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Constraints from Ca isotopes and kinetic-equilibrium modeling on CAI formation

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The elemental and isotopic compositions of Calcium-Aluminum-rich Inclusions (CAIs) in meteorites provide a record of the physical and chemical conditions present during the early evolution of the solar nebula (e.g., [1]). This work aims to characterize the elemental and Ca-isotope variability of CAIs and to draw inferences about evaporation-condensation processes occurring in the region of CAI formation.

To better characterize CAIs, we have analyzed 21 inclusions for elemental abundances and Ca-isotope ratios. Prior work has indicated a relationship between mass-dependent Ca-isotope variation and volatility fractionation of rare earth elements (REEs; [2-4]). Our dataset—which has been previously presented [5]—supports this observation. CAIs with unfractionated REE patterns ("Group I") have an average $\delta^{44/40}$Ca value relative to NIST SRM 915a of +0.16‰ and cover a range from -1.71 to +1.55‰—largely overlapping with the values of bulk carbonaceous chondrites (e.g., [6]). CAIs with volatility-fractionated REE patterns ("Group II") have an average value of -2.62‰ and cover a range from -8.84 to +0.80‰, exhibiting significant relative enrichments in light isotopes.

To investigate the implications of CAI isotopic compositions, we have carried out modeling of evaporation and condensation kinetics in the solar nebula. Our calculations track the elemental and isotopic composition of a small (e.g., 1 mm) multi-phase condensed particle and surrounding gas, as evaporation or condensation occurs. Our calculations illustrate that it is very challenging for evaporation events to produce a reservoir with significantly fractionated Ca-isotope ratios (as observed in Group II CAIs), without also depleting that reservoir in Al excessively, to an extent inconsistent with the Al/Ca ratios of CAIs. Accordingly, the Ca-isotope variation in Group II CAIs is probably a result of condensation rather than evaporation. Our calculations also suggest relatively high pressures (i.e., above 10^{-3} bar) and rapid temperature changes in the solar nebula in the region of CAI formation.

[1] Boynton (1975), GCA 39, 569-584; [2] Huang et al., (2012) GCA 77, 252-265; [3] Bermingham et al. (2018), GCA 226, 206-223; [4] Shollenberger et al. (2019), GCA 263, 215-234; [5] Parendo et al. (2023), Goldschmidt 2023; [6] Valdes et al. (2021), Chem. Geol. 581, 120396.