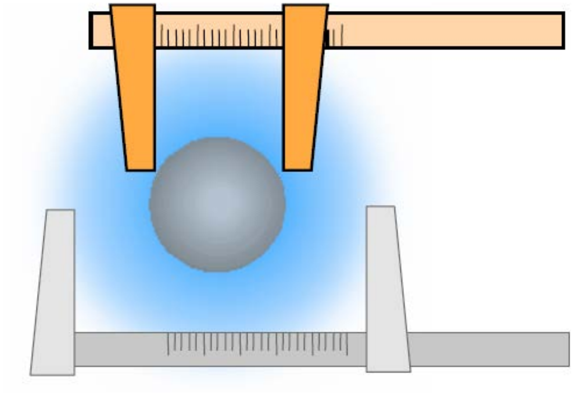

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Charge radii of unstable Sc and Zn isotopes
-from isotope shifts measurement

Xiaofei Yang

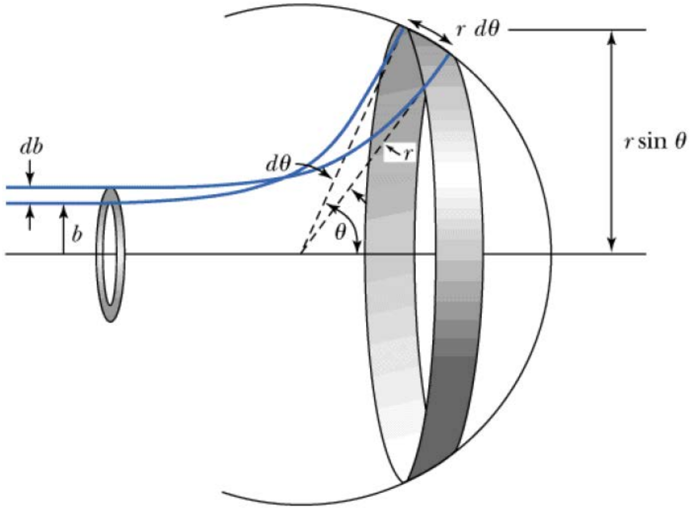
SKLNPT, School of Physics, Peking University

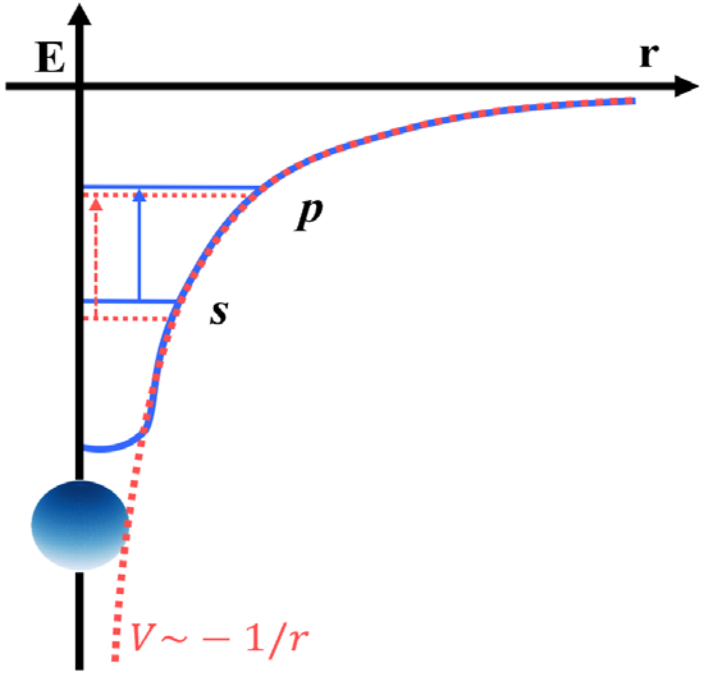
“IAEA Technical Meeting on Compilation and Evaluation of Nuclear Charge Radii ”, Jan. 27-Jan.30 2025, IAEA, Vienna

Outline

- Methods to measure the charge radii
- Charge radii of Sc isotopes
- Charge radii of Zn isotopes
- Summary

Methods to measure the charge radius





Scattering/reaction

- Electron scattering
  K. Tsukada et al., PRL, 131, 092502 (2023)
- Proton scattering
- Reaction cross section

Optical spectroscopy

- Optical isotope shifts
  X.F. Yang et al., PPNP, 129, 104005(2023)
- K X-ray isotope shifts
- Transition in μ-atoms

Electromagnetic probes

Nuclear-model independent

Charge radius from isotope shift

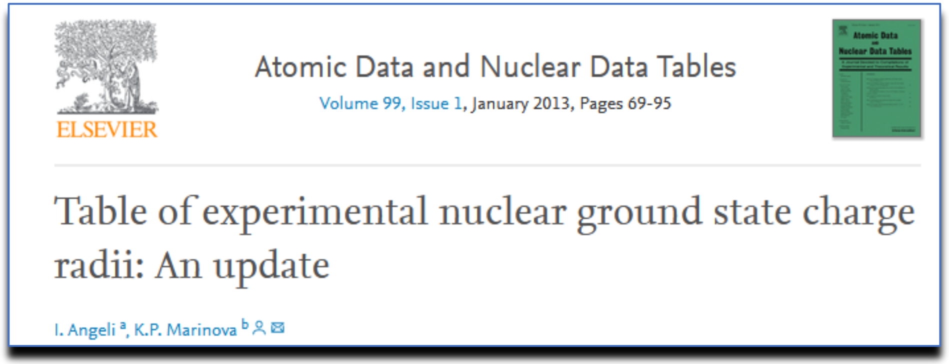

Atomic Data and Nuclear Data Tables
Volume 99, Issue 1, January 2013, Pages 69-95
ELSEVIER

Table of experimental nuclear ground state charge radii: An update

I. Angeli [a], K.P. Marinova [b]

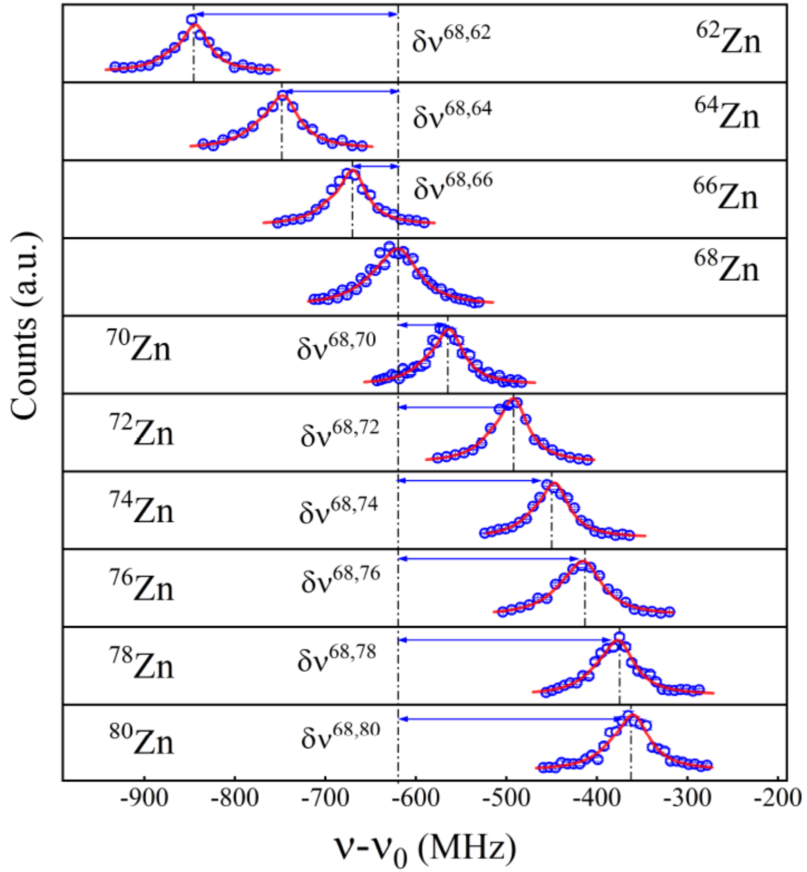
Summarized all the nuclear charge radii of isotopes measured using all different methods before 2013.

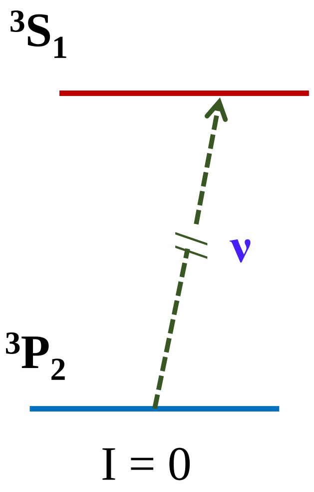
For unstable nuclei, most of them comes from isotope shifts!

Isotope shifts：

$$\delta\nu_{\mathrm{IS}}^{AA'} = K\frac{M^{A'}-M^{A}}{M^{A'}M^{A}} + F\,\delta\langle r_c^2\rangle^{AA'}$$

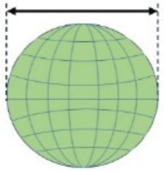
Changes in mean square charge radii





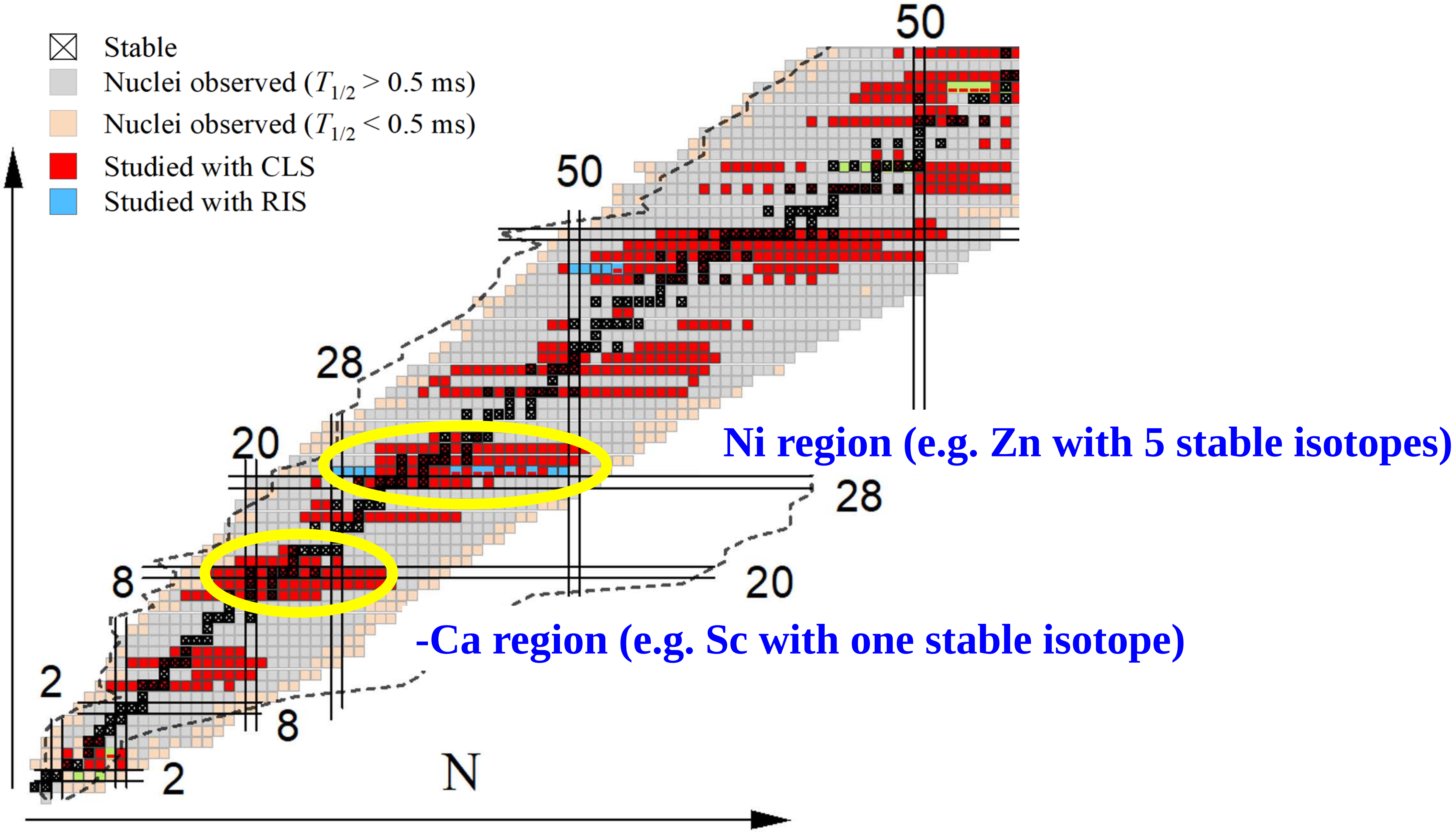
RMS：root mean square charge radii

$$R = \sqrt{\langle r^2\rangle^{A'}} = \sqrt{\delta\langle r_c^2\rangle^{AA'} + \langle r^2\rangle^{A}}$$



How to get F, K?

Charge radii from isotope shift



Outline

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- Methods to measure the charge radii
- Charge radii of Sc isotopes
- Charge radii of Zn isotopes
- Summary

Charge radii of isotopes in Ca region

- BECOLA
- IGISOL
- COLLAPS
- CRIS

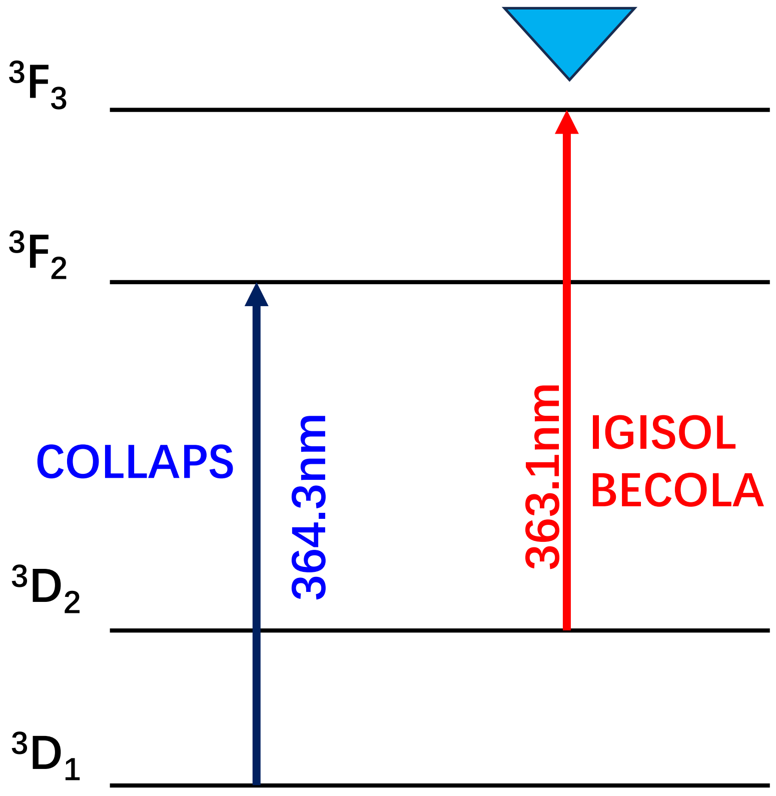
N = 20, N = 28, N = 32, Z = 20

	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Ti (Z = 22)	41	41	43	44	45	46	47	48	49	50	51	52	53	54	55	56
Sc (Z = 21)	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
Ca (Z = 20)	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
K (Z = 19)	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
Ar (Z = 18)	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	

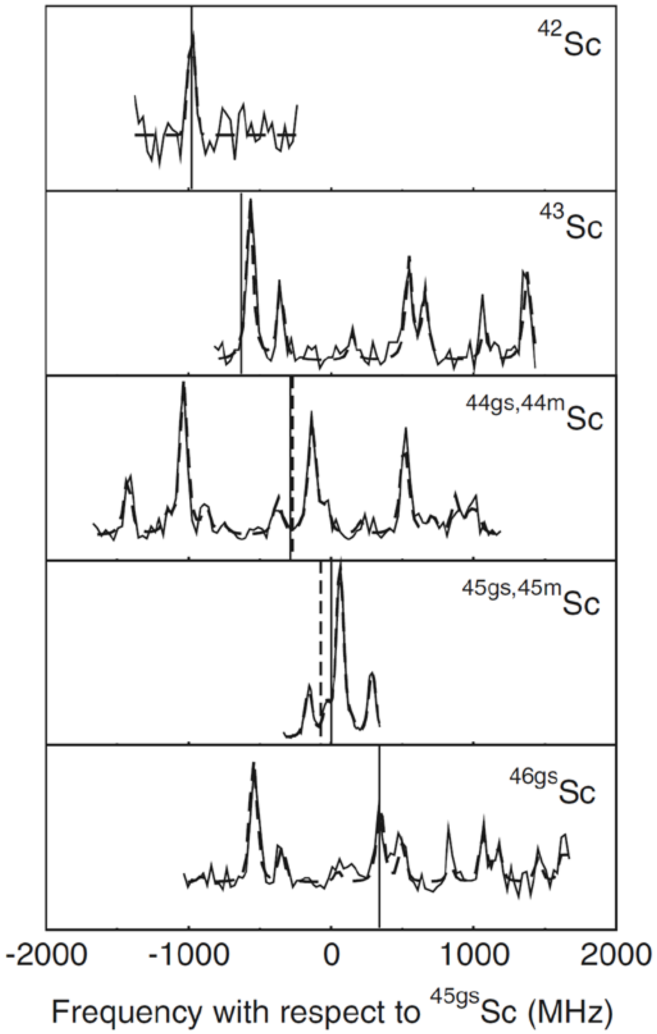
Studied by laser spec. | To be measured | Planned

K	Publications	Ca	Publications	Sc	Publications
^{36,37}K	*PRC92, 014305 (2015)*	$^{36\text{-}38}$Ca	*NP 15, 432 (2019).*	^{40,41}Sc	*PRL131, 102501 (2023)*
$^{38\text{-}51}$K	*PLB731, 97 (2014)* *PRL 113, 052502 (2014)*	$^{43\text{-}52}$Ca	*NP 12, 594 (2016).*	^{42m}Sc	*PLB819, 136439 (2021)*
$^{38\text{-}52}$K	*PRC100, 034304 (2019)* *NP17, 439 (2021)*	^{53,54}Ca	*To be published*	$^{44\text{-}49}$Sc	*PRL, under revision (2025)*

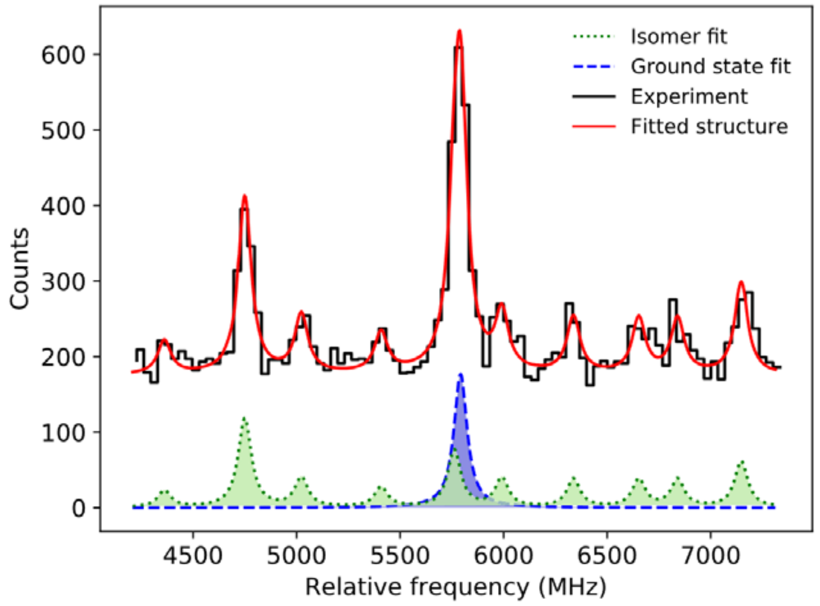
Charge radii of scandium isotopes



J. Phys. G 38 (2011) 025104

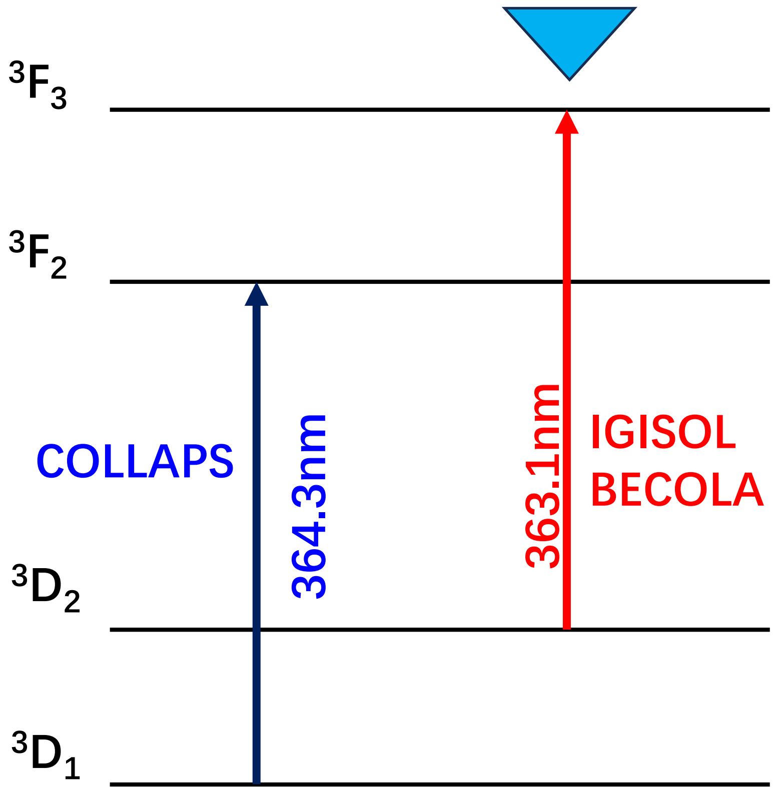


PLB 819, 136439 (2021)

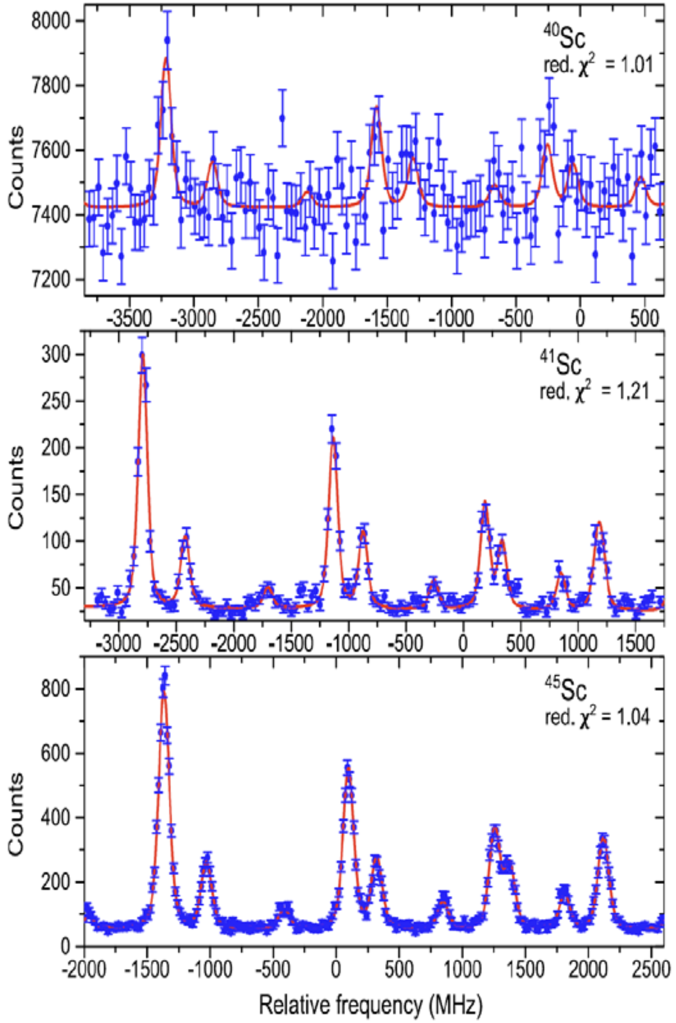


	F (MHz fm^{-2})	*M* (GHz u)	Method
2011 IGISOL	-355(50)	583(30)	MCDF
2021 IGISOL	-349(15)	625(60)	MCDF

Charge radii of scandium isotopes



PRL131, 102501 (2023)

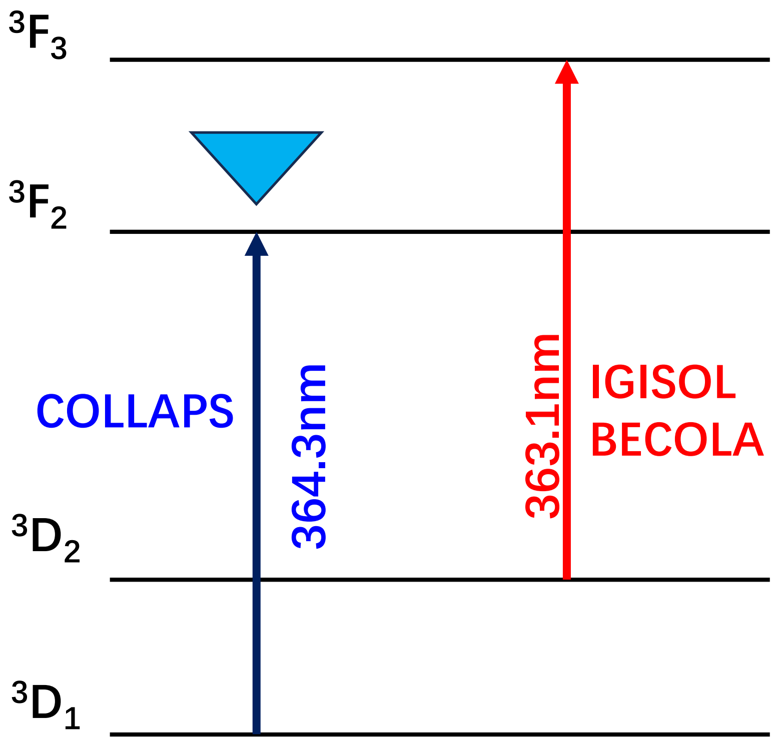


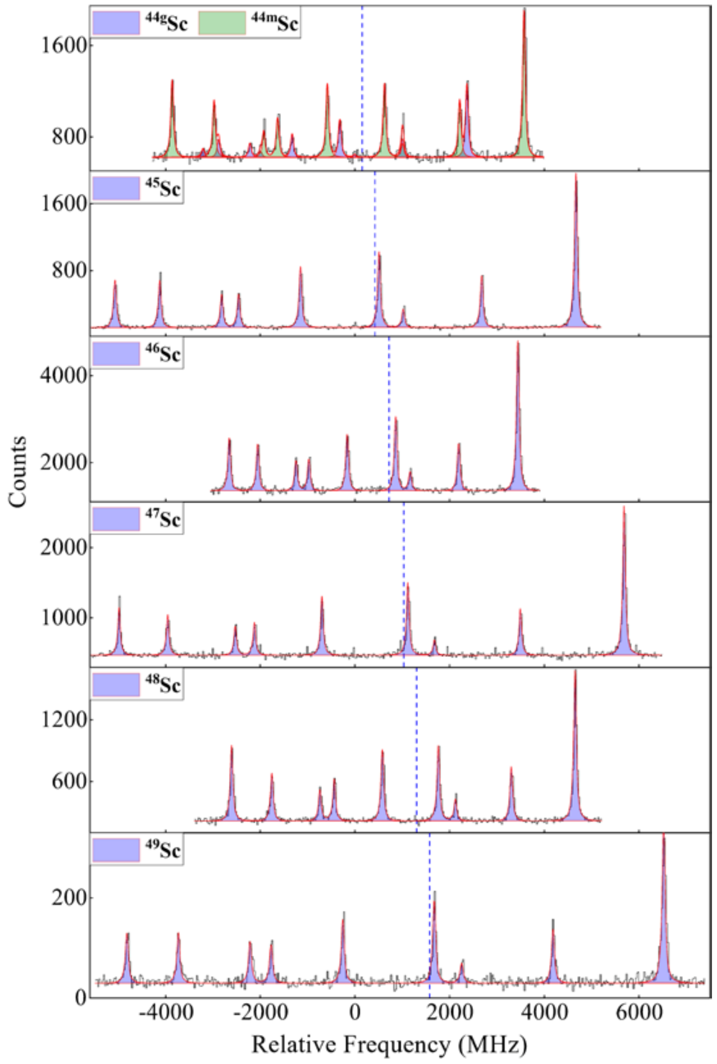
	F (MHz fm^{-2})	*M* (GHz u)	Method
2011 IGISOL	-355(50)	583(30)	MCDF
2021 IGISOL	-349(15)	625(60)	MCDF
2023 BECOLA	**-352(12)**	**604(22)**	**MCDHF**

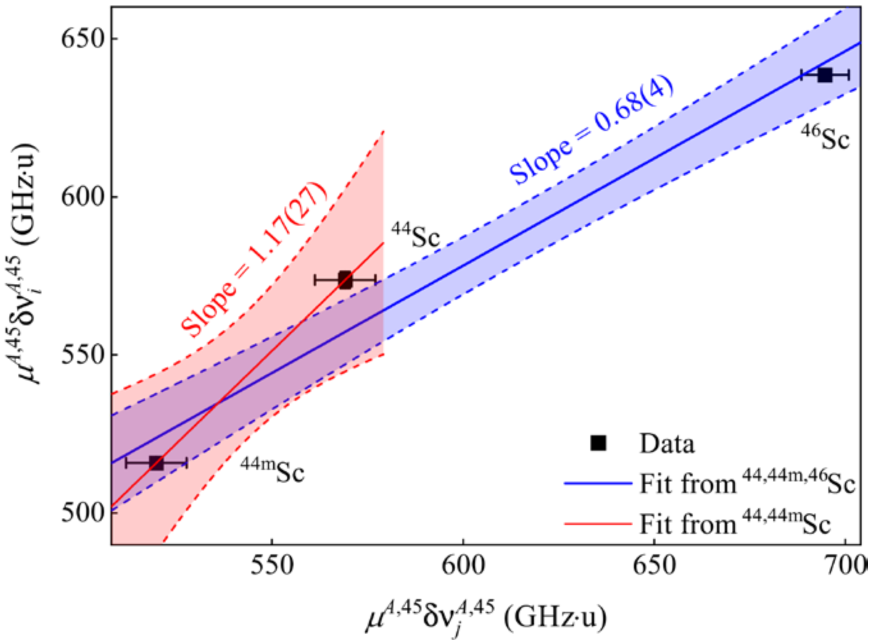
Series	$K^{(MS)}$ (GHz u)	$F^{(el)}$ (MHz/fm^2)
Ref. [33]	$+583 \pm 30$	-355 ± 50
Ref. [34]	$+625 \pm 60$	-349 ± 15
This Letter	$+633 \pm 40$	-358 ± 20
Weighted mean	$+604 \pm 22$	-352 ± 12

Charge radii of scandium isotopes @2018 experiment

PRL, under revision (2025)





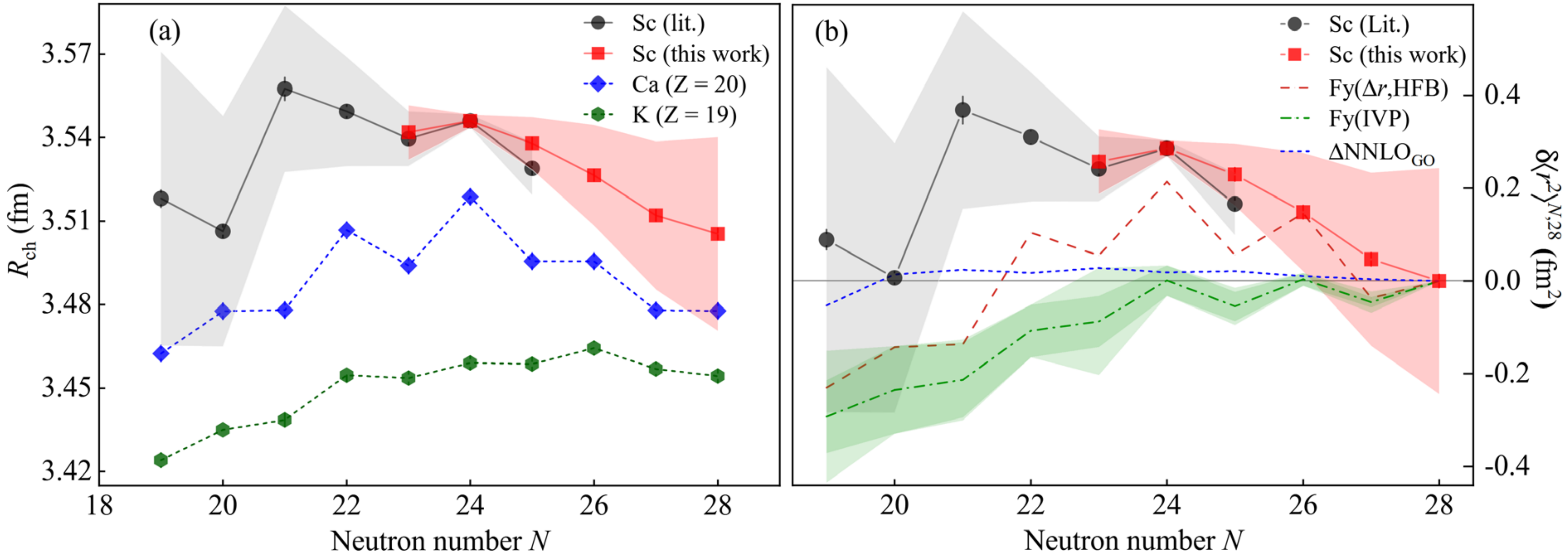


	F (MHz fm^{-2})	*M* (GHz u)	Method
$^3D_2$-$^3F_3$	-373(12)	602(50)	FSCC
	-352(12)	604(22)	MCDHF
$^3D_1$-$^3F_2$	-373(12)	595(50)	CI+MBPT

A. Borschevsky, M. L. Reitsma, J. C. Berengut

Charge radii of scandium isotopes

PRL, under revision (2025)



Outline

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- Methods to measure the charge radii
- Charge radii of Sc isotopes
- Charge radii of Zn isotopes
- Summary

Charge radii of isotopes in Ni region

- BECOLA
- COLLAPS
- CRIS

	39	40 (N = 40)	41	42	43	44	45	46	47	48	49	50 (N = 50)	51	52
Ge (Z = 32)	71	71	73	74	75	76	77	78	79	80	81	82	83	84
Ga (Z = 31)	70	71	72	73	74	75	76	77	78	79	80	81	82	83
Zn (Z = 30)	69	70	71	72	73	74	75	76	77	78	79	80	81	82
Cu (Z = 29)	68	69	70	71	72	73	74	75	76	77	78	79	80	81
Ni (Z = 28)	67	68	69	70	71	72	73	74	75	76	77	78	79	80

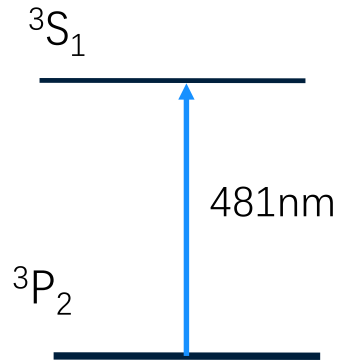
Z = 20

Studied by laser spec. To be measured Planned

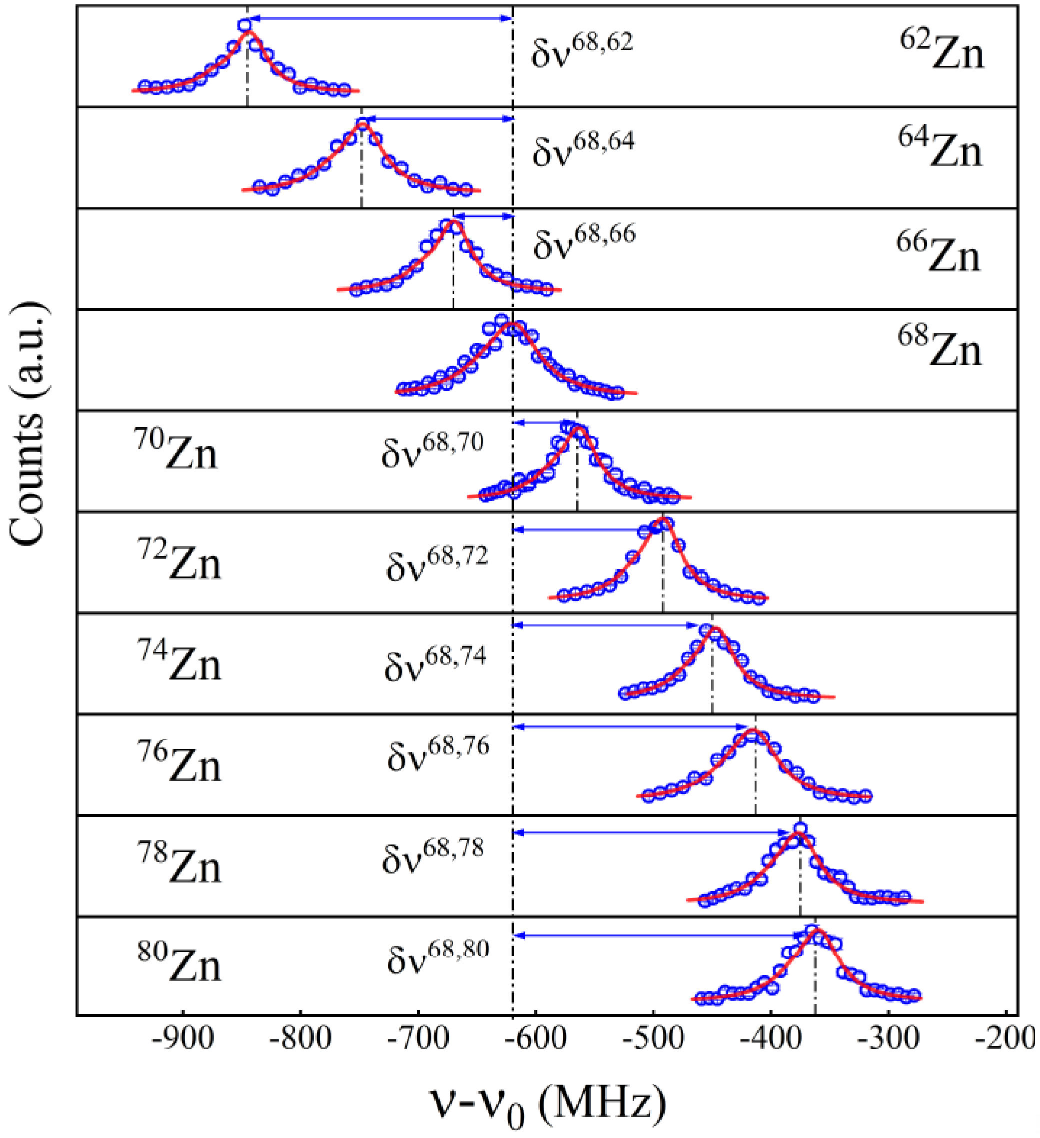
Ni	Publications	Cu	Publications	Zn	Publications
$^{55-56}$Ni	*PRL 129, 132501(2022)*	$^{58-75}$Cu	*PRC 93, 064318 (2016)*	$^{62-80}$Zn	*PRL 116, 182502 (2016)* *PLB 771, 385 (2017)*
$^{58-70}$Ni	*PRL 128, 022502(2022)*	$^{75-78}$Cu	*NP 16, 620 (2020)*	$^{80-82}$Zn	*To be published*

^{65,67}Ga *PRC 96, 044324 (2017)* $^{68-74}$Ge *PLB 856, 138867 (2024)*

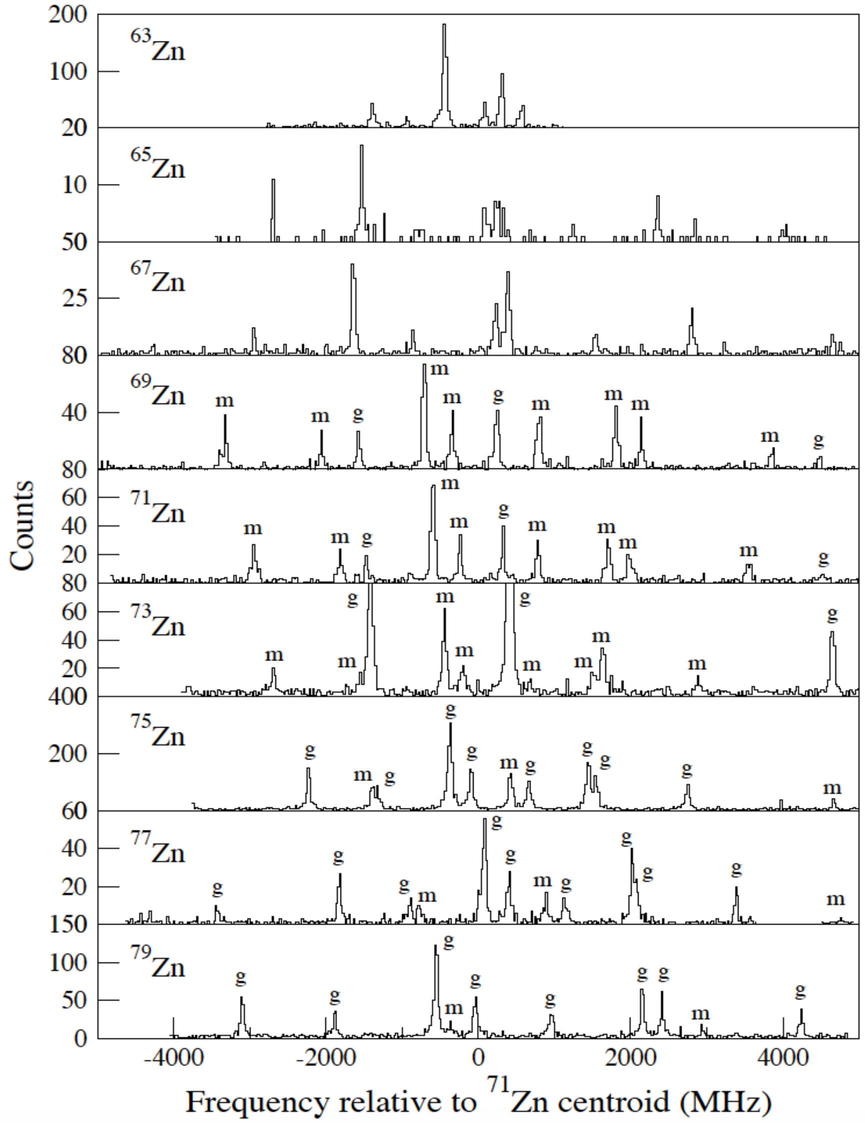
Charge radii of zinc isotopes @2014 experiment



Spin = 0



Spin >=1/2



Charge radii of zinc isotopes

MCDHF

PHYSICAL REVIEW A **96**, 042502 (2017)

Multiconfiguration calculations of electronic isotope-shift factors in Zn I

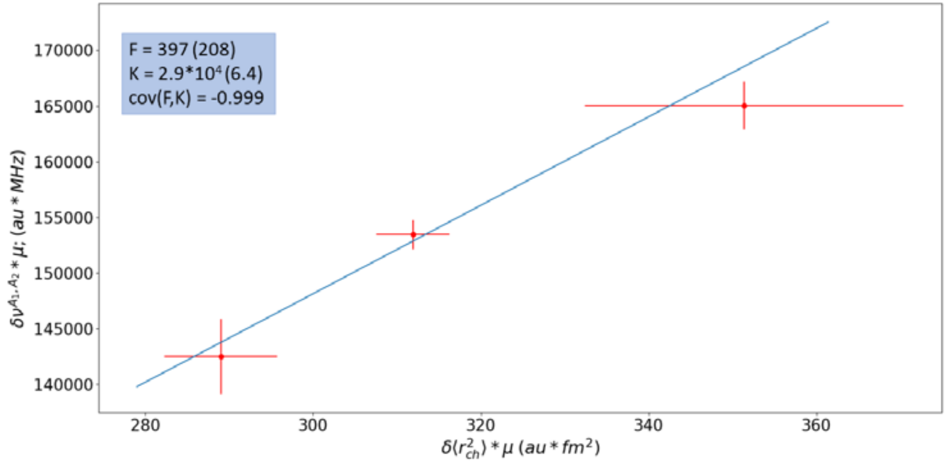
Livio Filippin,[1,*] Jacek Bieroń,[2,†] Gediminas Gaigalas,[3,‡] Michel Godefroid,[1,§] and Per Jönsson[4,¶]
[1]*Chimie Quantique et Photophysique, Université libre de Bruxelles, B-1050 Brussels, Belgium*
[2]*Instytut Fizyki imienia Mariana Smoluchowskiego, Uniwersytet Jagielloński, PL-30-348 Kraków, Poland*
[3]*Institute of Theoretical Physics and Astronomy, Vilnius University, LT-10222 Vilnius, Lithuania*
[4]*Group for Materials Science and Applied Mathematics, Malmö University, S-20506 Malmö, Sweden*
(Received 25 August 2017; published 12 October 2017)

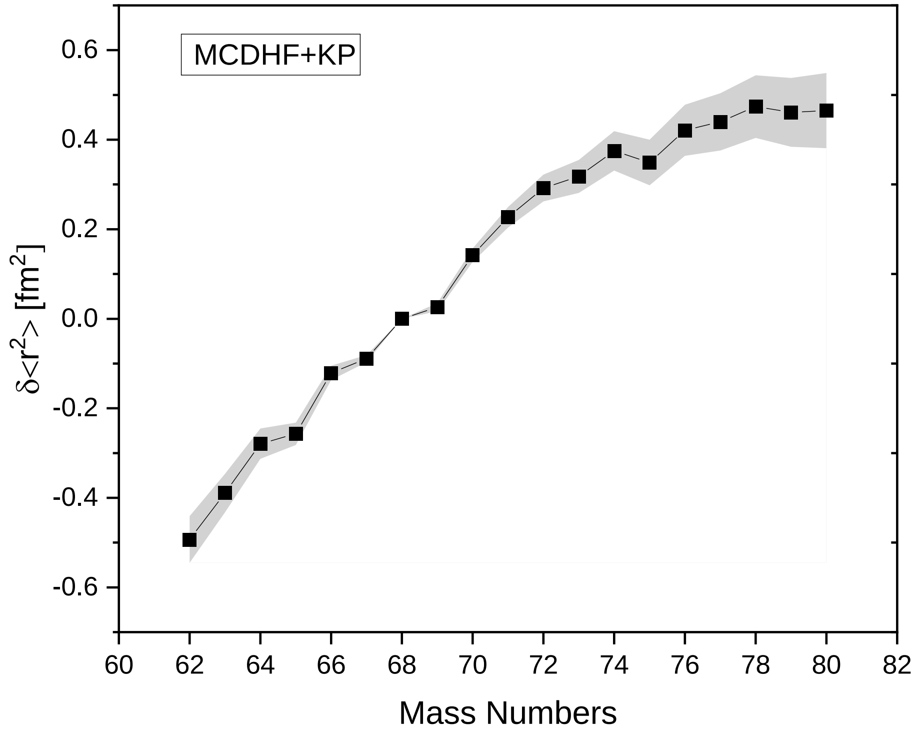
The present work reports results from systematic multiconfiguration Dirac-Hartree-Fock calculations of electronic isotope-shift factors for a set of transitions between low-lying states in neutral zinc. These electronic quantities, together with observed isotope shifts between different pairs of isotopes, provide the changes in mean-square charge radii of the atomic nuclei. Within this computational approach, different models for electron correlation are explored in a systematic way to determine a reliable computational strategy and to estimate theoretical error bars of the isotope-shift factors.

DOI: 10.1103/PhysRevA.96.042502

	F (MHz fm^{-2})	*M* (GHz u)	Method
2019 COLLAPS	+346(3)	+14(7)	**MCDHF**
2019 COLLAPS	**+346(35)**	**+49(17)**	**MCDHF + KP**

PLB 771, 385 (2017)





Charge radii of zinc isotopes

PHYSICAL REVIEW RESEARCH **5**, 043142 (2023)

All-optical differential radii in zinc

B. K. Sahoo[1,*] and B. Ohayon[2,†]

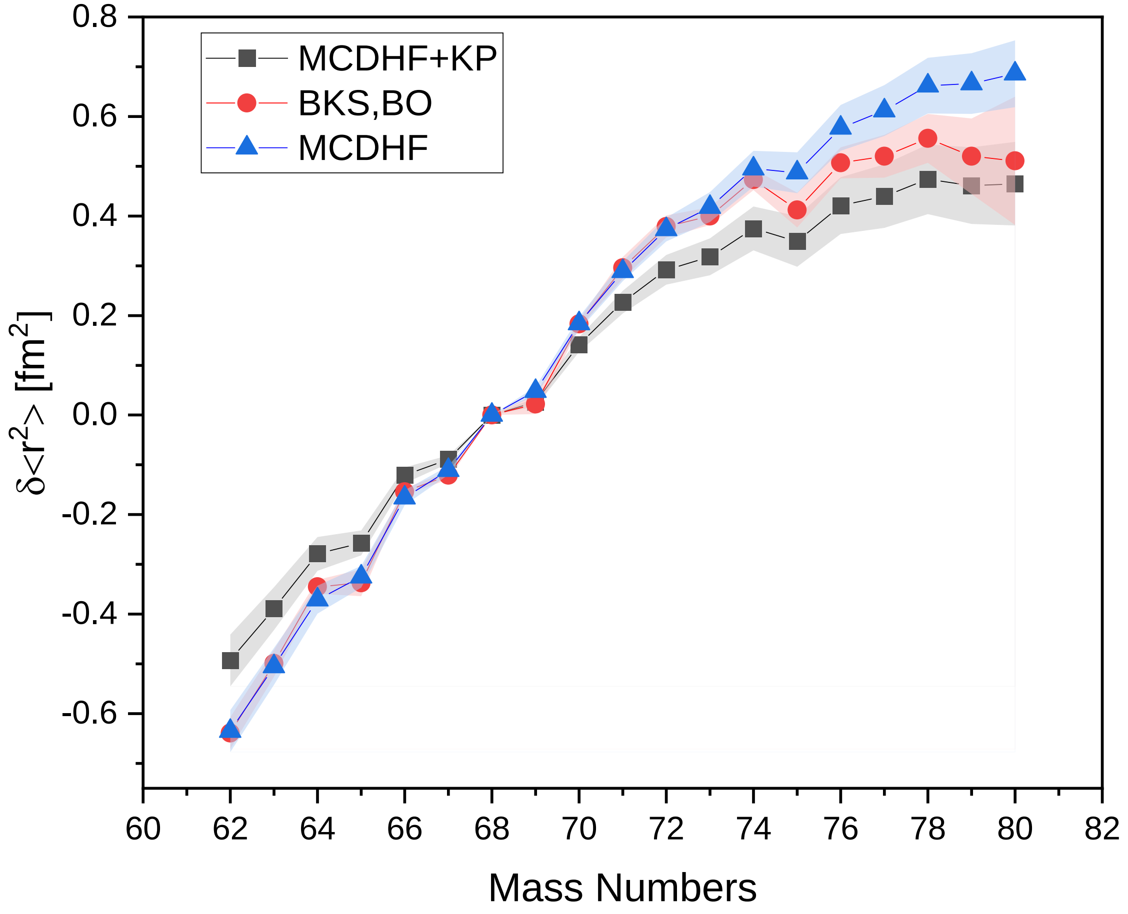
[1]*Atomic, Molecular and Optical Physics Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380058, Gujarat, India*
[2]*The Helen Diller Quantum Center, Department of Physics, Technion-Israel Institute of Technology, Haifa 3200003, Israel*

(Received 30 July 2023; accepted 13 October 2023; published 13 November 2023)

We conduct high-accuracy calculations of isotope shift (IS) factors of the states involving the D_1 and D_2 lines in Zn II. Together with a global fit to the available optical IS data, we extract nuclear-model independent, precise differential radii for a long chain of Zn isotopes. These radii are compared with the ones inferred from muonic x-ray measurements. Some deviations are found, which we ascribe to the deformed nature of Zn nuclei that introduces nuclear-model dependency into radii extractions from muonic atoms. We arrive at the conclusion that, in cases where the many-body atomic calculations of IS factors are well established, optical determinations of differential radii are more reliable than those from the muonic x-ray measurements, opening the door to obtaining more trustworthy nuclear radii across the nuclear chart.

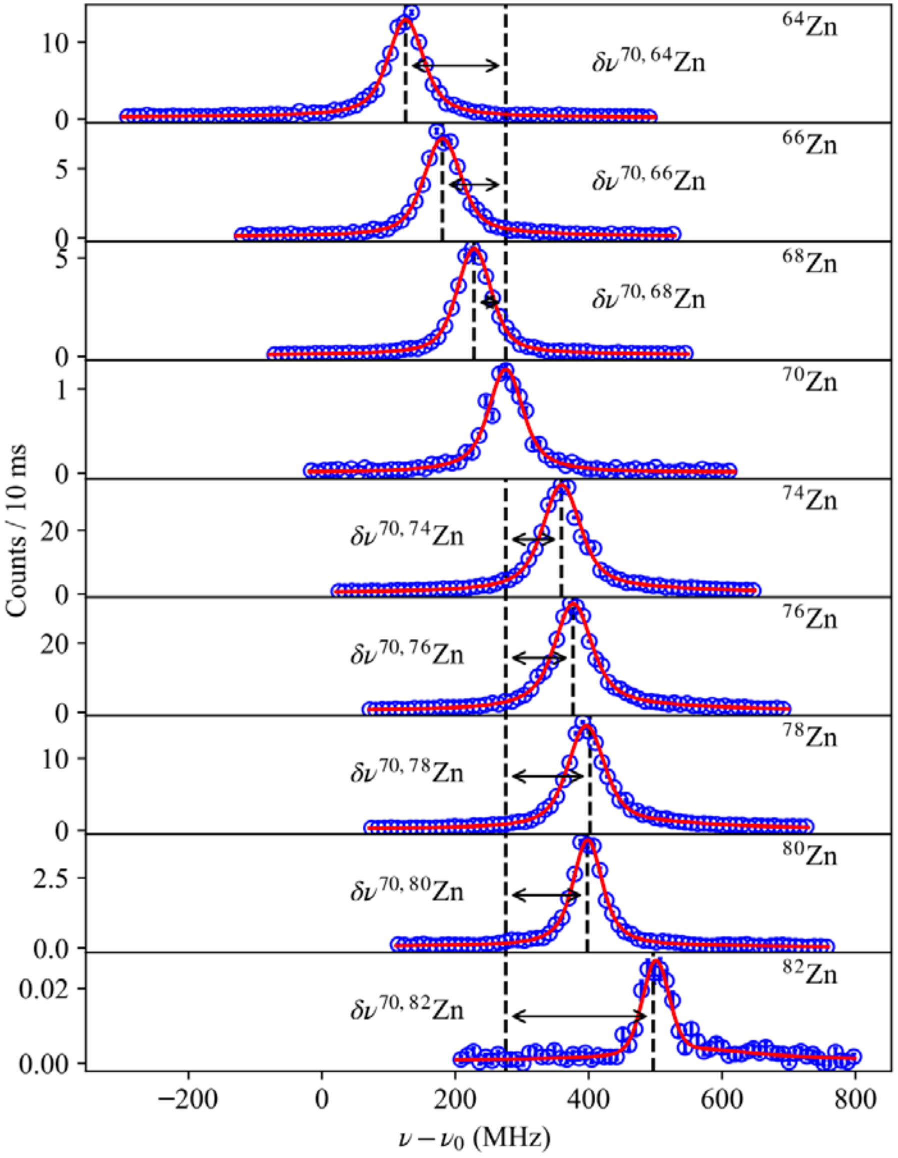
DOI: 10.1103/PhysRevResearch.5.043142

	F (MHz fm^{-2})	*M* (GHz u)	Method
2019 COLLAPS	+346(3)	+14(7)	**MCDHF**
2019 COLLAPS	+346(35)	+49(17)	**MCDHF + KP**
Combined analysis @ BKS, BO			

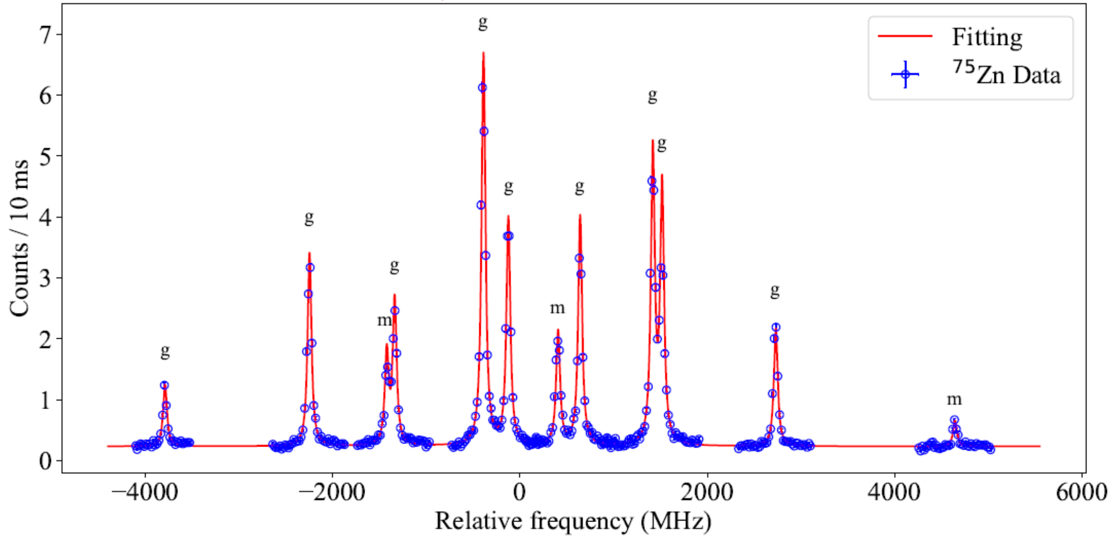


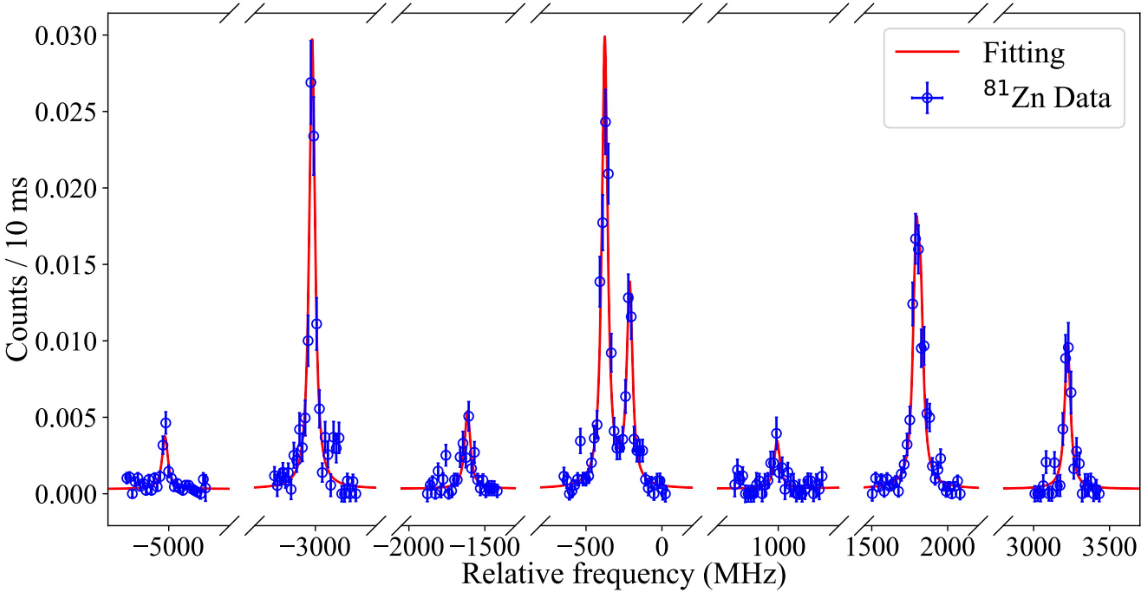
Charge radii of zinc isotopes @2023 experiment

Spin = 0

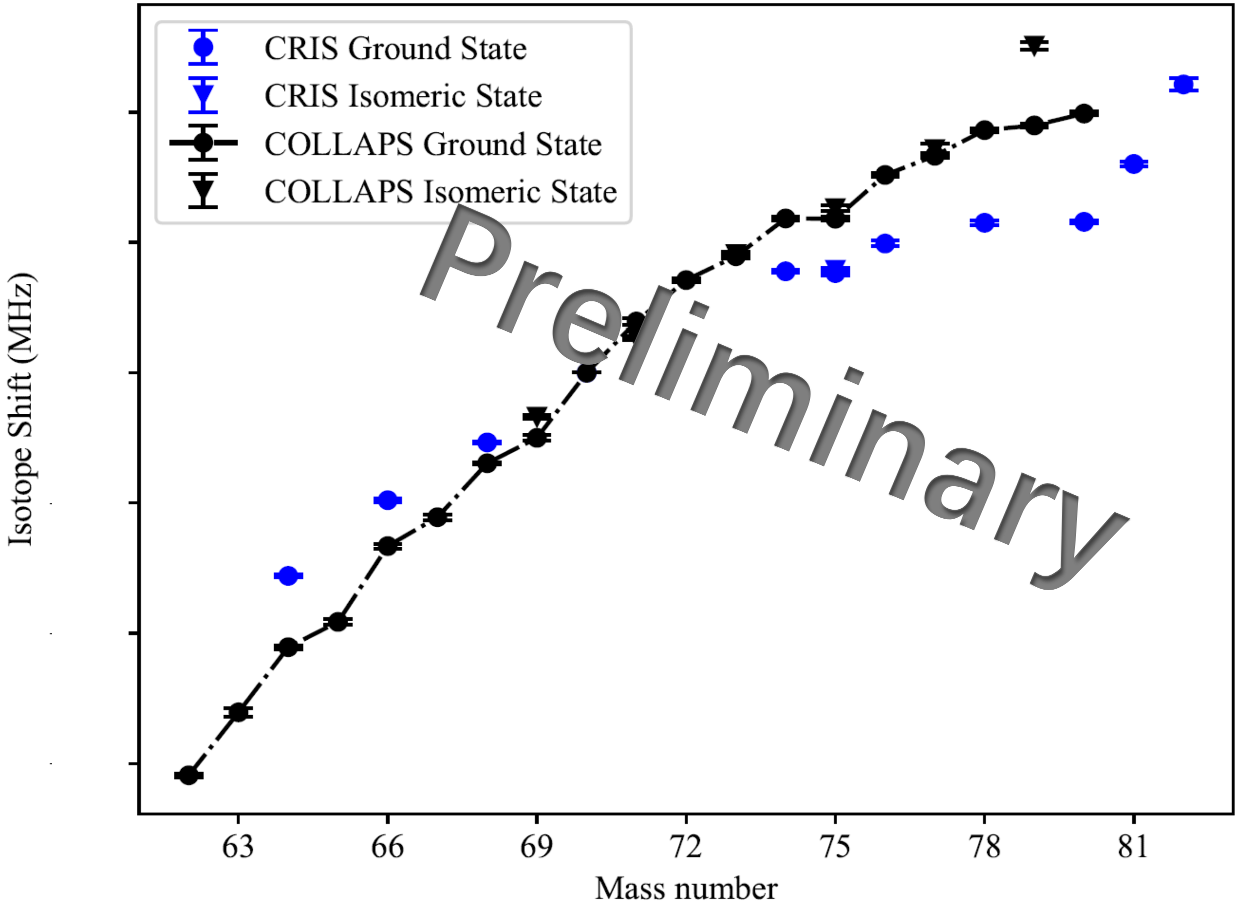


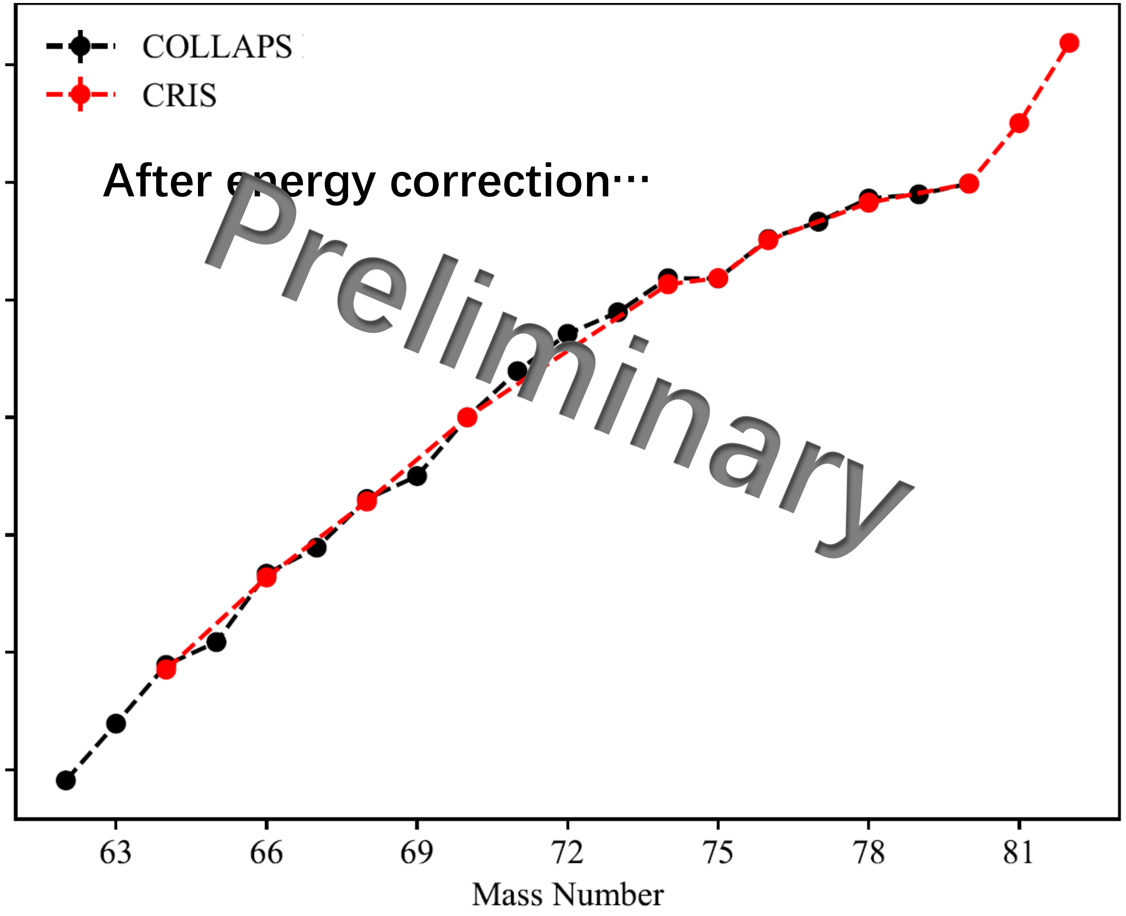
Spin >=1/2





Charge radii of zinc isotopes @2023 experiment

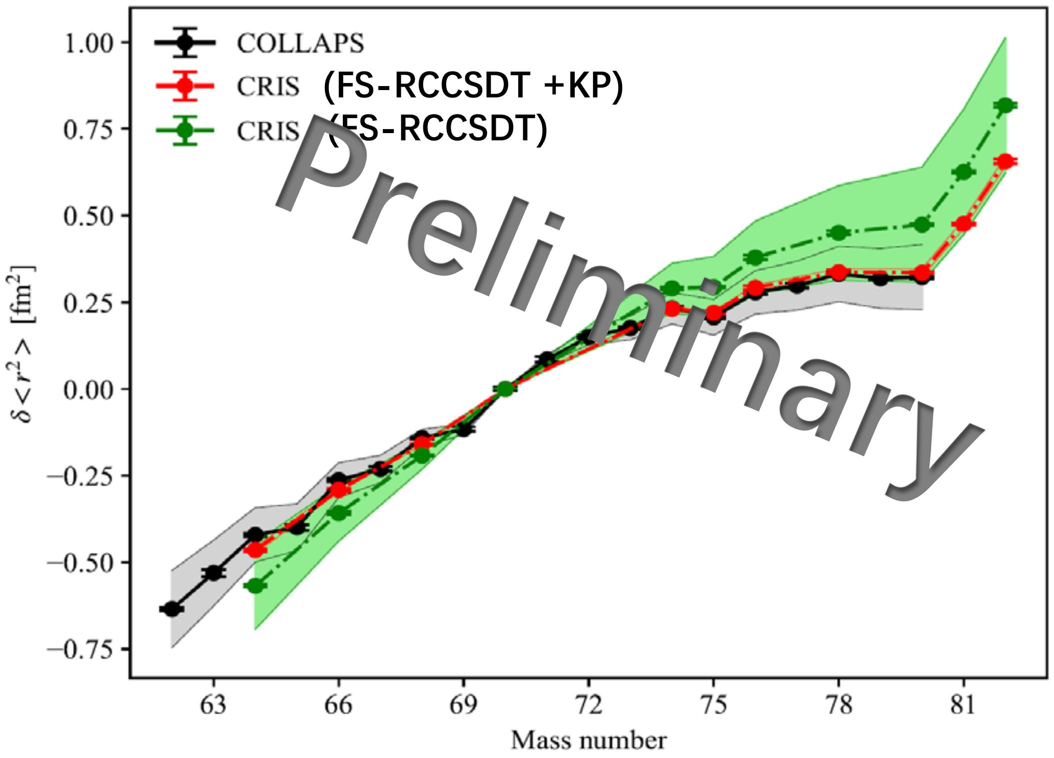


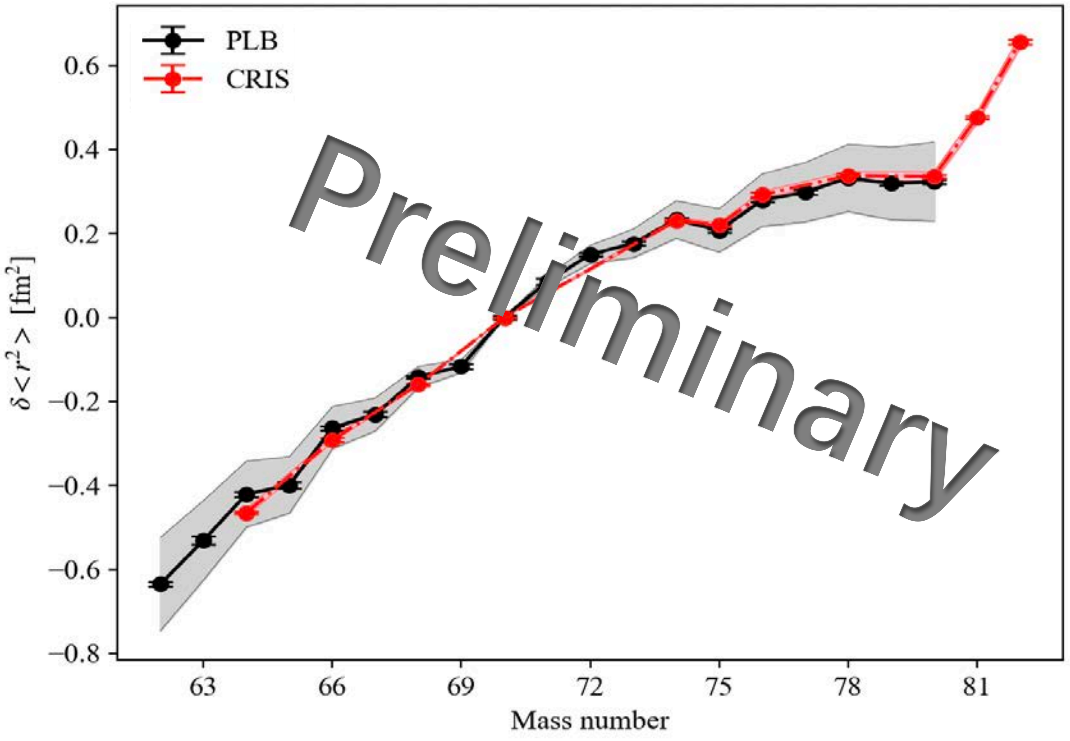


Charge radii of zinc isotopes @2023 experiment

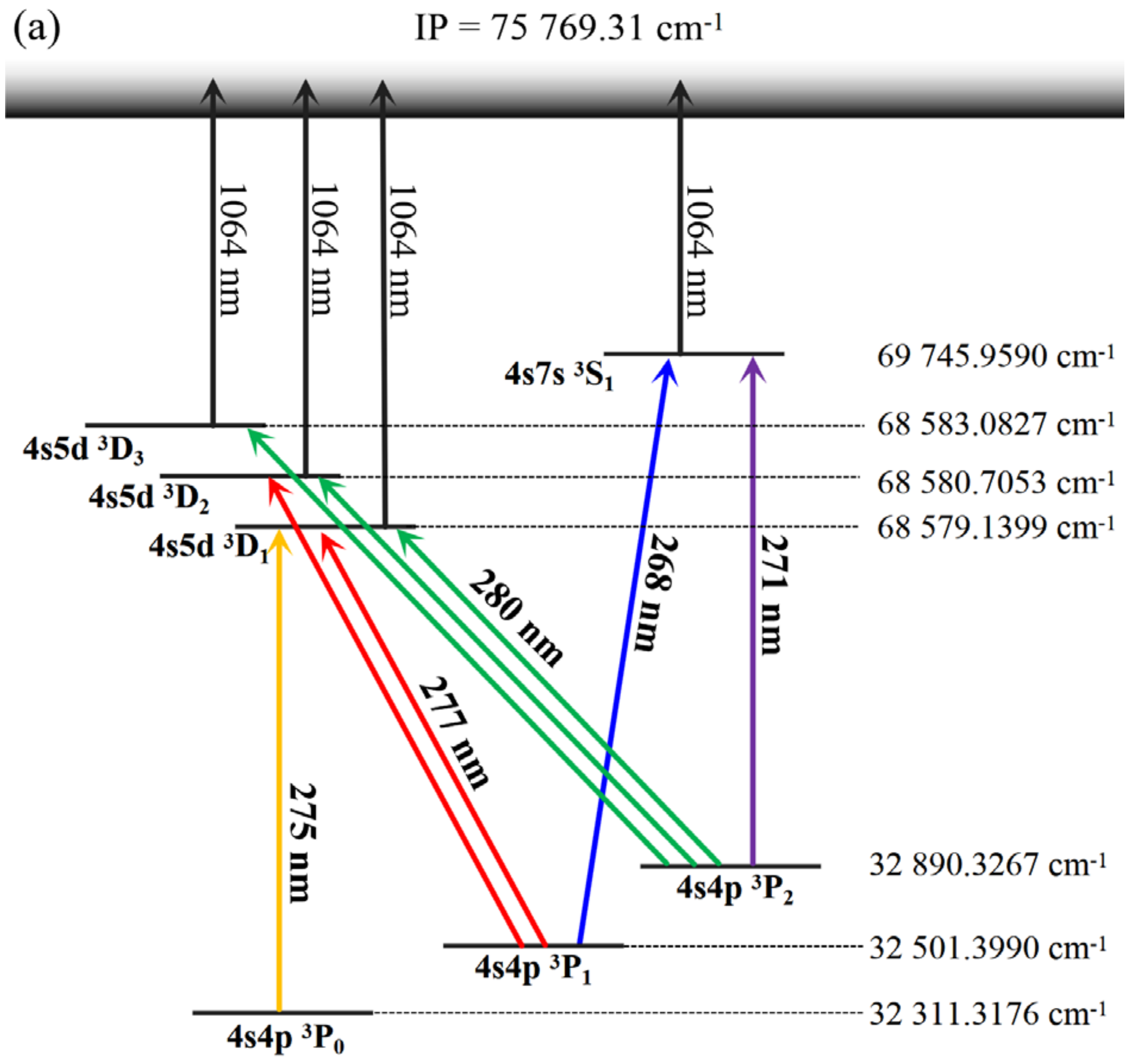
	F (MHz fm^{-2})	*M* (GHz u)	Method
2019 COLLAPS	+346(3)	+14(7)	**MCDHF**
2019 COLLAPS	+346(35)	+49(17)	**MCDHF + KP**
2023 CRIS	**+324(3)**	**-21(30)**	**FS-RCCSDT**
2023 CRIS	**+324(3)**	**+3.9(21)**	**FS-RCCSDT+KP**

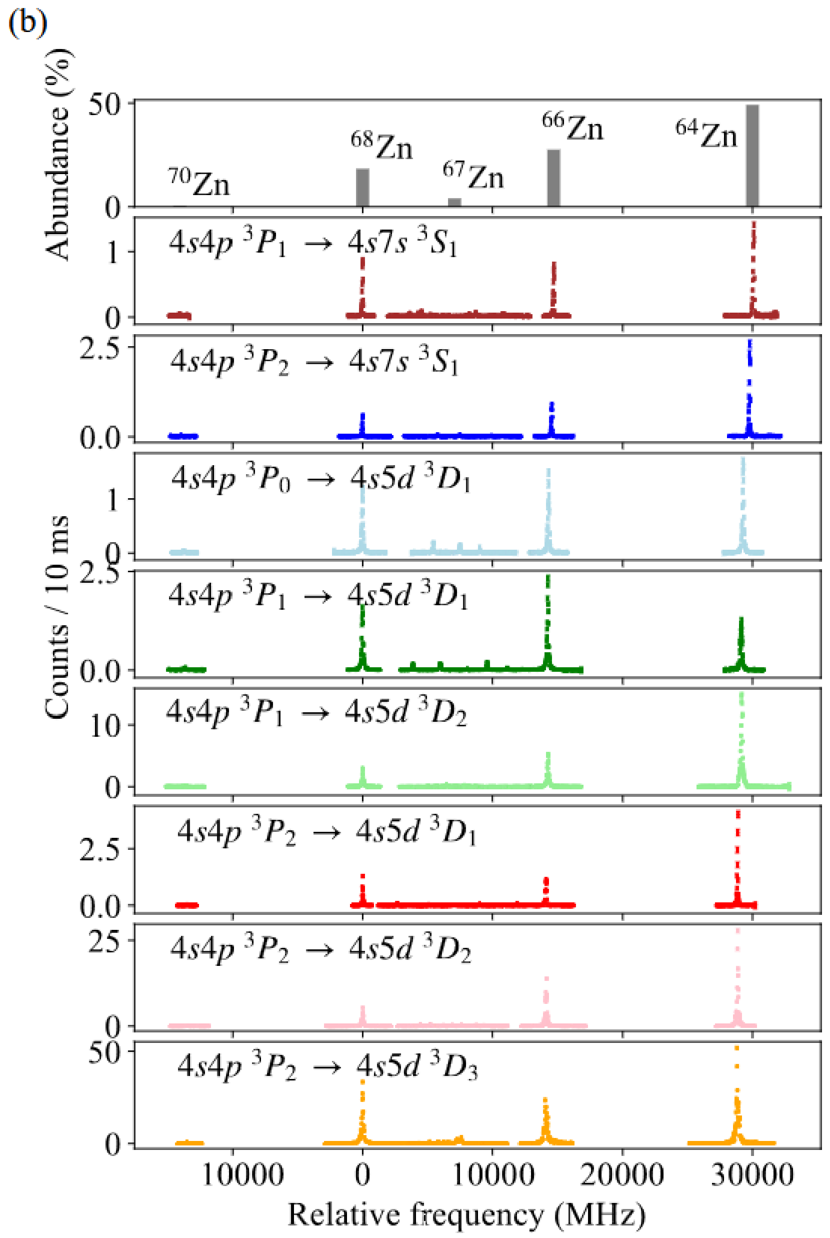
A. V. Oleynichenko; L. V. Skripnikov



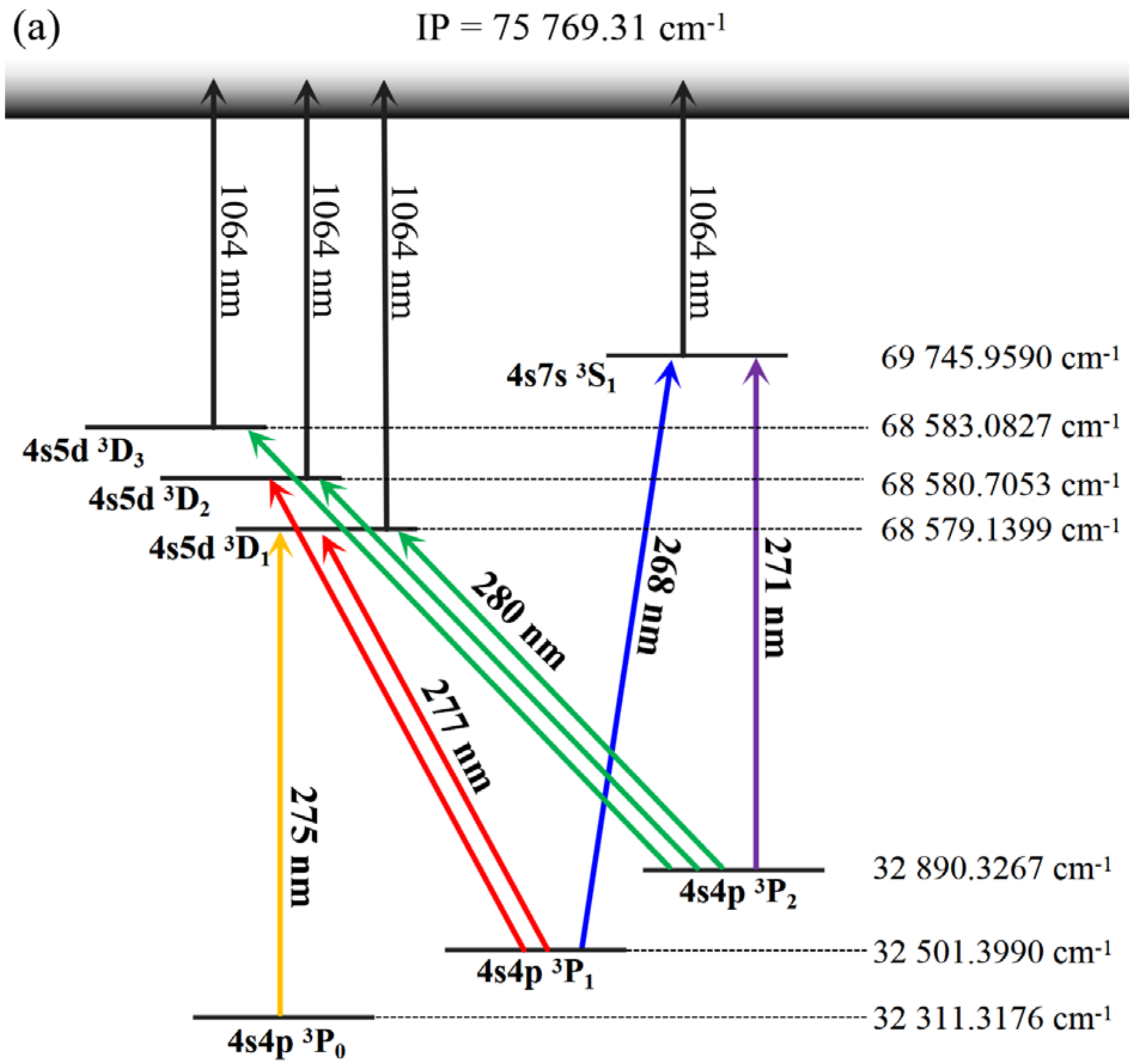


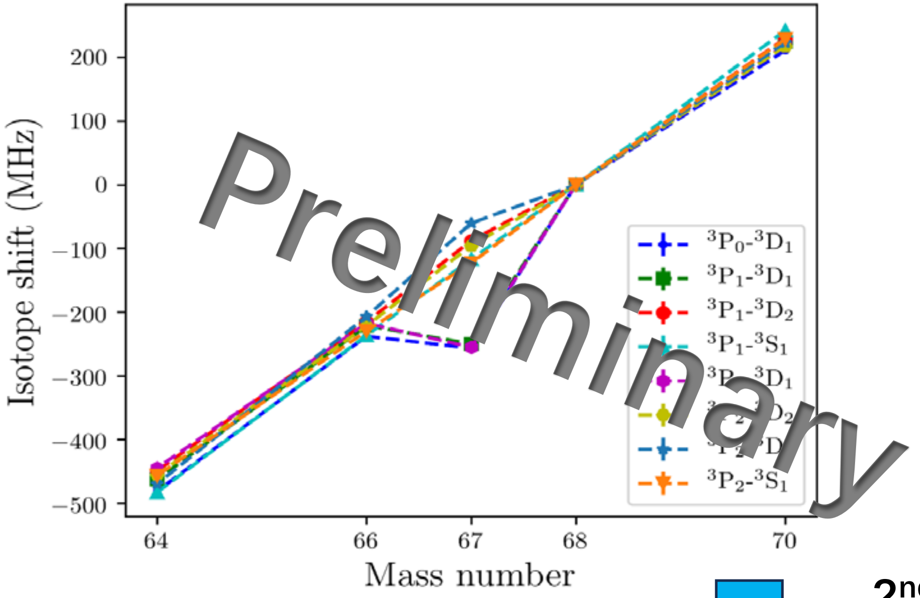
Charge radii of zinc isotopes



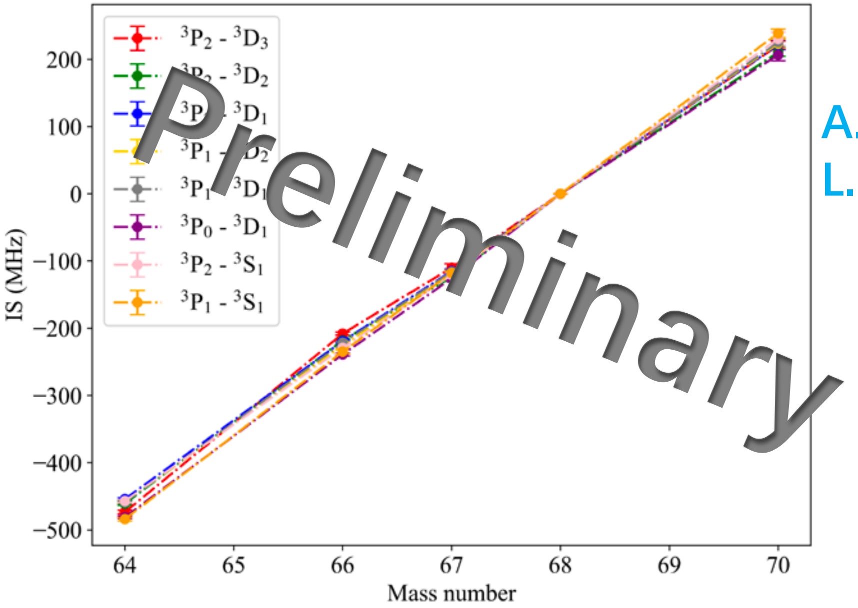


Charge radii of zinc isotopes



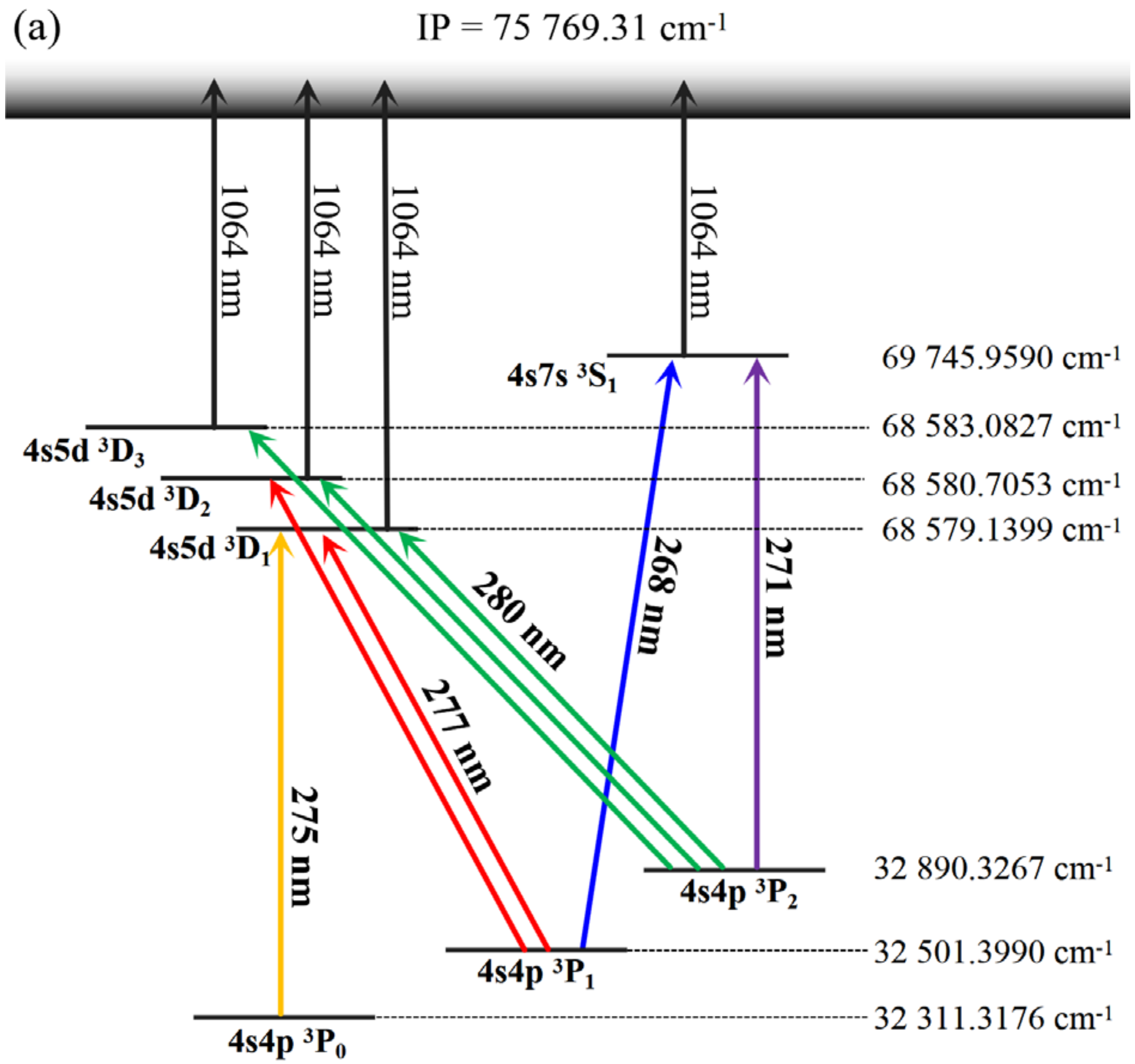


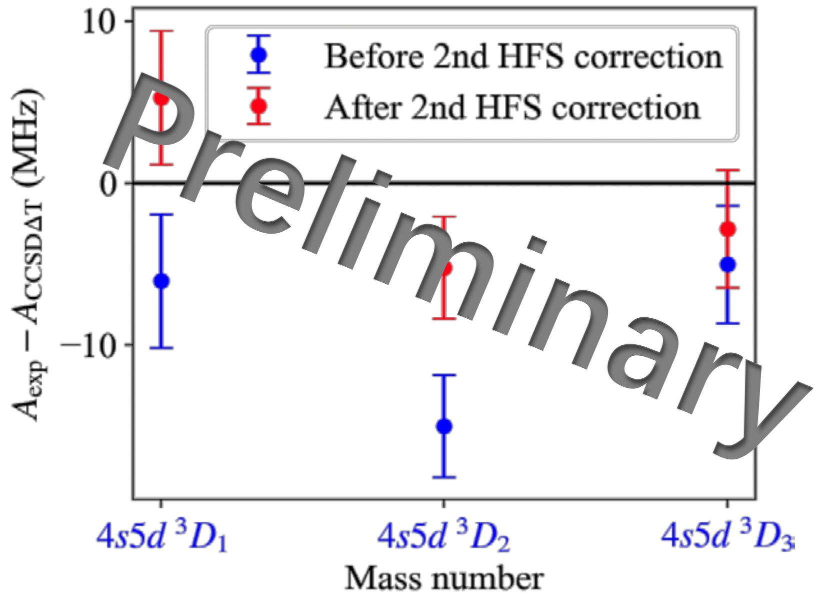
2nd order HFS

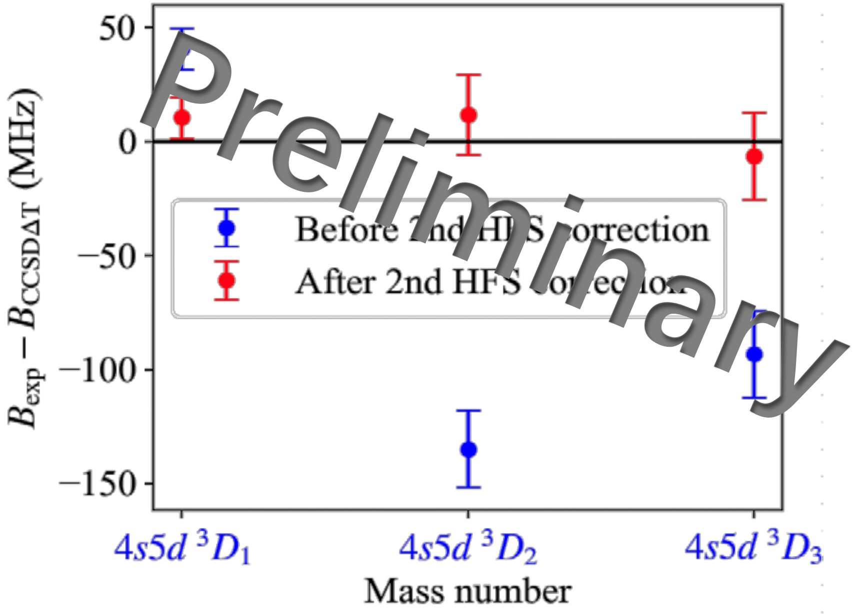


A.V.Oleynichenko
L. V. Skripnikov

Charge radii of zinc isotopes







Outline

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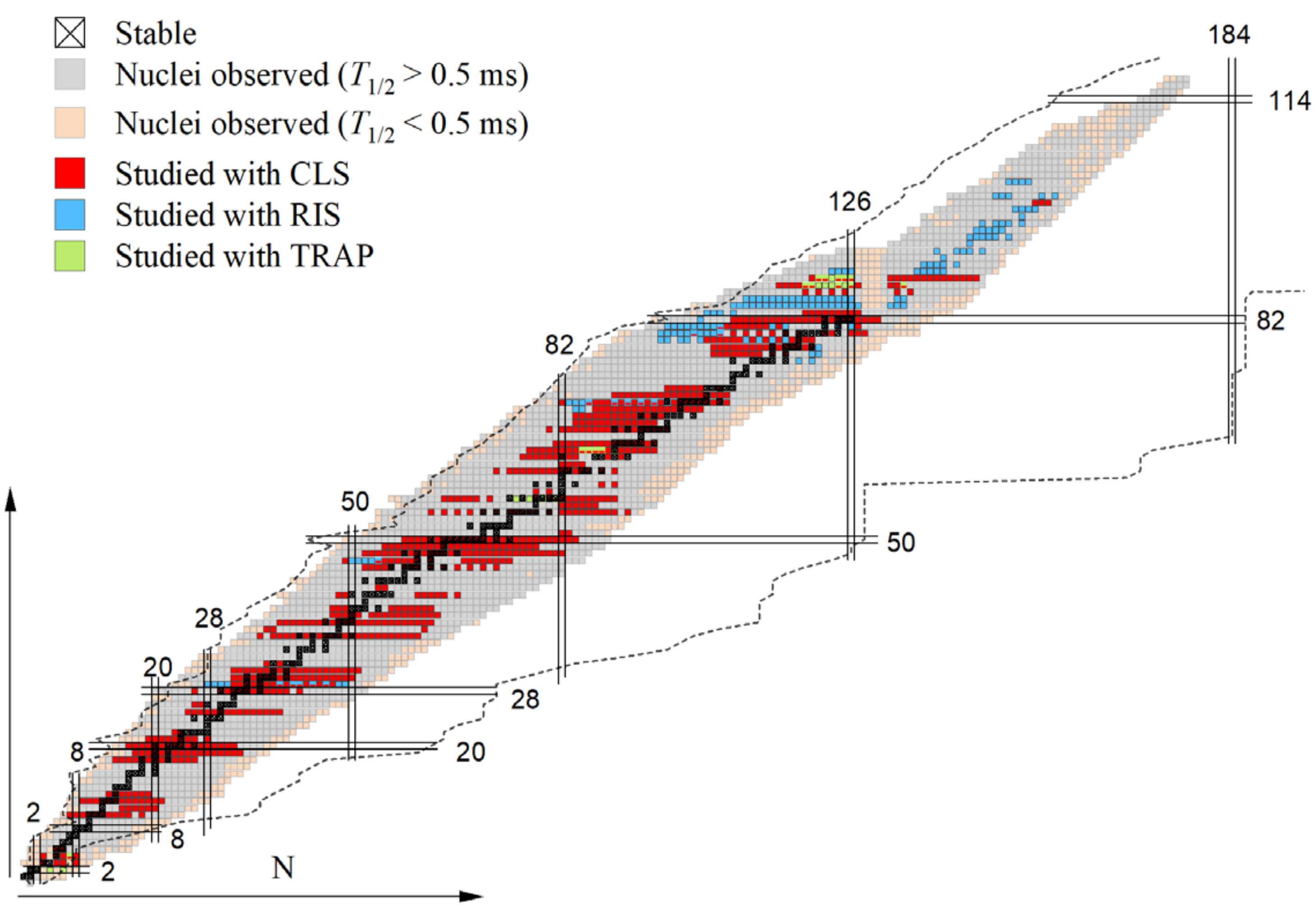
- ☐ Methods to measure the charge radii
- ☐ Charge radii of Sc isotopes
- ☐ Charge radii of Zn isotopes
- ☐ **Summary**

Summary and outlook



- Significant progress of nuclear charge radii measurement of unstable nuclei with laser spectroscopy has been made since 2013

- Even with one stable isotope available, we could now extract the nuclear charge radius by taking advantages of the state-of-the-art atomic theory.

- Nevertheless, in most cases, the accuracy of nuclear charge radii remains limited by the atomic mass- and field-shift factors, highlighting the need for further improvements.

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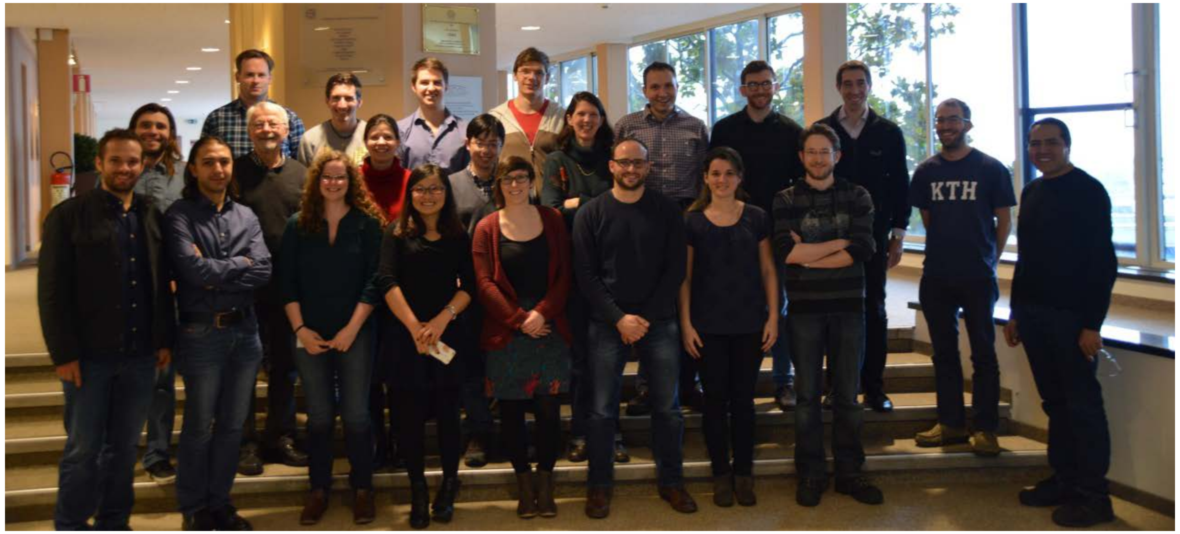
Thanks for your attention!

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

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



Thanks for your attention!