

Evaporation kinetics of forsterite in hydrogen gas and water vapor

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Introduction: Water vapor is a major oxidant in gas-solid reactions in the early Solar System. A wide variety of oxidation states among chondrites or chondritic components indicates that redox states varied within the chondrite forming region, which could have been caused by heterogeneous water vapor distribution due to accretion and sublimation of icy dust/pebbles [1, 2]. Such heterogeneous distribution of water vapor also explains the oxygen isotope evolution of dust in the inner Solar System [3].

Water vapor may also affect the evaporation kinetics of minerals and melts that was responsible for chemical fractionation in the early Solar System. The effect of water vapor on evaporation of forsterite was theoretically investigated for the $\text{Mg}_2\text{SiO}_4\text{-H}_2\text{-H}_2\text{O}$ system based on the Hertz-Knudsen equation [4, 5]. It was predicted that the evaporation occurs either (1) in the free evaporation-dominated (FED) regime, where the effects of H_2 and H_2O are ignored, under the low P_{H_2} and $P_{\text{H}_2\text{O}}$ condition, (2) in the hydrogen reaction-dominated (HRD) regime, where the evaporation rate increases proportionally to $P_{\text{H}_2}^{1/2}$, in the protoplanetary disk-like P_{H_2} condition, or (3) in the $\text{H}_2\text{-H}_2\text{O}$ buffer-dominated (HBD) regime, where the evaporation rate depends on $P_{\text{H}_2}/P_{\text{H}_2\text{O}}$, under the oxidizing or low temperature conditions. Evaporation in the FED and HRD regime is consistent with previous experiments [6, 7], but that in the HBD regime has not been experimentally confirmed yet.

Methods and Results: We carried out evaporation experiments of forsterite single crystal in a vacuum furnace at 1600 and 1350 K. H_2 gas was introduced into the furnace and its pressure was kept at 1 Pa. Water vapor was introduced by passing H_2 gas above liquid water in the gas supply line. Evaporation rates were obtained from weight losses of the samples.

Forsterite evaporated linearly and congruently both in H_2 gas and in the $\text{H}_2\text{-H}_2\text{O}$ mixed gas as in [6]. The evaporation rates at 1 Pa H_2 gas were $(1.13 \pm 0.06) \times 10^{-5}$ and $(6.5 \pm 0.2) \times 10^{-8} \text{ mol m}^{-2} \text{ s}^{-1}$ at 1600 and 1350 K, respectively, which are consistent with previous studies [6, 7]. Experiments in 1 Pa of the $\text{H}_2\text{-H}_2\text{O}$ mixture gas at 1350 K yielded the evaporation rates of $(6.9 \pm 0.7) \times 10^{-9}$ and $(7.4 \pm 0.6) \times 10^{-9} \text{ mol m}^{-2} \text{ s}^{-1}$ at $P_{\text{H}_2}/P_{\text{H}_2\text{O}}$ of 214 ± 8 and 429 ± 15 , respectively.

Discussion: The present experiments confirmed for the first time that water vapor suppresses evaporation of forsterite in the predicted HBD regime. The evaporation rates at 1350 K with $P_{\text{H}_2}/P_{\text{H}_2\text{O}}$ of ~ 210 and ~ 430 are close to each other, suggesting smaller ($P_{\text{H}_2}/P_{\text{H}_2\text{O}}$) dependence than that predicted in [5]. If this is the case, the evaporation behavior of forsterite in the presence of water vapor may not be simply expressed by the HK equation, which should be confirmed by further experiments.

It is not clear that evaporation of forsterite obeys the HK equation, but the present study showed that water vapor suppresses the evaporation rate in the HBD regime. When $P_{\text{H}_2\text{O}}$ in protoplanetary disks is enhanced by a factor of ten [1] from that for the system of solar abundance ($P_{\text{H}_2}/P_{\text{H}_2\text{O}} \sim 2 \times 10^3$ [8]), evaporation of forsterite is expected to occur in the HBD regime at temperature up to ~ 1600 K under the total pressure of ~ 10 Pa. The suppressed evaporation in the presence of water vapor extends the timescale of elemental and isotopic fractionation. If evaporation of CAI melts and chondrule melts also obey the evaporation in the HBD regime, the evaporative elemental and isotopic fractionation would have been suppressed under the enhanced $P_{\text{H}_2\text{O}}$ condition.

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