THE s-PROCESS BRANCHING AT 185W

K. SONNABEND, P. MOHR, K. VOGT, AND A. ZILGES
Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstrasse 9, D-64289 Darmstadt, Germany
A. MENGONI
ENEA, Viale G. B. Ercolani 8, I-40138 Bologna, Italy
T. RAUSCHER
Institut für Physik, Universität Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland
H. BEER AND F. KÄPPELER
Forschungszentrum Karlsruhe, Institut für Kernphysik, P.O. Box 3640, D-76021 Karlsruhe, Germany
AND
R. GALLINO
Dipartimento di Fisica Generale, Università di Torino and Sezione INFN di Torino, Via P. Giuria 1, I-10125 Torino, Italy

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ABSTRACT
The neutron capture cross section of the unstable nucleus 185W has been derived from experimental photoactivation data of the inverse reaction 186W(γ, n)185W. The new result of σ = 687 ± 110 mbarn confirms the theoretically predicted neutron capture cross section of 185W of σ ≈ 700 mbarn at kT = 30 keV. A neutron density in the classical s-process of n_n = (3.8±0.4) × 10^16 cm^-3 is derived from the new data for the 185W branching. In a stellar s-process model, one finds a significant overproduction of the residual s-only nucleus 186Os.

1. INTRODUCTION

The unstable nucleus 185W is a so-called branching point in the slow neutron capture process (s-process). The nucleus 185W is produced by neutron capture in the s-process from the stable nucleus 184W. At small neutron densities, 185W β-decays to 185Re, with a half-life T_T/2 of 75.1 days, and it has been pointed out that the β-decay half-life is practically independent of the temperature at typical s-process conditions (Takahashi & Yokoi 1987). At higher neutron densities 185W can capture one more neutron, leading to the stable 186W. It is obvious that the branching between β-decay and neutron capture depends on the β-decay half-life, the neutron capture cross section, and the neutron density. The half-life and the neutron capture cross section can be measured in the laboratory, and therefore one can determine the neutron density from the observed abundances of the various tungsten isotopes (Käppeler et al. 1991). In addition, this branching has minor influence on the 185Os/187Re cosmochronometer (Bosch et al. 1996).

Up to now, only theoretical estimates are available for the neutron capture cross section of 185W, because direct neutron capture experiments with radioactive targets are very difficult. Theoretical predictions for the Maxwellian averaged capture cross section at a typical temperature of 30 keV vary significantly, from 532 (Käppeler et al. 1991) and 560 (Rauscher & Thielemann 2000) to 794 mbarn (Holmes et al. 1976). In a recent compilation, a value of 703 ± 113 mbarn has been adopted (Bao et al. 2000). All calculations used the statistical model. The differences in the results come from the parameterizations of the level density, the γ-ray strength function, and the neutron-nucleus optical potential.

In order to reduce the uncertainties, a new experiment was performed on the inverse reaction 186W(γ, n)185W. The idea is to find a parameter set for the calculations that reproduces the cross section of 186W(γ, n)185W and to apply these parameters for the prediction of the 185W(n, γ)186W cross section. Such a prediction should be more reliable for one special reaction than previous calculations, which used global or local systematics to derive the relevant parameters from neighboring nuclei. The relevant energy region is located close above the threshold of the (γ, n) reaction at S_0 = 7194 keV (Mohr et al. 2001). At higher energies, experimental data on the 186W(γ, n)185W reaction are available in literature (Berman et al. 1969; Goryachev & Zalesnyi 1978; Gurevich et al. 1981), and the results can be found in the compilations of Dietrich & Berman (1988) and in CDFE (Varlamov et al. 2001). We have performed an additional measurement at energies close above the threshold.

In § 2 we present our experimental setup. In § 3 we calculate the cross sections of the (n, γ) and (γ, n) reactions, and in § 4 we derive the s-process neutron density from our experimental data and apply a stellar s-process model to the 185W branching. Section 5 gives a summary and conclusions.

2. EXPERIMENTAL SETUP AND PROCEDURE
The 186W(γ, n)185W experiment was performed using the photoactivation technique at the real photon setup at the superconducting linear electron accelerator S-DALINAC...
(Richter 1996). Recently, several photoactivation experiments have been performed here (Mohr et al. 2000b; Vogt et al. 2001; Lindenberg et al. 2001; Mohr et al. 2000a), and the reaction rates were determined using a quasi-thermal photon bath at temperatures of several times \(10^9\) K. These data are relevant for the nucleosynthesis of the neutron-deficient so-called \(p\)-nuclei (Lambert 1992).

Photons were generated by bremsstrahlung using our electron beam at an energy of \(E_\text{e} = 8775\) keV and with a beam current of about 30 \(\mu\)A. Usually, the photon beam is collimated and hits the target at a distance \(d_2 \approx 150\) cm behind the radiator target. This leads to a well-defined photon beam with a spectral composition that was analyzed in detail (Vogt et al. 2001). However, because of the relatively long half-life of \(^{185}\text{W}\) (\(T_{1/2} = 75.1 \pm 0.3\) days) and the weak \(\gamma\)-ray branch (\(E_\gamma = 125.4\) keV) in the \(\beta\)-decay of \(^{185}\text{Re}\) to \(^{185}\text{Re}\), the irradiation of \(^{185}\text{Re}\) at a distance \(d_1 \approx 3\) cm was used to determine the \(^{185}\text{W}\) activity. The photon flux was determined from the ratios of activities of the gold and tungsten targets at the regular target position and from the activation of the boron target, a relative measurement was carried out. We irradiated simultaneously the tungsten target and a very thin \(1\) \(\mu\)m gold disk at a position close to the radiator target. A second thin gold disk was sandwiched between two layers of boron. This sandwich target was mounted at the regular target position and irradiated simultaneously with the tungsten and gold targets close to the radiator. The boron target is used to normalize the incoming photon intensity by the \(^{11}\text{B}(\gamma, \gamma')\) reaction. From the absolute photon intensity at the regular target position and from the activation of the second thin gold target, one can determine the \((\gamma, n)\) cross section of \(^{196}\text{Au}\). The complete determination of the \(^{197}\text{Au}(\gamma, n)^{198}\text{Au}\) cross section is presented in Vogt et al. (2002). And finally, the \(^{180}\text{W}(\gamma, n)^{181}\text{Au}\) cross section can be determined from the ratios of activities of the gold and tungsten targets close to the radiator. Absorption of bremsstrahlung \(\gamma\)-rays in the targets can be neglected. Typical uncertainties for the photon flux determination are of the order of 10\%. Further details of the experimental setup can be found in Vogt et al. (2001) and Mohr et al. (1999).

The decay \(\gamma\)-rays of the activated tungsten and gold targets were measured using a well-shielded, high-purity germanium (HPGe) detector with a relative efficiency of 30\% and an energy resolution of 2 keV at \(1332.5\) keV. A typical spectrum of the tungsten target is shown in Figure 2. We followed the decay of the activity over more than one half-life, and the analysis of our decay curve leads to a half-life of

![Diagram](image)

**TABLE 1**

| Target          | Mass (mg) | Abundance (%) | \(S_n\) (keV) |
|-----------------|-----------|---------------|---------------|
| Tungsten        | 5847.8 (10) | 100.0         | 7194          |
| Gold            | 163.5 (5)  | 100.0         | 8071          |
| \(^{185}\text{W}\) |           |               |               |
| \(^{196}\text{W}\) |           |               |               |
| \(^{197}\text{Au}\) |           |               |               |

**TABLE 2**

| Nucleus   | \(T_{1/2}\) (days) | \(E_\gamma\) (keV) | \(I_\gamma\) (%) |
|-----------|--------------------|--------------------|-----------------|
| \(^{185}\text{W}\) | 75.1 (3)           | 125.4              | 0.0192 (7)      |
| \(^{196}\text{W}\) | 6.1669 (6)         | 333.0              | 22.9 (6)        |
| \(^{197}\text{Au}\) | 355.7              | 87.0 (8)           | 6.6 (8)         |
$T_{1/2} = 76.6 \pm 1.5$ days, which agrees with the adopted value of $T_{1/2} = 75.1 \pm 0.3$ days$^3$ within the uncertainties. The precise exponential decay of the activity confirms that the analyzed $\gamma$-ray line does not accidentally overlap with a background line. Of course, the excellent energy resolution of the HPGe detector also helps to measure a weak $\gamma$-ray branching. The efficiency of the HPGe detector was determined by calibrated sources (Vogt et al. 2001). In addition, for the 125.4 keV $\gamma$-ray from the $^{185}$W decay, the self-absorption in the tungsten target was taken into account by GEANT simulations (Brun & Carminati 1993), and the GEANT simulations of the absorption in tungsten were verified by transmission measurements of the tungsten target. The resulting uncertainty of the relative efficiency is about 5%.

The yield $Y$ in our experiment is proportional to the energy-integrated cross section $I_\gamma$,

$$ Y \sim I_\gamma = \int_{E_0}^{E_0} N_{br}(E, E_0) \sigma(E) \, dE, $$

where $E_0$ is the endpoint energy of the bremsstrahlung and kinetic energy of the electron beam, $N_{br}(E, E_0)$ is the number of bremsstrahlung photons at an energy $E$ with the endpoint energy $E_0$, and $\sigma(E)$ is the $^{185}$W$(\gamma, n)^{186}$W cross section. The factor between the yield $Y$ and the energy-integrated cross section $I_\gamma$ depends on characteristics of the observed isotope, as well as on parameters of the experimental setup (Vogt et al. 2001). From the experimentally measured ratio $Y_W / Y_{Au}$ between the tungsten and the gold yields one can derive the ratio of the integrated cross sections $I_{185W} / I_{196Au} = 12.3 \pm 0.9$ with relatively small uncertainties. Note that the relatively large value of this ratio does not indicate that the cross section of $^{185}$W is much larger than the cross section of $^{196}$Au. The reason for this large ratio is the much smaller neutron separation energy $S_n$ of $^{186}$W compared to that of $^{197}$Au, which leads to a broader integration range in equation (1) for $^{186}$W.

It is not possible to determine the energy dependence of the $^{186}$W$(\gamma, n)^{187}$W cross section from one photoactivation measurement with a white bremsstrahlung spectrum. If one adopts the theoretically calculated energy dependence of the cross section $\sigma(E)$ (see § 3), it is possible to solve the integral in equation (1) and to determine a normalization factor $F$ for the theoretical calculation by comparison of the theoretically predicted and experimentally measured yields. In the case of the $^{186}$W$(\gamma, n)^{187}$W reaction, this leads to normalization factors of $F = Y_{exp} / Y_{calc}$ close to unity for two different calculations of the $^{186}$W$(\gamma, n)^{187}$W cross section (see § 3). The same factors $F$ should be used for the prediction of the inverse $^{185}$W$(n, \gamma)^{186}$W cross section.

We used the reaction $^{197}$Au$(\gamma, n)^{196}$Au to normalize the experiment on $^{186}$W$(\gamma, n)^{187}$W. We have determined the cross section of $^{197}$Au$(\gamma, n)^{196}$Au as described in Vogt et al. (2001, 2002). Our new data agree nicely with several previous experiments (Berman et al. 1987; Veyssière et al. 1970) and a recent experiment with monochromatic photons from laser–Compton backscattering (Utsunomiya et al. 2003).

The experimental uncertainties are dominated by (1) the photon flux determination, which enters into the analysis of the experimental yields in equation (1) for both the target $^{186}$W and the standard $^{197}$Au and (2) the self-absorption of the 125.4 keV $\gamma$-rays in the tungsten target. The total uncertainty for the normalization factors $F$ is 14%.

The normalized calculations are compared with experimental data at higher energies in Figures 3 and 4. Within the uncertainties one finds excellent agreement. In addition, the dotted line shows the integrand of equation (1); this line defines the energy range in which our experiment was sensitive. As a consequence of the white bremsstrahlung spectrum and the calculated energy dependence of the $(\gamma, n)$ cross section, the energy range of our experiment is located directly above the $(\gamma, n)$ reaction threshold, and it has a width of roughly 1 MeV. It is not possible to present our results as one data point in Figures 3 and 4. Instead, the experimental results of this work are normalization factors $F$ for the theoretical calculations.

3. CALCULATION OF THE $(\gamma, n)$ AND $(n, \gamma)$ CROSS SECTIONS

Two sets of calculations of the relevant cross sections, HF-1 and HF-2, have been performed. In both cases the statistical model Hauser-Feshbach theory has been applied to describe the reaction process. In the case of HF-1, a global parameterization was used, where the main model parameters were derived from either microscopic approaches or global systematics. In the other case, HF-2, the model parameters were optimized to the mass region under consideration and, when possible, parameters derived from experimental nuclear structure data were used.

The calculation HF-1 was performed with the code NON-SMOKER (Rauscher & Thielemann 1998, 2000). The neutron transmission coefficients were computed using a microscopic potential (Jeukenne, Lejeune, & Mahaux 1977). Nuclear levels as given in Rauscher & Thielemann (2001) have been utilized. Above the last known state a global theoretical level density description was used (Rauscher, Thielemann, & Kratz 1997). The E1 $\gamma$-transition probabilities were described by a Lorentzian shape with a modified low-energy tail, following the prescription of McCullagh, Stelts, & Chrien (1981). Width and energy positions of the giant dipole resonance (GDR) were also taken from theory. From a hydrodynamic droplet approach

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$^3$ Data from ENDF database, revision of 2001 November 15, using NNDC On-line Data Service.
For example, the total cross section of $^{186}$W is $\sigma$ (MeV) $^{HF-1}$ ($^{HF-2}$), normalized by $x_{\text{Zalesny}}$ Boltzmann distribution with the astrophysically relevant energy range, which is defined by a Maxwell-Boltzmann distribution with $kT$ = 30 keV above the threshold at 7194 keV, is also shown (shading in bottom panel).

The modified energy-dependent width is then given as $f_1 \cdot \sigma_{\text{HF-1}}$ ($f_2 \cdot \sigma_{\text{HF-2}}$). The astrophysically relevant energy range, which is defined by a Maxwell-Boltzmann distribution with $kT$ = 30 keV above the threshold at 7194 keV, is also shown (shading in bottom panel).

(Myers et al. 1977), we obtain $E_{\text{GDR}} = 14.23$ MeV, and from a parameterized approach (Cowan, Thielemann, & Truran 1991) the width is determined as $\Gamma_{\text{GDR}} = 5.45$ MeV. The modified energy-dependent width is then given as $\Gamma(E_{\gamma}) = \Gamma_{\text{GDR}}(E_{\gamma}/E_{\text{GDR}})^{3/2}$. For a deformed nucleus, the energy and width split according to the description outlined in Cowan et al. (1991). However, within the droplet model (Myers et al. 1977) the nucleus $^{186}$W is spherical, and a single-humped Lorentzian with the above energy and width is obtained.

The calculation HF-2 was performed using the optical model parameters (OMP) of Moldauer (1963), for neutron transmission coefficients. This set of OMPs reproduces fairly well the total cross sections of nuclei with $A = 184$–188. For example, the total cross section of $^{188}$W is reproduced with an accuracy of better than 10% for neutron energies from 100 keV up to 10 MeV by this OMP set. Gamma-ray transmission coefficients were derived from the experimental double-humped GDR parameters (Dietrich & Berman 1988) derived from experimental $(\gamma, n)$ data in the GDR region. The relevant data are $E_{\text{GDR}} = 12.59$ and 14.88 MeV, $\Gamma_{\text{GDR}} = 2.29$ and 5.18 MeV, and $\sigma_{\text{peak}}$ = 211 and 334 mbarn for the two GDR components. Nuclear level densities were derived from the parameterization of Mengoni & Nakajima (1994). Experimental discrete levels have been used to fit the constant-temperature parameterization at low excitation energies, matched to the pairing+shell-corrected Fermi gas model (Gilbert-Cameron prescriptions) at excitation energies close to the neutron binding energy.

In order to compare the results of model predictions with the present $^{186}$W$(\gamma, n)^{185}$W experimental data, the calculation of the cross sections for $^{185}$W in the ground state, as well as in several excited states, must be performed. Here, we have included excited states up to about 500 keV. Higher excited states do not appreciably contribute to the cross section. This request is altogether similar to what is needed to evaluate the $(n, \gamma)$ cross section for thermally excited target states in stellar plasma (stellar cross sections).

From a comparison with the present experimental data close to the neutron threshold, a renormalization factor $F_1 = 1.223$ is obtained for the global HF-1 and $F_2 = 0.974$ for the local HF-2 calculations. Both calculations are able to reproduce the measured data from the neutron threshold up to the GDR region (see Figs. 3 and 4). The typical uncertainty of 25%–30% associated with neutron capture cross section calculations (see, for example, the prediction of the NON-SMOKER code; Rauscher et al. 1997; Bao et al. 2000) is therefore obtained with either model parameterization.

It is interesting to note the similarity in the results of both calculations despite the strongly differing treatments of the GDR, which would be expected to dominate the difference in the results. Although HF-1 uses a single-humped GDR shape, a similar strength distribution as for HF-2, with its double-humped GDR, is obtained at the low-energy side of the GDR. This is due to the use of an energy-dependent width, a slightly smaller GDR energy, and a slightly broader...
the quasi-stable $^{187}$Re. The indicated values are the terrestrial half-lives. Note that the half-life of $^{187}$Re decreases by 10 orders of magnitude at stellar temperatures and common densities of the He intershell, while $^{187}$Os becomes unstable (Takahashi & Yokoi 1987).

The effect of other model inputs, such as the optical neutron potential, is rather small. When comparing the Maxwellian averaged cross sections obtained in the two descriptions, we notice increasing deviations at the lowest energies, i.e., below 10 keV. This means that a different energy dependence of the cross sections is found that is mainly due to the different optical model potentials used. At higher energies the energy dependence of the HF-1 and HF-2 calculations is similar, and thus the uncertainties stemming from the optical potentials are not sufficient to explain further differences in the two approaches.

We assume that the same renormalization factors derived from the present experimental data and model calculations are also valid for the Maxwellian averaged cross section of the reverse reaction $^{185}$W$(n, \gamma)^{186}$W. This assumption requires some more discussion. What is actually measured and calculated here is a compound reaction in which the "compound" nucleus consists of excited states of $^{186}$W created by $\gamma$-excitation of the ground state of $^{186}$W. This compound nucleus subsequently decays in the neutron channel to all energetically possible final states in $^{185}$W, according to the Bohr hypothesis, i.e., independently of how it was formed. For a full application of detailed balance linking the $(n, \gamma)$ and $(\gamma, n)$ reaction rates, or Maxwellian averaged cross sections, one would have to use a Planck distribution of photons according to the astrophysical temperature of interest ($\approx 0.348 \times 10^9$ K) and account for thermal excitation of the target at the same temperature instead of keeping the target in the ground state. Thus, for each photon energy we are actually measuring a subset of the transitions relevant for the capture rate. Applying detailed balance directly yields a neutron capture cross section that is the thermally averaged sum of neutron captures on the ground state and excited states of $^{185}$W, forming $^{186}$W at the given energy and finally directly decaying to the ground state of the final nucleus $^{186}$W. However, this cross section is governed by the same uncertainties in the optical neutron potential, level densities, and GDR properties as the full stellar cross section. Since the energy dependence of the $(\gamma, n)$ reaction is well described by both models, it can safely be assumed that there is no further energy dependence in the renormalization factor. Therefore, we argue that the same renormalization factor can be applied also to the Maxwellian averaged cross section at 30 keV.

3.1. Results for $^{185}$W$(n, \gamma)^{186}$W

The normalized results of both calculations for the Maxwellian averaged cross section of $^{185}$W$(n, \gamma)^{186}$W at $kT = 30$ keV are in remarkable agreement: from HF-1 one obtains $\sigma = 734$ mbarn and from HF-2 $\sigma = 640$ mbarn. The average value is $687 \pm 100$ mbarn (experimental uncertainty) $\pm 47$ mbarn from different calculations, leading to a final result of $687 \pm 110$ mbarn. This value is already the stellar capture cross section at $kT = 30$ keV, where an enhancement factor of 0.92 was used; the cross section at $kT \approx 0$ is 747 mbarn, which is in agreement with the adopted value of 703 $\pm$ 103 mbarn (Bao et al. 2000), within the uncertainties. Contrary to this adopted value, which was based on an empirical renormalization of a theoretical value, the new result is based on experimental data of the inverse reaction. The compatibility of both values nicely confirms the estimate of the systematic error in the theoretical calculation, which was used to generate the adopted value in Bao et al. (2000).

4. The Branching at $^{185}$W

4.1. The Classical $s$-Process

The $s$-process synthesis path in the W-Re-Os mass region is shown in Figure 5. The nuclei $^{186}$Os and $^{187}$Os are partially bypassed by the $s$-process flow, especially by a branching at $^{185}$W. The stellar $\beta$-decay rates of $^{185}$W and $^{186}$Re are practically independent of temperature in the relevant temperature region (Takahashi & Yokoi 1987). Therefore, the isotopic abundance of $^{186}$Os is determined by the average $s$-process neutron density. In Figure 5, laboratory half-lives are indicated. However, according to Takahashi & Yokoi (1987), at stellar temperatures of interest the $^{187}$Re nucleus is almost fully ionized and its $\beta$-decay rate increases by about 10 orders of magnitude ($T_{1/2} = 21.3$ yr at a temperature $T = 3 \times 10^8$ K and electron density $n_e = 10 \times 10^{26}$ cm$^{-3}$). In the same stellar environment, $^{187}$Os, which is stable in terrestrial conditions, becomes unstable by electron capture ($T_{1/2} = 1243$ yr). Consequently, the abundance ratio between the two nuclei in the He intershell production zone and in the asymptotic giant branch (AGB) envelope must be followed carefully.

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**Fig. 5.—** The $s$-process path in the W-Re-Os mass region. Two branchings occur, at $^{187}$W and at $^{186}$Re. Unstable nuclei are marked by dashed boxes (except the quasi-stable $^{187}$Re). The indicated values are the terrestrial half-lives. Note that the half-life of $^{187}$Re decreases by 10 orders of magnitude at stellar temperatures and common densities of the He intershell, while $^{187}$Os becomes unstable (Takahashi & Yokoi 1987).
The classical s-process model formulated by Ward, Newman, & Clayton (1976) provides a simple way of estimating the s-process neutron density via branching analyses. Previous analyses (Käppeler et al. 1991) of the W-Re-Os branching can now be updated with a neutron capture cross section for $^{185}$W that is not based only on statistical model calculations.

Except for our $^{185}$W capture cross section, the other relevant stellar cross sections for the s-process were taken from the compilation of Bao et al. (2000). The s-process flow was normalized at the s-only isotope $^{150}$Sm, which represents an accurate measure of the unbranched $N\sigma$ curve, and calculated down to the W-Re-Os branching using programs described by Beer, Corvi, & Mutti (1997), with an average exposure of $\tau_0 = 0.296(kT/30 \text{ keV})^{1/2}$ mbarn$^{-1}$. This value also corresponds to a value reported by Arlandini et al. (1999). The relevant part of the calculation, the mass region from $A = 145$ to the termination of the s-process at $A = 209$, is shown in Figure 6. In this part, the overall feature of the $N\sigma$ curve is a slow decrease up to $A = 200$. This mass region includes not only the studied W-Re-Os branching and the s-only $^{150}$Sm isotope on the unique synthesis path used for normalization of the $N\sigma_s$ curve but also other important s-process branchings. These are (1) the branchings that are sensitive exclusively to the neutron density, i.e., the Nd-Pm-Sm ($A = 147-150$), Er-Tm-Yb ($A = 169-171$), W-Re-Os ($A = 185-187$), and Os-Ir-Pt ($A = 191-193$) branchings; and (2) the branchings dependent on neutron density, temperature, and electron density, i.e., the Sm-Eu-Gd ($A = 151-152$), Eu-Gd ($A = 154-156$), and Dy-Er ($A = 163-164$) branchings. To adjust the s-process neutron density, temperature, and electron density requires an s-only isotope to be located inside the branching. These empirical data points are shown in Figure 6 as circles with smaller $N\sigma_s$ values than that of the unique synthesis path represented by $N\sigma_s(^{150}$Sm). For the W-Re-Os branching (Fig. 5) the branch-point isotope is $^{166}$Os.

With the new stellar $^{185}$W cross section, an average neutron density of

$$n_n = (3.8^{+1.1}_{-0.9}) \times 10^4 \text{ cm}^{-3}$$

was found. The uncertainty of the $^{185}$W cross section contributes about 12%. The main uncertainty in the present $n_n$ determination comes from the 6.3% uncertainty in the $N\sigma$ value of $^{186}$Os, which transforms to an error of $\pm 22\%$ in the neutron density. The 6.3% uncertainty in $N\sigma(186$Os) is primarily the uncertainty of the solar osmium abundance (Anders & Grevesse 1989).

The present neutron density is still consistent with the Nd-Pm-Sm branching (Reifarth et al. 2003), but is too high for reproducing the Er-Tm-Yb and, in particular, Os-Ir-Pt branchings. While the parameters of the first case are rather uncertain, the Os-Ir-Pt branching has recently been studied with much improved cross sections, yielding a neutron density of only $0.7 \times 10^6 \text{ cm}^{-3}$ (Koehler et al. 2002). In Table 3, our present value for the neutron density is compared with corresponding results from other branchings.

The present neutron density, in combination with the adopted values for the s-process temperature of $kT = 27.1$ keV (Beer et al. 1997) and for the electron density of $n_e = 5.4 \times 10^{26} \text{ cm}^{-3}$ (Arlandini et al. 1999), also provides a fair reproduction of the other branchings shown (Fig. 5). The empirical $N\sigma_s$ values of $^{152}$Gd and $^{162}$Er are underestimated in the calculation. This is reasonable, as significant p-process contributions of up to 50% and about 10% can be expected for $^{152}$Gd and $^{162}$Er, respectively.

The discrepant neutron densities derived from different branchings, as listed in Table 3, indicate an inherent difficulty of the classical model due to the rather schematic assumption of constant neutron density and temperature during the s-process. Hence, a consistent description of the various branchings must be based on more realistic scenarios provided by stellar model calculations.

### Table 3

| Branching | s-Only Isotope | $n_n$ ($\times 10^4 \text{ cm}^{-3}$) | Reference |
|-----------|---------------|---------------------------------|-----------|
| $^{95}$Zr | $^{95}$Mo      | $4.0$                           | 1         |
| $^{147}$Nd/$^{147}$Pm/$^{146}$Pm | $^{146}$Sm | $3.0 \pm 1.1$                   | 1         |
| $^{169}$Er/$^{170}$Tm | $^{170}$Yb | $1.4^{+0.5}_{-0.8}$             | 1         |
| $^{185}$W/$^{186}$Re | $^{186}$Os | $4.1^{+1.1}_{-1.0}$             | 3         |
| $^{191}$Os/$^{192}$Ir | $^{192}$Pt | $3.8^{+1.1}_{-0.9}$             | 4         |
| $^{185}$W/$^{186}$Re | $^{186}$Os | $0.7^{+0.05}_{-0.02}$           | 5         |

References. (1) Käppeler et al. 1990; (2) Reifarth et al. 2003; (3) Käppeler et al. 1991; (4) this work; (5) Koehler et al. 2002.

4.2. The s-Process in AGB Stars

The main component of the s-process nucleosynthesis occurs during helium shell burning in low-mass AGB stars. The evolution of these stars and the related s-process nucleosynthesis have been discussed extensively by Gallino et al. (1998) and Busso et al. (2001), and it has been shown that this model is able to reproduce the main s-process component within 10% (Arlandini et al. 1999) as the result of the average composition of the s-process abundance distributions of two AGB stellar models of 1.5 and 3 $M_\odot$ and a metallicity of $Z = 0.01$. In this model, the s-process is driven by two neutron sources. The first, $^{13}$C($\alpha$, $n$)${}^{16}$O, operates in the interpulse period between two helium flashes, and the sec-
ond, $^{22}$Ne($\alpha$, $n$)$^{25}$Mg, is activated at higher temperatures during the helium shell flash, when almost the whole He intershell, i.e., the region between the H shell and the He shell, becomes convective for a relatively short period of time. The $^{13}$C neutron source accounts for about 95% of the total neutron exposure, in a thin radiative layer of about $10^{-4}$ $M_{\odot}$; however, the produced $s$-process abundances that depend on branching points along the $s$-path are significantly modified by the $^{22}$Ne source that is operating in the convective helium-burning zone. After a limited number of helium shell flashes, at the quenching of the thermal instability, the convective envelope penetrates the top region of the He intershell, dredging up $^{13}$C and $s$-process–rich material. The envelope is progressively lost by strong AGB winds and remixed into the interstellar medium.

It is important to emphasize that the profiles for neutron density and temperature are now provided by the stellar model. Therefore, the abundance patterns of $s$-process branchings represent a critical test for this stellar model.

The analysis of the branching at $^{185}$W shown in Figure 5 shows a significant overproduction of the $s$-only isotope $^{186}$Os by 20% in this stellar $s$-process model. All neutron capture cross sections have been taken from the compilation of Bao et al. (2000), with the exception of the $^{185}$W($n$, $\gamma$)$^{186}$W cross section, where the present result was used. This means that the model apparently overestimates the $\beta^-$-decay part and/or underestimates the neutron capture part of the $^{185}$W branching. Consequently, it underestimates the $s$-process contribution to $^{187}$Re. Note that the uncertainties of the previously existing calculated $^{185}$W cross sections (Bao et al. 2000) were generous enough to allow for a roughly consistent description of the observed $^{186}$Os abundance.

The observed abundance of $^{186}$Os can be reproduced by the stellar model if one increases the $^{185}$W($n$, $\gamma$)$^{186}$W cross section by 60%. However, such an enhancement is outside the present experimental uncertainties. If the $^{185}$W($n$, $\gamma$)$^{186}$W cross section is enhanced within the experimental uncertainties of about 20%, one still finds an overproduction of $^{186}$Os by 12%, which is still slightly inconsistent with the observed abundance.

There are several possible explanations to cure this problem. First, the $^{186}$Os($n$, $\gamma$)$^{187}$Os cross section could be 20% larger than the value adopted by Bao et al. (2000). However, this value is based on two independent experiments, which quote uncertainties between 5% and 10% (Winters & Macklin 1982; Browne & Berman 1981). Second, the additional branching at $^{186}$Re could reduce the $^{186}$Os abundance either by an increased $^{186}$Re($n$, $\gamma$)$^{187}$Re cross section or by enhanced electron capture of $^{186}$Re under stellar conditions. However, it has been pointed out by Takahashi & Yokoi (1987) that under any realistic assumptions for the capture cross section and the ratio between $\beta^-$-decay and electron capture, the $^{186}$Re $\beta^-$-decay is always faster than the neutron capture.

All these nuclear physics questions will be studied in additional experiments in the near future. Neutron capture experiments on osmium isotopes are planned at the new n_TOF facility at CERN and at the Karlsruhe Van de Graaff accelerator, where uncertainties of the order of 1% can be achieved using the $4\pi$ BaF$_2$ detector. In addition, the $^{187}$Re($\gamma$, $n$)$^{188}$Re cross section will be measured using the monochromatic photon beam available from laser-Compton backscattering at AIST, Tsukuba, thus allowing us to improve the cross section for the inverse $^{186}$Re($n$, $\gamma$)$^{187}$Re reaction.

With these improvements, and by using a realistic $s$-process model, there is a good chance of analyzing the $^{186}$W and $^{186}$Re branchings with sufficient confidence to establish the abundance of $^{186}$Os as a sensitive test for the stellar model.

5. SUMMARY AND CONCLUSIONS

We have measured the photodisintegration cross section of the $^{186}$W($\gamma$, $n$)$^{185}$W reaction at energies near the reaction threshold. The experimental data have been used to restrict model predictions for the $A = 186$ system and to derive the neutron capture cross section of the inverse $^{185}$W($n$, $\gamma$)$^{186}$W reaction. The result of $\sigma = 687 \pm 110$ mbarn is close to the calculated cross section that was recommended by Bao et al. (2000), but exhibits significantly improved reliability.

The $s$-process flow at the branch-point isotope $^{185}$W has been analyzed within the classical $s$-process model and within a realistic stellar model for AGB stars. With the classical model one obtains a neutron density of $3.8 \times 10^8$ cm$^{-3}$, compatible with the analyses of the branchings at $A = 147$–148, but incompatible with the branchings at $A = 169$–170 and 191–192. This inconsistency indicates that the assumptions of the classical model are too schematic to account for the stellar situation, where the $s$-process takes place. The corresponding analysis based on a more realistic stellar model overestimates the $^{186}$Os abundance by 20%. At present, we are facing the question of whether this mismatch is related to remaining uncertainties in other nuclear physics data or whether it originates from the $s$-process model itself. If the nuclear physics uncertainties can be further reduced, the $s$-process branching at $^{186}$W can be interpreted as a sensitive test of models for the important $A$-process phase of stellar evolution.

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