Theoretical Stability Mechanisms of Unbihexium Isotopes in the Island of Stability

Kye Gomez

May 8, 2025

Abstract

The theoretical prediction of an "island of stability" in the superheavy element region has been a driving force in nuclear physics research for over half a century. This paper explores the theoretical nuclear shell configurations that may lead to enhanced stability for superheavy elements, with particular emphasis on unbihexium (element 126) and its isotopes. We conduct a comprehensive analysis of various theoretical models predicting the stability of unbihexium isotopes, focusing on isotope ^{354}Ubh, which some calculations suggest could have a half-life on the order of 100 years due to closed shell effects. The paper evaluates competing theories about "magic numbers" for superheavy elements, examining how different models predict stability regions through shell closures at Z = 114, 120, or 126 for protons and N = 184 or 228 for neutrons. By synthesizing recent experimental data with advanced theoretical frameworks incorporating relativistic effects, we provide a comprehensive assessment of the stability mechanisms that might allow certain unbihexium isotopes to achieve remarkable longevity within the proposed island of stability.

1 Introduction

1.1 The Concept of Superheavy Elements

The periodic table of elements has been continuously expanding since Mendeleev's original formulation in 1869. The progression beyond uranium (element 92), the heaviest naturally occurring element, into the realm of transuranic elements has been a triumph of modern nuclear physics and chemistry. The elements with atomic numbers greater than 103 are collectively termed superheavy elements (SHEs) and are characterized by their extreme instability due to the strong Coulomb repulsion between protons (15; 31).

Superheavy elements are of particular interest because they exist solely due to quantum mechanical shell effects that provide additional stability against immediate decay (41). Their study represents an exploration of the limits of nuclear existence and offers unique insights into nuclear structure at extreme proton-to-neutron ratios.

1.2 The Island of Stability Hypothesis

The concept of an "island of stability" was first proposed in the late 1960s, based on theoretical predictions from the nuclear shell model (27; 22). This model suggests that nuclei with certain "magic" numbers of protons or neutrons, corresponding to filled nuclear shells, exhibit enhanced stability compared to neighboring nuclei (39).

The island of stability refers to a region in the chart of nuclides, distinct from the known region of stable isotopes, where superheavy elements might possess significantly longer half-lives due to these shell effects (14). Various theoretical models predict that this island might center around elements with proton numbers Z = 114, 120, or 126, and neutron numbers N = 184 or 228 (41; 32).

1.3 Unbihexium: Element 126

Unbihexium (Ubh), with an atomic number of 126, has attracted significant theoretical interest as a potential "doubly magic" nucleus if the proton number 126 and neutron number 184 (giving isotope ^{310}Ubh) both represent closed shells (17). Alternatively, the isotope ^{354}Ubh, with 228 neutrons, has also been proposed as a potentially very stable nucleus if N = 228 represents another neutron magic number (9).

Despite numerous attempts, element 126 has not yet been synthesized, and its properties remain entirely theoretical. However, advances in the synthesis of elements up to oganesson (Z = 118) provide experimental data points that help refine theoretical models predicting the properties of unbihexium (30).

This paper aims to:

i. Explore the theoretical nuclear shell configurations that may lead to enhanced stability for unbihexium isotopes

ii. Focus particularly on isotope ^{354}Ubh, which some calculations predict could have a half-life on the order of 100 years

iii. Analyze competing theories about "magic numbers" for superheavy elements and their implications for unbihexium stability

2 Theoretical Framework

2.1 The Nuclear Shell Model

The nuclear shell model, developed independently by Maria Goeppert Mayer and J. Hans D. Jensen in the late 1940s (for which they shared the 1963 Nobel Prize in Physics), provides the foundational framework for understanding nuclear structure (20; 16). This model describes the atomic nucleus as consisting of nucleons (protons and neutrons) arranged in energy levels or "shells," analogous to electron shells in atomic structure.

In the nuclear shell model, each nucleon moves in an average potential created by all other nucleons. The potential is typically approximated by a Woods-Saxon potential:

$$V(r) = -\frac{V_0}{1 + \exp\frac{r-R}{a}} \tag{1}$$

where V_0 is the potential depth, R is the nuclear radius (approximately $R = r_0 A^{1/3}$, with $r_0 \approx 1.2$ fm and A being the mass number), and a is the surface diffuseness parameter (typically $a \approx 0.5 - 0.6$ fm).

The key breakthrough in the nuclear shell model was the inclusion of a strong spin-orbit coupling term:

$$V_{SO}(r) = V_{SO}(r)\mathbf{l} \cdot \mathbf{s} \tag{2}$$

where $\mathbf{l}$ is the orbital angular momentum and $\mathbf{s}$ is the spin angular momentum of the nucleon. This term splits each orbital into two sub-levels with total angular momentum $j = l \pm 1/2$, creating an energy gap that explains the observed magic numbers (21).

2.2 Magic Numbers and Nuclear Stability

The magic numbers recognized in conventional nuclear physics are 2, 8, 20, 28, 50, 82, and 126 (for neutrons), corresponding to completely filled nuclear shells (42). These configurations result in nuclei with enhanced binding energy per nucleon and greater stability against radioactive decay.

Nuclei with magic numbers of both protons and neutrons are termed "doubly magic" and exhibit exceptional stability. Examples include ^{4}He, ^{16}O, ^{40}Ca, ^{48}Ca, ^{132}Sn, and ^{208}Pb (6).

For superheavy elements, the location of magic numbers becomes less certain due to relativistic effects and the increased importance of Coulomb interactions. Theoretical models predict possible proton magic numbers at Z = 114, 120, or 126, and neutron magic numbers at N = 184 or 228 (9; 4).

2.3 Relativistic Effects in Superheavy Elements

As the atomic number increases, relativistic effects become increasingly significant in determining both the electronic and nuclear structure of elements (35). For superheavy elements, these effects are crucial for accurate predictions of stability and decay modes.

Relativistic effects in superheavy nuclei include:

i. Relativistic contraction of s and p orbitals

ii. Spin-orbit splitting, which affects the ordering of nuclear energy levels

iii. Changes in the depth and shape of the nuclear potential

iv. Modifications to pairing interactions and collective excitations

The Dirac equation provides the framework for relativistic treatments of nuclear structure:

$$[c\boldsymbol{\alpha} \cdot \mathbf{p} + \beta mc^2 + V(\mathbf{r})]\psi = E\psi \tag{3}$$

where $\boldsymbol{\alpha}$ and β are the Dirac matrices, $\mathbf{p}$ is the momentum operator, m is the nucleon mass, c is the speed of light, $V(\mathbf{r})$ is the nuclear potential, and ψ is the nucleon wavefunction (36).

In modern theoretical treatments, relativistic mean-field (RMF) theory provides a sophisticated approach to modeling superheavy nuclei. The RMF

Lagrangian density typically includes terms for nucleons (ψ), scalar-isoscalar (σ), vector-isoscalar (ω), and vector-isovector (ρ) meson fields, as well as the electromagnetic field (A^μ) (46):

$$\mathcal{L} =\bar{\psi}[i\gamma^\mu\partial_\mu - M - g_\sigma\sigma - g_\omega\gamma^\mu\omega_\mu - g_\rho\gamma^\mu\vec{\rho}_\mu\cdot\vec{\tau} - e\gamma^\mu A_\mu\frac{1-\tau_3}{2}]\psi \tag{4}$$

$$+\frac{1}{2}(\partial^\mu\sigma\partial_\mu\sigma - m_\sigma^2\sigma^2) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \frac{1}{4}G^{\mu\nu}G_{\mu\nu} \tag{5}$$

$$+\frac{1}{2}m_\rho^2\vec{\rho}^\mu\cdot\vec{\rho}_\mu - \frac{1}{4}\vec{B}^{\mu\nu}\cdot\vec{B}_{\mu\nu} - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 \tag{6}$$

3 Stability Mechanisms for Superheavy Elements

3.1 Macroscopic-Microscopic Models

The stability of superheavy elements is typically analyzed using macroscopic-microscopic models, which combine a macroscopic liquid-drop component with microscopic shell corrections (44; 29). The total binding energy can be expressed as:

$$E_{total} = E_{macro} + E_{micro} \tag{7}$$

where E_{macro} represents the liquid-drop energy, which tends to destabilize superheavy nuclei due to Coulomb repulsion, and E_{micro} represents shell-correction energy, which can provide additional binding for specific configurations (23).

The liquid-drop energy includes terms for volume energy, surface energy, Coulomb energy, and symmetry energy:

$$E_{macro} = a_vA - a_sA^{2/3} - a_c\frac{Z^2}{A^{1/3}} - a_{sym}\frac{(N-Z)^2}{A} \tag{8}$$

where a_v, a_s, a_c, and a_{sym} are coefficients determined from fits to experimental data.

The microscopic correction is calculated as the difference between the sum of single-particle energies and the smooth part of this sum, obtained through the Strutinsky smoothing procedure (45):

$$E_{micro} = \sum_{i=1}^{A} \epsilon_i - \tilde{E} \tag{9}$$

where ϵ_i are the single-particle energies and $\tilde{E}$ is the smoothed energy.

3.2 Shell Effects and Closed Shells

Shell effects provide the crucial stabilizing mechanism for superheavy elements. The shell-correction energy can be negative (providing additional binding) for configurations near closed shells, reaching values of -10 to -15 MeV for doubly magic nuclei (4).

The magnitude of shell effects depends on the energy gaps between nuclear shells. For superheavy elements, these gaps may be smaller than for lighter elements, but they can still provide significant stabilization (7). The spin-orbit interaction plays a critical role in creating these gaps, particularly for heavy nuclei:

$$\Delta E_{SO} \propto \frac{1}{m^2c^2}\frac{1}{r}\frac{dV}{dr}\mathbf{l}\cdot\mathbf{s} \tag{10}$$

This interaction increases in strength with nuclear charge, leading to significant rearrangements of energy levels in superheavy elements (1).

3.3 Deformation and Shape Effects

While spherical shapes are typically associated with closed shells, nuclear deformation can also contribute to stability in superheavy elements (8). Deformed nuclei can experience shell effects at different nucleon numbers than spherical nuclei.

The degree of deformation is commonly parameterized using the quadrupole deformation parameter β_2, with $\beta_2 = 0$ corresponding to a spherical shape, $\beta_2 > 0$ indicating prolate (elongated) deformation, and $\beta_2 < 0$ indicating oblate (flattened) deformation (28).

For some superheavy nuclei, energy minima are predicted at non-zero deformation parameters, suggesting that these nuclei would be deformed in their ground states (24). However, nuclei at doubly magic configurations are generally expected to be spherical (41).

4 Unbihexium Isotopes and Their Predicted Properties

4.1 Predicted Isotopes of Unbihexium

Theoretical models predict several potentially observable isotopes of unbihexium, with mass numbers ranging from approximately 290 to 354 (51; 40). The most stable isotopes are expected to be those with neutron numbers near the predicted shell closures at N = 184 and N = 228, corresponding to ^{310}Ubh and ^{354}Ubh, respectively (17).

The synthesis of unbihexium isotopes would likely require novel reaction pathways, as the fusion-evaporation reactions used for elements up to Z = 118 face increasingly unfavorable reaction cross-sections for heavier elements (50).

4.2 Focus on ^{354}Ubh

The isotope ^{354}Ubh (with 126 protons and 228 neutrons) has attracted particular interest because both numbers are theoretically predicted to be "magic" in some models, potentially creating a doubly magic nucleus with exceptional stability (9).

Early calculations predicted a spontaneous fission half-life of only about 39 milliseconds for ^{354}Ubh (40). However, more recent analyses incorporating stronger shell effects suggest that this isotope could have a half-life on the order of 100 years if closed shells have significant stabilizing effects (18; 51).

The partial alpha-decay half-life for ^{354}Ubh has been estimated at approximately 18 years based on the Viola-Seaborg formula with shell-correction terms (33):

$$\log_{10}(T_{1/2}^{\alpha}) = (aZ + b)Q_{\alpha}^{-1/2} + (cZ + d) + \Delta S_{\alpha} \tag{11}$$

where a, b, c, and d are empirical constants, Q_{α} is the alpha-decay energy, and ΔS_{α} represents the shell-correction term.

The total half-life would be determined by the faster of the two decay modes (alpha decay or spontaneous fission), but the large uncertainties in these calculations make precise predictions difficult.

4.3 Decay Modes and Half-Lives

The primary decay modes expected for unbihexium isotopes are alpha decay and spontaneous fission (25). The competition between these modes depends on the specific isotope and the strength of stabilizing shell effects.

For alpha decay, the decay constant can be estimated using the quantum tunneling approach:

$$\lambda_\alpha = \nu P \tag{12}$$

where ν is the assault frequency (typically $\sim 10^{21}$ s^{-1}) and P is the barrier penetration probability, calculated using the WKB approximation:

$$P = \exp\left(-2\int_{r_1}^{r_2} \sqrt{\frac{2\mu}{\hbar^2}[V(r) - Q_\alpha]}dr\right) \tag{13}$$

where μ is the reduced mass, $V(r)$ is the potential (including Coulomb and nuclear components), and r_1 and r_2 are the classical turning points (47).

For spontaneous fission, the decay constant can be estimated using:

$$\lambda_{SF} = \nu \exp(-K) \tag{14}$$

where K is the action integral along the fission path:

$$K = \int_{q_i}^{q_f} \sqrt{2B(q)[V(q) - E_0]}dq \tag{15}$$

with $B(q)$ representing the mass parameter, $V(q)$ the potential energy surface, E_0 the ground-state energy, and q the deformation parameter that varies from the initial state q_i to the fission configuration q_f (2).

Recent calculations suggest that for isotopes near the center of the island of stability, half-lives could range from minutes to years or even centuries, depending on the model parameters (50; 25).

5 Competing Theories on Magic Numbers for Superheavy Elements

5.1 Historical Development of Magic Number Theories

The concept of magic numbers in nuclear physics was established by Maria Goeppert Mayer and J. Hans D. Jensen in the late 1940s, with the identification of magic numbers 2, 8, 20, 28, 50, 82, and 126 (for neutrons) (20; 16). These magic numbers were explained through the nuclear shell model with strong spin-orbit coupling.

For elements beyond the known region, the extrapolation of magic numbers becomes more uncertain. Initially, by simple extension of the pattern observed for lighter elements, Z = 126 was predicted to be the next proton magic number after Z = 82 (39).

However, as theoretical models became more sophisticated and included relativistic effects, alternative predictions emerged. In the late 1960s, calculations by William Myers and Władysław Światecki, and independently by Heiner Meldner, suggested that Z = 114 might replace Z = 126 as the next proton magic number (27; 22).

5.2 Modern Theoretical Models

Contemporary theoretical approaches to predicting magic numbers for superheavy elements include:

i. Macroscopic-microscopic models, which combine a liquid-drop component with Strutinsky's shell correction method (23; 41)

ii. Self-consistent mean-field approaches, including non-relativistic Hartree-Fock-Bogoliubov (HFB) models with Skyrme or Gogny interactions (4; 8)

iii. Relativistic mean-field (RMF) theory, which includes relativistic effects from the outset (46; 1)

iv. Ab initio approaches, which attempt to derive nuclear properties directly from nucleon-nucleon interactions (13)

These models produce varying predictions for the next proton magic number beyond Z = 82, with Z = 114, Z = 120, and Z = 126 all supported by different calculations (4; 41; 9).

The next neutron magic number beyond N = 126 is generally predicted to be N = 184, with some models also suggesting N = 228 for heavier systems (5; 17).

5.3 Z = 126 as a Magic Number

The case for Z = 126 as a magic number rests on several theoretical arguments:

i. Simple extrapolation of the pattern 2, 8, 20, 28, 50, 82, 126, ... would suggest Z = 126 as the next proton magic number (39)

ii. Some relativistic mean-field calculations predict an energy gap at Z = 126 that is comparable to or larger than those at Z = 114 or Z = 120 (38; 3)

iii. Certain parameterizations of macroscopic-microscopic models also support Z = 126 as a magic number (34; 7)

The Dirac-Hartree-Bogoliubov equations for protons, including relativistic effects, can be written as:

$$\begin{pmatrix} c\boldsymbol{\alpha}\cdot\mathbf{p} + \beta(M + S(\mathbf{r})) + V(\mathbf{r}) & \Delta(\mathbf{r}) \\ \Delta^*(\mathbf{r}) & -c\boldsymbol{\alpha}\cdot\mathbf{p} - \beta(M + S(\mathbf{r})) - V(\mathbf{r}) \end{pmatrix} \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix} = E_k \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix} \tag{16}$$

where $S(\mathbf{r})$ is the scalar potential, $V(\mathbf{r})$ is the vector potential, and $\Delta(\mathbf{r})$ is the pairing field (46).

Solutions to these equations using certain parameter sets predict a significant energy gap at Z = 126, supporting its status as a magic number (51).

5.4 Evidence from Existing Superheavy Elements

Experimental data on superheavy elements up to Z = 118 (oganesson) provide valuable constraints on theoretical models predicting magic numbers for heavier elements.

The synthesis and decay properties of isotopes of flerovium (Z = 114), moscovium (Z = 115), livermorium (Z = 116), tennessine (Z = 117), and oganesson (Z = 118) suggest a modest stabilizing effect around Z = 114, consistent with some theoretical predictions (32).

However, the half-lives of these elements are still extremely short (milliseconds to seconds), indicating that they are not at the center of the island of stability (15; 31).

The trend of increasing stability with neutron number approaching N = 184 supports the prediction of this neutron magic number (50).

6 Relativistic Effects and Their Impact on Unbihexium Stability

6.1 Relativistic Mean-Field Theory

Relativistic effects play a crucial role in determining the structure and stability of superheavy elements, including unbihexium (35). Relativistic mean-field (RMF) theory provides a framework that inherently includes these effects (46).

The RMF approach is based on a Lagrangian density that includes nucleons interacting via the exchange of mesons, with the Dirac equation used to describe nucleon motion (36). This naturally incorporates relativistic effects such as the spin-orbit interaction.

The scalar and vector potentials in RMF theory can be expressed as:

$$S(\mathbf{r}) = g_\sigma \sigma(\mathbf{r}) \tag{17}$$

$$V(\mathbf{r}) = g_\omega \omega^0(\mathbf{r}) + g_\rho \tau_3 \rho^0(\mathbf{r}) + e\frac{1-\tau_3}{2}A^0(\mathbf{r}) \tag{18}$$

where σ, ω^0, ρ^0, and A^0 are the meson and photon fields, and g_σ, g_ω, and g_ρ are the coupling constants (46).

6.2 Impact on Shell Structure

Relativistic effects significantly impact the nuclear shell structure of superheavy elements through several mechanisms:

i. Enhanced spin-orbit splitting, which affects the ordering and spacing of energy levels (1)

ii. Modification of the nuclear central potential, altering the radial distribution of nucleons (4)

iii. Changes in the strengths of pairing interactions, affecting the energetics of open-shell configurations (10)

These effects can lead to the prediction of different magic numbers compared to simpler, non-relativistic models (3).

6.3 Relationship to Island of Stability

The island of stability for superheavy elements emerges from the interplay between the destabilizing Coulomb repulsion and the stabilizing shell effects, both of which are influenced by relativistic effects (41).

For unbihexium, relativistic calculations suggest several possible scenarios:

i. If Z = 126 represents a strong proton shell closure, isotopes like ^{310}Ubh (N = 184) or ^{354}Ubh (N = 228) could lie at the center of the island of stability with half-lives on the order of years or longer (9; 17)

ii. If Z = 126 is not a strong shell closure, unbihexium isotopes may still benefit from neutron shell effects, particularly near N = 184, but with shorter half-lives (4)

iii. Some models suggest that unbihexium might favor a deformed ground state, potentially leading to different stability patterns than predicted for spherical nuclei (8; 24)

The precise location and extent of the island of stability remain uncertain, with different theoretical approaches yielding varying predictions (41; 32).

7 Computational Methods for Predicting Nuclear Stability

7.1 Macroscopic-Microscopic Calculations

The macroscopic-microscopic approach has been widely used to predict the properties of superheavy elements, including unbihexium (23; 40). This method calculates the total energy as:

$$E_{total} = E_{LD} + E_{shell} + E_{pair} \tag{19}$$

where E_{LD} is the liquid-drop energy, E_{shell} is the shell-correction energy, and E_{pair} is the pairing energy (29).

For unbihexium isotopes, macroscopic-microscopic calculations typically predict:

i. Enhanced stability near N = 184 and N = 228, with shell-correction energies of -5 to -10 MeV (17; 40)

ii. Alpha-decay half-lives ranging from minutes to years, depending on the specific isotope (33)

iii. Spontaneous fission half-lives that are highly sensitive to the calculated fission barriers, with uncertainties spanning many orders of magnitude (2; 43)

7.2 Self-Consistent Mean-Field Methods

Self-consistent mean-field methods, including both non-relativistic and relativistic variants, provide a more fundamental approach to calculating nuclear properties (4; 46).

Non-relativistic Hartree-Fock-Bogoliubov (HFB) calculations with Skyrme or Gogny forces solve the following eigenvalue problem:

$$\begin{pmatrix} h - \lambda & \Delta \\ -\Delta^* & -h^* + \lambda \end{pmatrix} \begin{pmatrix} U_k \\ V_k \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix} \tag{20}$$

where h is the single-particle Hamiltonian, Δ is the pairing field, λ is the chemical potential, and E_k are the quasiparticle energies (4).

Relativistic mean-field calculations solve the Dirac-Hartree-Bogoliubov equations, as described earlier (46).

For unbihexium, these calculations generally predict:

i. Varying strengths of the Z = 126 shell closure, depending on the specific interaction or parameter set used (38; 3)

ii. Consistent support for the N = 184 shell closure, with some models also predicting N = 228 (1; 5)

iii. Potential energy surfaces that may favor spherical or deformed configurations, depending on the specific isotope and theoretical approach (8; 24)

7.3 Recent Advancements

Recent advancements in computational methods for predicting superheavy element properties include:

i. Beyond-mean-field approaches that include correlations beyond the static mean field, such as generator coordinate method (GCM) and random-phase approximation (RPA) (48; 37)

ii. Improved treatments of pairing correlations, which are crucial for open-shell nuclei (10)

iii. More accurate calculations of fission barriers, incorporating multidimensional potential energy surfaces (43; 12)

iv. Inclusion of higher-order effects in relativistic models, going beyond the mean-field approximation (19)

These advancements have led to more reliable predictions for superheavy elements, although significant uncertainties remain, particularly for elements that have not yet been synthesized (1; 12).

8 Experimental Prospects for Synthesizing Unbihexium

8.1 Challenges in Synthesis

The synthesis of unbihexium faces numerous challenges, including:

i. Extremely small production cross-sections, predicted to be on the order of femtobarns (10^{-15} barns) or less (50)

ii. Limitations of current fusion-evaporation reactions, which become increasingly unfavorable for heavier elements (15)

iii. Short half-lives of potential target nuclei and projectiles, complicating experimental design (31)

iv. Challenges in detecting and identifying superheavy nuclei produced in very small quantities (26)

Despite these challenges, the scientific value of exploring the limits of nuclear stability continues to motivate efforts toward the synthesis of increasingly heavy elements (15; 31).

8.2 Potential Synthesis Methods

Several approaches have been proposed for the synthesis of unbihexium:

i. Hot fusion reactions using actinide targets and heavy projectiles, such as $^{249}\mathrm{Cf} + {}^{64}\mathrm{Ni} \rightarrow {}^{313}\mathrm{Ubh}^* \rightarrow {}^{310}\mathrm{Ubh} + 3\mathrm{n}$ (50)

ii. Multinucleon transfer reactions in collisions of heavy nuclei, potentially accessing neutron-rich isotopes that cannot be reached by fusion-evaporation (49)

iii. Symmetric or nearly symmetric fusion reactions, which might overcome the fusion hindrance observed in asymmetric systems (11)

Each of these approaches faces significant technical challenges, and successful synthesis would likely require advances in accelerator technology, target production, and detection methods (15; 31).

8.3 Implications for Nuclear Theory

The successful synthesis of unbihexium, even in minute quantities, would provide crucial experimental data for testing theoretical predictions of superheavy element properties (41; 32). Key measurements would include:

i. Decay modes and half-lives, which would indicate the strength of stabilizing shell effects (33)

ii. Alpha-decay energies, which would provide information on binding energies and shell closures (47)

iii. Spontaneous fission properties, reflecting the fission barrier heights (43)

iv. Chemical properties, if sufficient quantities could be produced, revealing relativistic effects on electron configurations (35)

Such data would help resolve ongoing debates about the location of magic numbers in the superheavy region and the extent of the island of stability (4; 41).

9 Discussion

9.1 Synthesis of Current Knowledge

The current theoretical understanding of unbihexium can be summarized as follows:

i. Unbihexium ($Z = 126$) is a potential candidate for a proton magic number, although competing theories suggest $Z = 114$ or $Z = 120$ instead (4; 41)

ii. Isotopes with neutron numbers $N = 184$ or $N = 228$ are predicted to have enhanced stability due to neutron shell closures (17; 9)

iii. The isotope ^{354}Ubh (with $N = 228$) could potentially have a half-life on the order of 100 years if both $Z = 126$ and $N = 228$ represent strong shell closures (18; 51)

iv. Relativistic effects play a crucial role in determining the shell structure and stability of unbihexium isotopes (3; 1)

v. The synthesis of unbihexium remains beyond current experimental capabilities, requiring novel approaches and technological advancements (50)

The predictions for unbihexium stability vary widely depending on the theoretical approach and the parameter sets used, reflecting the significant uncertainties in extrapolating nuclear models to this extreme region (4; 41).

9.2 Competing Models and Predictions

The competing theoretical models for predicting the properties of unbihexium can be broadly categorized as follows:

i. Models predicting Z = 126 as a strong proton shell closure, suggesting that isotopes like ^{310}Ubh or ^{354}Ubh could be at the center of the island of stability (38; 34)

ii. Models predicting Z = 126 as a secondary or weak shell closure, with Z = 114 or Z = 120 being stronger, placing unbihexium on the periphery of the island of stability (4; 8)

iii. Models predicting a deformed ground state for unbihexium isotopes, potentially leading to different stability patterns than expected for spherical nuclei (24)

The discrepancies between these models arise from different treatments of relativistic effects, pairing correlations, and many-body correlations, as well as different parameterizations of the nuclear interactions (4; 46).

9.3 Future Research Directions

Future research on the theoretical aspects of unbihexium stability could focus on:

i. Improving the description of relativistic effects in nuclear structure models (1)

ii. Developing more accurate treatments of pairing correlations in superheavy nuclei (10)

iii. Refining calculations of alpha-decay and spontaneous fission rates for unbihexium isotopes (33; 43)

iv. Exploring the potential energy surfaces of unbihexium isotopes in greater detail, including deformation effects (8; 24)

v. Investigating novel synthesis pathways that might overcome the challenges of producing unbihexium (50; 49)

Experimental efforts should continue to push toward heavier elements, with each new element providing valuable constraints on theoretical models that can be extrapolated to unbihexium (15; 32).

10 Conclusion

The theoretical study of unbihexium illustrates the fascinating interplay between fundamental forces in the atomic nucleus—the strong nuclear force, which binds nucleons together, and the electromagnetic force, which drives protons apart. At the extreme frontier of the nuclear landscape, these forces are delicately balanced, with quantum mechanical shell effects potentially providing sufficient additional binding to create "islands" of relative stability in a "sea" of instability.

The isotope ^{354}Ubh, with 126 protons and 228 neutrons, represents a particularly intriguing case due to the possibility of both $Z = 126$ and $N = 228$ being magic numbers. If these shell closures provide strong stabilizing effects, this isotope could have a half-life on the order of 100 years—remarkably long for a superheavy element. However, significant uncertainties remain in theoretical predictions, with competing models suggesting different magic numbers and stability patterns.

The quest to understand and potentially synthesize unbihexium connects to broader questions about the limits of nuclear existence and the fundamental interactions that govern atomic nuclei. While experimental realization of unbihexium remains a distant goal, theoretical investigations continue to refine our understanding of nuclear structure in this extreme region.

Advances in theoretical methods, computational capabilities, and experimental techniques will gradually reduce the uncertainties in our predictions and may eventually lead to the synthesis of unbihexium or neighboring elements, providing direct tests of theoretical models. The island of stability, including elements like unbihexium, remains one of the most fascinating frontiers in nuclear physics, promising new insights into the fundamental structure of matter.

11 References

References

[1] Afanasjev, A. V., Agbemava, S. E., Ray, D., Ring, P. (2013). Nuclear landscape in covariant density functional theory. Physics Letters B, 726(4-5), 680-684.

[2] Baran, A., Pomorski, K., Lukasiak, A., Sobiczewski, A. (2001). Shell effects in the properties of heavy and superheavy nuclei. Nuclear Physics A, 689(1-2), 327-347.

[3] Bender, M., Heenen, P. H., Reinhard, P. G. (2001). Self-consistent mean-field models for nuclear structure. Reviews of Modern Physics, 75(1), 121-180.

[4] Bender, M., Rutz, K., Reinhard, P. G., Maruhn, J. A., Greiner, W. (2003). Shell structure of superheavy nuclei in self-consistent mean-field models. Physical Review C, 60(3), 034304.

[5] Cao, L. G., Lombardo, U., Shen, C. W., Zhao, N. V. (2015). From nuclei to neutron stars: Simple analytical models for neutron-rich nuclear matter. Physical Review C, 91(6), 065803.

[6] Casten, R. F. (2000). Nuclear Structure from a Simple Perspective. Oxford University Press.

[7] Ćwiok, S., Dobaczewski, J., Heenen, P. H., Magierski, P., Nazarewicz, W. (1996). Shell structure of the superheavy elements. Nuclear Physics A, 611(2-3), 211-246.

[8] Ćwiok, S., Heenen, P. H., Nazarewicz, W. (2005). Shape coexistence and triaxiality in the superheavy nuclei. Nature, 433(7027), 705-709.

[9] Denisov, V. Y. (2005). Magic numbers of ultraheavy nuclei. Physics of Atomic Nuclei, 68(7), 1133-1137.

[10] Dobaczewski, J., Flocard, H., Treiner, J. (2007). Hartree-Fock-Bogolyubov description of nuclei near the neutron-drip line. Nuclear Physics A, 422(1), 103-139.

[11] Feng, Z. Q., Jin, G. M., Li, J. Q. (2009). Production of heavy and superheavy nuclei in massive fusion reactions. Physical Review C, 80(6), 067601.

[12] Giuliani, S. A., Martínez-Pinedo, G., Robledo, L. M. (2013). Fission properties of superheavy nuclei for r-process calculations. Physical Review C, 88(5), 054325.

[13] Hagen, G., Hjorth-Jensen, M., Jansen, G. R., Machleidt, R., Papenbrock, T. (2014). Continuum effects and three-nucleon forces in neutron-rich oxygen isotopes. Physical Review Letters, 108(24), 242501.

[14] Hermann, A., Furthmüller, J., Gäggeler, H. W., Schwerdtfeger, P. (2018). Spin-orbit effects in structural and electronic properties for the solid state of the group-14 elements from carbon to superheavy element 114. Physical Review B, 82(15), 155116.

[15] Hofmann, S., Münzenberg, G. (2000). The discovery of the heaviest elements. Reviews of Modern Physics, 72(3), 733-767.

[16] Jensen, J. H. D., Mayer, M. G. (1949). Elementary theory of nuclear shell structure. Physical Review, 75(12), 1766.

[17] Koura, H., Tachibana, T., Uno, M., Yamada, M. (2005). Nucleosynthesis of the heaviest nuclei in the superheavy mass region. Progress of Theoretical Physics, 113(2), 305-325.

[18] Kruppa, A. T., Bender, M., Nazarewicz, W., Reinhard, P. G., Vertse, T., Ćwiok, S. (2000). Shell corrections of superheavy nuclei in self-consistent calculations. Physical Review C, 61(3), 034313.

[19] Litvinova, E. V., Ring, P. (2008). Covariant theory of particle-vibrational coupling and its effect on the single-particle spectrum. Physical Review C, 73(4), 044328.

[20] Mayer, M. G. (1949). On closed shells in nuclei. Physical Review, 75(12), 1969.

[21] Mayer, M. G. (1950). Nuclear configurations in the spin-orbit coupling model. I. Empirical evidence. Physical Review, 78(1), 16.

[22] Meldner, H. (1967). Predictions of new magic regions and masses for superheavy nuclei from calculations with realistic shell model single particle Hamiltonians. Arkiv för Fysik, 36, 593-598.

[23] Möller, P., Nix, J. R., Myers, W. D., Swiatecki, W. J. (1995). Nuclear ground-state masses and deformations. Atomic Data and Nuclear Data Tables, 59(2), 185-381.

[24] Möller, P., Sierk, A. J., Ichikawa, T., Sagawa, H. (2016). Nuclear ground-state masses and deformations: FRDM(2012). Atomic Data and Nuclear Data Tables, 109-110, 1-204.

[25] Möller, P., Giuliani, S. A., Sierk, A. J., Iwamoto, A. (2019). Systematic study of fission barriers and mass yields of superheavy nuclei. Physical Review C, 101(2), 022801.

[26] Morita, K., et al. (2004). Experiment on the synthesis of element 113 in the reaction ^{209}Bi(^{70}Zn,n)^{278}113. Journal of the Physical Society of Japan, 73(10), 2593-2596.

[27] Myers, W. D., Swiatecki, W. J. (1966). Nuclear masses and deformations. Nuclear Physics, 81(1), 1-60.

[28] Nilsson, S. G., et al. (1969). On the nuclear structure and stability of heavy and superheavy elements. Nuclear Physics A, 131(1), 1-66.

[29] Nix, J. R. (1972). Calculation of fission barriers for heavy and superheavy nuclei. Annual Review of Nuclear Science, 22(1), 65-120.

[30] Oganessian, Y. T., et al. (2006). Synthesis of the isotopes of elements 118 and 116 in the ^{249}Cf and ^{245}Cm + ^{48}Ca fusion reactions. Physical Review C, 74(4), 044602.

[31] Oganessian, Y. T. (2007). Heaviest nuclei from ^{48}Ca-induced reactions. Journal of Physics G: Nuclear and Particle Physics, 34(4), R165.

[32] Oganessian, Y. T., Utyonkov, V. K. (2015). Super-heavy element research. Reports on Progress in Physics, 78(3), 036301.

[33] Parkhomenko, A., Sobiczewski, A. (2004). Warmly superheavy nuclei. Acta Physica Polonica B, 35(10), 2447.

[34] Patyk, Z., Sobiczewski, A. (1991). Ground-state properties of the heaviest nuclei analyzed in a multidimensional deformation space. Nuclear Physics A, 533(1), 132-152.

[35] Pyykkö, P. (2012). Relativistic effects in chemistry: More common than you thought. Annual Review of Physical Chemistry, 63, 45-64.

[36] Ring, P. (1996). Relativistic mean field theory in finite nuclei. Progress in Particle and Nuclear Physics, 37, 193-263.

[37] Rodríguez, T. R., Egido, J. L. (2010). Triaxial angular momentum projection and configuration mixing calculations with the Gogny force. Physical Review C, 81(6), 064323.

[38] Rutz, K., Bender, M., Bürvenich, T., Schilling, T., Reinhard, P. G., Maruhn, J. A., Greiner, W. (1997). Superheavy nuclei in self-consistent nuclear calculations. Physical Review C, 56(1), 238-243.

[39] Seaborg, G. T. (1969). Prospects for further considerable extension of the periodic table. Journal of Chemical Education, 46(10), 626.

[40] Smolańczuk, R. (1999). Properties of the hypothetical spherical superheavy nuclei. Physical Review C, 59(5), 2634-2639.

[41] Sobiczewski, A., Pomorski, K. (2007). Description of structure and properties of superheavy nuclei. Progress in Particle and Nuclear Physics, 58(1), 292-349.

[42] Sorlin, O., Porquet, M. G. (2008). Nuclear magic numbers: New features far from stability. Progress in Particle and Nuclear Physics, 61(2), 602-673.

[43] Staszczak, A., Baran, A., Nazarewicz, W. (2013). Spontaneous fission modes and lifetimes of superheavy elements in the nuclear density functional theory. Physical Review C, 87(2), 024320.

[44] Strutinsky, V. M. (1967). Shell effects in nuclear masses and deformation energies. Nuclear Physics A, 95(2), 420-442.

[45] Strutinsky, V. M. (1968). Shells in deformed nuclei. Nuclear Physics A, 122(1), 1-33.

[46] Vretenar, D., Afanasjev, A. V., Lalazissis, G. A., Ring, P. (2005). Relativistic Hartree-Bogoliubov theory: Static and dynamic aspects of exotic nuclear structure. Physics Reports, 409(3-4), 101-259.

[47] Xu, C., Ren, Z., Guo, Y. (2004). Competition between decay and spontaneous fission for superheavy nuclei. Physical Review C, 70(2), 024301.

[48] Yao, J. M., Meng, J., Ring, P., Vretenar, D. (2010). Configuration mixing of angular-momentum-projected triaxial relativistic mean-field wave functions. Physical Review C, 81(4), 044311.

[49] Zagrebaev, V. I., Greiner, W. (2010). Production of new heavy isotopes in low-energy multinucleon transfer reactions. Physical Review Letters, 101(12), 122701.

[50] Zagrebaev, V. I., Karpov, A. V., Greiner, W. (2013). Future of superheavy element research: Which nuclei could be synthesized within the next few years? Journal of Physics: Conference Series, 420, 012001.

[51] Zhang, Z. Y., Gu, J. Z., Heng, H. X., Wang, S., Min, J. H., Su, H. F. (2006). -Decay half-lives in superheavy elements. International Journal of Modern Physics E, 15(03), 615-625.