



Received: 24-09-2025
Accepted: 04-11-2025

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Decay Characteristics of Neutron Excess Gallium Nuclei

JJ Bevelacqua

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

Corresponding Author: JJ Bevelacqua

Abstract

The properties of neutron excess gallium nuclei are predicted utilizing a single-particle model. The single particle model calculations include alpha, beta, positron, electron capture, and spontaneous fission decay modes. Neutron emission decay modes that have short half-lives are not readily determined by the model. However, estimates of the neutron decay mode were evaluated using the methodology of Chowdhury *et al.* Using that model, spontaneous neutron emission is predicted to occur in the range of $A = 97 - 99$. The Japanese Nuclear Data

Compilation calculations terminate their calculations at $A = 92$. Given these results, single-particle model calculations are extended to encompass these values, and were extended to $A = 101$.

Single particle model calculations predict that $A = 87 - 101$ neutron excess gallium systems form bound systems that have limiting beta decay half-lives in the range of 0.707 – 28.6 ms. Model half-life results for the $A = 87 - 92$ gallium nuclei are within a factor of about two of the predictions of the Japanese Nuclear Data Compilation calculations.

Keywords: Nucleosynthesis, Neutron Excess Gallium Nuclei, Beta Decay, Nuclear Structure, Spontaneous Neutron Emission

1. Introduction

Interest in neutron excess nuclei ^[1-32] has stimulated both experimental and theoretical physics interest. Several physical processes generate neutron excess nuclei, but the r-process usually provides the most significant contribution. Production of neutron excess nuclei in mergers of astrophysical objects (e.g., black holes and neutron stars) is an active area of research in nuclear physics and astrophysics ^[1, 2].

This paper continues the investigation of neutron excess nuclei by focusing on the $Z = 31$ gallium systems. Neutron excess systems having $Z = 9 - 30$ were discussed in previous work ^[8-25, 29-32]. Studies of these systems provide additional insight into nuclear systematics involving the various nucleosynthesis mechanisms and decay modes, and their associated variation with atomic and mass numbers.

2. Calculational Methodology

Methods for investigating neutron excess nuclei are provided in Refs. 8-32. This paper follows the single particle methodology of Lukasiak and Sobiczewski ^[27] and Petrovich *et al.* ^[28]. Single particle energies of neutron excess nuclear systems are obtained by incorporating the numerical methods of Refs. 33 and 34.

The radial Schrödinger equation is utilized to determine binding energy of a nucleon interacting with a nuclear core ^[8-25, 29-32]:

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

In Eq. 1, E_{NLSJ} is the nucleon binding energy, r is the radial coordinate, $V_{LSJ}(r)$ is the nuclear interaction, and $U_{NLSJ}(r)$ is the radial wave function. L , S , and J represent the orbital, spin, and total angular momentum quantum numbers, respectively. The model definition is completed by defining the radial quantum number (N) and reduced mass (μ).

3. Nuclear Interaction

The Rost interaction ^[35] is selected for the nuclear interaction. This interaction has a central strength:

$$V_0 = 51.6 [1 \pm 0.73 (N - Z)/A] \text{ MeV} \quad (2)$$

In Eq. 2, the positive (negative) sign is assigned to protons (neutrons). The spin-orbit interaction strength (V_{so}) is defined in terms of the central interaction strength and the multiplier γ [35]:

$$V_{so} = \gamma V_0 / 180 \quad (3)$$

Inclusion of the pairing correction interaction of Blomqvist and Wahlborn [36] completes the definition of the model interaction.

The difficulties in defining an appropriate nuclear interaction are outlined in Refs. 37 and 38. Ray and Hodgson [37] and Schwierz, Wiedenhöver, and Volya [38] note that modifications, unique to each nuclear system, are required to ensure an accurate representation of the experimental energy levels and decay characteristics. In view of the conclusions of Refs. 37 and 38 and the results of previous excess neutron system calculations [8-25, 29-32], the Rost central interaction strength (V_A) is modified in the following manner:

$$V_A = V_0 \lambda [1 \pm a(A)] \text{ MeV} \quad (4)$$

Individual nuclear system characteristics are defined by incorporating a potential strength multiplier (λ) and a factor [$a(A)$] to adjust the potential strength as a function of A . For gallium systems, the multiplier λ is selected to have the value of 1.5. This multiplier value is consistent with previous excess neutron nuclei calculations [8-25, 29-32] that provided model results in agreement with available data [39-41].

4. Model Limitations

Previous calculations [8-25, 29-32, 42] provided a representative description of the various nuclear decay modes (e.g., alpha, beta, positron, electron capture, and spontaneous fission) that could be encountered in neutron excess nuclei. Neutron excess systems can also decay by neutron emission modes

that are not well-described by single-particle models. Since these neutron emission modes have very short half-lives, single-particle models will likely overestimate the lifetimes of neutron excess nuclei.

The onset of spontaneous neutron emission was estimated using the methodology of Chowdhury *et al.* [43]. Using the approach of Ref. 43, the onset of spontaneous neutron emission was estimated to occur in the range of $A = 97 - 99$ for gallium systems. Although independent of the calculated neutron single particle levels presented herein, the approach of Chowdhury *et al.* yields a logical value to terminate calculations for excess neutron gallium nuclei. The Japanese Nuclear Data Compilation terminate their calculations at $A = 92$. These results guide the A value selected to terminate the single-particle model calculations for gallium.

5. Results and Discussion

Table 1 summarizes the complete set of $101 \geq A \geq 76$ gallium isotopes considered in this paper. The $101 \geq A \geq 76$ gallium nuclei occupy a variety of neutron shells that are noted in Table 1. The heaviest observed gallium system is ^{86}Ga [41]. In view of the paucity of experimental data, extrapolations of nuclear characteristics beyond $A > 86$ become more uncertain.

5.1 $86 \geq A \geq 76$ Gallium Isotopes with Experimental Half-Life Data

The limiting decay mode (i.e., the transition that has the shortest decay half-life) for $86 \geq A \geq 76$ gallium isotopes observed experimentally is summarized in Table 1. For example, the ^{76}Ga calculations predict six beta decay transitions (i.e., allowed $1f_{5/2}(n)$ to $1f_{5/2}(p)$ [34.5 min], allowed $2p_{1/2}(n)$ to $2p_{3/2}(p)$ [32.8 s], allowed $2p_{3/2}(n)$ to $2p_{3/2}(p)$ [15.4 min], allowed $2p_{1/2}(n)$ to $2p_{1/2}(p)$ [22.7 min], allowed $1g_{9/2}(n)$ to $1g_{9/2}(p)$ [19.1 min], and first forbidden $1g_{9/2}(n)$ to $1f_{5/2}(p)$ [51.5 min]). For ^{76}Ga , the allowed $2p_{1/2}(n)$ to $2p_{3/2}(p)$ [32.8 s] transition is the limiting beta decay mode.

Table 1: Calculated Single-Particle and Experimental Decay Properties of Gallium Nuclei with $76 \leq A \leq 101$

Nuclide (neutron shell)	$a(A)$	Half-Life (Decay Mode)	
		Experiment ^{a,b,c} /Theory ^d	This Work
^{76}Ga ($1g_{9/2}$)	-0.0370	32.6 s ^c	32.8 s (β^-) ^e
^{77}Ga ($1g_{9/2}$)	-0.0380	13.2 s ^c	13.2 s (β^-) ^e
^{78}Ga ($1g_{9/2}$)	-0.0363	5.09 s ^c	5.09 s (β^-) ^e
^{79}Ga ($1g_{9/2}$)	-0.0369	2.847 s ^c	2.85 s (β^-) ^e
^{80}Ga ($1g_{9/2}$)	-0.0371	1.697 s ^c	1.69 s (β^-) ^e
^{81}Ga ($1g_{9/2}$)	-0.0394	1.217 s ^c	1.22 s (β^-) ^e
^{82}Ga ($2d_{5/2}$)	-0.0337	599 ms ^c	598 ms (β^-) ^e
^{83}Ga ($2d_{5/2}$)	-0.0267	310 ms ^c	310 ms (β^-) ^e
^{84}Ga ($2d_{5/2}$)	+0.0020	85 ms ^c	85.4 ms (β^-) ^e
^{85}Ga ($2d_{5/2}$)	-0.0076	93 ms ^c	92.9 ms (β^-) ^e
^{86}Ga ($2d_{5/2}$)	+0.0128	43 ms ^c	43.0 ms (β^-) ^e
^{87}Ga ($2d_{5/2}$)	0.0230	19.4 ms ^d	28.6 ms (β^-) ^e
^{88}Ga ($1g_{7/2}$)	0.0342	14.2 ms ^d	10.5 ms (β^-) ^f
^{89}Ga ($1g_{7/2}$)	0.0454	9.52 ms ^d	7.80 ms (β^-) ^f
^{90}Ga ($1g_{7/2}$)	0.0566	7.70 ms ^d	5.91 ms (β^-) ^f
^{91}Ga ($1g_{7/2}$)	0.0678	5.62 ms ^d	4.60 ms (β^-) ^f
^{92}Ga ($1g_{7/2}$)	0.0790	4.83 ms ^d	3.62 ms (β^-) ^f
^{93}Ga ($1g_{7/2}$)	0.0902	g	2.90 ms (β^-) ^f
^{94}Ga ($1g_{7/2}$)	0.1015	g	2.35 ms (β^-) ^f
^{95}Ga ($1g_{7/2}$)	0.1127	g	1.93 ms (β^-) ^f
^{96}Ga ($3s_{1/2}$)	0.1239	g	1.59 ms (β^-) ^f
^{97}Ga ($3s_{1/2}$)	0.1351	g	1.33 ms (β^-) ^f
^{98}Ga ($2d_{3/2}$)	0.1463	g	1.13 ms (β^-) ^f

^{99}Ga ($2d_{3/2}$)	0.1575	g	0.957 ms (β) ^f
^{100}Ga ($2d_{3/2}$)	0.1687	g	0.820 ms (β) ^f
^{101}Ga ($2d_{3/2}$)	0.1799	g	0.707 ms (β) ^f

^aRef. 39. ^bRef. 40. ^cRef. 41.

^dJapanese data Compilation calculation.

^eAllowed $2p_{1/2}(n)$ to $2p_{3/2}(p)$ beta decay transition.

^fAllowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta decay transition.

^gNo data provided in Ref. 39 - 41.

The model predicts the proper decay mode for the known $86 \leq A \leq 76$ gallium systems [39 - 41]. As noted in Table 1, the model half-lives are also consistent with data [39 - 41].

$^{76}\text{Ga} - ^{81}\text{Ga}$ nuclei occupy the $1g_{9/2}$ neutron shell. These systems decay through allowed $2p_{1/2}(n)$ to $2p_{3/2}(p)$ beta transitions. Model predictions for the beta decay half-lives of $^{76}\text{Ga} - ^{81}\text{Ga}$ are within about 0.6% of the experimental values [41]. In addition beta decay is the predicted decay mode in agreement with Ref. 41.

The $^{82}\text{Ga} - ^{86}\text{Ga}$ nuclei partially fill the $2d_{5/2}$ neutron shell. These systems decay through allowed $2p_{1/2}(n)$ to $2p_{3/2}(p)$ beta transitions. The half-life values of the ^{82}Ga and ^{86}Ga systems are within 0.5% of the data [41]. Model calculations also predict the correct decay mode for these $2d_{5/2}$ gallium nuclei.

5.2 $101 \geq A \geq 87$ Gallium Isotopes without Experimental Half-Life Data

The $a(A)$ values for $101 \geq A \geq 87$ gallium isotopes were obtained from a linear fit based on the half-lives of $^{82}\text{Ga} - ^{86}\text{Ga}$. The resulting $a(A)$ values are listed in Table 1.

^{87}Ga completes the $2d_{5/2}$ neutron shell, and decays through an allowed $2p_{1/2}(n)$ to $2p_{3/2}(p)$ beta decay transition. This gallium system has a beta decay half-life of 28.6 ms that is within a factor of about 1.5 of the Japanese Data Compilation calculations [41].

$^{88}\text{Ga} - ^{92}\text{Ga}$ nuclei partially fill the $1g_{7/2}$ neutron shell, and have beta decay half-lives in the range of 3.62 to 10.5 ms. These systems decay through allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta decay transitions. The model results for $^{88}\text{Ga} - ^{92}\text{Ga}$ within about a factor of 1.5 of the Japanese Data Compilation calculations [41]. ^{92}Ga is the last gallium system included in the Japanese Data Compilation calculations [41].

$^{93}\text{Ga} - ^{95}\text{Ga}$ nuclei complete filling the $1g_{7/2}$ neutron shell, and have predicted beta decay half-lives in the range of 1.93 to 2.90 ms. These systems decay through allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta decay transitions.

$^{96}\text{Ga} - ^{97}\text{Ga}$ fill the $3s_{1/2}$ neutron shell, and these systems decay through allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta decay transitions. The half-lives of $^{96}\text{Ga} - ^{97}\text{Ga}$ are 1.33 and 1.59 ms, respectively.

^{98}Ga and ^{101}Ga fill the $2d_{3/2}$ neutron shell, and these systems decay through allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta decay transitions. The half-lives of ^{98}Ga and ^{101}Ga are in the range of 0.707 - 1.13 ms.

The gallium calculations are terminated at $A = 101$ to account for the spontaneous neutron emission as the mass increases. Using the methodology of Chowdhury *et al.* [43], spontaneous emission is expected to occur at $A = 97 - 99$. The Japanese Data Compilation calculations [41] suggest that $A = 92$ terminates the gallium systems. Model calculations were extended to $A = 101$ to account for uncertainties in estimates of Ref. 41 and 43.

6. Conclusions

Single-particle model calculations readily incorporate alpha, beta, positron, electron capture, and spontaneous fission decay modes. Neutron emission decay modes have short half-lives that are not readily determined by a single-particle model. However, estimates on the neutron decay mode were evaluated using the methodology of Chowdhury *et al.* Using that model, spontaneous neutron emission in gallium nuclei is predicted to occur in the range of $A = 97 - 99$. The Japanese Nuclear Data Compilation calculations terminate their calculations at $A = 92$. Given these results, single-particle model calculations are extended to encompass these values, and were terminated at $A = 101$.

Single particle model calculations predict that $A = 87 - 101$ neutron excess gallium systems form bound systems that have limiting beta decay half-lives in the range of 0.707 - 28.6 ms. Model half-life results for the $A = 87 - 92$ gallium nuclei are within about a factor of about 1.5 of the predictions of the Japanese Nuclear Data Compilation calculations.

These neutron excess gallium systems decay through allowed $2p_{1/2}(n)$ to $2p_{3/2}(p)$ and $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta decay transitions. The model likely overestimates the actual half-life values, because it does not explicitly include the short-lived neutron emission decay modes.

7. References

1. Siegel DM, Metzger BD. Three-Dimensional General-Relativistic Magnetohydrodynamic Simulations of Remnant Accretion Disks from Neutron Star Mergers: Outflows and r-Process Nucleosynthesis, *Phys. Rev. Lett.* 2017; 119:231102.
2. National Academy of Sciences Report No. 11796, Scientific Opportunities with a Rare-Isotope Facility in the United States, Washington DC, National Research Council, 2007.
3. Fukuda N, *et al.* Identification of New Neutron-Rich Isotopes in the Rare-Earth Region Produced by 345 MeV/nucleon ^{238}U , *J. Phys. Soc. Jpn.* 2018; 87:14202.
4. Shimizu Y, *et al.* Observation of New Neutron-rich Isotopes among Fission Fragments from In-flight Fission of 345 MeV/nucleon ^{238}U : Search for New Isotopes Conducted Concurrently with Decay Measurement Campaigns, *J. Phys. Soc. Jpn.* 2018; 87:14203.
5. Kurcewicz J, *et al.* Discovery and cross-section measurement of neutron-rich isotopes in the element range from neodymium to platinum with the FRS, *Phys. Lett. B.* 2012; 717:371.
6. Baumann T, *et al.* Discovery of ^{40}Mg and ^{42}Al suggests neutron drip-line slant towards heavier isotopes, *Nature.* 2007; 449:1022.

7. Tarasov OB, *et al.* Production cross sections from ^{82}Se fragmentation as indications of shell effects in neutron-rich isotopes close to the drip-line, *Phys. Rev. C.* 2013; 87:54612.
8. Bevelacqua JJ. Decay Characteristics of Neutron Excess Calcium Nuclei, *Physics Essays.* 2018; 31(4):462.
9. Bevelacqua JJ. Decay Characteristics of Neutron Excess Iron Nuclei, *Physics Essays.* 2020; 32(2):175.
10. Bevelacqua JJ. Decay Characteristics of Neutron Excess Fluorine Nuclei, *Qeios* **24XLL9**. 2020; 1. Doi: <https://doi.org/10.32388/24XLL9>
11. Bevelacqua JJ. Decay Characteristics of Neutron Excess Zinc Nuclei, *Qeios* **JZ1ILG**. 2020; 1. Doi: <https://doi.org/10.32388/JZ1ILG>
12. Bevelacqua JJ. Decay Characteristics of Neutron Excess Neon Nuclei, *Qeios* **1WR291**. 2021; 1. Doi: <https://doi.org/10.32388/1WR291>
13. Bevelacqua JJ. Decay Characteristics of Neutron Excess Sodium Nuclei, *Qeios* **1Y819A**. 2021; 1. Doi: <https://doi.org/10.32388/1Y819A>
14. Bevelacqua JJ. Decay Characteristics of Neutron Excess Magnesium Nuclei, *Qeios* **KIB58L**. 2021; 1. Doi: <https://doi.org/10.32388/KIB58L>
15. Bevelacqua JJ. Decay Characteristics of Neutron Excess Aluminum Nuclei, *Qeios* **LCAO3W**. 2022; 1. Doi: <https://doi.org/10.32388/LCAO3W>
16. Bevelacqua JJ. Decay Characteristics of Neutron Excess Silicon Nuclei, *Qeios* **Y6HDZF**. 2022; 1. Doi: <https://doi.org/10.32388/Y6HDZF>
17. Bevelacqua JJ. Decay Characteristics of Neutron Excess Phosphorous Nuclei, *Qeios* **Z16MGO**. 2023; 1. Doi: <https://doi.org/10.32388/Z16MGO>
18. Bevelacqua JJ. Decay Characteristics of Neutron Excess Sulfur Nuclei, *Qeios* **QO9K3E**. 2023; 1. Doi: <https://doi.org/10.32388/QO9K3E>
19. Bevelacqua JJ. Decay Characteristics of Neutron Excess Chlorine Nuclei, *Qeios* **HXV1XN**. 2023; 1. Doi: <https://doi.org/10.32388/HXV1XN>
20. Bevelacqua JJ. Decay Characteristics of Neutron Excess Argon Nuclei, *Qeios* **JDLHDL**. 2023; 1. Doi: <https://doi.org/10.32388/JDLHDL>
21. Bevelacqua JJ. Decay Characteristics of Neutron Excess Potassium Nuclei, *Qeios* **RBFGK2**. 2024; 1. Doi: <https://doi.org/10.32388/RBFGK2>
22. Bevelacqua JJ. Decay Characteristics of Neutron Excess Scandium Nuclei, *Qeios* **25NGQR**. 2024; 1. Doi: <https://doi.org/10.32388/25NGQR>
23. Bevelacqua JJ. Decay Characteristics of Neutron Excess Titanium Nuclei, *Qeios* **NFSVCP**. 2024; 1. Doi: <https://doi.org/10.32388/NFSVCP>
24. Bevelacqua JJ. Decay Characteristics of Neutron Excess Vanadium Nuclei, *Qeios* **9VY02M**. 2024; 1. Doi: <https://doi.org/10.32388/9VY02M>
25. Bevelacqua JJ. Decay Characteristics of Neutron Excess Chromium Nuclei, *Qeios* **K7DJZP**. 2024; 1. Doi: <https://doi.org/10.32388/K7DJZP>
26. Terasawa M, Sumiyosh K, Kajino T, Mathews GJ, Tanihata I. New Nuclear Reaction Flow during r-Process Nucleosynthesis in Supernovae: Critical Role of Light Neutron-Rich Nuclei, *The Astrophysical Journal.* 2001; 562:470.
27. Lukasiak A, Sobiczewski A. Estimations of half-lives of far-superheavy nuclei with $Z \text{ approx. } = 154 - 164$, *Acta Phys. Pol.* 1975; B6:147.
28. Petrovich F, Philpott RJ, Robson D, Bevelacqua JJ, Golin M, Stanley D. Comments on Primordial Superheavy Elements, *Phys. Rev. Lett.* 1976; 37:558.
29. Bevelacqua JJ. Decay Characteristics of Neutron-Excess Manganese Nuclei, *Qeios* **FKQ489**. 2025; 1. Doi: doi.org/10.32388/FKQ489
30. Bevelacqua JJ. Decay Characteristics of Neutron Excess Cobalt Nuclei. *Sci Set J of Physics.* 2025; 4(3):1.
31. Bevelacqua JJ. Decay Characteristics of Neutron Excess Nickel Nuclei. *Sci Set J of Physics.* 2025; 4(4):1.
32. Bevelacqua JJ. Decay Characteristics of Neutron Excess Copper Nuclei. *Int. J. Adv. Multidisc. Res. Stud.* 2025; 5(5):242.
33. Brown GE, Gunn JH, Gould P. Effective mass in nuclei, *Nucl. Phys.* 1963; 46:598.
34. Fox L, Godwin ET. Some new methods for the numerical integration of ordinary differential equations, *Proc. Cambridge Philos. Soc.* 1949; 45:373.
35. Rost E. Proton Shell-Model Potentials for Lead and the Stability of Superheavy Nuclei, *Phys. Lett.* 1968; 26B:184.
36. Blomqvist J, Wahlborn S. Shell model calculations in the lead region with a diffuse nuclear potential, *Ark. Fys.* 1959; 16:545.
37. Ray L, Hodgson PE. Neutron densities and the single particle structure of several even-even nuclei from Ca40 to Pb208, *Phys. Rev. C.* 1979; 20:2403.
38. Schwierz N, Wiedenhöfer I, Volya A. Parameterization of the Woods-Saxon Potential for Shell-Model Calculations, Sep 21, 2007 arXiv:0709.3525v1 [nucl-th]
39. Baum EM, Ernesti MC, Knox HD, Miller TR, Watson AM. Nuclides and Isotopes - Chart of the Nuclides, 17th ed, Knolls Atomic Power Laboratory, 2010.
40. National Nuclear Data Center, Brookhaven National Laboratory, NuDat3 (Nuclear Structure and Decay Data), 2025. <http://www.nndc.bnl.gov/nudat3/>
41. Koura H, *et al.* Chart of the Nuclides 2018, Japanese Nuclear Data Committee and Nuclear Data Center, Japanese Atomic Energy Agency, 2018.
42. Wong CY. Additional evidence of stability of the superheavy element $^{310}126$ according to the shell model, *Phys. Lett.* 1966; 21:688.
43. Chowdhury PR, Samanta C, Basu DN. Modified Bethe-Weinsäcker Mass Formula with Isotonic Shift and New Driplines, *Mod. Phys. Lett A.* 2005; 20(21):1605.