Research Article

Decay Characteristics of Neutron-Excess Manganese Nuclei

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The properties of neutron excess manganese nuclei are determined utilizing a single-particle model. Single particle model calculations predict that A = 70 – 88 neutron excess manganese systems form bound systems that have limiting beta decay half-lives in the range of 0.318 – 11.8 ms. Model half-life results for the A = 70 – 77 manganese 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 = 70 – 88 manganese nuclei.

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1. Introduction

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][28] 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][2].

This paper continues the investigation of neutron excess nuclei by focusing on the Z = 25 manganese systems. Neutron excess systems having Z = 9 - 24, 26, and 30 were discussed in previous work[8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25]. 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][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25]. 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.[29] and[30].

The radial Schrödinger equation is utilized to determine binding energy of a nucleon interacting with a nuclear core[8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25]

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

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[31] is selected for the nuclear interaction. This interaction has a central strength

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

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[31]:

$$V_{so} = \gamma V_0/180 \tag{3}$$

Inclusion of the pairing correction interaction of Blomqvist and Wahlborn[32] completes the definition of the model interaction.

The difficulties in defining an appropriate nuclear interaction are outlined in Refs[33][34]. Ray and Hodgson[33] and Schwierz, Wiedenhöver, and Volya[34] 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[33][34] and the results of previous excess neutron

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system calculations[8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25], 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 manganese 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][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25] that provided model results in agreement with available data[35][36][37].

4. Model Limitations

Previous calculations[8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][27][28] 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.

5. Results and Discussion

Table 1 summarizes the complete set of $88 \geq A \geq 58$ manganese isotopes considered in this paper. The $88 \geq A \geq 58$ manganese nuclei occupy the $1f_{5/2}$ (^{58}Mn – ^{63}Mn), $2p_{1/2}$ (^{64}Mn – ^{65}Mn), $1g_{9/2}$ (^{66}Mn – ^{75}Mn), $2d_{5/2}$ (^{76}Mn – ^{81}Mn), $3s_{1/2}$ (^{82}Mn – ^{83}Mn), and $1g_{7/2}$ (^{84}Mn – ^{88}Mn) neutron single-particle levels. The heaviest observed manganese system is ^{69}Mn[35][36][37]. In view of the paucity of experimental data, extrapolations of nuclear characteristics beyond A > 69 become more uncertain.

5.1. 58 ≥ A ≥ 69 Manganese 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 $58 \geq A \geq 69$ manganese isotopes with experimental half-life data are summarized in Table 1. For example, the ^{61}Mn calculations include five beta decay transitions (i.e., allowed $1f_{7/2}$(n) to $1f_{7/2}$(p) [18.6 s], allowed $2p_{3/2}$(n) to $2p_{3/2}$(p) [51.8 s], allowed $2p_{3/2}$(n) to $2p_{1/2}$(p) [2.27 h], allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) [670 ms], and

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allowed $1f_{5/2}$(n) to $1f_{5/2}$(p) [50.3 s]). For ^{61}Mn, the allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) [670 ms] transition is the limiting beta decay mode.

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Nuclide	a(A)	Half-Life (Decay Mode)	
		Experiment[a,b,c]/Theory[d]	This Work
^{58}Mn	-0.0204	3.0 s[c]	3.01 s (β^-)[e]
^{59}Mn	-0.0368	4.59 s[c]	4.60 s (β^-)[e]
^{60}Mn	+0.0037	280 ms[c]	280 ms (β^-)[e]
^{61}Mn	+0.0263	670 ms[c]	670 ms (β^-)[e]
^{62}Mn	----	no ground state data	----
^{63}Mn	-0.0256	275 ms[c]	275 ms (β^-)[e]
^{64}Mn	-0.0019	90 ms[c]	90.1 ms (β^-)[e]
^{65}Mn	-0.0117	92 ms[c]	91.9 ms (β^-)[e]
^{66}Mn	-0.0084	65 ms[c]	65.0 ms (β^-)[e]
^{67}Mn	-0.0001	42 ms[c]	42.0 ms (β^-)[e]
^{68}Mn	+0.0091	28 ms[c]	28.0 ms (β^-)[e]
^{69}Mn	+0.0277	16 ms[c]	16.0 ms (β^-)[e]
^{70}Mn	+0.0364	24.2 ms[d]	11.8 ms (β^-)[e]
^{71}Mn	+0.0482	13.2 ms[d]	8.47 ms (β^-)[e]
^{72}Mn	+0.0599	9.04 ms[d]	6.25 ms (β^-)[e]
^{73}Mn	+0.0717	5.94 ms[d]	4.69 ms (β^-)[e]
^{74}Mn	+0.0835	5.39 ms[d]	3.61 ms (β^-)[e]
^{75}Mn	+0.0952	4.00 ms[d]	2.85 ms (β^-)[e]
^{76}Mn	+0.1069	2.19 ms[d]	2.26 ms (β^-)[e]
^{77}Mn	+0.1187	1.71 ms[d]	1.83 ms (β^-)[e]
^{78}Mn	+0.1304	[f]	1.49 ms (β^-)[e]
^{79}Mn	+0.1422	[f]	1.24 ms (β^-)[e]
^{80}Mn	+0.1539	[f]	1.03 ms (β^-)[e]

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Nuclide	a(A)	Half-Life (Decay Mode)	
		Experiment[a,b,c]/Theory[d]	This Work
^{81}Mn	+0.1657	f	0.869 ms (β^-)[e]
^{82}Mn	+0.1775	f	0.739 ms (β^-)[e]
^{83}Mn	+0.1892	f	0.632 ms (β^-)[e]
^{84}Mn	+0.2009	f	0.546 ms (β^-)[e]
^{85}Mn	+0.2127	f	0.472 ms (β^-)[e]
^{86}Mn	+0.2244	f	0.413ms (β^-)[e]
^{87}Mn	+0.2362	f	0.361ms (β^-)[e]
^{88}Mn	+0.2480	f	0.318ms (β^-)[e]

Table 1. Calculated Single-Particle and Experimental Decay Properties of Manganese Nuclei with $58 \leq A \leq 88$

[a] *Ref.* [36].

[b] *Ref.* [37].

[c] *Ref.* [38].

[d] *Japanese data compilation calculation.*

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

[f] *No data provided in Ref.* [36][37][38].

The model predicts the proper decay mode for the known $88 \geq A \geq 58$ manganese systems[35][36][37]. As noted in Table 1, the model half-lives are also consistent with data[35][36][37].

^{58}Mn – ^{63}Mn 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 ^{58}Mn – ^{63}Mn are within 0.5% of the experimental values[37]. In addition beta decay is the predicted decay mode in agreement with Ref. [37].

The ^{64}Mn – ^{65}Mn 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 ^{64}Mn – ^{65}Mn systems are in within 0.2% of the data[37]. Model calculations also predict the correct decay mode of these $2p_{1/2}$ manganese nuclei.

^{66}Mn – ^{69}Mn partially occupy the $1g_{9/2}$ neutron shell. The decay mode and half-life for these manganese systems are consistent with the data[37]. These $1g_{9/2}$ manganese systems decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta transitions.

5.2. 88 ≥ A ≥ 70 Manganese Isotopes without Experimental Half-Life Data

The a(A) values for $88 \geq A \geq 70$ manganese isotopes were obtained from a linear fit based on the half-lives of ^{66}Mn – ^{69}Mn. The resulting a(A) values are listed in Table 1.

^{70}Mn – ^{75}Mn complete the $1g_{9/2}$ neutron shell, and decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta decay transitions. These manganese systems have beta decay half-lives between 2.85 and 11.8 ms. Single-particle calculations are about a factor of two smaller than those summarized in the Japanese Data Compilation[37].

^{76}Mn – ^{81}Mn nuclei fill the $2d_{5/2}$ neutron shell, and have beta decay half-lives in the range of 0.869 to 2.26 ms. These systems decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta decay transitions. The model results for ^{76}Mn and ^{77}Mn are within 10% of the Japanese Data Compilation calculations[37]. ^{77}Mn is the heaviest system predicted by the calculations in Ref.[37].

^{82}Mn and ^{83}Mn fill the $3s_{1/2}$ neutron shell, and these systems decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta decay transitions. The half-lives of ^{82}Mn and ^{83}Mn are 0.739 and 0.632 ms, respectively.

The $1g_{7/2}$ neutron shell is partially filled by the ^{84}Mn – ^{88}Mn systems. These systems decay through allowed $1f_{5/2}$(n) to $1f_{7/2}$(p) beta decay transitions, and have half-lives in the range 0.318 – 0.546 ms.

No manganese systems with A > 88 are predicted by either the model or the Japanese Data Compilation calculations[37]. This model limitation occurs because only 63 neutrons are bound in manganese system.

6. Conclusions

Within the scope of the proposed single particle model, neutron excess manganese isotopes terminate with ^{88}Mn. The model predicts that the $70 \leq A \leq 88$ manganese systems have beta decay half-lives in the range of 0.318 – 11.8 ms. These neutron excess manganese 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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Declarations

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