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X-ray Crystallography at High Pressures

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X-ray crystallography (both powder and single crystal) is very widely used to elucidate the crystal structure aspects of materials under high pressures. This small note explains the basics of the techniques involved with references drawn mostly for work done in India.

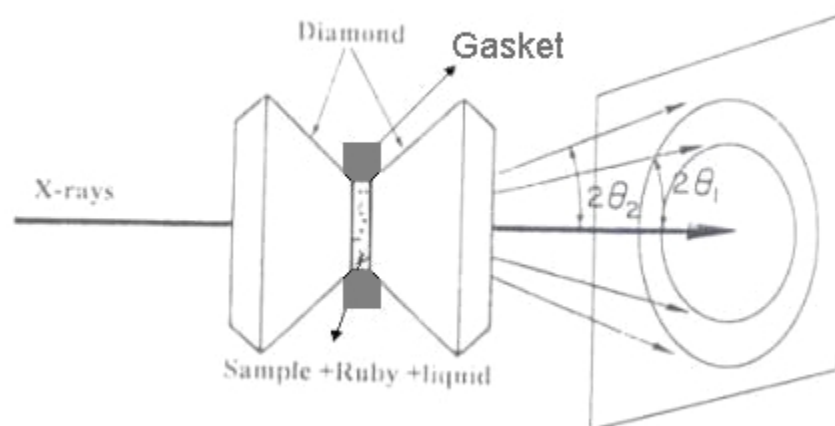
X-ray diffraction is the most direct tool for studying the crystal structures of materials at high pressures. Both powder and single crystal techniques have been employed. Their use for detection and characterization of phase transitions, determination of equations of state and studies for the kinetics of first order phase transitions is now very well established in high pressure science. Till date, many exotic and complex crystal structures have been discovered¹⁻². Some novel phenomena like pressure-induced crystal to amorphous transitions in solids have been the subject of intense investigations in recent past³⁻⁴. Equations of state of many materials of importance in both basic and applied sciences have been mapped⁵. Many theoretical concepts in the electronic band structure theory of solids, like s-d electron transfer and f electron delocalization etc., have also been verified. X-ray diffraction under high pressures provides vital inputs as well as stringent tests for total energy as well as molecular dynamics calculations. In fact the experiments have helped in bench marking of condensed matter theories so that the latter are now able to make accurate predictions⁶.

All the above have happened because of some major developments in the experimental technique of x-ray diffraction under pressure. Improvements in diamond anvil cells (DAC) in which the sample is subjected to pressure has helped produce Mbar

pressures on them in in-situ x-ray diffraction experiments⁷. The introduction of area detectors has resulted in reducing diffraction times and in doing more accurate experiments. Solid State detectors made this possible on laboratory sources by energy dispersive x-ray diffraction. Now imaging plate phosphors and CCD detectors⁸, along with the advent of synchrotron sources have revived the high-resolution angle dispersive technique for pressure studies. In fact, the high-pressure community is a major user of synchrotron sources with dedicated high-pressure beam lines for their experiments.

In India, there are a few groups doing diffraction studies under pressure⁹⁻¹¹. Many types of diamond anvil cells have been fabricated. Since 2.5 GeV Indus-2 synchrotron for hard X-rays is still under construction, most of the work is done employing rotating anode sources. The support provided by Department of Science and Technology (DST) has also enabled some good experiments to be done on synchrotron sources in other countries¹².

Figure below shows a schematic sketch of the principle of powder diffraction method. The equipment needed is a source of X-rays, a diamond anvil cell for applying pressure on the sample and a detector to measure the diffracted beam intensity. The sample is put in a sample chamber called gasket. This is squeezed between two diamond pistons for pressure generation. To ensure hydrostatic conditions on the sample, a liquid is also loaded in the gasket along with the sample. Liquids of the type 4:1 mixture of methanol-ethanol freeze at about 10 GPa and the sample environment becomes essentially quasi-hydrostatic beyond this. Noble gas liquids ensure hydrostatic conditions to much higher pressures (~70 GPa).



As is well known, one can derive the unit cell constants and hence the volume of the cell from Bragg peak positions and the unit cell contents from Bragg intensities. Pressure is measured on the sample by a pressure marker-usually ruby, included in the gasket along with the sample. On shining an appropriate laser beam it emits fluorescence lines R_1 and R_2 . The frequencies of these lines shift under pressure. This shift is now well calibrated against pressure using P-V data from shock wave experiments. The relative shift of these lines also provides an indication of the non-hydrostatic pressure component¹³.

It is clear from the above simple description that the x-ray diffraction technique under pressure has some inherent limitations compared to the room pressure condition. Both the incident and the diffracted x-ray beams have to pass through structural materials of the diamond cell. This restricts the range of the reciprocal space covered. For example, in angle dispersive technique, 2θ is limited to about 50° . Because of the non-uniformity of the pressure across the diamond culets, due to non-hydrostatic pressure component, the Bragg lines broaden and sometimes shift significantly from their true positions under increasing pressure (However, A.K. Singh and his collaborators¹⁴ have made a virtue of this non hydrostatic environment in DAC by deriving elastic moduli from these shifts up to Mbar pressures compared to 20 GPa limit of Brillouin spectroscopy). Thus, the powder patterns are of poorer resolution. Also, because of the uniaxial nature of force applied on diamond pistons, texture invariable develops under pressure in powder patterns. This makes the analysis of intensity data by Reitveld fitting technique more difficult. Single crystals break under stress.

Use of synchrotron beams has alleviated to some extent the above problems. Because of the high intensity of these beams one is able to use smaller samples and smaller collimators ($\sim 5 \mu\text{m}$). This means the pressure gradients on samples are smaller. The narrow beams also provide better resolution ($\Delta d/d \sim 5 \times 10^{-3}$). The ability to record full Debye-Scherrer rings has led to the mitigation of problems due to preferred orientation effects. This has allowed investigations of some very subtle phenomena like detection of electronic topological phase transitions¹⁵ and determination of structural mechanisms of phase transitions¹⁶⁻¹⁷. This higher intensity has also been helpful to look at low Z containing substances and low symmetry structures. In fact, due to the much shorter diffraction times one is able to laser heat the sample in a DAC for in-situ P, T phase diagram determinations.

As pointed out earlier, the x-ray diffraction data available from the high-pressure experiments are limited. This puts severe constraints for determining the structure by the usual techniques. Trial and error method is most often used. The diffraction pattern of a new phase has also been, sometimes, indexed by using the knowledge of phase diagrams of related substances. Ideas like empirical homology rule, which states that compression and chemical substitution by an element with a higher atomic number generally results in same structural trends as well as symmetry considerations have also, been useful because most of the high-pressure phase changes are displacive or martensitic. For compounds some clues to the plausible structures for the high-pressure phases have been obtained from the quantum structural sorting maps constructed at ambient conditions coupled with the knowledge that the high-pressure structure will usually have a higher coordination of the basic building block in it¹⁸. Even then the unique identification of the structure of a high-pressure phase may require the usage of several complementary measures. In a pioneering study at Trombay, it was shown that molecular dynamics calculations could be successfully used for identifying new structures¹⁹. Sometimes the first principles electronic structure calculations have also helped to prove/disapprove structural models from high-pressure x-ray diffraction data²⁰⁻²¹. The problem of limited data has been partly overcome by using a shorter wavelength, such as from the undulator at the synchrotrons, which help record a larger number of diffraction lines on a given sensitive area of the detector. This has already enabled the solution of the phase problem for a few high-pressure phases by Patterson and direct methods²².

More accurate structural and equation of state data are obtained from single crystal analysis. Here the diamond anvil cell is mounted on a standard single crystal equipment. Angle dispersive technique has been used up to ~10 GPa while the energy dispersive method has been employed to about 1.5 Mbar²³. Sometimes single crystal of high-pressure phases has been grown in-situ in DAC. As mentioned above, single crystals break under non-hydrostatic stresses in DAC. But the higher intensity available at synchrotron beam lines has enabled one to collect 3D-diffraction intensity data from only one fragment of the crystal. Software techniques have been employed to separate out the data when the sample consists of more than one mono crystal².

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