ISSN: 3066-8131
Research Article
Science Set Journal of Physics

Decay Characteristics of Neutron Excess Cobalt Nuclei

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Submitted: 19 May 2025 **Accepted:** 24 May 2025 **Published:** 30 May 2025

https://doi.org/10.63620/MKSSJP.2025.

Citation: *Bevelacqua, J. J. (2025). Decay Characteristics of Neutron Excess Cobalt Nuclei. Sci Set J of Physics, 4(3), 01-04.*

Abstract

The properties of neutron excess cobalt nuclei are determined utilizing a single-particle model. Single particle model calculations predict that A = 78 – 91 neutron excess cobalt systems form bound systems that have limiting beta decay half-lives in the range of 0.273 – 8.22 ms. Model half-life results for the A = 78 – 83 cobalt nuclei are within a factor of two of the predictions of the Japanese Nuclear Data Compilation calculations. 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, and were not evaluated. The omission of these short-lived neutron emission decay modes implies that the single particle model calculations could overestimate the half-lives of neutron excess A = 78 – 91 cobalt nuclei.

Keywords: Nucleosynthesis, Neutron Excess Cobalt Nuclei, Beta Decay, Nuclear Structure

Introduction

Interest in neutron excess nuclei has stimulated both experimental and theoretical physics interest [1-16]. 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 = 27 cobalt systems. Other neutron excess systems were addressed in previous work [8-13]. 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.

Calculational Methodology

Methods for investigating neutron excess nuclei are provided in Refs. 8-13. This paper follows the single particle methodology of Lukasiak and Sobiczewski [15] and Petrovich et al. [16]. Single particle energies of neutron excess nuclear systems are obtained by incorporating the numerical methods of Refs. 17 and 18.

The model used to describe the particle (i) plus core (c) system represents an application of the standard method of Refs. 15 and 16. 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:

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

$$+ Z_i Z_C e^2 C(r)$$

where

$$R_0 = r_0 A^{1/3} = R_C \quad (3)$$

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

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

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

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 (θ,ϕ) spherical coordinates, the solution of the angular equation is most easily expressed in terms of spherical harmonics $Y_{LM}(\theta,\phi)$. 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:

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

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 [17] using the methodology of Ref. 18 to obtain a converged solution Refs. 8-13,15, and 16 provide additional details of the model, numerical methods, and associated interactions.

Nuclear Interaction

The Rost interaction is selected for the nuclear interaction [19]. This interaction has a central strength

$$V_0 = 51.6\,[1 \pm 0.73\,(N - Z)/A]\ \text{MeV} \quad (12)$$

In Eq. 12, 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 [19]:

$$V_{so} = \gamma\, V_0 / 180 \quad (13)$$

Inclusion of the pairing correction interaction of Blomqvist and Wahlborn completes the definition of the model interaction [20]. The difficulties in defining an appropriate nuclear interaction are outlined in Refs. 21 and 22. Ray and Hodgson [21] and Schwierz, Wiedenhöver, and Volya [22] 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. 21 and 22 and the results of previous excess neutron system calculations [8-13], the Rost central interaction strength (V_A) is modified in the following manner.

$$V_A = V_0\, \lambda\, [1 \pm a(A)]\ \text{MeV} \quad (14)$$

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 cobalt systems, the multiplier λ is selected to have the value of 1.5. This multiplier value is consistent with previous excess neutron nuclei calculations [8-13] that provided model results in agreement with available data [23-25].

Model Limitations

Previous calculations 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 cobalt 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.

Results and Discussion

Table 1 summarizes the complete set of $91 \geq A \geq 63$ cobalt isotopes considered in this paper. The $91 \geq A \geq 63$ cobalt nuclei occupy the $1f_{5/2}$ (^{63}Co – ^{65}Co), $2p_{1/2}$ (^{66}Co – ^{67}Co), $1g_{9/2}$ (^{68}Co – ^{77}Co), $2d_{5/2}$ (^{78}Co – ^{83}Co), and $1g_{7/2}$ (^{84}Co – ^{91}Co) neutron single-particle levels. The heaviest observed cobalt system is ^{77}Co [23-25]. In view of the paucity of experimental data, extrapolations of nuclear characteristics beyond $A > 77$ become more uncertain.

$63 \geq A \geq 77$ Cobalt Isotopes with Experimental Half-Life Data

The half-life of the limiting decay mode (i.e., the transition that has the shortest decay half-life) for $63 \geq A \geq 77$ cobalt isotopes with experimental half-life data are summarized in Table 1. For example, the ^{64}Co calculations include six beta decay transitions (i.e., allowed $1f_{7/2}$(n) to $1f_{7/2}$p) [3.60 s], allowed $2p_{3/2}$(n) to $2p_{3/2}$(p) [7.17 s], allowed $2p_{3/2}$(n) to $2p_{1/2}$(p) [1.07 min], allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) [300 ms], allowed $1f_{5/2}$(n) to $1f_{5/2}$(p) [1.04 min]), and first forbidden $1d_{3/2}$(n) to $1f_{7/2}$(p) [6.03 yr]. For ^{64}Co, the allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) [300 ms] transition is the limiting beta decay mode.

Table 1 Calculated Single-Particle and Experimental Decay Properties of Cobalt Nuclei with 63 ≤ A ≤ 91

Nuclide	a(A)	Half-Life (Decay Mode)	
		Experiment [a,b,c]/Theory[d]	This Work
^{63}Co	-0.0433	27.4 s[c]	27.5 s (β^-)[e]
^{64}Co	+0.0119	300 ms[c]	300 ms (β^-)[e]
^{65}Co	-0.0256	1.16 s[c]	1.16 s (β^-)[e]
^{66}Co	-0.0032	200 ms[c]	200 ms (β^-)[e]
^{67}Co	-0.0245	425 ms[c]	425 ms (β^-)[e]
^{68}Co	-0.0151	200 ms[c]	200 ms (β^-)[e]
^{69}Co	-0.0270	227 ms[c]	227 ms (β^-)[e]
^{70}Co	-0.0154	112 ms[c]	112 ms (β^-)[e]
^{71}Co	-0.0126	80 ms[c]	79.9 ms (β^-)[e]
^{72}Co	-0.0083	56.2 ms[c]	56.2 ms (β^-)[e]
^{73}Co	-0.0040	41 ms[c]	41.0 ms (β^-)[e]
^{74}Co	-0.0004	31.3 ms[c]	31.3 ms (β^-)[e]
^{75}Co	-0.0008	26.5 ms[c]	26.5 ms (β^-)[e]
^{76}Co	+0.0010	21.7 ms[c]	21.7 ms (β^-)[e]
^{77}Co	+0.0198	13.0 ms[c]	13.0 ms (β^-)[e]
^{78}Co	+0.0386	4.84 ms[d]	8.22 ms (β^-)[e]
^{79}Co	+0.0574	3.70 ms[d]	5.47 ms (β^-)[e]
^{80}Co	+0.0762	3.28 ms[d]	3.81 ms (β^-)[e]
^{81}Co	+0.0950	2.55 ms[d]	2.72 ms (β^-)[e]
^{82}Co	+0.1138	2.24 ms[d]	2.00 ms (β^-)[e]
^{83}Co	+0.1326	1.71 ms[d]	1.51 ms(β^-)[e]
^{84}Co	+0.1514	f	1.16 ms (β^-)[e]
^{85}Co	+0.1702	f	0.908 ms (β^-)[e]
^{86}Co	+0.1890	f	0.721ms (β^-)[e]
^{87}Co	+0.2078	f	0.581ms (β^-)[e]
^{88}Co	+0.2266	f	0.475ms (β^-)[e]
^{89}Co	+0.2454	f	0.390ms (β^-)[e]
^{90}Co	+0.2642	f	0.325ms (β^-)[e]
^{91}Co	+0.2830	f	0.273ms (β^-)[e]

[a]Ref. 23. [b]Ref. 24. [c]Ref. 25. [d]Japanese data compilation calculation (Ref.25).[e]Allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta decay transition. [f] No data provided in Ref. 23 - 25.

- The model predicts the proper decay mode for the known 77 ≥ A ≥ 63 cobalt systems [23 – 25]. As noted in Table 1, the model half-lives are also consistent with data [23 – 25].
- ^{63}Co – ^{65}Co nuclei occupy the $1f_{5/2}$ neutron shell. These systems decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta transitions. Model predictions for the beta decay half-lives of ^{63}Co – ^{65}Co are within 0.4% of the experimental values [25]. In addition beta decay is the predicted decay mode in agreement with Ref. 25.
- The ^{66}Co – ^{67}Co nuclei fill the $2p_{1/2}$ neutron shell. These systems decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta transitions. The half-life values of the ^{66}Co – ^{67}Co systems are in agreement with the data [25]. Model calculations also predict the correct decay mode of these $2p_{1/2}$ cobalt nuclei. ^{68}Co – ^{77}Co fill the $1g_{9/2}$ neutron shell. The decay mode and half-life for these cobalt systems are consistent with the data [25]. These $1g_{9/2}$ cobalt systems decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta transitions.

91 ≥ A ≥ 78 Cobalt Isotopes without Experimental Half-Life Data

The a(A) values for 91 ≥ A ≥ 78 cobalt isotopes were obtained from a linear fit based on the half-lives of ^{76}Co – ^{77}Co. The resulting a(A) values are listed in Table 1. ^{78}Co – ^{83}Co nuclei fill the $2d_{5/2}$ neutron shell, and have beta decay half-lives in the range of 1.51 to 8.22 ms. These systems decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta decay transitions. The model results for ^{78}Co – ^{83}Co

are within a factor of two of the Japanese Data Compilation calculations [25]. ^{78}Co – ^{81}Co model half-lives are larger than the Ref. 25 values, but ^{82}Co – ^{83}Co values are smaller.

^{84}Co – ^{91}Co fill the $1g_{7/2}$ neutron shell, and these systems decay through allowed $1f_{5/2}(n)$ to $1f_{7/2}(p)$ beta decay transitions. The half-lives of ^{84}Co – ^{91}Co are between 0.273 and 1.16 ms, respectively. These systems were not predicted by the Japanese Data Compilation calculations [25]. No cobalt systems with $A > 91$ are predicted by either the model or the Japanese Data Compilation calculations [25]. This model limitation occurs because only 64 neutrons are bound in the cobalt system.

Conclusions

Within the scope of the proposed single particle model, neutron excess cobalt isotopes terminate with ^{91}Co. The model predicts that the $78 \leq A \leq 91$ cobalt systems have beta decay half-lives in the range of 0.273 – 8.22 ms. These neutron excess cobalt systems decay through allowed $1f_{5/2}(n)$ to $1f_{7/2}(p)$ beta decay transitions. The model likely overestimates the actual half-life values, because it does not include the short-lived neutron emission decay modes.

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