Fe-Ni ideality during core formation on Earth

DONGYANG HUANG1,* AND JAMES BADRO1,2

1Institut de Physique du Globe de Paris, Sorbonne Paris Cité, 75005 Paris, France
2École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

ABSTRACT

Earth’s core is essentially composed of a light-element bearing iron-nickel alloy (Birch 1964). The nickel content in the core has negligible effects on physical properties such as density and compressibility (e.g., Lin et al. 2003; Kantor et al. 2007; Martorell et al. 2013; Badro et al. 2014). This deter any attempt to determine or even estimate the nickel content of the core using seismological models, as in the case of light elements. It was recently proposed that the presence of nickel should fractionate iron isotopes in small planetary cores (Elardo and Shahar 2017), but the effect for a large (hot) planet such as the Earth would not be measurable; this observation, however, opens up the possibility that Ni can have an effect on element partitioning between the metallic alloy and the silicate melt during core formation. In this case, the siderophile trace-element composition of the mantle would, in turn, constrain the Fe/Ni ratio in the core. Here, we investigated the effect of nickel concentration in the metallic alloy on the partitioning of other elements at conditions directly relevant to core formation, using the laser-heated diamond-anvil cell. We found no measurable effect of nickel concentration on the partitioning of Ni, Cr, and V; the Fe-Ni alloy is chemically ideal over a broad range of Ni concentrations (3.5 to 48.7 wt%). The ideality of the Fe-Ni solution across a wide range of nickel concentration shows that Fe and Ni are not only twins from the standpoint for material properties, but also from that of chemical properties in those high P-T conditions.

Keywords: Fe-Ni “ideality”, core formation, metal-silicate partitioning, high pressure

INTRODUCTION

Earth’s core is composed of Fe-Ni alloy with ~5–10% of light element(s) to account for the observed density deficit (Birch 1964). Assuming a chondritic bulk Earth and a known Fe/Ni ratio in the bulk silicate Earth (BSE), the Fe/Ni ratio can be estimated using mass balance to be ~16 in the core (Allègre et al. 1995; McDonough and Sun 1995). At outer-core conditions, the effect of nickel content is negligible with respect to density, compressibility, and wave velocities (e.g., Lin et al. 2003; Kantor et al. 2007; Martorell et al. 2013; Badro et al. 2014). Therefore, it is common practice to ignore Ni when simulating or experimenting on core properties. A recent metal-silicate isotopic fractionation study (Elardo and Shahar 2017) found that nickel favors the fractionation of heavy iron isotopes in the core during planetary core formation. This raises the question whether nickel also affects the partitioning behavior of siderophile elements during core formation, which in turn would affect our current understanding of core formation.

Core formation on Earth occurs by metal-silicate differentiation in a magma ocean (e.g., Ringwood 1959; Li and Agee 1996; Wood et al. 2006). Accreting material melts in the magma ocean, and liquid metal separates and equilibrates with surrounding silicate melt as it gravitationally segregates toward the center of the planet to form the core. This equilibration process strips siderophile elements from the magma ocean (i.e., BSE) to the core, setting the trace-element composition of both reservoirs.

Their relative depletion in the BSE is obtained by comparing the composition of the most primitive mantle-derived rocks with that of chondrites (a proxy for bulk Earth composition). High-pressure and high-temperature experiments can then be used to match the observed depletions, and because metal-silicate partitioning is a function of pressure (P), temperature (T), composition (X), and oxygen fugacity (fO2), further constrain the thermochemical conditions of core formation (e.g., Li and Agee 1996; Wade and Wood 2005; Siebert et al. 2013; Fischer et al. 2015). Core formation models show that the P-T conditions for metal-silicate equilibration range up to 75 GPa, with temperatures as high as 4350 K (Badro et al. 2015), establishing that the core formed in a deep magma ocean. The presence of various (major and trace) elements in liquid iron alloy has an influence on the partitioning of siderophile trace elements, and extensive experiments have been designed to investigate the effect of silicon, oxygen, carbon, or sulfur (dissolved in metal) on element partitioning during core formation; however, the effect of nickel, another major element in the core, has never been experimentally tested, and it was always assumed that Ni-free or Ni-bearing systems behave similarly from the point of view of partitioning.

EXPERIMENTS AND ANALYSIS

In this study, we investigated the effect of nickel on the metal-silicate partitioning of three siderophile elements (Ni, Cr, and V) by performing laser-heated diamond-anvil cell (LHADAC) experiments up to 94 GPa and 4500 K. Starting materials were synthesized at IPGP using a gas-mixing aerodynamic levitation laser furnace (silicate) and a piston-cylinder press (metal). The samples were polished and cut using a picosecond laser-machining system (IPGP) then loaded in diamond-anvil cells using rhenium gaskets and compressed to target pressures.