The Re/Os clock: open questions regarding the neutron cross sections

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Abstract. The role of neutron cross section data on the analysis and interpretation of the Re/Os clock is described in some detail. Proposals for reducing some of the remaining uncertainties on the nuclear physics aspects of the clock are discussed.

INTRODUCTION

The Re/Os clock was proposed by D. Clayton in 1964 [1]. The various uncertainties playing a role in the analysis of this clock were investigated by Yokoi and collaborators [2]. The effect of the temperature dependent β-decay rate of ^{187}Re and of the e^--capture rate of ^{187}Os during astration were pointed out. These aspects received recently a neat clarification [3] as a consequence of the experimental determination of the β-decay half-life of fully-stripped ^{187}Re ions [4]. Hence, the main source of uncertainty, as far as the nuclear physics aspects of the clock are concerned, are presently related to the neutron capture cross sections which determine the s-process yields. Here we address the problem of the influence of the neutron cross section data on the analysis of the clock, in particular on the ^{186,187}Os capture rates, the principal players of this game.

NEUTRON CROSS SECTIONS DATA NEEDS

From the very beginning [1] it clearly appeared that the neutron capture cross sections or, more precisely, the neutron capture cross section ratio of ^{186}Os to ^{187}Os, was a crucial quantity, necessary to make this clock useful. A simple direct estimate of the impact of the capture cross section ratio $R_\sigma = \sigma(186)/\sigma(187)$ on the age determination can be obtained using a simple exponential model for the ^{187}Re r-process enrichment rate. The ratio between the comsmoradiogenic abundance of

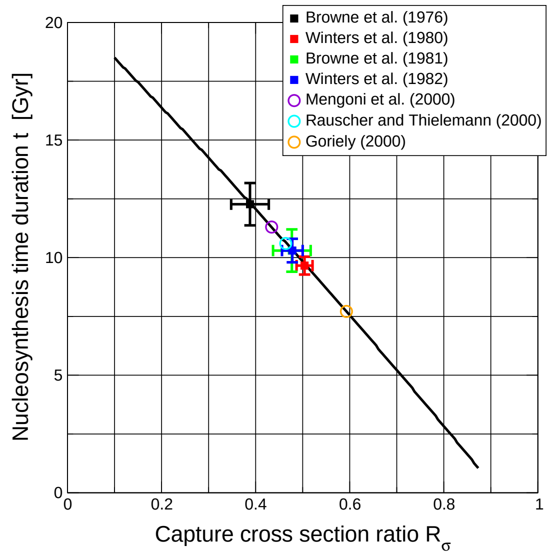

FIGURE 1. Time-duration of the nucleosynthesis related to the neutron capture cross section ratio R_σ. The experimental data are from Winters *et al.* [5] and Browne *et al.* [6]. The calculated values are from [7].

^{187}Os to the abundance of ^{187}Re is then given by

$$\frac{[^{187}\mathrm{Os}]_c}{[^{187}\mathrm{Re}]} = \frac{\Lambda - \lambda_{187}}{\Lambda} \frac{1 - \exp\left(-\Lambda t\right)}{\exp\left(-\lambda_{187} t\right) - \exp\left(-\Lambda t\right)} - 1.$$

Here, $\Lambda = (0.43t)^{-1}\mathrm{Gr}^{-1}$ is the enrichment rate and $\lambda_{187} = 0.0164\mathrm{Gr}^{-1}$ the ^{187}Re β-decay rate (laboratory rate, for the present purpose). This ratio is directly related to R_σ by

$$\frac{[^{187}\mathrm{Os}]_c}{[^{187}\mathrm{Re}]} = \frac{[^{187}\mathrm{Os}]/[\mathrm{Os}] - F_\sigma\ R_\sigma\ [^{186}\mathrm{Os}]/[\mathrm{Os}]}{[^{187}\mathrm{Re}]/[\mathrm{Re}]} \frac{[\mathrm{Os}]}{[\mathrm{Re}]},$$

derived imposing the s-process condition $\sigma(A)[A] \approx const.$ R_σ must evaluated with the capture cross sections averaged over a Maxwell-Boltzmann distribution of neutron energies at a given temperature and corrected for the effect of the thermal population of target states (incorporated into the F_σ factor in the relation above).

As can be seen in Figure 1, the time duration of the nucleosynthesis is within the range 7.5 Gyr $\leq t \leq$ 12.5 Gyr with the presently available capture cross sections data. The slope of the curve shown in Figure 1 is $|\delta t/\delta R_\sigma| = 22.5$ Gyr. Even excluding the extreme values for the cross sections, an uncertainty of ≈ 0.1 has to be assigned to R_σ. This reflects into an age uncertainty of 2.3 Gyr. Obviously, the uncertainty in R_σ has to be reduced down to 1-2% if one wants to reduce the age uncertainty of the clock to the level of the uncertainties deriving from other sources, such as the galactic chemical evolution modeling.

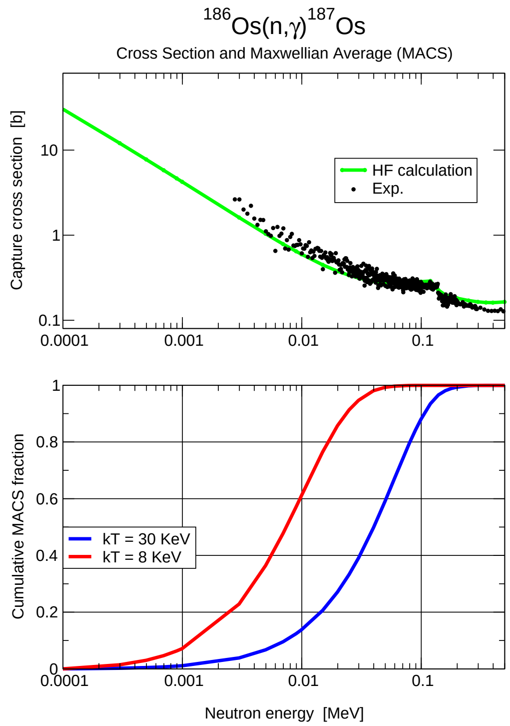

FIGURE 2. Neutron capture cross sections for ^{186}Os. The experimental data are from measurements made at ORELA. A comparison is shown with theoretical calculations based on the Hauser-Feshbach statistical model theory. The cumulative contribution to the Maxwellian averaged cross section (MACS) *vs* neutron energy is shown in the lower panel. Note the large contribution of the energy range below 10 keV to the $kT = 8$ keV situation, which dominates the stellar s-process environment. In this region data are very uncertain or even missing.

As an example, we show in Figure 2 the capture cross section of ^{186}Os as a function of the neutron energy. In the same figure, the cumulative fraction of the maxwellian averaged capture cross section (MACS) shows that, the lower energy side (say, $E_n \leq 10\,\mathrm{KeV}$) may influence a large fraction of the total rate (up to 60% for low temperatures).

STELLAR RATES

In general, the rate in a stellar environment may be influenced by the presence of low-lying excited states in the target nucleus. This is precisely the case in the $^{187}\mathrm{Os}(n,\gamma)^{188}\mathrm{Os}$. Here, ^{187}Os has an excited state at 9.8keV and several other states below 100 keV (see Figure 3). These states are populated in stellar environment for the temperatures of interest for the s-process ($kT \simeq 8\,\text{keV}$ to $kT \simeq 30\,\text{keV}$) and the capture cross section from these states are to be evaluated in order to provide the stellar rate.

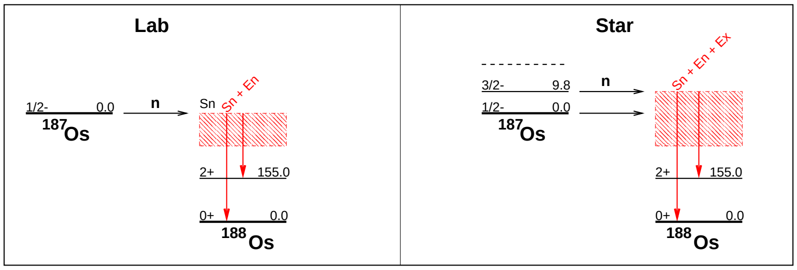

FIGURE 3. A scheme of the $n + {}^{187}$Os interaction processes in laboratory (left) and in a stellar environment (right) with some reaction channels shown.

An important role in these kind calculations is played by the presence of a super-elastic scattering channel, whenever the target nucleus is in an excited state. While in previous calculations of stellar enhancement factors the super-elastic scattering has been considered only by rough approximations, this effect can be treated in a self-consistent way once the inelastic scattering cross sections of ^{187}Os will be available.

Because $F_\sigma \approx 0.85$ at $kT = 30\,\text{keV}$, the effect of the stellar enhancement factor on the age determination gives an uncertainty of ≈ 2 Gyr. There is a plan to reduced this uncertainty with a neutron cross section measurement campaign, recently initiated at the CERN n_TOF facility [8].

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