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Superheavy Nuclei XVII: 1640 ≤ A < 1650 Systems

JJ Bevelacqua
Bevelacqua Resources, 7531 Flint Crossing Circle SE, Owens Cross Roads, AL 35763, USA

Corresponding Author: **JJ Bevelacqua**

Abstract
Superheavy nuclei and their associated stability continue to be active experimental and theoretical areas of research. Calculations in the superheavy mass region require the selection of an appropriate nuclear interaction. Although this interaction is usually based on the extrapolation of a known nuclear interaction, any approach becomes more uncertain as calculations proceed beyond mass regions that have been explored experimentally. In view of these uncertainties, calculations can only provide qualitative results. These extrapolations and the associated model results become more uncertain as the system mass increases.
Previous calculations explored the 570 ≤ A < 1640 mass region. This paper extends these calculations into the 1640 ≤ A < 1650 region. The single-particle level spectrum is generated using a Woods-Saxon potential with parameters optimized to permit extrapolation into the A ≥ 1600 superheavy region utilizing the Rost-1600 interaction that was based on existing nuclear systems as well as nuclear matter calculations. This interaction is essentially the Rost interaction that includes a 15% uncertainty in the potential strength. Calculated single-particle energies are also derived by incorporating the unmodified pairing interaction of Blomqvist and Wahlborn to investigate the bounding characteristics of A ≥ 1600 superheavy nuclear systems.
The stability of 1640 ≤ A < 1650 systems are determined by evaluating the various decay modes (i.e., alpha decay, beta decay, positron decay, electron capture, and spontaneous fission). Based on previous calculations, stability in the 1640 ≤ A < 1650 mass region is expected to be dominated by alpha decay and beta decay.
Given uncertainties in the model interaction, it is not practical to determine absolute values for the half-lives and Q-values. However, the model does permit establishing the relative stability of nuclear systems and to highlight possible islands of stability. Using the Rost-1600 interaction, 49 even-even nuclear systems are predicted in the 1640 ≤ A < 1650 mass region. For this mass region, the model predicts a new island of stability in the vicinity of the Z = 444 – 450. Model calculations suggest that the most stable 1640 ≤ A < 1650 system occurs at (Z, A) = (444, 1642).

Keywords: 1640 ≤ A < 1650 Superheavy Nuclei, Alpha Decay, Spontaneous Fission, Beta Decay, Positron Decay, and Electron Capture

1. Introduction

Superheavy nuclei and their associated stability have been active experimental and theoretical areas of research [1-38]. Calculations in the superheavy mass region require the selection of an appropriate nuclear interaction. This interaction is usually based on the extrapolation of a known nuclear interaction [2, 24, 29, 34], but this approach is fraught with uncertainty. In view of these uncertainties, the calculations can only provide qualitative results. These extrapolations and the associated model results become more uncertain as the system mass increases.

Table 1 summarizes previous calculations [21-38] in the 570 ≤ A < 1640 systems. The most stable (A, Z) system for the Ref. 21-38 calculations is provided in Table 1. Table 1 also provides the alpha Q value for the most stable system, its effective half-life, and the interaction strength utilized. The calculations are based on the unmodified (λ = 1.0) Rost interaction [2], the modified (λ = 1.05) Rost interaction [24], adjusted (λ = 1.10) Rost interaction [29], and the Rost-1600 (λ = 1.15) interaction [34].

Table 1: Most Stable 570 ≤ A ≤ 1640 Nuclear Systems

Range	(A, Z)	Q_α (MeV)	$T_{1/2}^{eff}$	λ
570≤ A ≤ 620	(610, 204)	16.2	2.2 h	1.0[a]
620< A < 700	(634, 204)	17.8	0.14 s	1.0[b]
700≤ A < 800	(730, 226)	20.0	0.44 s	1.0[c]
800≤ A < 900	(888, 274)	19.5	590 y	1.05[d]
900≤ A < 1000	(926, 282)	22.4	1.1 d	1.05[e]
1000≤ A < 1100	(1062, 312)	23.8	152 d	1.05[f]
1100≤ A < 1200	(1122, 330)	26.8	20 min	1.05[g]
1200≤ A < 1300	(1226, 354)	21.6	4.8×10^{12} yr	1.10[h]
1300≤ A < 1400	(1344, 382)	25.2	4.0×10^{8} yr	1.10[i]
1400≤ A < 1500	(1478, 410)	27.3	14 min	1.10[j]
1500≤ A < 1600	(1502, 414)	26.6	2.9×10^{10} yr	1.10[k]
1600≤ A < 1610	(1602, 438)	21.3	4.4×10^{32} yr	1.15[l]
1610≤ A < 1620	(1614, 438)	24.0	6.3×10^{21} yr	1.15[m]
1620≤ A < 1630	(1626, 440)	23.6	2.9×10^{23} yr	1.15[n]
1630≤ A < 1640	(1638, 442)	23.2	1.4×10^{25} yr	1.15[o]

[a] Ref. 21; [b]Ref. 22; [c]Ref. 23; [d]Ref. 25; [e]Ref. 26; [f]Ref. 27; [g]Ref. 28; [h]Ref. 30; [i]Ref. 31; [j]Ref. 32; [k]Ref. 33; [l]Ref. 35, [m]Ref. 36, [n]Ref. 37, and [o]Ref. 38.

Calculations for 1640 ≤ A < 1650 superheavy nuclei are presented in this paper. Model calculations suggest that 49 even-even nuclear systems theoretically exist within the 1640 ≤ A < 1650 mass range. The calculations utilized the Rost-1600 interaction [34].

1640 ≤ A < 1650 system stability is evaluated using the methodology utilized to investigate nuclear systems in the 570 ≤ A < 1630 [21-38] mass region. These calculations facilitate the investigation of superheavy systems that have received limited theoretical study, and provide insight into binding energy systematics and nuclear stability beyond the previously investigated mass regions.

Using a more sophisticated method than the single particle approach is not warranted in view of the uncertainties encountered in these calculations. These uncertainties include extrapolations of the nuclear interaction into the superheavy mass region. Since there are no experimental data to guide the calculations, single-particle energy level calculations are a reasonable approach for initial calculations into the superheavy mass region [3, 5].

The stability of 1640 ≤ A < 1650 systems is determined by evaluating the various decay modes (i.e., alpha decay, beta decay, positron decay, electron capture, and spontaneous fission). Based on previous calculations [21-38], stability in the 1640 ≤ A < 1650 mass region is expected to be dominated by alpha decay and beta decay.

2. Calculational Methodology

The model used to describe the particle (i) plus core (c) system represents an application of the standard method of Lukasiak and Sobiczewski [3] and Petrovich *et al* [5]. The calculational method used to generate a single particle level spectrum determines the binding energy E_{NLSJ} of a particle in the field of a nuclear core by solving the radial Schrödinger Equation.

$$\left[\frac{\hbar^2}{2\mu}\left(\frac{d^2}{dr^2}-\frac{L(L+1)}{r^2}\right)-E_{NLSJ}-V_{LSJ}(r)\right]U_{NLSJ}(r)=0 \quad (1)$$

Where r is the radial coordinate defining the relative motion of the nuclear core and the particle; $V_{LSJ}(r)$ is the model interaction; E_{NLSJ} is the core plus particle binding energy; $U_{NLSJ}(r)$ is the radial wave function; and L, S, and J are the orbital, spin, and total angular momentum quantum numbers, respectively. N is the radial quantum number and μ is the reduced mass. For the present application, V_{LSJ} is defined as:

$$V_{LSJ}(r)=-\frac{V_0}{1+exp\left(\frac{r-R_o}{a_o}\right)}-V_{so}\left(\frac{\hbar}{m_\pi c}\right)^2\frac{1}{a_{so}r}\frac{exp\left(\frac{r-R_{so}}{a_{so}}\right)}{\left[1+exp\left(\frac{r-R_{so}}{a_{so}}\right)\right]^2}F(L,S,J)$$

$$+Z_iZ_Ce^2C(r) \quad (2)$$

Where;

$$R_0=r_0A^{1/3}=R_C \quad (3)$$

and

$$R_{so}=r_{so}A^{1/3} \quad (4)$$

The parameters V_0, r_0, and a_0 are the strength, radius parameter, and diffuseness for the central potential. Similarly, V_{so}, r_{so}, and a_{so} are the corresponding parameters for the spin-orbit potential. To complete the specification of Eq. 2, we define:

$$F(L,S,J)=J(J+1)-L(L+1)-S(S+1) \quad (5)$$

and

$$C(r)=\frac{1}{2R_C}\left(3-\left(\frac{r}{R_C}\right)^2\right)\quad for\quad r<R_C \quad (6)$$

$$C(r)=\frac{1}{r}\quad for\quad r\geq R_C \quad (7)$$

For the Coulomb potential, it is assumed that the particle is a point charge of magnitude $z_i e$. The core has a charge $Z_C e$ uniformly distributed through a sphere of radius R_C. Since the potential is not a function of the spherical coordinates, the solution of the angular equation is most easily expressed in terms of spherical harmonics $Y_{LM}(\theta,\varphi)$.

The total bound-state wave function $(\Psi_{NLSJM}(\vec{r}))$ for the relative motion of the core plus particle, interacting through a spherically symmetric potential, is given by a product of space and spin wave functions:

$$\Psi_{NLSJM}(\vec{r})=\frac{1}{r}U_{NLSJ}(r)\sum_{M_LM_S}C(L,M_L,S,M_S;JM)Y_{LM_L}(\theta,\varphi)\chi_{SM_S} \quad (8)$$

Where M_L and M_S are the projections of angular momentum and spin, and χ is the spin wave function. For the calculation of single particle energy levels, N, L, S, and J specify the quantum numbers of the single particle level.

The binding energy of a single particle level is obtained by rewriting the radial Schrödinger equation in the form:

$$\left(\frac{d^2}{dr^2}-k(p,r)\right)U(p,r)=0 \quad (9)$$

Where;

$$U(p,r)=U_{NLSJ} \quad (10)$$

And

$$k(p,r) = \frac{L(L+1)}{r^2} + \frac{2\mu}{\hbar^2}\left(E_{NLSJ} + V_{LSJ}(r)\right) \quad (11)$$

The model searches for values of the parameter p in order to obtain the binding energy E_{NLSJ} for a given potential. The method of searching for p is provided by Brown, Gunn, and Gould [39] to obtain a converged solution. Refs. 2, 3, 5, and 21-41 provide additional details of the model, numerical methods, and associated interactions.

2.1 Determination of Q Values and Half-Lives

Given the uncertainties in the nuclear interaction, calculated half-life values only represent relative values. The largest values suggest regions of possible stability relative to other systems whose properties are calculated with the same interaction.

Table 2 provides the Q value for alpha decay and the alpha and beta decay half-lives for 1640 ≤ A < 1650 superheavy nuclei having effective half-lives ≥ 10^{20} yr based on the Rost-1600 interaction [34]. Alpha decay energies are calculated using the relationship.

$$Q_\alpha = 28.3 \text{ MeV} - 2 S_n - 2 S_P \quad (12)$$

In Eq. 12, S_n and S_p are the binding energies of the last occupied neutron and proton single-particle energy levels, respectively [1]. The alpha decay, positron decay, and electron capture half-lives were determined following the methodology noted in Ref. 3.

Table 2: Calculated Properties for 1640 ≤ A < 1650 Nuclei

Nucleus		$T^{\beta}_{1/2}$(yr)	Q_α (MeV)	$T^{\alpha}_{1/2}$(yr)
444	1196	a	23.5	3.5×10^{24}
446	1194	a	23.9	3.1×10^{23}
448	1192	a	24.4	3.0×10^{22}
444	1198	a	23.3	1.0×10^{25}
446	1196	a	23.8	8.8×10^{23}
448	1194	a	24.3	8.3×10^{22}
446	1198	a	23.6	2.5×10^{24}
448	1196	a	24.1	2.3×10^{23}
446	1200	a	24.6	3.1×10^{21}
448	1198	a	24.0	6.3×10^{23}
450	1196	a	24.4	6.1×10^{22}
446	1202	a	24.5	8.3×10^{21}
448	1200	a	25.0	6.8×10^{20}
450	1198	a	24.3	1.7×10^{23}
[a]Beta stable.				

The log ft methodology of Wong [1] is used to determine the beta decay half-lives. Allowed (first-forbidden) beta decay half-lives are obtained from the values of log ft = 5 (8) [1]. In view of the uncertainties in the calculated level energies, second and higher forbidden transitions were not determined. The beta half-lives summarized in Table 2 listed as *stable* are either beta stable or decay by these higher order forbidden transitions.

3. Nuclear Interaction

The single-particle level spectrum is generated using a Woods-Saxon potential with parameters optimized to permit extrapolation into the A ≥ 1600 superheavy region [34]. Based on the calculations summarized in Ref. 34, a 15% uncertainty in the potential strength of the Rost interaction [2] was judged to be reasonable.

The 15% potential strength uncertainty is incorporated into the Rost-1600 interaction [34].

$$V_0 = 51.6 \,[1 \pm 0.73\,(N - Z)/A] \text{ MeV} \quad (13)$$

With λ = 1.15. Calculated single-particle energies are also derived by incorporating the unmodified pairing interaction of Blomqvist and Wahlborn [41] to investigate the bounding characteristics of A ≥ 1600 superheavy nuclear systems.

4. Results and Discussion

The Rost-1600 model results should only be compared to calculations based upon this interaction. It is not appropriate to compare the Rost-1600 calculations with calculations based on the Rost interaction and its other variants [2, 24, 29] for 570 ≤ A<1600 [5, 21-23, 25-28, 30-38]. A comparison to the heavier 1600 ≤ A < 1640 mass region [35-38] is provided in Table 1. The A<1600 systems noted in Table 1 are only presented for information.

Figs. 1 and 2 present relevant calculational results for the bound 1640 ≤ A < 1650 even-even nuclei considered in this paper. The effective half-life (Eq. 14) for nuclei with 1640 ≤ A < 1650 is illustrated in Fig 1. Most 1640 ≤ A < 1650 nuclei decay through both alpha and beta emission. The Q_α values for nuclei with 1640 ≤ A < 1650 are plotted in Fig 2.

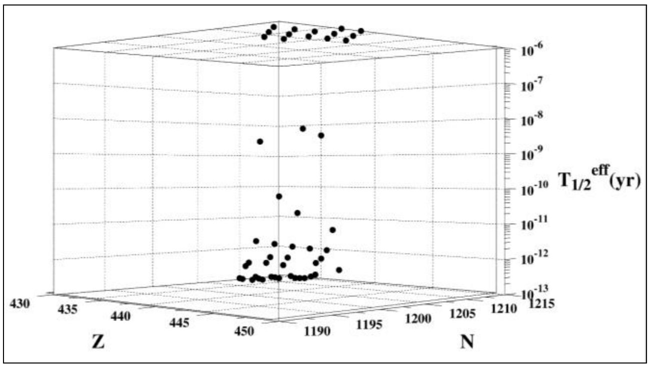

Fig 1 Three-dimensional plot of the effective half-life ($T_{1/2}^{eff}$) as a function of Z and N for 1640 ≤ A < 1650 nuclear systems. To simplify the plot, the half-lives of the systems summarized in Table 2 with half-lives > 10^{20} yr are depicted as 10^{-6} yr rather than their actual values. Using the actual half-life values would compress most of the figure causing a loss of detail.

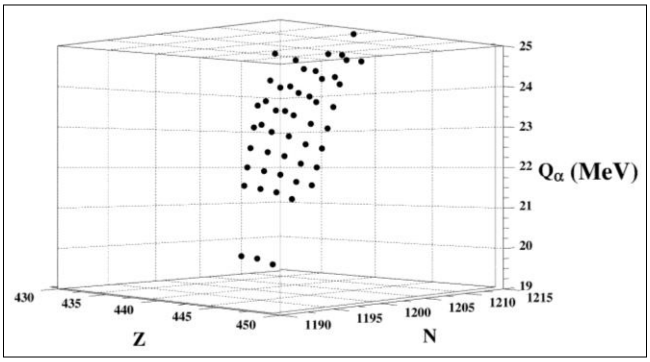

Fig 2: Three-dimensional plot of the Q_α values as a function of Z and N for 1640 ≤ A < 1650 nuclear systems

The stability of any bound superheavy nucleus is dependent on its shell structure. Closed-shell effects [3, 5, 21-38] tend to enhance the stability of a nuclear system. The importance of these shell effects is noted in subsequent discussion.

A new island of stability in the vicinity of Z = 444 - 450 (See Table 2) is suggested for $1640 \leq A < 1650$ systems. The most stable $1640 \leq A < 1650$ system is the (444, 1642) nucleus that has closed $1u_{33/2}$ neutron and partially filled $1o_{25/2}$ proton shells. This system is stable with respect to beta decay, and has an alpha decay half-life of $1.0x10^{25}$ yr.

Table 2 summarizes a subset of the 49 bound even-even nuclei within $1640 \leq A < 1650$ systems that have effective half-lives $\geq 10^{20}$ yr. The effective half-life, including the combined effect of the dominant alpha and beta decay modes, is defined as:

$$T_{1/2}^{eff} = (T^{\alpha}_{1/2}\, T^{\beta}_{1/2}) / (T^{\alpha}_{1/2} + T^{\beta}_{1/2}) \quad (14)$$

As noted in Fig 1, many of the $1640 \leq A < 1650$ systems have effective half-lives less than $\sim 10^{-4}$ s, and beta decay through allowed $4j_{15/2}(n)$ to $2j_{13/2}(p)$, $2o_{25/2}(n)$ to $1o_{25/2}(p)$ and $5g_{7/2}(n)$ to $3g_{9/2}(p)$ transitions and the first forbidden $4j_{15/2}(n)$ to $2k_{17/2}(p)$ transition.

Based on previous calculations [21-38], spontaneous fission stability is expected to be enhanced near closed shells. These spontaneous fission calculations utilized the Wentzel-Kramers-Brillouin (WKB) approximation methodology and the phenomenological parameter values of Ref. 3. The calculations suggest that fission half-lives near closed shells are greater than the effective decay half-lives calculated using Eq. 14 [21-38].

There are level systematics that are consistent with previous calculations [21-38]. For a given A value, S_p tends to decrease and S_n tends to increase as Z increases. These conditions lead to increasing Q_α values as Z increases for a fixed A value.

The systematics involved in the beta decay transitions are more complex. These depend on selection rules that depend on a number of considerations including (1) the occupancy of specific single-particle levels, (2) single-particle level quantum numbers, and (3) single-particle energy level values that permit an allowed or forbidden transition to occur.

Specific trends in alpha and beta half-lives are consistent with previous calculations [21-38]. If the A value is fixed, alpha decay half-lives tend to decrease and beta decay half-lives tend to increase as Z increases. For a fixed Z, alpha decay half-lives tend to increase and beta decay half-lives tend to decrease as A increases.

In the $1640 \leq A < 1650$ system, most decays occur through both alpha and beta pathways. Most of the calculated $1640 \leq A < 1650$ half-lives are shorter than the longest-lived Z = 114 – 118 nuclei [42], but Table 2 notes several long-lived exceptions. These systems are likely an artifact of the Rost-1600 interaction. However, the systems summarized in Tables 1 and 2 suggest possible islands of nuclear stability.

5. Model Weaknesses

Model limitations include uncertainties in the nuclear interaction [2, 24, 29, 34], exclusion of nonconventional decay modes that could exist in superheavy systems [21-38], and treating all system as spherically symmetric nuclei [21-38]. The model uncertainties prevent the determination of specific single-particle energies, Q values, and half-lives. However, the proposed model permits a comparison of the relative stability of nuclear systems and determination of possible islands of nuclear stability [42].

The accuracy of the proposed model can be partially addressed by comparing the (Z, A) values of calculated system properties to the predictions of Adler's relationship [43, 44]. The Alder relationship provides the most stable nucleus Z value for a given A:

$$Z = (0.487\, A) / (1 + A^{2/3} /166) \quad (15)$$

This relationship can be compared to the model predictions for the most stable $1640 \leq A < 1650$ nucleus. When applied to the (444, 1642) system, the Adler relationship predicts that the most stable A = 1642 Z value is 435. This is about 2% smaller than the Z = 442 result obtained from the spherical model outlined in this paper. This comparison between the model and predictions of the Adler relationship of Eq. 15 suggests at least the qualitative success of the proposed model.

6. Experimental Verification

The creation of elements with Z > 118 has yet to be successful. Production of $A \geq 1600$ systems is more complex than the challenge of creating Z > 118 nuclei.

Binary collision processes involving heavy ions beams are not currently capable of reaching the $1640 \leq A < 1650$ mass region. Creating these systems will require an unconventional approach (e.g., colliding multiple ^{238}U ions).

The alpha particle energies of the theoretical $1640 \leq A < 1650$ systems are greater than twice the Z = 114-118 values [42]. A measurable track length is produced when an alpha particle traverses a medium [44, 45]. Since the track length is related to the alpha particle energy, it provides a possible method to verify the existence of a $1640 \leq A < 1650$ superheavy system.

An additional verification method is based on the fact that various lead isotopes are the endpoint of known natural decay chains (e.g., ^{232}Th, ^{235}U, and ^{238}U) [44, 45]. This observation suggests that lead targets could be vaporized, accelerated, and then separated by mass. The remnants of a long-lived parent superheavy nuclei summarized in Tables 1 and 2 could be present in the mass spectrum [46].

7. Conclusions

Previous calculations explored the $570 \leq A < 1640$ mass region, and this paper extends these calculations to $1640 \leq A < 1650$. The single-particle level spectrum is generated using a Woods-Saxon potential with parameters optimized to permit extrapolation into the $A \geq 1600$ superheavy region utilizing the Rost-1600 interaction that was based on existing nuclear systems as well as nuclear matter calculations. This interaction is essentially the Rost interaction that includes a 15% uncertainty in the potential strength. Calculated single-particle energies are also derived by incorporating the unmodified pairing interaction of Blomqvist and Wahlborn to investigate the bounding characteristics of $A \geq 1600$ superheavy nuclear systems.

Given uncertainties in the model interaction, it is not practical to determine absolute values for the half-lives and Q-values. However, the model does permit establishing the relative stability of nuclear systems and to highlight possible islands of stability.

Model limitations include uncertainties in the nuclear interaction, exclusion of nonconventional decay modes that could exist in superheavy systems, and treating all system as spherically symmetric nuclei. The model uncertainties prevent the determination of specific single-particle energies, Q values, and half-lives. However, the proposed model permits a comparison of the relative stability of nuclear systems and determination of possible islands of nuclear stability.

The stability of 1640 ≤ A < 1650 systems is determined by evaluating the various decay modes (i.e., alpha decay, beta decay, positron decay, electron capture, and spontaneous fission). Stability in the 1640 ≤ A < 1650 mass region is dominated by alpha decay and beta decay.

The accuracy of the proposed model can be partially addressed by comparing the (Z, A) values of calculated system properties to the predictions of Adler's relationship. The Alder relationship provides the most stable nucleus Z value for a given A. This relationship can be compared to the model predictions for the most stable 1640 ≤ A < 1650 nucleus. When applied to the (444, 1642) system, the Adler relationship predicts that the most stable A = 1642 Z value is 435. This is about 2% smaller than the Z = 444 result obtained from the spherical model outlined in this paper. This comparison between the model and predictions of the Adler relationship of Eq. 15 suggests at least the qualitative success of the proposed model.

Using the Rost-1600 interaction, 49 even-even nuclear systems are predicted in the 1640 ≤ A < 1650 mass region. For this mass region, the model predicts a new island of stability in the vicinity of the Z = 444 – 450. The (444, 1642) system is stable with respect to beta decay, and has an alpha decay half-life of 1.0×10^{25} yr. This nucleus has a closed $1u_{33/2}$ neutron and partially filled $1o_{25/2}$ proton shells.

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