I128-P016 **Room: Poster Session Hall** **Time: May 27**

Effect of hydrogen and carbon on the melting temperature of iron

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The Earth's core consists of mainly Fe-Ni alloy. Seismological and experimental studies show that the Earth's outer core is 10% less dense than pure iron [e.g., Birch, 1952], which indicating the presence of light elements in the core such as hydrogen, carbon, oxygen, silicon and sulfur [e.g., Poirie, 1994]. The nature of the light element is the key of issue to understand the temperature of the core. Previous studies on the temperature regime of the core have been discussed based on mainly the Fe-O-S system [Boehler, 1996]. Although hydrogen and carbon are also the possible candidates of the core component, their effects on the melting temperature of iron at high-pressures are unclear. Therefore, we carried out a series of melting experiments on FeH and Fe_3C using a Kawai-type multi-anvil apparatus with an X-ray radiation.

In-situ X-ray diffraction experiments were conducted using a Kawai-type multi-anvil apparatus SPEED Mk. II installed at the beamline BL04B1 at SPring-8 synchrotron in Japan. The diffracted X-ray of the sample was collected using an energy dispersive spectrometer. In order to prevent the effect of crystal grain growth, the multi-anvil apparatus was oscillated during X-ray diffraction measurements. In the experiments on FeH, a mixture of sponge-like iron and MgO powder used as a starting material. The sample material was packed into a NaCl container with $LiAlH_4$ which was separated from the sample by a thin MgO disk. Hydrogen was supplied by thermal decomposition of $LiAlH_4$. The pressure was determined by an MgO pressure scale [Jamieson et al., 1982]. The experimental pressure range was between 10 and 24 GPa. Hydrogen concentration of FeH_X was estimated from the excess volume compared to pure Fe. It was found that FeH_X in the present study at pressures between 10 and 24 GPa are nearly stoichiometric FeH. The melting temperature of gamma-FeH was determined by the abrupt change in the X-ray diffraction patterns of crystal to liquid.

In the experiments on Fe_3C, powdered mixture of synthesized Fe_3C and MgO was used as the starting material, which was encapsulated into an MgO container. Pressure was determined from the unit cell volume of Au [Anderson et al., 1989]. High-pressure experiments on Fe_3C were performed between 20 and 28 GPa. In the diffraction sequences during heating experiments, the peaks of Fe_3C disappeared, and the new peaks identified as those of Fe_7C_3 were observed with halo caused by liquid. Finally, the Fe_7C_3 peaks disappeared, and only the halo pattern was observed. Based on these observations, the incongruent melting of Fe_3C to Fe_7C_3 plus liquid is estimated to occur at 1848 and 1948 K at 19.7 and 27.0 GPa, respectively.

Our experimental results show a possibility that the hydrogen and carbon lower the melting temperature of iron dramatically. The melting temperatures of FeH and Fe_3C are 1593 and 1848 K at 20 GPa, respectively. Those melting temperatures are less than 2260 K at 20 GPa of pure Fe [Anderson and Isaak, 2000]. Using Lindemann's melting law, we extrapolated the melting curves for gamma-FeH and Fe_3C obtained in our experiments to the core pressure. Those melting temperatures are estimated to be ~2600 and ~2800 K at the core-mantle boundary, respectively. In the presence study, we have demonstrated that hydrogen and carbon have a profound effect in lowering the melting temperature of iron. If a large amount of hydrogen and carbon are dissolved in the Earth's core, it is considered that the temperature of the outer core could be much lower than the previous estimation based on the melting temperatures of Fe, FeO and FeS [Boehler, 1996].