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Kinetic effects in source regions explain the Fe isotope dichotomy of lunar basalts

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Mare basalts are widely used to constrain the isotope compositions of the bulk silicate Moon. Data, including ours, however, have consistently shown that the Fe isotope compositions of lunar basalts exhibit a dichotomy: low-Ti basalts are light, while high-Ti basalts are heavy in their Fe isotope compositions. The origin of this dichotomy has been enigmatic, with the most probable explanation being differences in source mineralogy. The source regions are thought to contain olivine, orthopyroxene, ±clinopyroxene, and ±ilmenite [1]. If Fe isotopes partition differently between these phases, then differences in source mineralogy could explain the observed isotopic dichotomy.

Here, we use nuclear resonant inelastic X-ray scattering (NRIXS) to measure the bond strengths of Fe in olivine, orthopyroxene and clinopyroxene. Combined with literature data on ilmenite [2], we conclude that, at equilibrium, all minerals in the source region should have an identical Fe isotope composition. Therefore, partial melting of a heterogeneous but well-equilibrated mantle could not have produced the range of Fe isotope compositions observed for lunar basalts.

Given that equilibrium processes fail to explain the Fe isotope dichotomy, kinetic processes must be invoked. Iron partitioning into clinopyroxene depends on temperature [3]. During cooling, Fe diffuses from clinopyroxene to olivine and orthopyroxene. As the light isotopes diffuse faster, a snapshot of this process would involve clinopyroxene that is isotopically heavy. As clinopyroxene is more fusible [4] , partial melting of a clinopyroxene-bearing source material would yield a basalt that is isotopically heavy in Fe. Numerical modeling demonstrates that this process can enrich heavy Fe isotopes in the partial melt by up to 0.2 ‰ in δ^{56}Fe, which is enough to explain the isotope dichotomy between low- and high-Ti basalts. Attempts to constrain isotope compositions of the bulk silicate Moon must consider such kinetic processes in the source region, as equilibrium may be the exception rather than the norm.

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