Density deficit of the Earth's inner core revealed by a multi-megabar rhenium primary pressure scale

The interiors of the Earth and the planets are environments of extreme pressure. These pressures can be estimated by determining the density distribution inside the planets and assuming hydrostatic equilibrium, with, e.g., the pressure at the center of the Earth calculated to be 365 GPa. Meanwhile, seismological observations are used to create models of the Earth's interior, such as the Preliminary Reference Earth Model (PREM) [1] which tell us the density (ρ) and the compressional (v_p) and shear (v_s) wave velocities as a function of depth based on how acoustic (seismological) waves propagate through the planet. We can then understand the interior of the Earth by generating high pressure in the laboratory, determining the density and sound velocity of materials under high pressure, and comparing these physical properties with the seismic model. Thus, the accurate determination of pressure in laboratory experiments is essential for understanding planetary interiors, as well as for studying the physical properties of materials under high pressure. The value of the pressure in high-pressure experiments is determined using an equation of state (pressure scale) that relates the density of a standard material and the physical pressure. Therefore, the development of an appropriate pressure scale has long been a fundamental and important challenge in high pressure science.

Most of the pressure scales commonly used in previous studies are based on the Rankine–Hugoniot curve and theoretical calculations. However, there are inconsistencies among those scales, due to the assumptions and extrapolations in the correction methods, with inconsistencies that can be as large to 40% at the Earth's core pressures. This situation makes it difficult to accurately determine pressures in high-pressure experiments and then to discuss the interior of the Earth quantitatively. For this reason, determination of absolute pressure in high-pressure experiments without assumptions and extrapolations, a primary pressure scale, has been desired. Zha *et al.* [2] demonstrated that a primary pressure scale could be determined by three physical properties of materials, v_p, v_s, and ρ, which could be measured independently under high pressure. However, due to the difficulty of measuring sound velocity under extreme pressures, primary pressure scales have been based on measurements over limited pressure ranges that do not extend to the extreme pressures of the Earth's core.

In this work [3], we determined v_p, v_s, and ρ of the rhenium metal up to a density ρ of 30.24 g/cm^3 using inelastic X-ray scattering (IXS) at SPring-8 **BL43LXU** [4]. This was made possible by sustained technical development and extensive experience with DAC measurements over the last decade, including sophisticated optics [5], and the strong X-ray source at BL43LXU. Even so, signal rates small, were only ~0.025 cps at the highest pressure. Figure 1 shows a typical spectrum collected at the highest ρ of 30.24 g/cm^3 corresponding to 230 GPa. We identified the IXS peaks for the longitudinal acoustic (LA) and

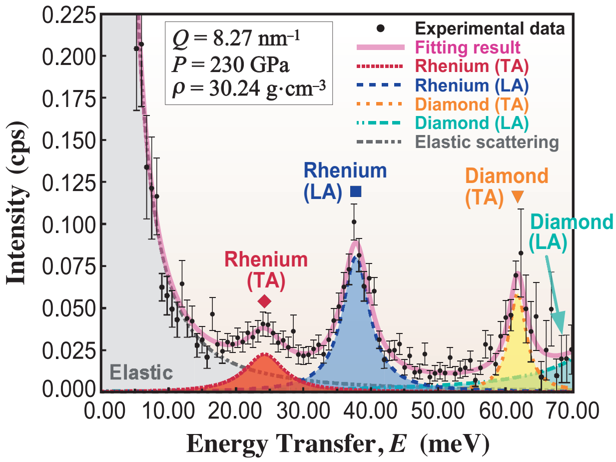

Fig. 1. An IXS spectrum of rhenium at 30.24 g·cm^{-3} corresponding to 230 GPa [3]. The experimental data (black dot with 1σ error bar) was fit (magenta solid line) with peaks for the IXS signal of TA (red dotted line) and LA (blue dashed line) modes from rhenium and TA (orange dashed-dotted line) and LA (green dashed-dotted line) modes from diamond.

the transverse acoustic (TA) modes of rhenium and diamond, allowing determination of a new primary pressure scale up to 230 GPa.

Figure 2 shows the density–pressure relations of rhenium metal, the new primary pressure scale, which can be applied to the extreme pressures of the Earth's core. Compared to curves of rhenium based on previous pressure scales, we found that the pressure value previously used was overestimated by 20% under the Earth's core pressures.

The composition of the Earth's core is a hot topic in the Earth science, as it is important for understanding the evolution of the Earth and planets in the solar system. While it is generally accepted that the Earth's core is mostly iron, the core also contains lighter materials. Therefore, investigating the compressional behavior of metallic iron at extreme pressures is important for determining the amount of light materials in the Earth's core. Figure 3 shows the density–pressure relations of hexagonal close-packed (hcp) iron, which is the main component of the Earth's core, evaluated by using our new rhenium pressure scale. Comparing the density of hcp-iron with that of the PREM at the Earth's inner core boundary (pressure and temperature are estimated to be 330 GPa and 6000 K), the density difference between metallic iron and PREM, which was previously estimated to be about 4%, is determined to be about 8%. The present density deficit can be interpreted as indicating that the light material hidden in the Earth's inner core is probably about double what was previously expected, and the total mass of light material in the entire core is probably about five times that of the Earth's crust assuming the core temperature is the same as previously estimated, or the core temperature should be by about 3000 K higher than the previous estimate if the previous amount of light material is assumed, or some combination thereof. Similar changes, perhaps even larger in magnitude, may be expected in considering the structure of other planets. This is an important finding that forces us to change the conventional discussion about the internal structure of the terrestrial and extraterrestrial planets, such as super-Earths.

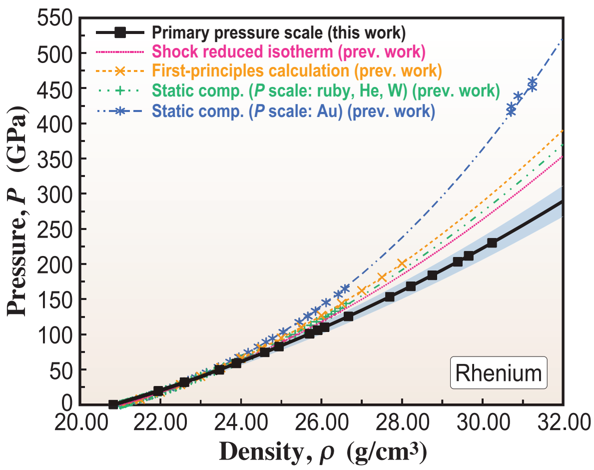

Fig. 2. Primary pressure scale for rhenium. The black curve is the compression curve of new rhenium pressure scale with the density determined experimentally and the pressure evaluated by our rhenium scale determined from density and sound velocities experimentally measured, and other colored curves and symbols are the compression curves of rhenium with experimental data based on pressure scales from previous studies [3].

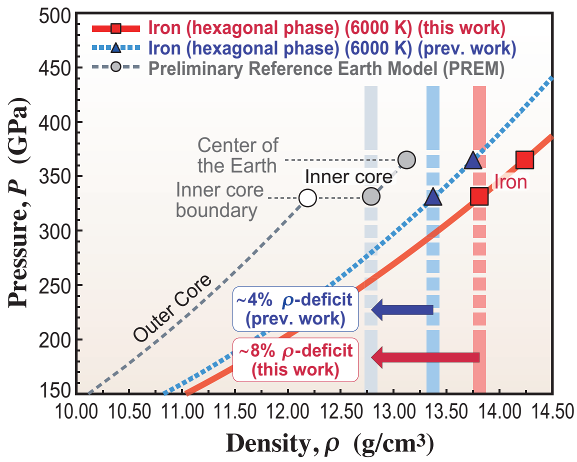

Fig. 3. Density–pressure relations of metallic iron (hexagonal phase) at the inner core conditions (330–365 GPa and 6000 K) compared with the PREM inner core. The relation at 6000 K re-evaluated by the new rhenium scale is shown as red symbols and solid line, and that by the previous scale is shown as blue symbols and dotted line [3]. The relation for the PREM inner core [1] is shown given as the gray symbols with dashed line.

Daijo Ikuta[a,*], Eiji Ohtani[b] and Alfred Q. R. Baron[c,d]

[a] Institute for Planetary Materials, Okayama University
[b] Department of Earth Science, Tohoku University
[c] RIKEN SPring-8 Center
[d] Japan Synchrotron Radiation Research Institute (JASRI)

*Email: dikuta@okayama-u.ac.jp

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