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Determination of Neutron Cross Sections and
Resonance Parameters for the Stable Tellurium Isotopes,
for Thallium 205 and for the Osmium Isotopes

Progress Report

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Abstract

Initial measurements by LLL and NBS of the ratio of the ^{186}Os capture cross section to that of ^{187}Os near 30 keV, provided a crucial input parameter for use of the Re-Os chronometer to estimate the duration of nucleosynthesis and hence the age of the universe. The resulting estimate of ≈ 20 billion years was much longer than the estimate from the only other method, U-Th dating. The Re-Os chronometer requires, however, not ratios of cross sections measured at laboratory temperatures, but rather the ratio appropriate to the stellar environment in which nucleosynthesis by the s-process occurs. Hence capture from low lying excited states is important. The capture cross section from the 9.75 keV first excited ^{187}Os state must be calculated using Hauser-Feshbach calculations. These calculations require estimates of level densities, neutron transmission functions (for ground and excited states) and radiative transmission functions. These calculations can be experimentally checked by measurements of the total and inelastic cross sections near threshold. The inelastic experiment is particularly difficult because of the requirement of low background and relatively high efficiency for detection of ≈ 30 keV neutrons. A proton-recoil detector has been developed which appears to provide adequate efficiency and energy resolution. A novel filter composed of alternate layers of iron, aluminum and air has been designed to eliminate neutrons other than those in the 25 keV Fe and Al window. Major problems in background reduction persist and might be helped with a sample of ^{187}Os of isotopic purity greater than that of the presently available 70% ^{187}Os sample.

Introduction

With a half-life $\tau = 4 \times 10^{10}$ years, greater than the best estimates of the age of the universe $\approx 10^{10}$ years, $^{187}\text{Re} \xrightarrow{\beta} ^{187}\text{Os}$ is one of the few decays which measure the time since element formation began. It is fortuitous that ^{187}Os , shielded from the r-process of nucleosynthesis by ^{186}W , can only be made by the s-process and by the decay of ^{187}Re . Hence, an estimate of the duration of nucleosynthesis, T , requires the rate of formation of ^{187}Os by neutron capture on ^{186}Os , the rate of formation of ^{188}Os by neutron capture on ^{187}Os , the rate of decay of ^{187}Re to ^{187}Os and the present abundances.

Given these measurable or calculable quantities, T can be calculated by the coupled set of equations,

$$^{7}\text{Os}_{\beta}/^{7}\text{Re} = \frac{^{7}\text{Os}/^{0}\text{Os} - [\bar{\sigma}_{\gamma}^{*}(6)/\bar{\sigma}_{\gamma}(7)] ^{6}\text{Os}/^{0}\text{Os}}{^{7}\text{Re}/^{0}\text{Re}} \frac{^{0}\text{Os}}{^{0}\text{Re}}$$

$$^{7}\text{Os}_{\beta}/^{7}\text{Re} = \frac{\lambda - \lambda_7}{\lambda} \frac{e^{\lambda_7 T} (1 - e^{-\lambda T})}{1 - e^{-(\lambda - \lambda_7)T}}$$

where

$^{7}\text{Os}_{\beta} \equiv$ abundance of ^{187}Os from the decay of ^{187}Re , etc.

$e^{-\lambda t} \equiv$ Rate of decrease of the r-process element production

$\lambda_7 \equiv \frac{\ln 2}{\tau}$: the ^{187}Re decay rate

$\bar{\sigma}_{\gamma}^{*}(6) \equiv$ 30 keV Maxwellian average capture cross section for $^{186}\text{Os} + n$ at stellar temperature. etc.

The $\bar{\sigma}_Y^*(6,7)$ takes into account the population of the low lying nuclear excited states due to the temperature of the stellar interior, the site of the s-process. This means that capture not only from the ground state, but also from excited states within ~ 50 keV of the ground state will be important. Hauser-Feshbach calculations have been done to estimate this effect, but the results of such calculations are sensitive to the assumptions made about the average nuclear level properties, i.e., level densities and widths.

The required capture cross section $\bar{\sigma}_Y^*$ has the form (summing over the ground state and excited states),

$$\bar{\sigma}_Y^* \sim g(\text{gs}) \bar{\sigma}_Y(\text{gs}) e^{-E_0/kT} + g(1\text{st}) \bar{\sigma}_Y e^{-E_1/kT} + \dots$$

or

$$\bar{\sigma}_Y^* = R^* \bar{\sigma}_Y(\text{gs}),$$

where the factor R^* must be calculated. The Hauser-Feshbach calculation of the factor R^* depends on neutron transmission functions $T_n(J\ell)$ in both the entrance and exit channels for all states, however it is clear that only states near the ground state will be important. In the case of ^{187}Os , the first two excited states are at 9.75 keV and 75 keV. Hence the effect of at least the 9.75 keV level on the reaction rates involving ^{187}Os must be calculated. Measurements of capture, total and scattering cross sections are required to provide reliable estimates of these parameters.

Progress and Current Status of Three Experiments

A. Capture Cross Section Measurements

Collaborators: R. L. Macklin and J. Halperin

Facility: ORELA, 40 meter Station, Flight Path 7

Status: Preliminary result: $\bar{\sigma}_Y(6)/\bar{\sigma}_Y(7) = 0.52$

Cosmological Implications: $T \approx 11.5 \times 10^9$ yr.

Age of Universe $\approx 18 \times 10^9$ yr.

The capture cross section measurements have been completed and preliminary analysis of the data yield a ratio of maxwellian averaged cross sections $\bar{\sigma}_Y(6)/\bar{\sigma}_Y(7) = 0.52$, larger than the result 0.39 published earlier by Browne and Berman and the result 0.41 by Browne, Lamaze and Schroder. Under the same set of assumptions used by the earlier workers, this cross section ratio implies a duration of nucleosynthesis $T \approx 11.5 \times 10^9$ yrs, $\approx 1.5 \times 10^9$ years shorter than that obtained by them, but well within their reported errors, $\pm 3 \times 10^9$ yr. Hence the Re-Os clock continues to predict a longer duration of nucleosynthesis than derived from U-Th dating method, $T = (7 \pm 2) \times 10^9$ yr., and hence an estimate of the age of the universe $\approx 18 \times 10^9$ years, larger than $\approx 14 \times 10^9$ years derived from other methods.

B. Total Cross Section Measurements

Collaborators: J. A. Harvey and N. W. Hill

Facility: ORELA, 80 meter station, Flight Path 1

Status: Measurements of the total cross section for ^{186}Os , ^{187}Os , and ^{188}Os from ≈ 200 eV to 300 keV incident neutron energy were completed March 6, 1979

The measurements coupled with the capture data should yield estimates of the neutron transmission functions and level densities for improvement of the calculation of R^* . For a given channel, $(J\ell)$, the total average cross section can be written as the sum of terms,

$$\begin{aligned}\bar{\sigma}_{nn} &\sim \frac{T_n^0(J,\ell) T_n^0(J,\ell)}{T_{\text{tot}}(J\ell)} && \text{elastic (gs)} \\ \bar{\sigma}_{nn'} &\sim \frac{T_n^0(J\ell) T_n^1(J\ell)}{T_{\text{tot}}(J\ell)} && \text{inelastic (gs,1st)} \\ \bar{\sigma}_{n\gamma} &\sim \frac{T_n^0(J\ell) T_\gamma(J\ell)}{T_{\text{tot}}(J\ell)} && \text{capture (gs)}\end{aligned}$$

Hence, at energies below the inelastic threshold, the total cross section measurements combined with the capture measurements yield the ground state transmission function T_n^0 . These measurements have just been completed and data analysis is just beginning.

C. Inelastic Scattering Cross Section Measurements

Collaborators: N. W. Hill, G. Morgan⁺, R. L. Macklin,
J. A. Harvey

Facility: ORELA, 10 meter station, Flight Path 3

- Status:
- 1) A neutron detector capable of reasonable efficiency at ≈ 30 keV is being developed.
 - 2) The development of the collimation and experimental station is $\approx 50\%$ completed.
 - 3) The Fe/Al short filter transmission has been estimated.

As noted above, the calculation of the factor R^* by which the observed laboratory capture cross sections are modified by the contribution from nuclear excited states at stellar temperatures requires as input the neutron transmission factor $T_n(J\ell)$ for all states which are populated. The average inelastic scattering cross section for a given channel $(J\ell)$ can be written

$$\sigma_{nn'}^{J\ell} \sim \frac{T_n^0(J\ell) T_n^1(J\ell)}{T_{\text{tot}}(J\ell)}$$

and hence a measurement of this cross section, coupled with information from the capture and total cross section measurements yield estimates of $T_n^1(J\ell)$, the neutron transmission function for the first excited state.

Work is in progress to measure this cross section near neutron

⁺Present address: Los Alamos Scientific Laboratory.

energy 25 keV using a filtered ORELA neutron beam (see figure 1). The filter must have a relatively narrow (4 keV), high transmission window near 25 keV, but be essentially opaque outside this region. Calculations (preliminary by R. L. Macklin) of the transmission properties for the composite Al/Fe filter (see figure 2) described in the previous progress report have been completed. The calculation is an approximate analytic calculation which estimates the total transmission of the filter by calculating the probability of escape from the filter via an air gap at each thin sheet. The spacing between the Fe and Al sheets was then adjusted to produce adequate relative transmission of the filter near 24.5 keV. It is estimated that the filter will have ≈ 200 times greater transmission at 24.5 keV than at 34.3 keV. While these calculations are encouraging, Monte Carlo calculations will be done to further confirm the transmission properties of the filter. It appears that 34.3 keV neutrons inelastically scattered from ^{187}Os (losing 9.75 keV) can be resolved from the 24.5 keV elastically scattered neutrons since they will be separated by the 10 meter flight path in time by ≈ 780 ns. The filter serves to remove most of the elastically scattered neutron background.

In addition, the group at Karlsruhe has continued to express an interest in attempting the inelastic experiment on their machine. John Browne, Livermore, and the ORELA group continue to strongly encourage this collaborative effort. Initial attempts to detect the inelastic level in tantalum (1^{st} excited state at ≈ 14 keV) by the Karlsruhe group indicate that they seem to have adequate neutron flux, energy resolution, and sufficiently low backgrounds to warrant an attempt to do the $^{187}\text{Os}(n,n')$ experiment at Karlsruhe. This experiment probably will take

place late this summer or next fall.

The attempt described in the current proposal to do the $^{187}\text{Os}(n,n')$ experiment at the NBS accelerator seems to have demonstrated that the NBS neutron yield is too low by a factor of 100 and the energy resolution not adequate. Thus, unless significant improvements at the NBS facility are achieved, that collaborative effort will not be actively pursued.

Figure Captions

Figure 1. The experimental arrangement for the $^{187}\text{Os}(n,n')$ experiment.

Note the position of the short Fe/Al filter.

Figure 2. The short Fe/Al filter.

Figure 3. Transmission (relative) of the short Fe/Al filter near 25 keV for the "best" thicknesses of the Fe, Al and air gaps.

Figure 1

note: Separation
Dimples near
corners

note: Separation Dimples
near corners

The Short Fe/Al Filter
RRW/RLM

05 Sample

Detector

approx. To Scale

Figure 2

Figure 3