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Dynamic Stellar Neutron-Capture Nucleosynthesis:
The Need for More Nuclear Data
for the s-Process

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DYNAMIC STELLAR NEUTRON CAPTURE NUCLEOSYNTHESIS:
THE NEED FOR MORE NUCLEAR DATA FOR THE s-PROCESS

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ABSTRACT

We summarize results from a detailed parameter study of the s-process in models which produce an exponential distribution of exposures by sequential irradiations and dredge up in the stellar environment. The calculations are based on a complete network of measured and calculated neutron capture and beta-decay rates as well as estimates for their temperature dependence. In the framework of these models we identify and systematically vary the astrophysical variables which affect the observed solar-system σN (cross section times abundance) curve. Constraints are placed on the s-process neutron exposure and flux as well as the temperatures, densities, neutron pulse shape and inter-pulse period. The results also highlight important needs for better nuclear data in various mass regions.

INTRODUCTION

Historically the s-process has been associated with red giant stars¹. From the beginning, however, it has been clear¹⁻³ that a single neutron exposure could not produce the observed behavior of the solar-system s-process σN curve (neutron capture cross section times abundance) as a function of atomic mass. An exponential distribution of exposures was found to give a good fit³ and was at first presumed to be the result of reprocessing during galactic chemical evolution.

Ulrich^{4,5} showed that an exponential distribution of exposures could be achieved in a single star which subjected initial seed material to periodic neutron exposures followed by dredge up of some fraction of the irradiated material to the stellar surface. This s-process scenario has been explored in a series of papers⁶⁻¹¹ based on a $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ neutron-source s-process during thermal pulses of asymptotic giant branch stars. There is sufficient uncertainty in the stellar models, however, that a different approach is warranted, i.e. to utilize the observed solar-system s-process σN curve to define the constraints on any stellar model for the s-process. This is the subject of the present work. This study reveals that the s-process neutron-capture flow is probably considerably more complicated than the continuous chain assumed in the classical s-process. Deviations of the best fit from the observed solar-system values highlight important needs for improved nuclear data.

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S-PROCESS PARAMETERS

In the classical s-process (without beta-decay branching) the abundance of an isotope is given simply by the solution to the set of coupled differential equations,

$$dN_A/d\tau = \sigma(A-1)N_{A-1} - \sigma(A)N_A, \quad (1)$$

where τ is the time integrated neutron flux (i.e. neutron exposure) and σ the Maxwellian averaged neutron capture cross section.

The implication of Eq. (1) is that at equilibrium, a single exposure would lead to a constant σN value for all isotopes in the s-process. This is not observed in the solar-system σN curve (see Fig. 1). The data require a distribution of exposures². A good fit can be obtained³ with an exponential distribution of neutron exposures, i.e. the probability, $\rho(\tau)$ for a given exposure is taken to be,

$$\rho(\tau) \propto \exp(-\tau/\tau_0). \quad (2)$$

This exponential distribution of exposures leads to a particularly simple solution¹² for Eq. (1),

$$\sigma(A)N(A) = \frac{\sigma(A-1)N(A-1)}{[1 + 1/(\tau_0 \sigma(A))]} \quad (3)$$

where, τ_0 is the mean neutron exposure from Eq. (2).

In large part the identification of the astrophysical site for the s-process has been the search for an environment which would produce the value τ_0 (or equivalently the number of neutron captures per seed) necessary to reproduce the solar-system σN curve.

In a periodic s-process operating in a single star^{4,5}, the mean exposure, τ_0 , is simply related to the average exposure per pulse, $\Delta\tau$, and the fraction of material, r , which remains after each dredge up. That is, after n exposures, the fraction of material, $\rho(\tau)$, which will have experienced an exposure of $\tau = n\Delta\tau$ will be $r^n = r\tau/\Delta\tau$. Thus, the mean exposure is simply, $\tau_0 = -\Delta\tau/\ln(r)$. Note, that the mixing fraction and exposure per pulse are not independent parameters. For any fraction, r , an average exposure per pulse can be chosen such that the σN curve can be fit. In our calculations, therefore, only the mean exposure is varied in the fit. We have set $r = 0.285$ which corresponds to the fraction remaining after dredge up for the thermal-pulse model with a $1.16M_{\odot}$ CO core⁸.

In realistic models for the s-process, unstable nuclei have the opportunity to capture a neutron before beta decay, and hence, lead to a branch point along the s-process chain. It has long been appreciated¹ that such branch points are valuable as a constraint on the average neutron flux for the s-process since the

neutron-capture flow in the s-process (and therefore the σN values) will depend upon the competition between neutron capture and beta decay^{5,13,14}.

Once a given exposure is determined, the dynamics of the variation of neutron density with time will affect the σN curve, i. e., a rapidly decreasing flux may produce significantly different nucleosynthesis than a constant-flux for the same neutron exposure. For the purposes of the present study we parameterize the flux history with the analytical form suggested in the thermal pulse models⁸, i. e. we write for the flux, ϕ_n , as a function of time, t ,

$$\ln(\phi_n) = (\Delta\tau/t_0)\exp(-t/t_0) \quad (4)$$

where $\Delta\tau$ is the average exposure per pulse. Variations of the decay constant, t_0 , characterize the intensity of the peak neutron exposure.

In addition to the flux, beta decay branch points will also depend on the temperature since thermal population of excited states can considerably alter beta decay rates^{13,15,16} and even induce beta decay in nuclei which are stable at $T=0$. Since the temperature does not vary much (after an initial rapid increase) during an individual pulse in the stellar models⁸, we assume various constant temperatures during the pulse in this parameter study. We assume an interpulse temperature⁸ of $kT = 14$ keV.

In principle, the s-process abundances could also depend upon whether long-lived unstable nuclei produced at the end of a pulse have time to decay before the next pulse. In the limit of a short interpulse period, this could make a difference in the final abundances. In this parameter study we investigate the extreme limits of zero and infinite time between pulses to study the effects of the interpulse period on the final abundances.

CALCULATION

In dynamic environments such as these the simplicity of the classical s-process (Eq. 1) is lost due to a break down of the assumption that neutron captures are slow compared to beta decay. The only way to compute the nucleosynthesis is with a network:

$$\frac{dN(Z,A)}{dt} = N(Z,A-1)\phi_n\sigma_{n,\gamma}(Z,A-1) + N(Z-1,A)\lambda_{\beta}(Z-1,A) - N(Z,A)[\phi_n\sigma_{n,\gamma}(Z,A) + \lambda_{\beta}(Z,A)] \quad (5)$$

The time-dependence of the flux and temperature dependence of the cross sections and beta rates are also included. In a few cases, positron, electron-capture, or alpha decay must also be added to Eq. (5).

Experimental neutron-capture cross sections were used when available. These were extracted from several recent reviews^{5,14,16,17} as well as more recent measurements¹⁸⁻²³.

Cross sections for unstable or unmeasured nuclei were taken from Hauser-Feshbach estimates²⁴. The temperature dependence of all cross sections was taken from ref. 24 and normalized to the experimental $kT = 30\text{keV}$ Maxwellian averaged cross sections where known. The Hauser-Feshbach calculations should give a good representation of the temperature dependence of the cross sections (including capture to excited states) over the range of temperatures of interest in this work²³.

Ground-state beta decay rates were taken from experiment. Decay rates from thermally populated excited states were calculated assuming thermal equilibrium and appropriately chosen f values²⁵. The initial seed abundances were taken from solar-system values²⁶.

RESULTS

We have adjusted each of the parameters to minimize χ^2 for the fit to 23 s-only nuclei with $Z \geq 40$. The value for ^{187}Os was omitted from the list of s-only nuclei because of the unknown contribution from ^{187}Re decay. Lighter nuclei were also omitted because of possible contribution from other sources¹⁵.

In Figure 1 we determine the mean exposure for the s-process in the classical model, i.e. a constant ($t_0 = \infty$) low flux ($\phi_n = 2 \times 10^{14} \text{cm}^{-2} \text{sec}^{-1}$) switched off after an average exposure, $\Delta\tau$, such that the neutron-capture time scale is long ($\sim 10^3$ yrs.) at a standard s-process temperature of $kT = 30 \text{keV}$.

Fig. 1. Classical s-process fit to the observed σN curve.

The interpulse period is taken as long so that unstable nuclei decay between pulses. A good fit is obtained with $\tau_0 = 0.26 \pm 0.01 \text{ mb}^{-1}$. In the next fit (Fig. 2) we have varied ϕ_n and τ_0 . Note that the character of the curve is considerably changed and the quality of the fit is improved. The χ^2 for the fit gradually decreases as the flux is increased until an optimum flux, $\phi_n = 3.2 \times 10^{16} \text{ cm}^{-2}\text{sec}^{-1}$. The quality of the fit then quickly deteriorates for higher fluxes. From this we conclude that the constant fluxes consistent with the observed σN curve for s-only nuclei must be in the range of $\phi < 4 \times 10^{16} \text{ cm}^{-2}\text{sec}^{-1}$. The best fit value of $3.2 \times 10^{16} \text{ cm}^{-2}\text{sec}^{-1}$ implies a neutron density of $n_n = 1.3 \times 10^8 \text{ cm}^{-3}$ for $kT = 30 \text{ keV}$. This is consistent with previous estimates^{5,21}.

Fig. 2. Fit to σN curve when both flux and mean exposure are varied.

At the present time, the optimization of the fit with respect to the temperature and pulse shape is still in progress. The basic features of Fig. 2 are not significantly affected by these parameters however. The best fit for the solar-system σN curve always exhibits pronounced deviations from the smooth monotonically decreasing classical s-process curve. The reason for this is that many stable nuclei are actually produced as beta-unstable progenitors due to neutron captures on beta-unstable nuclei. If the progenitor has a larger cross section there will be a dip in the σN curve when the cross section for the stable daughter is used. Similarly, if the cross section for the unstable nucleus is

smaller there will be a peak. This is the reason for the pronounced peaks on Fig. 2 at ^{93}Nb (produced as ^{93}Zr) and ^{151}Eu (significantly produced as ^{151}Sm).

One check on the importance of beta branching is the effect of these branches on the r-process abundances. A number of isotopes are produced which are normally considered to be produced only in the r-process. It is an additional constraint on the s-process, therefore, not to introduce unrealistic structure into the r-process abundance curve, and in particular, not to overproduce the r-process isotopes. The new r-process abundance curve is shown in figure 3. The gaps in the abundances correspond to overproduction of isotopes by the s-process. The gap at $A \approx 200$, however, is probably due to the large uncertainty in the elemental abundance of Hg and may not be significant. The minimum at $A = 182$ arises to some extent from the production of ^{182}W as ^{182}Ta and ^{182}Hf and is probably a real minimum in the r-process curve. The gap at $A = 137, 138$ is due to the subtraction of large numbers at the ^{138}Ba s-process peak and is probably not significant. The gaps at $A = 92$ and 94 are due to an s-process overproduction of Zr. It does not appear that this is due to a problem with the s-process flow through ^{93}Zr since ^{93}Nb is not overproduced. This discrepancy may indicate that the Zr cross sections or meteoritic solar-system abundance are too low.

Fig. 3 The r-process abundances from a subtraction of the s-process abundances from the solar-system abundances. The points are abundances of nuclei normally regarded as r-only.

For the purposes of this conference it is important to point out the nuclear data needs which are evident from this study. For one, there are still a number of stable nuclei along the s-process path for which neutron-capture cross sections are not measured. These include, ^{66}Zn , $^{72,73}\text{Ge}$, ^{77}Se , $^{83,84}\text{Kr}$, ^{99}Ru , $^{128-131}\text{Xe}$, $^{192-195}\text{Pt}$, and $^{198-201}\text{Hg}$. Among these isotopes ^{192}Pt and ^{198}Hg are particularly important s-only nuclei. The σ_N value for ^{192}Pt is predicted to be substantially less than the σ_N value for ^{198}Hg (see Fig. 2) due to branching at ^{192}Ir and ^{191}Os . The effect on the σ_N value of ^{204}Pb due to branching at ^{204}Tl and ^{203}Tl is also important, and would be much clearer if the uncertainties in the ^{204}Pb cross section could be reduced.

A second point is that there are several s-process only isotopes with measured neutron capture cross sections which can not be brought into agreement (within one standard deviation) with the solar-system s-process σ_N curve for any variation of parameters. The most notable discrepancies are for ^{104}Pd , and ^{116}Sn . The uncertainty in the abundances for these nuclides is probably not very large²⁵. Therefore, the nuclear data for these nuclei and neighboring isobars ought to be reexamined. The discrepancies in the light nuclei, ^{76}Se and ^{82}Kr , are probably due to a contribution from a lower mean exposure¹⁵. There are also several s-only nuclei which may exhibit important structure but the cross sections uncertainties are too large, particularly for ^{160}Dy and ^{176}Hf .

CONCLUSION

We have identified the model parameters which characterize the solar-system s-process abundances. These parameters have been varied to find optimum values which should be taken as constraints any stellar model for the s-process. We find that the s-process is mostly sensitive to the mean exposure, τ_0 , and the neutron flux. The best fit σ_N curve suggests an s-process environment in which beta-branching induces significant changes in the s-process curve. The deviations of this best fit from the solar-system σ_N curve indicate the needs for improved nuclear data.

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REFERENCES

1. G. R. Burbidge, E. M. Burbidge, W. A. Fowler, and F. Hoyle, *Rev. Mod. Phys.*, **29**, 547 (1957).
2. D. D. Clayton, W. A. Fowler, T. E. Hull, and B. A. Zimmerman, *Ann. Phys.*, **12**, 331 (1961).
3. P. A. Seeger, W. A. Fowler, D. D. Clayton, *Astrophys. J. Suppl.*, **97**, 121 (1965).

4. R. K. Ulrich, in "Explosive Nucleosynthesis", eds. D. N. Schramm and W. D. Arnett (Univ. Texas Press, Austin, 1973), p. 139.
5. R. K. Ulrich, in "Essays in Nuclear Astrophysics", eds. C. A. Barnes, D. D. Clayton, and D. N. Schramm (Cambridge Univ. Press, N. Y., 1982) p. 301.
6. I. Iben, Jr., *Astrophys. J.*, 196, 525 (1975).
7. I. Iben, Jr., *Astrophys. J.*, 196, 549 (1975).
8. I. Iben, Jr., *Astrophys. J.*, 217, 788 (1977).
9. J. W. Truran, and I. Iben, Jr., *Astrophys. J.*, 216, 197 (1977).
10. I. Iben, Jr., and J. W. Truran, *Astrophys. J.*, 220, 980 (1978).
11. K. R. Cosner, I. Iben, and J. R. Truran, *Astrophys. J. Lett.*, 238, L91 (1980).
12. D. D. Clayton, R. A. Ward, *Astrophys. J.*, 193, 397 (1974).
13. R. A. Ward, M. J. Newman, and D. D. Clayton, *Astrophys. J. Suppl.*, 31, 33 (1976).
14. B. J. Allen, J. H. Gibbons, and R. L. Macklin, *Adv. Nucl. Phys.*, 4, 205 (1971).
15. F. Käppeler, H. Beer, K. Wisshak, D. D. Clayton, R. L. Macklin, and R. A. Ward, *Astrophys. J.*, 257, 821 (1982).
16. A. G. W. Cameron, *Astrophys. J.*, 210, 489 (1955).
17. M. J. Newman, *Astrophys. J.*, 219, 676 (1978).
18. H. Beer and R. L. Macklin, *Phys. Rev.*, C26, 1404 (1982).
19. H. Beer, F. Käppeler, G. Reffo, and G. Ventorini, *Astrophys. Space Sci.*, 97, 95 (1983).
20. R. R. Winters, F. Käppeler, K. Wisshak, A. Mengoni, and G. Reffo, (submitted to *Astrophys. J.*, 1984).
21. H. Beer, F. Käppeler, K. Yokoi, and K. Takahashi, *Astrophys. J.*, 278, 388 (1984).
22. H. Beer and G. Walter, *Astron. Astrophys.* (1984 in press).
23. G. J. Mathews, and F. Käppeler, *Astrophys. J.*, 286, (1984 in press).
24. J. A. Holmes, S. E., Woosley, W. A. Fowler, and B. A. Zimmerman, *Atom. Nucl. Data Tables*, 18, 306 (1976).
25. K. Takahashi and K. Yokoi (to be published).
26. E. Anders and M. Ebihara, *Geochim. Cosmochim. Acta*, 46, 2263 (1982).