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Decay Characteristics of Neutron Excess Bromine Nuclei

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Abstract

The properties of neutron excess bromine 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 = 111 – 113. The Japanese Nuclear Data Compilation terminate their calculations at A = 104. Given these results, single particle model calculations are extended to encompass these values, and were extended to A = 104 with closure of the $2d_{3/2}$ neutron shell.

Single particle model calculations predict that A = 92 – 105 neutron excess bromine systems form bound systems that have limiting beta decay half-lives in the range of 1.44 – 40.2 ms. Model half-life results for the A = 95 – 104 bromine nuclei are within a factor of about 2.6 of the predictions of the Japanese Nuclear Data Compilation calculations.

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

1. Introduction

Interest in neutron excess nuclei [1-36] 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 = 35 bromine systems. Neutron excess systems having Z = 9 - 34 were discussed in previous work [8-25, 29-36]. 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. 8-36. 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. 37 and 38.

The radial Schrödinger equation is utilized to determine the binding energy of a nucleon interacting with a nuclear core [8-25, 29-36]:

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

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).

3. Nuclear Interaction

The Rost interaction [39] is selected for the nuclear potential. This interaction has a central strength:

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

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 [39]:

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

Inclusion of the pairing correction interaction of Blomqvist and Wahlborn [40] completes the definition of the model interaction.

The difficulties in defining an appropriate nuclear interaction are outlined in Refs. 40 and 41. Ray and Hodgson [41] and Schwierz, Wiedenhöver, and Volya [42] 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. 41 and 42 and the results of previous excess neutron system calculations [8-25, 29-36], the Rost central interaction strength (V_A) is modified in the following manner:

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

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 bromine 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, 29-36] that provided model results in agreement with available data [43-45].

4. Model Limitations

Previous calculations [8-25, 29-36, 46] 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.* [47]. Using the approach of Ref. 47, the onset of spontaneous neutron emission was estimated to occur in the range of A = 111 - 113 for bromine 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 bromine nuclei. The Japanese Nuclear Data Compilation terminate their calculations at A = 104. These results guide the A value selected to terminate the single particle model calculations for bromine.

5. Results and Discussion

Table 1 summarizes the complete set of 105 ≥ A ≥ 86 bromine isotopes considered in this paper. The 105 ≥ A ≥ 86 bromine nuclei occupy a variety of neutron shells that are noted in Table 1. The heaviest observed bromine system is ^{94}Br [45]. In view of the paucity of experimental data, extrapolations of nuclear characteristics beyond A > 94 become more uncertain.

5.1 86 ≥ A ≥ 94 Bromine Isotopes with Experimental Half-Life Data

The limiting decay mode (i.e., the transition that has the shortest decay half-life) for 94 ≥ A ≥ 86 bromine isotopes observed experimentally is summarized in Table 1. For example, the ^{87}Br calculations predict seven beta decay transitions (i.e., allowed $2d_{5/2}$(n) to $2d_{5/2}$(p) [40.0 d], allowed $2p_{3/2}$(n) to $2p_{3/2}$(p) [42.8 min], allowed $2p_{1/2}$(n) to $2p_{3/2}$(p) [53.3 s], allowed $2p_{1/2}$(n) to $2p_{1/2}$(p) [1.59 h], allowed $1g_{9/2}$(n) to $1g_{9/2}$(p) [22.7 min], first forbidden $2d_{5/2}$(n) to $2p_{3/2}$(p) [4.73 min]), and first forbidden $2d_{5/2}$(n) to $2p_{1/2}$(p) [9.96 min]). For ^{87}Br, the allowed $2p_{1/2}$(n) to $2p_{3/2}$(p) [53.3 s] transition is the limiting beta decay mode.

Table 1: Calculated Single Particle and Experimental Decay Properties of Bromine Nuclei with 86 ≤ A ≤ 105

Nuclide (neutron shell)	**a(A)**	**Half-Life (Decay Mode)**	
		Experiment ^{a,b,c}/Theory^{d}	**This Work**
^{86}Br ($2d_{5/2}$)	-0.0366	55.1 s^{c}	54.8 s (β^-)^{e}
^{87}Br ($2d_{5/2}$)	-0.0440	55.65 s^{c}	55.3 s (β^-)^{e}
^{88}Se ($2d_{5/2}$)	-0.0426	16.34 s^{c}	16.4 s (β^-)^{e}
^{89}Br ($2d_{5/2}$)	-0.0371	4.357 s^{c}	4.37 ms (β^-)^{e}
^{90}Br ($2d_{5/2}$)	-0.0335	1.92 s^{c}	1.92 ms (β^-)^{e}
^{91}Br ($2d_{5/2}$)	-0.0195	543 ms^{c}	544 ms (β^-)^{e}
^{92}Br ($1g_{7/2}$)	-0.0487	314 ms^{c}	314 ms (β^-)^{f}
^{93}Br ($1g_{7/2}$)	-0.0367	152 ms^{c}	152 ms (β^-)^{f}
^{94}Br ($1g_{7/2}$)	-0.0194	70 ms^{c}	69.9 ms (β^-)^{f}
^{95}Br ($1g_{7/2}$)	-0.0056	63.5 ms^{d}	40.2 ms (β^-)^{f}
^{96}Br ($1g_{7/2}$)	0.0090	49.3 ms^{d}	24.4 ms (β^-)^{f}
^{97}Br ($1g_{7/2}$)	0.0237	32.3 ms^{d}	15.7 ms (β)^{f}
^{98}Br ($1g_{7/2}$)	0.0383	23.6 ms^{d}	10.6 ms (β)^{f}
^{99}Br ($1g_{7/2}$)	0.0530	15.1 ms^{d}	7.37 ms (β)^{f}
^{100}Br ($3s_{1/2}$)	0.0676	11.6 ms^{d}	5.32 ms (β)^{f}
^{101}Br ($3s_{1/2}$)	0.0823	8.17 ms^{d}	3.94 ms (β)^{f}
^{102}Br ($2d_{3/2}$)	0.0969	6.98 ms^{d}	2.98 ms (β)^{f}
^{103}Br ($2d_{3/2}$)	0.1116	5.32 ms^{d}	2.31 ms (β)^{f}
^{104}Br ($2d_{3/2}$)	0.1262	4.77 ms^{d}	1.82 ms (β)^{f}
^{105}Br ($2d_{3/2}$)	0.1409	^{g}	1.44 ms (β)^{f}

[a] Ref. 43. [b] Ref. 44. [c] Ref. 45.
[d] Japanese data Compilation calculation.
[e] Allowed $2p_{1/2}$(n) to $2p_{3/2}$(p) beta decay transition.
[f] Allowed $1g_{7/2}$(n) to $1g_{9/2}$(p) beta decay transition.
[g] No data provided in Ref. 43 - 45.

The model predicts the correct decay mode for the known 94 ≥ A ≥ 86 bromine systems [43-45]. As noted in Table 1, the model half-lives are also consistent with data [43-45].

^{86}Br – ^{91}Br nuclei occupy the $2d_{5/2}$ 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 ^{86}Br – ^{91}Br are within about 0.7% of the experimental values [45]. In addition beta decay is the predicted decay mode in agreement with Ref. 45.

The ^{94}Br – ^{94}Br systems partially fill 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 ^{94}Br – ^{94}Br systems are within 0.2% of the data [45]. Model calculations also predict the correct decay mode for these $1g_{7/2}$ bromine nuclei.

5.2 105 ≥ A ≥ 95 Bromine Isotopes without Experimental Half-Life Data

The a(A) values for 105 ≥ A ≥ 95 bromine isotopes were obtained from a linear fit based on the half-lives of ^{92}Br - ^{94}Br. The resulting a(A) values are listed in Table 1.

^{95}Br - ^{99}Br complete the $1g_{7/2}$ neutron shell, and decay through allowed $1g_{7/2}$(n) to $1g_{9/2}$(p) beta decay transitions. The ^{95}Br - ^{99}Br systems have beta decay half-lives in the range of 7.37 – 40.2 ms. These values are within a factor of about 2.2 of the Japanese Data Compilation calculations [45].

^{100}Br – ^{101}Br nuclei fill the $3s_{1/2}$ neutron shell, and have calculated beta decay half-lives in the range of 3.94 to 5.32 ms. These systems decay through allowed $1g_{7/2}$(n) to $1g_{9/2}$(p) beta transitions. The model half-life results for ^{100}Br – ^{101}Br are within a factor of 2.2 of the Japanese Data Compilation calculations [45].

^{102}Br - ^{105}Br fill the $2d_{3/2}$ neutron shell, and these systems decay through allowed $1g_{7/2}$(n) to $1g_{9/2}$(p) beta transitions. The half-lives of ^{102}Br - ^{105}Br are in the range of 1.44 – 2.98 ms. These system half-lives are within a factor of about 2.6 of the Japanese Data Compilation calculations [45].

The bromine calculations are terminated at A = 105 to account for the spontaneous neutron emission as the mass increases. Using the methodology of Chowdhury *et al.* [47], spontaneous emission is expected to occur at A = 111 – 113. The Japanese Data Compilation calculations [45] suggest that A = 104 terminates the bromine systems. Model calculations were extended to A = 105 to account for uncertainties in estimates of Refs. 45 and 47, and were terminated with filling the $2d_{3/2}$ 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 bromine nuclei is predicted to occur in the range of A = 111 – 113. The Japanese Nuclear Data Compilation calculations terminate their bromine calculations at A =104. Given these results, single particle model calculations are extended to encompass these values, and were terminated at A = 105 with filling of the $2d_{3/2}$ neutron shell.

Single particle model calculations predict that A = 95 – 105 neutron excess bromine systems form bound nuclei that have limiting beta decay half-lives in the range of 1.44 – 40.2 ms. Model half-life results for the A = 95 – 105 bromine nuclei are within about a factor of about 2.6 of the predictions of the Japanese Nuclear Data Compilation calculations.

The A = 95 – 105 neutron excess bromine 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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