Neutron Capture Cross Sections for the Re/Os Clock

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Abstract. The radioactive decay of ^{187}Re $\rightarrow$ ^{187}Os ($t_{1/2}$ = 43 Gyr) is suited for dating the onset of heavy-element nucleosynthesis. The radiogenic contribution to the ^{187}Os abundance is the difference between the natural abundance and the corresponding *s*-process component. This component can be obtained via the well-established σN systematics using the neighboring *s*-only isotope ^{186}Os, provided the neutron-capture cross sections of both isotopes are known with sufficient accuracy. We report on a new set of experiments performed with a C_6D_6 detector array at the n_TOF neutron spallation facility of CERN. The capture cross sections of ^{186}Os, ^{187}Os, and ^{188}Os have been measured in the neutron-energy range between 1 eV and 1 MeV, and Maxwellian-averaged cross sections were deduced for the relevant thermal energies from kT=5 keV to 100 keV.

INTRODUCTION

Since Clayton proposed the Re/Os cosmochronometer forty years ago [1] a considerable effort has been devoted to determining with the required accuracy the basic nuclear physics quantities hampering its complete utilization. Not long ago, the temperature dependence of the half-life of ^{187}Re was deduced by the measurement of the half-life of fully stripped ^{187}Re performed at GSI [2]. This result provided the necessary experimental information on what was considered the largest source of uncertainty of the clock [3]. The effect of the shorter ^{187}Re half-life under stellar conditions has been analyzed by Takahashi [4] with the main conclusion being that the clock is still reliable.

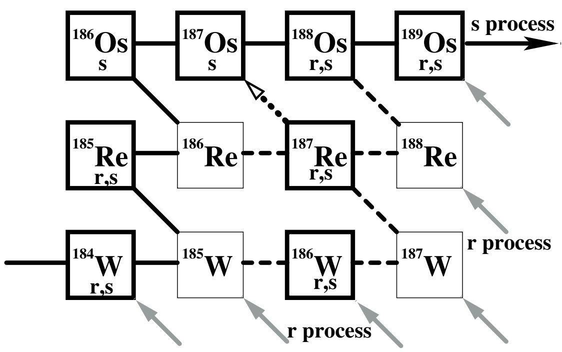

FIGURE 1. Canonical *s*-process (thick solid line) and r-process paths (gray arrows) in the mass region around $A = 187$. Branchings in the *s*-process path are denoted by dashed lines. Stable or long-lived nuclei are denoted by bold boxes, including their nucleosynthetic origin. The ^{187}Re β-decay is marked as a dotted arrow.

The effect of the *s*-process branchings (see Fig. 1) has been investigated [5] and the branching at ^{185}W was analysed on the basis of a new evaluation of the ^{185}W(n,γ) cross section obtained by the measurement of the inverse reaction at S-DALINAC [6] resulting in a discrepancy of 20% between the calculated and observed abundance of ^{186}Os. This result indicates the possibility of an error in the tabulated osmium cross sections.

Measurements of neutron-capture cross sections of ^{186}Os and ^{187}Os have been performed in the past by Winters *et al.* [7] and Browne *et al.* [8] in limited energy ranges,[1], which makes it difficult to calculate the Maxwellian-averaged cross sections at the energies predicted by the recent *s*-process models. In fact, a thermal energy of kT=8 keV is estimated for the ^{13}C(α,n)^{16}O reaction, which is considered to be the main neutron source for the *s*-process in thermally pulsing low-mass AGB stars. To evaluate the Maxwellian-averaged cross section in this wider range of relevant thermal energies, the cross section between 0.1 keV and 500 keV has to be known.

Moreover, the (n,γ) cross section of ^{187}Os measured in the laboratory is not sufficient to determine the stellar cross section because at the typical energies of the *s*-process a large fraction of the ^{187}Os nuclei are excited to the first level at 9.75 keV above the ground state [9]. To allow theoretical calculations of the (n,γ) cross section of the excited ^{187}Os nucleus, additional indirect experimental data are required. The measurement of the inelastic scattering cross section of ^{187}Os can help to evaluate the weight of the scattering channels of the compound nucleus. Measurements of this cross section were already performed at 34 keV [10] and 60 keV [11] but the uncertainties of these measurements are considered too large to allow a good theoretical determination of the Maxwellian-averaged cross section at stellar conditions [12]. A measurement of the inelastic-scattering cross section is planned at the 3.7-MV Van de Graaff accelerator of Forschungszentrum Karlsruhe. The measurement of neutron-capture cross sections performed at n_TOF and reported here is an attempt to improve the present uncertainties and to obtain consistent data over the entire neutron energy range for the isotopes of interest.

EXPERIMENTAL METHOD

The measurements of the ^{186,187,188}Os capture cross sections have been performed at the n_TOF facility at CERN [13]. Neutrons are produced by spallation reactions of 20-GeV protons on a lead target. Protons are accelerated by the CERN Proton Synchrotron (PS) in bunches of up to 7×10^{12} particles. The typical repetition rate of the proton beam of the PS accelerator for n_TOF is 0.4 Hz. A flight path of 185 m is used to obtain good energy resolution via the time-of-flight (TOF) technique. A flux of $\sim 10^6$ neutrons per bunch is obtained in the experimental area. A set of collimators is used to reduce the neutron beam diameter to 4 cm at the sample position.

In-beam photons are produced by the spallation reactions, leading to a prompt "γ-flash" that is used to identify the starting time t_0 of each pulse. In addition, thermal neutron capture on the materials surrounding the lead target, and especially in the cooling water are responsible for an additional γ-ray production that takes place between 1 μs and a few 100 μs after the t_0 and interferes with neutron-induced events in the experimental area in the energy range of astrophysical interest. This effect, which results in a background component for capture events, has to be carefully analysed, e.g., by means of neutron filters. The neutron filters are mounted 50 m up-

[1] The range of Browne measurements is from 1 keV to 148 keV. The Winters measurement covered a range from 2.5 keV to 2.5 MeV.

stream of the experimental area and can be inserted into or removed from the beam at any time. The material and the thickness of each filter have been chosen in order to ensure that the respective strongest resonances are becoming "black."

Experimental Setup and Procedure

Enriched ^{186,187,188}Os samples have been provided by Oak Ridge National Laboratory in the form of metallic powder and in amounts of 2 g for each sample. The main contaminant in the ^{187}Os sample (enriched to 70%) and in the ^{186}Os sample (enriched to 80%) is ^{188}Os. Therefore the ^{188}Os cross section has been additionally measured to improve the isotopic correction[2]. The sample material was sealed in cylindrical Al cans, 1.5 cm in diameter.

A thin foil of ^{6}Li, viewed by four silicon detectors located outside the beam served as a neutron monitor. The capture γ-ray detection system is based on two C_6D_6 scintillators, specifically designed for the n_TOF capture setup. The two detectors were mounted perpendicular to the neutron beam line and 9.8 cm upstream with respect to the sample position in order to reduce the effect of in-beam γ-ray scattering. The three osmium samples were mounted on a sample changer together with an empty canning for measuring the background, a lead sample for evaluating the effect the in-beam γ-rays, and a carbon sample to evaluate the effect of scattered neutrons. To determine carefully the neutron flux intercepted by the samples, a gold sample with the same diameter has been used. Additional measurements with neutron filters, 3-cm-thick aluminum and 1-mm-thick tungsten, have been performed.

DATA ANALYSIS AND RESULTS

The response of the scintillators has been analysed by means of the Pulse-height weighting technique [15] to make the detector efficiency proportional to the γ-ray energy, and hence independent on the multiplicity of the different capture cascades. The weighting functions were determined via Monte Carlo simulations, and were calculated independently by CEA/Saclay and INFN Bari using two different simulation tools. The count rate measured with the osmium samples has been corrected for "ambient" backgrounds by subtracting the spectra measured with the empty can. The neutron-scattering background obtained with a measurement of the carbon sample has been found to be negligible. The main source of background is the scattering of in-beam γ-rays.

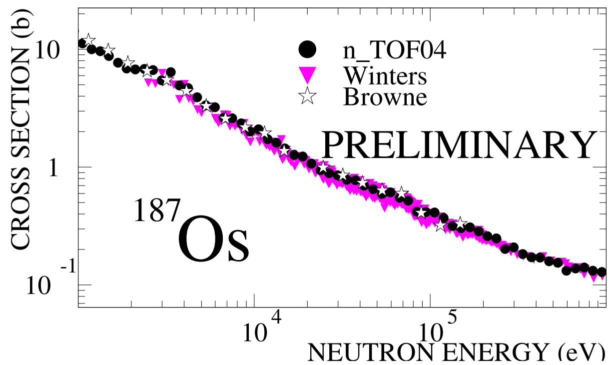

FIGURE 2. Preliminary ^{187}Os cross section between 1 keV and 1 MeV. The uncertainties on the n_TOF data are of the order of the point size or slightly smaller.

It has been evaluated considering that its shape at different neutron energies is given by the count rate measured with the lead sample. However, this rate had to be rescaled according to the different scattering properties of the osmium samples. The scaling factor was determined in simulations using GEANT 3.21, based on the photon-energy spectrum obtained by extensive simulations of the n_TOF facility [13].

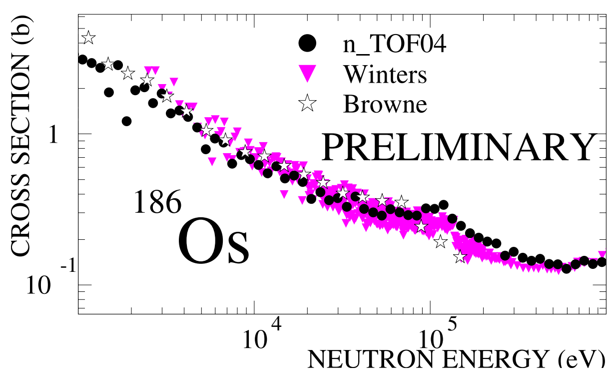

FIGURE 3. Preliminary ^{186}Os cross section between 1 keV and 1 MeV.

The results of the simulations were validated via spectra measured with the filters in beam. By rescaling the lead spectrum measured with the filters by a factor estimated with the simulations, the measured level of the black Al and W resonances could be perfectly matched. In this way it was also verified that the shape of the gamma background was the same for lead, osmium, and gold. This test yields good agreement for all the samples in the entire TOF region where this background component is significant. Assuming that the ratio between the in-beam γ background and ambient background is similar for osmium and lead, this comparison was applied at lower neutron energies as well. Also in this region

[2] All the stable osmium isotopes were measured by Browne from 1 keV to 148 keV [8]; only theoretical data are available at other energies [14].

good agreement was obtained for all samples but ^{188}Os. For this isotope, the background at low neutron energies seems to be slightly overestimated and the explanation of this result requires further investigation.

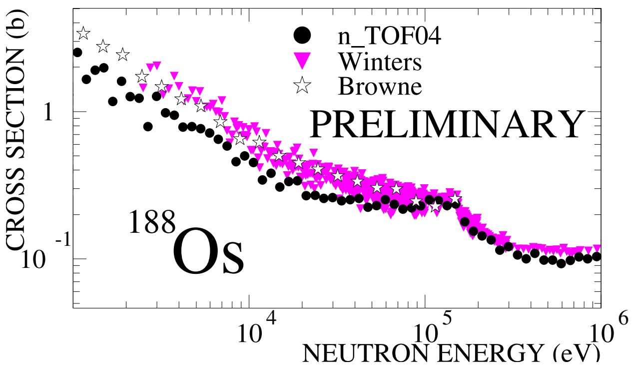

FIGURE 4. Preliminary ^{188}Os cross section between 1 keV and 1 MeV.

The neutron flux has been evaluated from the gold spectrum after subtraction of the different background components. In this analysis we have used the gold cross section of Macklin *et al.* [16] normalised to the more accurate measurement of Ratynski *et al.* [17].

The preliminary results for the capture cross sections of ^{186,187,188}Os are shown in Figs. 2, 3, and 4 in comparison with the previous data. For ^{186,187}Os the Maxwellian-averaged cross sections at 30 keV calculated with these preliminary data are in good agreement with the results of [7], but there seems to be a significant difference in the case of ^{188}Os.

CONCLUSIONS AND OUTLOOK

The preliminary results of neutron-capture cross sections of ^{186,187,188}Os measured at n_TOF exhibit good agreement with the previous results for ^{187}Os, whereas ^{186}Os and ^{188}Os are showing a somewhat different energy dependence. This will be verified by a refined background analysis, in particular in the case of ^{188}Os. In addition, the flux determination versus the Au standard will be extended toward lower energies by using the 4.9-eV resonance. The analysis will be extended to the resonance region, where resonance parameters will be extracted using the SAMMY code.

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