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Average $^{186,187,188}Os(n,\gamma)$ cross sections and the age of the galaxy via ^{187}Re decay to ^{187}Os

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One measure of the age of the galaxy is derived from the Re-Os decay chronometer. The $^{186,187}Os$ capture cross sections are crucially important in the use of this chronometer. In this paper we describe a small revision of our measurements and point out the high degree of consistency of the measured cross sections with the revised results from other laboratories. Using a standard model of nucleosynthesis and these cross sections, the duration of r-process nucleosynthesis is estimated to be $(8.9 \pm 2.0) \times 10^9$ yr, the age of the galaxy to be $\approx 13.5 \times 10^9$ yr, and the universe to be $\approx 14.5 \times 10^9$ yr.

NUCLEAR REACTIONS Maxwellian average capture cross sections, $E = 2.5 - 450$ keV, $^{187}Os(n,n')$, $E = 30$ keV; nucleosynthesis, r process, age of galaxy, age of universe.

INTRODUCTION

The importance of the ^{187}Re-^{187}Os decay in estimating the duration of galactic chemical element synthesis was first suggested by Clayton.[1] One apparent difficulty in using this nucleosynthetic chronometer has been the lack of careful measurements of the germane neutron capture cross sections for the nuclear reactions. There now have appeared three nearly independent measurements[2-4] of the $^{186}Os + n \rightarrow {}^{187}Os + \gamma$ and $^{187}Os + n \rightarrow {}^{188}Os + \gamma$ cross sections.

An error in data processing for some of the neutron capture cross sections measured on flight path 7 at the Oak Ridge electron linear accelerator (ORELA) has been recently reported.[5] This requires that the renormalization factors shown in Table I be applied to our published[2] average capture cross sections for $^{186,187,188}Os$. While the renormalized cross sections are not much ($<$ 10%) different from our earlier results, the importance of the osmium isotopes in nucleosynthesis warrants at least a brief discussion of the causes and implications of the renormalization.

TABLE I. Multiplicative factors required to correctly normalize the cross sections reported in Ref. 2.

Mass	Renormalization factor
186	0.90
187	0.94
188	0.97

RENORMALIZATION OF THE DATA

Pairs of cross section measurements for each isotope, made under carefully controlled experimental conditions, gave results[2] which were discrepant by more than our estimates of uncertainties due to all known sources of error. We have recently found that the problem was largely due to a systematic error in a computer code used to correct time-of-flight data for the effects on counting efficiency due to sample size and to gain shifts in the detector systems. The three osmium samples were much smaller than the 0.1 molecular mass normally used for capture measurements and, as indicated in Table I of Ref. 2, gain shifts were detected during the first measurements for $^{186,187}Os$ and during the second ^{188}Os measurement. The consequence of incorrectly making adjustments to the efficiency for these effects was to multiply the time-of-flight data and estimates of variance by a number (close to unity in the case of the osmium) peculiar to each measurement. The resulting correctly normalized cross sections are presented in Figs. 1–3. The uncertainties shown in those figures are estimated from the uncertainties due to background subtractions, flux normalizations, dead-time corrections, and comparison of replicate measurements as discussed in Ref. 2. It is encouraging that after renormalization the cross sections derived from replicate measurements are now concordant.

STATISTICAL MODEL FITS

Also shown in Figs. 1–3 are statistical model least squares fits to the capture cross sections. The s-(S_0), p-(S_1), and d-wave (S_2) neutron strength functions, the gamma ray (S_γ) strength functions, and the mean radiation widths $\bar{\Gamma}_\gamma$ used in or derived from the fitted models are presented in Table II. These results are essentially the same as those reported in Ref. 2, although more nearly accurate level spacings are now available.[3,6] In the case of ^{187}Os, the statistical model approximately accounts for the effect on the capture cross section of the opening of the inelastic scattering channel at 10 keV. Our reanalysis of the ^{187}Os(n,γ) cross section now yields an improved (lower χ^2) estimate of a lower bound for the average ^{187}Os(n,n') cross section near 30 keV, $\bar{\sigma}_{nn'}$ (30 keV) $\gtrsim 0.30$ b. This result is consistent with the only published[7] measurement $\bar{\sigma}_{nn'}$ (30 keV) $\lesssim 0.5$ b. Both of these results are smaller than the result of Hauser-Feshbach calculations by Woosley and Fowler,[8] $\bar{\sigma}_{nn'}$ (30 keV) ≈ 1 b. As noted below, the small value of $\bar{\sigma}_{nn'}$(30 keV) appears to be of importance in the use of the ^{187}Re-^{187}Os beta decay as nucleosynthetic chronometer.

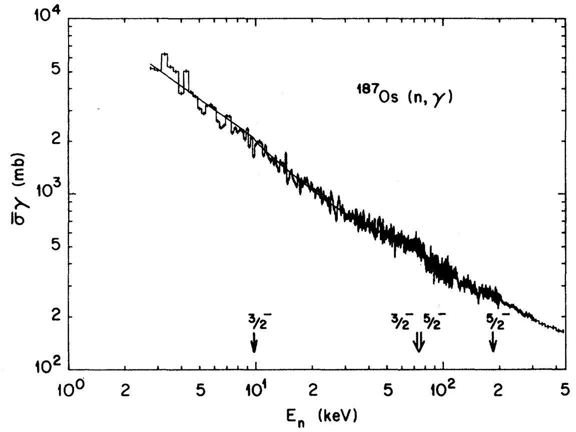

FIG. 2. Effective cross section for ^{187}Os(n,γ). The curve is a statistical model fit to the data below 112 keV. The arrow marks the location of four of the first five excited levels. A $\frac{7}{2}^-$ level at 100.7 keV is not shown. Note that evidence of inelastic competition effects for the 9.75-keV $\frac{3}{2}^-$ state is not obvious but such effects are observed for the three higher states.

MAXWELLIAN-AVERAGED NEUTRON CAPTURE CROSS SECTIONS

The Re-Os nucleosynthetic chronometer requires the ratio $r \equiv \langle \sigma_\gamma(186) \rangle / \langle \sigma_\gamma(187) \rangle$ of Maxwellian

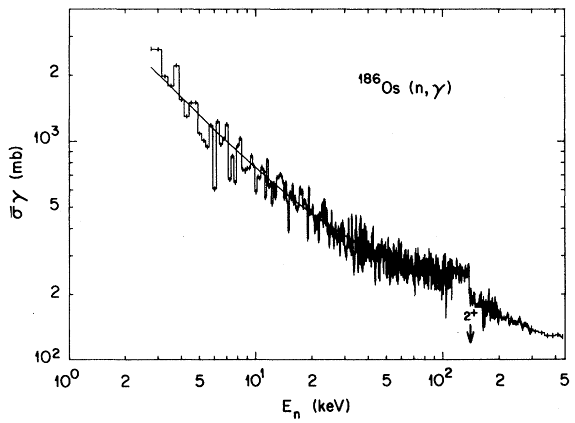

FIG. 1. Effective cross section for ^{186}Os(n,γ). The curve is a statistical model fit to the data below 112 keV. The arrow marks the position of the 2^+ first excited state 137 keV above ground. Note the marked effect of the opening of the inelastic channel.

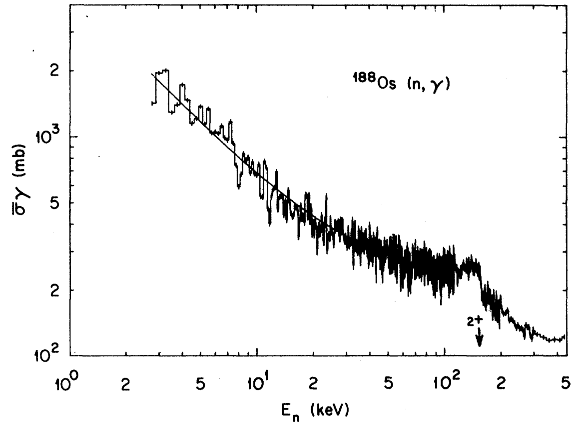

FIG. 3. Effective cross section for ^{188}Os(n,γ). The curve is a statistical model fit to the data below 112 keV. The arrow marks the location of the 2^+ first excited state at 155 keV. Note the competition effects as the inelastic channel opens.

TABLE II. Strength functions from statistical model least squares fits.

Isotope	$S_0\times 10^4$	$S_1\times 10^4$	$S_2\times 10^4$	$S_\gamma\times 10^4$	$\bar{\Gamma}_\gamma$ (meV)[a,d]
186	2.2[a]	0.25 ± 0.02	1.2 ± 0.1	24.1 ± 0.4	72 ± 5
187	2.2[a]	0.35[b]	$4\ \pm3$[c]	167 ± 2	77 ± 2[e]
188	2.2[a]	0.30 ± 0.02	1.3 ± 0.1	20.5 ± 0.4	82 ± 4

[a] Not varied.

[b] For $\sigma_{nn'}$ (30 keV) = 0.30 b.

[c] The large estimated uncertainty results from strong inelastic competition in the capture channel over the energy range in which capture is most sensitive to the d-wave strength.

[d] $\bar{\Gamma}_\gamma = S_\gamma D_0, D_0 \equiv$ average level spacings from Ref. 3.

[e] Average level spacing used is a weighted average of results in Refs. 3 and 6.

averaged capture cross sections. Since nucleosynthesis of osmium is assumed to take place primarily in the interior of giant stars (temperature $kT\approx$ 30 keV), the Maxwellian-averaged cross sections for various values of kT in the range 10–100 keV are presented in Table III (note that these are essentially the entries in Table V of Ref. 2 multiplied by the renormalization factors from Table I). Also presented in Table III are values of the cross section ratio r. In estimating the uncertainty in the ratio, it is assumed that the sample independent backgrounds, s-wave strength functions, and detector efficiency normalization are 100% correlated from measurement to measurement.

The results at $kT=30$ keV are in good ($\sim$ one standard deviation) agreement with cross sections [$\langle\sigma_\gamma(186)\rangle=438\pm$ 30 mb and $\langle\sigma_\gamma(187)\rangle=919\pm$ 43 mb] and ratio $r=0.48\pm0.04$ reported by Browne and Berman.[3] The measurements at (25 ± 2) keV of the cross sections (452 ± 70 mb and 953 ± 135 mb) and ratio $r=0.47\pm0.10$ by Browne, Lamaze, and Schroder[4] as revised by Browne and Berman[3] are also in good agreement with our results although the comparison is compromised by the fact that different averaging techniques were used in the two cases. Thus it appears that while there probably are other significant difficulties (discussed later) with the Re-Os chronometer, the relevant neutron capture cross sections are well determined.

THE DURATION OF GALATIC r-PROCESS NUCLEOSYNTHESIS

As discussed by Clayton,[1] the abundance of ^{187}Os due to the decay of ^{187}Re in terms of the abundance of ^{187}Re leads to an estimate of the duration of galatic r-process nucleosynthesis. The contribution of s-process nucleosynthesis to the observed ^{187}Os abundance can be calculated given the stellar cross section ratio $r^*\equiv f\cdot r$ appropriate for stellar interiors. Calculations by Woosley[9] show

TABLE III. The Maxwellian-averaged neutron capture cross sections for a range of temperature (kT) characteristic of assumed sites of r-process nucleosynthesis. The entries in the last column are the ratios to be used in calculating the duration of galactic r-process nucleosynthesis.

kT (keV)	$\langle\sigma_\gamma(186)\rangle$(mb)	$\langle\sigma_\gamma(187)\rangle$(mb)	$r\dfrac{\langle\sigma_\gamma(186)\rangle}{\langle\sigma_\gamma(187)\rangle}$
10	817 ± 39	1988 ± 100	0.411 ± 0.017
20	520 ± 19	1171 ± 39	0.444 ± 0.020
25	459 ± 16	995 ± 31	0.461 ± 0.021
30	418 ± 16	874 ± 28	0.478 ± 0.022
40	363 ± 14	715 ± 22	0.508 ± 0.023
50	326 ± 12	614 ± 19	0.531 ± 0.024
100	$237\pm\ 8$	391 ± 12	0.606 ± 0.025

that the factor f depends primarily on properties of the first excited state in ^{187}Os. In particular, Woosley finds that f varies from 0.83 if the ^{187}Os(n,n') cross section $\bar{\sigma}_{nn'}$ (30 keV)≈ 1 b to unity if $\bar{\sigma}_{nn'}$(30 keV) $= 0.5$ to 0.6 b. Given the discussion of $\bar{\sigma}_{nn'}$(30 keV) in the previous section of this note, we adopt $f=1.0$ in the following analysis.

The use of the Re-Os chronometer in connection with a model for r-process nucleosynthesis in which element formation decreases exponentially in time is carefully discussed by Fowler.[10] The exponential synthesis ceases at some fraction of the initial rate when the solar system begins to condense from the protosolar cloud. Fowler has suggested that the terminal r-process rate of nucleosynthesis might be taken as 10% of the initial rate. This value was used in Refs. 2, 3, and 11, and is adopted here. Also, as in the same earlier work,[2,3,11] we take the isotopic and elemental abundances of Os and Re from Ref. 12 and the ^{187}Re beta decay rate as 4.3 ± 10^9, an evaluation[3] of Refs. 13−15. Thus, using for the stellar cross section ratio 1.0 (0.478 ± 0.022), the exponential model yields for the duration of galatic r-process nucleosynthesis $\Delta=(8.9+-2.0)\times 10^9$ yr. The uncertainty estimate is obtained as described in Ref. 2. This result leads to an estimate of the age of the galaxy of $A_G=13.5\times 10^9$ yr and, assuming galactic formation began about 1 billion years following the big bang, the age of the universe is estimated to be about $A_U\approx 14.5\times 10^9$ yr. Our result, assuming $f=1$, for Δ is in excellent agreement with both the work of Fowler and Hoyle[16] (6.1 ± 2.3) $\times 10^9$ yr using the U-Th method and with the estimate by Beer and Käppeler[11] 9.5×10^9 yr using the ^{176}Lu s-process nucleosynthetic chronometer. Moreover, our estimate of A_U agrees well with that of Iben[17] (13 ± 3) $\times 10^9$ from globular clusters. It is interesting that our estimate of A_U is also rather close to the value (16.6 ± 1.7) $\times 10^9$ yr derived by Sandage and Tammann[18] from the Hubble time. As discussed by Browne and Berman,[3] this may have implications about the closure of the universe.

CONCLUSIONS

It appears that the neutron capture cross sections are now so well determined that the uncertainty associated with the effects of the stellar environment on the capture cross sections and on the β-decay rate must now be considered the major difficulties in obtaining reliable estimates of the duration of galactic r-process nucleosynthesis from the Re-Os chronometer. Detailed discussion of the beta decay rate uncertainties and other problems inherent in the use of the Re-Os chronometer may be found in Refs. 2, 3, and 19−21.

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