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Editorial

Nuclear isomers

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This special issue explores the intricate realm of nuclear isomers [1, 2], rare long-lived excited states of nuclei, some of which can store over 10 MeV of energy in a single nucleus. Their distinctive characteristics and intriguing lifetimes spanning from nanoseconds to millions of years, beckon us to uncover their underlying enigmas. Isomers hold brimming potential for basic research in nuclear physics, atomic physics, astrophysics, mathematical physics, and industrial applications such as energy storage, timekeeping, and medical imaging.

The genesis of this field can be traced back to a remark by Soddy in 1917 [3], “We can have isotopes with identity of atomic weight, as well as of chemical character, which are different in their stability and mode of breaking up.” This statement is often recognized as the earliest indication of isomeric existence. Otto Hahn is generally credited with the first experimental observation of an isomer in ^{234}Pa while working on uranium salts [4]. However, prior to Hahn’s work, Fajans and Gohring [5] had identified a 1.1 min activity in the UX_2 isotope in a new chemical element “brevium”, as they named it, which was to be identified later as an isomeric state of ^{234}Pa [6]. Hahn in his 1921 paper [4] observed for the first time the ground state activity of 6.7 h in ^{234}Pa, as well as the short-lived activity resulting from the beta decay of ^{234}Th, whose half-life was unspecified [7]. With the appearance of two states belonging to the same nuclide, Hahn recognised that “ein soleher Fall ist bis jetzt bei den radioaktiven Umwandlungen noch nicht beobachtet worden” [such a case has not been observed before in radioactive transformations] [7]. The short-lived activity was the 1.1 min isomer, whose connection to the ground state remained elusive. Consequently, the levels lying above the 1.1 min isomer did not have known energy values. Only recently, Korsakov et al. [8] confirmed the 1.1 min isomeric activity with a tentative spin of (0^-) that lies only 2.6 keV above the 73.9 keV, (3^+) state causing its decay to be almost impossible. Indeed, it was some years before this “first” case of nuclear isomerism was accepted as being correct.

The word “isomer” itself seems to have been used in the literature, for the first time in the nuclear context, by Gamow in 1934 [9], after the discovery of neutrons by Chadwick in 1932. Then, in 1935, Kurtchatov et al. [10] and, separately, Szilard and Chalmers [11] discovered isomers in bromine and indium isotopes, respectively. These new isomers, focused on by Bethe in his 1937 review [12], were the first of a wave of isomer discoveries made possible by exploiting Chadwick’s neutrons and other experimental advances.

With the global interest in isomer physics still growing today, along with new and expanding access to unexplored regions of the nuclear landscape, and with new ideas for applications beyond the domain of nuclear structure physics, this special issue presents a series of articles dedicated to the advances and insights gained in this field in recent years.

Nuclear isomers undeniably stand at the forefront of global nuclear science pursuits, with an abundance of isomeric data at our disposal. In the early times of developing state-of-the-art nuclear models, isomers revealed and quantified the shell gaps, basic building blocks of nuclear structure. Based on significant changes in the angular momentum of γ-decaying isomers, von Weizsäcker [13] gave the first explanation for the isomerism phenomenon now referred to as spin isomers. In this issue, Brown [14] provides a theoretical review for the origins of such γ-decaying isomers starting within a spherical shell model basis and adeptly explains many two-particle isomers

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near closed shells. The success of the shell model picture across various mass regions owes much to the large-scale configuration mixing calculations [15, 16]. Podolyák [17] discusses the existence of isomers decaying by high-multipolarity transitions with special attention to the electric octupole, $E3$-decaying isomers around ^{208}Pb. In deformed nuclei, additional hindrance comes from the operation of the K quantum number. Notably, the 31-y isomer in ^{178}Hf undergoes strongly K-forbidden $E5$ decay [18]. At the transition-multipolarity extreme, both Brown [14] and Podolyák [17] highlight the exceptional $E6$-decaying isomer in ^{53}Fe.

Watanabe [19] probes the isomers for understanding shell evolution in exotic nuclei, citing examples from neutron-rich $N = 80$ isotones, and neutron-rich dysprosium isotopes. These discussions are also of future research aimed at understanding the change in single-particle energies, and the strength of magic gaps when exploring the extremes of nuclear binding energies. The presence of symmetries in nuclei can also be deciphered through isomers. Van Isacker [20] underscores the significance of symmetry arising from the seniority quantum number and corresponding seniority isomers, whose longer lifetimes are a confluence of low γ energy and seniority selection rules, particularly in the middle of any shell. The particle-hole conjugation and seniority inversion offer generic explanations for the absence of seniority isomers in the ^{72,74}Ni isotopes, in contrast to their presence in the $N = 50$ isotones. Palit et al. [21] provide a comprehensive review of past endeavors on isomeric measurements in the $A \approx 135$ region especially for barium, lanthanum and cerium isotopes with neutron numbers $N = 72-82$, while also correlating the shape evolution in isomers. Most of these results originate from their in-house experimental facility at TIFR (Mumbai), with an eye toward future investigations in $A \approx 90$, 200 regions. Tandel [22] addresses the high-spin isomeric states due to multi core-excitations near ^{208}Pb placing special emphasis on mercury, thallium, lead and bismuth isotopes with $N = 118 - 126$, offering discriminating tests of the different effective interactions used in large-scale shell-model calculations.

The nucleus can adopt various shapes and so can the nuclear isomers. Dudek et al. [23] provide a stimulating review of exotic symmetries, with a focus on tetrahedral and octahedral point-group symmetries, and they point out possibilities to find new isomers of these kinds. An example case of ^{152}Sm is also discussed. In a comprehensive review, Walker and Kondev [24] delve into the properties of K isomers, with axially deformed shapes. The $\beta-$decay of K isomers is discussed, as well as speculations about the neutron-rich $N \approx 116$ region. In addition, an update to the $K-$isomer table [18] is also provided. Clark [25] conducts a detailed examination of the experimental findings on α-decay and the fission mechanism of high-K isomers which may have profound consequences in superheavy nuclei. Ackermann, Antalic, and Heßberger [26] explore the nature and experimental possibility of isomers in superheavy nuclei, shedding light on future opportunities. Sun [27] contributes a theoretical perspective to the study of $K-$isomers, particularly employing the angular-momentum-projected shell model, which is efficient in truncating the usual shell model space for heavy and deformed nuclei. Xu et al. [28] provide a theoretical review focused on the collective rotation of high-K isomers leveraging the configuration-constrained total Routhian surface calculations based on a macroscopic-microscopic model. Despite long and successful theoretical efforts on K isomers, the decay properties of K isomers are still an open issue necessitating future efforts. In weakly deformed nuclei, K ceases to serve as a good quantum number. Such isomers having different shapes than the lower-lying states to which they transition are referred to as shape isomers, and fission isomers in heavier actinides. Leoni et al. [29] review the current status of shape and fission isomers, both experimentally and theoretically, across the nuclear chart from lighter ^{64,66}Ni to heavier fissioning nuclei. Future perspectives are also discussed.

Nuclear isomers that can be distinguished from their respective ground states in pertinent astrophysical environments are known as astrophysically metastable nuclear isomers, or "astromers". Misch and Mumpower [30] elucidate the influence of astromers on nucleosynthesis, potential alterations in abundances, and the creation of new pathways that would otherwise be inaccessible, concluding with future prospects. Maheshwari and Jain [31] provide whys and wherefores of isomers exhibiting extreme nuclear properties such as spins, energies, decay modes, and underlying nucleonic surroundings. Note that the longest-lived of all nuclear isomers is a 77 keV excitation of ^{180}Ta, with a half-life greatly exceeding the age of the universe.

No discussion dedicated to isomers would be complete without addressing the famous case of ^{229}Th which, at 8 eV, is the lowest energy isomer of all, and is predicted to be able to outperform the existing optical atomic clocks in accuracy of timekeeping. Thirolf et al. [32] presents an in-depth review spanning 50 years of thorium isomer research, highlighting pivotal developments including the transformative year 2016. Also with optical photons, and given the capabilities of modern radioactive-ion-beam facilities, Koszorus and Cheal [33] delve into the laser hyperfine spectroscopy of isomers, making it possible to measure the nuclear electromagnetic moments, spins, and changes in mean-square charge radii with great precision, and facilitating discoveries of new isomers. Despite the elegant theory successes from density functional theory and ab initio shell model calculations, clear gaps in our knowledge are pointed out.

As a potential application of isomers, Carroll and Chiara [34] chronicle the history, struggles, and prospects associated with harnessing the energy storage capacity of nuclear isomers. They also spotlight the twelve isomer-battery contenders with half-lives in years. Balabanski and Luo [35] go on to describe the role of isomers in nuclear photonics, an emerging field of science, combining the new generation γ-ray sources based on traditional and laser-based electron accelerators. This is especially pertinent given the importance of nuclear photonic methods such as nuclear resonance fluorescence and nuclear excitation by electronic transition, in advancing the idea of an isomer battery—a promising avenue for clean energy production. Dickel and Mollaebrahimi [36] present the operational principles and contributions of a modern experimental technique, the multiple-reflection time-of-flight mass spectrometer, in identifying and characterizing nuclear isomers. Litvinov and Korten [37] explore the methodology and utilization of heavy-ion storage rings for investigating isomeric states. Hirayama [38] provides the current status of isotope separator facilities, ISOL and KISS, and their pivotal role in studying exotic nuclei and isomers. Additional details on the upgrade, KISS-II, could pave the way for proposing novel experiments in $N = 126$ and actinide regions. Finally, Jensen [39] underscores the indispensable role of isomers in nuclear medicine, especially the widely used case of the ^{99}Tc isomer, while explaining the underlying nuclear and atomic physics making this case so crucial in medical imaging.

We hope that this special issue will encourage early career researchers to study isomer physics. Now is a wonderful time, especially since many new isomers in unexplored regions of the nuclear landscape (with a huge range of nucleon numbers, excitation energies and spins) have excellent discovery potential, by exploiting the availability of novel state-of-the-art experimental facilities at leading laboratories around the world. An equal emphasis on isomer theory will be instrumental in realising the full potential of isomer physics in the coming years. A key message is that isomers can be useful—in revealing exotic nuclear structure, in understanding astrophysical processes, and in the real world of industry and medicine.

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