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Decay Characteristics of Neutron Excess Nickel Nuclei

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Abstract

The properties of neutron excess nickel nuclei are determined utilizing a single-particle model. Single particle model calculations predict that A = 81 – 95 neutron excess nickel systems form bound systems that have limiting beta decay half-lives in the range of 0.310 – 10.5 ms. Model half-life results for the A = 81 – 86 nickel 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 = 81 – 95 nickel nuclei.

Keywords: Nucleosynthesis, Neutron Excess Nickel Nuclei, Beta Decay, Nuclear Structure.

Introduction

Interest in neutron excess nuclei 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 [1-30].

This paper continues the investigation of neutron excess nuclei by focusing on the Z = 28 nickel systems. Neutron excess systems having Z = 28, and 30 were discussed in previous work [8-25, 29, 30]. 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. [8-30]. This paper follows the single particle methodology of Lukasiak and Sobiczewski and Petrovich et al. [27, 28]. Single particle energies of neutron excess nuclear systems are obtained by incorporating the numerical methods of Refs [31, 32].

The radial Schrödinger equation is utilized to determine binding energy of a nucleon interacting with a nuclear core [8-25, 29, 30].

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

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).

Nuclear Interaction

The Rost interaction is selected for the nuclear interaction [33]. This interaction has a central strength

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

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 [33]:

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

Inclusion of the pairing correction interaction of Blomqvist and

Wahlborn completes the definition of the model interaction [34].

The difficulties in defining an appropriate nuclear interaction are outlined in Refs. 35 and 36. Ray and Hodgson and Schwierz, Wiedenhöver, and Volya note that modifications, unique to each nuclear system, are required to ensure an accurate representation of the experimental energy levels and decay characteristics [35, 36]. In view of the conclusions of Refs. 35 and 36 and the results of previous excess neutron system calculations the Rost central interaction strength (V_A) is modified in the following manner [8-25, 29, 30].

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

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 nickel 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, 30] that provided model results in agreement with available data [37-39].

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 [8-25, 29, 30, 40]. 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.

Results and Discussion

Table 1 summarizes the complete set of 95 ≥ A ≥ 69 nickel isotopes considered in this paper. The 95 ≥ A ≥ 69 nickel nuclei occupy the $1g_{9/2}$ (^{69}Ni – ^{78}Ni), $2d_{5/2}$ (^{79}Ni – ^{84}Ni), $1g_{7/2}$ (^{85}Ni – ^{92}Ni), $3s_{1/2}$ (^{93}Ni – ^{94}Ni), and $2d_{3/2}$ (^{95}Ni) neutron single-particle levels. The heaviest observed nickel system is ^{80}Ni [37-39]. In view of the paucity of experimental data, extrapolations of nuclear characteristics beyond A > 80 become more uncertain.

80 ≥ A ≥ 69 Nickel Isotopes with Experimental Half-Life Data

The limiting decay mode (i.e., the transition that has the shortest decay half-life) for 69 ≥ A ≥ 80 nickel isotopes observed experimentally is summarized in Table 1. For example, the ^{73}Ni calculations include seven beta decay transitions (i.e., allowed $1f_{7/2}$(n) to $1f_{5/2}$(p) [5.57 min], allowed $1f_{5/2}$(n) to $1f_{5/2}$(p) [2.58 s], allowed $2p_{3/2}$(n) to $2p_{3/2}$(p) [2.13 s], allowed $2p_{3/2}$(n) to $2p_{1/2}$(p) [9.32 s], allowed $2p_{1/2}$(n) to $2p_{3/2}$(p) [839 ms], allowed $2p_{1/2}$(n) to $2p_{1/2}$(p) [2.54 s], and first forbidden $1f_{5/2}$(n) to $1g_{9/2}$(p) [5.08 d]). For ^{73}Ni, the allowed $2p_{1/2}$(n) to $2p_{3/2}$(p) [839 ms] transition is the limiting beta decay mode.

Table 1: Calculated Single-Particle and Experimental Decay Properties of Nickel Nuclei with 69 ≤ A ≤ 95

Nuclide	a(A)	Half-Life (Decay Mode)	
		Experiment [a,b,c]/Theory[d]	This Work
^{69}Ni	-0.0350	11.4 s[c]	11.4 s (β^-)[e]
^{70}Ni	-0.0371	6.0 s[c]	6.02 s (β^-)[e]
^{71}Ni	-0.0350	2.56 s[c]	2.56 s (β^-)[e]
^{72}Ni	-0.0360	1.57 s[c]	1.57 s (β^-)[e]
^{73}Ni	-0.0333	840 ms[c]	839 ms (β^-)[e]
^{74}Ni	-0.0310	507.7 ms[c]	507 ms (β^-)[e]
^{75}Ni	-0.0294	331.6 ms[c]	331 ms (β^-)[e]
^{76}Ni	-0.0285	234.6 ms[c]	234 ms (β^-)[e]
^{77}Ni	-0.0254	158.9 ms[c]	159 ms (β^-)[e]
^{78}Ni	-0.0249	122 ms[c]	122 ms (β^-)[e]
^{79}Ni	+0.0047	43.0 ms[c]	43.0 ms (β^-)[e]
^{80}Ni	+0.0232	23.9 ms[c]	23.9 ms (β^-)[e]
^{81}Ni	+0.0417	12.3 ms[d]	10.5 ms (β^-)[e]
^{82}Ni	+0.0602	8.74 ms[d]	9.17 ms (β^-)[e]
^{83}Ni	+0.0787	7.57 ms[d]	6.12 ms (β^-)[e]
^{84}Ni	+0.0972	5.56 ms[d]	4.25 ms (β^-)[e]
^{85}Ni	+0.1157	4.74 ms[d]	3.06 ms (β^-)[e]
^{86}Ni	+0.1342	3.45 ms[d]	2.26ms (β^-)[e]
^{87}Ni	+0.1527	f	1.70 ms (β^-)[e]
^{88}Ni	+0.1712	f	1.31 ms (β^-)[e]
^{89}Ni	+0.1897	f	1.03 ms (β^-)[e]
^{90}Ni	+0.2082	f	0.817 ms (β^-)[e]

^{91}Ni	+0.2267	f	0.659 ms (β^-)[e]
^{92}Ni	+0.2452	f	0.538 ms (β^-)[e]
^{93}Ni	+0.2637	f	0.444 ms (β^-)[e]
^{94}Ni	+0.2822	f	0.369 ms (β^-)[e]
^{95}Ni	+0.3007	f	0.310 ms (β^-)[e]

[a]Ref. 37. [b]Ref. 38. [c]Ref. 39.
[d]Japanese data Compilation calculation (Ref. 39).
[e]Allowed $2p_{1/2}$(n) to $2p_{3/2}$(p) beta decay transition.
[f]No data provided in Ref. 37 - 39.

The model predicts the proper decay mode for the known 80 ≥ A ≥ 69 nickel systems [37 – 39]. As noted in Table 1, the model half-lives are also consistent with data [37 – 39].

^{69}Ni – ^{78}Ni 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 ^{69}Ni – ^{78}Ni are within 0.4% of the experimental values [39]. In addition beta decay is the predicted decay mode in agreement with Ref. 39.

The ^{79}Ni – ^{80}Ni 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. Only ^{79}Ni and ^{80}Ni have measured half-lives. The half-life values of the ^{79}Ni – ^{80}Ni systems agree with the data [39]. Model calculations also predict the correct decay mode of these $2d_{5/2}$ nickel nuclei.

95 ≥ A ≥ 81 Nickel Isotopes without Experimental Half-Life Data

The a(A) values for 81 ≥ A ≥ 95 nickel isotopes were obtained from a linear fit based on the half-lives of ^{79}Ni – ^{80}Ni. The resulting a(A) values are listed in Table 1.

^{81}Ni – ^{84}Ni complete the $2d_{5/2}$ neutron shell, and decay through allowed $2p_{1/2}$(n) to $2p_{3/2}$(p) beta decay transitions. These nickel systems have beta decay half-lives between 4.25 and 10.5 ms. Single-particle calculations are within about 25% of the Japanese Data Compilation calculations [39].

^{85}Ni – ^{92}Ni nuclei fill the 1g7/2 neutron shell, and have beta decay half-lives in the range of 0.538 to 3.06 ms. These systems decay through allowed $2p_{1/2}$(n) to $2p_{3/2}$(p) beta decay transitions. The model results for ^{85}Ni and ^{86}Ni are within about 35% of the Japanese Data Compilation calculations [39]. ^{86}Ni is the last nickel system included in the Japanese Data Compilation calculations [39].

^{93}Ni and ^{94}Ni fill the $3s_{1/2}$ neutron shell, and these systems decay through allowed $2p_{1/2}$(n) to $2p_{3/2}$(p) beta decay transitions. The half-lives of ^{93}Ni and ^{94}Ni are 0.444 and 0.369 ms, respectively. The $2d_{3/2}$ neutron shell is partially filled by the ^{95}Ni system. This system decays through an allowed $2p_{1/2}$(n) to $2p_{3/2}$(p) beta decay transition, and has a half-life of 0.310 ms.

No nickel systems with A > 95 are predicted by either the model or the Japanese Data Compilation calculations [39]. This model limitation occurs because only 67 neutrons are bound in nickel system.

Conclusions

Within to are the scope of the proposed single particle model, neutron excess nickel isotopes terminate with ^{95}Ni. The model predicts that the 81 ≤ A ≤ 95 nickel systems have beta decay half-lives in the range of 0.310 – 10.5 ms. These neutron excess nickel systems decay through allowed $2p_{1/2}$(n) to $2p_{3/2}$(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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