Determination of Neutron Cross Sections and
Resonance Parameters for the Stable Tellurium Isotopes, *for*
Thallium 205, *needed for* the Osmium Isotopes, and for Uranium 238

PROGRESS REPORT

MASTER

March 1, 1979-November 1, 1979

R. R. Winters

Denison University
Granville, Ohio 43023

October 29, 1979

Prepared for the Department of Energy

Contract No. EY 76-S-02-2696.A003

DISCLAIMER
This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

EB
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Abstract

This report period, March-November 1979, includes the most intellectually stimulating and professionally satisfying events which I have experienced. We have:

- a. Successfully measured the ratio of Maxwellian-averaged $^{186,187}\text{Os}(n,\gamma)$ cross sections and the resulting Re-Os age of the elements is consistent with that from U/Th.
- b. The ORELA measurements of the capture cross sections stimulated a reexamination of the only previous work (Browne and Berman¹). Browne has now concluded that their earlier measurement was in error and has revised their result to be in good agreement with the ORELA result.
- c. The ORELA measurement of $\bar{\sigma}_{\gamma}^{186}\text{Os}(n,\gamma)/\bar{\sigma}_{\gamma}^{187}\text{Os}(n,\gamma)$ stimulated a reexamination by Browne, Lamaze and Schroder² of their measurement of the ratio. They now report a result in excellent agreement with the ORELA result.
- d. The $^{187}\text{Os}(n,n')/^{187}\text{Os}(n,n)$ cross section ratio required by the Re-Os chronometer has been measured and the resulting inelastic cross section implies a smaller correction to the laboratory capture cross section ratio than had been predicted by Holmes, Woosley and Fowler.
- e. The $^{238}\text{U}(n,n')/^{238}\text{U}(n,n)$ 82 keV cross section ratio has been measured and the results indicate that the only earlier

measurement had significantly underestimated the inelastic cross section.

- f. A new ORELA research program has been suggested by our analysis of high resolution neutron cross section data in terms of the optical model for partial ℓ -waves.

My sabbatical leave supported by DOE has been a stimulating experience and I look forward to carrying on this research program during the next years at Denison University.

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,

$$^{70}\text{Os}_{\beta}/^{7}\text{Re} = \frac{^{70}\text{Os}/\text{Os} - [\bar{\sigma}_Y^*(6)/\bar{\sigma}_Y^*(7)] ^{60}\text{Os}/\text{Os} \frac{\text{Os}}{\text{Re}}}{^{7}\text{Re}/\text{Re}}$$

$$^{70}\text{Os}_{\beta}/^{7}\text{Re} = \frac{\lambda - \lambda_7}{\lambda} \frac{(1 - e^{-\lambda T} - 1)}{1 - e^{-(\lambda - \lambda_7)T}}$$

where

$^{70}\text{Os}_{\beta} \equiv$ 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

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

The $\bar{\sigma}_\gamma^*(6,7)$ 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 $\bar{\sigma}_\gamma^*$ has the form (summing over the ground state and excited states),

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

or

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

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. R. Winters, R. L. Macklin and J. Halperin

Facility: ORELA, 40 meter Station, Flight Path 7

Status: Result: $\bar{\sigma}_\gamma(6)/\bar{\sigma}_\gamma(7) = 0.504(15)$

Cosmological Implications: 10.4 (25) byr.

Age of Universe 16 byr.

A paper (preprint included with this report) reporting the $^{186,187,188}\text{Os}(n,\gamma)$ cross section measurements and their cosmological implications has been submitted to the Phys. Rev. C. Our work has prompted reexamination of the only other measurement¹ of these cross sections and Browne has revised the ^{186}Os cross section to be in excellent agreement with our result. Browne's resulting revision of their $^{186}\text{Os}(n,\gamma)/^{187}\text{Os}(n,\gamma)$ 30 keV cross section ratio yields 0.47(4) in excellent agreement with our work. The only other measurement of the cross section ratio was performed by Browne et al.² at the NBS. Browne et al. reported the results of six measurements of the ratio

Run	$^{186}/^{187}$
1	0.35(8)
2	0.42(10)
3	0.46(10)
4	0.49(11)
5	0.38(9)
6	0.42(10)

Browne has reexamined the NBS data and finds that only runs No. 3 and 4 were not troubled by large and variable backgrounds. Browne now recom-

mends that only those two runs be used for estimating the ratio, this procedure yields a ratio 0.47(7) in good agreement with our result.

Thus, the value of the 30 keV ratio of capture cross sections seems well determined for use in the Re-Os chronometer to estimate the duration of nucleosynthesis.

B. Total Cross Section Measurements

Collaborators: R. R. Winters, 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 and analysis has begun.

Results: The average total cross section for $^{187}\text{Os} + n$ is 15 bn near 30 keV.

C. ^{187}Os Inelastic Scattering Cross Section Measurements

Collaborators: R. R. Winters, F. Kappeler and K. Wishak (IAK, Karlsruhe, W. Germany), B. Berman (LLL), and J. Browne (LASL)

Result: $\bar{\sigma}(n,n') = 376(153) \text{ mb}$

The DOE provided partial support for the principal investigator to travel to Karlsruhe, W. Germany to collaborate on a measurement of the 30 keV $^{187}\text{Os}(n,n')$ to the $^{187}\text{Os}(n,n)$ cross section ratio. The results of that measurement were reported at the APS fall meeting in Knoxville

(abstract is included with this report). A brief summary of the justification for the experiment and the results will be given here.

The total cross section 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,

$$\bar{\sigma}_{nn} \sim \frac{T_n^0(J,\ell) T_n^0(J,\ell)}{T_{\text{tot}}(J,\ell)} \quad \text{elastic (gs)} \quad 1.$$

$$\bar{\sigma}_{nn'} \sim \frac{T_n^0(J\ell) T_n^1(J\ell)}{T_{\text{tot}}(J\ell)} \quad \text{inelastic (gs,1st)} \quad 2.$$

$$\bar{\sigma}_{n\gamma} \sim \frac{T_n^0(J\ell) T_\gamma(J\ell)}{T_{\text{tot}}(J\ell)} \quad \text{capture (gs)} \quad 3.$$

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 .

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 $(J\ell)$ is given in equation 2 and hence a measurement of this cross section, coupled with information from the capture and total cross section

measurements yield estimates of $T_n^1(J\lambda)$, the neutron transmission function for the first excited state.

The measurement at Karlsruhe was made using the IAK 3 MV Van de Graaff. The experimental arrangement is shown in figure 1. The ${}^7\text{Li}(p,n)$ reaction was used to produce a kinematically collimated neutron beam with maximum neutron energy held at 35(2) keV. Measurements of the scattered neutron fluence were made at scattering angles 60° , 90° and 120° for ${}^{187}\text{Os}$, no sample, ${}^{188}\text{Os}$ and/or Pb targets. Figure 2 shows the ${}^{187}\text{Os}$ yield at 90° . Figure 3 shows the remarkably low background which was achieved with this arrangement. The elastic line shape (Pb or ${}^{188}\text{Os}$, figure 4) was then scaled to the ${}^{187}\text{Os}$ by least squares fitting to the leading time edge of the scattered neutron response. The scaled elastic line shape was subtracted from the ${}^{187}\text{Os}$ (figure 5) to yield the inelastic yield. The resulting cross section ratios are shown in the following table for the data which has so far been analyzed.

θ	$\bar{\sigma}(n,n')/\bar{\sigma}(n,n)$	$\bar{\sigma}(n,n',\theta)$
60°	0.047(33)	658(462) mb
60°	0.011(22)	125(251)
90°	0.043(19)	492(217)

The 30 keV average inelastic cross section given in the table is calculated from

$$\bar{\sigma}(n,n') = (\bar{\sigma}_{\text{total}} - \bar{\sigma}_{\text{capture}}) \frac{\bar{\sigma}(n,n')}{\bar{\sigma}(n,n)}$$

The total cross section $\bar{\sigma}_{\text{total}}$ measurement is reported in section B of this report and the capture cross section measurement in section A. The uncertainties for the entries in the table are so large as to preclude

the extraction of an angular distribution. Hence, we assume an isotropic distribution (s-in, s-out) and report the average of the three measurements $\bar{\sigma}(n,n') = 376(153)$ mb as our best estimate of the 30 keV average inelastic cross section. This is significantly smaller than the 1100 mb used by Woosley to calculate the stellar correction factor $R^* = 0.83$ and we expect this new result will substantially increase R^* .

It is clearly desirable that another measurement of this important cross section be performed and we plan to proceed with the ORELA measurement proposed for the current year.

II. ORELA Measurement of $^{187}\text{Os}(n,n')$ near 30 keV

Collaborators: R. R. Winters, G. Morgan (LASL),
R. L. Macklin and J. A. Harvey

Facility: ORELA, 10 meter station, Flight Path 2

- Status:
1. A neutron detector capable of reasonable efficiency and stability at 30 keV has been developed.
 2. Permission to use Flight Path 2 with its excellent collimation has been granted.
 3. The Fe/Al short filter transmission has been constructed.

The measurement at ORELA of the $^{187}\text{Os}(n,n')$ cross section near 30 keV using a filtered ORELA neutron beam was described in the last report. The filter must have a relatively narrow (~ 4 keV), high transmission window near 25 keV, but be essentially opaque outside this

region. The composite Al/Fe filter described in the previous report has now been fabricated. 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.

D. The 82 keV $^{238}\text{U}(n,n')$ Cross Section

Collaborators: R. R. Winters, N. W. Hill, J. A. Harvey and
R. L. Macklin (ORNL), and G. L. Morgan (LASL)

Results: The 82 keV $^{238}\text{U}(n,n')$ cross section has been measured.

This measurement has now been completed and figure 6 presents the results. The measurements were performed using the 3-phototube/NE110 detector described in the last progress report. This detector has more than met our expectations in terms of efficiency and bias drift insensitivity. We have found that at 35% shift in discriminator bias produces less than a 1% change in counting rate when all three tubes are biased below the single-photoelectron distribution.

E. High Resolution Total Cross Section Data for $^{32}\text{S} + n$, the R-Matrix Formalism and the Optical Model

Collaborator: C. H. Johnson (ORNL)

Results: An ℓ -dependent optical model for $^{32}\text{S} + n$

Because one of the collaborators, J. Halperin (ORNL), was leaving ORELA, part of the past few months have been given over to finishing the work involving him. The results of that work are reported in a paper (a preprint is included with this report) accepted for publication in Phys. Rev. C. This work has led to a very interesting extension using the results of the R-matrix analysis of the high resolution ORELA data to extract strength functions $s_{\ell J}$ and "smooth R-functions" $\bar{R}_{\ell J}$ for $^{32}\text{S} + n$ over the range 0-1.1 MeV. This work was reported at the Washington APS spring meeting (an abstract of that paper is included with this report). The optical model can be used to calculate $\bar{R}_{\ell J}$ and $s_{\ell J}$. In figure 7 is shown the resulting optical model potentials for $s_{1/2}$, $p_{1/2}$ and $p_{3/2}$ incident neutrons. If a spherical optical model is used, then both an ℓ -dependent real well depth and spin-orbit splitting are required. The imaginary well depths (the spreading of the single-particle states) seem independent of ℓ for $^{32}\text{S} + n$ in this energy region. We plan to extend this work to 2 MeV including scattering measurements to aid in the J^π assignments.

References

1. J. C. Browne and B. L. Berman, Nature 262, pp. 197-199 (1976).
2. J. C. Browne, G. P. Lamaze and I. G. Schroder, Phys Rev C 14, No. 3, 1287-1288 (1976).

Figure Captions

1. The experimental arrangement for the 30 keV $^{187}\text{Os}(n,n')$ cross section measurement at the IAK 3 MV Van de Graaff, Karlsruhe, West Germany.
2. $^{187}\text{Os}(n,n')$ yield at $\theta = 90^\circ$. The arrow indicates the centroid of the inelastic distribution.
3. The background for the $^{187}\text{Os}(n,n')$ experiment.
4. The elastic line-shape as determined using ^{188}Os at $\theta = 90^\circ$.
5. The inelastic residue. The region labelled by I gives the inelastic yield.
6. $^{238}\text{U}(n,n')$ 82 keV scattering yield using 22 inches of iron to filter the ORELA beam.
7. Optical model potentials for $^{32}\text{S} + n$ derived from high resolution ORELA data.

Figure 1.

Figure 2

Figure 3

Figure 4

figure 5.

ORNL - DWG 79-19274

figure 6.