INTERNAL EQUILIBRATION RATE OF ^{186}RE AND PRESOLAR GRAINS. Bradley S. Meyer and Joseph P. Johnson, Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978, USA.

Introduction: Overproduction of ^{186}Os in s-process models led Meyer and Wang to speculate that s-process enhanced s-process branching across ^{186}Re might occur because neutron capture from ^{185}Re would feed the long-lived 8^+ isomeric state at 149 keV, which, if it did not de-excite rapidly to the 1^+ ground state, would neutron capture to ^{187}Re, thereby bypassing ^{186}Os [1]. Meyer and Wang also speculated that this enhanced branching could explain the apparently large neutron flux environment inferred from Os isotopic measurements in presolar SiC grains [2].

Recent experiments and calculations suggest that it is no longer necessary to invoke a high-flux environment to explain the presolar grain data [3]. The suggestion further is that nuclear flow via the ^{186}Re isomeric state is unlikely to give the 20% enhancement in the branching needed to account for the ^{186}Os overproduction problem because the isomeric state will de-excite sufficiently rapidly to the ground [3] in s-process conditions.

In order to address this question, we seek to study the de-excitation of the 8+ isomeric (or meta-stable) state in ^{186}Re and its role is s-process branching quantitatively.

wn_two_level: Gupta and Meyer computed the effective equilibration rate between a ground state and a long-lived isomer by assuming all other states quickly attained a steady state because of their rapid destruction and creation timescales [4]. This treatment allows the nucleus to be divided into two separate nuclear species that can then be considered separate species in a nuclear reaction network. The two species are a ground state ensemble, that is, the ground state and the portion of all higher-lying states connected to the ground state, and the meta-state ensemble, that is the isomer and the portion of all higher-lying states connected to the isomer. Interestingly, a higher-lying state can belong to both ensembles, a portion of the state belonging to the ground state ensemble and another portion belonging to the meta-state ensemble. The effective equilibration rate is the transition rate between the two ensembles.

Calculation of the effective equilibration rates requires operations on matrices containing rates between individual levels within the nucleus. To facilitate calculation of internal equilibration rates for other nuclei, we have constructed a C code module, called wn_two_level, that performs these operations. wn_two_level is released under the GNU General Public License and is publicly available for download from http://www.webnucleo.org/home/modules

Equilibration rate of ^{186}Re: We used wn_two_level-based codes to compute the internal equilibration rate of ^{186}Re. Few of the necessary internal transition rates between nuclear levels are experimentally known, so, where necessary, we computed them from Weisskopf estimates [5]. The results are shown in Fig. 1. At low temperature ($T_9<10^7$), the transition rate from the isomer to the ground is simply that due to spontaneous transitions down. As the temperature rises, however, transition rates within the nucleus increase. Multi-step transitions then increase the effective transition rate from the isomer to the ground. Similarly, the transition rate from the ground to the isomer grows with temperature.

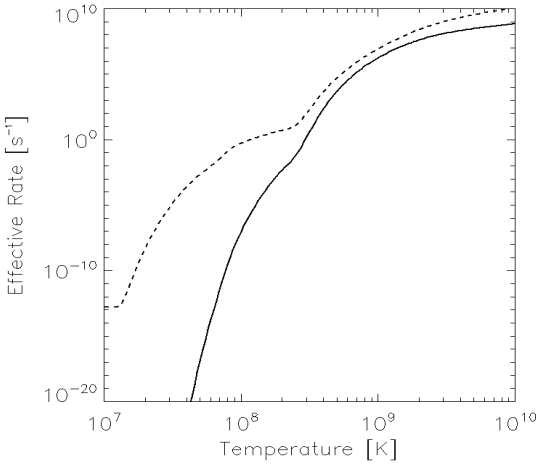

Fig. 1: The effective transition rate between the meta-stable state ensemble and the ground state ensemble (dashed curve) and the effective transition rate between the ground state ensemble and the meta-stable state ensemble (solid curve).

Nearly all transitions in the effective rate calculations shown in Fig. 1 rely on Weisskopf estimates. While these are only estimates, they are typically good to within a factor of ten or so. We repeated our calculations with all estimated transition rates increased or decreased by a factor of ten. The results were than the effective rates similarly increased or decreased by about a factor of ten. A factor of ten is thus a good estimate for the accuracy of our calculated transition rates between the ensembles.

Fig. 2 shows the result of an equilibration calculation for ^{186}Re at $T_9 = T/10^9$ K = 0.2 in which the initial population of the states is entirely in the isomer. As time progresses, however, the population of the ground state grows while that of the isomer declines. The two states are fully equilibrated within about one second, as expected from the effective rate at $T_9 = 0.2$ in Fig. 2.

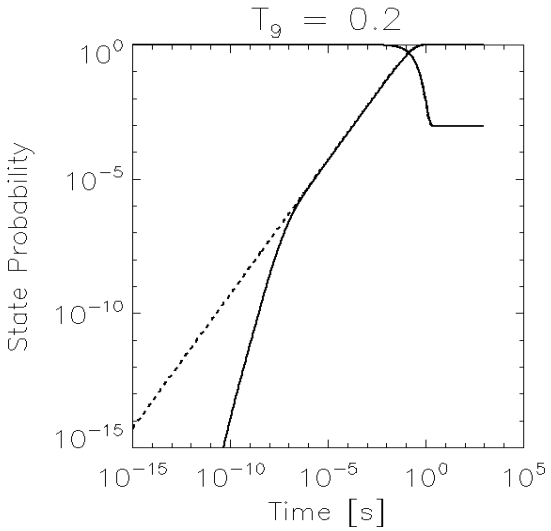

Fig 2: The state population probabilities for the ground state and isomer as a function of time for an internal equilibration calculation for ^{186}Re at T = 2x10^8 K in which the initial population is 100% in the isomer. The solid curve is for a calculation that includes all energy levels within about 1 MeV of the ground state while the dashed curve is for a two-state reduced system using the effective equilibration rate computed from wn_two_level.

s-Process branching at ^{186}Re: With an effective equilibration rate between the ground and isomeric states in ^{186}Re, it is possible to analyze the s-process branching in the steady-state approximation. If we neglect electron capture from ^{186}Re to ^{186}W, we find that the abundance of ^{186}Os, Y(^{186}Os), is related to the abundance of ^{185}W, Y(^{185}Os), by the expression

$$Y(^{186}Os) = \frac{\lambda_{\beta,^{186}\mathrm{Re},g}}{\Lambda_g} \times R \times \frac{\langle \sigma v \rangle_{^{185}\mathrm{Re}}}{\langle \sigma v \rangle_{^{186}Os}} Y(^{185}W)$$

where λ_β is a beta-decay rate, $\langle \sigma v \rangle$ is a thermally-averaged neutron-capture cross section, and Λ_g is the total destruction rate of ^{186}Re$_g$:

$$\Lambda_g = \lambda_{gm} + \lambda_{\beta,186\mathrm{Re}} + N_A \langle \sigma v \rangle_{186\mathrm{Re},g} \rho Y_n$$

where here λ_{gm} is the excitation rate from the ground to the meta-stable ensemble, ρ is the mass density and Y_n is the abundance of neutrons per nucleon. The quantity R is given by

$$R = \left[1 - \frac{\langle \sigma v \rangle_{^{185}\mathrm{Re},m}}{\langle \sigma v \rangle_{^{185}\mathrm{Re}}} \times \left(1 - \frac{\lambda_{mg}}{\Lambda_{m.}} \right) \right] \times \left[1 - \frac{\lambda_{mg}}{\Lambda_{m.}} \times \frac{\lambda_{gm}}{\Lambda_g} \right]^{-1}.$$

Here Λ_m is defined analogously to Λ_g (with λ_{mg} replacing λ_{gm}) and the subscript ^{185}Re indicates the total capture cross section from ^{185}Re while ^{185}Re,m indicates the cross section for capture from ^{185}W into the meta-stable (m) state of ^{186}Re . Were there no contribution to the branching at ^{186}Re from the isomer, R = 1 and

$$\Lambda_g = \lambda_{\beta,186\mathrm{Re}} + N_A \langle \sigma v \rangle_{186\mathrm{Re}} \rho Y_n$$

in which case the flow from ^{185}W to ^{186}Re would simply be the steady flow corrected for the simple branching at ^{186}Re. When there is flow into the meta-stable state and between the meta-stable state and the ground state, R differs from unity. R < 1 indicates an increase in the branching and a bypassing of ^{186}Os.

With rates λ_{gm} and λ_{mg} available from our wn_two_level-based code calculation, and assuming $\langle \sigma v \rangle_{^{185}\mathrm{Re},m} = \langle \sigma v \rangle_{^{185}\mathrm{Re},g}$, we find that R≈0.99 for T=2x10^8 K and a typical ρY_n for the s-process of nucleosynthesis. We thus find that the isomer increases the branching at ^{186}Re only the order of a few percent or less at typical s-process conditions. Indeed, at this temperature, the ground and isomeric states are nearly equilibrated. At lower temperatures the contribution is typically even less. This means that branching via the ^{186}Re isomer does not solve the problem of overproduction of ^{186}Os in the s-process. As emphasized by [3], however, this apparent overproduction is probably due to an incomplete accounting for all the other uncertainties in the problem. We further conclude that consideration of branching via the ^{186}Re isomeric state will only need to be accounted for when comparison of s-process models and presolar grain data reaches the level of roughly a percent.

While we have only considered ^{186}Re in this paper, there are isotopes in the s-process that have long-lived isomers at branch points. The code and techniques presented in this paper would be appropriate for them as well.

References: [1] Meyer B. S. and C. Wang (2007) *LPS XXXVIII,* Abstract #2055. [2] Brandon A. D. et al. (2005) *Science,* 309, 1233-1236 [3] Reisberg L. et al. (2009) *Earth & Planet. Sci. Lett., 277,* 334-344. [4] Gupta S. S. and Meyer B. S. (2001) *Phys. Rev. C, 64,* 025805. [5] Weisskopf V. F. (1951) *Phys. Rev., 82,* 1073.