Nuclear Science and Techniques (2025) 36:230
https://doi.org/10.1007/s41365-025-01813-1

RESEARCH HIGHLIGHT

New laser spectroscopy measurements challenge modern nuclear theories

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Received: 31 July 2025 / Revised: 31 July 2025 / Accepted: 1 August 2025 / Published online: 29 September 2025

When discussing atomic nuclei, deformation is one of the most common topics. However, when we connect the concept of shape with high-precision experimental measurements, sometimes the explanation may not be as simple as we think. A recent measurement of nuclear charge radii (Phys. Rev. Lett. **134**, 182501 (2025)) challenges current nuclear *ab initio* models.

Removal or addition of just a few particles for closed-shell nuclei may lead to drastic changes in nuclear shape, resulting in different shapes to coexist and interact at low excitations [1]. This suggests to us that individual particles (holes) can decisively affect the overall picture of nuclei. But which are the correct observables?

There are some measurable quantities in nuclear physics, such as nuclear mass, binding energy, symmetry energy, nuclear radius and charge radius, which characterize the overall behavior and structure of the nucleus. We can call them bulk properties to distinguish them from many other measurable quantities that describe individual energy levels. Deformation, or shape in common saying, is a very special quantity because it seems to be related to almost all physical properties, but it itself is not a measurable quantity.

Among these measurable quantities, nuclear charge radii, which measure the size of the positive charge distribution within a nucleus, can provide direct information about nuclear shapes. For example, deviations of charge radii from spherical charge distributions indicate emergence of deformation (e.g., prolate or oblate shapes), signaling the evolution of collectivity or coexistence of nuclear shapes [2–4]. Abrupt changes in charge radii across isotopes often indicate the presence of closed-shell configurations, revealing magicity in exotic nuclei far from stability [5–8]. Comparing charge radius (from protons) to matter radius (from all nucleons) allows inferring the neutron skin thickness [9], one of the most exotic shape phenomena in nuclei.

Laser spectroscopy is an interdisciplinary technique that has seen increasing implementation at facilities across the globe in recent years [10]. By detecting minute frequency shifts—as small as one part in a million relative to the total atomic transition frequency—caused by the electromagnetic interaction between the atomic nucleus and its surrounding electrons, laser spectroscopy enables high-precision, model-independent determinations of charge radii, as well as other electromagnetic properties of atomic nuclei. This has led to significant advances in the investigation of the structure of exotic nuclei [10]. Although electron scattering, which measures form factors, remains the standard method for determining charge radii of stable or long-lived isotopes and has recently seen progress toward applications on unstable nuclei [11], the majority of charge radii for unstable nuclei—produced at radioactive ion beam (RIB) facilities worldwide—are measured using laser spectroscopy.

Nuclear shape is tightly connected to charge radii because the charge radii reflects the spatial distribution of protons in a nucleus, and this distribution changes when the nucleus deforms. Traditionally, one can extract quadrupole deformation parameter β_2 in deformed nuclei from experimental mean-square charge radii $\langle r^2 \rangle$ using the relation

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

where $\langle r^2 \rangle_0$ represents the radius of spherical equivalence.

During recent years, series of experiments at CERN-ISOLDE confirmed a fascinating phenomenon—pronounced odd–even staggering in mean-square charge radii. It was observed that along the mercury ($Z = 80$) isotopic chain, a sudden occurrence of large charge radii in the

This work is supported by the National Natural Science Foundation of China (No. 12235003).

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odd-mass mercury isotopes ^{181,183,185}Hg shows up, forming together with the neighboring even-mass Hg isotopes a localized staggering [12]. According to the relation in (1), one can call the phenomenon *shape staggering*. For the bismuth ($Z = 83$) isotopes, irregularities were found in the odd-mass $^{189-193}$Bi as the neutron number approaches the midshell. Remarkably, in the ground state of $N = 105$, $\langle r^2 \rangle$ of the odd–odd ^{188}Bi increases suddenly, from which a large prolate deformation, $\beta_2 = 0.28$, was deduced [13]. To compare to its neighboring odd–even ^{187}Bi with a deduced $\beta_2 = 0.19$, the change in deformation is significant. In Ref. [14], the calculation by Kaneko et al. using the PMMU shell model reproduced the sudden increase in deformation in ^{188}Bi and further predicted pronounced odd–even shape staggering down to $N = 103$.

This staggering phenomenon is fascinating because of two observational facts. First, it is a local effect, with large staggering amplitude only seen in a few isotopes that are close to the magic number of protons (such as $Z = 82$ in examples above) and the number of neutrons close to the midshell. Second, it is remarkable that a difference of just one neutron between the adjacent odd–even pairs can cause a significant change in deformation. This represents a fantastic example of how changes in nuclear structure (perhaps very small) can reshape the systematic properties of nuclei.

Similar staggering in charge radii has been known also in light nuclei. Already long ago, Palmer et al. [15] observed a key feature in the calcium ($Z = 20$) chain, showing the archlike charge radii trend at $20 \leq N \leq 28$, with almost identical radii for ^{40}Ca and ^{48}Ca and pronounced odd–even staggering. In a very recent work [16], Bai, Yang and coauthors reported their measurement on nuclear charge radii of neutron-rich $^{47-49}$Sc isotopes using collinear laser spectroscopy at CERN-ISOLDE. The new data revealed that the charge radii of scandium ($Z = 21$) isotopes exhibit a distinct trend between the neutron magic numbers $N = 20$ and $N = 28$, with ^{41}Sc and ^{49}Sc having similar values, mirroring the closeness of the charge radii of ^{40}Ca and ^{48}Ca. However, compared to the calcium isotopes, the scandium data indicated a much suppressed odd–even staggering in charge radii, despite that there is only one proton difference between the scandium and calcium chains.

To understand the observed trend in scandium radii, authors in [16] carried out calculations using the density functional theory (DFT) and valence-space in-medium similarity renormalization group (VS-IMSRG) methods. The DFT calculations were performed using two Fayans energy density functional parametrizations. The *ab initio* VS-IMSRG calculations used the ΔNNLO$_{\mathrm{GO}}$ chiral interaction. However, Ref. [16] concluded that both modern nuclear models fail in reproducing the observed differential radii trend for scandium isotopes with $19 \leq N \leq 28$. Without a correct description of the charge radii data, no further discussion on shape variation in the nuclei is possible by these models.

The work of [16] has posted great challenges to current theoretical modes, such as Fayans DFT, which was successful in describing the strong odd–even staggering observed in calcium charge radii. It is further discussed [16] that with the inclusion of the new radius measurement for the key isotope ^{49}Sc, a pronounced odd–even staggering emerges in the charge radii of $N = 28$ isotones where protons fill the $0f_{7/2}$ shell orbital atop the ^{48}Ca core—closely analogous to the behavior observed in the $Z = 20$ isotopes where neutrons filling the same orbital atop the ^{40}Ca core. This indicates the underlying mechanism likely tied to the unique role of the $0f_{7/2}$ orbital situated between two major shell closures, suggesting that the valence pairing and quadrupole interactions in the Fayans DFT models align well with the simple seniority model.

The performance of the *ab initio* VS-IMSRG method with ΔNNLO$_{\mathrm{GO}}$ chiral interaction is unsatisfying. Despite years of development, current *ab initio* calculations have made only marginal progress in reproducing the different radius trends for calcium and scandium isotopes, as well as the $N = 28$ isotones. On the other hand, the simple seniority model is successful, possibly because it captures key features of the structure of the nuclei with partially filled shells, especially for like nucleons (protons or neutrons) interacting through pairing forces. The success of the seniority model may suggest that capturing the underlying physics of a problem may not require complex, large-scale calculations.

This example also shows that high-precision data across long isotopic chains are valuable for advancing our understanding of the nuclear force and benchmarking quantum many-body theories [5–7]. It is worth mentioning that China's RIB facilities have recently built a set of fully functional, high-resolution and high-sensitivity collinear resonant ionization laser spectrometers (PLASEN) [17], which are very suitable for studying exotic nuclei in different regions of the nuclear map.

Acknowledgements The author thanks Professor Yu-Gang Ma for calling his attention to Ref. [16] and for Professor Xiao-Fei Yang helpful discussion.

References

1. K. Heyde, J.L. Wood, Shape coexistence in atomic nuclei. Rev. Mod. Phys. **83**, 1467 (2011). https://doi.org/10.1103/RevModPhys.83.1467

2. X.F. Yang, C. Wraith, L. Xie et al., Isomer shift and magnetic moment of the long-lived $1/2^+$ isomer in $^{79}_{30}Zn_{49}$: signature of shape coexistence near ^{78}Ni. Phys. Rev. Lett. **116**, 182502 (2016). https://doi.org/10.1103/PhysRevLett.116.182502
3. B.A. Marsh, T.D. Goodacre, S. Sels et al., Characterization of the shape-staggering effect in mercury nuclei. Nat. Phys. **14**, 1163 (2018). https://doi.org/10.1038/s41567-018-0292-8
4. J.G. Cubiss, A.N. Andreyev, A.E. Barzakh et al., Deformation versus sphericity in the ground states of the lightest gold isotopes. Phys. Rev. Lett. **131**, 202501 (2023). https://doi.org/10.1103/PhysRevLett.131.202501
5. A. Koszorús, X.F. Yang, W.G. Jiang et al., Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of $N = 32$. Nat. Phys. **17**, 439 (2021). https://doi.org/10.1038/s41567-020-01136-5
6. R.P. de Groote, J. Billowes, C.L. Binnersley et al., Measurement and microscopic description of odd-even staggering of charge radii of exotic copper isotopes. Nat. Phys. **16**, 620 (2020). https://doi.org/10.1038/s41567-020-0868-y
7. S. Malbrunot-Ettenauer, S. Kaufmann, S. Bacca et al., Nuclear charge radii of the nickel isotopes $^{58-68,70}Ni$. Phys. Rev. Lett. **128**, 022502 (2022). https://doi.org/10.1103/PhysRevLett.128.022502
8. C. Gorges, L.V. Rodríguez, D.L. Balabanski et al., Laser spectroscopy of neutron-rich tin isotopes: a discontinuity in charge radii across the $N = 82$ shell closure. Phys. Rev. Lett. **122**, 192502 (2019). https://doi.org/10.1103/PhysRevLett.122.192502
9. R. Sánchez, W. Nörtershäuser, G. Ewald et al., Nuclear charge radii of $^{9,11}Li$: the influence of halo neutrons. Phys. Rev. Lett. **96**, 033002 (2006). https://doi.org/10.1103/PhysRevLett.96.033002
10. X.F. Yang, S.J. Wang, S.G. Wilkins et al., Laser spectroscopy for the study of exotic nuclei. Prog. Part. Nucl. Phys. **129**, 104005 (2023). https://doi.org/10.1016/j.ppnp.2022.104005
11. K. Tsukada, Y. Abe, A. Enokizono et al., First observation of electron scattering from online-produced radioactive target. Phys. Rev. Lett. **131**, 092502 (2023). https://doi.org/10.1103/PhysRevLett.131.092502
12. S. Sels, T.D. Goodacre, B.A. Marsh et al., Shape staggering of midshell mercury isotopes from in-source laser spectroscopy compared with density-functional-theory and Monte Carlo shell-model calculations. Phys. Rev. C **99**, 044306 (2019). https://doi.org/10.1103/PhysRevC.99.044306
13. A. Barzakh, A.N. Andreyev, C. Raison et al., Large shape staggering in neutron-deficient Bi isotopes. Phys. Rev. Lett. **127**, 192501 (2021). https://doi.org/10.1103/PhysRevLett.127.192501
14. K. Kaneko, N. Shimizu, T. Mizusaki et al., Shape coexistence and shape staggering beyond $Z = 82$ induced by $T = 0$ monopole and quasi-SU(3) quadrupole interactions. Phys. Rev. C **111**, 054319 (2025). https://doi.org/10.1103/PhysRevC.111.054319
15. C.W.P. Palmer, P.E.G. Baird, S.A. Blundell et al., Laser spectroscopy of calcium isotopes. J. Phys. B **17**, 2197 (1984). https://doi.org/10.1088/0022-3700/17/11/014
16. S.W. Bai, X.F. Yang, Á. Koszorús et al., Charge radii of neutron-rich scandium isotopes and the seniority symmetry in the $0f_{7/2}$ shell. Phys. Rev. Lett. **134**, 182501 (2025). https://doi.org/10.1103/PhysRevLett.134.182501
17. H.R. Hu, Y. F. Guo, X. F. Yang et al., Development and characterization of a high-resolution, high-sensitivity collinear resonance ionization spectroscopy system. Sci. Bull. **70**, 2721–2724 (2025). https://doi.org/10.1016/j.scib.2025.06.036