

Research Article

Decay Characteristics of Neutron Excess Fluorine Nuclei

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In neutron star mergers, neutron excess nuclei and the r-process are important factors governing the production of heavier nuclear systems. An evaluation of fluorine nuclei suggests that the heaviest $Z = 9$ nucleus will have mass 43 with filling of the $2p_{1/2}$ neutron shell. $A = 30 - 43$ fluorine isotopes have limited experimental half-life data, but the model predicts beta decay half-lives in the range of 0.550 – 2.12 ms. Based on comparisons to lighter $Z = 20$ and 26 systems, these results likely overestimate the half-lives of $A = 30 - 43$ neutron excess fluorine nuclei.

1.0 Introduction

The nucleosynthesis of heavy elements occurs by three basic processes that add protons or neutrons to a nuclear system^{1,2}. The p-process adds protons and the s- or slow process and r- or rapid process adds neutrons. Capture of protons by nuclear systems produces predominantly proton-rich nuclei that tend to decay by positron emission and electron capture^{1,2}. Neutron capture creates neutron-rich nuclei, and the resulting nuclear systems depend upon the rate of neutron addition and the beta decay rates of the residual nuclei.

In the s-process neutron capture chain, the time between successive neutron captures is sufficiently long for the product nucleus to beta decay to a stable system. Within the r-process, the time between neutron captures is too short to permit decays except for very rapid beta transitions. Therefore, the r-process must occur in an environment that has a high density of neutrons. The s-process typically occurs in red giant stars. The r-process occurs in a variety of astronomical events, including supernovae explosions and stellar mergers.

Binary neutron star or neutron star and stellar-mass black hole mergers can form a massive rotating torus around a spinning black hole¹. The matter ejected from these structures and from supernovae explosions is an important source of rapid neutron capture (r-process) nucleosynthesis¹. Fully understanding the r-process requires knowledge of the properties of neutron excess nuclei involved in creating heavy nuclear systems. Unfortunately, the majority of these neutron excess systems have never been studied².

Closing this knowledge gap was a motivation for funding facilities for rare-isotope beams constructed at research facilities located around the world. These facilities are located at RIKEN (Japan)^{3,4}, GSI (Germany)^{5,6},

and Michigan State University (US)^{7,8}. These facilities enable a new class of experiments to determine the physical properties needed by theoretical models of the structure of unstable neutron excess nuclei. Theoretical studies would complement the forthcoming experiments that will provide critical information on the unstable nuclei that must be understood in order to explain nuclear abundances observed in the universe². In particular, the study of neutron excess systems and their decay properties are significant considerations in understanding the r-process, and its importance in producing the observed elements in the universe.

The study of neutron excess systems is also important for studying nuclear decay properties, nuclear structure under extreme conditions, and nuclear reaction mechanisms. Existing theoretical models have not been extensively applied to many of these neutron excess nuclei.

This paper attempts to partially fill this void by calculating the decay properties of neutron excess systems that are important in nucleosynthesis. These theoretical studies should also assist in planning future experiments associated with neutron excess systems that are far removed from the line of stability.

Neutron excess nuclei that merit study occur throughout the Periodic Table²⁻⁸ including nuclei in the $Z \leq 32$ range⁸. Although neutron excess nuclei occur throughout the periodic table, this paper focuses on fluorine systems as part of a continuing investigation of neutron excess nuclei that are of potential astrophysical significance. Previous publications addressed neutron excess calcium⁹ and iron systems.¹⁰

The study of light nuclear systems including fluorine is important for a comprehensive astrophysical interpretation of nucleosynthesis. For example, Terasawa et al.¹¹ studied the role of light neutron-rich nuclei during r-process nucleosynthesis in supernovae. In addition, Recio-Blanco et al.¹² noted the importance of fluorine in nucleosynthesis, but observed that knowledge of excess neutron $Z=9$ systems and their associated properties are not well established. Mowlavi et al.¹³ also investigated the nucleosynthesis of fluorine with a focus on asymptotic giant branch stars. Ref. 1 noted that most previous studies of the r-process have concentrated on the synthesis of heavy unstable nuclei. However in extreme environments such as those encountered in a supernova, light-mass nuclei are also expected to provide an important role in the production of r-process elements. Specifically, Ref. 11 noted that $Z < 10$ systems can significantly affect the heavy-element abundances.

A recent study of fluorine isotopes in intermediate-mass stellar systems^{14,15} concluded that oxygen fusion could occur at lower densities than initially assumed. This result suggests that intermediate-mass stars are more likely to encounter thermonuclear excursion rather than undergoing gravitational collapse. The resulting white dwarf stars would predominantly contain oxygen, neon, and magnesium. This result was a direct consequence of the nuclear structure of ^{20}F , and its influence on the beta decay to the ^{20}Ne system^{14,15}. Refs. 14 and 15 further support the study of neutron excess fluorine systems in understanding the nucleosynthesis of heavier elements.

2.0 Computational Methodology

A variety of models could be applied to the investigation of neutron excess nuclei. These models vary in sophistication, but the proposed model utilizes a basic single-particle approach. This is a reasonable first step because there are uncertainties in the nuclear potential that likely are more significant than the limitations introduced by a single-particle approach.

Since the method for calculating single-particle energies in a spherically symmetric potential is well-established only salient features are provided. The model used to describe the particle plus core system represents an application of the standard method of Lukasiak and Sobiczewski¹⁶ and Petrovich et. al.¹⁷

The binding energy E_{NLSJ} of a particle in the field of a nuclear core is obtained by solving the radial Schrödinger Equation

$$\left[\frac{\hbar^2}{(2\pi)^2 2\mu} \left(\frac{d^2}{dr^2} - \frac{L(L+1)}{r^2} \right) - Q \right] U_{NLSJ}(r) = 0 \quad (1)$$

$$Q = E_{NLSJ} + V_{LSJ}(r) \quad (1A)$$

where r is the radial coordinate defining the relative motion of the nuclear core and the particle; $V_{LSJ}(r)$ is the model interaction; E_{NLSJ} is the core plus particle binding energy; $U_{NLSJ}(r)$ is the radial wave function; and L , S , and J are the orbital, spin, and total angular momentum quantum numbers, respectively. The N quantum number is the radial quantum number, and μ is the reduced mass.

The method of searching for E_{NLSJ} is provided by Brown, Gunn, and Gould¹⁸, and the methodology of Ref. 19 is utilized to obtain a converged solution. Refs. 9, 10, and 17 provide a more complete description of the model, its numerical solution, and further definition of the individual terms appearing in Eq. 1.

3.0 Nuclear Interaction

Nuclear stability with respect to alpha decay, beta decay, positron decay, and electron capture is addressed using the method previously published by the author and coworkers¹⁷ that is similar to the approach of Ref. 20. The single-particle level spectrum is generated using a Woods-Saxon potential. Parameters of the potential are obtained from a fit to the particle levels in ^{209}Pb and ^{209}Bi performed by Rost²¹. The central potential strength of the Rost interaction²¹ has a standard form and can be explicitly defined as

$$V_0 = 51.6 \left[1 \pm 0.73 \frac{(N-Z)}{A} \right] \text{MeV} \quad (2)$$

where the upper (lower) sign applies to protons (neutrons). The remaining parameters were held constant and are given by Rost²¹: $r_0 = 1.262$ (1.295) fm, $r_{s0} = 0.908$ (1.194) fm, $a = 0.70$ (0.70) fm, and $\gamma = 17.5$ (28.2) for protons (neutrons) 17,21. V_{s0} is related to γ by the relationship²¹:

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

The scaling relationship of Eq. 2 yields reasonable fits to observed single-particles levels in ^{120}Sn and ^{138}Ba . The pairing correction term of Blomqvist and Wahlborn²² is used in the calculations presented herein. The pairing correction improves the predicted energies of occupied levels in ^{120}Sn , ^{138}Ba , and ^{208}Pb ¹⁷.

When applied to calcium nuclei, this methodology requires modification. Ray and Hodgson²³ note that ^{40}Ca and ^{48}Ca require different potentials to properly fit their single-particle level structure. Schwierz, Wiedenhöver, and Volya²⁴ also investigated ^{40}Ca and ^{48}Ca and noted that a proper fit to the single-particle levels required a different potential for each energy level. Difficulties in the selection of an appropriate potential is an additional motivation for the utilization of single-particle levels and was noted in studies of neutron excess calcium⁹ and iron¹⁰ nuclei.

In view of the results of Refs. 23 and 24, the following modification is made to obtain the fluorine potential strength (V_{0F}):

$$V_{0F} = V_0 \lambda [1 \pm a(A)] \quad (4)$$

where λ is a potential strength multiplier that is selected to ensure consistency with available data, and $a(A)$ is a constant that is introduced to account for the variations in potential strength with A ^{23,24}. In previous excess neutron nuclei calculations for calcium⁹ and iron¹⁰, a value of $\lambda = 1.0$ was utilized. A λ value of 1.5 for fluorine was determined by the available experimental data^{25,26}. Since the paper's primary purpose is investigation of the neutron excess nuclei, determining a common $a(A)$ value for the heaviest fluorine systems is desirable.

In the fluorine system, the heaviest mass $A = 9$ isotope^{25,26} suggested to date is ^{31}F . Given the expected order of energy levels, ^{31}F would have a $1f_{7/2}$ neutron single-particle level structure. Isotopes heavier than ^{31}F would require filling of the $1f_{7/2}$ and the more weakly bound $2p_{3/2}$ and $2p_{1/2}$ neutron single-particle levels. The possibility of bound fluorine isotopes with $A \geq 31$ is addressed in subsequent discussion.

4.0 Calculation of Half-Lives

Using Eq. 4, single-particle levels are calculated for $A \geq 17$ fluorine isotopes. $A \geq 17$ fluorine nuclei were evaluated for stability with respect to alpha decay, beta decay, positron decay, and electron capture. These calculations were performed to ensure that the nuclear structure contained no interloping states or structural defects, and that any decay modes in conflict with data were identified.

The decay modes and half-lives of $A = 17 - 43$ fluorine isotopes are summarized in Table I and compared to available data^{25,26}. The alpha decay energies are calculated using the relationship based on Ref. 27

$$Q_{\alpha} = 28.3\text{MeV} - 2S_n - 2S_p \quad (5)$$

where S_n and S_p are the binding energies of the last occupied neutron and proton single-particle levels, respectively. Alpha decay half-lives can be estimated from Q_{α} using standard relationships¹⁶. Fortunately, no alpha decay modes occurred in the Table I summary of $A = 17 - 43$ fluorine isotope decay properties.

The beta decay half-lives are determined following the log ft methodology of Wong²⁷. Allowed (first forbidden) transition half-lives were derived using the values of $\log ft = 5$ (8). Given the uncertainties in the calculated level energies, second and higher order forbidden transitions were not determined. Positron and electron capture half-lives were determined following the approach of Ref. 16.

5.0 Model Issues

Spherical single-particle energy calculations produce reasonable results for alpha, beta, positron, and electron capture transitions^{9,10,17,20-24}. However, these calculations are not expected to accurately model the very short-lived proton decay modes of ^{15}F and ^{16}F . Since ^{15}F and ^{16}F are far removed from the neutron excess fluorine isotopes of interest in this paper, they are not addressed. In addition, very heavy fluorine isotopes have the potential to decay via neutron emission modes. The single-particle model is not the best approach for these calculations, and these decay modes are not included in this paper. Therefore, the results for the heaviest neutron excess nuclei only include the alpha decay, beta decay, positron decay, and electron capture modes.

Except as noted previously, the single-particle model should provide reasonable results for the systems considered in the paper. Since the focus of this paper is the more massive fluorine nuclei, single-particle methods provide the desired results for the most important nuclei considered in this study, and their decay via the alpha decay, beta decay, positron decay, and electron capture pathways.

6.0 Results and Discussion

Using Eq. 4, the $a(A)$ value was varied in increments of 0.005 to assess the applicability of the proposed model to predict the decay properties of $A = 17 - 43$ fluorine isotopes. In view of uncertainties in the model and associated interaction, a smaller increment was not deemed to be justified for most fluorine systems. However, for nuclei that have half-lives that significantly deviate from neighboring systems, a smaller increment was utilized. In particular, $a(A)$ was adjusted in increments of 0.0001 (0.00002) in view of the rapid variation in decay properties of ^{18}F (^{19}F) relative to adjacent systems.

The issues associated with fitting all calcium and iron nuclei with a single potential^{23,24} were noted in Refs. 9 and 10. These considerations are also applicable to the fluorine systems considered in this work.

Table I			
Calculated Single-Particle and Experimental Decay Properties of Fluorine Systems with $17 \leq A \leq 43$			
Nuclide	a(A)	Half-Life (Decay Mode) ^{a,b}	
		Experiment	This Work
¹⁷ F	0.07	1.08 min (β^+) ^a	1.24 min (f)
¹⁸ F ^d	0.0475	1.8293 h (β^+) ^a	1.80 h (f)
¹⁹ F ^e	0.01688	Stable ^a	Stable
²⁰ F	0.035	11.1 s (β^-) ^a	9.26 s (f)
²¹ F	0.01	4.16 s (β^-) ^a	4.65 s (f)
²² F	-0.02	4.23 s (β^-) ^a	4.02 s (f)
²³ F	-0.04	2.2 s (β^-) ^a	2.38 s (f)
²⁴ F	-0.025	0.39 s (β^-) ^a	0.409 s (f)
²⁵ F	0.015	0.07 s (β^-) ^a	0.0695 s (f)
²⁶ F	0.055	10 ms (β^-) ^a	9.88 ms (f)
²⁷ F	0.09	5 ms (β^-) ^a	4.94 ms (f)
²⁸ F	0.115	^h	3.05 ms (f)
²⁹ F	0.115	2.5 ms (β^-) ^a	2.52 ms (f)
³⁰ F	0.115	^h	2.12 ms (f)
³¹ F	0.115	ⁱ	1.81 ms (f)
³² F	0.115	^j	1.57 ms (f)
³³ F	0.115	^j	1.37 ms (f)
³⁴ F	0.115	^j	1.21 ms (f)
³⁵ F	0.115	^j	1.08 ms (f)
³⁶ F	0.115	^j	0.997 ms (f)
³⁷ F	0.115	^j	0.885 ms (f)
³⁸ F	0.115	^j	0.806 ms (f)
³⁹ F	0.115	^j	0.740 ms (f)
⁴⁰ F	0.115	^j	0.682 ms (f)
⁴¹ F	0.115	^j	0.632 ms (f)
⁴² F	0.115	^j	0.590 ms (f)
⁴³ F	0.115	^j	0.550 ms (f)

^aRef. 25.
^bRef. 26.
^cAllowed $1d_{5/2}(p)$ to $1d_{5/2}(n)$ positron decay transition.
^da(A) was adjusted in increments of 0.0001 in view of the rapid variation in decay properties of ¹⁸F relative to adjacent systems.
^ea(A) was adjusted in increments of 0.00002 in view of the rapid variation in decay properties of ¹⁹F relative to adjacent systems.
^fAllowed $1d_{5/2}(n)$ to $1d_{5/2}(p)$ beta decay transition.
^gAllowed $1d_{3/2}(n)$ to $1d_{5/2}(p)$ beta decay transition.
^hNo data provided in Ref. 25. Ref. 26 suggests a neutron decay mode, but no half-life is provided.
ⁱNo data provided in Ref. 25. Ref. 26 suggests a beta decay mode, but no half-life is provided.
^jNo data provided in Ref. 25 or 26.

Table I summarizes the complete set of $A = 17 - 43$ isotopes considered in this paper. The lighter $A = 17 - 29$ fluorine isotopes fill the $1p_{1/2}$ (^{17}F), $1d_{5/2}$ ($^{18}\text{F} - ^{23}\text{F}$), $2s_{1/2}$ (^{24}F and ^{25}F), and $1d_{3/2}$ ($^{26}\text{F} - ^{29}\text{F}$) neutron single-particle levels. These systems are the heaviest fluorine systems noted in Ref. 25. ^{29}F has a complete $1d_{3/2}$ neutron single-particle shell. Given the extrapolation used in formulating the single-particle potential of Eq. 4, the results become more uncertain due to the paucity of data for $A > 30$ fluorine isotopes. The heavier $A = 30 - 43$ fluorine isotopes that fill the $1f_{7/2}$, $2p_{3/2}$, and $2p_{1/2}$ neutron single-particle levels are also summarized in Table I. These systems represent the heaviest possible neutron excess systems that would occur in the $Z=9$ system.

The excess neutron systems of Table I are based on the $a(A)$ values of the heaviest fluorine systems summarized in Table I and the results of previous work^{9,10}. In view of these considerations, the calculations for $A = 30 - 43$ fluorine isotopes are based on an $a(A)$ value of 0.115.

The neutron excess systems summarized in Table I were based on an evaluation of alpha, beta, electron capture, and positron decay modes. Other decay modes that could possibly occur in neutron excess systems (e.g., n and $2n$) are not readily evaluated using a single particle model, and were not evaluated. The results of Table I must be viewed with this limitation. However, since the neutron and proton decay modes tend to be much shorter than the alpha, beta, electron capture, and positron decay modes^{25,26}, the model results provide upper bounds on the half-lives of neutron excess fluorine isotopes.

6.1 $A = 17 - 29$ Fluorine Isotopes

The ^{17}F system completes the $1p_{1/2}$ neutron shell, and was best fit with an $a(A)$ value of 0.07. As noted previously, ^{15}F and ^{16}F were not evaluated since these nuclei decay by proton emission that is not readily evaluated using the single-particle approach utilized in this paper.

^{18}F to ^{23}F systems were best fit with $a(A)$ values between -0.04 and 0.048 with an average value of about 0.01. The ^{18}F to ^{23}F nuclei fill the $1d_{5/2}$ neutron shell. ^{24}F and ^{25}F fill the $2s_{1/2}$ neutron shell and are best fit with $a(A)$ values of -0.025 and 0.015 , respectively; with an average value of -0.005 .

The heaviest known fluorine neutron excess systems (i.e., ^{26}F , ^{27}F , and ^{29}F) fill the $1d_{3/2}$ neutron shell. There is no experimental half-life data for ^{28}F or systems heavier than ^{29}F .

The ^{26}F , ^{27}F , and ^{29}F systems were best fit with $a(A)$ values of between 0.055 and 0.115 with an average value of about 0.09. Since the ^{29}F system is accurately fit with an $a(A)$ value of 0.115, and the highest mass calcium and iron isotopes were also best fit with an $a(A)$ value of 0.115^{9,10}, that value is used to extrapolate the half-lives of ^{28}F and heavier fluorine systems.

Table I lists the half-life of the limiting beta decay transition (i.e., the transition that has the shortest beta decay half-life). For example, ^{22}F has two beta decay transitions that are possible within the scope of the

aforementioned single-particle model (i.e., allowed $1d_{5/2}(n)$ to $1d_{3/2}(p)$ [18.0 d] and allowed $1d_{5/2}(n)$ to $1d_{5/2}(p)$ [4.02 s] transitions). For ^{22}F , the limiting beta decay mode is the allowed $1d_{5/2}(n)$ to $1d_{5/2}(p)$ [4.02 s] transition.

As noted in Table I, the model predicts the proper decay mode for $A = 17 - 29$ fluorine nuclei²⁵. The results for the known systems summarized in Table I suggest that the model predictions of the neutron excess fluorine systems are reasonably credible. For $Z = 9$ systems filling the $1p_{1/2}$ shell, the ^{17}F positron decay half-life is overestimated by 15%. ^{17}F decays by an allowed $1d_{5/2}(p)$ to $1d_{5/2}(n)$ positron decay transition.

For nuclei filling the $1d_{5/2}$ neutron shell, model predictions for ^{18}F , ^{20}F , ^{21}F , ^{22}F , and ^{23}F are within 20 percent of the experimental positron or beta decay half-lives²⁵. ^{19}F is correctly determined to be a stable system. ^{18}F decays by an allowed $1d_{5/2}(p)$ to $1d_{5/2}(n)$ positron decay transition. ^{20}F , ^{21}F , ^{22}F , and ^{23}F decay by an allowed $1d_{5/2}(n)$ to $1d_{5/2}(p)$ beta decay transition.

The $2s_{1/2}$ systems, ^{24}F and ^{25}F , are within 5% of their respective experimental beta decay half-lives²⁵. Both ^{24}F and ^{25}F decay by an allowed $1d_{5/2}(n)$ to $1d_{5/2}(p)$ beta decay transition.

^{26}F , ^{27}F , ^{28}F , and ^{29}F fill the $1d_{3/2}$ neutron shell. Although Ref. 26 suggests that ^{28}F decays by neutron emission, no half life data is available. The single-particle model suggests that ^{28}F is a beta emitter with a half-life of 3.05 ms. This decay mode and half-life are consistent with the decay properties and half-lives of neighboring fluorine systems. The ^{26}F , ^{27}F , and ^{29}F decay by an allowed $1d_{3/2}(n)$ to $1d_{5/2}(p)$ beta decay transition, and their beta decay half-lives are within 2% of the measured values²⁵. ^{28}F also decays by an allowed $1d_{3/2}(n)$ to $1d_{5/2}(p)$ beta decay transition.

6.2 $A = 30 - 43$ Fluorine Isotopes

Table I also summarizes calculated single-particle and available experimental decay properties of fluorine systems with $30 \leq A \leq 43$. Although experimental data for $30 \leq A \leq 43$ fluorine systems are extremely limited^{25,26}, these are nuclei of interest in astrophysical applications^{1-8,11-15}.

The existence of $30 \leq A \leq 43$ fluorine systems as predicted by the proposed model is dependent on the characteristics of the interaction of Eq. 4. Although the existence of some of these systems may be an artifact of the model interaction, their study is of critical importance to understanding the role of neutron excess fluorine systems in nucleosynthesis.

The $^{30}\text{F} - ^{37}\text{F}$ systems fill the $1f_{7/2}$ neutron single-particle energy level. Ref. 26 suggests a neutron decay mode for ^{30}F , but no half-life information is provided. The single particle model predicts a 2.12 ms beta decay half-life for ^{30}F that occurs through an allowed $1d_{3/2}(n)$ to $1d_{5/2}(p)$ beta decay transition. Ref. 26 suggests a beta decay mode for ^{31}F , but no half-life is provided. The single particle model predicts a 1.81 ms beta decay half-life for ^{31}F that also occurs through an allowed $1d_{3/2}(n)$ to $1d_{5/2}(p)$ beta decay transition.

The remaining $^{32}\text{F} - ^{37}\text{F}$ systems filling the $1f_{7/2}$ neutron single-particle level decay through an allowed $1d_{3/2}(\text{n})$ to $1d_{5/2}(\text{p})$ beta decay transition. The $^{32}\text{F} - ^{37}\text{F}$ beta decay half-lives decrease from 1.57 to 0.885 ms.

The $^{38}\text{F} - ^{41}\text{F}$ systems fill the $2p_{3/2}$ neutron shell. These systems also decay through an allowed $1d_{3/2}(\text{n})$ to $1d_{5/2}(\text{p})$ beta decay transition. The $^{38}\text{F} - ^{41}\text{F}$ beta decay half-lives decrease from 0.806 to 0.632 ms.

The ^{42}F and ^{43}F systems fill the $2p_{1/2}$ neutron shell. In a similar manner, these systems decay through an allowed $1d_{3/2}(\text{n})$ to $1d_{5/2}(\text{p})$ beta decay transition. The ^{42}F and ^{43}F half-lives are 0.590 and 0.550 ms, respectively.

No fluorine isotopes with $A > 43$ were predicted by the model. This occurs because the $2p_{1/2}$ neutron single-particle level is the last bound neutron state, and only 34 neutrons are bound by the model potential. However, in view of the model potential uncertainties, the calculated properties of the heaviest fluorine systems summarized in Table I are not definitive.

The predicted $A = 30 - 43$ fluorine isotopes have limited experimental half-life data, but the model predicts beta decay half-lives in the range of 0.550 – 2.12 ms. Based on calculations in $Z = 20$ and 26 systems^{9,10}, these results likely overestimate the beta decay half-lives of these neutron excess fluorine nuclei. The model results are also likely to be an overestimate of the half-lives because the single-particle level calculations do not evaluate the short-lived neutron decay mode in the $A = 30 - 43$ fluorine nuclei.

7.0 Conclusions

Single-particle level calculations suggest that neutron excess fluorine isotopes terminate with ^{43}F and filling of the $2p_{1/2}$ neutron single-particle level. The $30 \leq A \leq 43$ fluorine systems have predicted beta decay half-lives in the 0.550 – 2.12 ms range, and likely overestimate the actual half-life values.

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