ESRF	**Experiment title:** Kinetics and structural changes in shock-compressed Bismuth	**Experiment number**: HC3971
Beamline: ID09	**Date of experiment**: from: 11/09/2018 to: 16/09/2018	**Date of report**: 26/03/2019
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Report: Kinetics and structural changes in shock-compressed Bismuth

Detailed understanding of pressure-induced phase transitions is an active field of research both theoretically and experimentally. Shock compression of matter induced by powerful lasers is typically used to study the transformations over ns time scales. Using X-ray diffraction as a probe, important information can be obtained, such as the kinetics and path of compression (and release)-induced structural transitions, nucleation processes and texturization. Time-resolved x-ray diffraction of dynamically compressed matter could only be obtained recently by using various large facilities x-ray sources, such as: KJ laser ; x-ray free electron laser; synchrotron. Up to now, differences between dynamic and static data sets have been discussed mostly in terms of phase transitions kinetics. Observing the structural response of a shocked material now enables rigorous comparisons with the structural phase transitions disclosed by static compression. The 100ps time-resolved capability offered by the ESRF on the ID09 beamline is ideally suited to probe a warm and dense state of matter under dynamic compression.

The target assembly and the compression schemes were designed so as to obtain very reproducible single-shot laser-pump/X-ray probe data with a 0.1 ns resolution time delay, to follow different compression paths covering a large domain of the Bi phase diagram below 8~GPa and to perform accurate XRD measurements on homogeneous sample states. The sample consisted of a 4 µm thick foil of poly-crystalline bismuth (Goodfellow, 99,97% purity) glued to a 100 µm thick sapphire on the laser side and to a 125 µm thick black polyimide on the other side. The sample assembly was mechanically pressed in the sample holder with a calibrated force to approximately 1 µm in thickness and the epoxy glue layer was then UV cured. The targets have thus been designed to operate in a so-called confined geometry which allows to achieve a stable warm and dense state of a 2-3ns lifetime and then to probe the shock release. Three starting temperatures, 300 K, 400 K and 500 K, of the compression path were studied by pre-heating the targets with a transportable resistive heater. Figure 1 shows the quality of the signal obtained for the different observed phases.

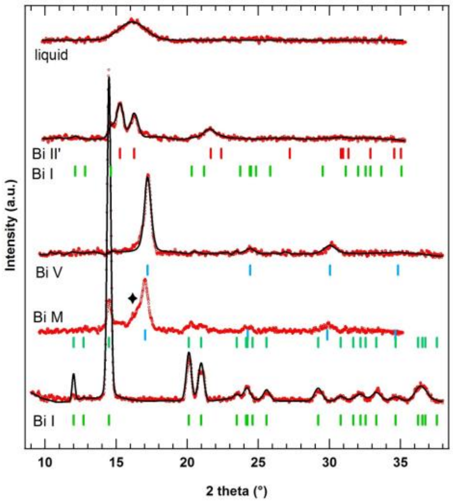

Figure 1: Integrated x-ray diffraction patterns (red points) with a LeBail refinement (black lines) for Bi-I before compression, Bi-V at 3.5 ns and Bi-II' at 15 ns, taken at λ=0.8266 Å. The diffuse scattering peak of the liquid is also shown, taken at 6ns. An intermediate phase, Bi-M, was observed at the Bi-I – V transition but could not be resolved.

The compression path obtained by shocking the Bi target at 300 K was aimed at probing structural differences in the solid phases when compared to static pressure results. In the shock configuration used, with a fixed laser energy, the initial pressure obtained was around 4 GPa. As shown in figure 2 the compression path over time should cross various phase boundary lines of the equilibrium phase diagram and so should give the following sequence of phases Bi-I, Bi-II, Bi-III and Bi-V on the compression and reversely on release. However, the Bi-II and III phases are never observed, instead Bi-V appears in the stability domain of Bi-II and III, both under compression and under release. We also note the appearance of Bi-II', a high-temperature phase, far from its stability domain which was determined under static compression.

Starting form 400 and 500 K we observed a superheating of ~60 K during the release when going from Bi-V to the liquid phase. An undercooling of ~80 K is also measured when going form the liquid to the solid Bi-I phase.

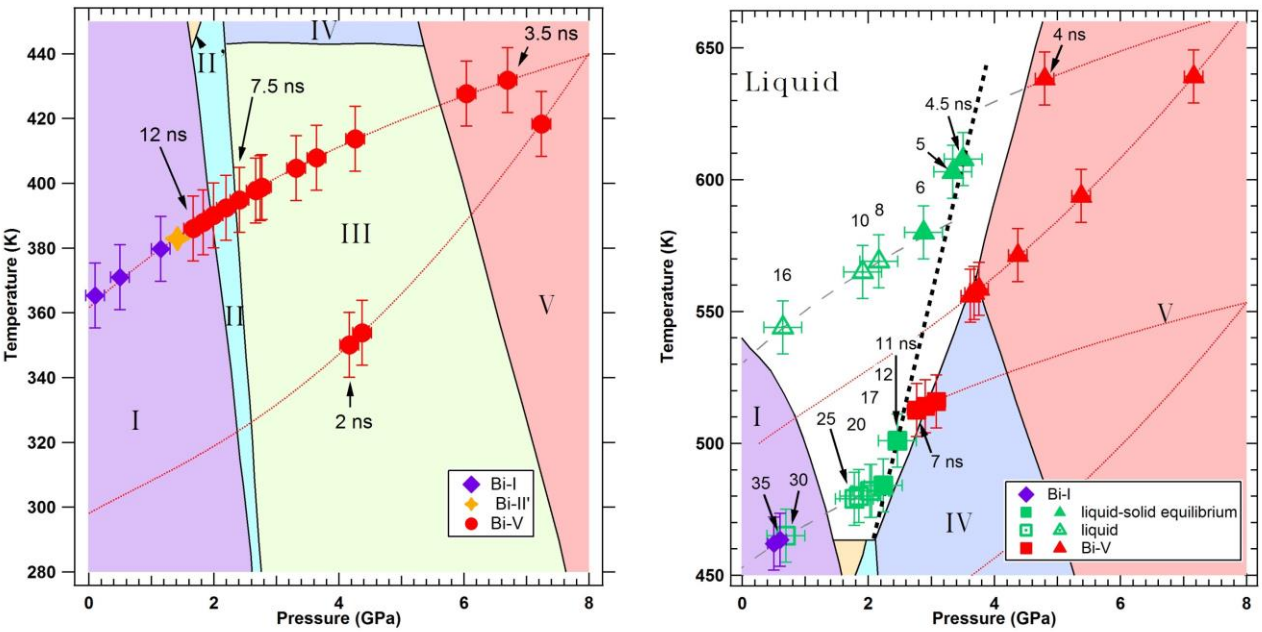

Figure 2: Compression and release paths for the three starting temperature is shown superimposed to the known phase diagram of Bi (left :low-temperature, right: high-temperature). The Bi-II and Bi-III phases are never observed during the release, instead Bi-II' appears at longer delays. A superheating of ~60 K is observed during the release when going from Bi-V to the liquid phase. An undercooling of ~80 K is measured when transforming from the liquid to the solid Bi-I phase.

We show here that the phase diagram measured under nanosecond compression experiment can be very different from equilibrium behavior, not only, as well-known, by shifting the boundary lines between various phases but more surprisingly by giving a different sequence of structures. These results highlight the importance of performing time-resolvedc X-Ray Diffraction to probe matter under shock compression. This microscopic diagnosis, complementary to macroscopic diagnosis like VISAR for example, should become standart. The ESRF-EBS should offer the possibility in the future to greatly improve our understanding of the warm dense matter probed under shock compression and to answer a large number of remaining open questions.