Viscosity of Earth’s inner core constrained by Fe–Ni interdiffusion in Fe–Si alloy in an internal-resistive-heated diamond anvil cell

YOHAN PARK1, KYOKO YONEMITSU2, KEI HIROSE2,3, YASUHIRO KUWAYAMA2, SHINTARO AZUMA1, AND KENJI OHTA1,*

1Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Tokyo 152-8551, Japan
2Department of Earth and Planetary Science, The University of Tokyo, Tokyo 113-0033, Japan
3Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo 152-8550, Japan

ABSTRACT

Diffusivity in iron (Fe) alloys at high pressures and temperatures imposes constraints on the transport properties of the inner core, such as viscosity. Because silicon (Si) is among the most likely candidates for light elements in the inner core, the presence of Si must be considered when studying diffusivity in the Earth’s inner core. In this study, we conducted diffusion experiments under pressures up to about 50 GPa using an internal-resistive-heated diamond-anvil cell (DAC) that ensures stable and homogeneous heating compared with a conventional laser-heated DAC and thus allows us to conduct more reliable diffusion experiments under high pressure. We determined the coefficients of Fe–nickel (Ni) interdiffusion in the Fe–Si 2 wt% alloy. The obtained diffusion coefficients follow a homologous temperature relationship derived from previous studies without considering Si. This indicates that the effect of Si on Fe–Ni interdiffusion is not significant. The upper limit of the viscosity of the inner core inferred from our results is low, indicating that the Lorentz force is a plausible mechanism to deform the inner core.

Keywords: Earth’s inner core, diffusion, viscosity, iron, silicon, high pressure

INTRODUCTION

Viscosity is a crucial physical property to understanding dynamical processes in planetary interiors. The viscosity of the Earth’s inner core constrains the modes and mechanisms of viscous flows responsible for the observed seismic anisotropy of the inner core (Lasbleis and Deguen 2015). Seismological observations of the inner core reveal its complicated anisotropic structures; the P wave travels ~3–4% faster along the polar direction compared to its equatorial direction (e.g., Poupinet et al. 1983). This anisotropy of the inner core can be attributed to lattice-preferred orientation (LPO) induced by the viscous flow of inner core materials (Deguen 2012; Romanowicz and Wenk 2017). The Rayleigh-Bénard convection was first proposed as a possible mechanism of viscous flow in the inner core (Jeanloz and Wenk 1988). Yoshida et al. (1996) argued that the inner core grows preferentially to the equatorial direction due to the columnar convection of the outer core. Such heterogeneous inner core growth leads to isostatic disequilibrium, and the resultant differential stress gives rise to a viscous flow in the inner core. External forces related to the Earth’s magnetic field, such as the Lorentz force or force induced by heterogeneous joule heating, have been proposed as possible mechanisms for the viscous flow in the inner core (Karato 1999; Takehiro 2011). The strength and mode of viscous flows (i.e., the plausibility of the proposed mechanisms) heavily depend on the viscosity of the inner core; however, there is significant uncertainty in its estimates, which range from \(10^{19}\) to \(10^{22}\) Pa s (Buffett 1997; Davies et al. 2014; Frost et al. 2021; Jackson et al. 2000; Koot and Dumberry 2011; Reaman et al. 2011; Ritterbex and Tsuchiya 2020; Van Orman 2004; Yoshida et al. 1996). These studies estimated the viscosity of the inner core either from experiments, ab initio calculations, or geophysical observations.

From a mineral physics point of view, the approach often adopted is an estimate of the viscosity based on the diffusion coefficient of iron (Fe) under high pressure (Yunker and Van Orman 2007; Reaman et al. 2012; Ritterbex and Tsuchiya 2020). Terrestrial cores are thought to be composed of Fe alloyed with nickel (Ni) and some light elements. Solid Fe alloys composing the Earth’s inner core assume a hexagonal closed packed (hcp) structure, while pressure and temperature conditions of the centers of smaller terrestrial planets, such as Mercury and Mars, favor face-centered cubic (fcc) structures of iron alloys as a dominant phase of their possible solid inner cores, depending on light element concentrations (Komabayashi et al. 2019; Tsuji et al. 2013). Although the self-diffusivity of Fe under high pressure is a critical limiting factor of crystal plasticity of inner core materials, the self-diffusion coefficient of Fe under pressures relevant to the deep Earth has not been studied experimentally due to experimental difficulties. Instead, experimental attempts have been made to estimate the effects of pressure on Fe–Ni interdiffusion coefficients as an analogy of Fe self-diffusion coefficients (Reaman et al. 2012; Yunker and Van Orman 2007).

An open question unaddressed by previous studies is the effect of light elements on Fe–Ni interdiffusion coefficients, as the Earth’s inner core must contain ~1–3 wt% light elements