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NUCLEAR SHELL STRUCTURE EVOLUTION IN NEUTRON-RICH ISOTOPES BEYOND THE N=82 MAGIC NUMBER: A THEORETICAL INVESTIGATION

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ABSTRACT
The development of nucleus shell configuration in a neutron-enriched nucleus is still a major problem in atomic physics due to its importance in terms of both nuclear structure and quick neutron-capture (r-) process nucleosynthesis. This review synthesizes current theoretical and experimental advances concerning shell evolution beyond the N = 82 magic number, with particular emphasis on the region approaching the closure of the N = 126 shell that governs the third r-process abundance peak's formation. Recent breakthroughs in large-scale shell-model computations, chiral effective field theory, ab initio many-body techniques, energy density functional approaches, and relativistic mean-field models are critically evaluated for their descriptions of shell-gap evolution, effective single-particle energies, and proton–neutron interactions in neutron-rich nuclei. The review highlights the roles of tensor-force effects, monopole interactions, three-nucleon forces, and pairing correlations in modifying shell structure under extreme isospin conditions while summarizing current experimental evidence supporting these theoretical predictions. Although the N = 82 shell gap exhibits moderate evolution with decreasing proton number, the N = 126 shell closure remains comparatively robust despite model-dependent uncertainties in its predicted behaviour. The implications of shell evolution for neutron separation energies, β-decay properties, and r-process abundance calculations are also discussed. Overall, this review provides an integrated perspective on the microscopic mechanisms governing shell evolution beyond N = 82 and identifies key challenges and future directions for improving theoretical predictions and experimental constraints.

KEYWORDS: Nuclear shell model, Shell evolution, N=82, N=126, Tensor force

1. INTRODUCTION
The nuclear shell model has traditionally been regarded as one of the most protruding hypotheses in research of the atomic nucleus, including proposals to explain the stability and structure of atomic nuclei. The model accurately anticipated the magic numbers (2, 8, 20, 28, 50, 82, 126) that correlate to better nuclear stability, which is caused by wider gaps among unoccupied and occupied single-particle energy levels. Mayer's and Haxel's and Jensen's and Suess's incorporation of a strong spin–orbit interaction marked a milestone in understanding nuclear physics, as they were able to reproduce these magic numbers and lay the foundation for the shell model, the starting point of all nuclear structure theory. This discovery marked a paradigm shift in the way people think about the structure of atomic nuclei, revealing that nucleons are organized in quantized shells that control many of the observed structural properties of atomic nuclei.
Later, the ability to predict was greatly expanded in the shell model by incorporation of realistic residual interactions between the valence nucleons. These improvements allowed to describe accurately excitation spectra, electromagnetic transition probabilities, magnetic moments, and nuclear binding energies for a wide variety of isotopes and therefore to make the shell model one of the most successful microscopic models in low energy nuclear physics (Brown, 2001; Caurier et al., 2005). However, nearly all of these advances have been made along nuclei that are near the valley of β-stability, where shell closures were typically assumed to be strong and not much affected by changes in the n/Z ratio. As a result, magic numbers were for a long time treated as universal Properties of the NMF, and the absence of magic numbers in the nuclear chart was hardly discussed. The establishment of ion beam facilities, which are radioactive, allowing the production and learning of neutron-rich and neutron-deficient nuclei, has challenged this classical view to a large extent. Experimental research done during the last 20 years has shown that the structure of the shell is by no means constant as the quantity of protons and neutrons varies. The conventional nuclei's magic numbers can be modified or even disappear in very neutron-rich nuclei, while new shell or subshell closures can appear in regions that are away from stability. The disappearance of the N = 20 and N = 28 shell closures, and the appearance of the N = 32 and N = 34 subshells, provided strong evidence that shell evolution is a characteristic of the nuclear many-body system, and not just a phenomenon of specific isotopic chains (Otsuka et al., 2005; Otsuka et al., 2010; Steppenbeck et al., 2013). These observations showed the importance of proton–neutron interactions, tensor-force components, and many-body correlations in the modifications of effective single-particle energies and shell-gap magnitudes, leading to the subject of shell evolution being considered one of the most vital areas of research in the field of nuclear structure nowadays.
The development of the envelope is critical not just for nuclear structure, but it is also essential for the rapid capture of neutrons a (r-) technique that facilitates the formation of roughly 50 percent of all elements heavier than iron. R-process

nuclei are neutron-rich nuclei that develop under astrophysical settings that are not accessible in typical laboratory studies. Nuclei close to N = 82 and N = 126 are waiting-point nuclei, where the β-decay half-life and the probability of neutron capture is relatively large for a short period of time, resulting in the characteristic abundance peaks observed in the solar system and metal-poor stars (Arnould et al., 2007; Grawe et al., 2007; Cowan et al., 2021). The strengths of such shell gaps significantly affect the reaction path and the final elemental abundance distribution through their influence on neutron separation energies, β-decay characteristics, nuclear masses and neutron capture rates. Uncertainties involved with shell evolution are among the main uncertainty sources in modern r-process calculations, making reliable theoretical descriptions of neutron-rich nuclei near the neutron drip line (Mumpower et al., 2016) very important.

To meet these challenges, theoretical models must be capable of describing the interactions between the constituent nucleons at micro scale but still have predictive power in areas where experimental data is limited. With the combination of effective interactions obtained from chiral effective field theory and renormalization procedures which respect low-energy nuclear observables, it is now possible to define systematically the link between the underlying nucleon–nucleon interaction and finite nuclear systems (Bogner et al., 2010; Hebeler et al., 2011). Concurrently, significant progress in non-empirical valence-space interactions, coupled-cluster theory and the valence-space based in-medium similarity renormalization group (VS-IMSRG) have been greatly enhanced the clear representation of heavy and medium-mass nuclei, which includes the content of three-nucleon forces. It is now known that these forces are necessary to consistently describe shell evolution, nuclear saturation properties and isotopic trends throughout the nuclear chart (Stroberg et al., 2019; Holt et al., 2019). There are also complementary self-consistent models based on Skyrme energy density practical theory and Hartree–Fock–Bogoliubov mass models which add the global descriptions of nuclear masses, deformation, pairing correlations and shell-gap evolution. Despite all these models, however, the uncertainties in predicting nuclear properties still remain large, especially in the prediction of the properties of nuclei far from stability, and therefore the models require further development and testing (Goriely et al., 2009).

While great strides have been made in the understanding of shell evolution, there are still some questions that have yet to be answered. The long-lived N = 126 shell closure at extreme neutron-rich environment, the relative importance of tensor interactions, central monopole effects, three-nucleon interactions, and collective correlations to single-particle energies are still under discussion. To identify areas of agreement, to assess what is lacking in the current theories, and to prioritize future research, it is important to conduct a broad and thorough synthesis of the existing theories. The purpose of this review is to critically discuss the development of the shell structure of the nucleus having isotopes that are neutron-rich beyond the magic number N = 82, utilizing the most recent advances in shell-model calculations, realistic actual connections, ab initio many-body approaches, and energy density functional approaches. Special focus is given to understanding the microscopic processes that identify the efficient single-particulate energy evolution, the stability (or instability) of the closure of N = 126 shell, and the implications of shell evolution for r-process nucleosynthesis, providing an up-to-date and comprehensive view of one of the most active areas of modern structure of nuclues and nuclear astrophysics research.

3. METHODOLOGY

To evaluate the state-of-the-art information on nuclear shell structure development for neutron-rich isotopes beyond the N = 82 shell closure, a thorough literature search was carried out. The relevant peer-reviewed articles have been retrieved from Web of Science, Scopus, Google Scholar, INSPIRE-HEP, ScienceDirect, and American Physical Society journals by using keywords such as nuclear shell evolution, N = 82, N = 126, shell model, single particle effective energies, tensor force, three-nucleon forces, VS-IMSRG, energy density functional, and r-process nucleosynthesis. Classical studies that lay down the theoretical background and the modern achievements in the arena of the shell model, ab initio, and energy density functional approaches were selected, while irrelevant articles were omitted. This literature was critically analyzed and synthesized using a comparative approach to theories, nuclear interactions, predictions, and agreement with experimentally observed phenomena, especially concerning effective one-body energy terms, evolution of shell gaps, three-body interactions, and relevance to r-process nucleosynthesis. The overall procedure used for identifying, selecting, classifying, and synthesizing the literature is shown schematically in Figure 1.

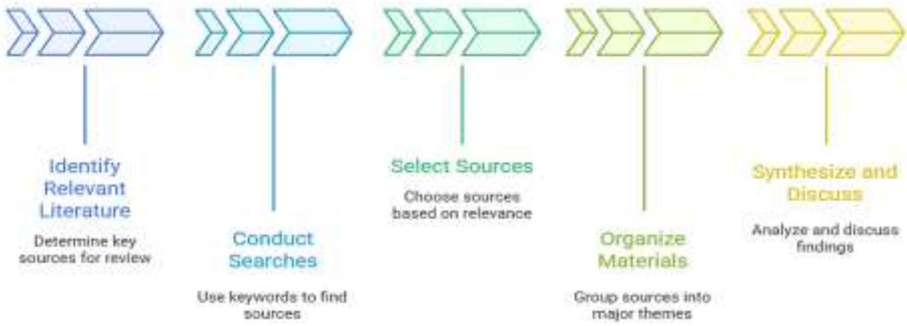

Figure 1. Overview of the Comprehensive Review Process

The review procedure presented in Figure 1 includes six steps performed consecutively: setting the aim of the review, finding the appropriate literature through database search, selecting the studies according to pre-defined criteria of relevance, categorizing the selected literature, critical synthesis of the theory and experimental results, and lastly, synthesizing all the information to detect the art of state in studies on shell evolution.

4. RESULTS

4.1 Evolution of the N = 82 Shell Gap

N = 82 is one of the most important neutron magic numbers, and It is important to comprehend the structural characteristics of medium-mass to heavy neutron-rich nuclei. In the administration of β-stability, spherical nuclei with N = 82 are known to have an unusually well-developed shell closure effect, with higher binding energies, higher energies for the first 2^+ excited state, lower quadrupole collectively, and distinct jumps in separation energies of two-neutron. The presence of such a big energy gap between occupied and unoccupied neutron orbitals is reflected by these observables, which indicate that the shell structure is still present for stable and near-stable isotopes (Brown, 2001; Caurier et al., 2005). Experimental studies have continued to increasingly go to the neutron-rich isotones, and crosses of the development of the N = 82 gap of shell with decreasing proton number have appeared. Based on the measurements obtained from β-decay spectroscopy, transfer reactions, and systematics of excitation energy, a moderate decrease in the magnitude of the shell gap has been proposed, but shell quenching has not been confirmed from experiments (Steppenbeck et al., 2013). It has been suggested that this behavior is due to the changes of effective single-particle energy resulting from the monopole part of the proton–neutron interaction and the tensor force, which affects the relative energy of neutron orbitals in decreasing proton occupancy (Otsuka et al., 2005; Otsuka et al., 2010). In addition, recent microscopic studies that combine chiral effective field theory and include explicit three-nucleon forces successfully capture the observed shell evolution, while retaining the general shell structure of neutron-rich nuclei, and thus enhance the predictive power of modern nuclear models (Bogner et al., 2010; Hebeler et al., 2011; Stroberg et al., 2019; Holt et al., 2019). The theoretical prediction, Table 1 summarizes the experimental verification and development of the N = 82 shell gap.

Table 1. Summary of Indication for the Evolution of the N = 82 Shell Gap

Aspect	Key Finding	Evidence	References
Stable nuclei	Strong N = 82 shell closure	Spectroscopic observables	Brown (2001); Caurier et al. (2005)
Neutron-rich nuclei	Moderate shell-gap reduction	β-decay and transfer studies	Steppenbeck et al. (2013)
Tensor-force effect	ESPEs evolve with proton removal	Calculations of Shell-model	Otsuka et al. (2005, 2010)
Three-nucleon forces	Stabilize the shell gap	*Ab initio* and VS-IMSRG studies	Bogner et al. (2010); Hebeler et al. (2011); Stroberg et al. (2019); Holt et al. (2019)

4.2 Evolution of the N = 126 Shell Gap

The next important neutron magic number after N = 82 is N=126 shell closure and forms an essential part of the structure of neutron-rich and heavy nuclei as well as the r-process nucleosynthesis flow. In comparison to the shell gap at N = 82, in general, theoretical calculations show that the N = 126 shell gap stays relatively stable because the orbitals outside of the gap are not as prone to the effect of tensor-force-induced monopole interactions (Otsuka et al., 2010; Stroberg et al., 2019). However, various theoretical calculations suggest that there is a slight decrease in the shell gap value with the decreasing proton number (Goriely et al., 2009; Holt et al., 2019). Because of the lack of spectroscopic data available for nuclei near the drip line of neutron, theoretical studies are still the main resource for obtaining information concerning the stability of the closure of sell at N = 126. A diagram of the development of the N = 126 shell gap with proton number decreasing is shown in Fig. 3.

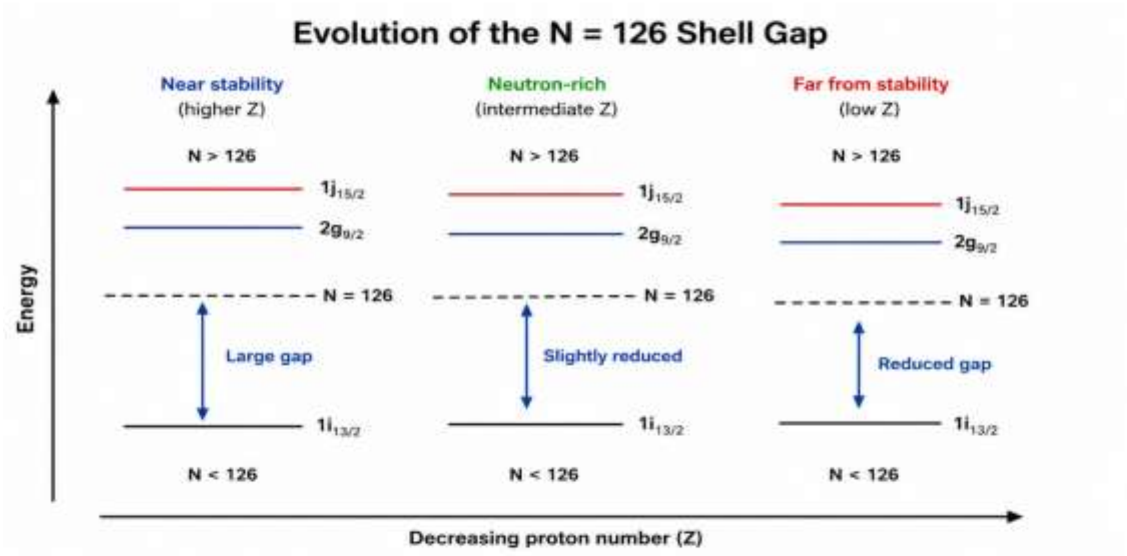

Figure 3. Schematic evolution of the N = 126 shell gap with proton number decreasing

4.3 Proton–Neutron Correlations and Pairing Effects

In addition to shell-gap evolution, protons-neutrons interaction and pairing correlations affect neutron-rich nuclei in the region N=82 to N=126 structure. Pairing correlations soften shell closures through the spread of nucleon occupation into adjacent orbitals thus affecting the energy spectrum of single-particle and the excitation spectrum. Hartree–Fock–Bogoliubov, quasiparticle random-phase approximation, and large-scale shell-model calculations demonstrate an increasing role of pairing correlations in open-shell nuclei, especially in the mid-shell region, where quadrupole and octupole collectivities appear (Bogner et al., 2010; Hebeler et al., 2011; Stroberg et al., 2019). Collective modes give rise to slow deformation change and change of orbital occupancies while maintaining the shell structure. Based on the available theoretical investigations, the shell evolution in the region is caused by the combined effect of correlations pairing, monopole interactions, and many-body effects. The main effects of correlations on shell evolution are enumerated in Table 3.

Table 3. Influence of Proton–Neutron Correlations and Pairing on Shell Evolution

Mechanism	Effect on Nuclear Structure	References
Interaction of Proton–neutron	Changes effective energies of single-particle and shell gaps	Otsuka et al. (2005, 2010)
Pairing correlations	Smoothens shell closures and fragments single-particle strength	Bogner et al. (2010); Hebeler et al. (2011)
Quadrupole collectivity	Enhances nuclear deformation in open-shell nuclei	Stroberg et al. (2019)
Many-body correlations	Improve the explanation of shell evolution in neutron-rich systems	Holt et al. (2019)

4.4 Comparison of Nuclear Interaction Models

There have been several theoretical methods which are formulated to understand the structure of shell beyond the N = 82 shell closure, each providing different strengths when used to define nuclei rich in neutrons. The large-scale shell model approach gives accurate spectroscopy of states and accurately predicts the energy spectrum and transitions but is difficult to apply in heavier elements due to computational limitations. The use of interactions based on chiral effective field theory along with the ab initio many body techniques such as the valence-space in-medium similarity renormalization group gives a microscopic picture of the two- and three-nucleon interaction (Bogner et al., 2010; Hebeler et al., 2011; Stroberg et al., 2019). In turn, consistent models utilizing Skyrme energy density functionals and relativistic mean field theory can give global descriptions of nuclear masses, deformations, and shell evolution through the nuclear chart, yet the different parameterizations of the interactions between the two approaches produce different predictions for the strength of the shell gaps (Goriely et al., 2009; Holt et al., 2019). Overall, these approaches, taken together, help build up knowledge of shell evolution.

4.5 Astrophysical Implications for the r-Process

Changes in shell structure with respect to the magic number N = 82 have implications for the process called nucleosynthesis, i.e., quick neutron-capture (r-). Specifically, the width of the N = 126 shell gap disturbs the values of neutron separation energies, beta-decay lifetimes, and the creation of waiting point nuclei, which control the creation of heavier nuclei. The strong shell closure delays the rate of the reaction, allowing matter to collect at the third abundance peak ($A \approx 195$) of the r-process, while a narrower shell gap promotes fast beta decay and neutron capture, thereby changing the expected abundance profile (Arnould et al., 2007; Grawe et al., 2007; Mumpower et al., 2016). Modern studies of the r-process reaction network reveal that uncertainties associated with the evolution of shell gaps continue to be one of the significant contributors to the uncertainty in heavy element nucleosynthesis models (Cowan et al., 2021). In light of this, theoretical and experimental investigations of neutron-rich nuclei are crucial to improving astrophysical models and nucleosynthesis calculations.

5. DISCUSSION

The results compiled in this review have shown that the shell structure evolution is beyond the N = 82 magic number is dictated by a complicated interplay of proton–neutron monopole interactions, tensor-force effects, pairing correlations and many-body interactions. The theory and experiment available do not show the total absence of shell closures, but instead suggest that the strength of the gap in the shell decreases gradually as the number of neutron increases. The N = 82 shell closure remains even when the nuclear magicity is varied, along with a small decrease of the effective value of the shell gap, which implies that nuclear magicity is continuous as a function of the nuclear isospin. This interpretation is consistent with that of Otsuka et al. (2020) of the evolution of the shell structure with modern interpretations involving the nucleon–nucleon force and the monopole and tensor parts of the nucleon–nucleon force. Likewise, the classical models of the structure of the nucleus have focused on the persistent role of shell closures in the nuclear many-body problem, and the growing role of collective degrees of freedom in nuclei away from stability (Bohr et al., 1970; Casten, 2000; Otsuka, 2002).

The trends identified in this review are also confirmed by comparison with the previous studies. The smooth transition of the N = 82 shell gap is consistent with the recent spectroscopic studies of neutron-rich Te and Ag isotopes, as shell closure features are still observed as the isotopes get more neutron-rich (Moon et al., 2021; Luo et al., 2025). Similarly, it is found that large scale mass calculations using the finite-range droplet model, can reproduce the persistence of major shell closures, but also predict small changes in the strength of the shell gaps as the nuclei approach the neutron drip line

(Möller et al., 2016). These observations further support the finding that shell evolution is mainly a quantitative change in the size of the gap(s) in the shell.
The closure of N = 126 shell is a big puzzle in modern nuclear structure physics. A similar comparative study of N = 50, 82, 126 and 184 isotones with a large number of nucleons recently showed that shell-driven structural features are retained across major magic numbers and vary with interactions at extreme neutron excess (Seif & Adel, 2026). In addition, shell-model calculations point towards shell evolution involving modifications to nuclear density distributions and spin–orbit interactions, in addition to the tensor-force mechanism that is well established in shell-model calculations (Shi et al., 2026). These results indicate that none of these theories completely explains the evolution of shells, showing the need to use combinations of theories.
It is also shown from the present review that there is an increasing importance of pairing correlations and collective effects between the closures of N = 126 and N = 82 shell. The collectivity of quadrupole and octupole gain in strength in mid-shell nuclei, and there are smooth variations in the operative single-particle energies by combining the pairing interactions with neighbouring orbitals to distribute nucleon distributions. In the case of neutron-rich nuclei with weak, non-saturable interactions, similar behavior has been observed in studies of neutron–neutron correlations, which have a strong effect on the structure of nuclei near the drip line (Suzuki et al., 2016). Therefore, evolution of the shells is to be understood as a result of several concurrent microscopic mechanisms, not necessarily the tensor force.
Astro physically, these changes in structure are significant, since the nuclei just underneath and above the closure of the N = 126 shell are important for making the third peak of the r-process. Changes in the strength of the separation energy of the neutron, β-decay half-life, and neutron capture reaction rates alter heavy element nucleosynthesis. Therefore, better theory descriptions of shell evolution is a critical need to decrease the worries in the r-process simulations and enhance the link between nuclear structure and astrophysical observations.
While significant advances have been made, there are still some shortcomings. The many systems of medium mass (82 < N < 126) are still too difficult to calculate using the model of shell, and the determination of the gaps of shell may be affected by model truncations. Moreover, the phenomenological interactions, which are primarily tuned to nuclei near stability, might not be predictive of the most neutron-rich isotopes, while microscopic calculations using chiral effective field theory remain subject to uncertainties stemming from many-body approximations as well as truncation of the interaction. Moreover, many theoretical works have considered spherical reference configurations of the nuclei, although there is mounting experimental indication for the presence of quadrupole and octupole deformations of open-shell nuclei, which calls for the development of approaches beyond mean field or shell-models.
Plans should thus emphasize further experimental efforts with the expansion of radioactive ion beam facilities for the next generation to extend spectroscopy and precision mass measurements through N = 126. Further advances in ab initio methods, such as the development of the valence-space IMSRG, the coupled-cluster approach, and generator-coordinated techniques, will help to enhance the predictive power of these methods and convey with confidence an uncertainty quantification. Lastly, using refined shell-evolution predictions for a self-consistent r-process reaction network calculation will permit us to better separate the uncertainties of the structure of the nucleus from those of astrophysical environment influences on nucleosynthesis and thus better understand the nucleosynthesis of heavy elements.

6. CONCLUSION

This review comprehensively examined the evolution of nuclear shell structure in neutron-rich nuclei beyond the N = 82 shell closure and the microscopic mechanisms that underlie the changes of the behaviour of the shell gaps under extreme isospin conditions. At present, there is no single mechanism for the development of the structure of the shell, and the theoretical and experimental evidence points to a combination of proton–neutron monopole, tensor force, three-nucleon, pairing, and many-body interactions to drive this evolution. The N = 82 shell conclusion shows a gradual weakening of the strength of the shell-gap with a decrease of the proton number, whereas the N = 126 closure of the shell is still rather strong, but its behavior in most nuclei, which are neutron-rich is still model dependent. The comparison of the shell-model, ab initio, energy density functional, and relativistic mean-field approaches reveals significant improvement in the understanding of shell evolution. However, the paucity of experimental data creates major uncertainty due to the variety of different theoretical interactions. The uncertainties directly affect predictions of r-process nucleosynthesis, including production of the third abundance peak, highlighting the close connection of nuclear structure with astrophysical modelling. Some improvements in radioactive ion beam facilities, precision mass measurements, and future many-body calculations are anticipated that will further constrain the evolution of the shells and enhance the predictive power. In summary, ongoing observation and modelling efforts will be crucial in order to fully comprehend shell progress and its contribution to the heavy elements' production in the Universe.

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