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Decay Characteristics of Neutron Excess Strontium Nuclei

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Abstract

The properties of neutron excess strontium 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 $A = 121 - 123$. The Japanese Nuclear Data Compilation terminate their calculations at $A = 111$. Given

these results, strontium single particle model calculations are extended to encompass these values, and were extended to $A = 120$ with closure of the $1h_{11/2}$ neutron shell.

Single particle model calculations predict that $A = 95 - 120$ strontium nuclei form bound systems that have limiting beta decay half-lives in the range of 0.275 ms – 23.9 s. Model half-life results for the $A = 108 - 111$ neutron excess strontium nuclei are within a factor of about 2.6 of the predictions of the Japanese Nuclear Data Compilation calculations.

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

1. Introduction

Interest in neutron excess nuclei ^[1-39] has stimulated both experimental and theoretical 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 $Z = 38$ strontium systems. Neutron excess systems having $Z = 9 - 37$ were discussed in previous work ^[8-25, 29-39]. 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. 8-39. 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. 40 and 41.

The radial Schrödinger equation is utilized to determine the binding energy of a nucleon interacting with a nuclear core ^[8-25, 29-39].

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

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 ^[42] is selected for the nuclear potential. 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 ^[42]:

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

Inclusion of the pairing correction interaction of Blomqvist and Wahlborn ^[43] completes the definition of the model interaction.

The difficulties in defining an appropriate nuclear interaction are outlined in Refs. 44 and 45. Ray and Hodgson ^[44] and Schwierz, Wiedenhöver, and Volya ^[45] 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. 44 and 45 and the results of previous excess neutron system calculations ^[8-25, 29-39], 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 strontium 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, 29-39] that provided model results in agreement with available data ^[46-48].

4. Model Limitations

Previous calculations ^[8-25, 29-39, 49] 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.* ^[50]. Using the approach of Ref. 50, the onset of spontaneous neutron emission was estimated to occur in the range of $A = 121 - 123$ for strontium systems. Although independent of the calculated neutron single particle levels presented herein, the approach of Chowdhury *et al.* yields a candidate value to terminate calculations for excess neutron strontium nuclei. The Japanese Nuclear Data Compilation terminate their calculations at $A = 111$. These results guide the A value selected to terminate the single particle model calculations for strontium.

5. Results and Discussion

Table 1 summarizes the complete set of $120 \geq A \geq 95$ strontium isotopes considered in this paper. The $120 \geq A \geq$

95 strontium nuclei occupy a variety of neutron shells that are noted in Table 1. The heaviest observed strontium system is ¹⁰⁷Sr ^[48]. In view of the paucity of experimental data, extrapolations of nuclear characteristics beyond $A > 107$ become more uncertain.

5.1 $95 \leq A \leq 107$ Strontium Isotopes with Experimental Half-Life Data

The limiting decay mode (i.e., the transition that has the shortest decay half-life) for $107 \geq A \geq 95$ strontium isotopes observed experimentally is summarized in Table 1. For example, the ⁹⁶Sr calculations predict six beta decay transitions (i.e., allowed $2d_{5/2}(n)$ to $2d_{5/2}(p)$ [1.86 h], allowed $1g_{7/2}(n)$ to $1g_{7/2}(p)$ [2.07 h], allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ [1.07 s], allowed $2p_{1/2}(n)$ to $2p_{1/2}(p)$ [11.9 min], allowed $1g_{9/2}(n)$ to $1g_{9/2}(p)$ [2.97 min], and first forbidden $2d_{5/2}(n)$ to $2p_{1/2}(p)$ [7.87 min]). For ⁹⁶Sr, the allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ [1.07 s] transition is the limiting beta decay mode.

Table 1: Calculated Single Particle and Experimental Decay Properties of Strontium Nuclei with $95 \leq A \leq 120$

Nuclide (neutron shell)	a(A)	Half-Life (Decay Mode)	
		Experiment ^{a,b,c/Theory^d}	This Work
⁹⁵ Sr (1g _{7/2})	-0.0731	23.90 s ^c	23.9 s (β ⁻) ^e
⁹⁶ Sr (1g _{7/2})	-0.0458	1.07 s ^c	1.07 s (β ⁻) ^e
⁹⁷ Sr (1g _{7/2})	-0.0354	429 s ^c	428 ms (β ⁻) ^e
⁹⁸ Sr (2d _{5/2})	-0.0495	653 ms ^c	654 ms (β ⁻) ^e
⁹⁹ Sr (2d _{5/2})	-0.0375	269 ms ^c	270 ms (β ⁻) ^e
¹⁰⁰ Sr (2d _{5/2})	-0.0365	201 ms ^c	201 ms (β ⁻) ^e
¹⁰¹ Sr (2d _{5/2})	0.0275	115 ms ^c	115 ms (β ⁻) ^e
¹⁰² Sr (2d _{5/2})	-0.0186	71 ms ^c	71.0 ms (β ⁻) ^e
¹⁰³ Sr (3s _{1/2})	-0.0228	68 ms ^c	68.1 ms (β ⁻) ^e
¹⁰⁴ Sr (3s _{1/2})	-0.0156	46.9 ms ^c	46.9 ms (β ⁻) ^e
¹⁰⁵ Sr (2d _{3/2})	-0.0252	53 ms ^c	52.9 ms (β ⁻) ^e
¹⁰⁶ Sr (2d _{3/2})	-0.0196	39 ms ^c	39.1 ms (β ⁻) ^e
¹⁰⁷ Sr (2d _{3/2})	0.0025	20 ms ^c	20.0 ms (β ⁻) ^e
¹⁰⁸ Sr (2d _{3/2})	0.0246	13.3 ms ^d	11.3 ms (β ⁻) ^e
¹⁰⁹ Sr (1h _{11/2})	0.0467	12.0 ms ^d	6.89 ms (β ⁻) ^e
¹¹⁰ Sr (1h _{11/2})	0.0688	8.78 ms ^d	4.45 ms (β ⁻) ^e
¹¹¹ Sr (1h _{11/2})	0.0909	7.82 ms ^d	3.00 ms (β ⁻) ^e
¹¹² Sr (1h _{11/2})	0.1130	f	2.10 ms (β ⁻) ^e
¹¹³ Sr (1h _{11/2})	0.1351	f	1.52 ms (β ⁻) ^e
¹¹⁴ Sr (1h _{11/2})	0.1572	f	1.13 ms (β ⁻) ^e
¹¹⁵ Sr (1h _{11/2})	0.1793	f	0.856 ms (β ⁻) ^e
¹¹⁶ Sr (1h _{11/2})	0.2014	f	0.662 ms (β ⁻) ^e
¹¹⁷ Sr (1h _{11/2})	0.2235	f	0.521 ms (β ⁻) ^e
¹¹⁸ Sr (1h _{11/2})	0.2456	f	0.415 ms (β ⁻) ^e
¹¹⁹ Sr (1h _{11/2})	0.2677	f	0.336 ms (β ⁻) ^e
¹²⁰ Sr (1h _{11/2})	0.2898	f	0.275 ms (β ⁻) ^e

^aRef. 46. ^bRef. 47. ^cRef. 48.

^dJapanese data Compilation calculation.

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

^fNo data provided in Ref. 46 – 48.

The model predicts the correct decay mode for the known $107 \geq A \geq 95$ strontium systems [46 – 48]. As noted in Table 1, the model half-lives are also consistent with data [46 – 48].

The ⁹⁵Sr – ⁹⁷Sr systems occupy the $1g_{7/2}$ neutron shell. These systems decay through allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta transitions. The half-life values of the ⁹⁵Sr – ⁹⁷Sr systems are within 0.25% of the data ^[48]. Model calculations also predict the correct decay mode for these $1g_{7/2}$ strontium nuclei.

⁹⁸Sr – ¹⁰²Sr nuclei occupy the $2d_{5/2}$ neutron shell. These systems decay through allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta

transitions. Model predictions for the beta decay half-lives of ^{98}Sr - ^{102}Sr are within about 0.4% of the experimental values [48]. In addition beta decay is the predicted decay mode in agreement with Ref. 48.

^{103}Sr and ^{104}Sr nuclei occupy the $3s_{1/2}$ neutron shell. These systems decay through allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta transitions. Model predictions for the beta decay half-lives of ^{103}Sr and ^{104}Sr are within 0.2% of the experimental values [48]. In addition beta decay is the predicted decay mode in agreement with Ref. 48.

^{105}Sr - ^{107}Sr nuclei occupy the $2d_{3/2}$ neutron shell. These systems decay through allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta transitions. Model predictions for the beta decay half-lives of ^{105}Sr - ^{107}Sr are within about 0.3% of the experimental values [48]. In addition beta decay is the predicted decay mode in agreement with Ref. 48.

5.2 $120 \geq A \geq 108$ Strontium Isotopes without Experimental Half-Life Data

The $a(A)$ values for $108 \geq A \geq 120$ strontium isotopes were obtained from a linear fit based on the half-lives of ^{106}Sr and ^{107}Sr . The resulting $a(A)$ values are listed in Table 1.

^{108}Sr completes the $2d_{3/2}$ neutron shell, and this system decays through an allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta transition. The half-life of ^{108}Sr is 11.3 ms. This system half-life is within a factor of about 1.2 of the Japanese Data Compilation calculations [48].

^{109}Sr - ^{120}Sr fills the $1h_{11/2}$ neutron shell, and these systems decay through allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta transitions. The half-lives of ^{109}Sr - ^{120}Sr are in the range of 0.275 – 6.89 ms. These half-lives are within a factor of about 2.6 of the Japanese Data Compilation calculation [48].

The strontium calculations are terminated at $A = 120$ to account for the spontaneous neutron emission as the mass increases. Using the methodology of Chowdhury *et al.* [50], spontaneous emission is expected to occur at $A = 121 - 123$. The Japanese Data Compilation calculations [48] suggest that $A = 111$ terminates the strontium systems. Model calculations were extended to $A = 120$ to account for uncertainties in estimates of Refs. 48 and 50, and were terminated with filling of the $1h_{11/2}$ neutron shell.

6. Conclusions

Single particle model calculations 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 of the neutron decay mode were evaluated using the methodology of Chowdhury *et al.* Using that model, spontaneous neutron emission in strontium nuclei is predicted to occur in the range of $A = 121 - 123$. The Japanese Nuclear Data Compilation calculations terminate their strontium calculations at $A = 111$. Given these results, single particle model calculations are extended to encompass these values, and were terminated at $A = 120$ with filling of the $1h_{11/2}$ neutron shell.

Single particle model calculations predict that $A = 108 - 120$ neutron excess strontium systems form bound nuclei that have limiting beta decay half-lives in the range of 11.3 – 0.275 ms. Model half-life results for the $A = 108 - 111$ strontium nuclei are within about a factor of about 2.6 of the predictions of the Japanese Nuclear Data Compilation calculations.

The $A = 108 - 120$ neutron excess strontium systems decay through an allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta decay transition. The model likely overestimates the actual half-life values, because it does not explicitly include the short-lived neutron emission decay modes.

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