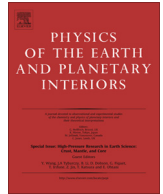




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The abundance of potassium in the Earth's core



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ABSTRACT

We studied partitioning of potassium (K) between aluminosilicate (adularia, KAlSi_3O_8) and metals with and without light elements, oxygen and silicon (Fe–O, Fe–Si, and pure Fe metals). We conducted experiments at pressures up to 50 GPa, temperatures up to 3500 K, and oxygen fugacities ($\log f_{\text{O}_2}$) between 2.5 and 4.0 log units below the iron-wüstite (IW) buffer using a double-sided laser-heated diamond anvil cell. Our results on pressure, temperature, and compositional effects on partition coefficient of potassium, D_K (i.e., the content of potassium in metal [wt%] divided by the content of potassium in silicate [wt%]), revealed that the temperature effect is slightly positive but weaker than that reported previously, whereas the pressure effect is negative. Oxygen in metal increases the potassium content in metal, whereas silicon in metal has the opposite effect. According to the present study on potassium partitioning, we estimated that the amount of potassium in the core is less than 40 ppm and that it generates less than 0.17 TW heat in the core. The amount of heat generated in the core is very small compared with the heat escaping from the core at the core–mantle boundary (5–15 TW).

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1. Introduction

The density of the Earth's core is lower than that of pure iron under the core condition (e.g., Birch, 1964; Anderson and Isaak, 2002). It has thus been considered that the Earth's core contains one or more light elements, such as hydrogen (H), carbon (C), sulfur (S), oxygen (O), and/or silicon (Si) (e.g., Poirier, 1994). Although which and what quantity of light elements are included in the core are not yet known well, high-pressure experiments (e.g., Badro et al., 2007; Tsuno et al., 2013) and cosmochemical estimations (e.g., McDonough, 2003) suggested that Si and O might be the plausible light elements. Si is one of the most abundant elements in the Earth but it is depleted in the mantle relative to its concentration in chondritic meteorites (e.g., Ringwood, 1959). Recently, it was reported that the solubility of both Si and O in metallic iron increases with increasing pressure (e.g., Sakai et al., 2006). O is also one of the most abundant elements in the Earth.

The energy that drives the geodynamo through the convection of the outer core is derived from accretion energy at the early stage of the Earth, the latent heat of crystallization of the inner core, the gravitation energy associated with the exclusion of light materials

from the inner core, and the decay of radiogenic elements that are potentially present in the core. The Earth's core might contain long-lived radioactive elements, such as U, Th, and K, as heat sources. In particular, potassium (K) is thought to be taken by the core. Although potassium, a volatile element, evaporated to the outside of the Earth during the early Earth's accretion, it is more depleted in the mantle than other volatile elements (e.g., Gast, 1960; Wasserburg et al., 1964). This may indicate that a certain amount of potassium has been incorporated into the core by the equilibrium during the core–mantle differentiation in the early core formation stage of the Earth. It was reported that potassium alloyed with iron at pressures above 26 GPa (Lee and Jeanloz, 2003). In addition, core energetics calculations suggested that a certain amount of potassium as a heat source in the core was necessary for sustaining the geodynamo and obtaining the inner core of the correct size (e.g., Nimmo et al., 2004). Potassium-40 (^{40}K) is a radioactive isotope of potassium that generates radiogenic heat when it undergoes a radioactive decay. If there is a large amount of ^{40}K in the core, the decay could serve as a heat source in the Earth's interior and power Earth's “long-lived” magnetic field.

In order to estimate the amount of potassium partitioned into the core in the early core formation stage of the Earth, partitioning experiments of potassium have been conducted at high pressure

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and high temperature (e.g., Ito et al., 1993; Ohtani and Yurimoto, 1996; Chabot and Drake, 1999; Gessmann and Wood, 2002; Murthy et al., 2003; Hirao et al., 2006; Bouhifd et al., 2007; Corgne et al., 2007). These studies reported that the partition coefficient of potassium, D_K (=the content of potassium in metal [wt%]/the content of potassium in silicate [wt%]), could vary from 0.0047 to 2.4, depending on the effects of temperature, pressure, oxygen fugacity, and metal and silicate compositions (e.g., NBO/T; the number of non-bridging oxygen divided by the number of tetrahedral cations). These previous studies thus concluded that the potassium abundance in the core varied from 2 to 250 ppm. Although previous studies helped to understand the behavior of potassium in the core, the actual potassium abundance in the core are still controversial and under debate. Additionally, these studies were not conducted at the pressure corresponding to the base of the magma ocean during the early stage of the Earth. From the point of partitioning experiments of siderophile elements (e.g., Ni, Co, V, and Cr), the composition of the mantle reflects the chemical equilibrium at about 27–60 GPa and 3000–3500 K corresponding to the base of the magma ocean (e.g., Allegre et al., 1995; Chabot et al., 2005; Siebert et al., 2013). Therefore, in order to constrain the abundance of potassium in the Earth's core accurately, partitioning experiments of potassium need to be carried out at the core material-silicate melt equilibrium conditions, i.e., at the base of the magma ocean during the early stage of the Earth's accretion.

We conducted experiments to clarify potassium partitioning between iron alloys and a K-bearing phase at the pressure and temperature conditions corresponding to the base of the magma ocean using a laser-heated diamond anvil cell (LHDAC). We investigated the effect of pressure, temperature, oxygen fugacity ($\log f_{O_2}$), and silicate polymerization (NBO/T) on D_K in Fe–light-element systems and the effect of light elements (Si and O) on D_K under the core–mantle equilibrium condition at the base of the magma ocean to determine accurately the abundance of potassium in the Earth's core.

2. Experimental methods

In order to ensure the potassium contents in the metal above detection limits of the analysis, we selected K-feldspar (adularia, $K_{0.95}Na_{0.03}Al_{1.00}Si_{3.00}O_8$, Switzerland) as a starting silicate material that contains a large amount of potassium. The chemical composition of adularia analyzed by an electron probe microanalyzer (EPMA/WDS: JEOL JXA-8800 M) is shown in Table 1. K-feldspar was also used in the previous studies (Ito et al., 1993; Chabot and Drake, 1999; Hirao et al., 2006) and the reason using K-feldspar in our study includes the purpose for comparing with these previous studies. The chemical composition of this mineral is far from the compositions of the early and current mantles. However, the previous works reported that the chemical composition of the silicate has little effect on partitioning of potassium into metal (Bouhifd et al., 2007). Thus, in this study, we did not consider the effect of chemical composition of the silicate, although we should conduct the experiments using geophysically relevant composition in future. A single crystal of adularia was ground using an agate mortar and pestle to make fine powder. This powdered adularia was also used as a pressure-transmitting medium and a thermal insula-

tor during the high-pressure and high-temperature experiments using an LHDAC. Because the core may contain light elements, we conducted experiments using Si and O as light elements in the metallic iron liquid to investigate the effect of light elements on D_K . Although the exact amounts of Si and O in the core as light elements have not been revealed yet, it is thought that they are related to the redox state of the early Earth. Therefore, the potassium solubility in metal may largely depend on the amounts of light elements in the metal phase. For metallic phases, we prepared a powdered mixture of Fe and light-element alloys, which were Fe (99.9%, Wako), a mixture of Fe and FeO (99.9%, Rare Material Co. Ltd), and a mixture of Fe and FeSi (99.9%, High Purity Chemicals). FeO and FeSi were ground using an agate mortar and pestle to make fine powders with typical grain size of less than 5 μm . A thin foil with thickness of about 10 μm was made by cold compression of the powdered mixtures and used as a metal component of the starting materials. In the Fe–Si system, we employed the starting powdered mixture of Fe and FeSi with different Fe–Si ratios (Fe–14.4 wt% Si, Fe–20.0 wt% Si, Fe–25.0 wt% Si, and Fe–30.0 wt% Si) to clarify the dependency of the Si content in molten metal on D_K . All of the experiments in the Fe–Si system were conducted at 28 GPa and 2700 K to enable us to ignore the effects of pressure and temperature on partitioning. The effect of O in the metallic melt on D_K was studied at 46 and 48 GPa for a constant temperature of 3200 K.

We used a double-sided LHDAC with a culet diameter of 300 μm . The rhenium or tungsten gasket was preindented to 50 μm thickness and a hole 150 μm in diameter was drilled as a sample chamber using an Nd:YAG laser with a pulse mode. The metallic foil embedded in powdered adularia was loaded into the sample chamber. The sample was first compressed to the desired pressure and then annealed at about 1500 K for 10 min using the double-sided laser heating system (Shen et al., 1996) employing a fiber laser ($\lambda = 1090 \text{ nm}$). After annealing, the sample was heated to the desired temperature for 15 min. Pressures were measured at room temperature according to the pressure dependence of the edge of the T_{2g} Raman band of diamond at the surface of the culet of the diamond anvil (Akahama and Kawamura, 2004). An experimental pressure was determined by averaging the pressures after annealing (before heating) and after heating. The pressure error was defined as the pressure difference between the two pressures before and after heating. In this experiment, we did not make a pressure correction for the thermal pressure. Therefore, the present pressure values could be underestimated. According to the previous experiments with a similar cell configuration, however, the thermal pressure was about 4–6% in the pressure range from 50–100 GPa, i.e., about 3 GPa to 2700 K at 50 GPa and about 4 GPa to 3000 K at 100 GPa (Asanuma et al., 2010). Therefore, the thermal pressure in our experiments is comparable with the pressure uncertainty of the present experiments.

Temperature was measured on both sides, and determined by fitting the emission spectra from the heated sample to the gray-body formula. The temperature fluctuation during the heating experiments was about 100 K at a constant laser power. The errors in temperature given in Table 2 were determined from the temperature fluctuations on both sides of the sample. The sample was quenched by shutting off the laser power.

The recovered samples were prepared for chemical composition analyses using a focused ion beam system (JEOL JEM-9320FIB)

Table 1
Chemical composition of Adularia (wt%).

	Fe	O	Si	Al	K	Na	Total					
^a n = 35	^b <D.L.	45.68	±0.18	30.08	±0.12	9.64	±0.11	13.38	±0.08	0.28	±0.02	99.05

^a The number of analysis point.

^b Below the detection limit.

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