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Mass-dependent carbon isotope fractionation by diffusion in Fe-metal as potential record of processes in the early solar system

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The chemical versatility and diverse chemical forms of carbon (organics, carbonates, carbides, graphite, diamond, etc.) make this element a promising source of information on the origin and evolution of the early solar system including processes of core formation of planetary bodies. The abundance of carbon in chondrites and other meteorites is relatively low (0.2 - 4 wt%) and its occurrence is frequently associated with Fe-Ni metal. Carbon typically exhibits large isotopic heterogeneities of several tens of per mil, even in differentiated meteorites which experienced periods of extensive heating. Hence, this record of incomplete diffusive equilibration of carbon in Fe-Ni metal raises the possibility that carbon isotopes might be fractionated by diffusion during formation and evolution of carbonaceous matter in the solar system—perhaps to an extent that could affect the C isotope ratio of the bulk silicate Earth.

In this study we present experimentally derived data for mass-dependent diffusive fractionation of carbon isotopes in Fe-metal at 1 GPa and 1000-1100°C. Diffusion couples consist of a pre-synthesized Fe-C cylinder with ∼1wt% carbon placed next to a cylinder of high purity, polycrystalline Fe with ∼10ppm C encapsulated by silica glass. Experiments were conducted in a piston cylinder apparatus for durations ranging up to several hours. The chemical and isotope composition of carbon in the run products was measured by EMPA and SIMS. Measured profiles from the more carbon-rich half of the diffusion couple into the Fe-metal which contains only a trace C content reveal significant carbon penetration, with isotope values becoming progressively lighter -i.e. ^{12}C is enriched relative to ^{13}C because of faster diffusion of the lighter isotope- with increasing distance from the original interface. The maximum resulting fractionation is on the order of 40-50‰ comparable with the range of natural observations. The relative diffusivities (D) of the carbon isotope species can be related to their masses (m) by $D[^{12}C]/D[^{13}C] = (m[^{13}C]/m[^{12}C])^{\beta}$ for which β has been determined by the experiments of this study to be as high as ∼0.3 for the case of carbon. Such high β-values have previously been reported for diffusion in metals, suggesting that, as expected, diffusion of carbon occurs by an interstitial mechanism. Most importantly, such a high value for the exponent β highlights the great potential of carbon isotope fractionation to be recorded by transport processes of carbon during formation and/or evolution of meteorites and planetary bodies leaving the compositional and isotopic fingerprint of incomplete diffusive equilibration.