S-PROCESS BRANCHING AT $^{186}$RE, THE ABUNDANCE OF $^{186}$OS, AND PRESOLAR GRAINS. B. S. Meyer$^1$ and C. Wang$^2,3$ Department of Physics and Astronomy, Clemson University, Clemson, South Carolina, 29634-0978, USA, mbradle@clemson.edu, $^2$Department of Physics and Astronomy, Clemson University, Clemson, South Carolina, 29634-0978, USA, cwang@clemson.edu.

Introduction: Recent measurements of neutron-capture cross sections on isotopes of W, Re, and Os by inverse techniques have renewed interest in this region of the nuclide chart [1-3]. An important result of the new measurements is that the neutron-capture cross section on $^{185}$W is now considerably smaller than previously thought [1,2]. The consequence is that realistic s-process models in thermally-pulsing asymptotic giant branch stars now overestimate the abundance of $^{186}$Os by ~20%.

Along related lines, measurements of Os extracted from bulk unequilibrated chondrites show isotopic anomalies due, most likely, to incomplete digestion of SiC grains that carry s-process Osmium [4]. The primary implication of this work is that s-process grains were well mixed in the solar nebula by the time of planetesimal accretion. Another significant but puzzling finding is that the $^{186}$Os/$^{185}$W s-process ratio inferred from the measurements is lower than that expected from s-process models. A possible explanation is that the Osmium in the s-process carriers accessed by these measurements was from nucleosynthesis sites with neutron densities about 2-4 times higher than that of the average solar s-process [4].

Related Puzzles?: Here we consider whether the two puzzles, the overproduction of $^{186}$Os in s-process models and the lower than expected $^{186}$Os/$^{185}$W ratio inferred for the SiC grains, might be related. In particular, could a solution to the $^{186}$Os overproduction problem also provide insight into the $^{186}$Os/$^{185}$W puzzle?

The s-process flow in the W-RE-Os region branches at $^{185}$W (ground-state beta-decay lifetime of 75 days) and $^{186}$Re (ground-state beta-decay lifetime of 3.8 days). Neutron capture on $^{185}$W allows the s-process flow to continue on to stable $^{186}$W. This flow ultimately bypasses $^{186}$Os. If $^{185}$W beta decays instead of capturing a neutron, however, the s-process flow passes through $^{185}$Re. This flow then branches again at $^{186}$Re. If $^{186}$Re captures a neutron, the flow bypasses $^{186}$Os. If $^{186}$Re beta decays, the flow passes through $^{186}$Os. The various flow branches rejoin at $^{186}$Os.

With this picture in mind, it becomes clear how the lower cross section for $^{185}$W with all other cross sections and rates remaining the same leads to increased production of $^{186}$Os. The smaller $^{185}$W cross section leads to an increased s-process flow through $^{185}$Re and, ultimately, through $^{186}$Os.

Proposed solutions for the $^{186}$Os overproduction problem are 1) an increase in the $^{186}$Os neutron capture cross section over the value used in the s-process models [5] and 2) increased branching of the s-process flow at $^{186}$Re.

S-process flows achieve an approximate steady state, at least locally. This means that the abundance of an isotope is very nearly inversely proportional to its neutron-capture cross section. Thus, a 20% increase in the $^{186}$Os cross section would lower that isotope’s abundance in s-process models and thereby bring it into agreement with observed abundances. This would also help explain the $^{186}$Os/$^{185}$W in the undigested s-process carriers in the bulk chondrites without an appeal to an unusually large neutron density. In particular, the $^{186}$Os/$^{185}$W abundance ratio would decrease by ~20%, nearly the value observed in the chondrites. The difficulty with this explanation is that the necessary increase in the cross section is larger than the 5 -10% uncertainties expected from experiments [6,7].

The second possibility is that there is increased branching at $^{186}$Re. This could occur by increased electron capture of $^{186}$Re under stellar conditions, which would lead to $^{186}$W and thereby bypass $^{186}$Os. This is generally not a favored explanation since, under realistic conditions, the beta decay dominates [8].

The increased branching at $^{186}$Re could also occur by enhanced neutron capture. As already mentioned, an increased neutron density would increase branching [4] since the larger abundance of neutrons favors capture over beta decay. In order to solve the overproduction of $^{186}$Os, however, this larger neutron density would have to apply to the s-process in general, not a special population of s-process nuclei, as inferred for the undigested s-process carriers. An alternative is an increase in the $^{186}$Re cross section. This would increase the neutron capture across $^{186}$Re without requiring an increase in the s-process neutron density. Measurements of this cross section by inverse processes are becoming available [3] and may have sufficient accuracy in the near future to address the issue of branching at $^{186}$Re at the desired level.

Another effect that might increase the neutron-capture flow across $^{186}$Re is the fact that this isotope has a long-lived isomeric 8+ isomeric state at 149 keV. This state decays by internal transition to the ground state in 2x10$^3$ years. We have used the Clemson Uni-
to follow the de-excitation of the 8+ state in conditions appropriate for the s-process (T = 1-3 x 10^4 K) and have found that its lifetime remains little changed due to induced transitions at these temperatures because the large spin difference between this state and its neighbors prevents rapid communication at s-process temperatures. A possible scenario, then, is that neutron capture by ^185Re produces a highly excited compound nucleus of ^186Re. Normally, the compound nucleus decays by rapid internal transitions down to the ground state, which has a short beta-decay lifetime of 3.8 days. If a significant fraction of the cascading de-excitation flow reaches the 8+ isomeric state, however, it is arrested there and must wait for 2x10^5 years to continue. Such a long time will most likely allow the fraction of the ^186Re caught in this state to neutron capture before this transition occurs. Thus, the fraction of ^186Re captured in the 8+ state will bypass ^186Os.

The difficulty with this scenario is that it is not clear that a significant fraction of neutron capture by ^186Re leads to the 8+ state in ^186Re. The large spin difference of this state with its neighbors that prevents it from equilibrating also makes it difficult to populate in the first place. Nevertheless, there is a difference between the transitions that populate and de-populate the 8+ state: the populating transitions are spontaneous ones, unlike the transitions that might enhance equilibration of this state once it is populated. Moreover, it is important to point out that at a temperature of 10^4 K (10 keV), there will be a number of induced transitions near the excited levels of the compound nuclear state since nuclear levels will be spaced very close together. Such transitions will be difficult to replicate in Earth-based laboratories, and analysis of this scenario by comparison with experiment will require care.

While enhanced branching at ^186Re can compensate for the decreased branching at ^185W and thereby lead to an appropriate level of production of ^186Os, it does not necessarily solve the problem of the lower than expected ^186Os/^188Os abundance ratio seen in the undigested s-process carriers in bulk meteorites. In the case of a steady state characterized by a single exposure, increasing the ^186Re branching to compensate for the decreased ^185W branching must be such as to lead to the same flow through ^186Os required to produce the solar abundance of ^186Os. Since all branched flows rejoin at ^188Os, the abundance of this isotope does not change either. As a consequence, the ^186Os/^188Os will remain unchanged.

The s-process abundances, however, are not the result of a single, steady-state exposure. Rather, they arise from a distribution of exposures, and this may allow the increased branching at ^186Re to decrease the ^186Os/^188Os abundance ratio. The reason is that the decreased branching at ^185W sends less flow through ^186W, which has a relatively small neutron capture cross section (~176 mb at 30 keV), while the compensating increased branching at ^186Re sends more flow through ^186Re, which has a much larger neutron capture cross section (~2300 mb at 30 keV). When we use an exponential distribution of exposures [9], we find a ~3% decrease in the ^186Os/^188Os abundance ratio for an average exposure typical for the s-process in AGB stars. This, by itself, is not enough to explain the meteoritic data, but it helps.

**Conclusions:** Increasingly accurate neutron-capture cross measurements in the W-^Re-Os region of the chart of the nuclides and new measurements of Os isotopes in meteorites are providing important new constraints on the theory of s-process nucleosynthesis. Two key puzzles are arising: 1) why are s-process models overproducing ^186Os and 2) why do s-process carriers show lower ^186Os/^188Os abundance ratios than predicted by the s-process models? An increase by ~20% in the ^186Os neutron-capture cross section can simultaneously solve both puzzles, but does not seem to be allowed by current experiments. Enhanced branching at ^186Re, due to higher neutron density, an enhanced ^186Re neutron capture cross section, population of the 8+ isomeric state in ^186Re by ^185Re neutron capture, or enhanced electron capture on ^186Re can compensate the decreased branching at ^185W and yield the appropriate amount of ^186Os but does not necessarily solve the ^186Os/^188Os abundance ratio puzzle.

While answers to the above two puzzles may not be immediately forthcoming, consideration of them presents an interesting and important nexus in studies of nuclear physics, s-process nucleosynthesis, and cosmochemistry.

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