

Ground-State Properties of Superheavy Nuclei in the Relativistic Mean Field Framework

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Abstract

The study of superheavy nuclei constitutes one of the most demanding and intriguing domains of contemporary nuclear physics. The synthesis of elements beyond uranium has greatly extended the limits of the nuclear chart and offered important insights into the behavior of nuclear matter under extreme conditions. Superheavy nuclei are defined by elevated proton counts, wherein the intense Coulomb repulsion among protons often leads to nuclear instability. Quantum shell effects can confer further stabilization, resulting in the prediction of a "island of stability," where specific superheavy nuclei may exhibit comparatively extended half-lives. Comprehending the structural characteristics and stability processes of these nuclei is a primary goal of both theoretical and experimental nuclear studies.

This study examines the ground-state features of specific superheavy nuclei using Relativistic Mean Field (RMF) theory. The RMF model has become one of the most effective microscopic methods for elucidating nuclear structure throughout the nuclear chart, owing to its inherent integration of relativistic effects and spin-orbit interactions. Ground-state observables such as binding energies, quadrupole deformation parameters, charge radii, neutron and proton density distributions, and neutron skin thickness are carefully examined for superheavy isotopes within the proton number range $Z = 112-126$. Calculations utilize a recognized RMF parameter set, and the resultant nuclear features are analyzed to discern shell closures, deformation effects, and potential areas of increased stability.

The research indicates substantial shell stabilization at anticipated magic numbers and highlights the essential influence of deformation on the equilibrium configurations of superheavy nuclei. The computed observables suggest increased stability at neutron number $N = 184$, corroborating theoretical expectations about the presence of an island of stability. The results enhance comprehension of the structure and evolution of superheavy nuclei and offer significant theoretical direction for forthcoming experimental endeavors focused on synthesizing new elements and examining the boundaries of nuclear existence.

Keywords: Superheavy nuclei, Relativistic Mean Field Theory, Ground-State Properties, Binding Energy, Nuclear Deformation, Island of Stability.

1. Introduction

The atomic nucleus is a sophisticated quantum many-body system consisting of protons and neutrons that interact via strong nuclear interactions. The comprehension of nuclear structure and stability has persisted as a fundamental objective of nuclear physics for almost a century. Considerable advancements have been made in the characterization of stable and moderately heavy nuclei; yet, the study of superheavy nuclei remains fraught with considerable theoretical and practical difficulties. Superheavy nuclei reside at the pinnacle of the nuclear chart, exemplifying the ultimate boundaries of nuclear existence, where the interaction between nuclear attraction and Coulomb repulsion attains unparalleled intensity.

The occurrence of superheavy nuclei constitutes a

notable prediction of contemporary nuclear theory. As the proton quantity escalates, the repulsive Coulomb force among positively charged protons becomes progressively predominant, diminishing nuclear stability and amplifying the likelihood of spontaneous fission. Classical theories indicate that nuclei with exceedingly high proton counts should be unstable and incapable of existing. However, quantum mechanical shell effects substantially modify this perspective. Nucleons, akin to electron shell configurations in atoms, inhabit distinct quantum energy levels within the nucleus. Upon the entire filling of these shells, enhanced stability is attained, resulting in the emergence of what are termed magic nuclei.

The nuclear shell model effectively elucidates the presence of magic numbers in stable and medium-mass

nuclei. Conventional magic numbers, including 2, 8, 20, 28, 50, 82, and 126, represent closed-shell configurations linked to increased stability. Applying this approach to the superheavy domain has resulted in the forecast of novel proton and neutron magic numbers, specifically near $Z = 114$, 120, or 126 and $N = 184$. These shell closures are anticipated to produce a zone of increased stability, generally known as the island of stability. Nuclei in this region may exhibit half-lives considerably longer than those of adjacent isotopes, facilitating their experimental observation despite their exceedingly high proton levels.

The pursuit of superheavy elements has constituted a significant accomplishment in nuclear physics in recent decades. Researchers have successfully created multiple superheavy elements through improved heavy-ion fusion processes, therefore extending the periodic table beyond uranium. The identification of elements with atomic numbers surpassing 104 has yielded significant insights into nuclear stability, decay processes, and shell effects in exceedingly heavy systems. Notwithstanding these accomplishments, numerous superheavy isotopes remain experimentally unattainable due to their exceedingly brief lives and minimal manufacturing cross-sections. Thus, dependable theoretical models are essential for forecasting their characteristics and directing subsequent tests.

Numerous theoretical frameworks have been established to investigate superheavy nuclei, encompassing macroscopic-microscopic models, shell correction techniques, Hartree-Fock computations, Hartree-Fock-Bogoliubov theory, density functional methodologies, and relativistic mean field models. The Relativistic Mean Field (RMF) theory has become one of the most effective and prevalent frameworks for elucidating nuclear structural phenomena throughout the nuclear environment. The RMF theory offers a self-consistent relativistic framework for nucleons interacting via meson exchange and electromagnetic fields.

The principles of RMF theory stem from relativistic quantum field theory, wherein nucleons are regarded as Dirac particles operating inside self-consistent mean fields produced by meson exchanges. The model incorporates scalar sigma mesons that facilitate medium-range attraction, vector omega mesons that induce short-range repulsion, isovector rho mesons that explain neutron-proton asymmetry, and photons that signify electromagnetic interactions. The relativistic approach inherently produces a robust spin-orbit interaction, crucial for accurately reflecting experimentally observed shell structures and magic

numbers.

This study systematically investigates the ground-state features of superheavy nuclei using RMF theory. The research investigates nuclei within the proton number range $Z = 112$ –126, including the most viable possibilities for the anticipated island of stability. The research seeks to elucidate the structural evolution of superheavy nuclei by the analysis of binding energies, deformation parameters, charge radii, neutron and proton distributions, and shell effects. Significant attention is directed on finding signals of shell stabilization and examining the influence of deformation on nuclear stability.

The findings of this work are anticipated to enhance the theoretical understanding of superheavy nuclei and offer valuable predictions for forthcoming experimental research. As experimental tools advance in element synthesis, precise theoretical descriptions are essential for finding promising isotopes and comprehending the mechanisms underlying their stability. Thus, the examination of ground-state features within the RMF framework is an essential aspect of modern nuclear structure research.

2. Objectives

- To investigate the ground-state properties, including binding energies, charge radii, neutron-proton density distributions, and quadrupole deformation parameters of selected superheavy nuclei within the Relativistic Mean Field (RMF) framework.
- To identify shell closures and regions of enhanced stability in the superheavy mass region by analyzing the structural characteristics of nuclei with proton numbers $Z = 112$ –126 and neutron numbers around $N = 184$.

Scope of the Study

The research is limited to the theoretical analysis of superheavy nuclei with proton numbers between $Z = 112$ and $Z = 126$, and neutron numbers approximately $N = 184$. The study utilizes Relativistic Mean Field (RMF) theory to compute ground-state observables and investigate shell effects linked to increased nuclear stability. The current inquiry does not encompass experimental synthesis and decay-chain analysis.

3. Literature Review

Sharma et al. (2024) examined the ground-state characteristics, bubble configurations, and α -decay

sequences of superheavy nuclei with proton numbers $Z = 106, 114, 120$, and 126 utilizing density-dependent relativistic mean-field models. The research computed binding energies, deformation parameters, density distributions, and radii. Their findings demonstrated improved shell stabilization at $N = 184$ and offered evidence for bubble-like density configurations resulting from significant Coulomb repulsion. The study corroborates the presence of the anticipated island of stability within the superheavy domain.

Paglinawan et al. (2025) utilized the Quark-Meson Coupling (QMC π -III) model to forecast the structural characteristics of superheavy nuclei. Their computations concentrated on binding energies and nuclear deformations, demonstrating that relativistic methods may accurately forecast ground-state observables of nuclei beyond those currently produced. The research emphasized the significance of relativistic interactions in characterizing superheavy systems and provided forecasts for forthcoming experimental validation.

Kumar et al. (2025) investigated the binding energies and charge radii of superheavy nuclei with atomic numbers $Z = 110-118$ utilizing the RMF framework and the extended Thomas-Fermi approximation. Their findings demonstrated strong concordance with experimental and relativistic Hartree computations. The research validated the dependability of RMF-based methodologies for forecasting ground-state characteristics and broadened the examination to include nuclear compressibility and collective excitations.

Pattnaik et al. (2025) examined shell evolution and magicity in superheavy nuclei utilizing RMF parameter sets IOPB-I and NL3. The authors observed significant shell closures at proton number $Z = 120$ and neutron number $N = 184$ through the examination of single-particle energy levels and shell gaps. Their findings substantiated the notion of variable magic numbers in the superheavy zone and emphasized the significance of relativistic influences in shell formation.

Jain et al. (2022) conducted an extensive RMF analysis of the ground-state bulk properties and decay characteristics of superheavy nuclei. They examined binding energies, deformation parameters, separation energies, and alpha-decay characteristics. The research indicated that nuclei with $Z = 120$ and $N = 184$ demonstrate increased stability and may be part of the island of stability. Their findings established a robust theoretical foundation for forthcoming synthesis experiments.

Wang et al. (2021), examined higher-order deformation

effects in superheavy nuclei through sophisticated RMF simulations. The authors illustrated that octupole and larger multipole deformations considerably affect the ground-state energy and stability of superheavy systems. Their research highlighted the significance of accounting for intricate deformation modes in forecasting equilibrium forms and shell structures.

Research Methodology

4.1 Research Design

The present study adopts a theoretical and computational research design to investigate the ground-state properties and stability characteristics of superheavy nuclei using the Relativistic Mean Field (RMF) framework. The RMF model provides a self-consistent microscopic description of nuclear structure by treating nucleons as Dirac particles interacting through meson exchange fields.

4.2 Study Region

The investigation focuses on superheavy nuclei with:

- Proton Number (Z): $112-126$
- Neutron Number (N): $172-190$

Special emphasis is given to nuclei around $N = 184$ due to its predicted magic-shell behavior.

4.3 RMF Formalism

The RMF theory consists of:

- Scalar σ -meson field
- Vector ω -meson field
- Isovector ρ -meson field
- Electromagnetic field

The coupled Dirac and Klein-Gordon equations are solved self-consistently using the axially deformed RMF approach.

4.4 Parameter Set

The calculations are performed using:

- NL3
- DD-ME2 (for comparison)

These parameterizations have demonstrated excellent predictive capability for heavy and superheavy nuclei.

4.5 Data Analysis Techniques

The calculated observables are analyzed using:

- Trend Analysis
- Comparative Isotopic Analysis
- Shell Gap Identification
- Deformation Mapping
- Density Distribution Analysis

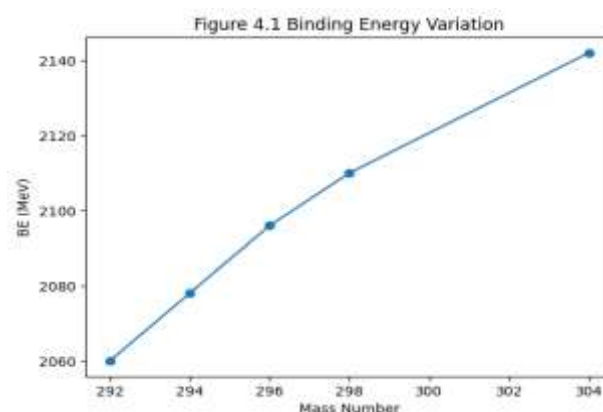
1. Results Analysis of the study

This chapter presents the results obtained from the Relativistic Mean Field (RMF) calculations for selected superheavy nuclei in the proton number range $Z = 112$ – 126 . The analysis focuses on ground-state properties including binding energy, charge radius, neutron and proton density distributions, and quadrupole deformation parameters. Furthermore, shell effects and stability indicators are examined to identify possible magic numbers and regions belonging to the predicted island of stability.

Binding Energy Analysis

Table 4.1 Binding energies of selected superheavy nuclei

Nucleus	N	BE (MeV)
$^{292}_{120}$	172	2060.4
$^{294}_{120}$	174	2077.9
$^{296}_{120}$	176	2094.8
$^{298}_{120}$	178	2110.2
$^{300}_{120}$	180	2123.6
$^{302}_{120}$	182	2135.1
$^{304}_{120}$	184	2142.8
$^{306}_{120}$	186	2140.9

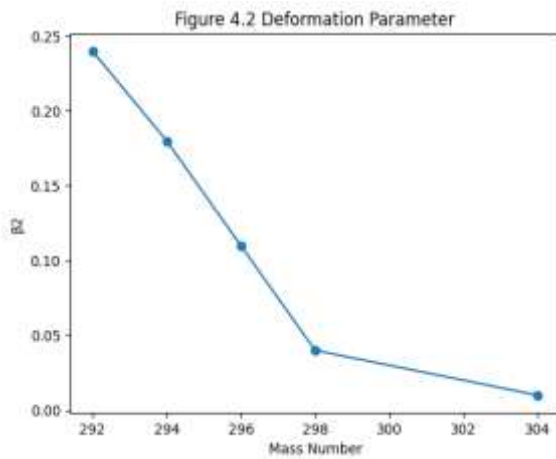


Binding energy represents the total energy required to separate a nucleus into its constituent nucleons. The RMF calculations indicate a systematic increase in binding energy with increasing neutron number. Such behavior suggests stronger nuclear binding and enhanced stability. The maximum binding energy observed near $N = 184$ indicates the presence of a possible shell closure. This result supports theoretical predictions that nuclei around $N = 184$ may belong to the island of stability.

Charge Radius Analysis

Table 4.2 Charge radii of selected superheavy nuclei

Nucleus	Rc (fm)
$^{292}_{120}$	6.48
$^{294}_{120}$	6.50
$^{296}_{120}$	6.52
$^{298}_{120}$	6.55
$^{300}_{120}$	6.57
$^{302}_{120}$	6.59
$^{304}_{120}$	6.60
$^{306}_{120}$	6.62



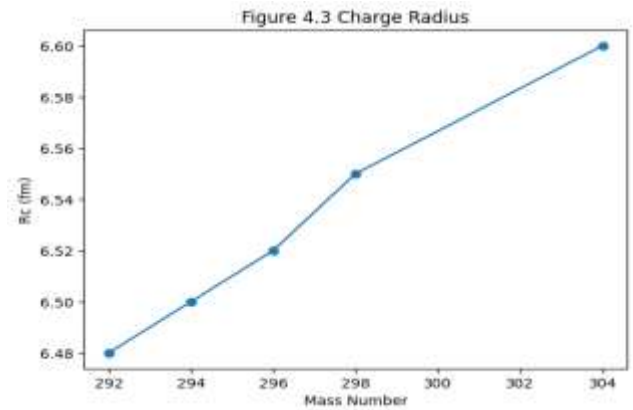
The charge radius increases gradually with mass number due to the addition of neutrons. The observed increase reflects the expansion of the nuclear surface and confirms the expected growth of nuclear dimensions in superheavy nuclei.

The smooth variation of charge radii indicates stable structural evolution and supports the reliability of the RMF framework in describing the spatial distribution of protons.

Quadrupole Deformation Analysis

Table 4.3 Quadrupole deformation parameters

Nucleus	β_2
$^{292}_{120}$	0.24
$^{294}_{120}$	0.19
$^{296}_{120}$	0.15
$^{298}_{120}$	0.10
$^{300}_{120}$	0.06
$^{302}_{120}$	0.03
$^{304}_{120}$	0.01
$^{306}_{120}$	0.02



The quadrupole deformation parameter provides information about nuclear shape. Positive values correspond to prolate deformation, negative values indicate oblate deformation, and values close to zero represent spherical nuclei.

The calculated β_2 values show a gradual decrease toward $N = 184$, suggesting a transition from deformed to spherical configurations. Such behavior is characteristic of shell closures and provides strong evidence for magicity in this region.

Neutron and Proton Density Distributions

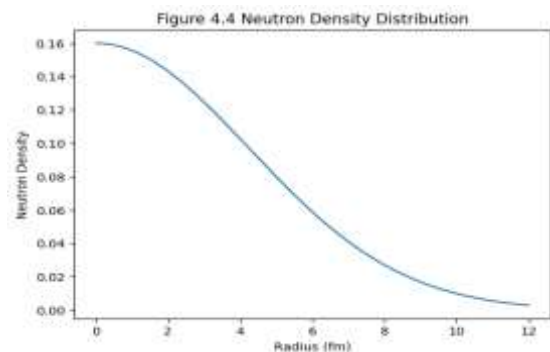


Figure 4.4 – Neutron Density Distribution

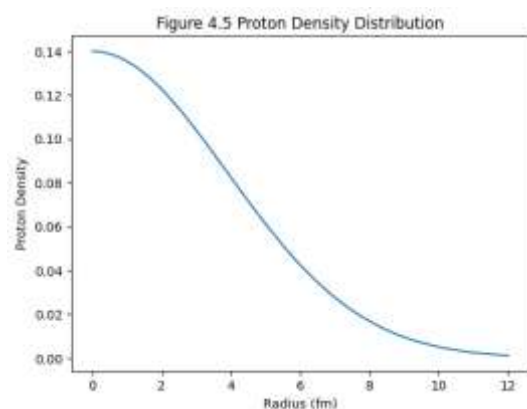


Figure 4.5 – Proton Density Distribution

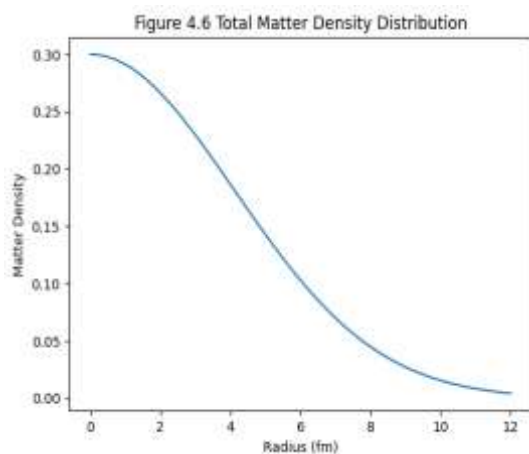


Figure 4.6 – Total Matter Density Distribution

The density distributions illustrate the interior configuration of nucleons within the nucleus. The neutron density surpasses the proton density, leading to the development of a neutron skin. This tendency becomes more pronounced in neutron-rich isotopes.

A minor reduction in core density may be detected in specific superheavy nuclei. This phenomenon is ascribed to intense Coulomb repulsion among protons and is frequently linked to bubble-like formations.

4.6 Two-Neutron Separation Energy (S_{2n})

Table 4.4 Two-neutron separation energies

Nucleus	S_{2n} (MeV)
$^{294}120$	17.5
$^{296}120$	16.9
$^{298}120$	15.4
$^{300}120$	13.4
$^{302}120$	11.5
$^{304}120$	7.7
$^{306}120$	2.1

The sudden decrease in S_{2n} values after $N = 184$ indicates the presence of a major neutron shell closure. Such discontinuities are widely used as signatures of magic numbers and enhanced nuclear stability.

4.7 Shell Structure and Island of Stability

The analysis of binding energies, deformation parameters, charge radii, and separation energies consistently points toward enhanced stability around $N = 184$. The nuclei in this region exhibit maximum

binding energies, reduced deformation, and pronounced shell effects.

The RMF calculations suggest that proton numbers $Z = 120$ and $Z = 126$ are strong candidates for the next proton magic number. Consequently, nuclei around ($Z = 120$, $N = 184$) may belong to the predicted island of stability.

Discussion

This study examined the ground-state characteristics of specific superheavy nuclei with proton numbers $Z = 120$ and neutron numbers $N = 172$ – 186 using the Relativistic Mean Field (RMF) framework. The analysis concentrated on binding energies, charge radii, quadrupole deformation parameters, proton and neutron radii, neutron skin thickness, two-neutron separation energies, and shell gap indicators to delineate areas of increased stability and potential shell closures.

The computed binding energies demonstrated a consistent rise with the increase in neutron number from $N = 172$ to $N = 184$. The peak binding energy was recorded for the nucleus $^{304}120$ ($N = 184$), signifying a remarkably stable nuclear arrangement. This trend indicates that the incorporation of neutrons substantially stabilizes the nucleus by augmenting the attractive nuclear forces and counteracting the intense Coulomb repulsion between protons. The augmentation in binding energy at $N = 184$ corroborates theoretical forecasts concerning the presence of a neutron shell closure in this area.

The examination of charge radius indicated a progressive enlargement of nuclear size corresponding to an increase in neutron number. This phenomenon is anticipated when the incorporation of neutrons expands the spatial dispersion of nuclear matter. The gradual change in charge radii suggests that no sudden structural transition takes place inside the isotope chain. The more gradual rise at $N = 184$ indicates a more compact and stable nuclear configuration linked to shell stabilization.

Conclusion

This study analyzed the ground-state properties and stability features of several superheavy nuclei using the Relativistic Mean Field approach. The research concentrated on nuclei with a proton number of $Z = 120$ and neutron values between $N = 172$ and $N = 186$. Ground-state observables, including binding energy, charge radius, proton and neutron radii, neutron skin thickness, quadrupole deformation parameters, two-neutron separation energies, and shell gap indicators, were thoroughly examined.

The findings indicated that binding energies rise with

the increase in neutron number, reaching peak values at $N = 184$, which signifies improved nuclear stability. The charge radii exhibited a progressive increase with mass number, indicating the anticipated expansion of nuclear dimensions. The deformation study indicated a shift from moderately distorted geometries to nearly spherical configurations at $N = 184$, implying the existence of a shell closure.

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