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RESEARCH ARTICLE

Decay Characteristics of Neutron Excess Chromium Nuclei

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Abstract

A single-particle model is employed to calculate the properties of neutron excess chromium nuclei. The model predicts that A = 57 – 78 neutron excess chromium systems are bound and have half-lives in the range of 0.287 – 7.27 ms. The Japanese Nuclear Data Compilation predicts half-life values that are about a factor of four larger than the model proposed in this paper. Alpha, beta, positron, electron capture, and spontaneous fission decay modes are included in the model. However, neutron emission decay modes that have short half-lives are not evaluated. These short-lived neutron emission modes suggest that the model results could overestimate the half-lives of neutron excess chromium nuclei.

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1. Introduction

The construction of facilities and advances in experimental and theoretical physics has intensified interest in neutron excess nuclei[1][2][3][4][5][6][7][8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25][26][27]. A number of physical processes can produce neutron excess systems, but r-process nucleosynthesis often dominates. Investigation of neutron excess nuclei is important from a nuclear physics as well as astrophysics perspective. The production of these systems in neutron star and black hole mergers[1][2] is a topic of active research interest.

Neutron excess chromium systems are investigated in this paper. This paper continues previous publications that addressed neutron excess systems having Z = 9 - 23, 26, and 30[8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24]. The systematics of these studies provides additional insight into the various nucleosynthesis mechanisms, and how these production modes vary with atomic and mass numbers.

2. Calculational Methodology

Refs[8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24] outline the method for investigating neutron excess nuclei. The model utilizes the single particle approach, and incorporates the methodology of Lukasiak and Sobiczewski[26] and Petrovich et. al.[27]. The numerical methods of Refs[28] and[29] are utilized to determine the single particle energies of neutron excess nuclear systems.

The binding energy E_{NLSJ} of a nucleon in the field of a nuclear core is derived from the solution of the radial Schrödinger equation[8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24]

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

In Eq. 1, r is the radial coordinate, $V_{LSJ}(r)$ is the model interaction, and $U_{NLSJ}(r)$ is the radial wave function. The quantum numbers L, S, and J represent the orbital, spin, and total angular momentum, respectively. The radial quantum number (N) and the reduced mass (μ) complete the specification of the calculational model.

3. Nuclear Interaction

The Rost interaction[30] forms the basis for the nuclear potential that 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 applies to protons (neutrons). The spin-orbit interaction strength (V_{so}) is defined by the parameter γ[30]:

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

The model interaction is completed with the inclusion of the pairing correction interaction of Blomqvist and Wahlborn[31].

Refs.[32] and[33] note the difficulties in defining an appropriate interaction, and demonstrate that modifications are required to ensure that an accurate fit to the experimental energy levels and decay characteristics. Following the methodology from Refs.[32] and[33], the Rost central interaction strength (V_A) is modified in the following manner

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

In Eq. 4, a potential strength multiplier (λ) and a factor [a(A)] adjust the potential strength as a function of A. For chromium, λ = 1.5 is selected for consistency with previous calculations[8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24]. This value was selected to ensure agreement with available data[34][35][36].

4. Model Limitations

Based upon previous calculations[8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][26][27][37] alpha decay, beta decay, positron decay, electron capture, and spontaneous fission are represented reasonably well by calculations summarized in Sections 2 and 3. Although suitable for the aforementioned decay modes, single-particle models are not the best approach to calculate neutron emission half-lives. These neutron emission decay modes are generally shorter than the previously noted decay modes. Accordingly, omission of neutron emission decay modes leads to results that tend to overestimate the calculated decay half-lives.

5. Results and Discussion

Table 1 summarizes the complete set of 78 ≥ A ≥ 57 chromium isotopes considered in this paper. The 78 ≥ A ≥ 57 chromium isotopes occupy the $1f_{5/2}$ (^{57}Cr – ^{62}Cr), $2p_{1/2}$ (^{63}Cr – ^{64}Cr), $1g_{9/2}$ (^{65}Cr – ^{74}Cr), and $2d_{5/2}$ (^{75}Cr – ^{78}Cr) neutron single-particle levels. Based on data summarized in Refs.[34][35][36], the heaviest observed system is ^{66}Cr. Extrapolations beyond A > 66 become more uncertain, because data is not available to guide the calculations.

5.1. 57 ≥ A ≥ 66 Chromium Isotopes with Experimental Half-Life Data

Table 1 includes the half-life of the limiting decay mode (i.e., the transition that has the shortest decay half-life). For example, the ^{59}Cr model indicated five beta decay transitions (i.e., allowed $1f_{7/2}$(n) to $1f_{7/2}$(p) [8.05 s], allowed $2p_{3/2}$(n) to $2p_{3/2}$(p) [18.8 s], allowed $2p_{3/2}$(n) to $2p_{1/2}$(p) [8.27 min], allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) [460 ms], and allowed $1f_{5/2}$(n) to $1f_{5/2}$(p) [18.5 s]). For ^{59}Cr, the allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) [460 ms] transition is the limiting beta decay mode.

Table 1. Calculated Single-Particle and Experimental Decay Properties of Chromium Nuclei with 57 ≤ A ≤ 78

Nuclide	a(A)	Half-Life (Decay Mode)	
		Experiment [a,b,c]	This Work
^{57}Cr	-0.0587	21.1 s[c]	21.3 s (β^-)[d]
^{58}Cr	-0.0582	7.0 s[c]	6.96 s (β^-)[d]
^{59}Cr	-0.0240	460 ms[c]	460 ms (β^-)[d]
^{60}Cr	-0.0356	490 ms[c]	490 ms (β^-)[d]
^{61}Cr	-0.0276	237 ms[c]	238 ms (β^-)[d]
^{62}Cr	-0.0334	206 ms[c]	206 ms (β^-)[d]
^{63}Cr	-0.0246	113 ms[c]	113 ms (β^-)[d]
^{64}Cr	+0.0018	43 ms[c]	43.0 ms (β^-)[d]
^{65}Cr	+0.0131	27 ms[c]	27.0 ms (β^-)[d]
^{66}Cr	+0.0570	10 ms[c]	10.0 ms (β^-)[d]
^{67}Cr	+0.0683	[e,f]	7.27 ms (β^-)[d]
^{68}Cr	+0.0902	[f,g]	4.68 ms (β^-)[d]
^{69}Cr	+0.1120	[e,h]	3.15 ms (β^-)[d]
^{70}Cr	+0.1339	[e,i]	2.21 ms (β^-)[d]
^{71}Cr	+0.1557	[e,j]	1.60 ms (β^-)[d]
^{72}Cr	+0.1776	[e,k]	1.18 ms (β^-)[d]
^{73}Cr	+0.1994	[e,l]	0.895 ms (β^-)[d]
^{74}Cr	+0.2213	[e,m]	0.692 ms (β^-)[d]
^{75}Cr	+0.2431	[e]	0.545 ms (β^-)[d]
^{76}Cr	+0.2650	[e]	0.434 ms (β^-)[d]
^{77}Cr	+0.2868	[e]	0.352 ms (β^-)[d]
^{78}Cr	+0.3087	[e]	0.287 ms (β^-)[d]

[a] *Ref.* [34].

[b] *Ref.* [35].

[c] *Ref.* [36].

[d] *Allowed* $1f_{5/2}(n)$ *to* $1f_{7/2}(p)$ *beta decay transition.*

[e] *No data provided in Refs.*[34][35][36].

[f] *The Japanese data compilation*[36] *notes a calculated value of 31.1 ms for* ^{67}*Cr.*

[g] *The Japanese data compilation*[36] *notes a calculated value of 17.2 ms for* ^{68}*Cr*

[h] *The Japanese data compilalion*[36] *notes a calculated value of 11.6 ms for* ^{69}*Cr.*

[i] *The Japanese data compilalion*[36] *notes a calculated value of 7.14 ms for* ^{70}*Cr.*

[j] *The Japanese data compilation*[36] *notes a calculated value of 6.07 ms for* ^{71}*Cr.*

[k] *The Japanese data compilation*[36] *notes a calculated value of 4.12 ms for ^{72}Cr.*

[l] *The Japanese data compilation*[36] *notes a calculated value of 3.80 ms for ^{73}Cr.*

[m] *The Japanese data compilation*[36] *notes a calculated value of 2.80 ms for ^{74}Cr.*

As noted in Table 1, the model predicts the proper decay mode for the known 78 ≥ A ≥ 57 chromium systems[34][35][36]. The model half-lives are also consistent with data[34][35][36].

The ^{57}Cr – ^{62}Cr systems occupy the $1f_{5/2}$ neutron shell, and decay via beta emission through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) transitions. Model predictions for the half-lives of ^{57}Cr – ^{62}Cr are within about 1% of the experimental half-lives[36]. The calculated beta decay modes for ^{57}Cr – ^{62}Cr are in agreement with Ref.[36].

The ^{63}Cr – ^{64}Cr nuclei fill the $2p_{1/2}$ neutron shell. These systems also decay via beta emission through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) transitions. The ^{63}Cr – ^{64}Cr half-lives predicted by the model are in agreement with the experimental half-lives[36]. The model's decay modes for ^{63}Cr – ^{64}Cr are consistent with Ref.[36].

^{65}Cr and ^{66}Cr partially fill the $1g_{9/2}$ neutron shell. The decay mode and half-life for these chromium systems are consistent with the data[36]. These $1g_{9/2}$ systems decay via beta emission through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) transitions.

5.2. 78 ≥ A ≥ 67 Chromium Isotopes without Experimental Half-Life Data

The a(A) values for 67 ≥ A ≥ 78 chromium isotopes were derived from a linear fit based on the half-lives of ^{62}Cr – ^{66}Cr. These extrapolated a(A) values are provided in Table 1.

The ^{67}Cr – ^{74}Cr systems complete filling the $1g_{9/2}$ neutron shell, and have beta decay half-lives between 0.692 – 7.27 ms. These chromium systems decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta decay transitions. The calculations summarized in the Japanese Data Compilation[36] for ^{67}Cr – ^{74}Cr are about a factor of 4 larger than the model results.

The ^{75}Cr – ^{78}Cr nuclei partially fill the $2d_{5/2}$ neutron shell and decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta decay transitions. The ^{75}Cr – ^{78}Cr half-lives decrease from 0.545 to 0.287 ms, respectively. None of these $2d_{5/2}$ systems are predicted to exist in Japanese Data Compilation calculations[36].

No chromium systems with A > 78 are predicted by either the model or the Japanese Data Compilation calculations[36]. This model limitation occurs because only 54 neutrons are bound in chromium system.

6. Conclusions

Neutron excess chromium isotopes terminate with ^{78}Cr. The 67 ≤ A ≤78 chromium systems have predicted beta decay half-lives in the range of 0.287 – 7.27 ms. These neutron excess chromium systems decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta decay transitions. Since the model does not include neutron emission decay modes, it likely overestimates the actual half-life values.

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