NEW s-PROCESS PATH AND ITS IMPLICATIONS FOR A $^{187}$Re-$^{187}$Os NUCLEO-COSMOCHRONOMETER

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Received 2004 August 2; accepted 2005 March 7

ABSTRACT

We study a new s-process path through an isomer of $^{186}$Re to improve a $^{187}$Re-$^{187}$Os nucleo-cosmochronometer. The nucleus $^{187}$Re is produced by this new path of $^{185}$Re($n, \gamma$)$^{186}$Re(m, $\gamma$)$^{187}$Re. We measure a ratio of neutron-capture cross sections for the $^{185}$Re($n, \gamma$)$^{186}$Re and $^{185}$Re($n, \gamma$)$^{187}$Re reactions at thermal neutron energy because the ratio with the experimental uncertainty has not been reported. Using an activation method with reactor neutrons, we obtain the ratio of $R_{th} = 0.543 \pm 0.11\%$. From this ratio we estimate the ratio of Maxwellian-averaged cross sections in a typical s-process environment at $kT = 30$ keV with the help of the temperature dependence given in a statistical-model calculation because the energy dependence of the isomer/ground ratio is smaller than the absolute neutron-capture cross section. The ratio at $kT = 30$ keV is estimated to be $R_k = 1.3\% \pm 0.8\%$. We calculate the s-process contribution from the new path in a steady-flow model. The additional abundance of $^{187}$Re through this path is estimated to be $N_e = 0.56\% \pm 0.35\%$ relative to the abundance of $^{186}$Os. This additional increase of $^{187}$Re does not make any remarkable change in the $^{187}$Re-$^{187}$Os chronometer for an age estimate of a primitive meteorite, which has recently been found to be affected strongly by a single supernova r-process episode.

Subject headings: meteorites, meteoroids — methods: laboratory — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

Two neutron-capture processes are important for astrophysical nucleosynthesis of heavy elements. The first one is a rapid neutron-capture process (r-process) that is considered to occur in supernova (SN) explosions (Meyer et al. 1992; Woosley et al. 1994; Qian et al. 1998; Cowan et al. 1999; Otsuki et al. 2000), and the other is a slow neutron-capture process (s-process) in low-mass asymptotic giant branch (AGB) stars (Käppeler et al. 1990; Straniero et al. 1995; Gallino et al. 1998; Arlandini et al. 1999) or massive stars (Prantzos et al. 1990; Woosley & Weaver 1995; The Astrophysical Journal 578:1010 yr (Lindner et al. 1986), which is longer than the age of the universe. It should be noted that the $^{187}$Re-$^{187}$Os chronometer has the advantage that applying this chronometer is free from the uncertainty of the initial abundances calculated by the r-process models. The epoch from an r-process nucleosynthesis event to the present can be evaluated by the present abundances of $^{187}$Re and $^{187}$Os after the subtraction of the s-process contributions to these nuclei. Although the initial abundances of $^{187}$Re and $^{187}$Os should be calculated using the s-process models, the uncertainty of the calculated s-process abundances is generally smaller than those in the r-process models.

The $^{187}$Re-$^{187}$Os chronometer has been applied for studying the GCE (Clayton 1969; Cosner & Truran 1981; Yokoi et al. 1983; Arnould et al. 1984). This chronometer was also used in analyses of meteorites (Lick et al. 1980; Luck & Allegre 1983; Birck & Allegre 1998). The measurements of the $^{187}$Re and $^{187}$Os abundances in iron meteorites and ordinary chondrites were used for evaluating the ages of the meteorites, which were formed from a metal reservoir at the solar system formation. These results lead to an upper-limit estimation of the age of the Galaxy (Luck et al. 1980; Luck & Allegre 1983). It was pointed

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out that the half-life of the $\beta^-$ decay of $^{187}\text{Re}$ is affected by stellar environments (Takahashi & Yokoi 1983). The half-life depends on the temperature and the electron density of the stellar environments. The half-life becomes shorter in high temperature such as $T > 10^4 \text{K}$ due to the enhanced bound-state $\beta$ decay in ionized atoms. This phenomena was verified in a measurement of the change of the half-life of the ionized $^{186}\text{Re}$ (Bosch et al. 1996). However, the $^{186}\text{Re}$-$^{187}\text{Os}$ system is still an important chronometer in the astronomical observations of old stars and in the analyses of presolar grains in primitive meteorites for the chronology of the $\beta$-process.

The chemical compositions of the extremely metal-poor stars are enhanced by the production of heavy elements in neutron-capture isotope separation in the first-generation stars. Recently astronomical observations with isotope separations have been carried out for several heavy elements such as Ba (Lambert & Prieto 2002) and Eu (Sneden et al. 2002; Aoki et al. 2003a, 2003b). Likewise, the presolar grains in the primitive meteorites provide samples affected strongly by a single nucleosynthesis event. Heavy elements such as Mo, Te, and Ba in the presolar grains have already been separated into isotopes. The origins of these presolar grains are considered to be the ejecta of core-collapse SN explosions (Richter et al. 1998; Pellin et al. 2000; Yin et al. 2002).

The purpose of this paper is to present a contribution of a new $s$-process path to $^{185}\text{Re}$ and $^{187}\text{Os}$ in order to improve the accuracy of this cosmochronometer. Previously the $s$-process contributions via two weak paths, $^{184}\text{W}(n, \gamma)^{185}\text{W}(n, \gamma)^{186}\text{W}(n, \gamma)^{187}\text{W} (\nu, e^-)^{187}\text{Re}$ and $^{185}\text{Re}(n, \gamma)^{186}\text{Re}(n, \gamma)^{187}\text{Re}$, were studied. Käppeler et al. (1991) measured the neutron-capture cross sections of $^{185}\text{Re}$ and $^{187}\text{Re}$ at $kT = 25$ keV. The neutron-capture cross section of an unstable nucleus $^{185}\text{W}$ is evaluated from the inverse reaction $^{186}\text{W}(\gamma, n)^{185}\text{W}$ (Sonnabend et al. 2003; Mohr et al. 2004). Here we propose another new weak $s$-process branch to produce $^{187}\text{Re}$: a path through a $^{186}\text{Re}$ isomer, which has a half-life of $2.0 \times 10^3$ yr. This isomer was found by Lindner about 50 years ago (Lindner 1951), and then Seegmiller et al. (1972) measured the half-life of this isomer by a mass-spectrometric analysis and $\gamma$-ray spectroscopy of samples after neutron irradiation. However, the absolute value of the neutron-capture cross section for the $^{185}\text{Re}(n, \gamma)^{186}\text{Re}$ reaction has not been reported. Seegmiller et al. reported a ratio of the neutron-capture cross section of $^{185}\text{Re}$ leading to the isomer and the ground state, but the uncertainty was not given in the article. Therefore, the neutron-capture cross section to the isomer has not been established (Firestone et al. 1998). The half-life of the ground state of $^{186}\text{Re}$ is only 3.718 days, while that of the isomer, $2.0 \times 10^3$ yr, is longer than the timescale of the $s$-process, $10^7$-$10^8$ yr. The $s$-process contribution should thus be estimated with high accuracy.

In the present work we measure the neutron-capture cross section ratio $^{185}\text{Re}(n, \gamma)^{186}\text{Re}$ and $^{185}\text{Re}(n, \gamma)^{187}\text{Os}$ at the thermal energy, two thin natural Re foils were irradiated with thermal neutrons from the nuclear reactor JRR-4 at the Japan Atomic Energy Research Institute (JAERI). Two Al-Co wires were also irradiated simultaneously to monitor the neutron flux. The samples were irradiated by the reactor neutrons for six hours. After the irradiation the samples were cooled in a water pool for about four months in order to reduce the background of the unstable isotopes with short half-lives. Four and eight months after the irradiation, $\gamma$-rays emitted from the activated samples were measured by two HPGe detectors. In addition, 16 months later, the $\gamma$-rays from one sample were measured by one HPGe detector.

The weights of the Re foils are 43.8 and 58.1 mg, whereas the weights of the Al-Co wires are 1.74 and 4.58 mg. The Co element composition is 0.475%. The natural Re sample consists of two stable isotopes, namely $^{185}\text{Re}$ (37.4%) and $^{187}\text{Re}$ (62.6%), and thus two unstable isotopes, $^{185}\text{Re}$ and $^{187}\text{Re}$, are mainly produced by the neutron-capture reactions. The half-lives of the ground states of these isotopes are $T_{1/2} = 3.718$ days ($^{185}\text{Re}$) and $T_{1/2} = 17$ hr ($^{187}\text{Re}$), which are much shorter than the $^{186}\text{Re}$ isomer. The average flux of the neutrons is estimated to be $4.37 \times 10^{13}$ cm$^{-2}$ s$^{-1}$, which is evaluated by a measurement of decay $\gamma$-rays after $\beta$ decay from the activated Co in the wires. The $\gamma$-rays from $^{28}\text{Al}$ cannot be measured, because a cooling time of four months is much longer than the half-life of $^{28}\text{Al}$. The total efficiency of the HPGe detectors is approximately equal to 20% relative to a $3'' \times 3''$ NaI detector and the energy resolution is 2.2 keV for a $1.3 \text{MeV} \gamma$-ray in $^{60}\text{Co}$. The efficiency is calibrated with standard sources of $^{152}\text{Eu}$ and $^{133}\text{Ba}$. The $\gamma$-rays from the samples are measured at a 5 or 3 cm distance from the end caps of the detectors in the first or second (third) measurement, respectively, with a lead-shielded low-background environment.

Figure 2 shows a partial decay scheme of the $^{186}\text{Re}$ isomer (Baglin 2003). The isomer with $J^\pi = (8^+) \gamma$ locates at an excitation energy of 149 keV. This state decays to the ground state through a cascade of $\gamma$ decay. The ground state subsequently decays to $^{180}\text{Os}$ or $^{186}\text{W}$ with $T_{1/2} = 3.718$ days. The $\gamma$-ray transitions from the isomer to the ground state cannot be distinguished from $\gamma$-rays emitted from other activities. Strong $\gamma$-rays are emitted from $^{184}\text{Re}$ ($T_{1/2} = 38$ days), which is produced by a $(n, 2n)$ reaction with fast neutrons existing in the nuclear reactor (see Fig. 3). Its half-life is comparable to the cooling time, and hence the intensities are enhanced. However, we observe a $137 \text{keV}$ transition of $^{186}\text{Os}$ (see Fig. 4), which is the strongest $\gamma$-ray in the decay scheme associated with the isomer. The yield of the $137 \text{keV} \gamma$-ray is contributed not only from the isomer but also from the ground state produced directly by the $^{185}\text{Re}(n, \gamma)^{186}\text{Re}$ reaction.
are observed, which is produced by the $^{185}$Re($\gamma$,n)$^{186}$Os or $^{186}$W.

In order to obtain the ratio of the neutron-capture cross section between the isomer and the ground state, we select a cooling time of four months after the irradiation for the first measurement. After the cooling, the ground state of $^{186}$Re still remains because of its large capture cross section relative to the isomer. Although the surviving number of the ground state is small, the contribution to the 137 keV $\gamma$-ray yield is competitive with that of the isomer because the decay rate of the ground state is much higher than that of the isomer. In the second and third measurements the ground states do not remain. The yields of the 137 keV $\gamma$-ray at the second and third measurements are, thus, proportional to the neutron-capture cross section to the isomer.

The number of the nuclei produced by the neutron-capture reaction is proportional to the $\beta$ decay events, which are evaluated from the $\gamma$-ray intensity in the measured spectra by applying the following equation:

$$N_{\text{total}} = \frac{n_{\text{peak}}}{\epsilon R f_{\text{decay}}},$$

where $N_{\text{total}}$ is the total number of the $\beta$ decays, $n_{\text{peak}}$ denotes the peak counts corresponding to the decay $\gamma$-rays, $R$ is the emission probability of the measured $\gamma$-ray per decay, $\epsilon$ is the efficiency of the HPGe detectors, and $f_{\text{decay}}$ is the correction of the $\beta$ decay during the measurement time. The $f_{\text{decay}}$ is expressed by

$$f_{\text{decay}} = \exp(-t_1 \lambda) - \exp(-t_2 \lambda),$$

where $t_1$ and $t_2$ stand for the start and stop times of the measurement, respectively. The experimental uncertainty consists mainly of the statistical error of the yields of the $\gamma$-rays and the efficiency of the HPGe detectors. The $\gamma$-ray energy of 137 keV is near the peak of the efficiency curve of the detectors. We evaluate the efficiency uncertainty to be approximately 7% from the deviation of the $\gamma$-ray efficiency obtained with the calibration sources from the efficiency curve estimated by $\chi^2$ fitting. The pileup effect of the $\gamma$-rays is negligibly small because the absolute efficiency is lower than 5%. The self-absorption of the $\gamma$-rays is also negligibly small.

An energy spectrum of neutrons produced by a nuclear reactor consists of a thermal flux with energy below 0.2 eV and an epithermal one above. The rate of the neutron-capture reaction is expressed by

$$N^x = \int n(x) \sigma(x) d\nu = \phi_{\text{th}} \sigma^g_0 + \phi_{\text{epi}} I^g_0,$$

where $N^x$ denotes the reaction rate for the reaction $x$, $n(x)$ the neutron density at velocity $\nu$, $\sigma(x)$ the cross section of the reaction $x$ at velocity $\nu$, $\phi_{\text{th}}$ and $\phi_{\text{epi}}$ the thermal and epithermal flux, respectively, and $\sigma^g_0$ and $I^g_0$ the cross section at the thermal energy and the resonance integral for the reaction $x$, respectively. A measurement for a sample with a Cd absorber is not carried out in the present experiment and we cannot obtain the thermal neutron flux. Instead we use an average neutron flux, which is defined by

$$\phi_{\text{ave}} = \frac{N_{\text{total}}(^{60}\text{Co})}{\sigma_{\text{th}}(^{60}\text{Co})},$$

where $\phi_{\text{ave}}$ is the average neutron flux and $\sigma^g_{\text{eff}}$ the effective cross section of the reaction $x$ in the reactor neutron spectrum. The effective neutron-capture cross sections with the average neutron flux are defined by

$$\sigma^g_{\text{eff}} = \frac{N^g}{\phi_{\text{ave}}} = \frac{\phi_{\text{th}} \sigma^g_0 + \phi_{\text{epi}} I^g_0}{\phi_{\text{ave}}},$$

$$\sigma^m_{\text{eff}} = \frac{N^m}{\phi_{\text{ave}}} = \frac{\phi_{\text{th}} \sigma^m_0 + \phi_{\text{epi}} I^m_0}{\phi_{\text{ave}}}.$$

Applying these equations, we obtain the effective neutron-capture cross sections leading to the isomer of $^{186}$Re as given in Table 1, where the mean value derived from the second and third measurements is 0.74 $\pm$ 0.05 barn. The yield of the $\gamma$-ray at the first measurement consists of contributions from the ground-state decay as well as the isomer decay. The effective
neutron-capture cross section to the ground state can be evaluated by subtracting the contribution of the isomer decay, which is calculated from the average cross section of 0.74 ± 0.05 barn, from the total yield at the first measurement (see Table 2). The obtained cross section to the ground state is 132 ± 26 barn. This value is consistent with the thermal values of 118 barn (Nakajima 1991) and 112 barn (Mughabghab 1984) within the uncertainty, and thus the effective cross section derived here is essentially the thermal cross section. To verify this conjecture, we compare the thermal cross sections and resonance integrals leading to the ground state and isomer of $^{186}$Re and their ratio in Table 3. These values are calculated from Japanese Evaluated Nuclear Data Library (JENDL) Activation Cross Section File 96 (Nakajima 1991). The ratios, $I_0/\sigma_0$, for both the ground state and isomer are approximately equal (see Table 3). This fact indicates that the resonance integrals are written as

$$I_0^g = \alpha \sigma_0^g,$$

$$I_0^m = \alpha \sigma_0^m,$$

with the common coefficient $\alpha$. The isomer/ground ratio of the capture cross sections at the thermal energy can be derived as

$$\frac{\sigma_0^m}{\sigma_0^g} = \frac{\sigma_0^m(\phi_0 + \alpha \phi_{\text{epi}})}{\sigma_0^g(\phi_0 + \alpha \phi_{\text{epi}})} = \frac{\sigma_0^m}{\sigma_0^g} \frac{\phi_0 + \alpha \phi_{\text{epi}}}{\phi_0} = \frac{\sigma_0^m}{\sigma_0^g} \frac{\sigma_0^m}{\sigma_0^m},$$

which verifies our conjecture. The isomer/ground ratio obtained by applying this equation is $R_{0m} = 0.54\% \pm 0.11\%$. This value is a factor of 1.8 larger than the value of 0.3% reported in a previous report (Seegmiller et al. 1972). Note that experimental uncertainty was not reported there.

6 For the JENDL Activation Cross Section file, see their Web site: http://wwwndc.tokai.jaeri.go.jp/jendl/jendl.html.

There are strong $\gamma$-rays from $^{184}$Re produced by the $^{185}$Re($n, 2n$)$^{184}$Re reaction with fast neutrons in Figure 3. The half-life of $^{184}$Re ($T_{1/2} = 38$ days) is long enough to remain after the cooling time. This fact suggests the possibility that the isomer of $^{186}$Re might be also produced by the $^{185}$Re($n, 2n$)$^{184}$Re reaction. To estimate the contribution of the $^{185}$Re($n, 2n$)$^{184}$Re reaction, we evaluate the effective cross section of the $^{185}$Re($n, 2n$)$^{184}$Re reaction as

$$\sigma_{\text{eff}}^{(n, 2n)}(^{184}\text{Re}) = \frac{N(^{184}\text{Re})}{\phi_{\text{ave}}},$$

where $R$ is the production ratio of the isomer to the ground state of $^{186}$Re, $A(x)$ is the isotope abundance ratio in the sample, and $N(\chi)$ is the number of the nuclei produced by the neutron-induced reactions. The contribution of the $^{187}$Re($n, 2n$)$^{186}$Re reaction is approximately equal to 0.00078 barn. Since the decay rate of $^{184}$Re is much higher than $^{186}$Re, the $\gamma$-ray intensities of $^{186}$Re are stronger than the $^{186}$Re isomer. Assuming that the effective cross section of the $^{187}$Re($n, 2n$)$^{186}$Re is equal to that of the $^{186}$Re($n, 2n$)$^{184}$Re reaction, we can calculate the contribution to the $^{186}$Re isomer by

$$N(^{186}\text{Re}) = R \frac{A(^{185}\text{Re})}{\sigma_{\text{eff}}^{(n, 2n)}(^{184}\text{Re})} \phi_{\text{ave}},$$

We obtain the result that the effective cross section of the $^{185}$Re($n, 2n$)$^{184}$Re reaction is approximately equal to 0.00078 barn. Since the decay rate of $^{184}$Re is much higher than $^{186}$Re, the $\gamma$-ray intensities of $^{186}$Re are stronger than the $^{186}$Re isomer. Assuming that the effective cross section of the $^{187}$Re($n, 2n$)$^{186}$Re is equal to that of the $^{186}$Re($n, 2n$)$^{184}$Re reaction, we can calculate the contribution to the $^{186}$Re isomer by

3. DISCUSSION

3.1. s-Process Branch to $^{187}\text{Re}$ through the $^{186}\text{Re}$ Isomer

We here estimate the effect of the new path in the s-process using a classical steady-flow model (BBFH57; Clayton 1964). The steady-flow model was extended by Ward et al. (1976) to apply to a branching point where the s-process nucleus is produced by a neutron capture and/or a feeding by a steady-state decay. The abundance of the residual nucleus can be calculated by

$$\frac{dN(A)}{dt} = - \sum_i \lambda_i(A) N_i(A) - \sum_j \lambda_j(A') N_j(A'),$$

where $\lambda$ is the neutron-capture rate $(\langle \sigma v \rangle)$ or the $\beta$ decay rate $(\ln 2/T_{1/2})$, $n$ is the neutron number density, $T_{1/2}$ is the half-life of the $\beta$ decay, $N$ is the isotope abundance, $A$ and $A'$ are the nuclear mass numbers, which have the relationship $A = A'$ (for $\beta$ decay) or $A' + 1$ (for neutron capture). In the limit that the timescale of the s-process is much longer than a mean time of

| TABLE 1 |
|Effective Neutron-Capture Cross Sections of $^{185}$Re Leading to the $^{186}$Re Isomer|
|---|---|---|---|
| Sample | Time (months) | $\sigma_{\text{eff}}$ (barn) | Error (barn) |
| 1................. | 8 | 0.78 | 0.06 |
| 2................. | 12 | 0.60 | 0.08 |
| Average ........... | 8 | 0.84 | 0.10 |

| TABLE 2 |
|Effective Neutron-Capture Cross Section of $^{185}$Re Leading to Ground State of $^{186}$Re|
|---|---|---|---|
| Sample | Time (month) | $\sigma_{\text{eff}}$ (barn) | Error (barn) |
| 1................. | 4 | 136 | 30 |
| 2................. | 4 | 142 | 52 |
| Average ........... | ... | 132 | 26 |

Notes.—Two samples were irradiated for about six hours by reactor neutrons. Time is the cooling time after the irradiation. The capture cross section was obtained by subtracting the contribution of the isomer decay.
neutron capture, \(dN/dt\) vanishes and hence the “steady flow” becomes a good approximation of the \(s\)-process. The equation in this limit is expressed by
\[
\sum_i \lambda_i(A)N_i(A) = \sum_j \lambda_j(A')N_j(A').
\]

Applying this equation to the Re-Os branching point displayed in Figure 1, we obtain a set of the following equations:
\[
\lambda_\beta \cdot N_s(186\text{Re}) = \lambda(\text{to } 187\text{Os})N_s(186\text{Os}),
\]
\[
\lambda_\beta \cdot N_s(185\text{W}) = \lambda(\text{to } 186\text{Os})N_s(185\text{W})
\]
\[
+ \lambda(\text{to } 186\text{Re})N_s(186\text{Re}),
\]
\[
\lambda(\text{to } 186\text{Re})N_s(185\text{W}) = \left( \lambda_\beta + \lambda_{EC/\beta} \right) N_s(186\text{Re}),
\]
\[
\lambda(\text{to } 186\text{W})N_s(184\text{W}) = \lambda_\beta \cdot N_s(185\text{W})
\]
\[
+ \lambda(\text{to } 186\text{W})N_s(185\text{W}),
\]
\[
\lambda_\beta + N_s(186\text{Re}) + \lambda(\text{to } 186\text{W})N_s(185\text{W})
\]
\[
= \lambda(\text{to } 187\text{W})N_s(186\text{Os}).
\]

We here assume that the internal transition rate between the ground state and the isomer is negligibly lower than the neutron-capture rate. The validity of this assumption should be discussed later. A typical astrophysical nucleosynthesis environment of the \(s\)-process is \(kT = 30\) keV and \(n = 10^7\) cm\(^{-3}\). Since the following two relations hold, \(\lambda(\text{to } 186\text{Re}) \gg \lambda_\beta \cdot (187\text{Re})\) at \(187\text{Re}\) and \(\lambda_\beta + \lambda_{EC/\beta} \approx \lambda(\text{to } 187\text{Re})\) at \(186\text{Re}\), on the environmental condition for \(T_{1/2}(187\text{Re}) = 43.5\) Gyr and \(T_{1/2}(186\text{Re}) = 3.718\) days, we omit those two slower reaction rates in equations (16) and (17). The situation does not change when the atom of \(187\text{Re}\) is ionized in the stellar interior during the \(s\)-process and the half-life decreases by \(9 - 10\) orders of magnitude (Yokoi et al. 1983; Bosch et al. 1996). Two weak \(s\)-process contributions are known (Käppeler et al. 1991). The unstable nucleus \(185\text{W}\) is a branching point where it decays to \(185\text{Re}\) with a half-life of 75.1 days and it is transmuted to \(186\text{W}\) by the neutron-capture reaction. The nucleosynthesis flow from \(186\text{W}\) reaches to \(187\text{Re}\). The \(\beta\) decay rate at \(185\text{W}\) is higher than the neutron-capture rate by an order of magnitude in the case of \(n = 10^7\) cm\(^{-3}\), but it depends on the neutron density in the \(s\)-process environment. The ground state of \(186\text{Re}\) is the second branching point, which decays to both \(186\text{Os}\) and \(186\text{W}\). Using equations (14)–(19), we calculate the \(s\)-process abundance of \(187\text{Re}\) relative to \(186\text{Os}\) that is produced by the \(s\)-process including the new \(s\)-process path by
\[
N_s(187\text{Re}) = \left[ \frac{R}{A + \lambda_\beta \cdot (186\text{Re}) + \left( \frac{1 + R}{A} \right) \lambda(\text{to } 186\text{W})} \right] 
\times \frac{\lambda(\text{to } 187\text{Os})}{\lambda(\text{to } 186\text{Re})} N_s(186\text{Os}),
\]

where \(R\) is defined by \(\lambda(\text{to } 186\text{Re})/\lambda(\text{to } 186\text{Os})\) and \(A\) is the branching ratio of the \(\beta\) decay of \(186\text{Re}\), namely, \(A = \lambda_\beta / (\lambda_\beta + \lambda_{EC/\beta})\). We use the branching ratio of 0.9253 for \(A\) (Baglin 2003). It should be noted that the \(s\)-process abundance of \(187\text{Re}\) has two terms proportional to the ratio of the neutron-capture rates leading to the isomer and the ground state of \(186\text{Re}\).
$R_\text{st} = 1.3\% \pm 0.8\%$, to equation (20) we obtain the $s$-process abundance of $^{187}\text{Re}$, $N_s = 0.56\% \pm 0.35\%$, relative to $^{186}\text{Os}$. This value is larger than that at the thermal energy by a factor of 2.4. This difference shows that the energy dependence of the ratio is important for the study of the $s$-process and an experimental measurement of the cross section at the stellar energy is a further subject.

Figure 6 shows that the calculated ratio increases drastically above 10 keV. This tendency indicates that the abundance ratios for the Re and Os isotopes can be used as a nucleo-thermometer of the $s$-process due to the strong temperature dependence of the isomer/ground ratio.

Finally, we would like to discuss a problem concerning the transition probability between the isomer and the ground state. We assume that this transition probability on a typical $s$-process condition is ignored. The case of the nucleus $^{180}\text{Ta}$ gives a clue for this problem. The nucleus $^{180}\text{Ta}$ has a similar nuclear structure: the isomer is metastable with $J^\pi = 9^+$ ($T_{1/2} > 10^{13}$ yr) existing in the solar system, while the ground state with $J^\pi = 1^+$ is unstable against the $\beta$ decay with a half-life of 8.15 hr. This nucleus is proposed to be synthesized through a weak branch of the $s$-process (Yokoi & Takahashi 1983; Belic et al. 1999) and by photodisintegration reactions in supernova explosions (Arnould & Goriely 2003; Utsunomiya et al. 2003). The isomer synthesized by either process may decay to the ground state through intermediate states ($s$-process) or a weak branch of the $s$-process due to the strong temperature dependence of the isomer/ground ratio.

3.2. Effect on $^{187}\text{Re}$-$^{187}\text{Os}$ Chronometry

The $^{187}\text{Re}$-$^{187}\text{Os}$ chronometer is useful for the study of the age estimate of an $r$-process event. The purpose of this subsection is to discuss the effect of the new $s$-process path on the $^{187}\text{Re}$-$^{187}\text{Os}$ chronology. The contribution from the new $s$-process path through the $^{187}\text{Re}$ isomer has been totally ignored in the past. We first present the age estimate without the effects of all weak $s$-process branchings. In such a case the age of an object that exhibits both the $^{187}\text{Re}$ and $^{187}\text{Os}$ abundances is calculated by

$$T = -\frac{T_{1/2}(^{187}\text{Re})}{\ln 2} \times \ln \left[ \frac{N_{\text{ob}}(^{187}\text{Re})}{N_{\text{ob}}(^{187}\text{Os}) - N_s(^{187}\text{Os}) + N_{\text{ob}}(^{187}\text{Re})} \right]$$ (21)

where $N_{\text{obs}}(A)$ is the observed abundance and $N_s(A)$ is the abundance contributed from the $s$-process. Note that we here adopt a simple model taking a sudden approximation that the $r$-process occurred at look-back time $t = T$ only once. Although the sudden approximation is not generally a good approximation for analyses of the solar materials, it is still useful in analyses of primitive meteorites that have recently been found to be affected strongly by a single supernova $r$-process episode (Amari et al. 1992; Yin et al. 2002). This approximation also applies to an analysis of astronomical date such as the abundances of the $r$-process elements detected in metal-poor stars with isotope separation because the elements on the surface of the old low-metallicity stars are probably generated in a single nucleosynthesis event (Sneden et al. 1996; Cayrel et al. 2001; Otsuki et al. 2003; Honda et al. 2004).

We present the age estimate by taking into account the new $s$-process path to $^{187}\text{Re}$. In this case, equation (21) should be replaced by

$$T = -\frac{T_{1/2}(^{187}\text{Re})}{\ln 2} \times \ln \left\{ \frac{N_{\text{obs}}(^{187}\text{Re}) - N_s(^{187}\text{Re}) \exp \left[ -T_5 \ln 2 / T_{1/2}(^{187}\text{Re}) \right] }{N_{\text{obs}}(^{187}\text{Os}) - N_s(^{187}\text{Os}) + [N_{\text{obs}}(^{187}\text{Re}) - N_s(^{187}\text{Re})]} \right\}$$ (22)
where we assume that the s-process occurred at different lookback time $T_s$ from the r-process episode; i.e., $T \neq T_s$, $N_s(A)$ is the contribution by the s-process, and $N_{bb}(A)$ is the observed abundance. The s-process contribution to $^{187}$Os should be modified by the change of the nucleosynthesis flow at $^{186}$Re. The s-process contribution to $^{187}$Re presented in equation (20) is calculated from equations (14)–(19), which contain all the weak s-process paths. In equation (20) the contribution of the new s-process path is expressed by the $f$ term.

Substituting the estimated MACS ratio of $R_{st} = 1.3\%$ at $kT = 30$ keV, we obtain the results shown in Tables 4 and 5. The neutron-capture cross sections at $kT = 30$ keV are taken from the previous article (Käppeler et al. 1991). Those of $^{186}$Os, $^{187}$Os, and $^{187}$Re are 418, 874, and 1160 mbarn, respectively. We use the solar abundances for $N_{bb}(^{187}$Re) and $N_{bb}(^{186}$Os), $N_s(^{187}$Os) is calculated from the observed abundance $N_{ob}(^{186}$Os) = $N_s(^{186}$Os). The $N_{bb}(^{186}$Os)/$N_{bb}(^{187}$Re) ratios in the primitive meteorites or the metal-poor stars may be different from the solar abundance ratio because $N_{bb}(^{187}$Re) should be enhanced in the sample, which is strongly affected by the single r-process event. We thus introduce a parameter, $f$, which is defined by

$$ N_{bb}(^{186}$Os)/N_{bb}(^{187}$Re) = f N_s(^{186}$Os)/N_s(^{187}$Re), \tag{23} $$

for allowing the variation of $N_{bb}(^{186}$Os)/$N_{bb}(^{187}$Re).

The difference between the calculated ages for $R = 0$ and $1.3\%$ is at most $1\%$ in either case $T_s = 5 \times 10^9$ yr (Table 4) or $T_s = 10^{10}$ yr (Table 5). The ages are slightly sensitive to the neutron density. Aoki et al. (2003a, 2003b) reported isotope ratios of Eu in s-process element-rich metal-poor stars and show the possible neutron density range of the s-process environment by comparing their data with the s-process calculation: $10^7 \leq n \leq 10^9$ cm$^{-3}$. Thus, we also present the age for neutron densities of both $10^7$ and $10^9$ cm$^{-3}$ in Tables 4 and 5. The difference between the ages for two different neutron densities is at most $\sim 2\%$.

Several metal-poor halo stars are thought to form from either the s-process element-rich gas (Aoki et al. 2003a) or the r-process element-rich material (Sneden et al. 1996; Cayrel et al. 2001; Honda et al., 2004), which are ejected from progenitor stars. The parameter $f$ can be even larger or smaller than unity. The primitive meteorites, which are affected by a single supernova r-process, can have f-values smaller than unity. The column of $f$ in Tables 4 and 5 shows this parameter. The estimated ages for $R = 0$ and $1.3\%$ under the conditions of $f < 1.0$ show almost the same results because the absolute nucleosynthesis flow from the s-process decreases with decreasing f-value. In particular, the ages become slightly different with increasing f-value for the case of $T_s = 10^{10}$ yr (Table 5). Although the effect of the new s-process path seems to be small, the effect is almost the same as those of the other s-process paths under the condition of $f \leq 1.0$. Therefore, the direct measurement of the absolute neutron-capture cross section of $^{185}$Re leading to the isomer of $^{186}$Re at $kT = 8$–30 keV is important for the $^{187}$Re-$^{187}$Os chronometer.

### 4. SUMMARY

We propose a new s-process path that leads to synthesis of $^{187}$Re and $^{187}$Os, which form an important nuclear pair as a nucleo-cosmochronometer of the r-process. The new path consists of a neutron-capture reaction chain from $^{185}$Re to the isomer of $^{186}$Re and from the $^{186}$Re isomer to $^{187}$Re, namely, $^{185}$Re$(n, \gamma)^{186}$Re*$(n, \gamma)^{187}$Re, which has been ignored in all previous studies. We measure the ratio of the reaction cross sections $^{185}$Re$(n, \gamma)^{186}$Re* and $^{185}$Re$(n, \gamma)^{186}$Re with thermal neutrons provided by a nuclear reactor at the JAERI. We measure $\gamma$-rays after the $\beta$ decay from the Re samples by HPGe detectors and thereby we obtain the ratio of $R_{th} = 0.54\% \pm 0.11\%$.

### TABLE 4

| $f$   | Eq. (21) | Eq. (22), $n = 10^8$, $R = 0\%$ | Eq. (22), $n = 10^8$, $R = 1.3\%$ | Eq. (22), $n = 10^8$, $R = 1.3\%$ |
|-------|----------|---------------------------------|---------------------------------|---------------------------------|
| 1.5   | 4.86     | 4.86                            | 4.86                            | 4.86                            |
| 1.2   | 7.73     | 7.80                            | 7.80                            | 7.76                            |
| 1.0   | 9.56     | 9.66                            | 9.67                            | 9.61                            |
| 0.5   | 13.9     | 14.0                            | 14.1                            | 14.0                            |
| 0.1   | 17.2     | 17.3                            | 17.3                            | 17.2                            |

**Notes.** Ages in units of Gyr. An age of the s-process of $T_s = 5 \times 10^9$ yr is assumed; $f$ is a parameter to allow the variation of observed $^{186}$Os/$^{187}$Re ratio relative to the solar ratio (see eq. [23]), and $n$ is the neutron density in units of cm$^{-3}$. $R$ is the ratio of the neutron capture leading the isomer and the ground state of $^{186}$Re.

### TABLE 5

| $f$   | Eq. (21) | Eq. (22), $n = 10^8$, $R = 0\%$ | Eq. (22), $n = 10^8$, $R = 1.3\%$ | Eq. (22), $n = 10^8$, $R = 1.3\%$ |
|-------|----------|---------------------------------|---------------------------------|---------------------------------|
| 1.5   | 4.86     | 4.69                            | 4.68                            | 4.79                            |
| 1.2   | 7.73     | 7.67                            | 7.66                            | 7.70                            |
| 1.0   | 9.56     | 9.55                            | 9.55                            | 9.56                            |
| 0.5   | 13.9     | 14.0                            | 14.0                            | 14.0                            |
| 0.1   | 17.2     | 17.2                            | 17.2                            | 17.2                            |

**Notes.** Ages in units of Gyr. An age of the s-process of $T_s = 10^{10}$ yr is assumed; $f$ is a parameter to allow the variation of observed $^{186}$Os/$^{187}$Re ratio relative to the solar ratio (see eq. [23]), and $n$ is the neutron density in units of cm$^{-3}$. $R$ is the ratio of the neutron capture leading the isomer and the ground state of $^{186}$Re.
The Maxwellian-averaged cross section reaction ratio at the stellar energy $kT = 30$ keV is estimated with the help of the statistical model calculation. The result is used to calculate the $s$-process abundance of $^{187}\text{Re}$ relative to the abundance of $^{186}\text{Os}$ in the classical steady state flow model, which yielded a value of $N_s = 0.56\% \pm 0.35\%$. The proposed new $s$-process path does not make any remarkable change in the $^{187}\text{Re}$-$^{187}\text{Os}$ chronometer in the sudden approximation when all other possible $s$-process branchings are included in the calculation. This confirms the robustness of the $^{187}\text{Re}$-$^{187}\text{Os}$ chronometer, which applies to the age estimated by the analyses of primitive meteorites that are presumed to be affected strongly by a single supernova $r$-process episode. Since the $^{187}\text{Re}$ atom in these meteorites most likely has not been averted in the stellar interior after it was produced in the $r$-process, the chronometer is free from the change of the half-life of ionized $^{187}\text{Re}$. We, however, need further experimental study to measure the cross section precisely at the stellar energy $kT = 8-30$ keV. We would like to thank K. Takahashi, H. Utsunomiya, and M. Fujiwara for valuable discussions. We also thank the crew of the nuclear reactor at JAERI. This work has been supported in part by Grants-in-Aid for Scientific Research (15740168) of the Ministry of Education, Culture, Sports, Science, and Technology of Japan and by the Mitsubishi Foundation.

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