Sound velocity of hexagonal close-packed iron to the Earth's inner core pressure

Despite the fact that space probes can now reach outside the solar system and humans can directly observe many planets/asteroids, the interior of the Earth, our home planet, is still shrouded in mystery. The main reason is that humans cannot observe it directly. Therefore, the most reliable information about the Earth's interior is based on observation of seismic waves propagating inside the Earth. The seismic model of the Earth's interior, the Preliminary Reference Earth Model (PREM) [1], tells us the density (ρ) and the sound velocity, specifically the compressional (v_p) and shear (v_s) wave velocities, as a function of depth. It is also widely accepted that the main component of the core of the Earth is iron, based on the solar abundance of elements and research on meteorites.

Determining a core structure that is consistent with PREM has been the subject of many experiments, since the exact core composition has important implications for understanding the formation and evolution of the Earth in the solar system. These experiments, with great effort, have suggested that there must be something more than just iron in the core to match PREM, and, in particular, that Earth's core contains light elements [2]. However, the investigations rely on *extrapolations of the sound velocity of iron and iron alloys measured at low pressure*. This is because it is difficult to reach core pressures, and to measure the sound velocity, in a laboratory: even using the hardest material, diamond, as an anvil, achieving core pressures is challenging. However, it is very important that such measurements be done, as the use of different methods to extrapolate the relation between sound velocity and density, lead to significant uncertainties in discussing the Earth's core [3].

In this work [4], we were able to measure the sound velocity, v_p, of hexagonal close-packed (hcp) iron up to a density ρ of 13.87 g/cm^3 using inelastic X-ray scattering (IXS) at SPring-8 **BL43LXU** [5]. This density is larger than that of the inner core, about double that of ambient iron, and corresponds to a pressure of 310–327 GPa (depending on the pressure scale). Measurement at such extreme pressure — approximately double that previously achieved with IXS, world-wide — was made possible by taking advantage of several technical developments including an improved design of the diamond anvil cell using a "stepped-bevel" anvil combined with sophisticated optics and the strong source at BL43LXU. Even so, count rates were only ~0.01–0.02 cps at the highest pressure. Figure 1 shows a typical spectrum collected at the highest ρ of 13.87 g/cm^3 corresponding to 310–327 GPa. We identified the IXS peaks for the longitudinal acoustic (LA) mode of hcp-iron and the transverse acoustic (TA) and LA modes of diamond.

The v_p of hcp-iron determined in this work is plotted in Fig. 2(a). It is clear that a linear v_p–ρ relation, Birch's law, is valid for hcp-iron up to 13.87 g/cm^3 which covers inner core density regions of 12.8–13.1 g/cm^3. Combining the present results and those of previous work we found the Birch's law for hcp-iron as:

$$v_p\ [\text{km/s}] = 1.162\,\rho\ [\text{g/cm}^3] - 3.450 \qquad (1)$$

Figure 2(b) shows the pressure dependence of v_p of hcp-iron using pressures determined by the equation of state (EoS) by Dewaele *et al.* [2]. The effect of temperature on the v_p–ρ relation of hcp-iron at high temperature was then evaluated by combining the present results with previous measurements at high temperature. We parameterized the temperature

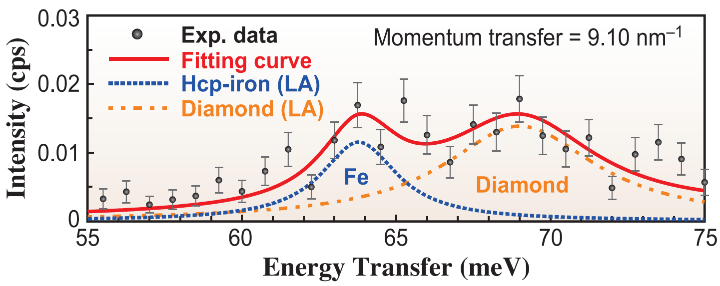

Fig. 1. An IXS spectrum of hcp-iron at 13.87 g/cm^3 corresponding to 310–327 GPa [4]. The experimental data (black dot with 1σ error bar) was fit (red solid line) with peaks for the IXS signal of LA mode from iron (blue dotted line) with TA mode from diamond (orange dashed line).

dependence of the Birch's law for hcp-iron as:

$$v_p \text{ [km/s]} = 1.162\,\rho \text{ [g/cm}^3\text{]} - 3.450 - 2.5\times10^{-5} (T \text{ [K]} - 300)(19.2 - \rho \text{ [g/cm}^3\text{]}), \quad (2)$$

where T is temperature in kelvin.

Figure 3 shows the v_p–ρ and v_s–ρ relations for hcp-iron at pressures varying from 330 GPa (inner core boundary, ICB) to 365 GPa (center of the Earth/core, COE) at temperatures of 300 K and 6000 K, compared to the values of the PREM inner core [1]. The v_p at high pressure and temperature is derived from equation (2) with the pressures and temperatures based on the EoS of Dewaele *et al.* [2]. The v_s is derived from the v_p of the present results and the adiabatic bulk modulus (K_S) of the EoS as follows: $K_S = \rho\,(v_p^2 - 4/3\,v_s^2)$. Pure hcp-iron has 2±2% higher v_p and 29±17% higher v_s at the ICB, and 4±2% higher v_p and 36±17% higher v_s at the COE, respectively, compared to those of the PREM inner core with a typical estimated inner core temperature of 6000 K [4]. A large v_s deficit compared to the v_p deficit of the PREM inner core relative to hcp-iron is an important constraint on the sound velocity deficits determined by direct static measurements at core densities. This provides a strong constraint for estimation of the light element contents in the inner core.

The present result combined with previous work at high pressure and temperature for iron-silicon alloy, iron sulfide, and iron oxide suggests the Earth's core may be enriched in 3±1 wt% silicon and 3±2 wt% sulfur with ~5 wt% nickel with negligible amount of oxygen, consistent with the existing outer core model with oxygen, as the growth of the inner core from the outer core may have created a secular enrichment of oxygen in the outer core [4].

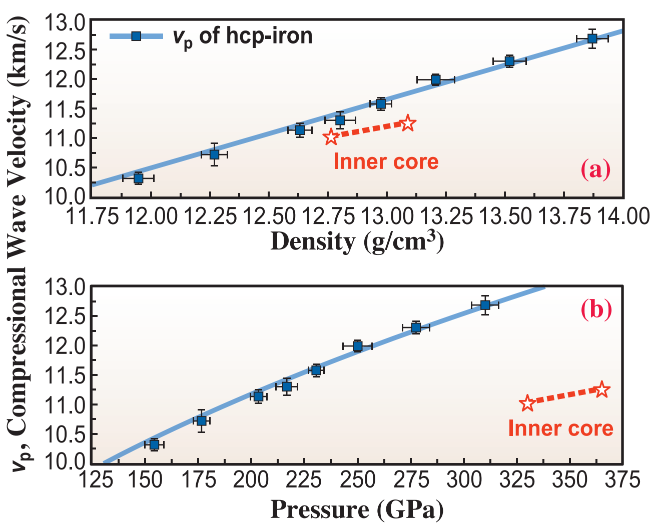

Fig. 2. Density–v_p **(a)** and pressure–v_p **(b)** of hcp-iron at high pressure determined by the present work (blue square symbols with 1σ error bars and light blue solid line) compared with the PREM inner core (red dashed line with stars). Pressure in (b) is evaluated by Dewaele *et al*. [2].

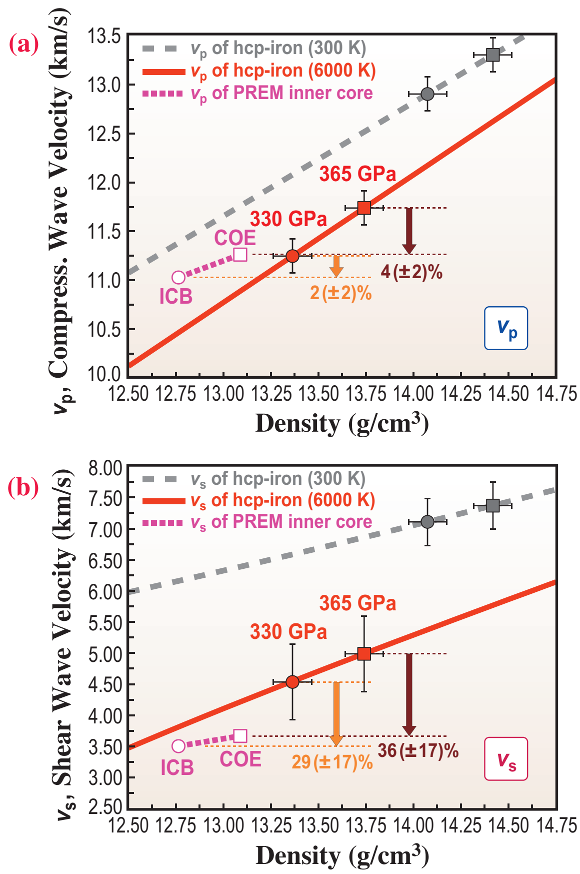

Fig. 3. Density–v_p **(a)** and density–v_s **(b)** relations of hcp-iron under the inner core pressures (330–365 GPa) at 300 K and 6000 K compared with the PREM inner core. The relations at 300 K are shown as gray symbols and dashed lines, and those at 6000 K are shown as red symbols and solid lines. The error bars represent 1σ uncertainties. The relation for the PREM inner core is given as the magenta open symbols with dotted lines.

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