Research on Exotic Structures of Unstable Nuclei: Developments and Prospects (Postprint)

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Abstract

The atomic nucleus is a complex quantum many-body system governed by the nuclear force, relatively susceptible to collective phenomena such as deformation, rotation-vibration, fission, and cluster resonance. Over the past three decades, we have witnessed the rapid expansion of the laboratory-accessible chart of nuclides, along with a series of novel discoveries and breakthroughs in the study of unstable nuclei. Typical examples include halo nuclei and their associated exotic structural phenomena, in-beam γ-spectroscopy measurements under weak-beam conditions using achromatic magnetic spectrometers to observe shell evolution in unstable nuclear regions, measurements of fundamental properties of unstable nuclei and the identification of new magic numbers, rich multi-nucleon correlations, and cluster and molecular structures. In the future, exploration of new territories in the chart of nuclides, particularly the medium-to-heavy mass neutron-rich region, will address major scientific questions concerning extreme exotic structures, r-process nucleosynthesis, and pathways to the island of superheavy nuclei. To investigate these issues, major scientific and technological powers worldwide are constructing large-scale facilities capable of producing radioactive nuclear beams far from the valley of stability, and research on exotic structures of unstable nuclei is poised for even greater breakthroughs.

Full Text

Preamble

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Progress and Perspectives on Research into Exotic Structures of Unstable Nuclei

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Abstract

The atomic nucleus is a quantum many-body complex system governed by the nuclear force, and it is prone to global changes such as deformation, rotation, vibration, fission, and clustering. Over the past three decades, we have witnessed the rapid expansion of the experimentally accessible nuclear chart and a series of new discoveries and breakthroughs in studies of unstable nuclei. Typical examples include halo nuclei and their associated exotic structural phenomena, the observation of shell evolution in unstable nuclear regions through in-beam γ spectroscopy measurements under weak beam conditions using achromatic magnetic spectrometers, measurements of basic properties of unstable nuclei and the discovery of new magic numbers, and rich multi-nucleon correlations along with cluster and molecular structures. In the future, the newly accessible regions of the nuclear chart, particularly the medium-heavy mass neutron-rich region, will involve major scientific questions such as extreme exotic structures, the astrophysical r-process, and pathways to the superheavy island. To explore these questions, major scientific facilities capable of producing radioactive ion beams far from the valley of stability are being constructed worldwide, and research on exotic structures of unstable nuclei will usher in even greater breakthroughs.

Keywords: Unstable nuclei, Exotic nuclear structure, Halo nuclei, In-beam γ-ray spectroscopy, New magic numbers

Introduction

The atomic nucleus is a quantum many-body complex system governed by the nuclear force. The nuclear force is the residual interaction that emerges after the strong interaction described by Quantum Chromodynamics (QCD) is screened by hadrons, representing a short-range interaction analogous to chemical bonding. Protons and neutrons aggregate into atomic nuclei through this force, and such quantum many-body systems exhibit characteristic features of diversity and relative instability. For instance, atoms possess a strong core that dominates the motion of extranuclear electrons, making them essentially spherical and unlikely to undergo significant deformation or fission. Similarly, hadrons have extremely strong confinement boundaries, making deformation, vibration, or fission difficult. The atomic nucleus, however, lacks a stable center (its mean field is collectively formed by many nucleons) and has a rather diffuse boundary, making it susceptible to global changes such as deformation, rotation, vibration, various types of particle emission and decay, and fission.

This diversity of nuclear structure can be visualized schematically in Figure 1 [Figure 1: see original paper] [1]. The ground state and low-lying excited states of nuclei can be reasonably well described by the shell model (including particle-hole excitations). In these states, nuclei can also undergo collective motions such as vibration and rotation, and cluster effects (such as the influence of α-cluster structure) may appear. Along the excitation energy axis (E*), new structural phenomena emerge, including high-spin states, superdeformation, giant resonances, and cluster resonances. At even higher excitations, phase transition phenomena such as α-condensate states and nucleon gas in thermal equilibrium can occur (phase transitions involving sub-nucleonic degrees of freedom produced in high-energy heavy-ion collisions, which are important research topics in high-energy physics, are not discussed here). Along the nucleon number axis (A), familiar phenomena such as α-cluster formation and decay, and fission occur. In recent years, as the experimentally accessible nuclear chart has expanded toward neutron-rich or proton-rich unstable regions on both sides of the valley of stability, a series of exotic phenomena including halo nuclei, molecular cluster structures, and multi-nucleon correlations have been discovered, greatly enriching our understanding of nuclear structure.

These changes in structural images have profound physical implications. Describing many-body systems within the quantum mechanics framework always involves the question of how to formulate the Hamiltonian. The usual approach is to first select an approximate Hamiltonian H_0 that represents the dominant interaction while being theoretically tractable, using its eigenstates as a basis set to expand the physically realistic many-body quantum states. The residual interaction H is then added, and perturbation theory (which can be expanded to multiple orders) is employed to obtain the most realistic many-body quantum states (i.e., to determine the expansion coefficients in the basis). In other words, for each constituent of the system, its binding energy (or separation energy S) generally consists of two parts [2]:

$$S = \lambda + \Delta$$

where the λ term originates from the dominant interaction associated with H_0 (such as mean-field effects), while the Δ term arises from the residual interaction (such as pairing correlations). Clearly, if the choices of H_0 and H are consistent with the true interaction state of the system, the resulting quantum states will agree well with experimental results. However, if the description provided by H_0 and H deviates significantly from reality, or even reverses the primary and secondary effects, perturbative treatments will struggle to match measured results. This situation actually occurs in atomic nuclei. For example, when cluster structures appear on the nuclear surface, the local correlation effects experienced by nucleons within the cluster from nearby nucleons may become stronger than the mean-field effects from distant nucleons, effectively creating a multi-center configuration. In such cases, the conventional H_0 + H treatment becomes inadequate for describing the true state. This likely explains why theoretical calculations within the mean-field (shell model) framework have difficulty reproducing experimentally observed cluster structures (such as the Hoyle state in ^{12}C). Clearly, as the nuclear chart extends toward the drip lines, many nucleons within the nucleus have small binding energies and expanded spatial distributions, making it easy to form complex nucleon correlations and cluster structures on the nuclear surface. In these regions, the conventional single-center-dominated $H_0 + H$ approach inevitably requires substantial modification. This is a fundamental issue that warrants serious attention.

This article provides an overview of important breakthroughs in the study of unstable (radioactive) nuclei over the past three decades and looks ahead to future research directions.

Discovery of Halo Nuclei

In 1985, experiments revealed that the interaction cross sections of ^{11}Li and ^{6}He showed significant enhancement compared to their neighboring isotopes [3], a phenomenon based on the strong absorption property of nuclear matter. The concept of neutron halo nuclei was first proposed in 1987 [4] to explain the anomalous increase in the cross section (radius) of ^{11}Li. This proposal simultaneously introduced the concept of the dineutron cluster and predicted the soft dipole resonance and its associated greatly enhanced Coulomb breakup cross section. While conventional giant resonances appear at high excitation energies requiring equivalent photon energies in the 10–20 MeV range, the soft dipole resonance can be excited much more easily, requiring only 1 MeV or even lower virtual photon energy. Using ^{208}Pb or ^{197}Au targets to Coulomb-excite halo nuclei can increase the breakup cross section by more than an order of magnitude. Experiments soon confirmed that the Coulomb excitation breakup cross section of ^{11}Li was indeed enormously enhanced [5], which subsequently became one of the important criteria for identifying halo nuclei. For example, ^{31}Ne was identified as a halo nucleus through this characteristic [6]. The concept of neutron halo nuclei was fully established in 2006 after the direct measurement of the charge radius of ^{11}Li using laser spectroscopy of atomic hyperfine structure [7], confirming that its exceptionally large radius resulted solely from the expansion of the neutron distribution while its proton radius remained unchanged. Research on the tightly correlated dineutron cluster in halo nuclei has continued to the present day, with numerous experimental and theoretical investigations still underway. This topic involves the transition from fermionic to bosonic systems and the structure of neutron star surfaces, making it a persistent research hotspot, though both experimental and theoretical challenges remain substantial [8].

Application of In-beam γ Spectroscopy

The spatial distribution expansion of valence nucleons in halo nuclei corresponds to a narrowing of their momentum distribution. This momentum distribution is relative to the nuclear center of mass, so the width of the valence nucleon momentum distribution equals that of the corresponding core fragment (such as ^{9}Li in ^{11}Li). Indeed, just one year after the halo nucleus concept was proposed, the momentum distribution of ^{9}Li core fragments from ^{11}Li breakup was measured to be significantly narrowed [9], providing another criterion for halo structure.

Since the transverse momentum width of core fragments is heavily influenced by scattering mechanisms, a method for measuring longitudinal momentum distributions was later developed at Michigan State University (MSU) [10]. To accurately measure the momentum width caused by internal nuclear motion, the momentum spread from the incident unstable nuclear beam itself must first be eliminated as much as possible. This requires the use of an achromatic magnetic spectrometer, which compensates for the momentum spread of the unstable nuclear beam before the physical target such that it is canceled at the spectrometer' s focal plane after the target. The momentum distribution within the projectile nucleus (carried out by the core fragment after the breakup reaction on the target) can then be fully expanded and precisely measured at the focal plane. This technique was implemented at MSU in 1992 [10] and subsequently established at other radioactive ion beam laboratories such as the Gesellschaft für Schwerionenforschung (GSI) in Germany [11]. Later theoretical and experimental studies revealed that the longitudinal momentum distribution width correlates well with the angular momentum of the valence nucleon, enabling its use to extract angular momentum information. Traditional angular momentum measurements relied primarily on angular distributions (differential cross sections), which typically require high beam intensities ($>10^{8}$ particles) for measurements over a wide angular range—feasible for stable nucleus experiments but essentially impossible for unstable nucleus studies. With the longitudinal momentum width measurement method, experiments need only be conducted near 0°, drastically reducing the beam intensity requirement and allowing results to be obtained with intensities as low as $\sim 10^{2}$ particles. This represents a revolutionary technological advancement that has greatly expanded the scope of unstable nuclear experiments. To simultaneously determine the energy state of the removed valence nucleon while measuring longitudinal momentum (corresponding to angular momentum), γ-ray detectors are typically placed near the target, constituting in-beam γ spectroscopy. Indeed, the two most important physical quantities for valence nucleons are their quantum state energy and angular momentum. The realization and widespread application of in-beam γ spectroscopy have provided a wealth of crucial data for studying shell evolution in unstable nuclei [11].

Measurement of Basic Properties and Discovery of New Magic Numbers

For light nuclei near the valley of stability, the binding energy (separation energy) for adding one more neutron decreases significantly at neutron numbers 8 and 20, providing evidence for these being neutron magic numbers. However, for nuclei far from stability (with increasing isospin asymmetry), this phenomenon shifts from neutron number 20 to neutron number 16, leading to the concept of new magic numbers [12].

In addition to studying magic number positions through mass measurements that yield neutron separation energies, the energy difference and decay strength of the first 2^+ excited state also serve as important signatures of magicity. Through measurements of the first 2^+ excited state, a new neutron magic number at N=34 was discovered in the neutron-rich nucleus ^{54}Ca [13]. It is worth noting that nuclear charge radius measurements can also be used to test new magic numbers. In 2021, experimental measurements of charge radii near the proton-magic calcium isotopes were extended to neutron number 32, with results showing no manifestation of new magic number characteristics [14].

Exotic Correlation Structures of Nucleons

With advances in various measurement techniques, researchers worldwide have made important discoveries regarding exotic nuclear structures. Such structures often manifest as strong correlations among a few nucleons, forming new structural degrees of freedom and effective interactions within these degrees of freedom. Conventional mean-field shell models struggle to describe exotic structures because, fundamentally, the interaction environment for some nucleons has changed, and the central mean-field effects are no longer dominant. Consequently, the selection of primary and perturbation terms in the shell model Hamiltonian becomes inconsistent with the actual physical situation (see discussion in the introduction section).

Dineutron correlations, mentioned earlier in the context of halo nuclei, remain an important and far-reaching issue in neutron-rich systems that requires further investigation [8]. Theoretical calculations previously predicted the existence of a four-neutron resonance state [15], and in 2022 experimental evidence for such a state was discovered [16]. In proton-rich systems, strong correlations may also exist among valence protons. In 2021, a four-proton correlated state was observed for the first time in the unbound nucleus ^{18}Mg [17]. Also in 2021, direct knockout reactions were used to knock out α-clusters from the low-density surface region of heavy nuclei [18], confirming cluster structures on the surfaces of heavy nuclei and providing a basis for theoretical descriptions of α-decay in heavy nuclei.

Nuclear cluster structure is a universally existing exotic phenomenon that was systematically analyzed as early as the 1930s. In 1968, Ikeda et al. proposed the threshold rule [19]: while most stable nuclei do not exhibit significant cluster structure in their ground states, when nuclei are excited near certain cluster decay thresholds, the reduced binding energy between clusters causes the nuclear volume to expand, making it easier for some nucleons to form relatively compact cluster structures (particularly α-clusters) locally, creating a relatively stable state. From a quantum system perspective, the precise location of cluster resonance states is closely related to the inter-cluster interaction potential, the continuity characteristics of the wavefunction inside and outside the potential barrier, and the antisymmetrization requirements of the overall wavefunction. As excitation energy increases, the number of clusters in principle increases, eventually forming multi-α systems.

Extending the Ikeda diagram to the neutron-rich region reveals even richer cluster structures [20]. For weakly bound neutron-rich nuclei, the presence of valence neutrons can lead to molecular orbital configurations analogous to those in atomic and molecular physics. Clusters arrange themselves in specific configurations, creating two-center or multi-center structures, while valence neutrons move in molecular orbitals between multiple cores, functioning similarly to electrons forming covalent bonds in molecular orbitals. As the excitation energy of neutron-rich nuclei increases, the diversity of bonding between valence neutrons and clusters makes nuclear molecular structures even more abundant. Of course, the specific configurations that can be realized in a quantum system depend on threshold effects, effective interactions, quantum state orthogonality, and the asymptotic characteristics of wavefunctions.

Currently, cluster structures in light nuclei that have been extensively studied experimentally are illustrated in Figure 2 [Figure 2: see original paper]. The ground state of ^{8}Be is a typical two-α cluster structure. ^{10}Be and ^{12}Be can be viewed as having a two-α core based on ^{8}Be with additional valence neutrons, and such cluster structures have been experimentally confirmed [20]. Experimental research on molecular cluster structures currently focuses on the carbon isotope chain. The ${0_2}^+$ (Hoyle) state in ^{12}C is a typical 3α structure, though its arrangement has long been debated. The currently accepted view is that it exists in a state similar to α-condensation, where all α particles move in s-waves in an expanded environment [22]. Theoretical predictions suggest that various types of three-center molecular structures exist in ^{14}C and ^{16}C, including triangular configurations, linear chain structures with mixed π-σ bonds, and linear chain structures with pure σ bonds (Figure 2) [23,24]. Linear chain structures are particularly intriguing as they represent an extremely exotic configuration. Here, π-bonding refers to valence neutrons primarily located on both sides of the line connecting α-clusters, while σ-bonding refers to valence neutrons mainly situated on the line connecting α-clusters, with the latter giving the longest chain and thus the largest moment of inertia [20]. Experimentally, mixed π-σ bond linear chain structures in excited states of ^{14}C and ^{16}C have been confirmed [25], while studies of the other two chain structures (Figure 2) are ongoing, with several experimental indications already obtained.

Numerous methods exist for experimentally measuring and identifying nuclear cluster structures, including measuring resonance energies and spins to construct rotational bands, deriving cluster structure spectroscopic factors from measured cluster decay branching ratios, measuring characteristic excitation strengths (such as monopole transition strengths with small energy spacing), and measuring selective decay pathways. These methods are described in detail in the articles reporting the aforementioned examples and will not be elaborated here. For theoretical and methodological studies of cluster structures, readers may refer to previous review articles [26].

Future Prospects

Over the past three decades, nuclear structure research has expanded into the territory of unstable nuclei, yielding a series of important discoveries that have driven theoretical development. A key feature of nuclear physics is its dual emphasis on fundamental and applied research while simultaneously supporting interdisciplinary studies such as nuclear astrophysics. Research on unstable nuclei is actually still in its infancy, with most of the nuclear chart awaiting exploration in the coming decades. In particular, the medium-heavy mass neutron-rich region will concentrate major scientific questions including exotic structures, the astrophysical r-process, and pathways to the superheavy island. To explore these questions, scientific and technological powers worldwide are constructing large-scale facilities capable of producing radioactive ion beams far from the valley of stability (Figure 3 [Figure 3: see original paper]), including both currently operating and next-generation (3rd–4th generation) facilities that will be commissioned in the coming years.

Regarding exotic structures, the surface expansion of weakly bound systems naturally induces corresponding structural changes, particularly the emergence of clusters and multi-center configurations, which will drive the development of new theoretical frameworks. Experimental detection apparatus must also advance significantly, especially for coincidence measurements of multi-particle (including multi-neutron) and multi-fragment emissions, requiring support from a series of novel detection technologies and methodologies.

Author Contributions

CHEN Ying was responsible for drafting the manuscript based on the presentation; YE Yanlin was the presenter and responsible for finalizing the manuscript; WEI Kang assisted with figure preparation.

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Note: Figure translations are in progress. See original paper for figures.