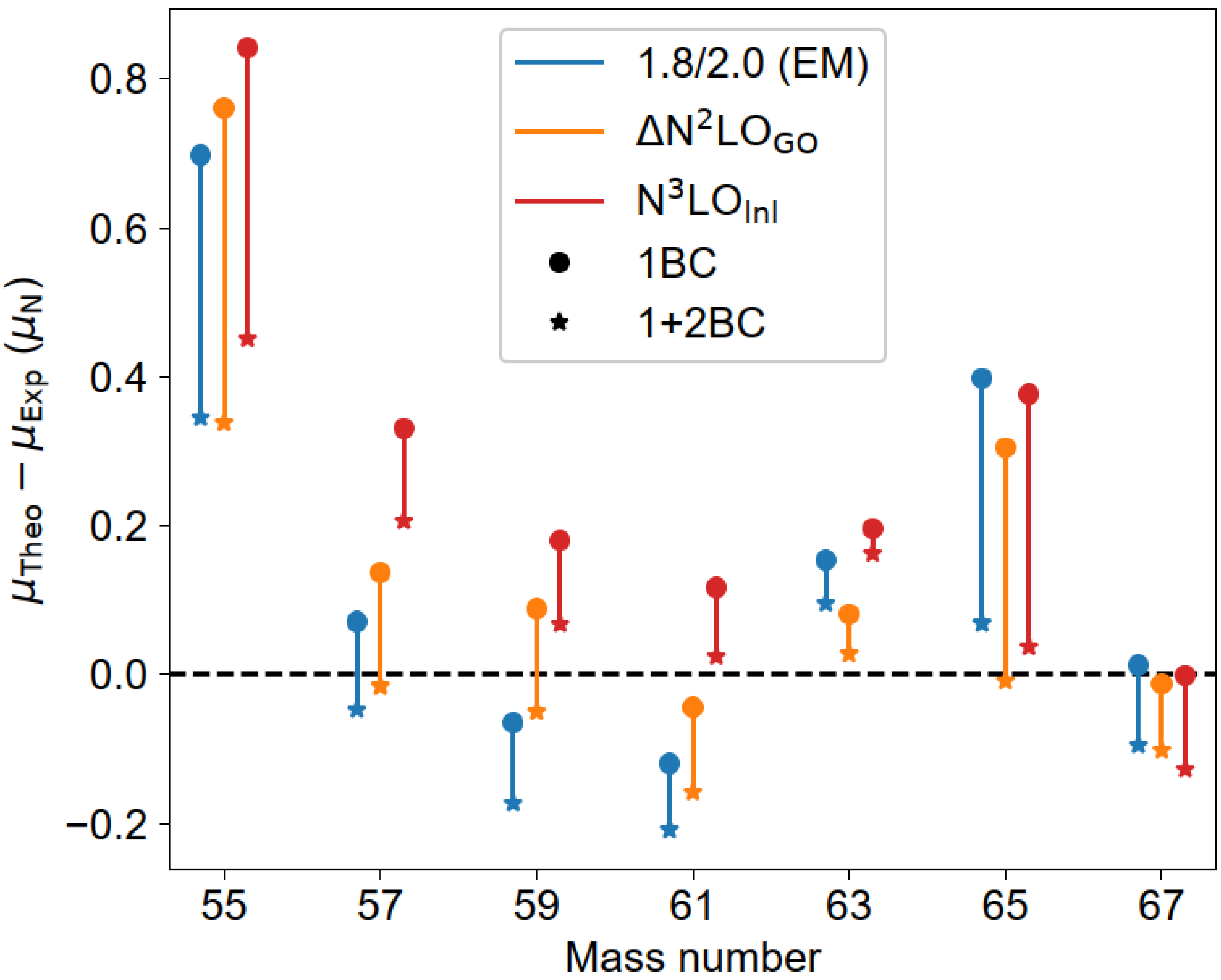
- LEFT: ^{71}Ni
- RIGHT: ^{71m}Ni





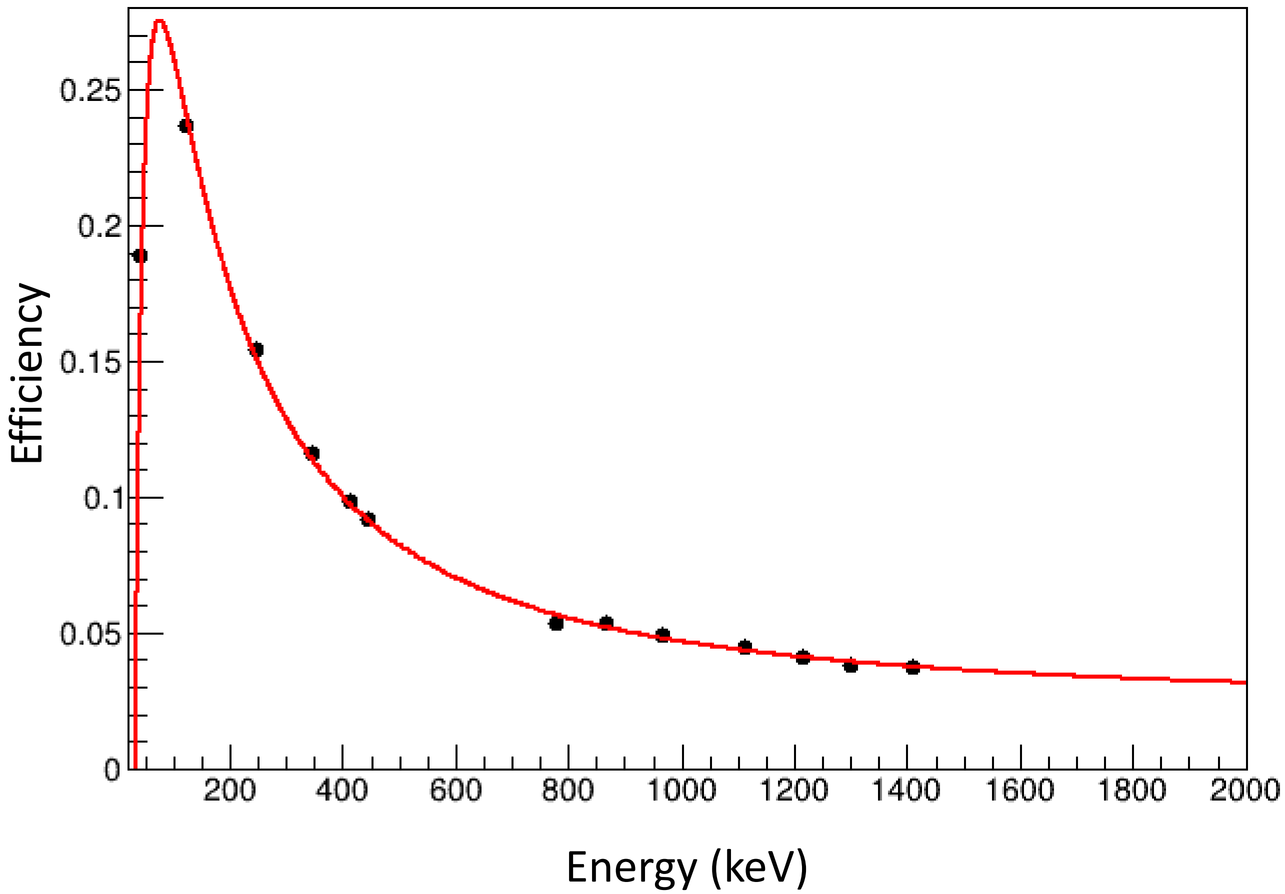
Back-up Slides

COLLAPS μ values



Back-up Slides

γ – efficiency curve from recent Hg (Oct 2024) run at IDS



Back-up Slides

Simulated Spectrum