Nuclear structure/deformation from laser spectroscopy

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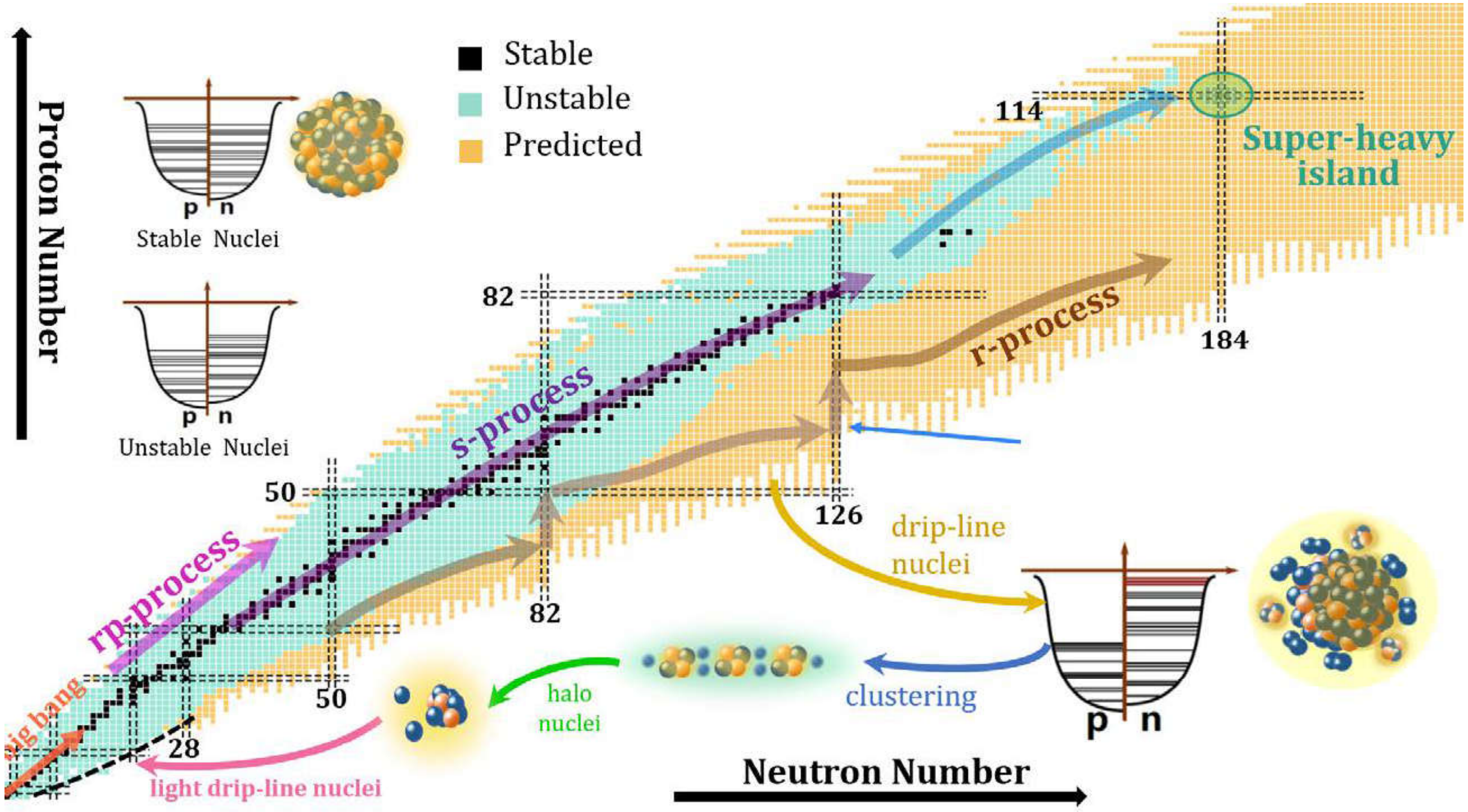
"Exploring Nuclear Physics across Energy Scales", 15-27 April 2024, Beijing, China

Outline

北京大學
PEKING UNIVERSITY

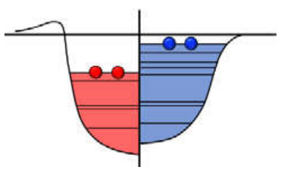
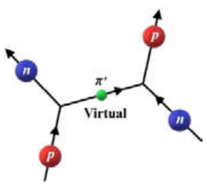
- Nuclear structure and g.s. properties
- Hyperfine interaction and laser spectroscopy
- Nuclear structure studied from laser spectroscopy
- Laser spectroscopy development and near future work

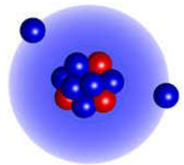
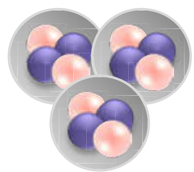
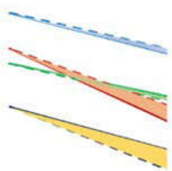
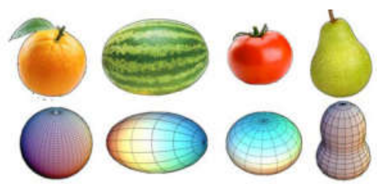
Nuclear structure of exotic nuclei

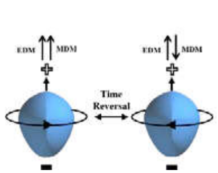


- ☐ Exotic structure
- ☐ Nuclear astrophysics
- ☐ Superheavy element
- ☐ Fundamental symmetry
- ☐ Applications

- ➢ **Radioactive ion beam**
- ➢ **Experimental probing**
- ➢ **Theoretical development**



Nuclear structure of exotic nuclei

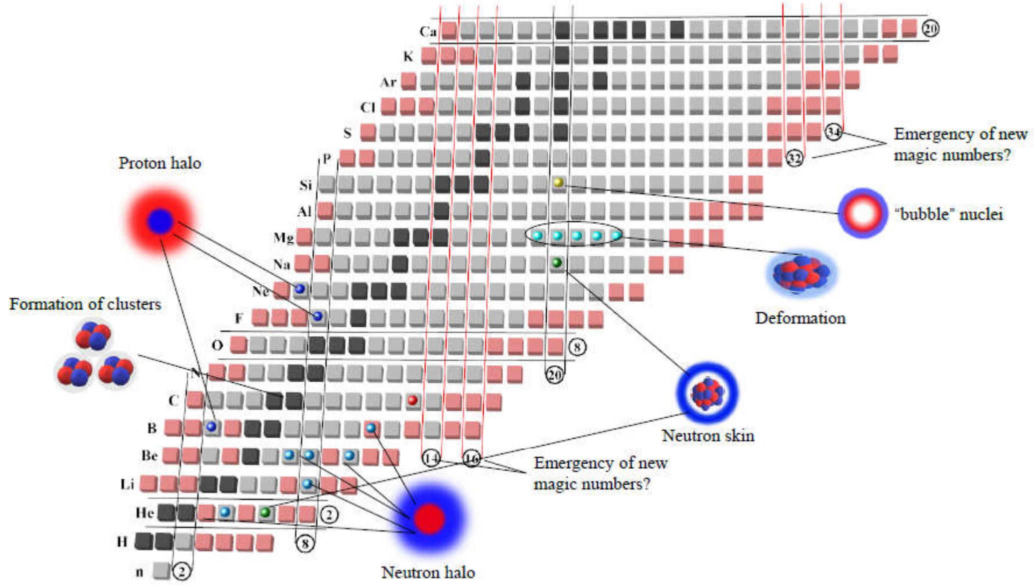
K. Heyde, Basic ideas and concepts in nuclear physics

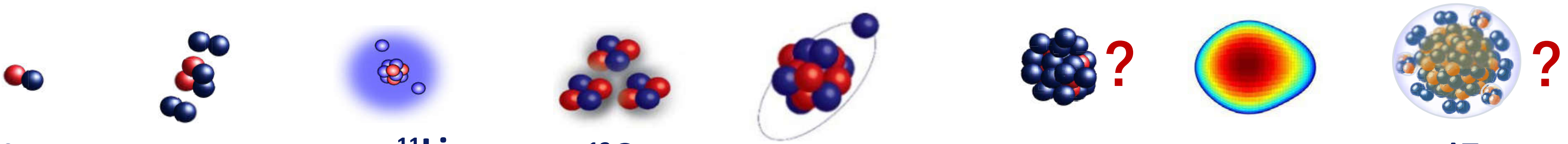
$$S \sim -\lambda - \Delta$$

λ: Mean Field
Δ: Correlations

Y.L. Ye et al., Sci Sin-Phys Mech Astron, 50(2022)112003

- ☐ Strong coupling in the low density
- ☐ M-DOF structure
- ☐ New effective interactions
- ☐ Correlated reaction and decay



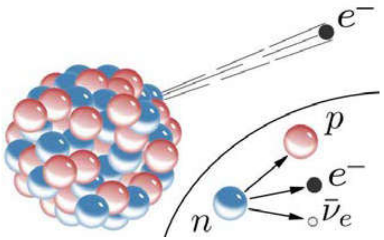


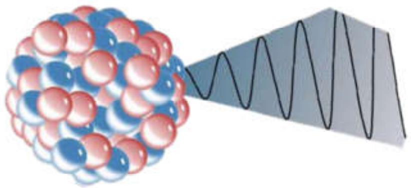
^{2}H	^{8}He	^{11}Li	^{12}C	^{23}O	^{60}Ca	^{225}Ra	^{A}Z
Z=1, N=1 stable	Z=2, N=6 $T_{1/2}$=119.1 ms	Z=3, N=8 $T_{1/2}$=8.75 ms	Z=6, N=6 *stable*	Z=8, N=15 $T_{1/2}$=97 ms	Z=20, N=40 $T_{1/2}$=?	Z=88, N=137 $T_{1/2}$=14.9 d	Dripline nuclei in medium/heavy mass region

Nuclear structure of exotic nuclei (Experimental approaches)

Nuclear decay

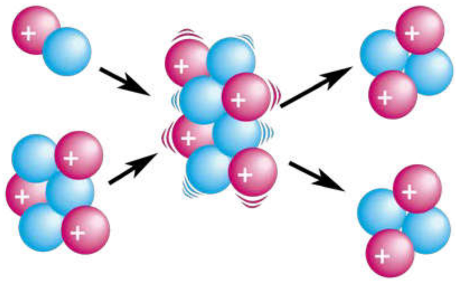
- α, β, γ, SF
- p-emitter
- n-emitter
- ....

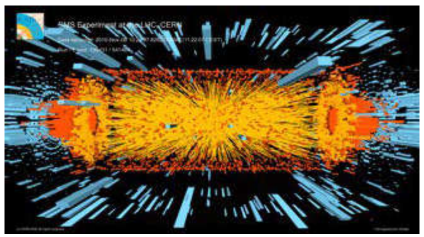




Nuclear reaction

- Direction reaction
- Fusion reaction
- MNT reaction
- ......

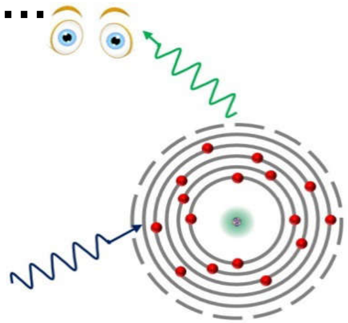


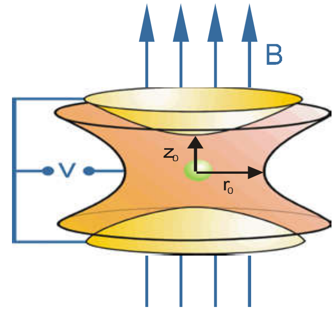


+Heavy ion collision

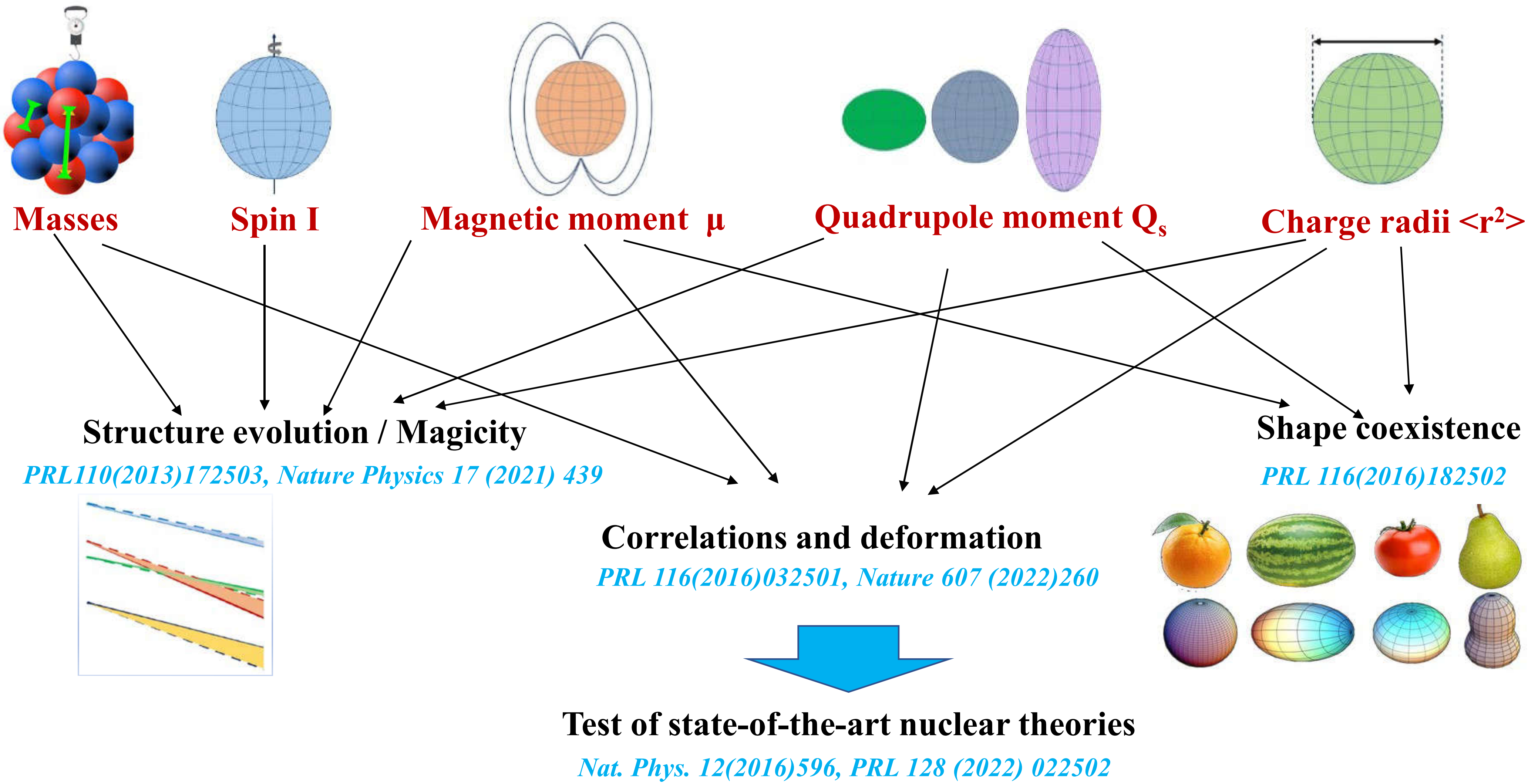
g.s. properties

- Ion trap/storage ring
- Laser spectroscopy
- β NMR/NQR
- ......





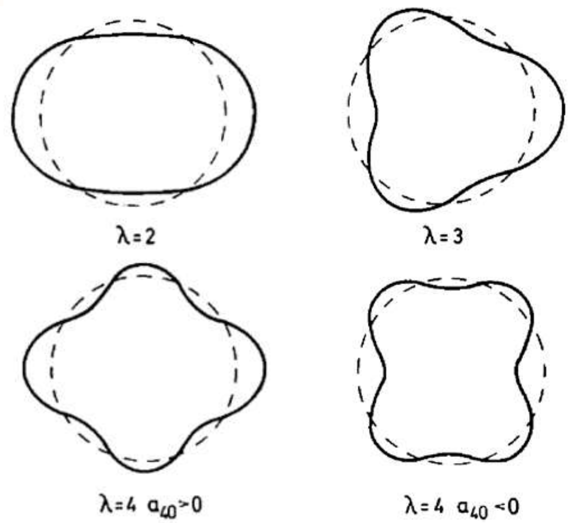
Ground state (g.s.) properties – Nuclear structure



Ground state (g.s.) properties – Nuclear shapes

- general description of a shape:

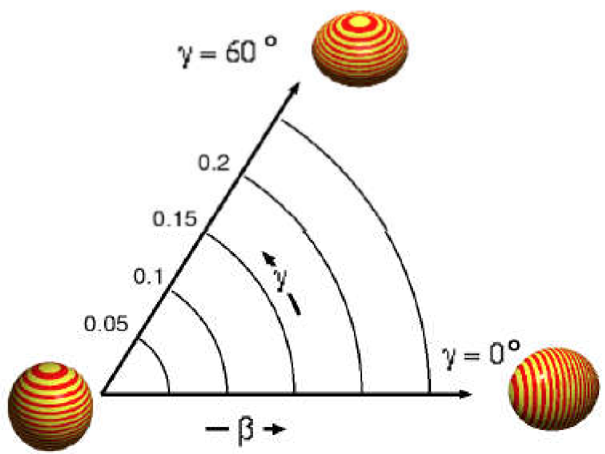
$$R(\theta,\phi) = R_0\left[1+\sum_{\lambda=0}^{\infty}\sum_{\mu=-\lambda}^{\lambda} a_{\lambda,\mu} Y_{\lambda\mu}(\theta,\phi)\right]$$



- important nuclear shapes:
  - $a_{2,\mu}$ quadrupole deformation (triaxial ellipsoid)
  - $a_{3,\mu}$ octupole deformation (pear shape)
- in the principal axes frame $a_{2,1} = a_{2,-1} = 0$ and only two parameters are enough to describe all possible quadrupole shapes:

$$a_{2,0} = \beta\cos\gamma$$
$$a_{2,2} = a_{2,-2} = \frac{\beta\sin\gamma}{\sqrt{2}}$$

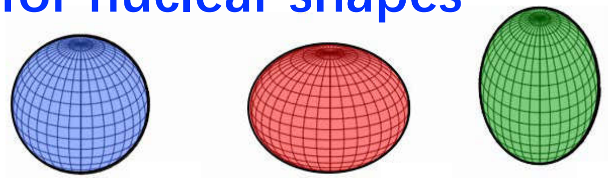
--from the talk of magdalena zielinska @Wednesday



Ground state (g.s.) properties – Nuclear shapes

- Experimental observables for nuclear shapes

❑ **Quadrupole moment Q_s**



$Q_{intr.} = 0$ $Q_{intr.} < 0$ $Q_{intr.} > 0$

$$Q_s = \frac{3K^2 - I(I+1)}{(2I+3)(I+1)} Q_{\text{intr.}} \Rightarrow Q_{\text{intr.}} = \frac{3}{\sqrt{5\pi}} Z R_0^2 \beta_2 (1 + 0.36 \boxed{\beta_2})$$

❑ **Nuclear charge radii $R = \sqrt{\langle r^2 \rangle}$**

$$\langle r^2 \rangle = \langle r^2 \rangle_0 \left(1 + \frac{5}{4\pi} \boxed{\langle \beta_2^2 \rangle}\right)$$

❑ **Transition probability for E2**

$$B(E2; 0^+ \rightarrow 2^+) = ((3/4\pi) e Z R_0^2)^2 \boxed{\beta_2{}^2}$$

$$\boxed{\langle \beta_2^2 \rangle = \langle \beta_2 \rangle^2 + \left(\langle \beta_2^2 \rangle - \langle \beta_2 \rangle^2\right) = \beta_{\text{static}}^2 + \beta_{\text{dynamic}}^2 .}$$

Laser spectroscopy

This talk

Coulomb-excitation exp.

γ spectroscopy

Talk of magdalena zielinska

J. Phys. G: Nucl. Part. Phys. 37 (2010) 113101

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- ☐ Nuclear structure and g.s. properties
- ☐ Hyperfine interaction and laser spectroscopy
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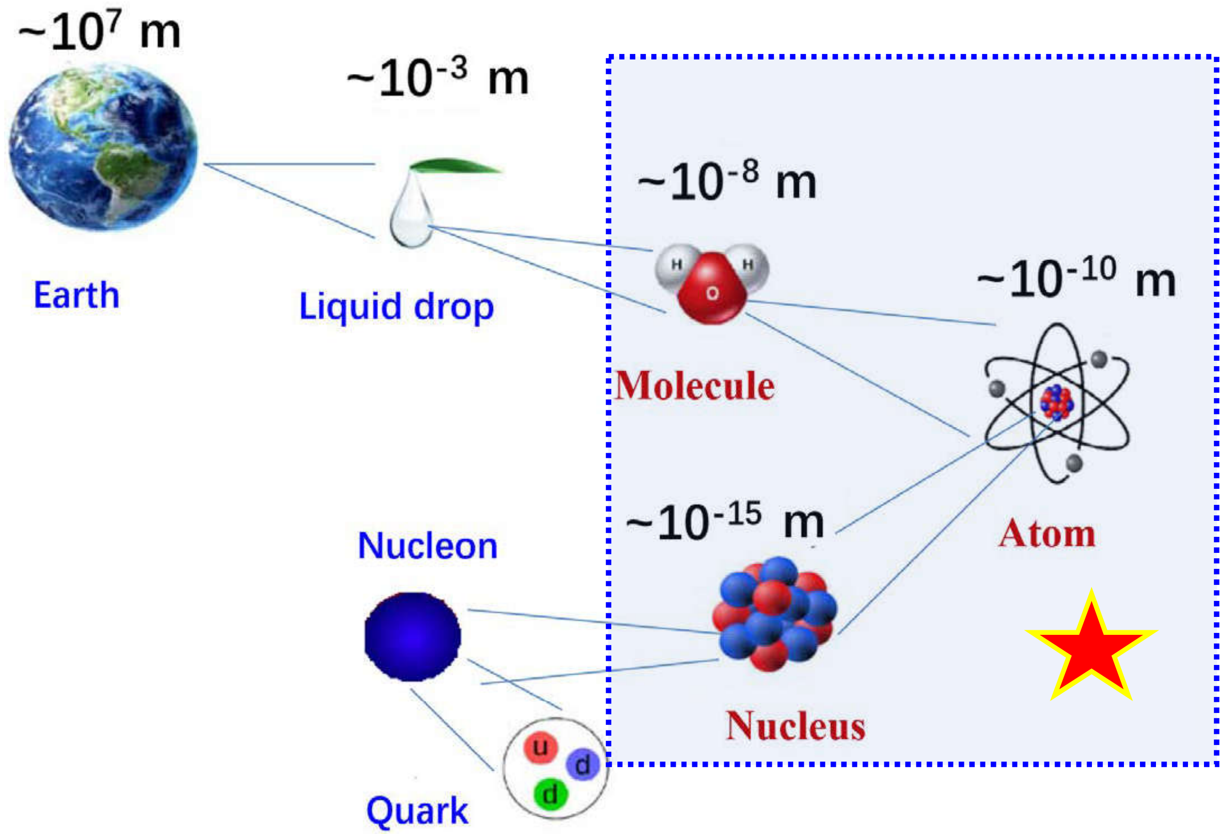
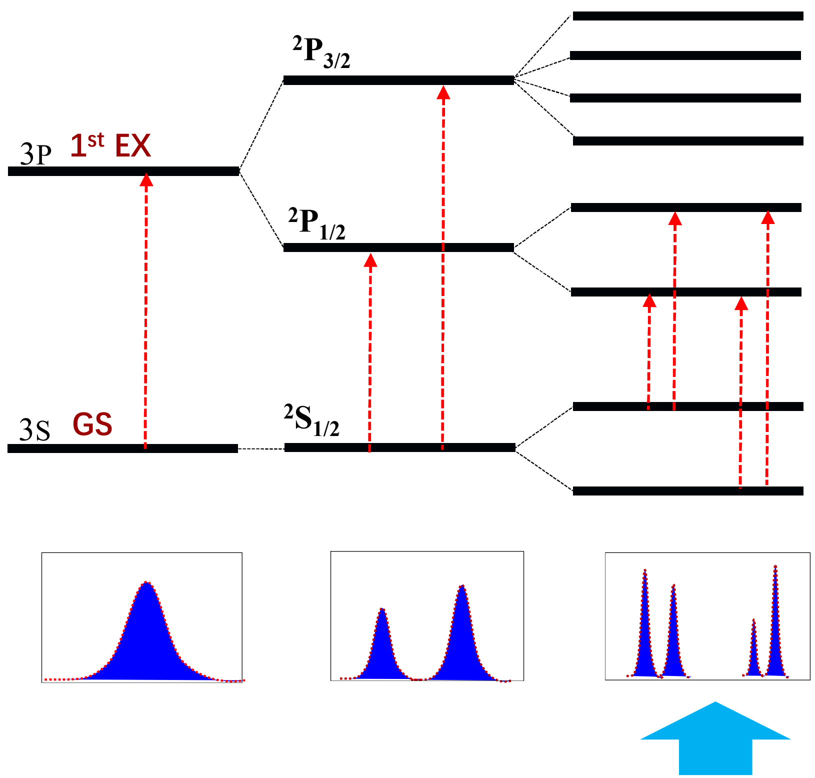
Hyperfine interaction and laser spectroscopy

Hyperfine interaction: EM interaction between atomic nucleus and the surrounding electrons



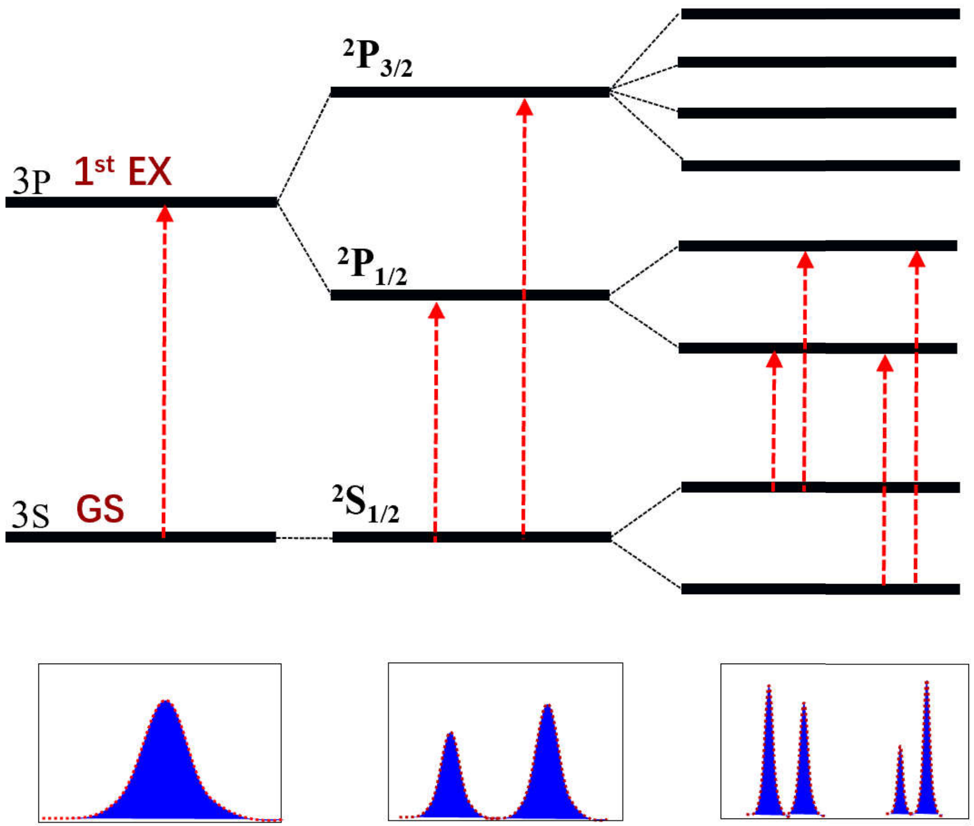
Hyperfine structure/Isotope shift



Hyperfine structure (HFS) spectrum

Hyperfine interaction and laser spectroscopy

Optical HFS spectrum



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

$$H_{\mathrm{hf}} = \sum_k \hat{\mathrm{T}}^k_{\mathrm{N}} \cdot \hat{\mathrm{T}}^k_{\mathrm{e}}$$

K=0 electric monopole interaction
K=1 magnetic dipole interaction
K=2 electric quadrupole interaction
} Dominate part

K=3 magnetic octupole interaction

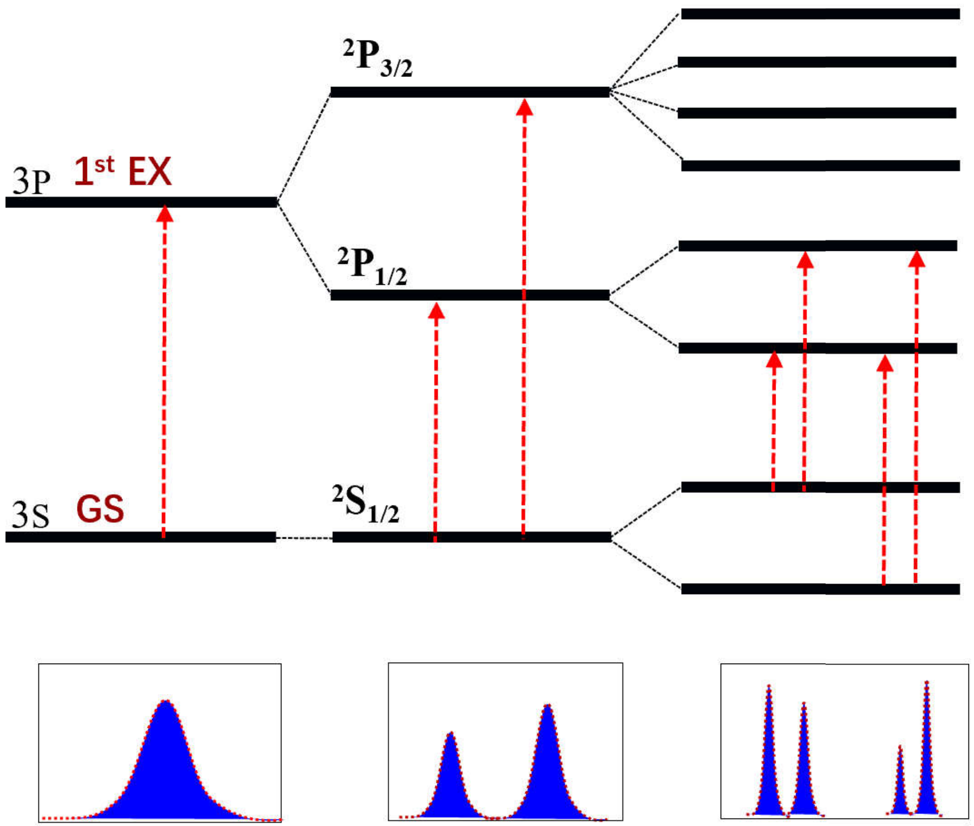
……

EDM?
MQM?
P, T violating

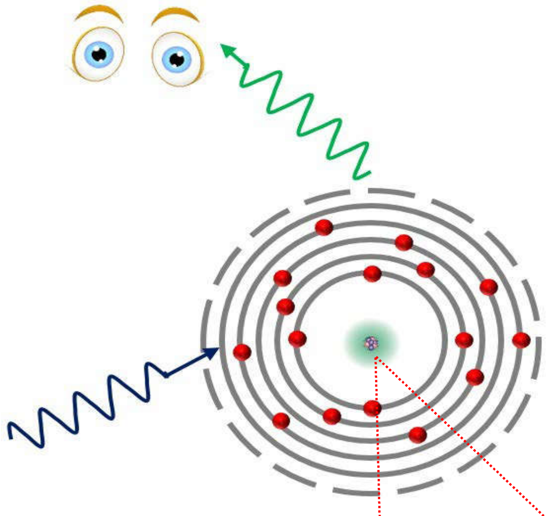
M.S. Safronova et al., RMP 90, 025008(2018)
T.E. Chupp et al., RMP 91,015001(2019)

Hyperfine interaction and laser spectroscopy Atoms or ions

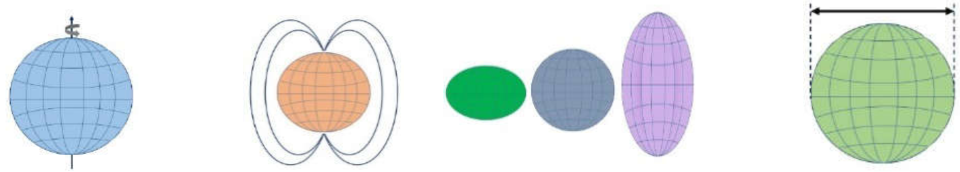
Optical HFS spectrum



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



Nuclear properties

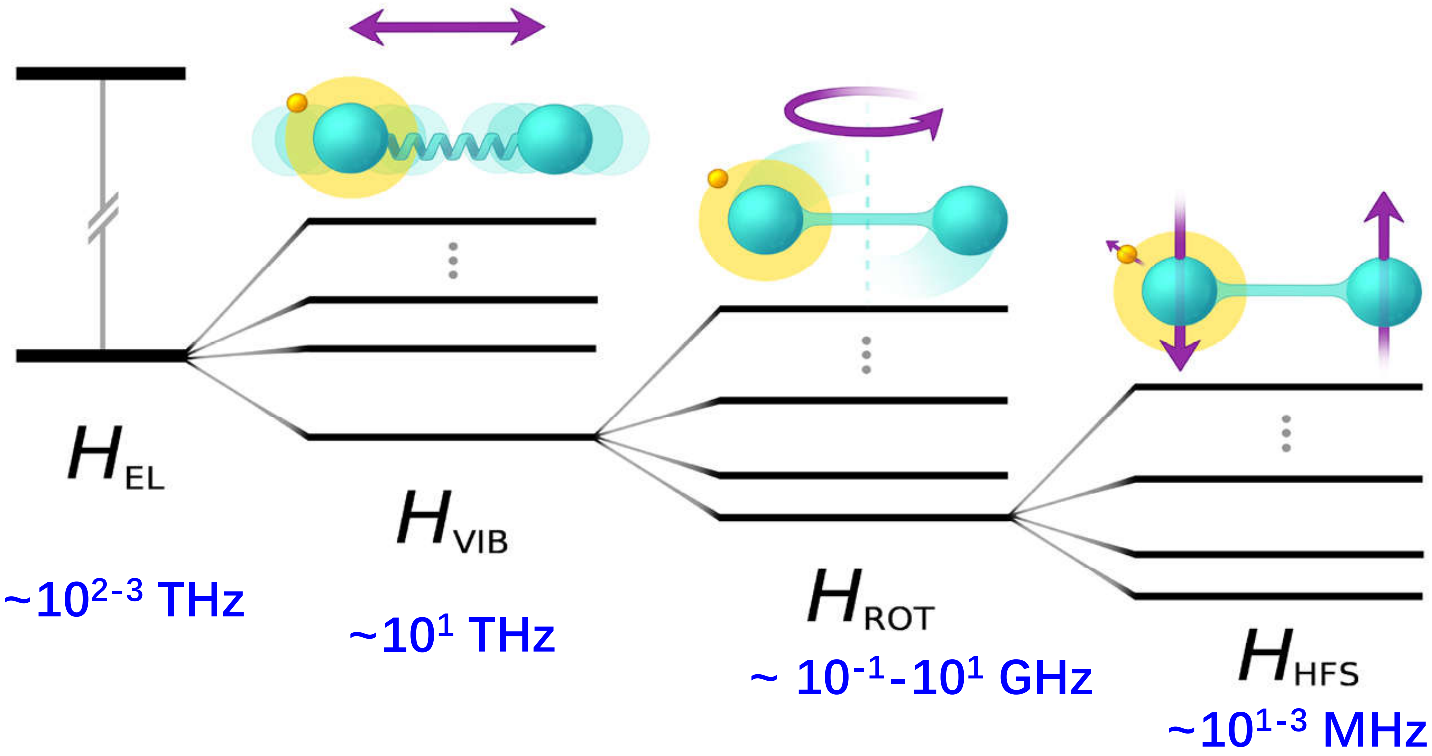


Spin I   Magnetic and quadrupole moments   Radii $\langle r_c^2 \rangle$

In a nuclear-model independent manner

Hyperfine interaction and laser spectroscopy **Radioactive molecules**

$$H_{\text{Mol.}} = H_{el} + H_{\text{vib.}} + H_{\text{rot.}} + H_{\text{hfs}} + H_{\text{PV}} + H_{\text{PTV}}$$



Nuclear Structure

- Moments
- Radii

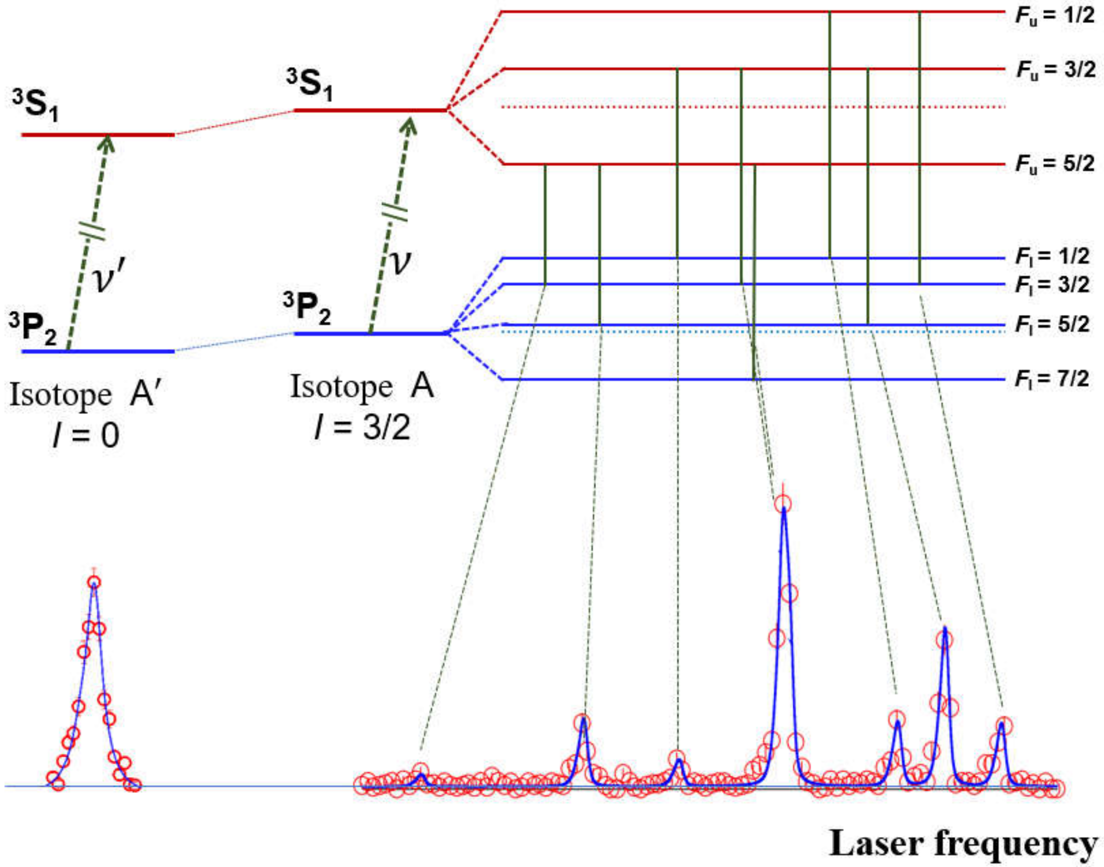
Symmetry voilating

EDM, MQM

Opportunities for Fundamental Physics Research with Radioactive Molecules. Rep Prog Phys. 2024
doi: 10.1088/1361-6633/ad1e39

Hyperfine interaction and laser spectroscopy

$\Delta E = A \cdot K/2 + B \cdot \{3K(K+1)/4 - I(I+1)J(J+1)\}/\{2(2I-1)(2J-1)IJ\}$, $K = F(F+1) - I(I+1) - J(J+1)$



Atomic parameters

- Magnetic dipole HF parameter

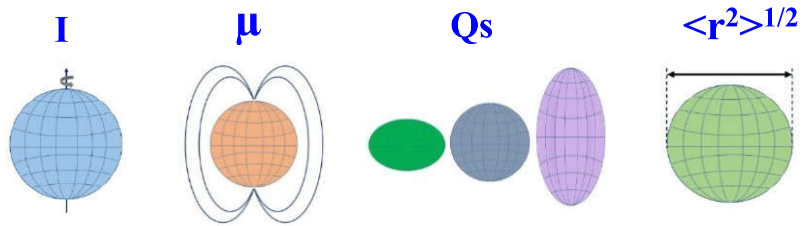
$$A = \frac{\mu_I B_J}{IJ} \qquad \mathbf{I, \mu}$$

- Electric quadrupole HF parameter

$$B = eQV_{zz} \qquad \mathbf{Qs}$$

- Centroid ν_0 => Isotopes shift

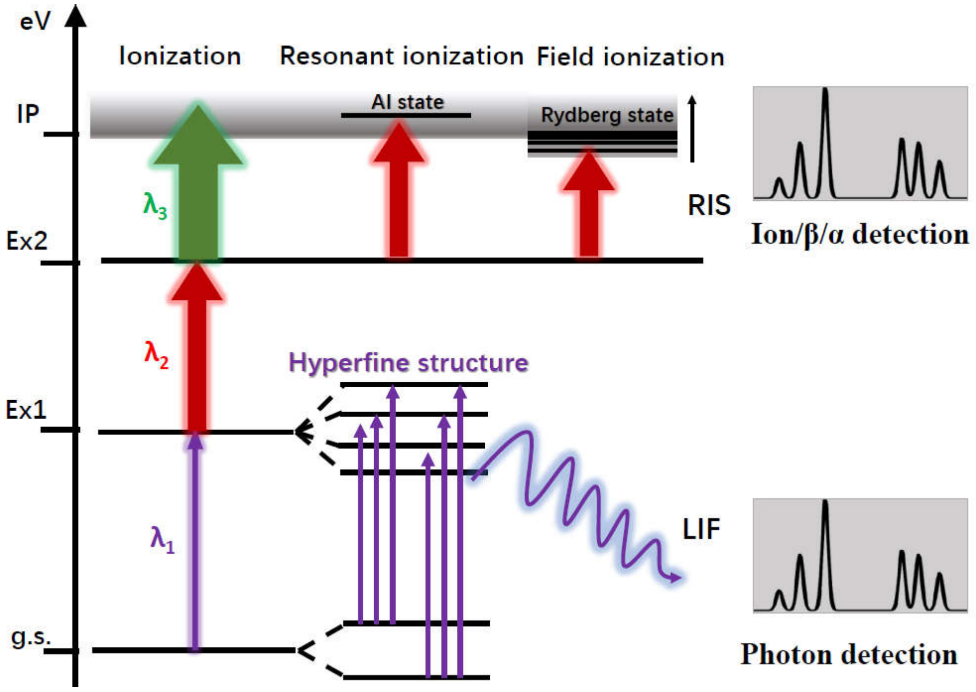
$$\delta\nu^{AA'} = M\frac{A'-A}{AA'} + F\ \delta\langle r^2\rangle^{AA'}$$



X.F. Yang et al., "Laser Spectroscopy for the Study of Exotic Nuclei", Prog. Part. Nucl. Phys. 129, 104005(2023)

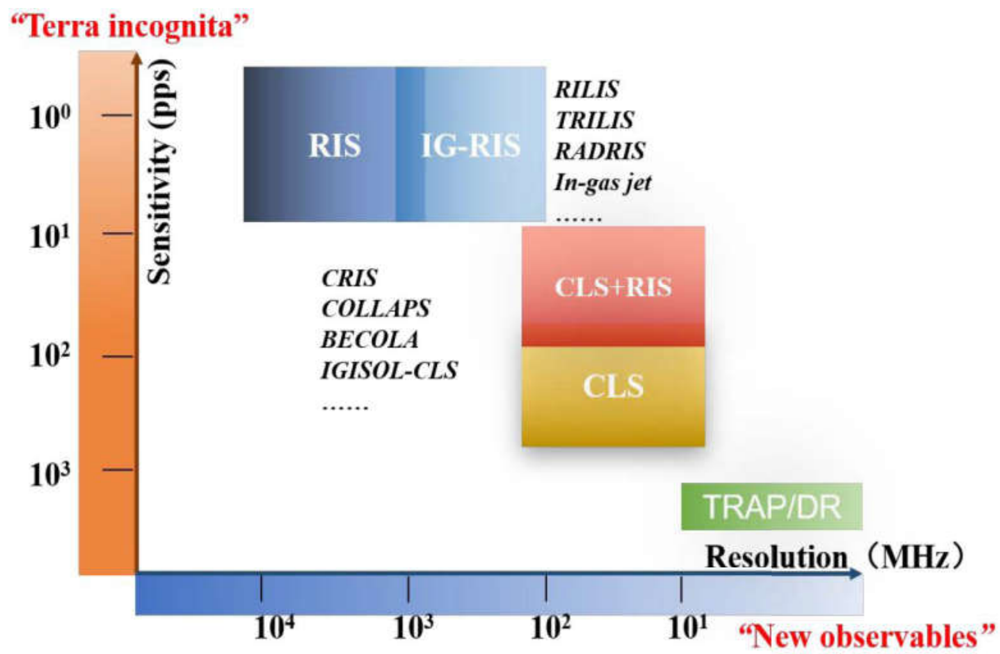
Hyperfine interaction and laser spectroscopy

Approaches used to measure the HFS spectrum



LIF: laser-induced fluorescence
RIS: laser resonance ionization spectroscopy

Three main categories of laser spectroscopy



- Collinear laser spectroscopy
- In-source laser spectroscopy
- Trap-assisted laser spectroscopy.

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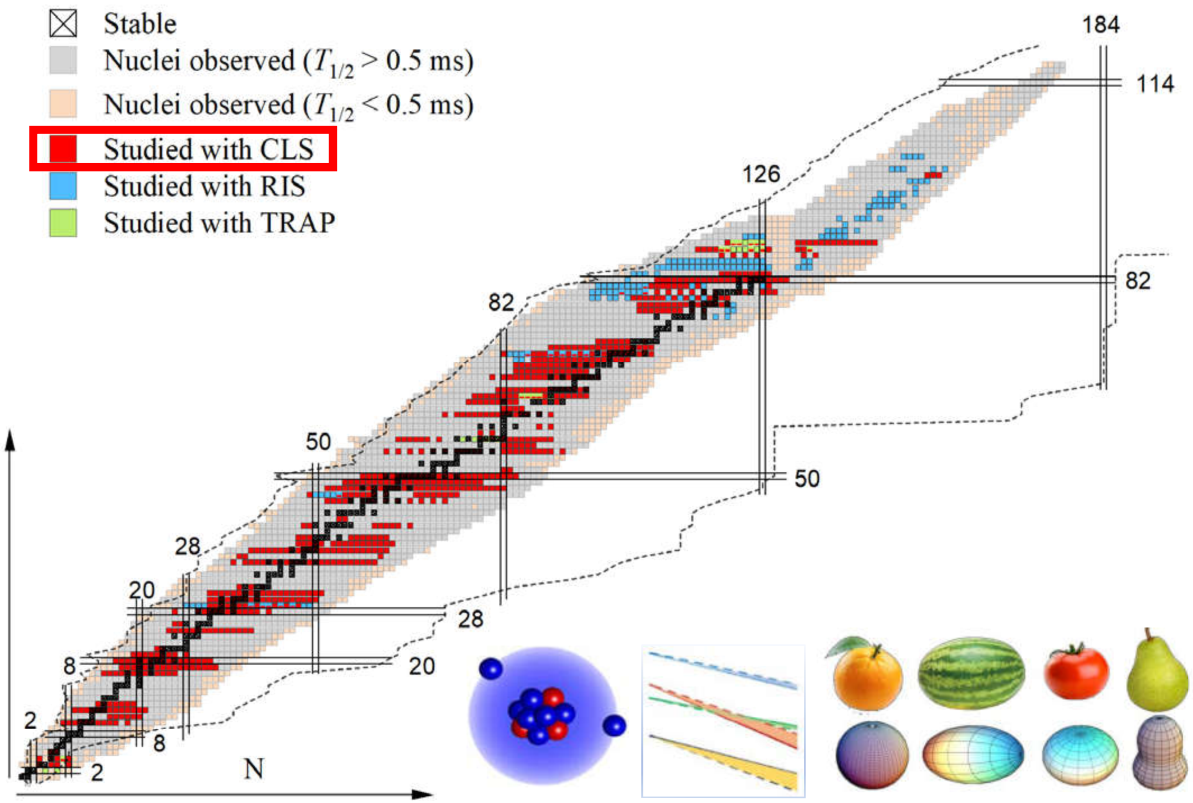
Hyperfine interaction and laser spectroscopy



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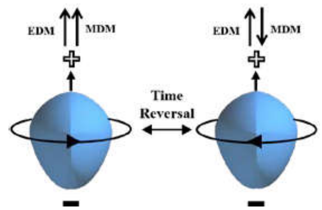
About 1000 nuclei was investigated

-contribute significantly to the study of nuclear structure and NN interaction

- *Nature 607, 260-265 (2022)*
- *Nat. Phys. 17,439 (2021)*

First laser spectroscopy of RaF (radioactive molecule)

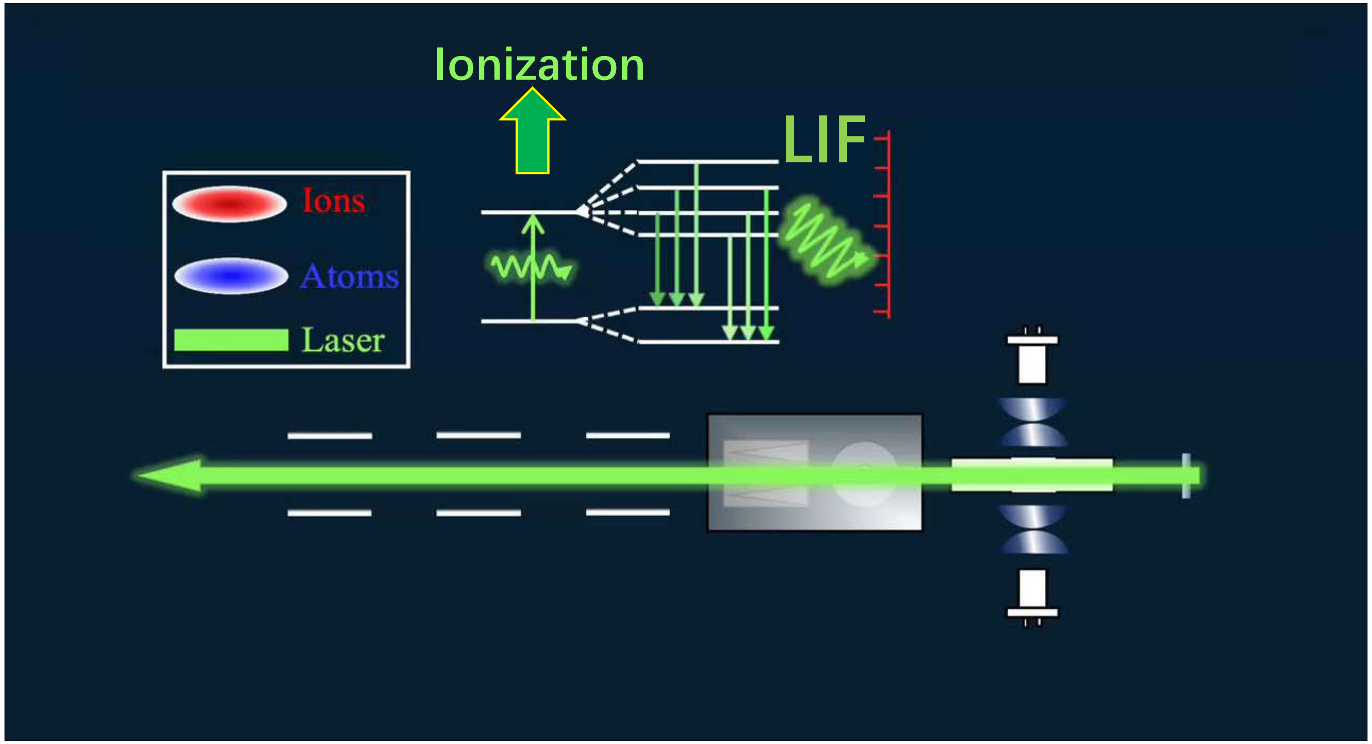
-offer new opportunity for the study of fundamental symmetry



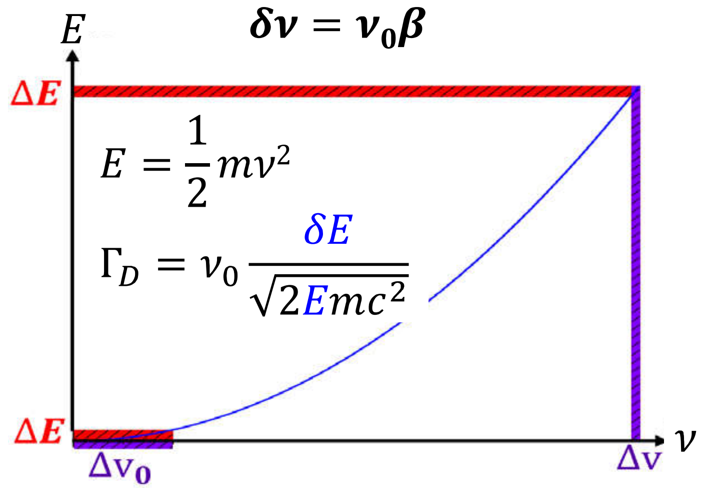
- *Nature 581, 396 (2020)*
- *Nat. Phys. 20,202(2024)*

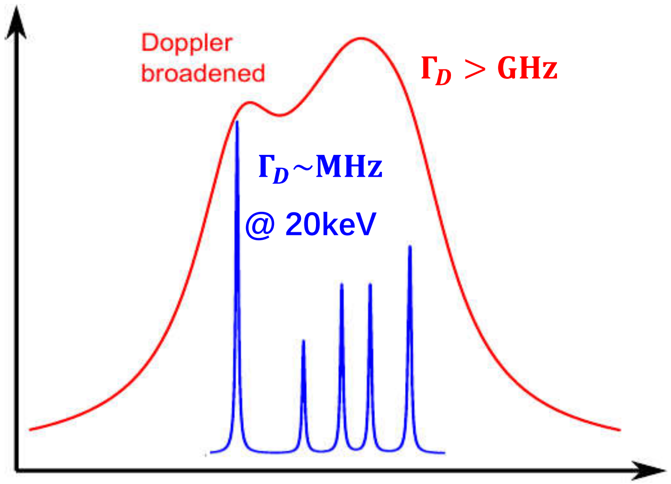
"New field"

CLS: Collinear laser spectroscopy



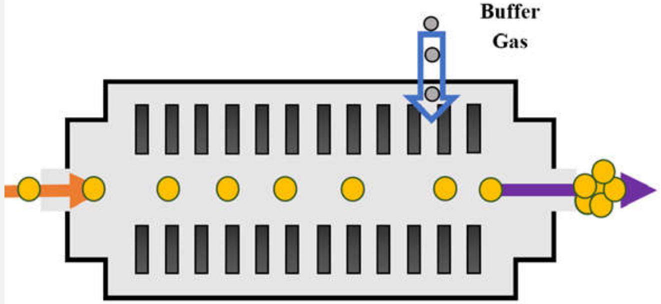
RI beam is overlapped with laser in a collinear/ant-collinear geometry



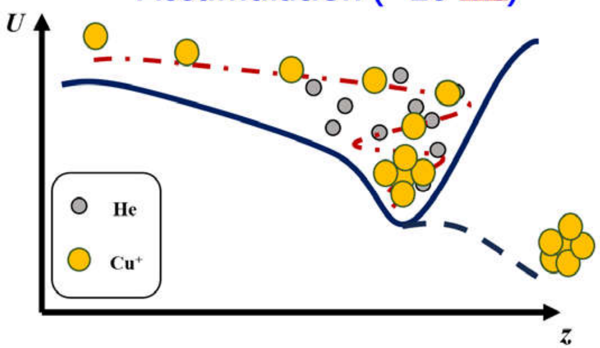


Hyperfine interaction and laser spectroscopy (e.g. CLS)

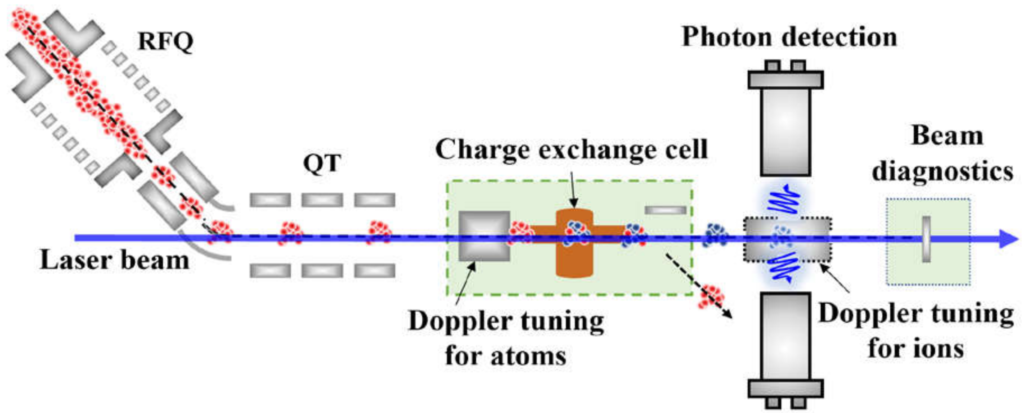
CW beam to bunched beam

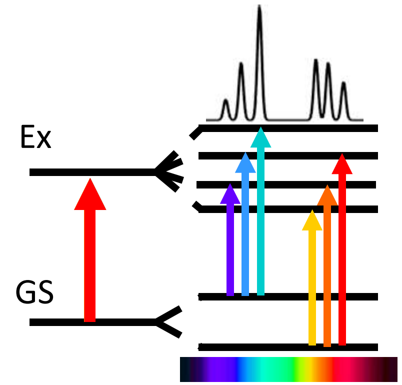


Accumulation (~10 ms)



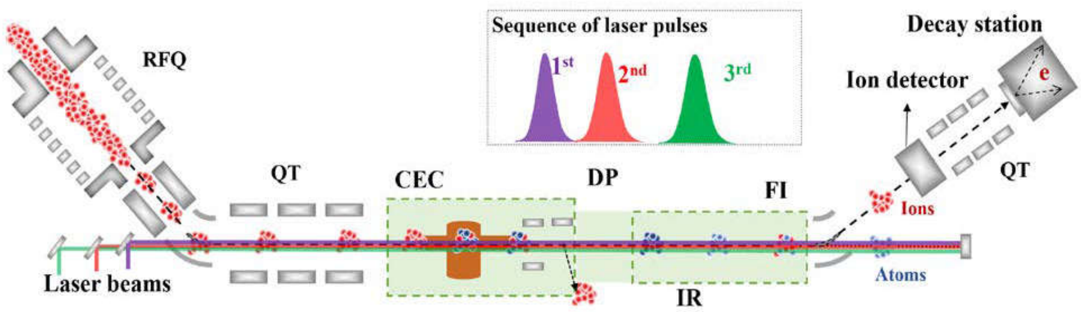
Release < 5μs

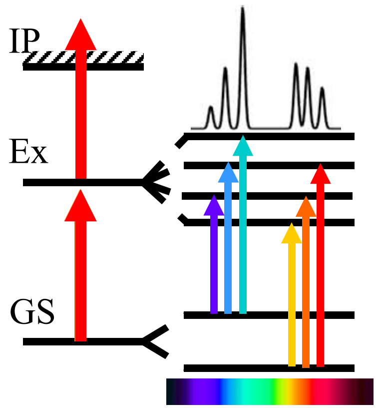




Photon detection

Resolution < 100 MHz, Sensitivity 10^3 pps





Ion detection

Resolution < 100 MHz, Sensitivity $10^{1\text{-}2}$ pps

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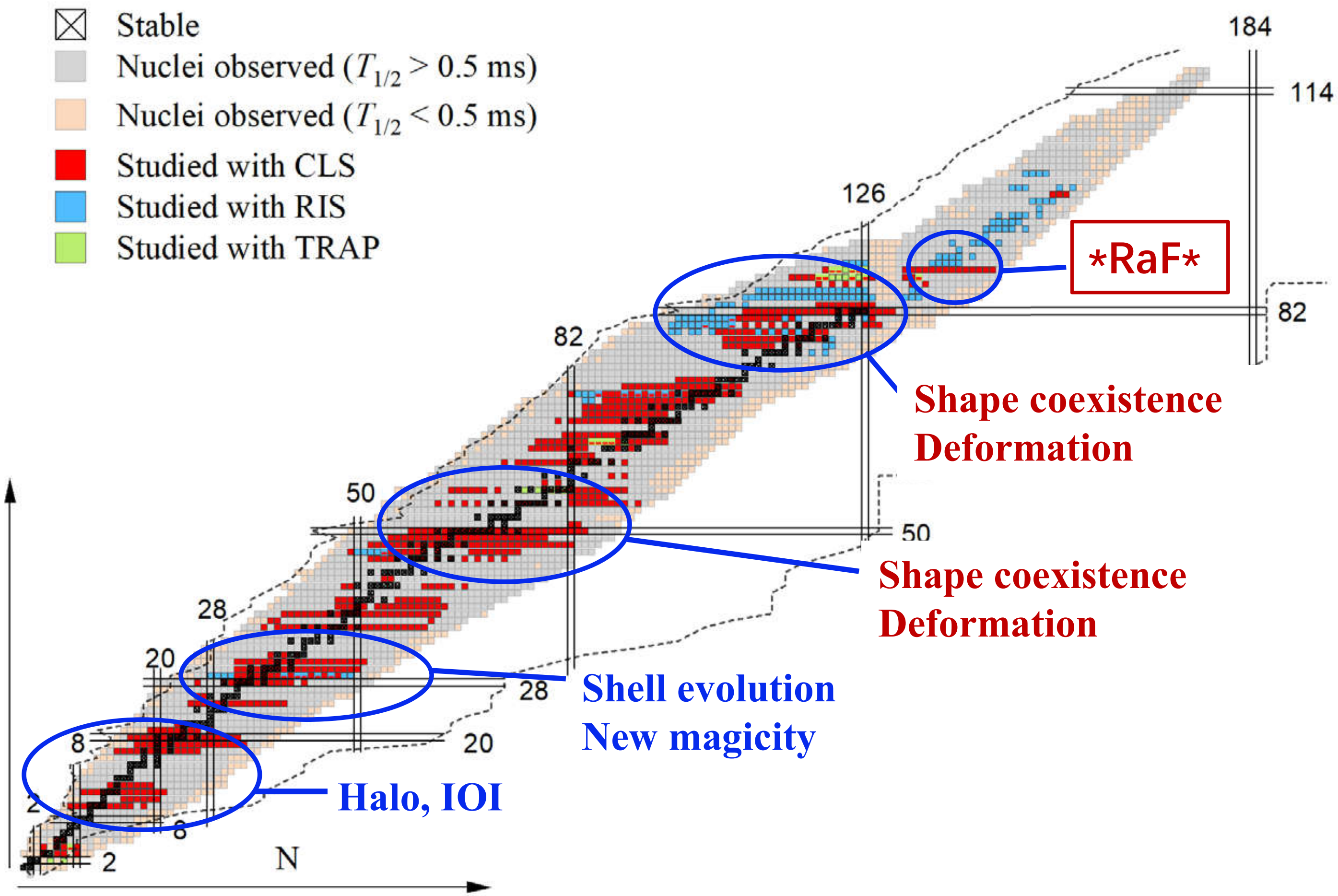
  e.g. Nuclear shapes in neutron rich nickel region

  e.g. Nuclear shapes in neutron deficient lead region

  e.g. Nuclear information from radioactive molecules
- ☐ Laser spectroscopy development and near future work

Unstable nuclei probed by laser spectroscopy



X.F. Yang et al., "Laser Spectroscopy for the Study of Exotic Nuclei", Prog. Part. Nucl. Phys. 129, 104005(2023)

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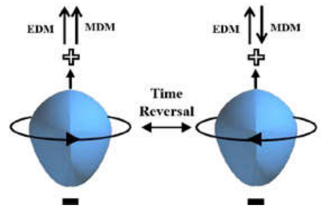
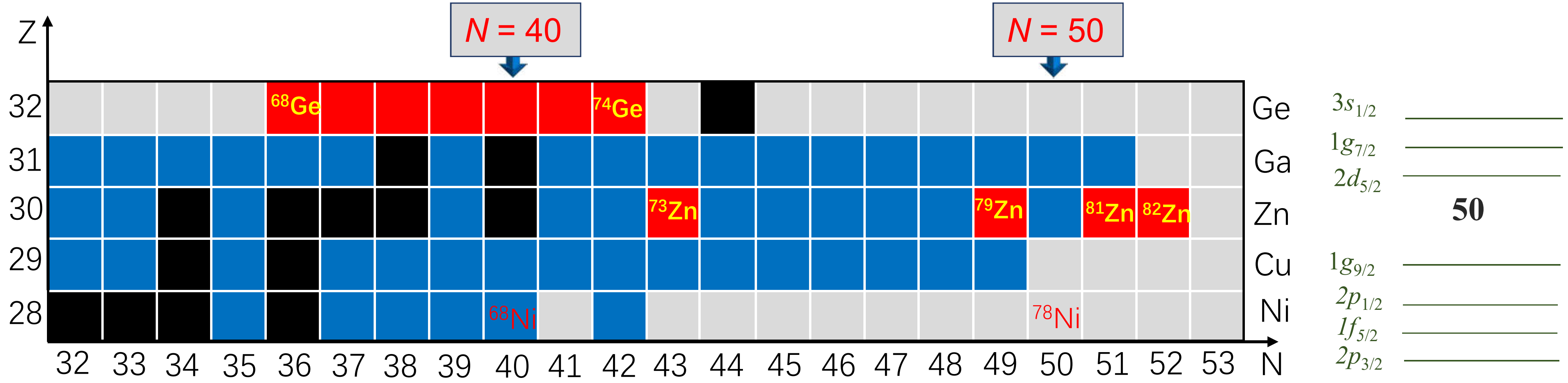
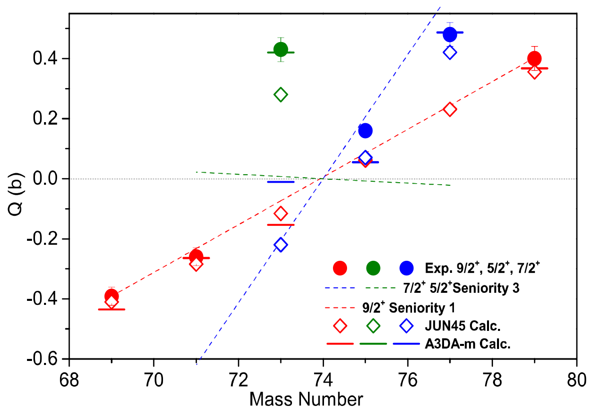


- *Nature 581, 396 (2020)*
- *Nat. Phys. 20,202(2024)*

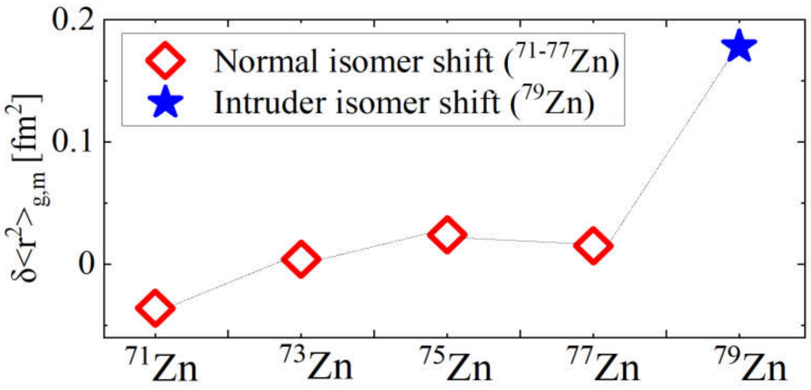
"New field"

e.g. Nuclear shapes in neutron-rich Ni region

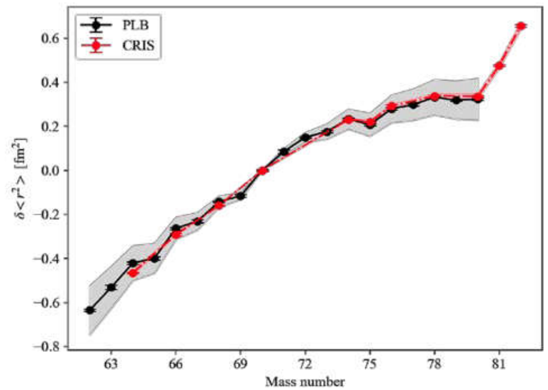




Triaxial deformation in ^{73}Zn

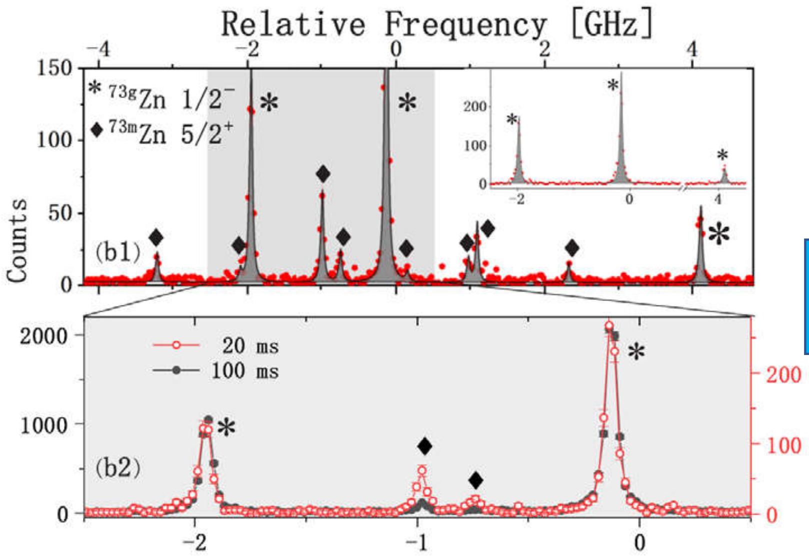


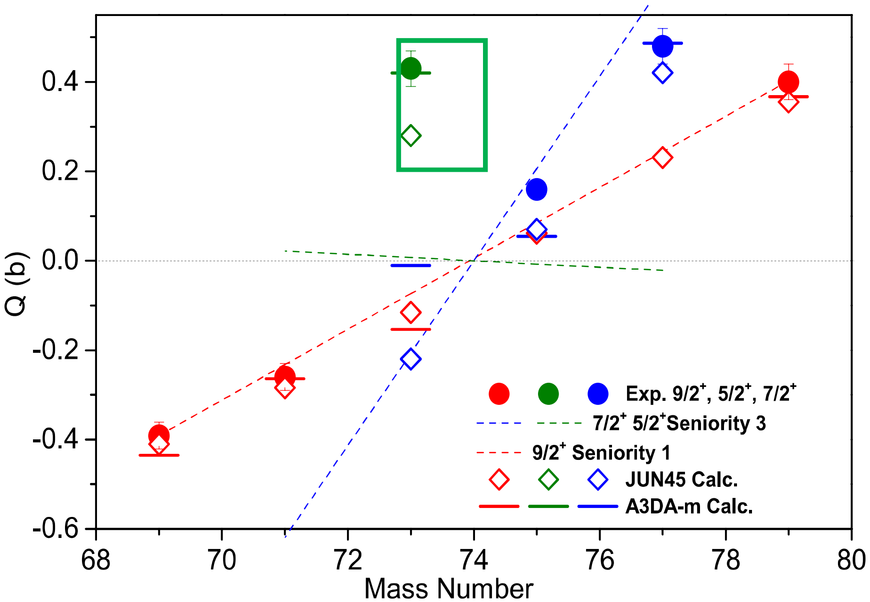
Shape coexistence in ^{79}Zn

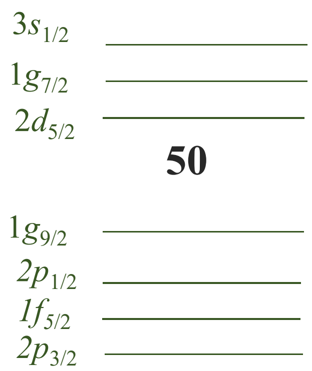


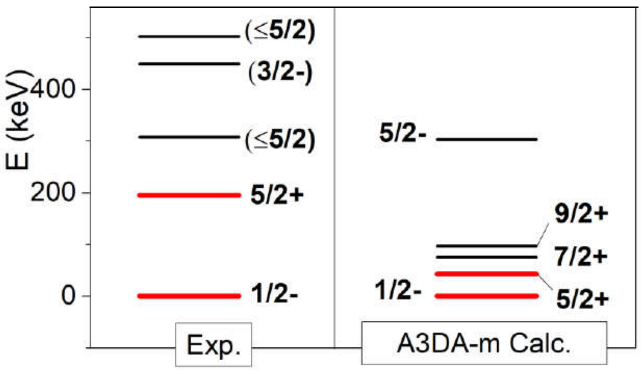
Defromation in $^{81\text{-}82}$Zn?

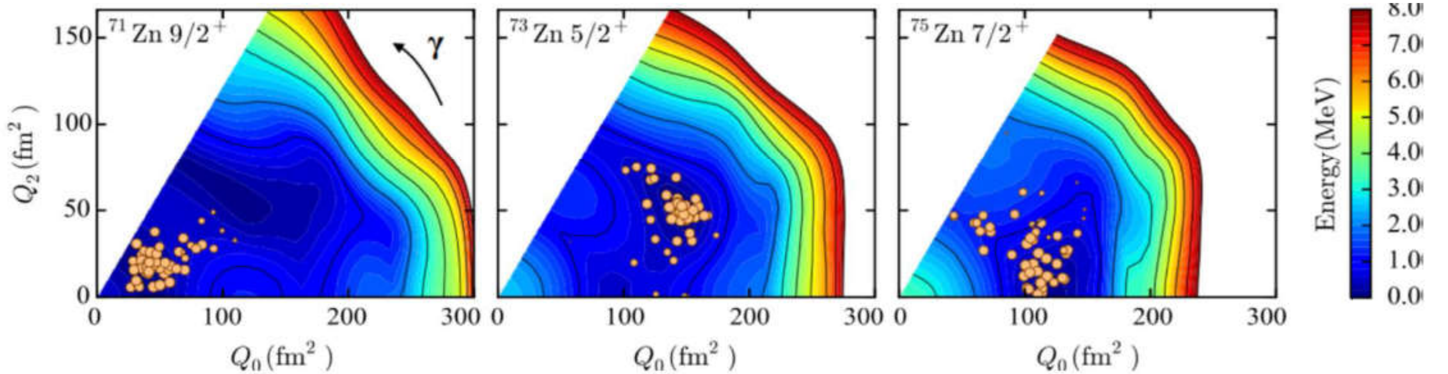
e.g. Nuclear shapes in neutron-rich Ni region (triaxiality in ^{73m}Zn)





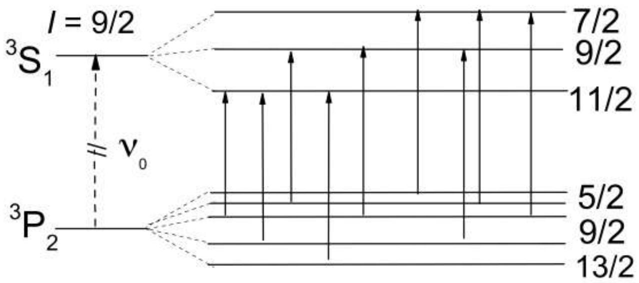


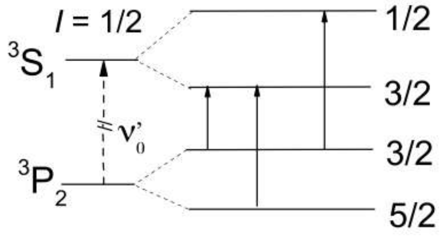


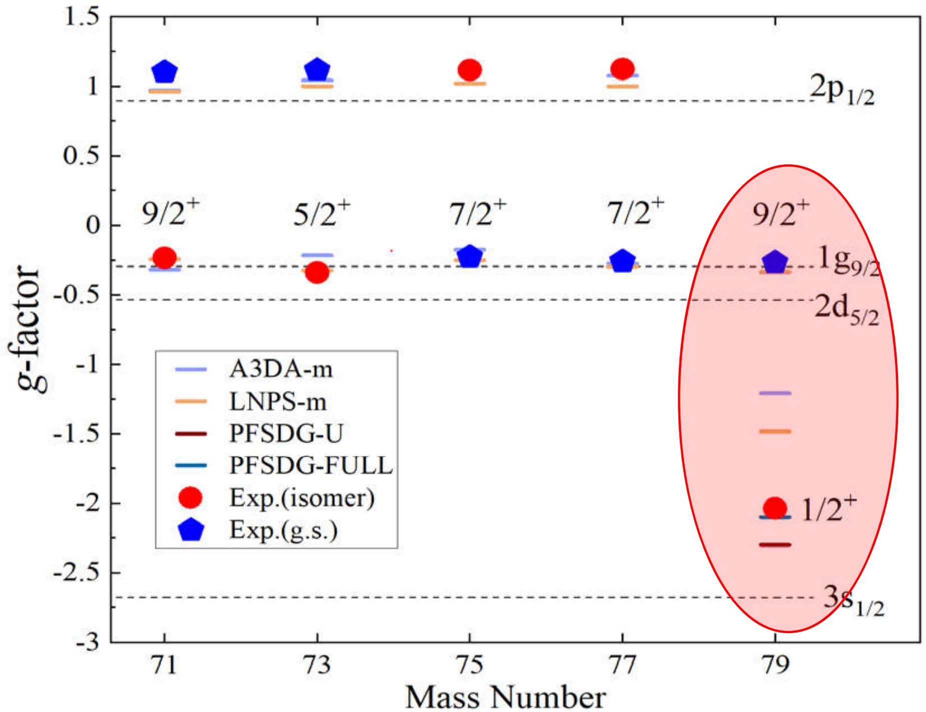


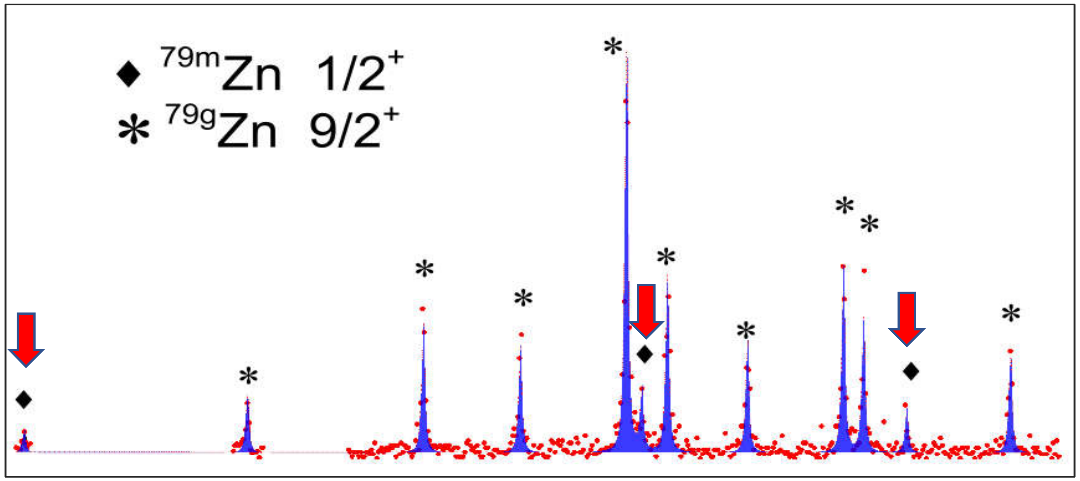
X. F. Yang et al., PRC 97, 044324 (2018)

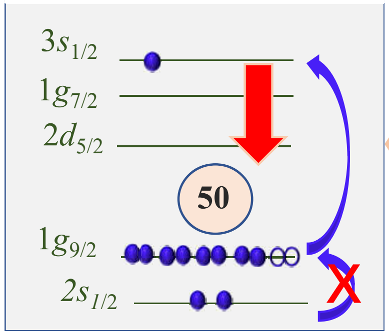
e.g. Nuclear shapes in neutron-rich Ni region (shape coexistence in ^{79}Zn)









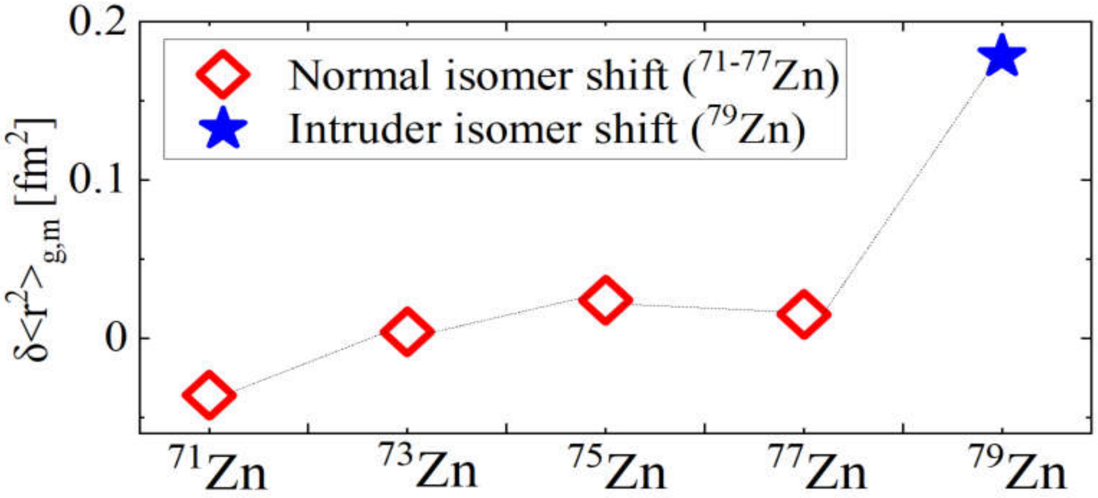


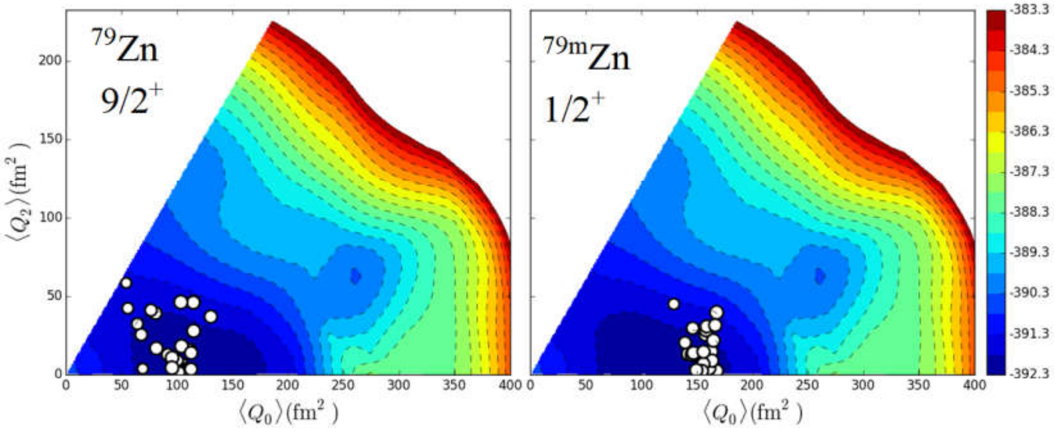
Intruder nature of ½⁺ state

Identification of a long-lived isomeric state in ^{79}Zn

X.F Yang* et al PRL 116(2016)182502, L.Xie. X.F. Yang et al., PLB797 (2019) 134805

e.g. Nuclear shapes in neutron-rich Ni region (shape coexistence in ^{79}Zn)





- **Quadrupole moment of 9/2+ g.s.**
  =>near spherical shape

$$Q_{\mathrm{intr.}} = \frac{3}{\sqrt{5\pi}} Z R_0^2 \beta_2 (1 + 0.36\beta_2)$$

$$\beta_2 = 0.15(2)$$

- **Larger isomer shift of the ½+ state**
  =>a larger deformation

$$\langle r^2\rangle = \langle r^2\rangle_0 \left(1 + \frac{5}{4\pi}\langle \beta_2^2\rangle\right)$$

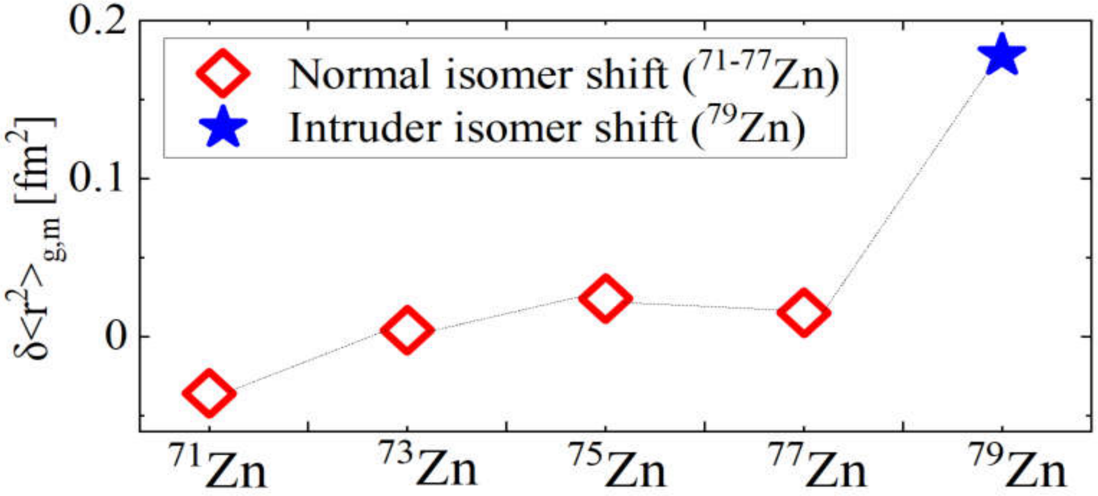
$$\delta\left\langle r^2\right\rangle^{A,A'} = \delta\left\langle r^2\right\rangle_0^{A,A'} + \left\langle r^2\right\rangle_0 \cdot \frac{5}{4\pi}\delta\left\langle \beta_2^2\right\rangle^{A,A'}$$

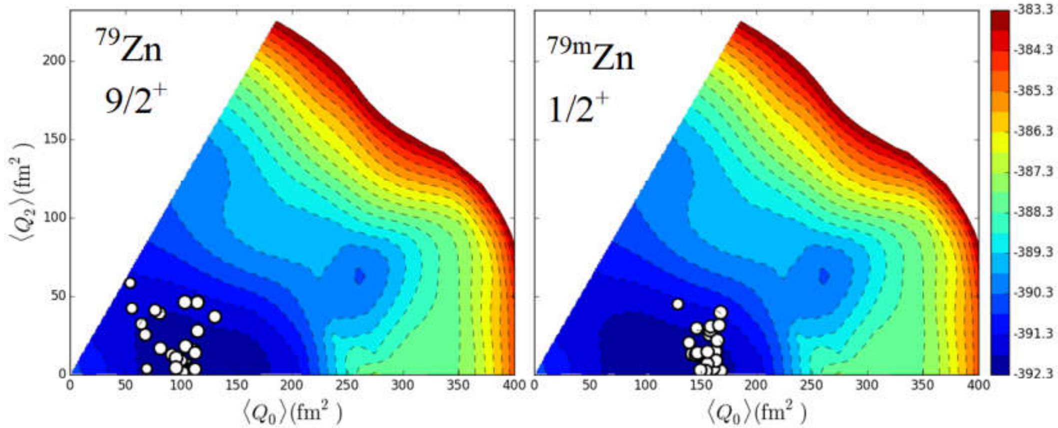
$$\langle \beta_2^2\rangle^{1/2} \sim 0.22$$

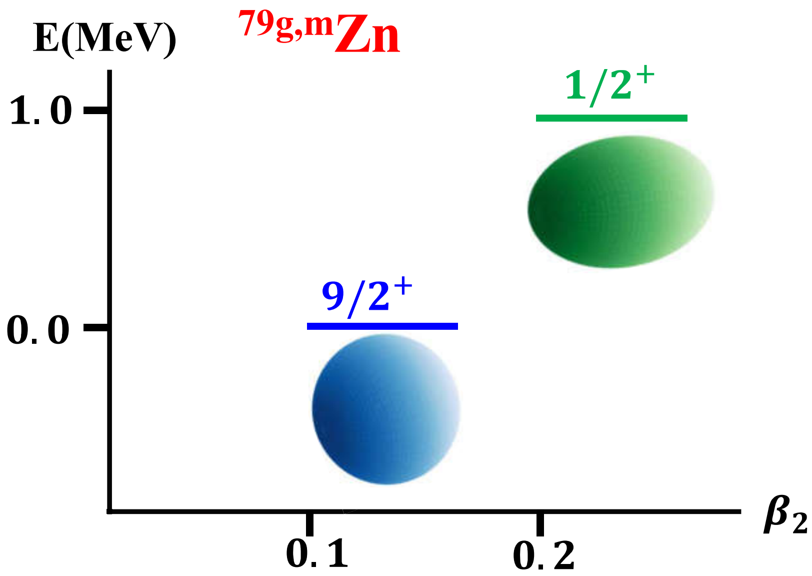
Deformation of the 1/2$^+$ state

[X.F Yang* et al PRL 116(2016)182502, L,Xie. X.F. Yang et al., PLB797 (2019) 134805]

e.g. Nuclear shapes in neutron-rich Ni region (shape coexistence in ^{79}Zn)



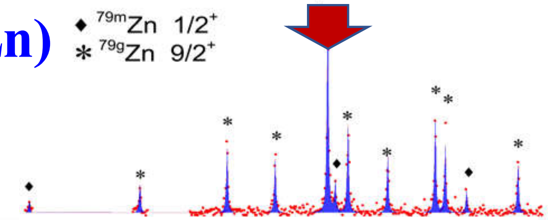


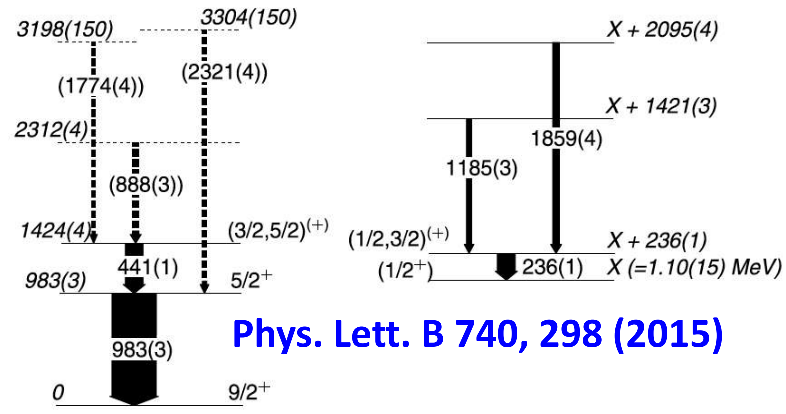


=> Experimental evidence for shape coexistence in ^{79}Zn

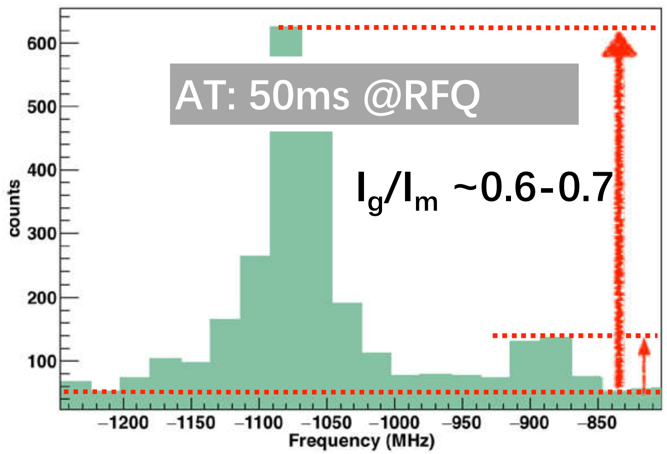
[X.F Yang* et al PRL 116(2016)182502, L,Xie. X.F. Yang et al., PLB797 (2019) 134805]

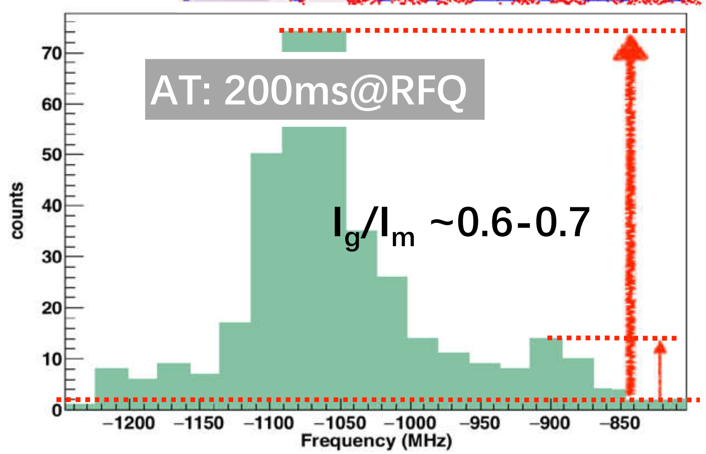
e.g. Nuclear shapes in neutron-rich Ni region (shape coexistence in ^{79}Zn)

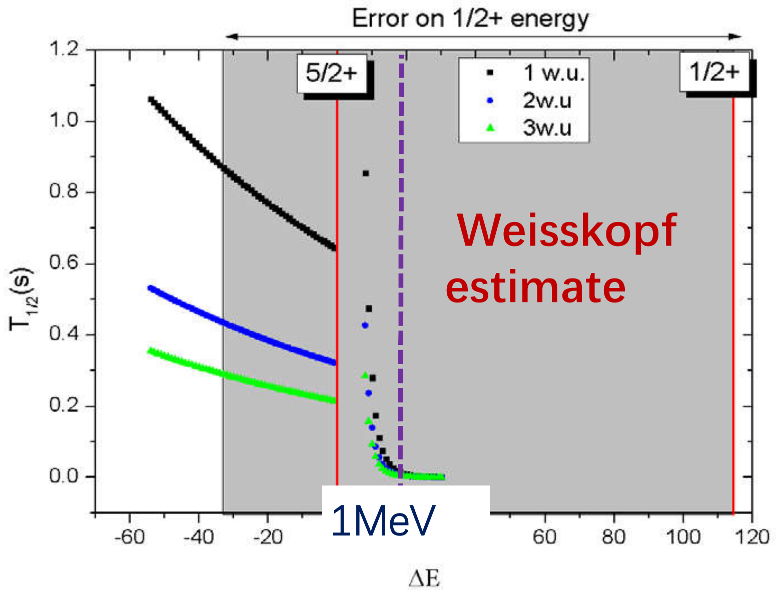




Phys. Lett. B 740, 298 (2015)





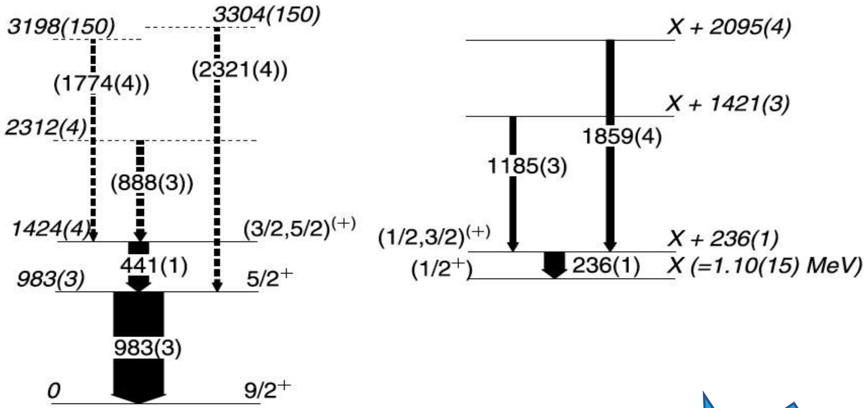


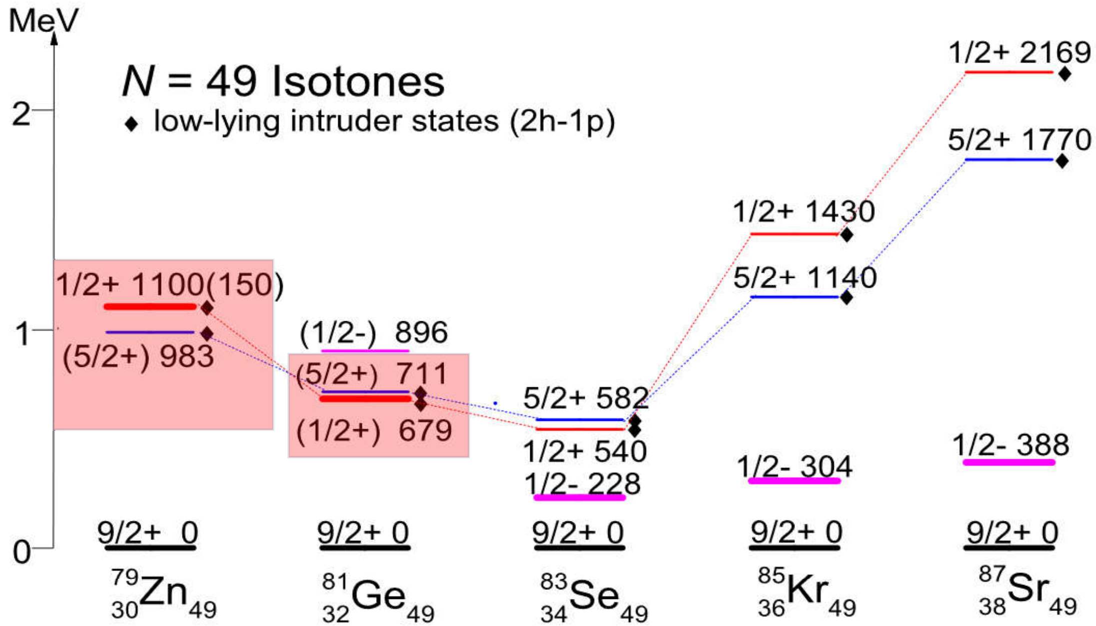
Conclusion:

1. Few hundreds ms half life for ^{79m}Zn as I_g/I_m stay no change using 50, 100, 200ms accumulation time in the RFQ

2. The energy of the ½$^+$ isomer is lower than 1 MeV

e.g. Nuclear shapes in neutron-rich Ni region (shape coexistence in ^{79}Zn)





- $T_{1/2}$> 200 ms ?

  E4 or E2?

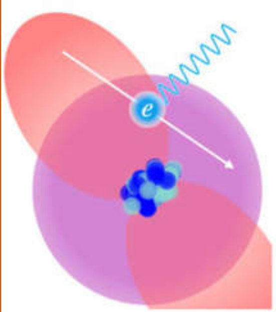
- Mass (E) of ½+ ?

L. Nies *et al.* Phys. Rev. Lett. 131, 222503 (2023) =》 $1/2^+$ is the 1st excitation state of ^{79}Zn
E($1/2^+$) = 943 keV

- The long-lived $1/2^+$ state has been known in ^{81}Ge for 40 years *Nucl. Phys. A368, 210 (1981).*
- To confirm the shape coexistence in ^{81}Ge, high-resolution laser spectroscopy is needed.

M. L. Bissell, X. F. Yang et al., CERN-INTC-2016-036 ; INTC-I-170.

e.g. Nuclear shapes in neutron-rich Ni region (shape coexistence in ^{79}Zn)



EDITORS' SUGGESTION

Shape Coexistence Near ^{78}Ni 2016

Two different experiments observe nuclei with excited nuclear state that differ in shape from their ground states, so called shape coexistence. These nuclei lie close to the neutron-rich doubly-mag ^{78}Ni region of the nuclear chart.

X.F. Yang *et al.* A. Gottardo *et al.*

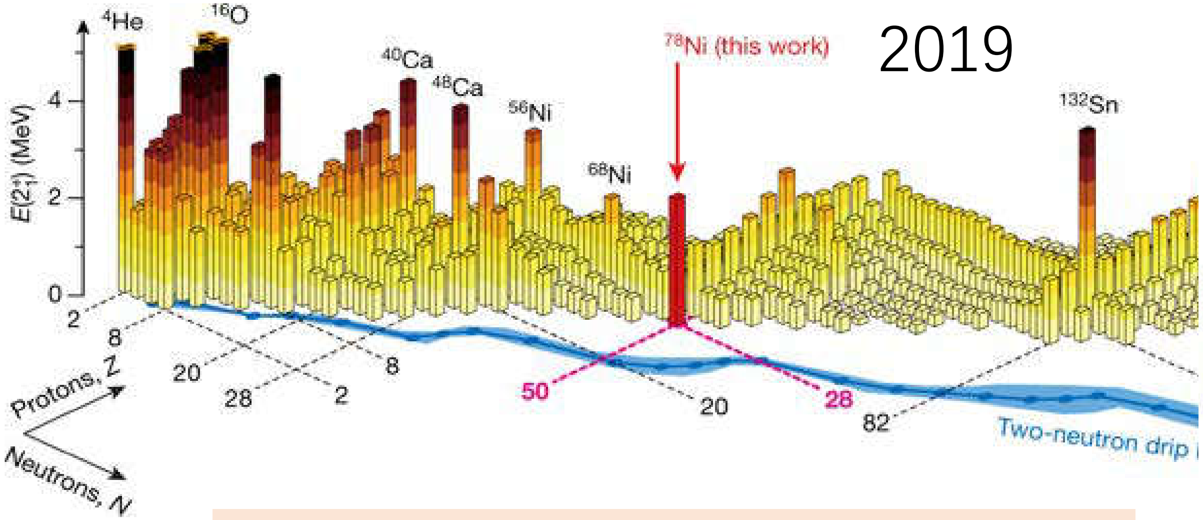
PRL 116(2016)182502;PRL116(2016)182501

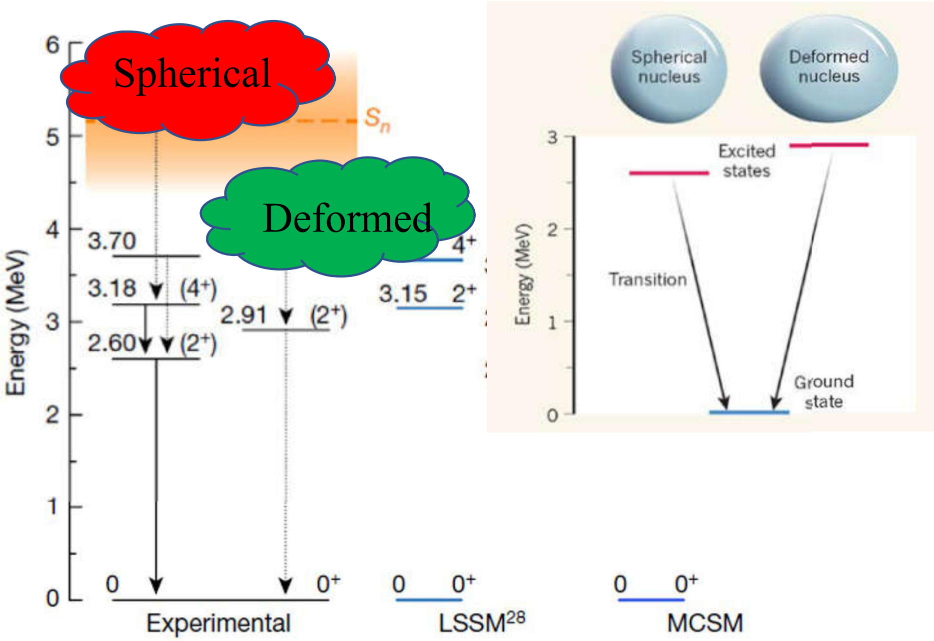
Physics Viewpoint: Doubly Magic Nickel 2017

Two independent experiments on the isotope copper-79 confirm that its nuclear neighbor nickel-78 is indeed a doubly magic nucleus.

A. Welker *et al.* L. Olivier *et al.*

PRL119(2017)192502; PRL119(2017)192501

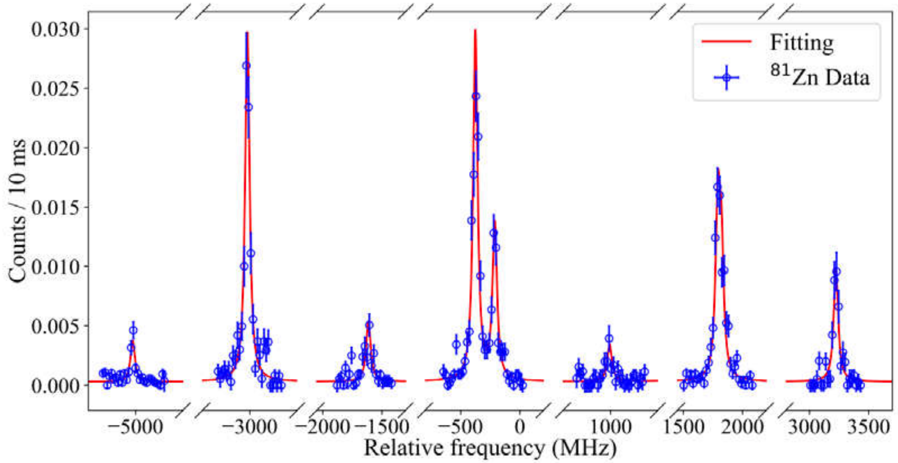




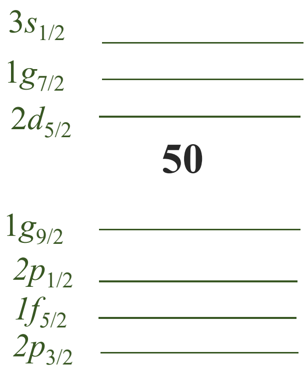
Deformed g.s. for more exotic nickel isotopes (N > 50) are suggested！ ！

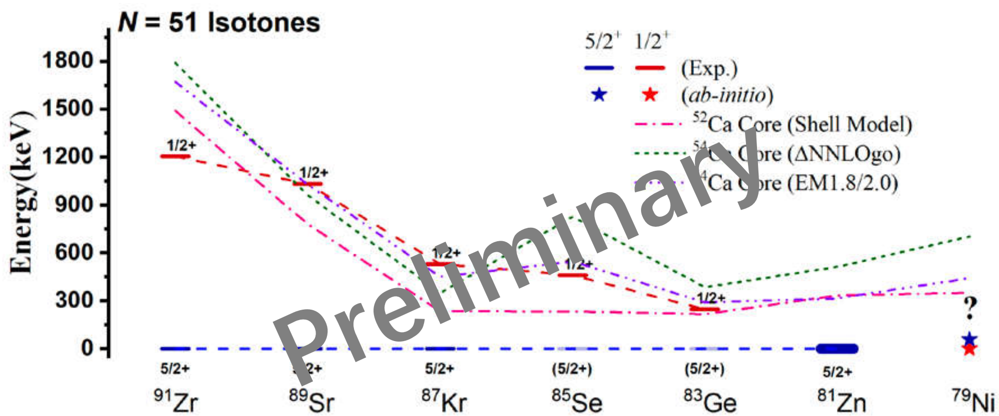
R. Taniuchi, et al. Nature 569 (2019) 53

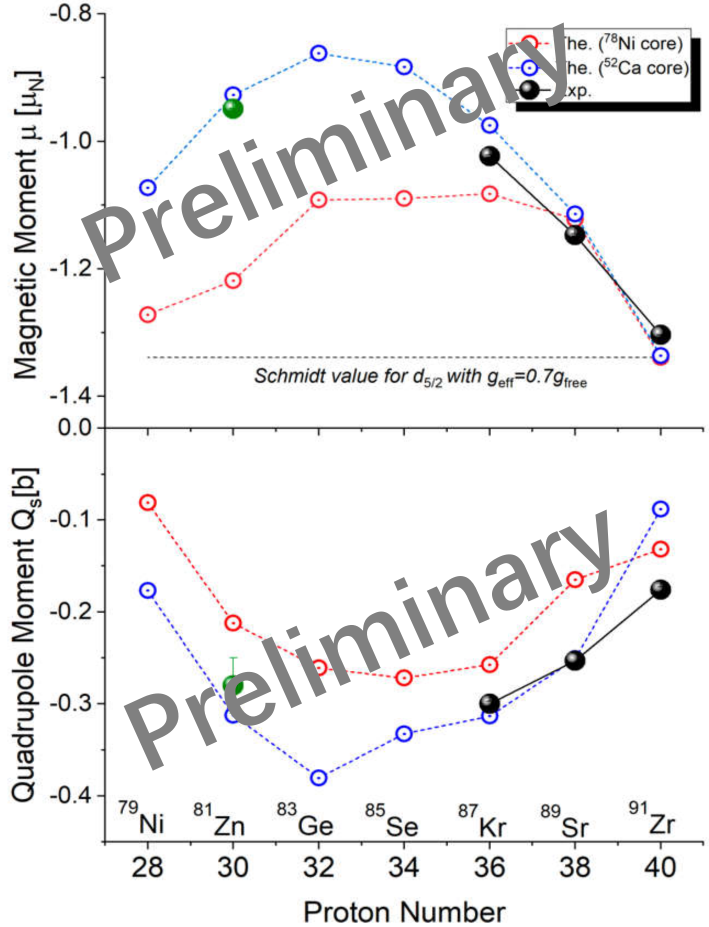
e.g. Nuclear shapes in neutron-rich Ni region (deformation in ^{81,82}Zn?)



Spin I = 5/2$^+$

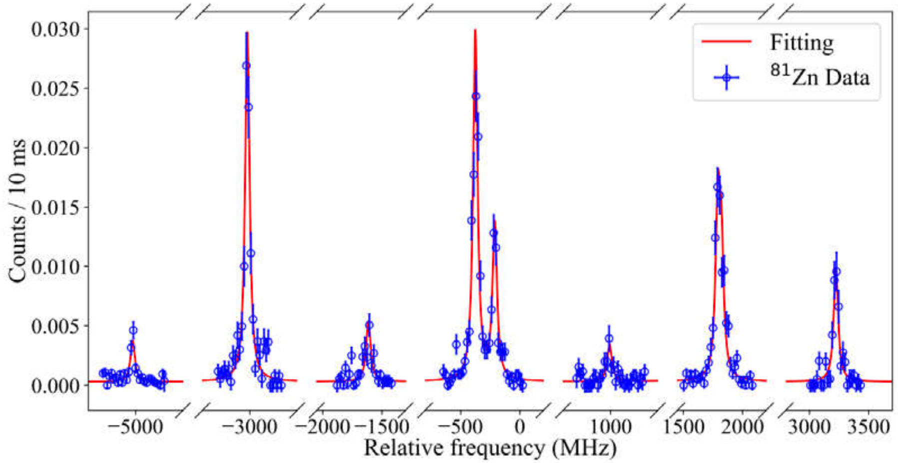


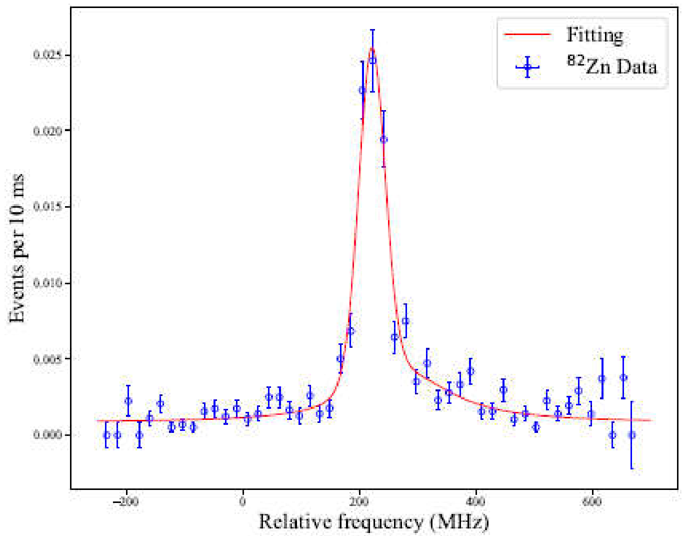


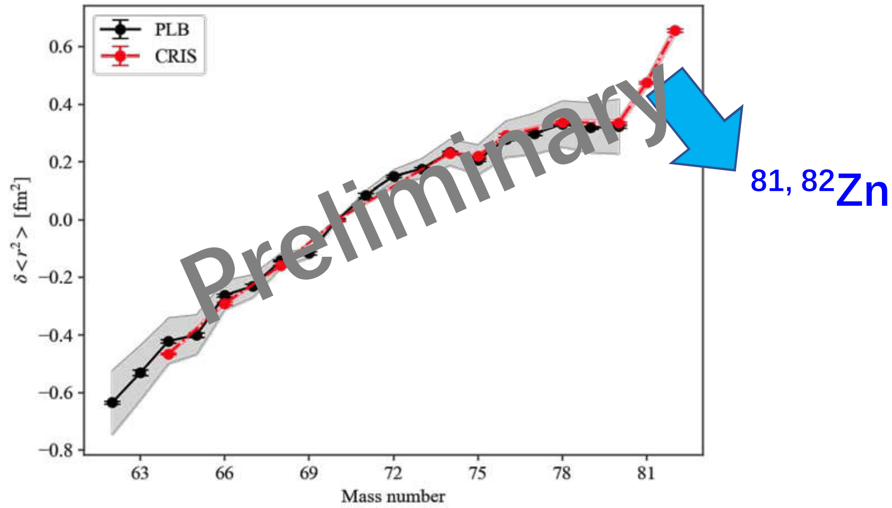


Cross-core excitations of ^{78}Ni is needed to reproduce ^{81}Zn moments

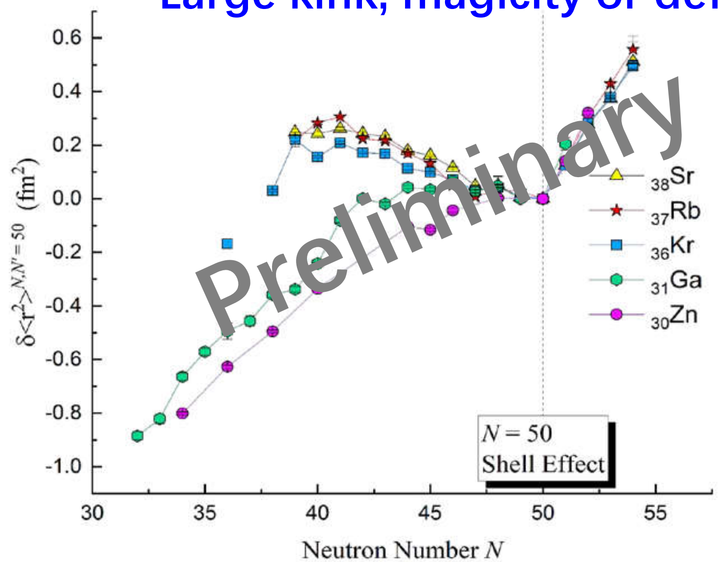
e.g. Nuclear shapes in neutron-rich Ni region (deformation in $^{81,82}Zn$?)



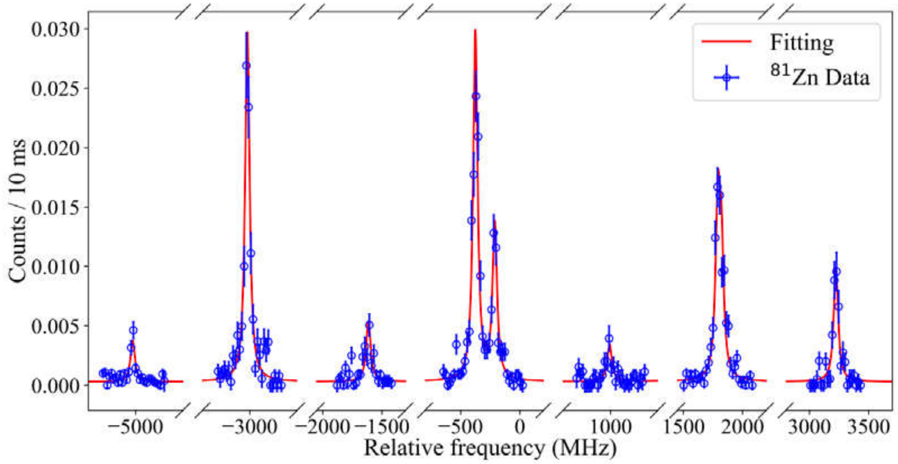


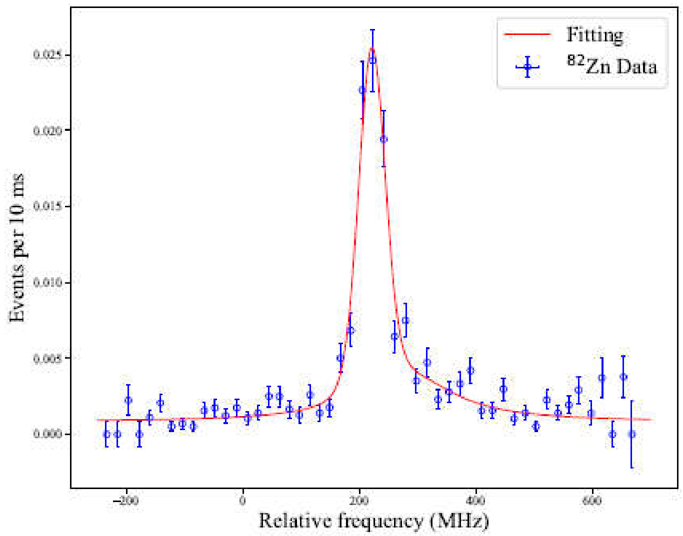


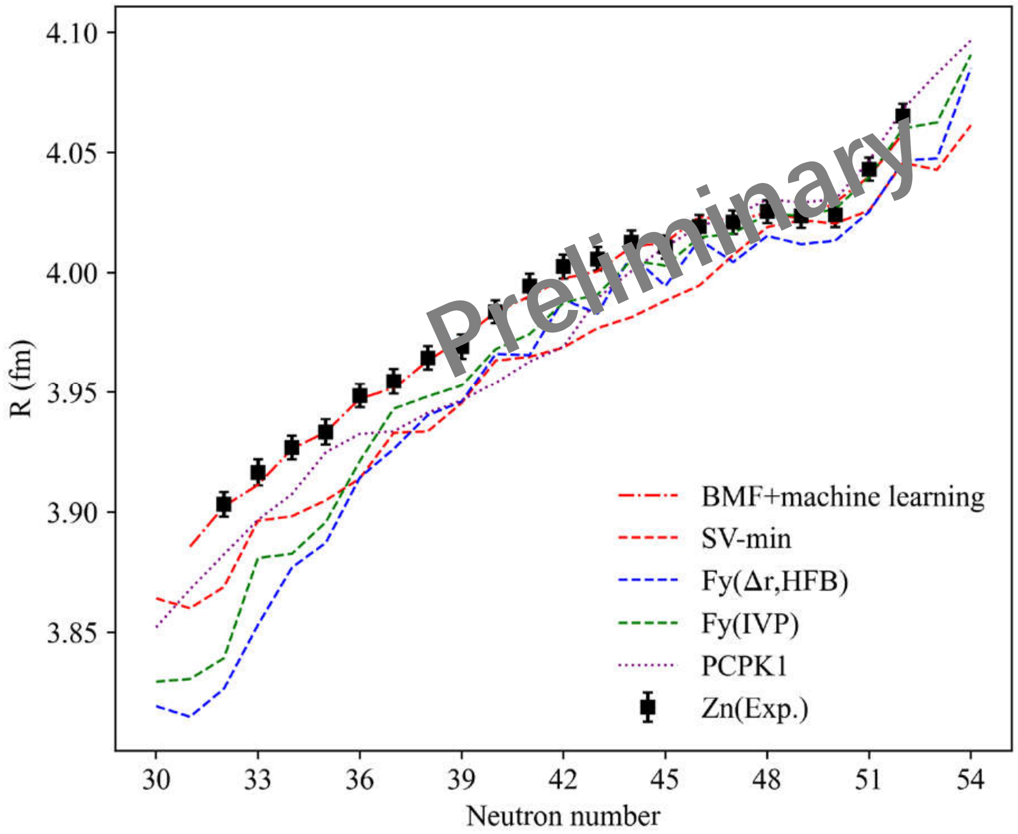
Large kink, magicity or deformation?



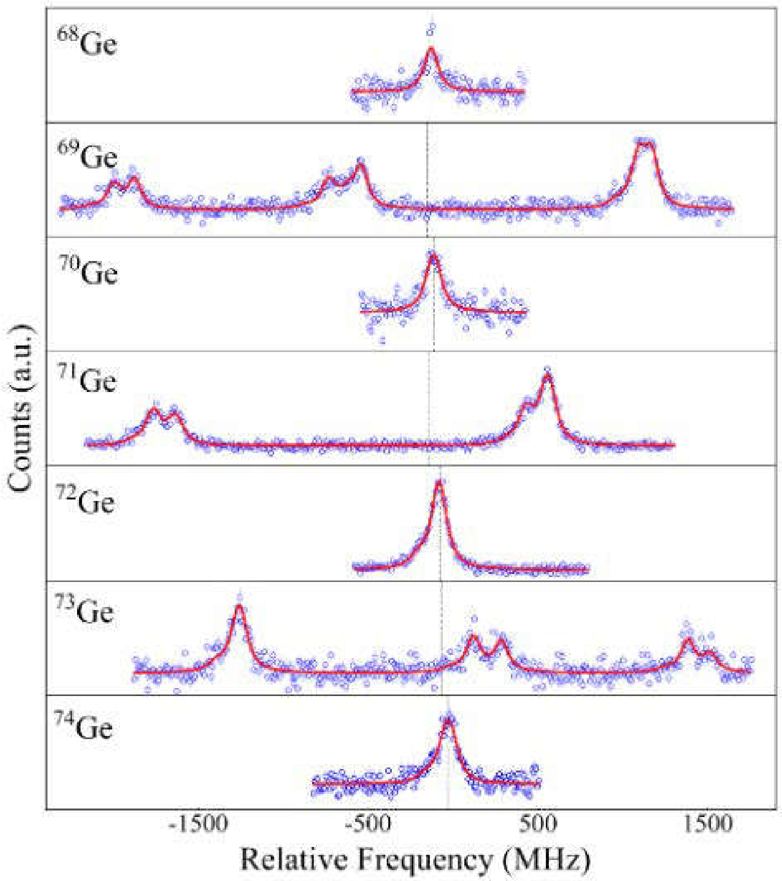
e.g. Nuclear shapes in neutron-rich Ni region (deformation in $^{81,82}Zn$?)



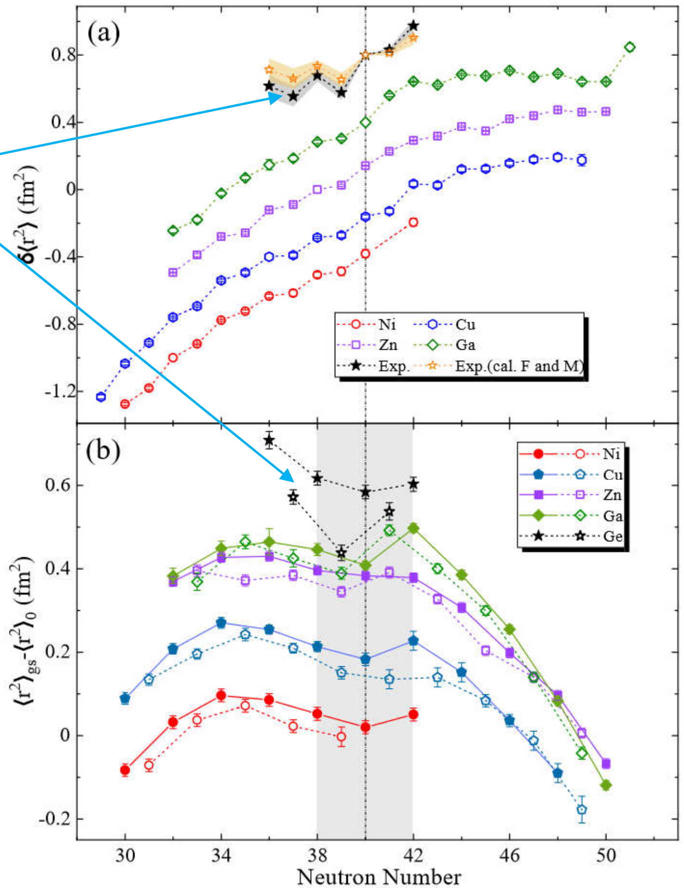




e.g. Nuclear shapes in neutron-rich Ni region (deformation in Ge around $N = 40$)



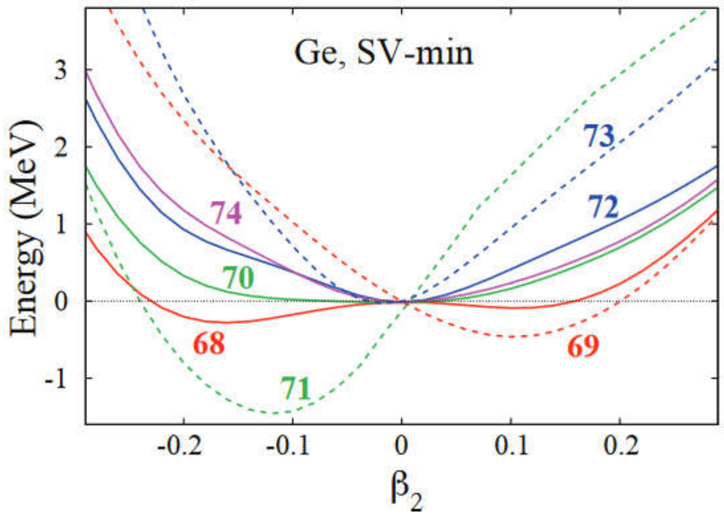
Ge radii



Enhanced even-odd staggering (OES) is observed in the charge radii of Ge isotopes around $N = 40$

S.J. Wang, A. Kanellakopoulos, X.F. Yang et al., Submitted to PLB (2024), arXiv preprint arXiv:2404.06046

e.g. Nuclear shapes in neutron-rich Ni region (deformation in Ge around $N = 40$)

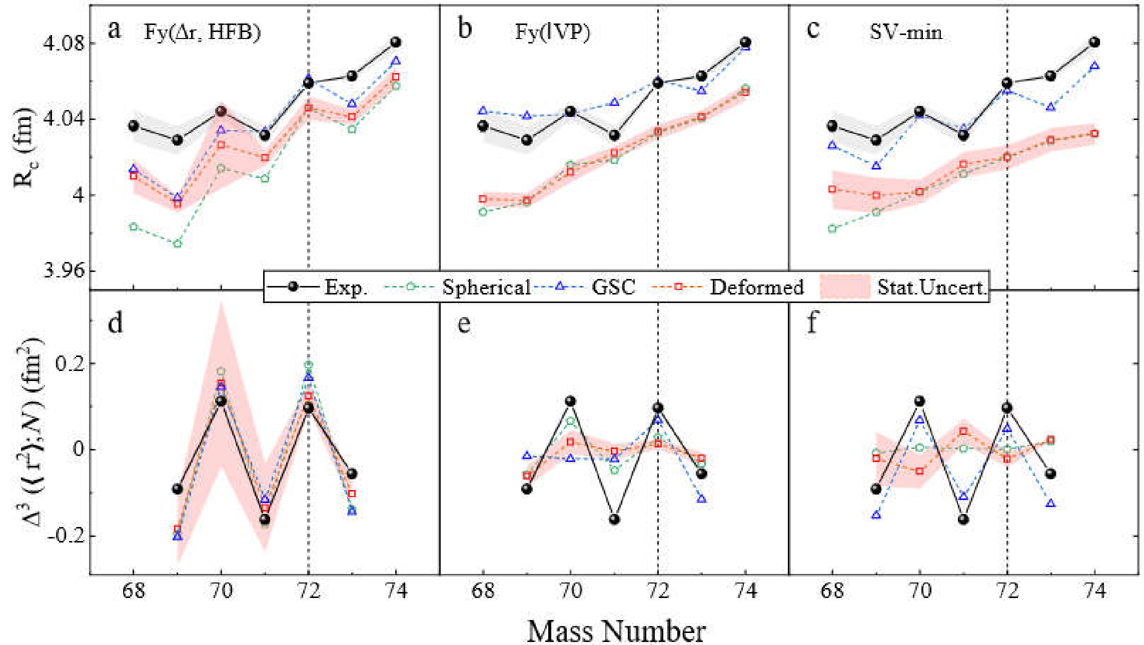


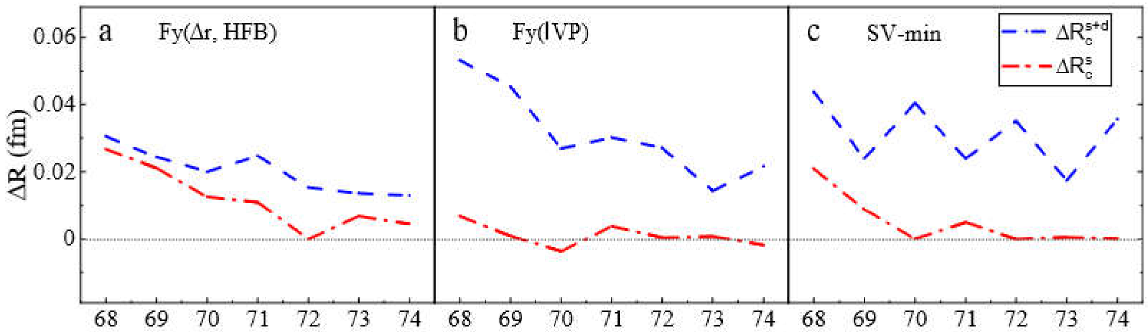
$$\Delta R_c^s \equiv R_c^{\text{Deformed}} - R_c^{\text{Spherical}}$$

- from the static deformation

$$\Delta R_c^{s+d} \equiv R_c^{\text{GSC}} - R_c^{\text{Spherical}}$$

- from the static deformation +dynamic fluctuations

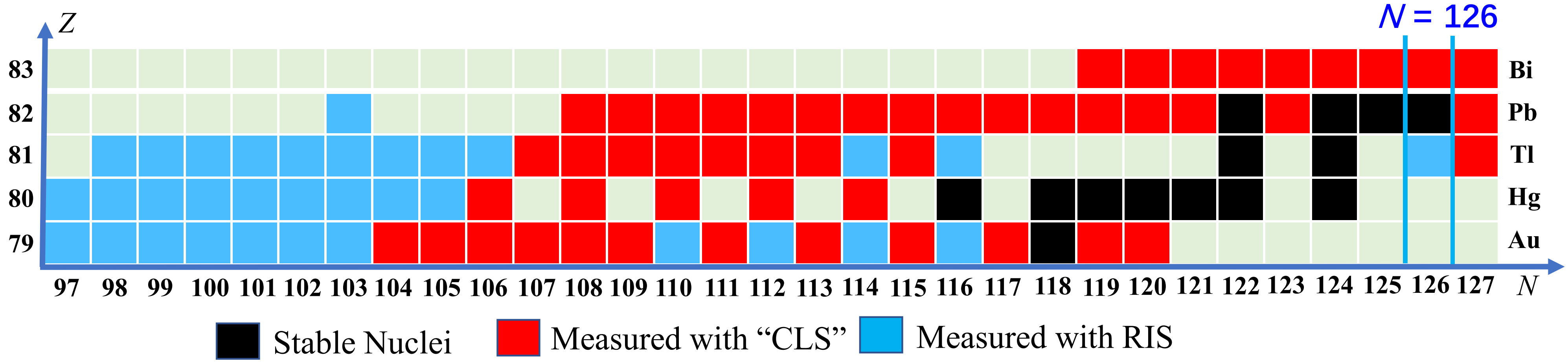


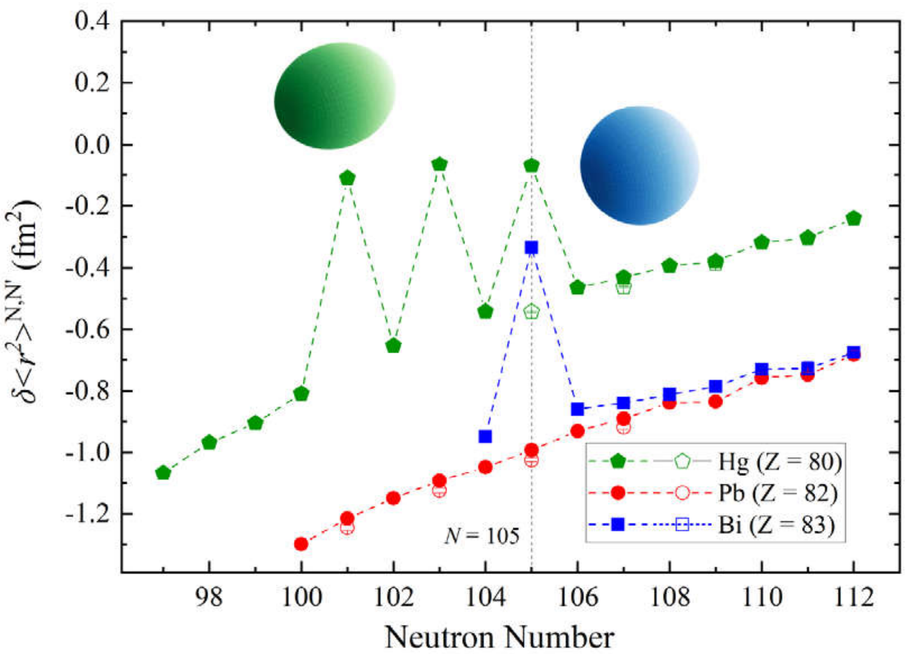


Both pairing and deformation contribute to the enhanced OES in the Ge charge radii around $N = 40$

S.J. Wang, A. Kanellakopoulos, X.F. Yang et al., Submitted to PLB (2024), arXiv preprint arXiv:2404.06046

e.g. Nuclear shapes in neutron-deficient lead region





- **Large shape staggering in Hg from *N* = 105 to 100**

  MCSM: interplay between monopole and quadrupole interactions driving a quantum phase transition

  B. A. Marsh, et al. Nat. Phys. 14, 1163-1167(2018)

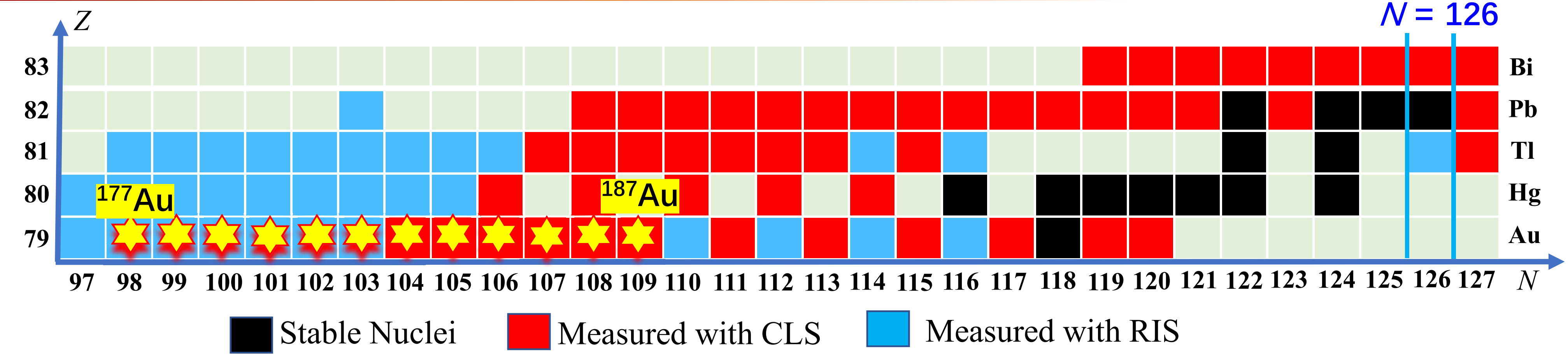
- **Same phenomenon in Bi isotopes around *N* =105**

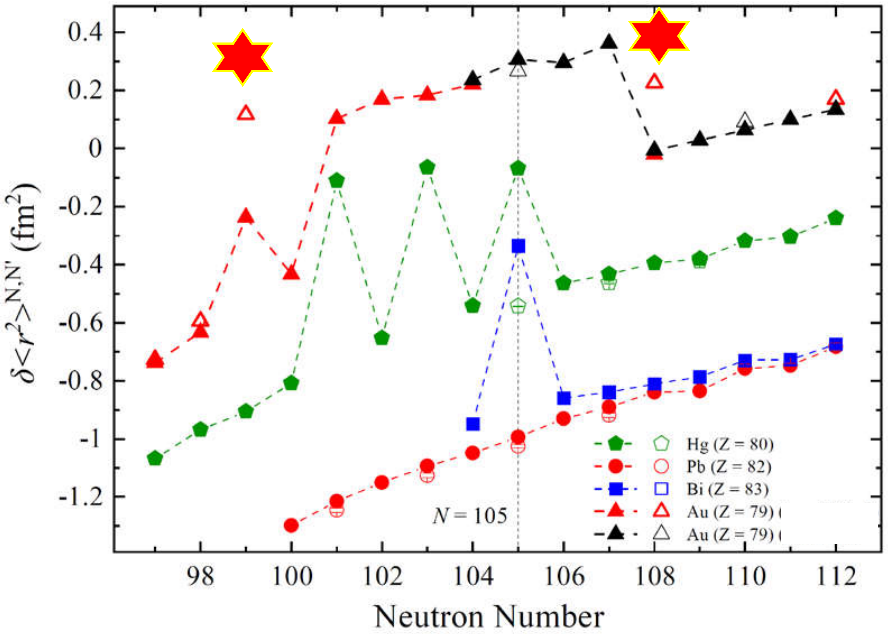
  A. Barzakh, et al. Phys. Rev. Lett. 127, 192501(2021)

- **Pb isotopes remain spherical down to *N* = 101**

  H. De. Witte et al., Phys. Rev. Lett., 98, 112502 (2007)

e.g. Nuclear shapes in neutron-deficient lead region (Island of deformation in Au?)





The scenario is very different in Au (Z = 79)

- A sudden onset of strong deformation with at N = 107

  K. Wallmeroth et al., Nuclear Physics A 493, 224 (1989)

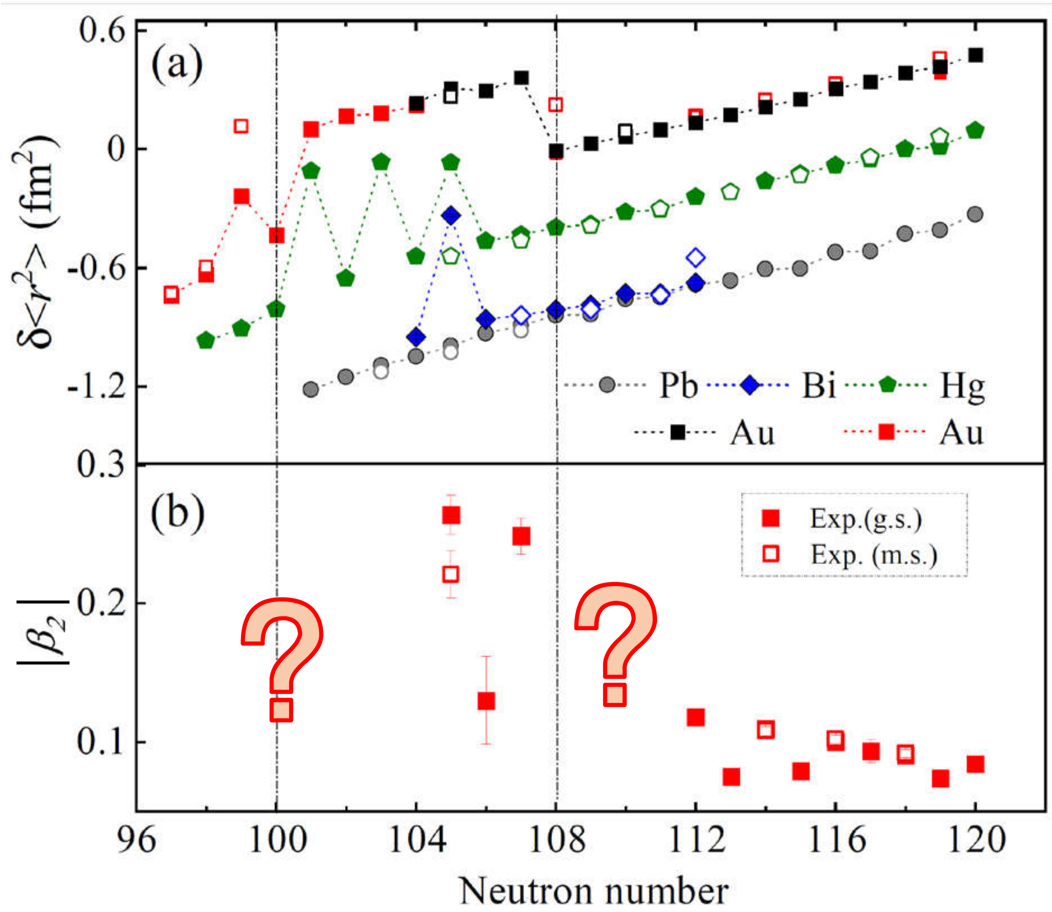
- Deformation remains constantly large down to N = 101
- Deformation ends at N ~100?

  J. G. Cubiss et al. Phys. Rev. Lett. 131, 202501 (2023)

- Large isomer shifts found in ^{178,187}Au

A region called "island of deformation"

e.g. Nuclear shapes in neutron-deficient lead region (Island of deformation in Au?)

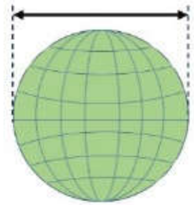


$$\langle\beta_2^2\rangle = \langle\beta_2\rangle^2 + \left(\langle\beta_2^2\rangle - \langle\beta_2\rangle^2\right) = \beta^2_{\text{static}} + \beta^2_{\text{dynamic}}.$$

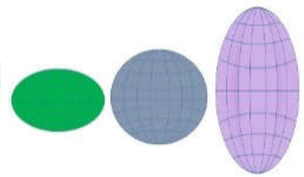
$$\langle r^2\rangle = \langle r^2\rangle_0\left(1 + \frac{5}{4\pi}\langle\beta_2^2\rangle\right)$$

Nuclear Charge radii

=> static deformation
+dynamic fluctuations



$$Q_{\text{intr.}} = \frac{3}{\sqrt{5\pi}} Z R_0^2 \beta_2 (1 + 0.36\beta_2)$$

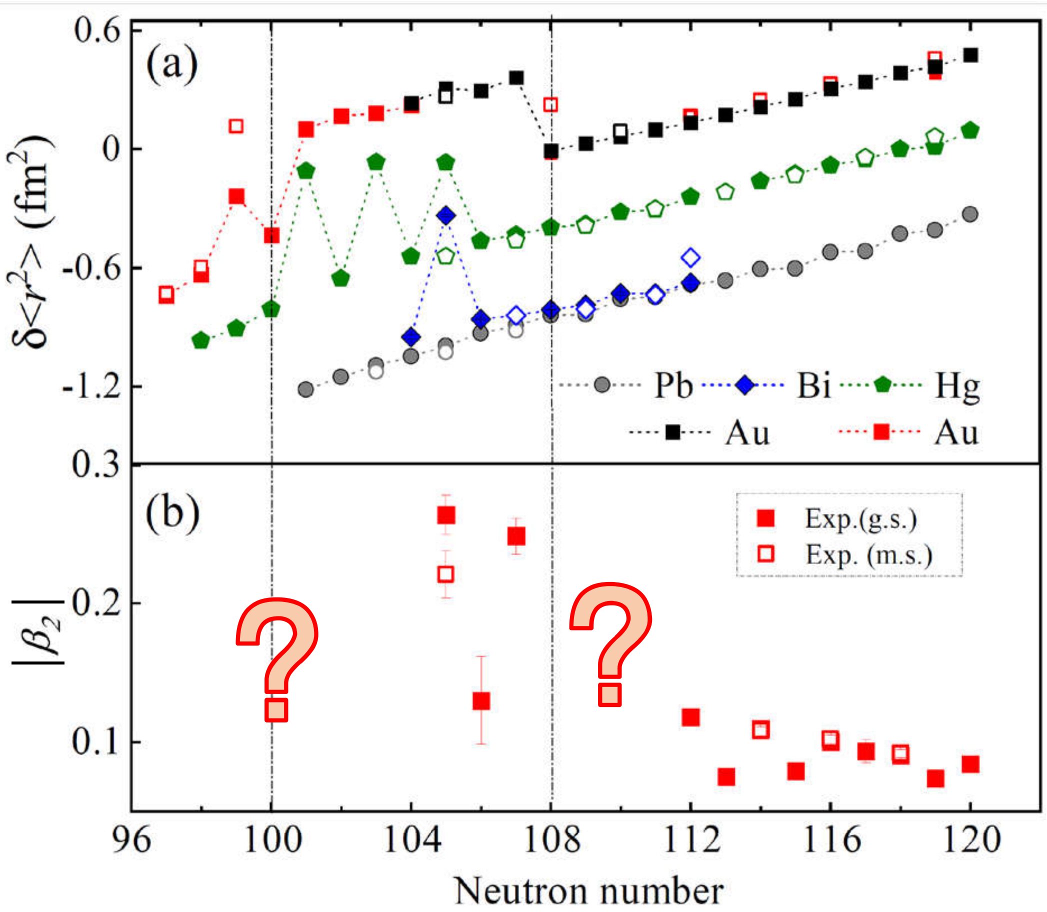


Quadrupole moment

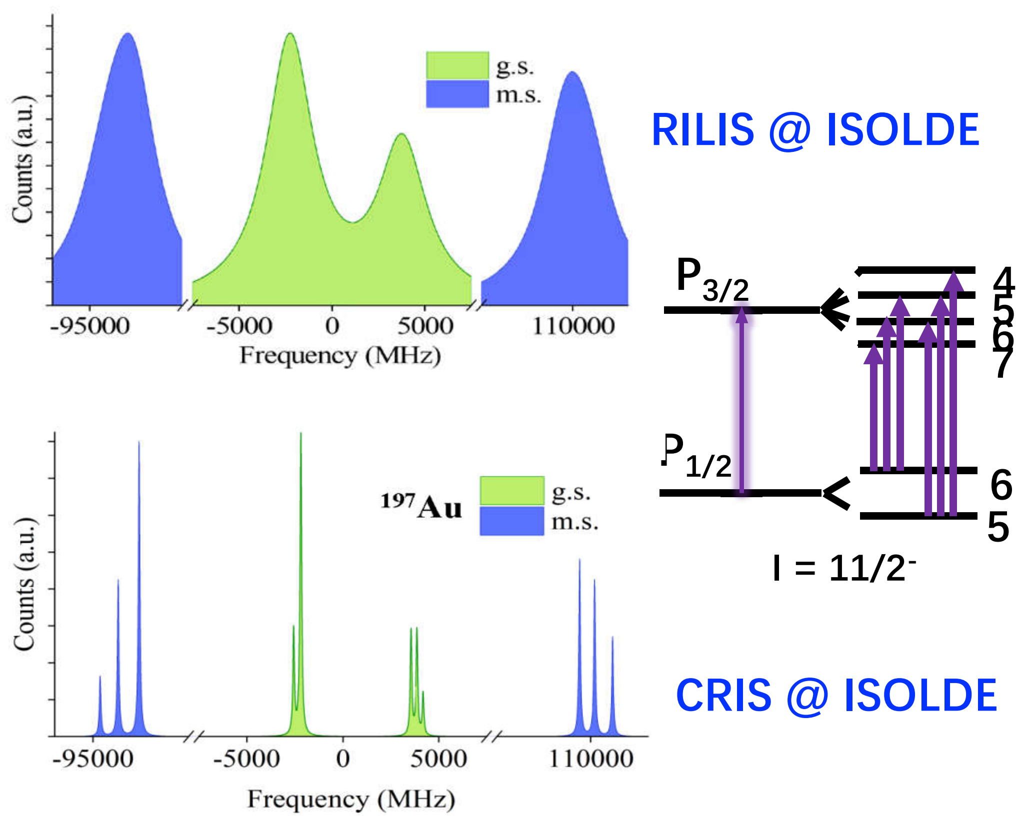
=> static deformation

X.F. Yang et al., CERN-INTC-2023-044 ; INTC-P-667(2023)

e.g. Nuclear shapes in neutron-deficient lead region (Island of deformation in Au?)

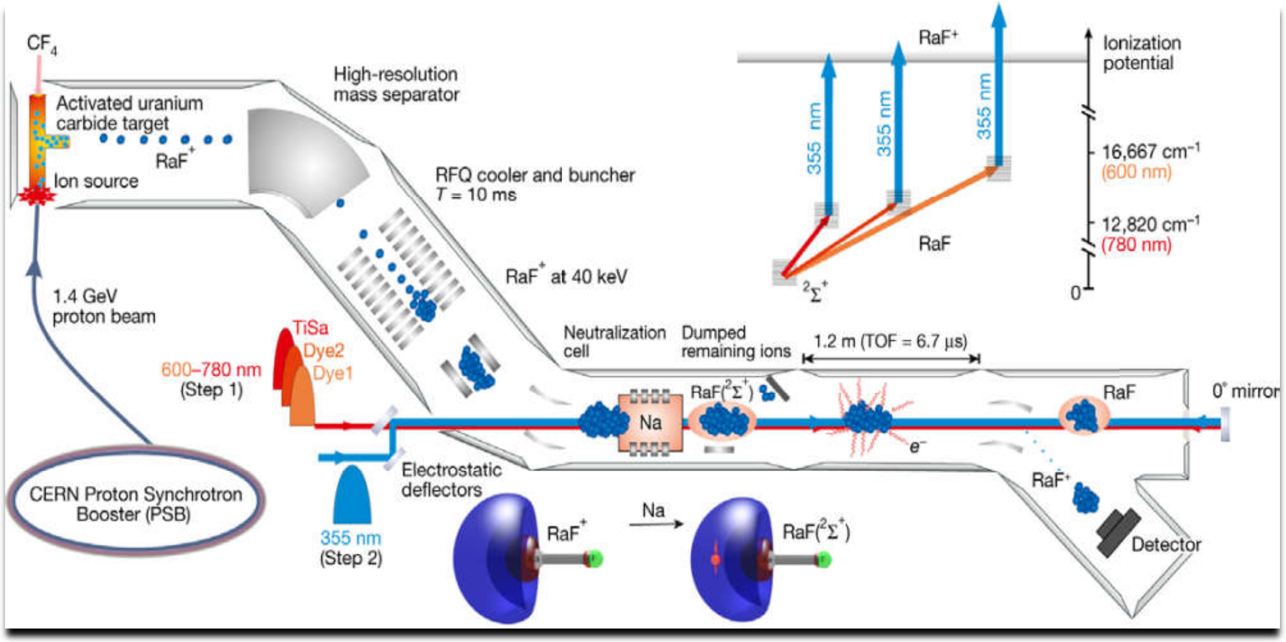


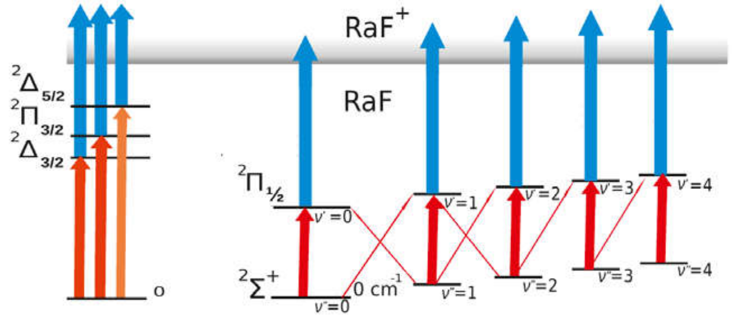
HFS of Au atom



X.F. Yang et al., CERN-INTC-2023-044 ; INTP-P-667(2023)

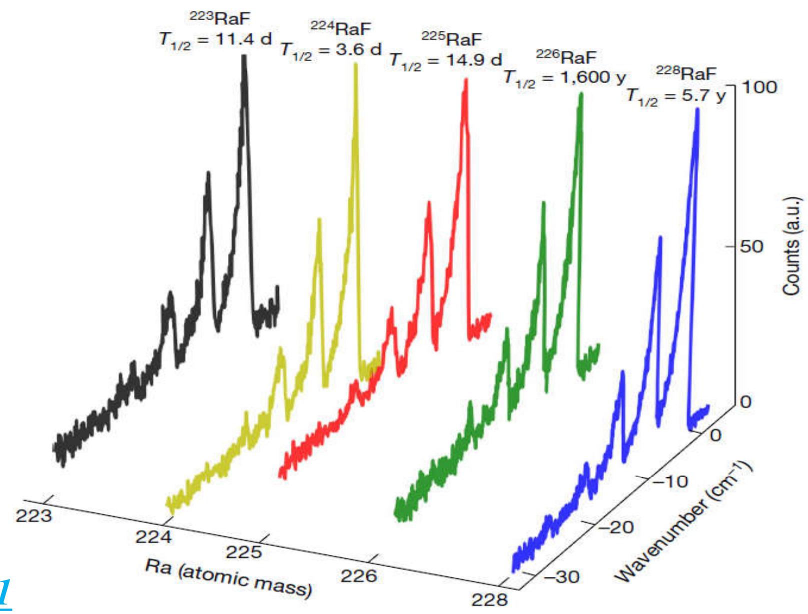
e.g. Nuclear information from radioactive molecules





$$H_{\text{Mol.}} = H_{el} + H_{\text{vib.}} + H_{\text{rot.}} + H_{\text{hfs}}$$

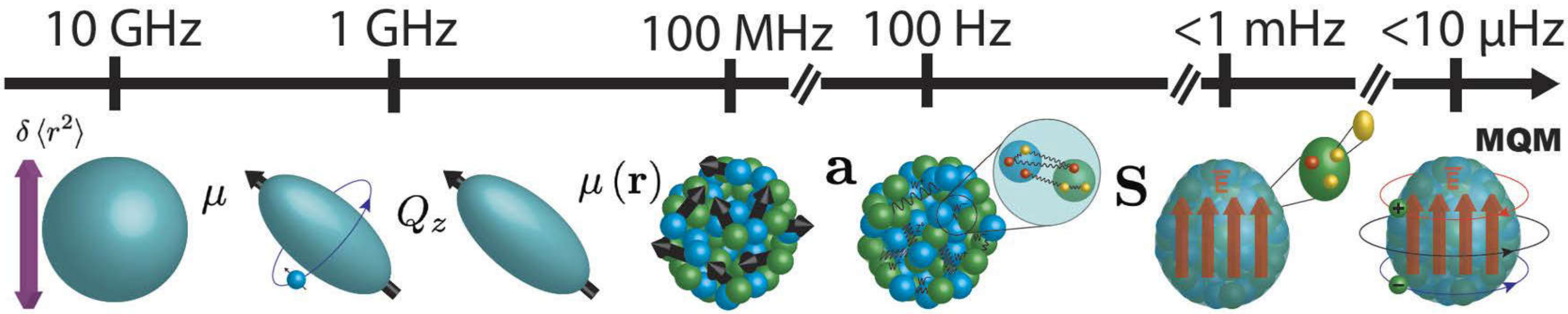
☑ ☑ ☑ ☑



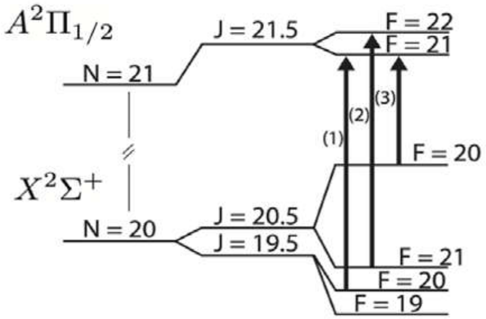
Nature 581, 396 (2020) ; PRL 127,033001(2021)
Nat. Phys. 20, 202 (2024) ; Science, under review (2023) arXiv.2311.04121

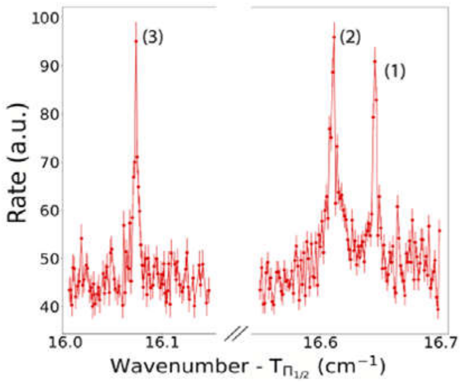
https://isolde-cris.web.cern.ch/

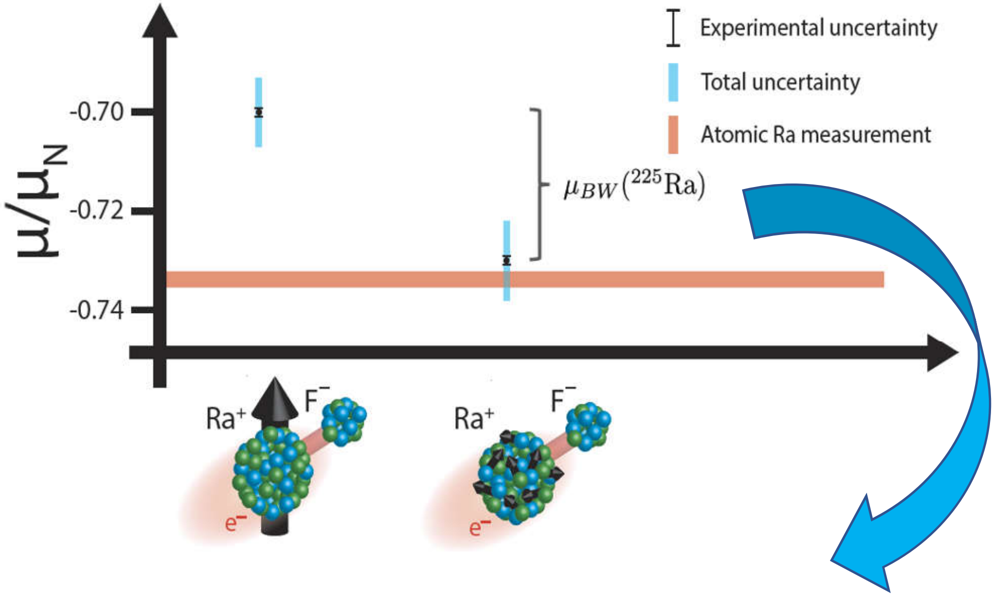
e.g. Nuclear information from radioactive molecules



$^{225}Ra^{19}F$, Z = 88







https://doi.org/10.48550/arXiv.2311.04121

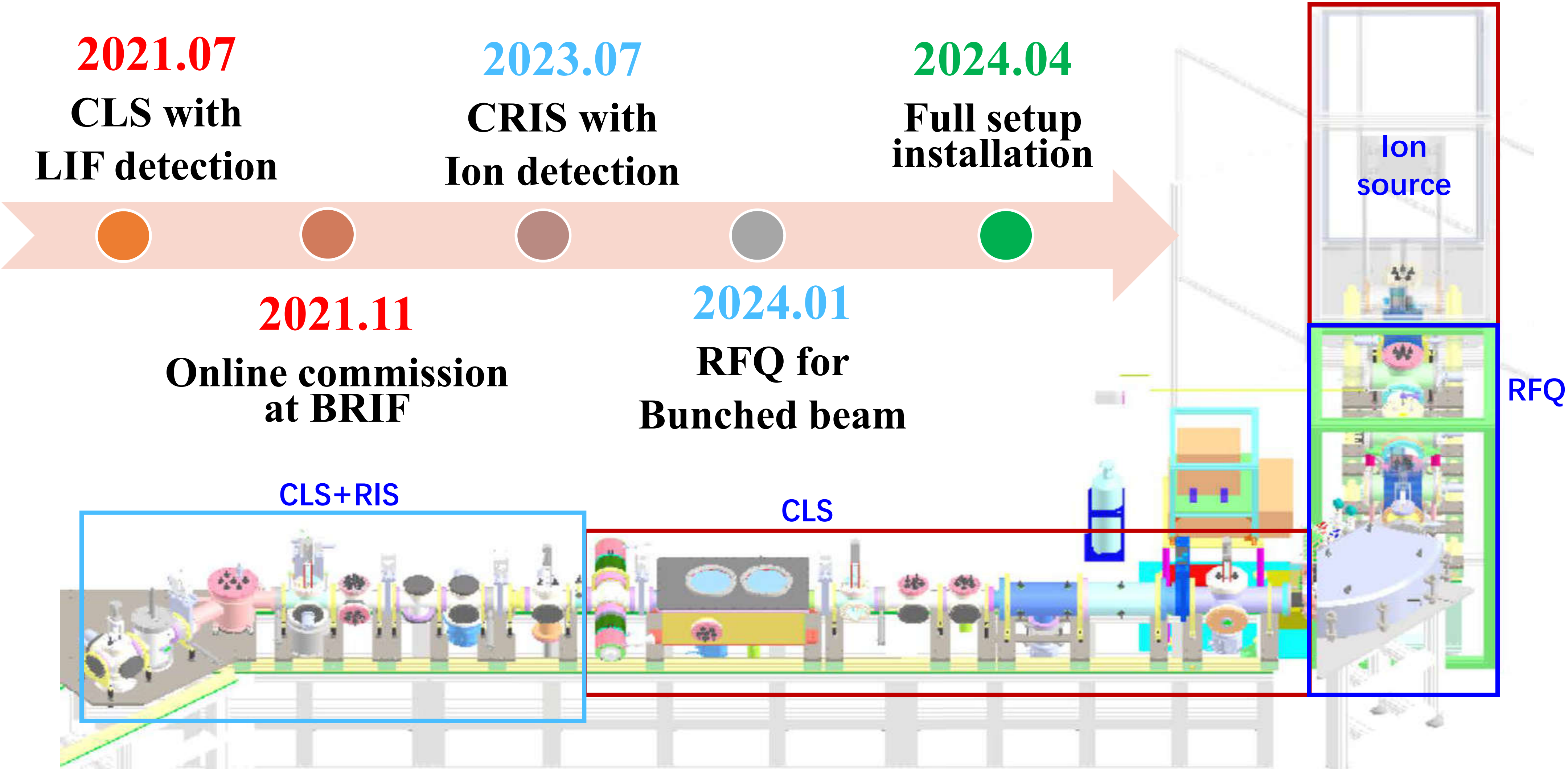
Bohr-Weisskopf effect (BW) arising from the non-uniform distribution of magnetization over the nucleus

Outline

北京大學 PEKING UNIVERSITY

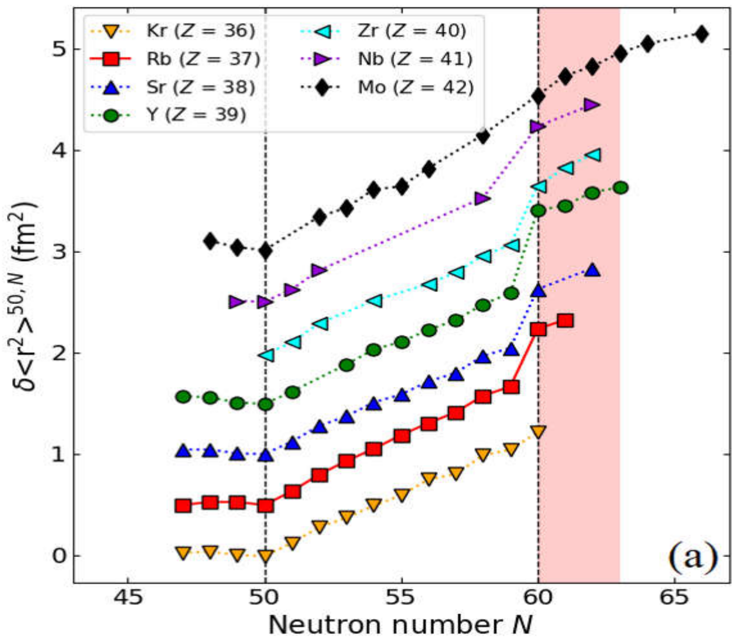
- □ Nuclear structure and g.s. properties
- □ Hyperfine interaction and laser spectroscopy
- □ Nuclear structure studied from laser spectroscopy
- □ **Laser spectroscopy development and near future work**

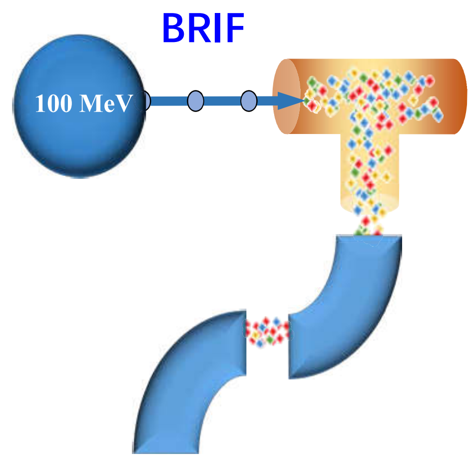
Laser spectroscopy development in China (PKU, CIAE, IMP, LZU)

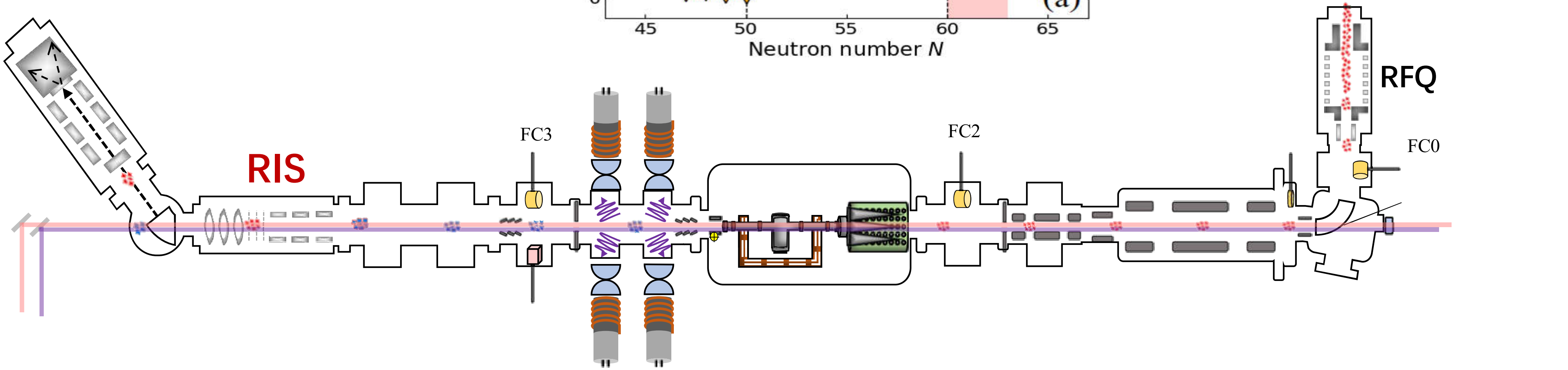


Near future work: CRIS @BRIF-CIAE

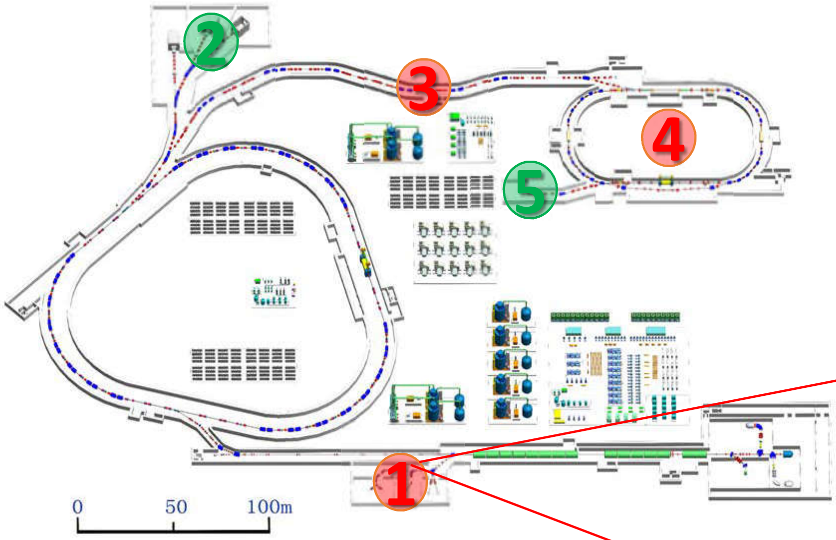
- UCx-> Neutron rich Rb
- Installation of RFQ+CRIS
- $^{98-100}$Rb for deformation

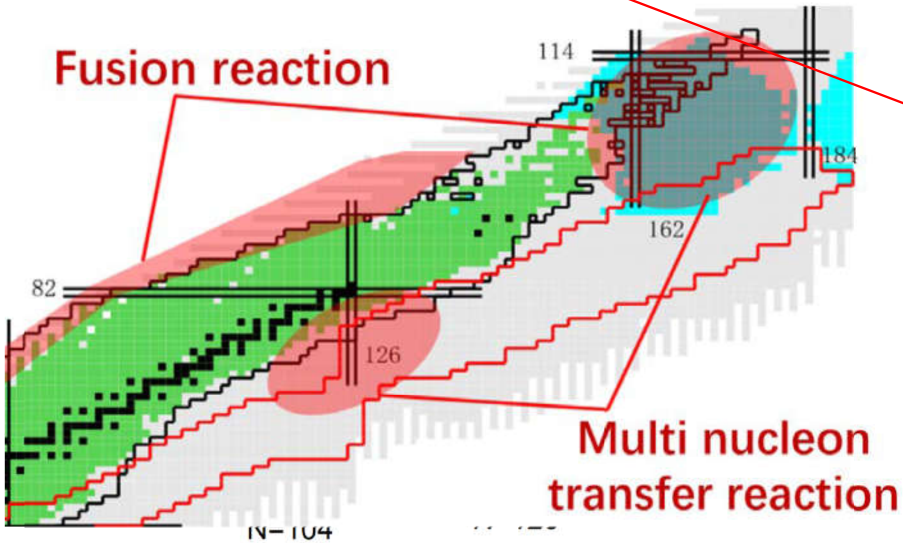


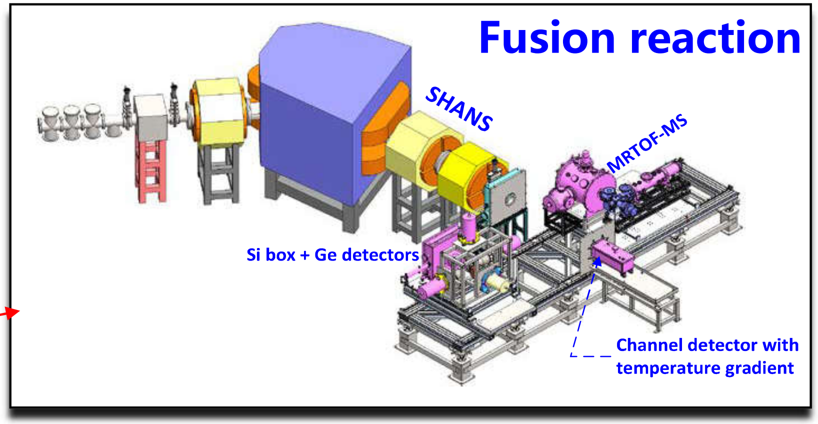




Near future work: CRIS @HIAF-IMP







- ☐ MR-TOF
- ☐ Decay spectroscopy
- ☐ Collinear laser spectroscopy

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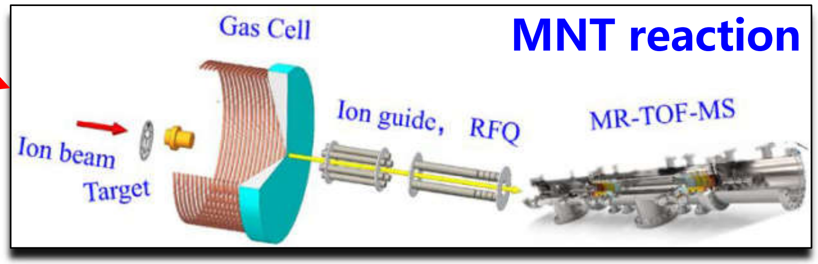

- ☐ MR-TOF
- ☐ Decay spectroscopy
- ☐ Collinear laser spectroscopy

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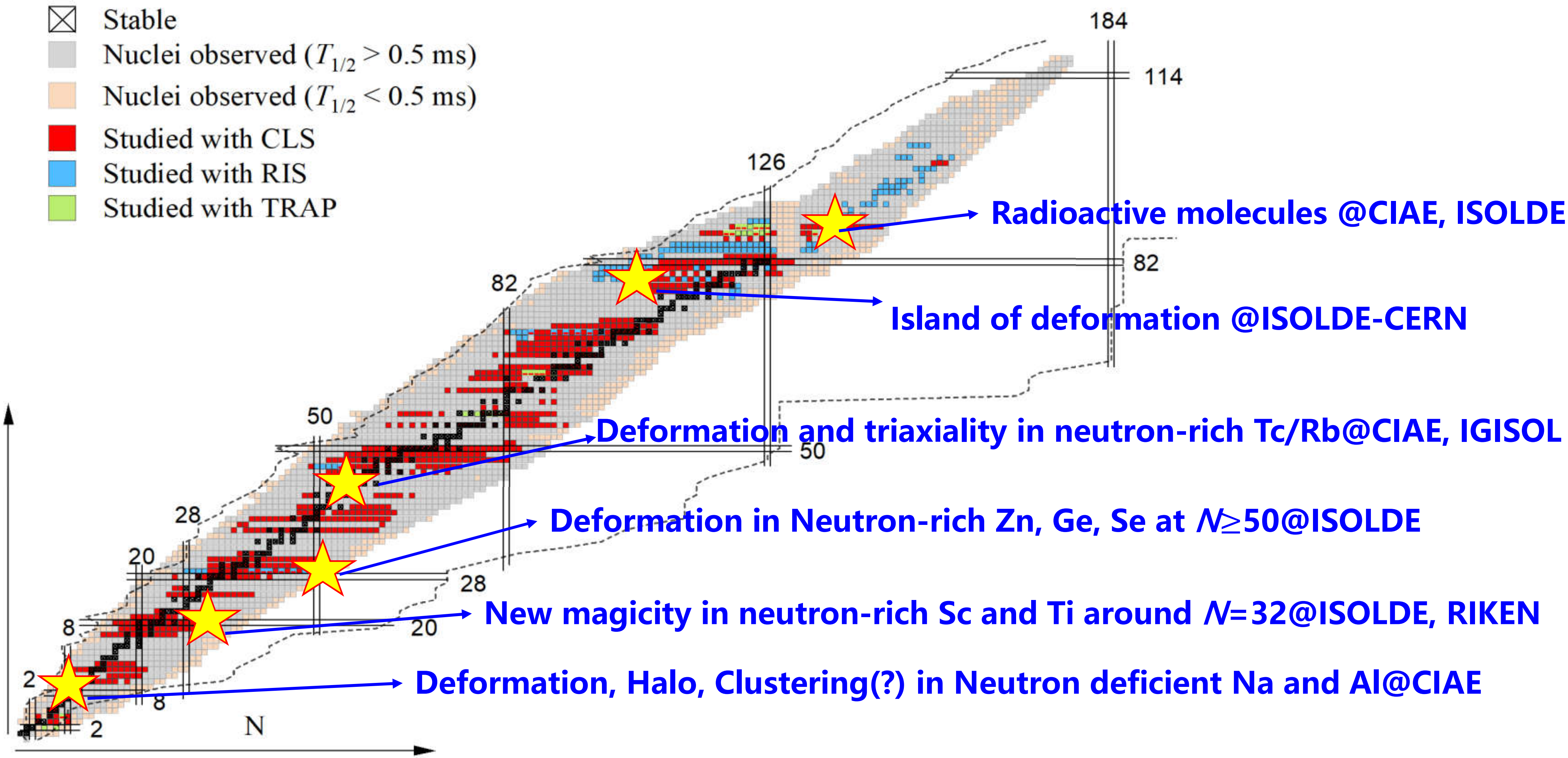
Near future work: more exotic cases

Approved or planned experiments



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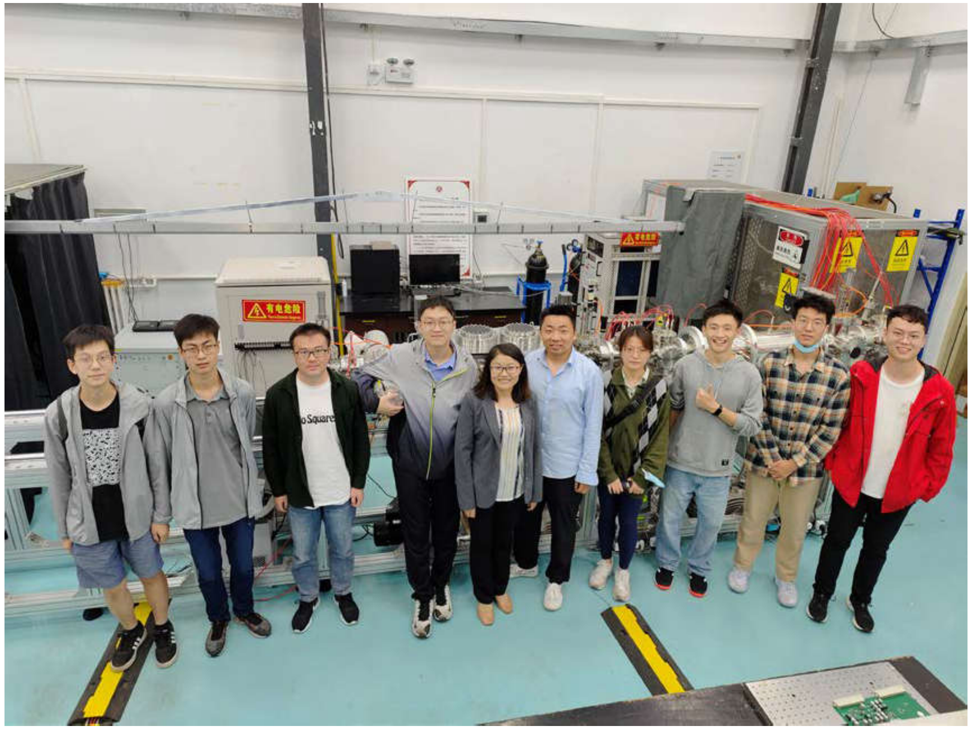
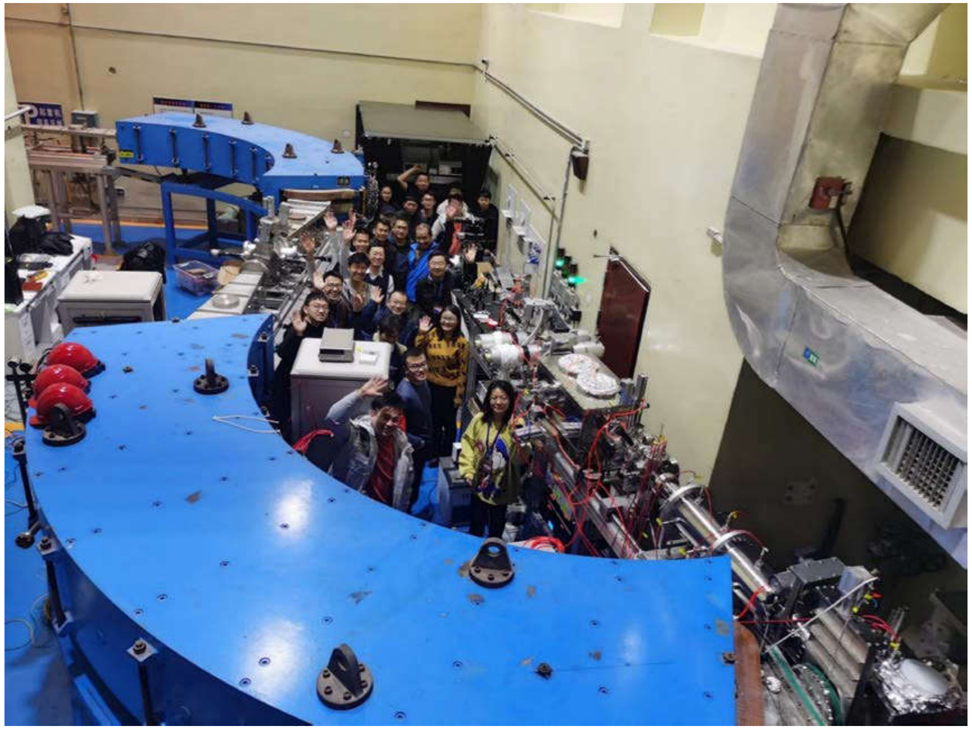
Thanks for your attention!





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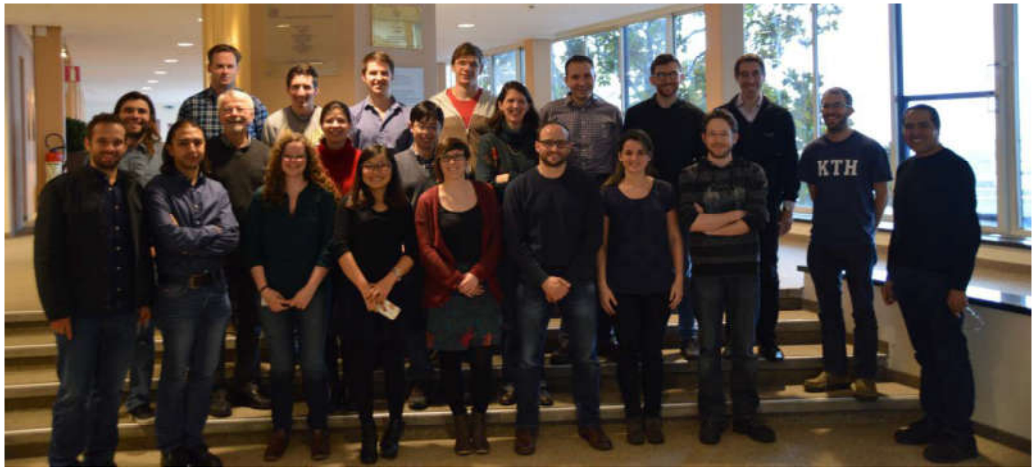
Thanks for your attention!

https://collaps.web.cern.ch/



https://isolde-cris.web.cern.ch/