

## EFFICIENT OXYGEN ISOTOPE EXCHANGE BETWEEN CHONDRULE MELT AND AMBIENT GAS IN THE PROTOPLANETARY DISK

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**Introduction:** Chondrules in carbonaceous chondrites show a range of  $\delta^{17,18}\text{O}$  values mostly from  $-15\%$  to  $+5\%$  [e.g., 1], suggesting that chondrule formed in the environment depleted in  $^{16}\text{O}$  relative to Ca, Al-rich inclusions (CAIs) and the composition of Sun ( $-50\%$  to  $-60\%$  [2-3]). An earlier study of Allende (CV) chondrules by Clayton et al. [4] shows that completely melted barred olivine (BO) chondrules are depleted in  $^{16}\text{O}$  compared to partially melted porphyritic chondrules, suggesting that chondrules acquired  $^{16}\text{O}$ -poor signature through isotope exchange between chondrule melt and  $^{16}\text{O}$ -poor nebula gas. However, recent high precision SIMS oxygen isotope analyses of minerals and glass in chondrules revealed that individual chondrules are generally homogeneous in oxygen isotope ratios, except for minor occurrence of relict olivine grains with distinct isotope ratios [5-11]. Even in porphyritic chondrules, multiple analyses of olivine grains are indistinguishable from those of co-existing pyroxene, which is inconsistent with the idea of incomplete exchange with  $^{16}\text{O}$ -poor gas during chondrule formation. Below, we point out several key observations from recent SIMS studies and discuss their significance to chondrule formation processes.

**Oxygen isotope homogeneity in single chondrules from least metamorphosed chondrites:** If chondrule melt incompletely exchanges oxygen isotopes with surrounding  $^{16}\text{O}$ -poor gas, the  $\Delta^{17}\text{O}$  ( $=\delta^{17}\text{O}-0.52\times\delta^{18}\text{O}$ ) values of the later forming phases, such as glass and plagioclase in mesostasis, would be higher than those of olivine and pyroxene phenocrysts. However, Ushikubo et al. [6] found that  $\Delta^{17}\text{O}$  values of glassy mesostasis in chondrules from Acfer 094 are consistent with those in co-existing olivine and pyroxene phenocrysts. Similar results are reported for  $\Delta^{17}\text{O}$  of plagioclase in chondrule mesostasis from other chondrites [8-9]. Thus, chondrules do not show evidence of isotope zoning with respect to crystallization sequence, which would be a consequence of incomplete isotope exchange.

**Oxygen isotope systematics in CC chondrules:** Schrader et al. [12] extensively examined  $\Delta^{17}\text{O}$  of BO chondrules in CR chondrites to clarify if there are systematic difference in  $\Delta^{17}\text{O}$  between BO and porphyritic chondrules. The range of  $\Delta^{17}\text{O}$  values among BO chondrules are diverse ( $-4\%$  to  $+1\%$ ) and similar to those of porphyritic chondrules. In general, there are no systematic differences in  $\Delta^{17}\text{O}$  values related to textures of chondrules, but there is a systematic relationship of  $\Delta^{17}\text{O}$  values against Mg# ( $=[\text{MgO}]/[\text{MgO}+\text{FeO}]$  molar% in olivine and pyroxene) [6-11]. Tenner et al. [8] observed monotonic increase of  $\Delta^{17}\text{O}$  with decreasing Mg# among FeO-poor chondrules in CR chondrites. By using mass an balance model, [8] suggested that the addition of  $^{16}\text{O}$ -poor water ice to  $^{16}\text{O}$ -rich anhydrous silicate in the chondrule precursors would produce the observed trend.

**OC-like chondrules in carbonaceous chondrites:** Among 10 large chondrule separates from Allende, Defouilloy et al. [13] found 3 FeO-rich BO chondrules with  $\Delta^{17}\text{O}$  values  $\sim 0\%$ , which are similar to those reported by [4]. However, these BO chondrules show negative  $\varepsilon^{54}\text{Cr}$  values similar to those of ordinary chondrites and achondrites, which are members of the so called “non-CC” group. Thus, the  $^{16}\text{O}$ -poor isotope signature of BO chondrules in Allende suggests a distinct formation region for these chondrules. There are several porphyritic chondrules in Acfer 094, CV, and Y-82094 that are considered to be “OC-like” chondrules [9] with intermediate Mg# ( $\sim 85$ ) and  $\Delta^{17}\text{O} \sim 0\%$  [6, 9-10].

**Summary:** Chondrules are likely formed in dust-enriched environments [8, 14-15]. Evaporation of oxides during chondrule formation would produce an ambient gas with a  $\Delta^{17}\text{O}$  value similar to that of the average solid chondrule precursor. Recondensation of oxides from gas to the chondrule melt would enhance isotope exchange between gas and melt. Internally homogeneous oxygen isotope ratios of olivine suggest that most olivine phenocrysts crystallized from the final chondrule melt, or that they formed in a previous chondrule-forming event in an environment with indistinguishable oxygen isotope ratios. Thus, oxygen isotope ratios of chondrules represent those of the mean solids in the environments where they formed. In the case of carbonaceous chondrite chondrules, variability of  $\Delta^{17}\text{O}$  values mainly resulted from the addition of various amounts of  $^{16}\text{O}$ -poor water ice to the chondrule-forming disk regions.

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