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Decay Characteristics of Neutron Excess Krypton Nuclei

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Abstract

The properties of neutron excess krypton 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 $A = 114 - 116$. The Japanese Nuclear Data

Compilation terminate their calculations at $A = 107$. Given these results, single particle model calculations are extended to encompass these values, and were extended to $A = 108$. Single particle model calculations predict that $A = 91 - 108$ krypton systems form bound systems that have limiting beta decay half-lives in the range of 5.53 ms – 8.59 s. Model half-life results for the $A = 101 - 108$ neutron excess krypton nuclei are within a factor of about 1.4 of the predictions of the Japanese Nuclear Data Compilation calculations.

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

1. Introduction

Interest in neutron excess nuclei ^[1-37] 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 $Z = 36$ krypton systems. Neutron excess systems having $Z = 9 - 35$ were discussed in previous work ^[8-25, 29-37]. 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. 8-37. 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. 38 and 39.

The radial Schrödinger equation is utilized to determine the binding energy of a nucleon interacting with a nuclear core ^[8-25, 29-37].

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

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 ^[40] 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 [40]:

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

Inclusion of the pairing correction interaction of Blomqvist and Wahlborn [41] completes the definition of the model interaction.

The difficulties in defining an appropriate nuclear interaction are outlined in Refs. 42 and 43. Ray and Hodgson [42] and Schwierz, Wiedenhöfer, and Volya [43] 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. 42 and 43 and the results of previous excess neutron system calculations [8-25, 29-37], 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 krypton 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, 29-37] that provided model results in agreement with available data [44-46].

4. Model Limitations

Previous calculations [8-25, 29-37, 47] 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.* [48]. Using the approach of Ref. 48, the onset of spontaneous neutron emission was estimated to occur in the range of $A = 114 - 116$ for krypton 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 krypton nuclei. The Japanese Nuclear Data Compilation terminate their calculations at $A = 107$. These results guide the A value selected to terminate the single particle model calculations for krypton.

5. Results and Discussion

Table 1 summarizes the complete set of $108 \geq A \geq 91$ krypton isotopes considered in this paper. The $108 \geq A \geq 91$

krypton nuclei occupy a variety of neutron shells that are noted in Table 1. The heaviest observed krypton system is ^{100}Kr [46]. In view of the paucity of experimental data, extrapolations of nuclear characteristics beyond $A > 100$ become more uncertain.

5.1 $91 \leq A \leq 100$ Krypton Isotopes with Experimental Half-Life Data

The limiting decay mode (i.e., the transition that has the shortest decay half-life) for $100 \geq A \geq 91$ krypton isotopes observed experimentally is summarized in Table 1. For example, the ^{91}Kr calculations predict eight beta decay transitions (i.e., allowed $2d_{5/2}(n)$ to $2d_{5/2}(p)$ [4.40 min], allowed $2p_{3/2}(n)$ to $2p_{3/2}(p)$ [53.3 s], allowed $2p_{1/2}(n)$ to $2p_{3/2}(p)$ [8.59 s], allowed $2p_{1/2}(n)$ to $2p_{1/2}(p)$ [1.26 min], allowed $2p_{3/2}(n)$ to $2p_{1/2}(p)$ [1.45 h], allowed $1g_{9/2}(n)$ to $1g_{9/2}(p)$ [37.8 min], first forbidden $2d_{5/2}(n)$ to $2p_{3/2}(p)$ [2.76 min], and first forbidden $2d_{5/2}(n)$ to $2p_{1/2}(p)$ [5.23 min]). For ^{91}Kr , the allowed $2p_{1/2}(n)$ to $2p_{3/2}(p)$ [8.59 s] transition is the limiting beta decay mode.

Table 1: Calculated Single Particle and Experimental Decay Properties of Krypton Nuclei with $91 \leq A \leq 108$

Nuclide (neutron shell)	a(A)	Half-Life (Decay Mode)	
		Experiment ^{a,b,c} /Theory ^d	This Work
$^{91}\text{Kr} (2d_{5/2})$	-0.0394	8.57 s ^c	8.59 s (β^-) ^e
$^{92}\text{Kr} (2d_{5/2})$	-0.0284	1.840 s ^c	1.84 s (β^-) ^e
$^{93}\text{Kr} (1g_{7/2})$	-0.0640	1.286 s ^c	1.28 s (β^-) ^f
$^{94}\text{Kr} (1g_{7/2})$	-0.0349	214 ms ^c	214 ms (β^-) ^f
$^{95}\text{Kr} (1g_{7/2})$	-0.0241	114 ms ^c	114 ms (β^-) ^f
$^{96}\text{Kr} (1g_{7/2})$	-0.0193	80 ms ^c	80.0 ms (β^-) ^f
$^{97}\text{Kr} (1g_{7/2})$	-0.0170	62 ms ^c	62.1 ms (β^-) ^f
$^{98}\text{Kr} (1g_{7/2})$	-0.0095	43 ms ^c	43.0 ms (β^-) ^f
$^{99}\text{Kr} (1g_{7/2})$	-0.0097	37 ms ^c	37.0 ms (β^-) ^f
$^{100}\text{Kr} (1g_{7/2})$	0.0655	7 ms ^c	7.00 ms (β^-) ^f
$^{101}\text{Kr} (3s_{1/2})$	0.0030	24.3 ms ^d	21.0 ms (β^-) ^f
$^{102}\text{Kr} (3s_{1/2})$	0.0080	15.0 ms ^d	16.7 ms (β^-) ^f
$^{103}\text{Kr} (2d_{3/2})$	0.0129	12.2 ms ^d	13.5 ms (β^-) ^f
$^{104}\text{Kr} (2d_{3/2})$	0.0178	8.59 ms ^d	11.1 ms (β^-) ^f
$^{105}\text{Kr} (2d_{3/2})$	0.0227	7.61 ms ^d	9.20 ms (β^-) ^f
$^{106}\text{Kr} (2d_{3/2})$	0.0276	5.64 ms ^d	7.70 ms (β^-) ^f
$^{107}\text{Kr} (1h_{11/2})$	0.0325	5.15 ms ^d	6.50 ms (β^-) ^f
$^{108}\text{Kr} (1h_{11/2})$	0.0375	^g	5.53 ms (β^-) ^f

^aRef. 44. ^bRef. 45. ^cRef. 46.
^dJapanese data Compilation calculation.
^eAllowed $2p_{1/2}(n)$ to $2p_{3/2}(p)$ beta decay transition.
^fAllowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta decay transition.
^gNo data provided in Ref. 44 - 46.

The model predicts the correct decay mode for the known $100 \geq A \geq 91$ krypton systems [44-46]. As noted in Table 1, the model half-lives are also consistent with data [44 - 46].

^{91}Kr and ^{92}Kr 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 ^{91}Kr and ^{92}Kr are within about 0.3% of the experimental values [46]. In addition beta decay is the predicted decay mode in agreement with Ref. 46.

The $^{93}\text{Kr} - ^{100}\text{Kr}$ systems 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 $^{93}\text{Kr} - ^{100}\text{Kr}$ systems

are within 0.5% of the data [46]. Model calculations also predict the correct decay mode for these $1g_{7/2}$ krypton nuclei.

5.2 $108 \geq A \geq 101$ Krypton Isotopes without Experimental Half-Life Data

The $a(A)$ values for $108 \geq A \geq 101$ krypton isotopes were obtained from a linear fit based on the half-lives of ^{94}Kr - ^{99}Kr . The resulting $a(A)$ values are listed in Table 1.

^{101}Kr and ^{102}Kr nuclei fill the $3s_{1/2}$ neutron shell, and have calculated beta decay half-lives in the range of 16.7 to 21.0 ms. These systems decay through allowed $1g_{7/2}(n)$ to $1g_{9/2}(p)$ beta transitions. The model half-life results for ^{101}Kr and ^{102}Kr are within a factor of 1.2 of the Japanese Data Compilation calculations [46].

^{103}Kr - ^{106}Kr 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 ^{103}Kr - ^{106}Kr are in the range of 7.70 – 13.5 ms. These system half-lives are within a factor of about 1.4 of the Japanese Data Compilation calculations [46].

^{107}Kr and ^{108}Kr partially fill 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 ^{107}Kr and ^{108}Kr are in the range of 5.53 – 6.50 ms. The ^{107}Kr half-life is within a factor of about 1.3 of the Japanese Data Compilation calculation [46].

The krypton calculations are terminated at $A = 108$ to account for the spontaneous neutron emission as the mass increases. Using the methodology of Chowdhury *et al.* [48], spontaneous emission is expected to occur at $A = 114 - 116$. The Japanese Data Compilation calculations [46] suggest that $A = 107$ terminates the krypton systems. Model calculations were extended to $A = 108$ to account for uncertainties in estimates of Refs. 46 and 48, and were terminated with partially filling 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 krypton nuclei is predicted to occur in the range of $A = 114 - 116$. The Japanese Nuclear Data Compilation calculations terminate their krypton calculations at $A = 107$. Given these results, single particle model calculations are extended to encompass these values, and were terminated at $A = 108$ with partially filling of the $1h_{11/2}$ neutron shell.

Single particle model calculations predict that $A = 101 - 108$ neutron excess krypton systems form bound nuclei that have limiting beta decay half-lives in the range of 5.53 – 21.0 ms. Model half-life results for the $A = 101 - 107$ krypton nuclei are within about a factor of about 1.4 of the predictions of the Japanese Nuclear Data Compilation calculations.

The $A = 101 - 108$ neutron excess krypton 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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