Measurements of mineral thermal conductivity across a phase transition

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Phase transitions can have important consequences for thermal transport properties of minerals. In Earth, there is a major structural phase transition at the core-mantle boundary, where heat flow is determined by the thermal conductivity of the phases present. Furthermore, spin-state changes in iron-bearing oxides and silicates may affect the depth dependence of transport properties in the lower mantle. In this study, we demonstrate how measurements in the laser-heated diamond anvil cell (LHDAC) can be used to determine relative changes in thermal conductivity across a pressure-induced phase change.

A finite element 3D thermal model, developed for heat flow in the LHDAC, is used show that the temperature in the cell is sensitive to a variety of factors, principally geometry and thermal conductivity. If the geometry of the cell is controlled, the numerical model can predict a change in temperature, given a laser power input, due to a change in thermal conductivity of a sample. Forward modeling demonstrates that we can distinguish the sign and magnitude of a thermal conductivity change due to a pressure-induced phase change. We perform a series of experiments to test our models. In one set of experiments, we measure temperature vs. laser power as a function of pressure for two salts: KCl and NaCl. The KCl experiment, carried out over a pressure range (5 to 22 GPa), is a control, as there are no phase transitions over this pressure range. As expected, solving for the experimental change in temperature using the 3D thermal model indicates that KCl thermal conductivity increases with pressure. The NaCl experiment covers the pressure range (18 to 54 GPa) over which the B1-B2 phase transition occurs (~28 GPa). Using the same combined model-experiment approach, we observe a decrease in thermal conductivity across the NaCl B1-B2 phase transition ($d\kappa/dP = -1.0 \pm 0.17$ W/(mk GPa)). This result is consistent with thermal conductivity measurements of other ionic salts, which undergo the B1-B2 phase transition at lower pressure. This experiment demonstrates that we can measure thermal conductivity across a phase transition, including the case of a negative pressure dependence.

We apply this experiment design to investigate the effect of spin transition on an iron-bearing magnesium oxide sample. In a series of experiments, we measure temperature vs. laser power for (Mg,Fe)O with 24 mol% Fe, loaded in Ne, over a pressure range from 22 to 60 GPa. We observe an increase in thermal conductivity between 22 and 42 GPa. But between 42 and 60 GPa, a pressure range consistent with previously reported mixed-spin state phase of (Mg,Fe)O, we observe a decrease in thermal conductivity. This result suggests that there may be a broad zone, in the depth range of 1000 - 1500 km, of reduced thermal transport properties in the mantle. Such a region could play an important role in governing the mode of convection in Earth's lower mantle.