p-PROCESS SIGNATURE IN A UNIQUE PRESOLAR SILICON CARBIDE GRAIN.

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Introduction: Presolar grains are samples of stellar matter that contain isotopic records of nucleosynthesis in individual stars. Presolar SiC grains come in several distinct types, distinguishable by their C, N, and Si isotopic compositions, which show large deviations from solar system material. Each grain type represents a distinct class of stars. More than 90% of SiC grains are classed as mainstream. Mainstream SiC grains are the best studied and are produced by Asymptotic Giant Branch stars [1].

The remaining presolar SiC grain types are less well understood. Grains of types A and B comprise 3-4% of presolar SiC. Their light isotopic composition differs from mainstream grains only with regard to carbon isotopes. Type A grains are defined [2] as having $^{12}C/^{13}C \leq 3.5$, and B-gains are defined as having $3.5 < ^{12}C/^{13}C < 10$. The progenitor stars of type A and B grains are unknown. Amari et al. [3] measured C, N, Si, and Ti isotopic compositions and trace element abundances in a number of grains and concluded that no single stellar source can account for all of the observations. We have analyzed Mo and Ru isotopes in several grains of type A and B, and found one with a singular isotopic composition, namely a large enhancement in the *p*-process isotopes, along with lesser but still significant enhancements in the *r*-process isotopes. This grain is the first to show *p*-process enhancements, and as such must derive from a stellar source not yet identified.

Experimental Methods and Results: The grain in this study, KGJM1-133-1, was from size fraction KJG (2-5 μm) of the Murchison meteorite. It was approximately 3 μm in diameter. Its C, N, and Si isotopic compositions were determined by Secondary Ion Mass Spectrometry (SIMS). Details of the sample preparation and SIMS analysis were reported previously [3]. Molybdenum and ruthenium isotopic compositions were measured by Resonant Ionization Mass Spectrometry (RIMS). A description of the RIMS method is given elsewhere [4]. The isotopic compositions were normalized to terrestrial metals and indexed to the pure *s*-process isotopes ^{96}Mo and ^{100}Ru. The reported uncertainties are statistical only. The Mo isotopic composition was published previously [5].

The light element isotopic composition of this grain classifies it as Type B: $^{12}C/^{13}C = 4.54 \pm 0.03$, $^{14}N/^{15}N = 3602 \pm 249$, $\delta^{29}Si = 15 \pm 5.4$, $\delta^{30}Si = -4.3 \pm 7.8$. Some type B grains show trace element abundances consistent with solar system values; others appear to have condensed from gasses with *s*-process enrichments up to 3-5 times solar [3]. RIMS analyses of nine other A- and B-grains have shown either normal (i.e. solar) Mo or, in one case, enhancements in the mixed *r*- and *s*-process isotopes ^{97,98}Mo [5]. The salient features of this grain are the strong enhancement of the *p*-process isotopes ^{92,94}Mo and ^{96,98}Ru and, to a lesser extent, the *r*-process isotopes ^{100}Mo and ^{104}Ru (Fig. 1). There is also a small but apparently significant depletion (3σ) in the mixed *r,s*-process isotope ^{98}Mo. The Mo *p*-isotope enhancements are very clear, on the order of 150‰ with more than 7σ deviation from solar. Ruthenium was measured last, after much of the grain had been consumed in the Si, C, N, and Mo analyses, thereby limiting the number of Ru ion counts. Despite the lower precision, it is clear that the Ru isotopic pattern is the same as that of Mo. Recent RIMS and NanoSIMS studies have shown that terrestrial contamination can affect SiC grains [6,7], however this would only make the *p*-process anomalies appear smaller.

Discussion: The production of most *p*-isotopes is well explained by the γ-process, in which seed nuclei are exposed to temperatures of $2\text{-}3\times10^9$ K, absorb γ-rays from the photon bath and photodisintegrate via (*γ, n*) reactions into proton-rich nuclei [8]. Such conditions are achieved briefly in models of core-collapse supernovae (SNII) and do produce most *p*-nuclei in amounts commensurate with the observed solar system abundances, but the models do not account for the high abundances of the light *p*-nuclei near the closed neutron shell at $N = 50$, specifically ^{92,94}Mo and ^{96,98}Ru [9]. Several promising models have been proposed recently, which include neutrino interactions in winds from nascent neutron stars just after core collapse [10-13]. These models are very sensitive to input nuclear physics drawn from areas of the chart of the nuclides which are little explored at present, and thus the results vary from model to model. Nonetheless, they show great promise in resolving the mystery of the production site of the light *p*-nuclei. Detonating white dwarfs [14] and fallback onto new-born supernova remnants [15] have also been shown to be viable candidates under some conditions.

All of the models produce Mo and Ru isotopic compositions far too extreme to explain the modest *p*-process overabundances in this grain, however a mixture of material from these models, specifically from certain zones within the models, with isotopically normal matter may be invoked. Most grains of types A & B have isotopically normal Mo and Ba [5]. Therefore it is reasonable to assume that their progenitor stars do not expose nuclei to significant doses of neutrons, at least not the material that eventually comprises the grains. The heavy element isotopic composition of these grains may be representative of the protostellar nebula, or it may be acquired during the star's lifetime by mass transfer from a companion.

While standard SNII models underproduce the light *p*-isotopes, there are zones near the mass cut that show large ratios of ^{92,94}Mo and ^{96,98}Ru relative to the other Mo and Ru isotopes [9]. To investigate whether this grain was produced by a star that was contaminated with such material, we mixed inner zone material from 15, 20, and 25 $M_\odot$ SNII (taken from nucleosynthesis.org, models described in ref. 9) with isotopically normal material and optimized the mixtures to match the Mo or Ru isotopic composition of the grain. The results were similar for all so we report only the 15 $M_\odot$ model. Mixing about 6-7×10^{-3} $M_\odot$ of SNII inner zone material per solar mass of isotopically normal matter does in fact reproduce the *p*-process enhancement observed in this grain (Fig. 1), however slightly different mixtures are required for Mo and Ru (see Fig. 1 caption), and the *r*-isotopes show no enhancement. Further, the C, N, and Si isotopic compositions resulting from these mixtures do not match the observation. The mixture that best matches the Mo composition has ^{12}C/^{13}C = 90 and ^{14}N/^{15}N = 220, in strong contrast to the ratios found in the grain. The grain's progenitor star may have strongly processed C and N, so that these ratios would not have survived, however it does not appear to have significantly altered its Si isotopic composition, and here the mixing model predicts δ^{29}Si = 400‰ and δ^{29}Si = 3300‰, which is clearly not seen in the grain. A further problem is that the material is drawn from near the mass cut, and our mixing model ignores the more than 10 $M_\odot$ of material above it. Including the overburden brings the Si isotopes closer to normal, but erases the *p*-process enhancement.

The newer SNII models may address these issues. While the relevant zones are still near the mass cut in the neutrino wind models, the Mo and Ru abundances are higher, so that overburden has less effect. Also, in the Wanajo model [13] both the *p*- and *r*-isotopes for Mo and Ru are overproduced relative to the *s*-only isotopes ^{96}Mo and ^{100}Ru. The white dwarf [14] and fallback [15] models have the advantage of little or no overburden, though mass ejection may be an issue.

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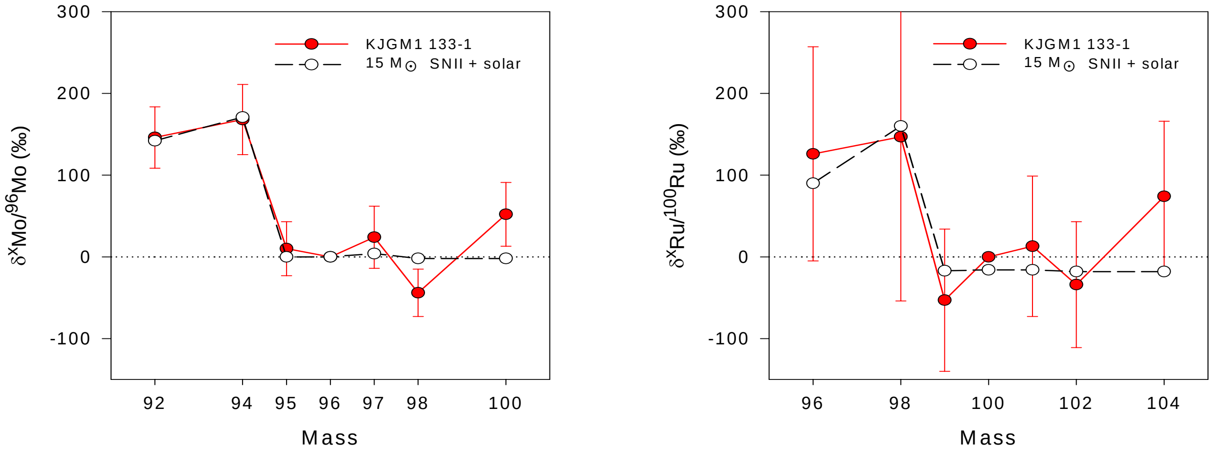

Figure 1: The observed Mo and Ru isotopic composition of SiC grain KJGM-1-133-1 (filled circles) compared to a theoretical mixture of 15 $M_\odot$ SNII material near the mass cut from model s15a28d of nucleosynthesis.org (open circles). The Mo composition was fit using material from zones 415-422, while the Ru composition was fit using material from zones 412-413. Uncertainties are 2σ.