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Effects of β-Decays of Excited-State Nuclei on the Astrophysical r-Process

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A rudimentary calculation is employed to evaluate the possible effects of β-decays of excited state nuclei on the astrophysical r-process. Single particle levels calculated with the FRDM are adapted to the calculation of β-decay rates of these excited state nuclei. Quantum numbers are determined based on proximity to Nilson model levels. The resulting rates are used in an r-process network calculation in which a supernova hot-bubble model is coupled to an extensive network calculation including all nuclei between the valley of stability and the neutron drip line and with masses 1≤A≤283. β-decay rates are included as functional forms of the environmental temperature. While the decay rate model used is simple and phenomenological, it is consistent across all 3700 nuclei involved in the r-process network calculation. This represents an approximate first estimate to gauge the possible effects of excited-state β-decays on r-process freezeout abundances.

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1. Introduction

The r-process is responsible for the synthesis of roughly half of all nuclei heavier than A$\sim$70 and all of the actinides [1, 2]. The solar system r-process abundances act as the canonical constraint to r-process theories as well as the prime indicator of the success of r-process models. Several r-process sites have been proposed; the hot-bubble region of a type II supernova (SNII) has been modeled fairly successfully. The composition of the environment in which the r-process occurs might be expected to have a profound effect on the final abundance distribution. Observations indicate that the r-process site is primary [3] and further evidence may suggest that the r-process is also unique [4]; it may occur in a single site or event. The uniqueness of the r-process site, however, remains a subject of study [5].

Nuclear properties also constrain the r-process, and the purpose of this work is the examination of one particular characteristic - β-decay - as it relates to the r-process. The β-decay inputs, and other nuclear physics inputs, have been shown [6, 7] to have important effects on the success or failure of r-process models. This is somewhat unfortunate, as properties of only a few nuclei on the neutron closed shells closer to stability have been experimentally determined, while data for the rest are relegated to calculation [1]. Of paramount importance is the determination of nuclear masses and β-decay rates. Nuclear mass formulae based on the microscopic properties of nuclei are slowly replacing the empirical droplet models, and these can change resulting reaction rates by factors as large as 10^8 [8]. As well, the r-process path is affected by the choice of mass formula, since the path roughly follows a line of constant S_n [1].

For the purposes of this study, the most recent semi-gross theory of β-decay [9] has been adapted to neutron-rich nuclei relevant to the r-process. The ability of this model to determine decay properties of an extremely wide range of nuclei with reasonable accuracy and speed makes it ideal for this preliminary calculation. In particular, the semi-gross theory has good agreement for very neutron-rich nuclei [10, 11]. It has also been used to improve the accuracy of decay rates for astrophysical calculations by incorporating first-forbidden transition strengths [12]. In its original form, the gross theory of β-decay assumed that the energy states of a nucleus consist of a smoothed distribution with transition strengths that peak at or near the energy of the isobaric analog state [13, 14]. Subsequent evolutions of the gross theory incorporated strength functions allowing for transitions of higher forbiddenness [15], as well as improvements over the original theory to include odd-odd effects [16], sum rules [17], even-odd mass differences [18], and improvements on the strength functions [19].

Since decay rates of nearly all of the nuclei along the r-process path have yet to be studied in a laboratory, r-process calculations rely heavily on calculated decay rates. Further, the temperature of the r-process environment (10^9K) necessitates accounting for nuclei in excited states, especially given the expected high level density of these far-from-stability nuclei. Some of the effects that might be expected if one considers excited state nuclei in r-process simulations include increased (n,γ) and (γ,n) rates, which might shift the r-process path, but would tend to counteract each other as the r-process is generally presumed to proceed at (n,γ)$\leftrightarrow$(γ,n) equilibrium, increased neutrino spallation rates, tending to enhance smoothing in post-processing, and increased beta-decay rates. However, at signicant excitation, neutron separation energies are low enough that neutron emission may be a dominant decay mode. This is discussed briefly along with the discussion of excited-state decays in the network calculation.

2. Excited-State Weak Transitions and the r-Process

Details of the β-decay rate calculations are described in detail in reference [20] and will not be discussed here. Decay rates and Q-Values have been calculated with the FRDM in previous works [21]. The level of accuracy of these calculations have been shown to be within an order of magnitude of the true rate.

A next logical step is to calculate decay rates for nuclei in excited states. The present formulation gives no preferential treatment to nucleons in single-particle excited states. Levels can be calculated beyond the maximum filled level in the ground state, although the simplicity of the model can render these values slightly different from their experimental counterparts.

In stellar environments, the probability of finding a nucleus in an excited state at a given temperature can be obtained from the partition function by knowing the spin and energy of the excited state. Since each particle level holds only two nucleons, the degeneracy of each level is two, and the quantum numbers are given by the level's proximity to those of the spherical shell model. The difference in energy:

$$\Delta E = \sum_{i_{N,Z}=1}^{m} n^{*}_{n,i}\varepsilon^{*}_{i} - \sum_{i_{N,Z}=1}^{\mu} n^{0}_{n,i}\varepsilon^{0}_{i} \tag{2.1}$$

where values with an * are those for an excited-state nucleus, while those with a ^{0} are those corresponding to a ground-state nucleus. The summation is taken over neutron and proton levels. The value m is the highest bound state level. The first term represents the total energy of the excited nucleus, and the second term is the total energy of the ground-state nucleus. The average decay rate of an isotope in a stellar environment is then the weighted sum over energy states [22]:

$$\lambda = \sum_{\Delta E} P(\Delta E)\lambda(\Delta E) \tag{2.2}$$

where P(ΔE) is calculated using the partition function.

Relative changes in decay rates along the r-process path have been calculated for all nuclei between stability and the neutron drip line. The effect is to increase slightly the relative ratios of the ground-state rates at lower mass. However, this effect is only slight (<10%) in temperature regimes relevant to the r-process. A network calculation is necessary to evaluate fully the magnitude of the effect on the r-process. The increase in the ^{132}Sn rate may be enough to make a significant difference in the final abundances, but this is not clear yet.

The results from several hydrodynamic parameter sets, as well as electron fraction parameter values Y_e, were examined. For each parameter set, the core mass in solar masses, core radius, neutrino luminosity, initial electron fraction, and whether or not β-

delayed neutron emission is included are listed. Using these parameters and the calculations of reference [23] the dynamic timescale and the entropy in the expansion are constrained. Though still in agreement with current predictions, the dynamic timescales in these calculations are shorter than average. However, the entropy is lower, and no artificial increase in the entropy (as is often assumed) was required [6].

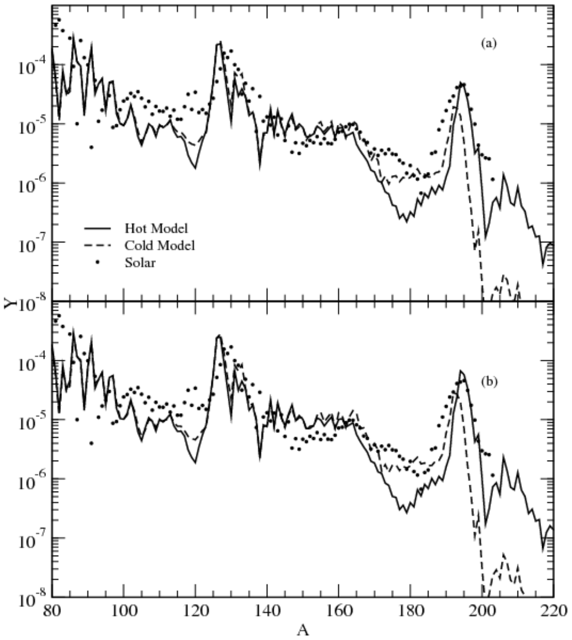

Figure 1: Comparison of r-process freezeout abundance distributions for models A and B in plots (a) and (b) respectively. Solid lines and dashed curves display the calculated results with (hot model) and without (cold model) excited-state β-decays respectively. The solar distribution is also shown by the dots.

Each simulation is run until several seconds beyond freezeout. While this time is sufficient to gauge the gross features of the r-process abundance distribution, a longer simulation may have resulted in more post-processing, allowing for smoother abundance distributions. Figure 1 shows models A and B which were chosen as intermediate points in the entropy-timescale phase space. Both produce a more acceptable r-process abundance distribution incorporating excited-state decay rates, although the A$\sim$195 peak is still underproduced. For comparison, the solar r-process abundance distribution is displayed in the figure. One notes some residual even-odd effects in the calculated distribution as the effects of smoothing may not be complete, though the gross features of the distribution are noted.

3. Conclusion

This work provides a study of the effects of excited state β-decays on the r-process. A preliminary method was used to evaluate the possible effects of β-decay rates of excited-state nuclei. Though the accuracy of the model is limited by the knowledge of single particle levels, an approximate treatment allows one to gauge the magnitude of effects on the r-process and provide impetus for further study. An empirical calculation was employed to find single-particle levels, and quantum numbers were deduced based on the level proximity to those of the spherical shell model. Although minor effects were found to result from inclusion of the excited state decays, there are also other possible effects that the inclusion of excited state nuclei may have on the r-process. One can imagine that if the excitation is due to the promotion of neutrons to higher-lying single-particle orbitals, then the photoneutron Q-value will decrease, and the (γ,n) reaction rate may increase. Thus the effect of an increased rate might be to shift the r-process path closer to β-stability.

The dynamical treatment of the r-process is an important factor here in that the path continues to evolve even during freezeout, a result of β-delayed neutron emission. With the mass formula used in this evaluation, it was found that the low mass nuclei have a higher probability of emitting two neutrons during β-decay than the higher mass nuclei, which have a higher probability of emitting a single neutron during β-decay. These available neutrons are recaptured, with the cross section roughly increasing with mass. The net result is a slight shift in the A$\sim$195 abundance peak.

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