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PROPOSAL

The Re/Os Clock Revisited

Abstract

The purpose of the proposed project of an accurate measurement of the relevant neutron cross sections of ^{186}Os and ^{187}Os is to remove the principal nuclear physics uncertainties in the analysis of the Re/Os cosmochronometer. The necessary cross section information will be obtained in complementary experiments at the n_TOF facility at CERN and at the Karlsruhe Van de Graaff accelerator. Transformation of these results into significantly improved stellar reaction rates will allow to evaluate the age of the elements in the framework of galactic chemical evolution models.

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1 Introduction

There are essentially three ways to estimate the age of the universe:

- a Cosmological way (based on the Hubble time definition)
- an Astronomical way (based on observations of globular clusters)
- a Nuclear way (based on abundances of long-lived radioactive species)

The most recent estimate of the Hubble constant (based on observations) provides $H_0 = 65 \pm 8$ km/sec/Mpc and implies an age of 15 ± 1.6 Gyr.

The age derived from observation of the luminosity of stars in globular clusters ranges from > 8.5 Gyr to 11.5 ± 1.3 Gyr (see for example [1]).

Methods based on radioactive decays of long lived nuclear species have been used since the very early years of cosmochronology. The age of the solar system, based on the age determination of the oldest rocks found on the earth surface, of moon samples and of meteorites has been obtained using these techniques [2].

The time duration of the nucleosynthesis of the heavy elements produced by neutron capture processes can be used to set limits on the age of the universe. Several cosmic clocks based on the abundances of long-lived radioactive isotopes have been proposed. Among these, traditional clocks are those based on the ^{235}U/^{238}U, ^{232}Th/^{238}U, ^{187}Os/^{187}Re, and Th/Eu abundances (for a recent review see for example [3]).

It has to be noted here that the quoted uncertainties in the ages given above always refer to *intrinsic* limitations of the adopted technique. For example, the age determined by the Hubble constant includes only the observational uncertainty and not the uncertainty due to the cosmological assumptions. This limitation is inherent to all the proposed clocks and therefore only the degree of consistency among the various clocks can provide a reliable estimate of the uncertainty in the determination of the age of the universe.

2 The Re/Os clock

The Re/Os clock has been proposed by Clayton in 1964 [4]. The clock is based on the extremely long half-life of ^{187}Re ($\tau_{1/2} = 42.3$Gyr) decay to ^{187}Os and on the fact that ^{186}Os and ^{187}Os are shielded against direct r-process production (see Figure 1). Then, thanks to the well established s-process abundances of ^{186}Os and ^{187}Os, the Re/Os clock can be characterized by the enhancement in the abundance of ^{187}Os due to the $^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os}$ decay (cosmoradiogenic ^{187}Os).

This clock is sensitive to galactic chemical evolution (GCE), which determines the formation rate of ^{187}Re, but independent on the primary r-process yields. In this respect it is the counterpart of the Th clock [5] for which the GCE part plays a minor role due to the abundance patterns recently observed in very old metal-poor stars. In turn, the primary r-process yields are crucial for the Th clock due to the yet uncertain (read *model-dependent*) description of the required r-process nucleosynthesis.

The most recent study of the Th clock results into an age of 15.6 ± 4.6 Gyr [5] where the combined effect of the uncertainties in the abundances and in the modeling of primary yields have been considered. The most recent estimate of an age based on the Re/Os clock provides 15 ± 2 Gyr [6] (see, however, the next section for a discussion on the uncertainty).

To establish the age of the universe, modern nuclear cosmochronology requires therefore considering both these two clocks as complementary, one to each other(see also [3]).

Since the original proposal of the nuclear cosmochronometer based on the abundances of the Re/Os pairs, several improvements on the data base for the analysis of this clock have been obtained.

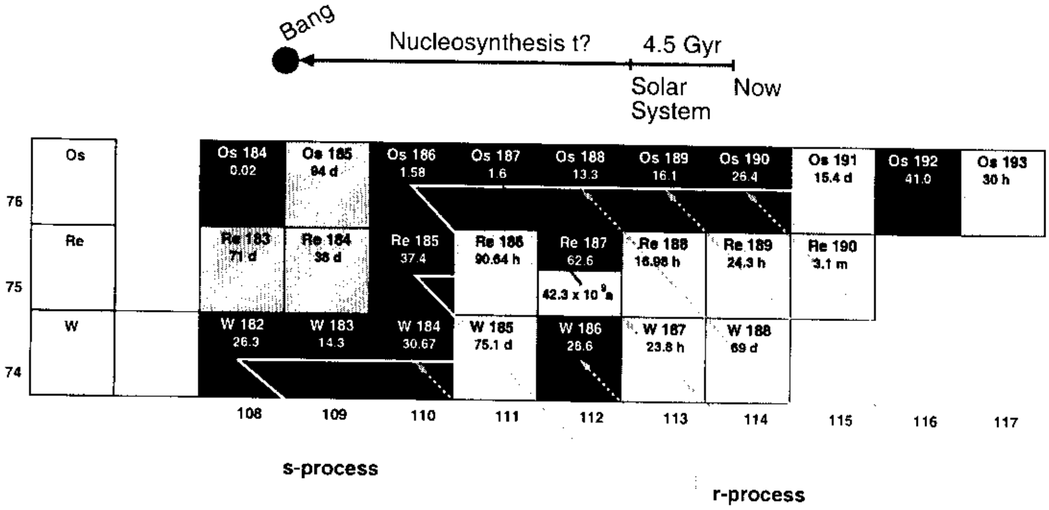

Figure 1: The nuclide chart in the $A \approx 187$ region. The s- and r-process paths for the nuclei involved in the clock are indicated.

The essential nuclear physics data required for the analysis of the Re/Os clock are

- the temperature dependence of the ^{187}Re half-life
- the stellar (n, γ) cross sections of ^{186}Os and ^{187}Os.

An important step forward in settling the first of these two items has been recently made by an experiment at GSI [7], where the β-decay half-life of fully-stripped ^{187}Re atoms has been measured, thus providing all the necessary information for describing the temperature dependence of the ^{187}Re β-decay rate.

Therefore, the status of the presently available (n,γ) cross sections of ^{186,187}Os constitutes the remaining crucial nuclear data uncertainty for the Re/Os clock.

3 Call for neutron cross section data

An estimate of the impact of the neutron capture cross section data on the analysis of the Re/Os clock can be made observing that the amount of ^{187}Os due to the decay of ^{187}Re is given by

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

This quantity can be evaluated from known isotopic and elemental abundances and from the neutron capture cross section ratio $R_\sigma \equiv \sigma(186)/\sigma(187)$. This ratio must evaluated with capture cross sections averaged over a Maxwell-Boltzmann distribution of neutron energies and corrected for the effect of thermal population of target states (incorporated into the F_σ factor in the relation above).

Using a simple exponential model for the time dependence of the chemical evolution of the galaxy, (over the time interval t the supernovae rate decreases exponentially with rate Λ), the ratio above can be calculated as

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

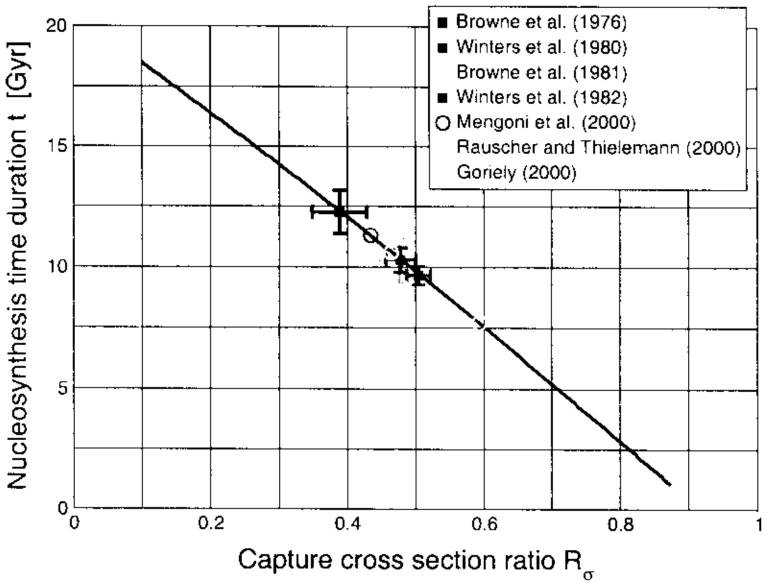

Figure 2: Time-duration of the nucleosynthesis related to the neutron capture cross section ratio R_σ. The experimental data are from Winters *et al.* [8] and Browne *et al.* [9]. The calculated values are from [10]. To obtain the age of the universe (≈ age of the galaxy), 4.5 Gyr (age of the solar system) must be added. The slope of the curve is quite large and equals to $|\delta t/\delta R_\sigma| = 22.5\,\mathrm{Gyr}$.

Here, $\Lambda = (0.43t)^{-1}$ and $\lambda_{187} = 0.0164\,\mathrm{Gyr}^{-1}$. The resulting ages, t, are shown *vs* the neutron capture cross section ratio R_σ in Figure 2.

The experimental $^{186,187}\mathrm{Os}(n,\gamma)$ cross section data so far available amount to a reactor-based measurement [9] and to an ORELA measurement [8] which do not cover the relevant energy range below 3 keV.

From the discrepant data shown in Figure 2, it appears that the quoted uncertainties associated with the two measurements have been strongly underestimated. Assuming an uncertainty of 0.1 in R_σ, we obtain an age uncertainty of 2.3 Gyr, larger than the claimed uncertainty of the clock itself [6]. Obviously, a more reliable value of this crucial quantity for the clock has to be established.

It is worth mentioning that the contribution of the low energy part may be crucial in the reaction rate evaluation, especially in the case of low s-process temperatures (see Figure 3). The previous experimental determinations of this ratio may have suffered form additional uncertainties related to the neutron sensitivity of the γ-ray detectors used in previous measurements. This might be the cause for the disagreement, in case of the $^{186}\mathrm{Os}$ cross section, appearing in the comparison of present experimental data with model calculations, as shown in Figure 3.

Finally, the inelastic scattering cross sections of $^{187}\mathrm{Os}$, which are important for evaluating the stellar enhancement factor, are still uncertain and fairly incomplete.

Therefore, we suggest a project consisting of three steps, starting with improved cross section measurements, followed by the evaluation stellar cross sections including the effect of excited nuclear states, and completed by a study of the GCE effects on the Re/Os

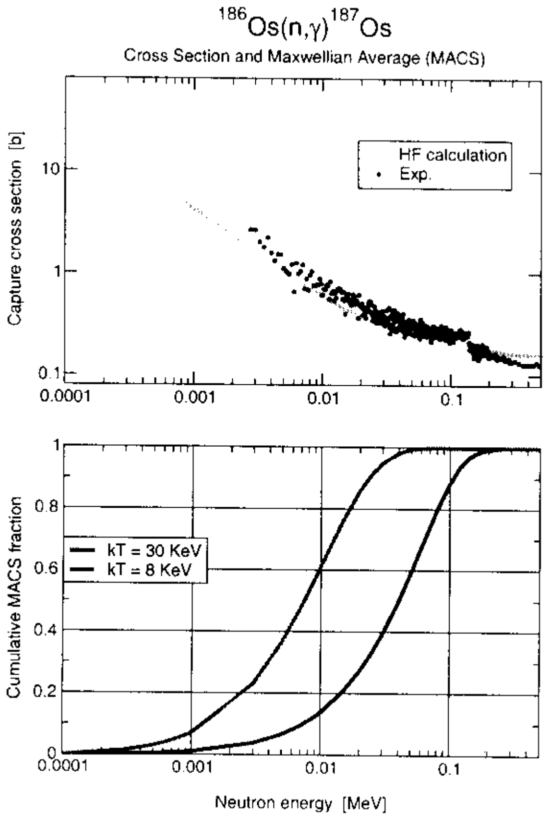

Figure 3: Neutron capture cross sections for ^{186}Os. The experimental data are from measurements made at ORELA. A comparison is shown with theoretical calculations based on the Hauser-Feshbach statistical model theory. The cumulative contribution to the Maxwellian averaged cross section (MACS) *vs* 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.

abundances.

4 Cross section measurements

For a substantial improvement of the Re/Os clock accurate measurements are suggested for

1. the (n,γ) cross sections of ^{186}Os and ^{187}Os, and
2. the (n,n') cross section of ^{187}Os .

We propose to measure the (n,γ) cross sections of ^{186}Os and ^{187}Os as a function of neutron energy over the entire astrophysical energy range from 0.1 to 500 keV in a dedicated experiment at the CERN n_TOF facility using an array of 4 C_6D_6 liquid scintillators.

The samples for the planned measurement will be provided by Oak Ridge National Laboratory in form of metal powder. In view of the available ^{186}Os and ^{187}Os enrichments (see Table I) the cross sections of the other Os isotopes must be determined as well to provide the corresponding corrections.

Table 1: Isotopic composition of samples

Sample isotope	Isotopic composition					
	186	187	188	189	190	192
186	79.48	0.91	4.88	4.29	5.09	5.32
187	1.06	70.43	12.73	5.13	5.42	5.21
188	0.11	0.12	94.99	2.55	1.27	0.97
190	<0.05	<0.05	0.57	1.01	96.56	1.86

Based on the present cross sections and assuming the simulated detection efficiency for capture events of 10%, the sample masses will be chosen such as to achieve count rates of typically 10^4 to 10^3 $events/(\Delta E \times pulse)$ with $\Delta E/E = 0.1$ for neutron energies of 0.1 and 500 keV, respectively. Though this estimate indicates that a total measuring time per isotope of 2 to 3 days might be sufficient, the unavoidable backgrounds will require about two times better statistics. Therefore a total beam time of 14 days is requested for this experiment.

From the existing expertise in the collaboration for measurements with C_6D_6 detectors [11, 12] the relative cross section shapes can be determined with an accuracy of better than 2%. The overall absolute uncertainty of the resulting cross section ratio ^{186}Os/^{186}Os is expected to be 4% or better, the main contributions coming from the C_6D_6 efficiency for capture events (weighting function) and from the flux measurement.

It is important to note, that this experiment will definitely solve the unsatisfactory situation at low neutron energies. Most of the s abundances are produced by the ^{13}C$(\alpha, n)^{16}$O neutron source at a thermal energy of 8 keV. Under these conditions, about 60% of the stellar rates are contributed by the cross sections in the neutron energy range below 10 keV where the cross sections are either very uncertain or even missing (Fig. 3). The proposed experiment will also resolve the present ambiguity in the cross section shape of ^{186}Os.

For further improvement, a complementary cross section measurement will be performed in a restricted energy range from 5 to 200 keV using the 4π BaF_2 array at the Karlsruhe Van de Graaff accelerator. The combination of both data sets will eventually provide the 1% accuracy required for the improved analysis of the Re/Os clock.

In parallel, the measurement of the (n, n') cross section of ^{187}Os in the relevant range from 10 to 100 keV neutron energy is also planned at the Karlsruhe Van de Graaff, taking advantage of the fast timing and of the possibility for tailoring the neutron spectra obtained from proton bombardment of various light isotopes.

5 Reaction rate evaluation

The evaluation of the neutron capture reaction rate can be easily made once the capture cross section is available. However, 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 of the ^{187}Os$(n, \gamma)^{188}$Os. Here, ^{187}Os has an excited state at 9.8 keV and several other states below 100 keV. These states are populated in a stellar plasma environment for temperatures of interest in the s-process nucleosynthesis ($kT \simeq 8$ keV to $kT \simeq 30$ keV) and the capture cross section *from* these states are to be evaluated in order to provide the stellar rate.

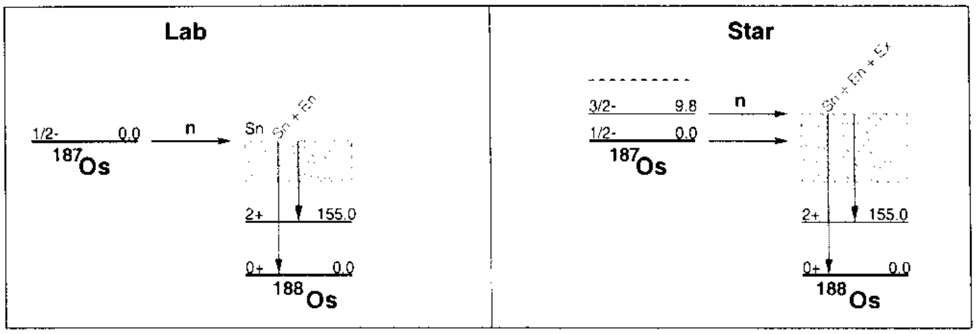

Figure 4: A scheme of the n + ^{187}Os interaction processes in laboratory (left) and in a stellar environment (right). All the reaction channels induced by the thermal population of ^{187}Os target states need to be included in the evaluation of the neutron capture rate.

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.

A preliminary evaluation of the effect of the stellar enhancement factor to the determination of the age furnish a value of $\approx$ 2 Gyr. This uncertainty will be considerably reduced by the results of the present project.

6 Stellar models and Galactic chemical evolution

In this last part the astrophysical consequences of the experimental results for the Re/Os clock will be worked out, starting from the s-process yields for stars of different mass and metallicity. These results will then be used for investigating the consequences for the Re/Os clock in terms of GCE. Essentially, here, the simple uniform-synthesis model adopted in the estimate of the $[^{187}\mathrm{Os}]_c/[^{187}\mathrm{Re}]$ ratio shown above, will be replaced by up-to-date GCE model which will include the effect of astration and temperature dependence of the ^{187}Re β-decay half-life [13]. In turn, a consistency of the results with the age determined with other clocks could be used to constrain the GCE models.

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