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Development of The Theory of Nuclear Structure from The Perspective of Nuclear Physics

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ABSTRACT

The study of the atomic nucleus's structure is a fundamental aspect of nuclear physics that continues to evolve in tandem with advances in theory, experimentation, and computation. The development of nuclear structure theory does not proceed linearly, but rather through the evolution of various complementary approaches, ranging from experimental foundations to modern theoretical formulations. This study aims to provide a comprehensive overview of the development of nuclear structure theory from a nuclear physics perspective, utilizing a Systematic Literature Review (SLR) approach and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. The literature search process was conducted through reputable scientific databases with the inclusion criteria of relevant journal articles published between 2020 and 2025. The results of the study resulted in 13 selected articles representing the stages of development of nuclear structure theory, including experimental foundations, phenomenological models such as the liquid drop model, microscopic approaches through shell models, to modern theories based on many-body, ab initio, and alternative frameworks. The synthesis of findings shows that the development of nuclear structure theory is evolutionary and cumulative, with each approach making specific contributions to explaining the properties and dynamics of atomic nuclei. This study emphasizes the importance of integrating various models and methods in forming a comprehensive understanding of modern nuclear physics.

Keywords: *Structure of the atomic nucleus; core physics; systematic literature review; PRISMA; core structure theory*

ABSTRAK

Studi tentang struktur inti atom merupakan aspek fundamental fisika nuklir yang terus berkembang seiring dengan kemajuan teori, eksperimen, dan komputasi. Perkembangan teori struktur nuklir tidak berjalan secara linier, melainkan melalui evolusi berbagai pendekatan komplementer, mulai dari landasan eksperimental hingga formulasi teoretis modern. Studi ini bertujuan untuk memberikan gambaran komprehensif tentang perkembangan teori struktur nuklir dari perspektif fisika nuklir, dengan menggunakan pendekatan *Systematic Literature Review* (SLR) dan metode *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA). Proses pencarian literatur dilakukan melalui basis data ilmiah terkemuka dengan kriteria inklusi artikel jurnal relevan yang diterbitkan antara tahun 2020 dan 2025. Hasil penelitian menghasilkan 13 artikel terpilih yang mewakili tahapan perkembangan teori struktur nuklir, termasuk landasan eksperimental, model fenomenologis seperti model tetesan cairan, pendekatan mikroskopis melalui model kulit, hingga teori modern berdasarkan banyak partikel, ab initio, dan kerangka kerja alternatif. Sintesis temuan menunjukkan bahwa perkembangan teori struktur nuklir bersifat evolusioner dan kumulatif, dengan setiap pendekatan memberikan kontribusi spesifik untuk menjelaskan sifat dan dinamika inti atom. Studi ini menekankan pentingnya mengintegrasikan berbagai model dan metode dalam membentuk pemahaman komprehensif tentang fisika nuklir modern.

Kata Kunci: *Struktur inti atom; fisika inti; tinjauan literatur sistematis; PRISMA; Teori struktur inti*

1. INTRODUCTION

The study of the structure of the atomic nucleus is an essential element in the field of nuclear physics, namely the branch of science that studies the characteristics, dynamic behavior, and interactions between nucleons, protons, and neutrons in the nucleus (Ferreira et al., 2025). Understanding the atomic nucleus is crucial not only for the development of fundamental theories of physics but also for a wide range of scientific applications, from nuclear technology to astrophysical research and the study of extreme matter in objects such as neutron stars (Tichai et al., 2024a). Understanding the structure of the nucleus is important not only for the development of fundamental theories of physics but also for scientific applications such as nuclear energy technology, nuclear medicine, and nuclear astrophysics, which require high-precision predictions of nuclear properties (Sammarruca, 2023). Since Ernest Rutherford's alpha particle scattering experiments in the early 20th century revealed the existence of the atomic nucleus, the study of nuclear structure has developed into an increasingly complex and multidisciplinary research domain, combining the principles of quantum mechanics, the theory of the strong force, and the many-body systems approach (Chen et al., 2025a).

The development of nuclear structure theory has progressed rapidly from experimental to conceptual aspects through the integration of quantum mechanics, strong interaction theory, and many-body theory to explain the collective and individual behavior of nucleons in the atomic nucleus (Maris et al., 2023). Macroscopic models such as the liquid drop model describe the nucleus as a collective system with volume, surface, Coulomb, and symmetry energy contributions, which can describe the average binding energy of all atomic nuclei (Dew, 2024). The liquid drop model is one of the initial approaches that examines the atomic nucleus from a macroscopic perspective by describing it as a fluid system that is stable due to collective cohesive forces (Ojala et al., 2025). This model is capable of explaining a wide range of nuclear phenomena, including binding energy and fission processes. However, the macroscopic model has limitations in explaining the structure of discrete energy levels and the stability of certain nuclei, which require a more detailed quantum approach (Machleidt & Sammarruca, 2024). The discovery of nuclear stability patterns and magic numbers indicates the existence of an internal quantum structure that requires a microscopic approach, such as the shell model, in explaining the spectral properties of atomic nuclei (Saini, 2025). The combination of these two approaches ultimately yields a more comprehensive understanding of both the collective and individual properties of nucleons in the nucleus (Zeng et al., 2024).

Entering the end of the 20th century to the modern era, the development of nuclear structure theory was increasingly driven by the quantum effective field theory (chiral effective field theory), which formulated nuclear forces based on the basic symmetry principles of quantum chromodynamics at low energies (Machleidt & Sammarruca, 2024). Chiral EFT provides a systematic framework for the derivation of two-nucleon and three-nucleon forces with controllable theoretical uncertainty estimates in modern many-body (ab initio) calculations, thereby increasing the predictive power of nuclear structure theory (Maris et al., 2023). At the same time, advances in computational technology support the application of many-body methods such as ab initio, energy density functional theory, and large-scale shell model calculations, which can expand the scope of analysis to include heavy nuclei that were previously difficult to handle with conventional approaches (Indiani, 2022).

However, a literature review shows that discussions on the development of core structure theory are often still fragmented, where recent scientific publications focus heavily on certain technical or methodological aspects without presenting a comprehensive conceptual synthesis (Dew, 2024). This gap indicates the need for a synthetic study that systematically summarizes the development of core structure theory from the macroscopic approach to the framework of quantum effective field theory in one complete conceptual narrative (Suhaimi et al., 2024). Based on this background, this article aims to present a comprehensive review of the development of nuclear structure theory from the perspective of nuclear physics by emphasizing the historical evolution, theoretical paradigm shifts, and major conceptual contributions of various models developed up to the modern era (ab initio and chiral EFT).

2. METHOD

This research uses a Systematic Literature Review (SLR) approach, which is implemented using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. (Yudistira & Veri, 2025). The PRISMA method was introduced in 2009 and is one of the best guidelines to help authors conduct systematic reviews and meta-analyses correctly, while also providing a structured framework, like a roadmap, in reviewing and organizing research flows (Luh et al., 2024). The PRISMA method can facilitate a structured process for identifying, screening, and selecting studies related to a research topic (Ma'ruf et al., 2025). Through this method, the author conducts a review and identifies journals systematically by following clear and structured steps at each stage, so that the results obtained are more comprehensive (Dini et al., 2024). This method consists of several stages, namely identification, screening, eligibility, and inclusion, which can be seen in Figure 1.

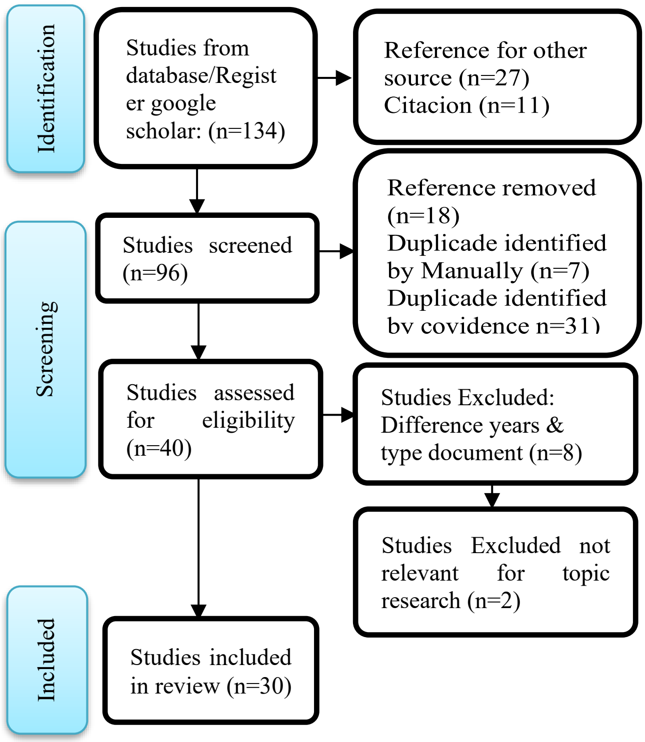

Figure 1. PRISMA Flowchart

2.1. Identification

The identification stage begins with a systematic search of international and national journals through Scopus, Google Scholar, and Semantic Scholar, each of which uses the "search" feature. In the identification stage, researchers conduct a comprehensive literature search through various scientific databases using a combination of keywords relevant to the research focus. The search technique used keywords such as "nuclear structure," "liquid droplet model," "shell or skin model," and "collective model." This comprehensive search is designed to cover all relevant publications (Latifah et al., 2024). The search process was conducted without any initial restrictions on publication year or document type to maximize the potential coverage of all literature related to the topic. Furthermore, the author reviewed the bibliographies of key articles to identify additional sources that might not have been detected through database searches. This step aimed to generate a comprehensive initial data set so that the subsequent selection process could be conducted more systematically and purposefully.

2.2. Reference data selection

The next step, the author carried out the data extraction stage, which was based on the inclusion and exclusion criteria method to make the data more specific with the existing research variables (Syahriannor et al., 2024). In the screening stage, all articles collected during the identification stage were re-examined by removing duplicates from various databases. Screening involved a careful examination of the titles and abstracts of the documents identified in the previous stage. Researchers reviewed the title and abstract of each article to assess their relevance to the research topic and focus. Articles that were irrelevant, out of scope, or did not meet the basic criteria were excluded at this stage. The screening process was systematic so that only articles that truly supported the research objectives could proceed to the eligibility assessment stage. This process was guided by specific criteria: only journal articles, not seminar proceedings, with an exclusive focus on those published within the last six years. This time restriction ensured the review's relevance to current trends and practices in the field of nuclear structure physics development. Further restrictions were made regarding publication time, limiting the scope to articles published within the last six years, specifically between 2020 and 2025. By establishing inclusion and exclusion criteria, documents that did not meet these criteria were excluded, simplifying the collection to include only the most relevant and recent publications (Ghorbiy et al., 2024). The specified inclusion and exclusion criteria can be seen in Table 1.

Table 1. Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclussion
Title and Content	In relation to the core structure of physics	Not relevant to the title
Year of publication	From 2020-2025	>2019
Publication type	Journal	Proceedings, seminars, theses
Focus of discussion	Core Structure Development	Others
Accessibilty	Full tex	Others

2.3. Eligibility

After screening is complete, the remaining documents undergo a detailed eligibility assessment. In the eligibility stage, articles that have passed the screening process are further analyzed through a full-text review. The authors assess whether each article meets the established inclusion criteria, such as the appropriateness of the research methods, the appropriateness of the study focus, the quality of the data, and the clarity of the reporting of the results. Articles that do not provide sufficient information, do not meet scientific quality standards, or are irrelevant to the research question are excluded at this stage. The eligibility assessment is conducted carefully to ensure that only studies with adequate validity and reliability are considered in the final analysis. This step involves a thorough review of the articles to verify their direct relevance to the specific theme of nuclear structure development in nuclear physics. This process is conducted manually, ensuring that each document is evaluated based on its substantive contribution to the field and its alignment with the study's thematic focus. The eligibility criteria are rigorously applied to select articles that specifically address nuclear structure development. This focused approach helps refine the literature pool to the most relevant studies for assessing nuclear structure, providing a clear path for detailed analysis.

2.4. Inclusion

During the inclusion stage, articles deemed eligible are included as the primary sample in the systematic analysis. These selected studies are used to answer the research questions and form the basis for synthesizing the findings. Articles submitted at this stage have undergone a rigorous selection process, ensuring their quality and relevance meet the standards of a systematic literature review. The inclusion stage marks the end of the selection process and serves as the primary foundation for compiling the research results and discussion.

3. RESULT AND DISCUSSION

3.1. Result

Based on the Systematic Literature Review (SLR) stages using the PRISMA method, 13 articles were obtained that met the inclusion criteria and were relevant to the topic of the development of nuclear structure theory from a nuclear physics perspective. These articles cover early historical studies of atomic and nuclear structure, the development of macroscopic models, microscopic models, many-body and ab initio approaches, and advanced collective phenomena in the atomic nucleus. A table of the literature review results containing the article titles, authors, and a summary of the main results is presented in Table 2.

Table 2. Summary of Selected Articles on the Development of Core Structure Theory

No.	Title	Author Name	Results
1.	Nucleus-nucleus scattering and the Rutherford experiment	(Barrette, 2021)	Nuclear scattering experiments became the empirical foundation for the discovery of the atomic nucleus and nuclear interactions.
2.	The Development of Atomic Structures by Dalton, Thomson, Rutherford, and Bohr, and their Mathematical Equations	(Suhaimi et al., 2024)	The development of atomic models shows a complementary evolution of scientific understanding from the classical to the early quantum models.
3.	A Commentary on Atomic Nucleus and its Fundamental Properties	(Rice, 2022)	Affirms the basic properties of the atomic nucleus, its size, mass, and the role of the strong nuclear force.
4.	Anisotropic liquid drop models	(Choksi et al., 2022)	Anisotropic liquid drop models broaden understanding of core shape and stability.

No.	Title	Author Name	Results
5.	Microscopic Nuclear Structure Study of ^{229}Th by Projected Shell Model	(Chen et al., 2025b)	PSM successfully reproduces the energy level structure of heavy nuclei and low-energy isomeric phenomena.
6.	Quantum entanglement patterns in the structure of atomic nuclei within the nuclear shell model	(Pérez-Obiol et al., 2023)	Quantum entanglement patterns reveal microscopic correlations between nucleons in the shell model framework.
7.	Anomalous collective modes in atomic nuclei within the proton-neutron interacting boson model	(Teng et al., 2025)	IBM-2 explains anomalous collective modes and proton-neutron dynamics consistently.
8.	Multifaceted character of shape coexistence phenomenainatomic nuclei	(Leoni et al., 2024)	The phenomenon of shape coexistence shows the complexity of the collective structure of the core.
9.	Generalized molecule-like structure in atomic nuclei	(Zeng et al., 2024)	The molecule-like structure bridges the shell model and the deformed collective state.
10.	Converging many-body perturbation theory for ab-initio nuclear structure: Brillouin-Wigner perturbation series for closed-shell nuclei	(Li & Smirnova, 2024)	BW-MBPT is capable of producing systematic convergence and high precision in the calculation of the ground state energy of closed nuclei.
11.	Towards heavy-mass ab initio nuclear structure: Open-shell Ca, Ni and Sn isotopes from Bogoliubov coupled-cluster theory	(Tichai et al., 2024b)	The Bogoliubov coupled-cluster method extends the ab initio approach to heavy and open-shell nuclei.
12	THE STRUCTURE OF ATOMIC NUCLEUS	(Sarkadi, 2020)	Alternative models offer a new conceptual approach to nuclear binding energy.
13	The Structure of the Atomic Nucleus, Force and the Role of Neutrinos	(Thompson, 2024)	RST theory provides an alternative causal perspective on the formation of core structures.

3.2. Discussion

The results summarized in Table 2 demonstrate that the development of nuclear structure theory is an evolutionary process driven by the interaction between experimental discoveries and theoretical innovation. The first finding shows that the initial understanding of atomic and nuclear structure stems from the development of the classical atomic model formulated by Dalton, Thomson, Rutherford, and Bohr (Suhaimi et al., 2024). This study confirms that each atomic model emerged in response to the limitations of previous models, with Rutherford's experiments being a crucial turning point, revealing the existence of the atomic nucleus as the center of mass and positive charge. Although not specifically addressing nuclear interactions, this conceptual foundation laid the foundation for the study of nuclear structure in modern nuclear physics. A second finding strengthened this empirical basis through the study of Rutherford's pioneering nuclear-nuclear scattering experiments (Barrette, 2021). Alpha particle scattering experiments provided compelling evidence for the extremely small size of nuclei and the existence of Coulomb repulsion, while also indicating the existence of short-range nuclear forces at very short distances. These findings were not only of historical importance but also provided a fundamental method for determining the size, potential shape, and nature of nuclear interactions, paving the way for the development of more quantitative models of nuclear structure.

Next, the third finding addresses the fundamental characteristics of the atomic nucleus, including mass concentration, nuclear size, and the role of the strong nuclear force as the binding force between protons and neutrons. (Rice, 2022). This study confirms that the atomic nucleus is a highly compact quantum system with interactions much stronger than electromagnetic ones, thus requiring a specialized theoretical approach distinct from atomic physics. This understanding provides the conceptual basis for developing a phenomenological model of nuclear structure. This phenomenological approach is reflected in the fourth finding, the development of the liquid drop model. (Choksi et al., 2022). This model views the atomic nucleus as a collective system resembling a liquid drop, thus explaining nuclear binding energy, relative nuclear stability, and the phenomenon of nuclear fission. The development of the anisotropic liquid drop model demonstrated that surface properties and nuclear shape play a crucial role in determining the equilibrium configuration of the nucleus. However, this model has limitations in that it cannot explain the discrete energy levels and magic numbers observed experimentally.

The limitations of the macroscopic approach encouraged the birth of microscopic models, as shown in the fifth finding through the shell model (Chen et al., 2025b). In this framework, the atomic nucleus is viewed as a collection of nucleons moving in an effective potential and occupying quantized energy levels. Studies on the heavy nucleus ^{229}Th have shown that the projected shell model is capable of reproducing the structure of low-energy levels and isomeric states with high accuracy, while also emphasizing the importance of the interaction between the single and collective degrees of freedom of particles in the atomic nucleus. Further insight into the microscopic aspects of nuclear structure is demonstrated in the sixth finding through the study of quantum entanglement patterns within the shell model framework (Pérez-Obiol et al., 2023). This research reveals that correlations between nucleons, particularly between like nucleons, play a crucial role in shaping nuclear structure. This finding broadens our understanding of the microscopic correlation structure of nuclei and demonstrates that the description of modern nuclear structure depends not only on energy levels but also on the nature of quantum entanglement between nuclear components.

Further developments show an attempt to bridge the individual and collective nature of the core, as reflected in the seventh finding through the interacting boson model (IBM-2) (Teng et al., 2025). This model successfully explains the emergence of anomalous collective modes that conventional collective models cannot explain. The differences in intrinsic deformation between protons and neutrons and the effects of band mixing are key to understanding the collective dynamics of nuclei, thus strengthening the view that nuclear structure is complex and multicomponent. The complexity of nuclear structure is also reflected in the eighth finding, which discusses the phenomenon of shape coexistence (Leoni et al., 2024). This study demonstrated that atomic nuclei can have more than one configuration of nearly identical energies, with varying degrees of mixing. This phenomenon confirmed that nuclear structure is not static, but rather dynamic, strongly influenced by the evolution of shell structures and collective deformation. With this ninth finding, many-body and ab initio approaches began to dominate modern nuclear structure studies (Li & Smirnova, 2024), demonstrating that Brillouin–Wigner many-body perturbation theory is capable of stable convergence and high precision in calculating the ground state energy of closed nuclei. This approach marks a shift towards a more fundamental and systematic description of nuclear structure.

The extension of the ab initio approach to heavy and open-shell nuclei is shown in the tenth finding via the Bogoliubov coupled-cluster theory (Tichai et al., 2024b). This study demonstrates that ab initio methods are no longer limited to light nuclei but have been able to reach nuclei with large masses, thus expanding the scope of theoretical predictions in nuclear physics. An alternative conceptual approach to nuclear structure is presented in the eleventh finding through a model of a nuclear molecule-like structure (Zeng et al., 2024). This approach bridges the gap between the shell model and the deformed collective structure, demonstrating the relative dynamics of valence protons and neutrons forming molecule-like configurations. This finding opens up new perspectives for understanding the collective properties of atomic nuclei. The twelfth finding proposes an alternative model of nuclear structure based on thermal and extreme astrophysics approaches (Sarkadi, 2020). This model offers a new perspective on binding energy and nuclear mass, although it is still conceptual and requires further validation.

Finally, the thirteenth finding introduces the Rotation-Space-Time (RST) theory as an alternative causal framework in explaining the structure of the atomic nucleus and the role of neutrinos in the formation and stability of nuclear configurations (Thompson, 2024). Unlike the conventional nuclear approach that emphasizes the interaction of nucleons through the strong force within the framework of quantum mechanics, the RST theory views nuclear structure as a direct consequence of the fundamental rotational dynamics of three-dimensional space-time, where protons and neutrons are arranged in certain configurations due to the causal balance between relativistic rotational motion, quanta energy, and the role of neutrinos as force field stabilizers during the process of nuclear formation under extreme conditions. Although still alternative and requiring further empirical testing, this approach demonstrates a broadening of perspectives in the study of nuclear structure by linking it to cosmological principles and astrophysical processes, thus demonstrating that the development of nuclear structure theory does not stop at the conventional nuclear model, but continues to evolve towards a more fundamental and interdisciplinary formulation. Overall, these results and discussion emphasize that the development of nuclear structure theory is evolutionary and complementary, where experimental foundations, phenomenological models, microscopic approaches, as well as modern many-body and ab initio theories contribute continuously to building an increasingly comprehensive understanding of atomic nuclear structure, which ultimately forms the framework of modern nuclear physics that is dynamic and continues to evolve.

4. CONCLUSION AND RECOMMENDATION

This systematic literature review concludes that the development of nuclear structure theory is an evolutionary and complementary process shaped by experimental discoveries, phenomenological models, microscopic descriptions, and modern many-body and ab initio approaches. The analysis of 13 selected articles demonstrates that early atomic models and scattering experiments established the conceptual and empirical foundations of nuclear physics, which were subsequently refined through macroscopic models such as the liquid drop model and later advanced by microscopic shell-model frameworks, collective theories, and first-principles calculations. These developments reveal that nuclear structure is inherently complex, dynamic, and multiconfigurational, and cannot be fully described by a single theoretical approach. Therefore, it is recommended that future research in nuclear physics further integrate microscopic, collective, and ab initio models to achieve a more unified understanding of nuclear structure, particularly for heavy and exotic nuclei, supported by continued collaboration between theoretical and experimental studies, as well as the expansion of systematic literature reviews incorporating recent publications and quantitative analysis methods to better map emerging trends in the field.

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