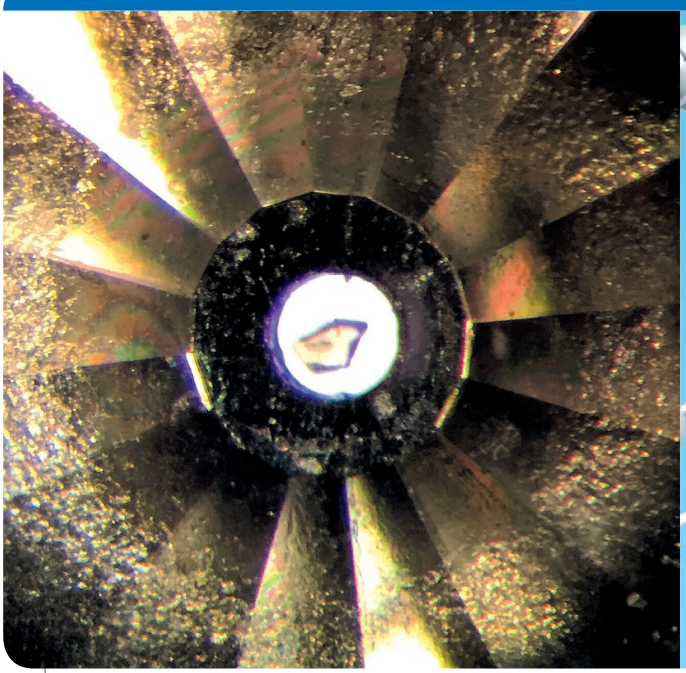

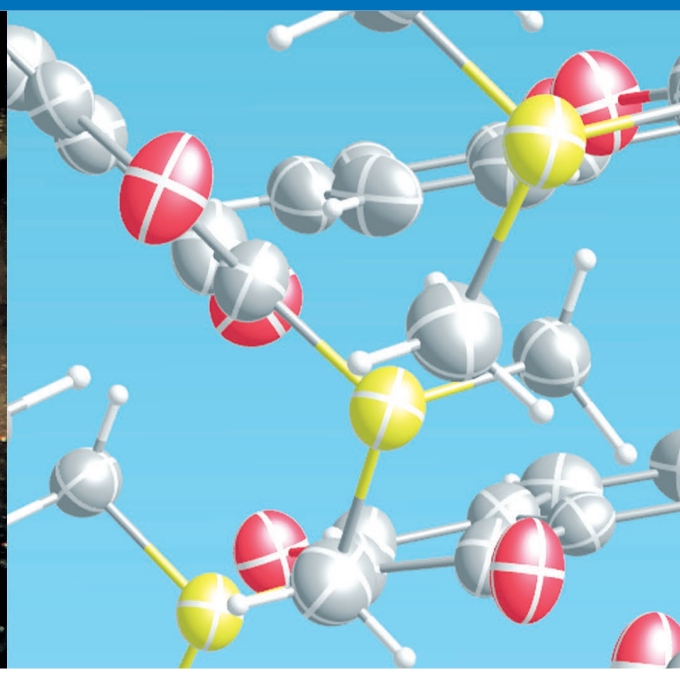

Application Note SC-XRD 511

D8 QUEST and D8 VENTURE for High-Pressure Experiments

- Acquisition and processing of single-crystal diffraction (SC-XRD) data collected with a Diamond Anvil Cell (DAC).

This Application Note explores acquisition and processing of single-crystal diffraction (SC-XRD) data collected with a Diamond Anvil Cell (DAC). Experiments were conducted with several Bruker instrument configurations and wavelengths. Data from a crystal mounted in a diamond anvil cell at ambient conditions is compared to standard experimental data from the same crystal, putting software and hardware to the test.

Figure 1: D8 QUEST and D8 VENTURE

High-Pressure Crystallography

Varying pressure introduces an additional dimension to crystal structure determination, and it helps to broaden our understanding of matter at the atomic scale. High-pressure experiments [1,2,3] allow the investigation of polymorphism, phase changes, and structure/property relationships, giving us a deeper understanding of the solid state and of materials in general. Pressures of up to 10^{12}pascals (1 TPa) [4] can be reached.

Traditionally, high-pressure crystallography has been associated with the study of rocks and minerals in the earth's crust. More recently, however, pharmaceutical development has benefitted from organic solid-state chemistry and its perspectives on structure and function in biologically-relevant molecules, with polymorphism being of critical importance. Of growing interest is the effect of pressure on drugs, since many solid drugs are exposed to mechanical manipulation during manufacturing.

In recent years, increased interest in high-pressure crystallography for the home lab has prompted the development of powerful software solutions that address its particular challenges, evolving high-pressure crystallography into a powerful method that can be routinely used on modern diffractometers, such as the D8 QUEST or the D8 VENTURE (Figure 1).

High-Pressure Setup

The pressure-generating device used for single-crystal experiments is the DAC: a steel vise with conical X-ray windows, holding two opposing brilliant-cut diamonds with phased culets. The sample chamber itself is a hole drilled into a thin metal gasket. Pressure is generated when hydrostatic fluid in the sample chamber is squeezed between the diamond anvils and the gasket. The choice of hydrostatic fluid depends on its pressure of solidification and on the solubility of the sample crystal. For most routine single-crystal high-pressure experiments with pressures up to about 5 GPa, a miniature DAC is a very convenient choice (Figure 2).

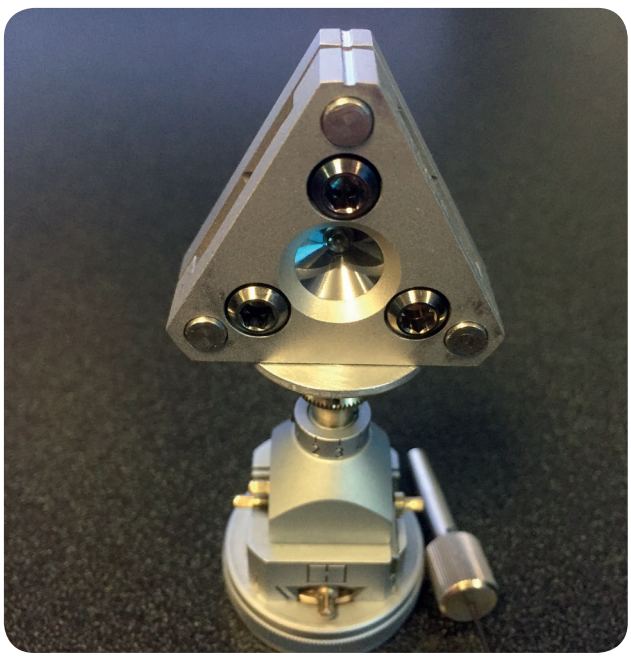

Figure 2: Bragg-Mini, a Merrill-Bassett DAC from Almax easyLab Inc.

Experimental Challenges

Even miniature DACs are relatively large, requiring special collimators and beamstops to accommodate their additional bulk. Control software must take into account the DAC's dimensions during goniometer movements to avoid collisions. The DAC itself obstructs the incident and diffracted beams, adding geometric limits to both the source and the detector sides of the instrument. A small X-ray beam is necessary to avoid parasitic diffraction from the edges of the metal gasket, and the conical windows constrain the diffraction pattern to a relatively small opening angle of less than 90 degrees. In addition, the data are limited by diffraction, high background, and absorption from the diamonds and gaskets. Diffraction data is also hampered by varying partial obstruction of the diffraction pattern by the DAC itself. Due to the geometrical limitations, only about 30% of reciprocal space is accessible during high-pressure experiments. Shorter-wavelength radiation (such as Ag Kα or In Kα) is advantageous, as it reduces background scatter and absorption. It also compresses the diffraction pattern providing better overall resolution, hence significantly increasing the number of unique reflections.

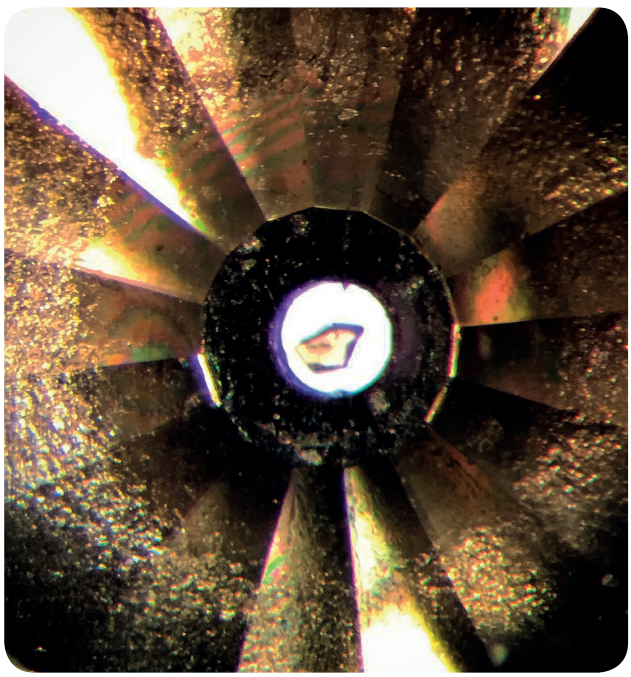

Figure 3: Small ylid sample mounted in the DAC

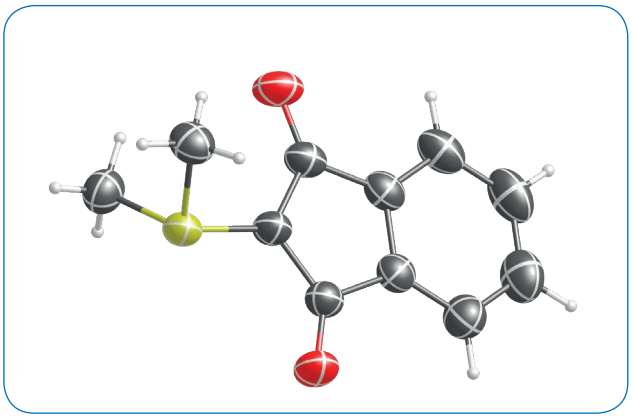

Figure 4: Ylid structure from experiment

The Experiment

The purpose of the experiment was to put advanced processing methods for DAC data to the test, to produce DAC data comparable in quality to standard single-crystal data.

The crystal investigated was a small specimen of the monoclinic polymorph of the sulfonium ylid [5]. The sample was chosen for its easy availability, stability, low symmetry, and yellow color for better visibility [6,7] in the DAC (Figure 3).

- Sulfonium ylid (Figure 4)
- Yellow (habit)
- 0.05 × 0.05 × 0.12 mm^3
- $C_{11}H_{10}O_2S$
- $P2_1/c$
- a = 9.7901(25) Å, b = 10.4803(23) Å, c = 10.5923(24) Å, β = 105.311(9)° based on experiment (1)

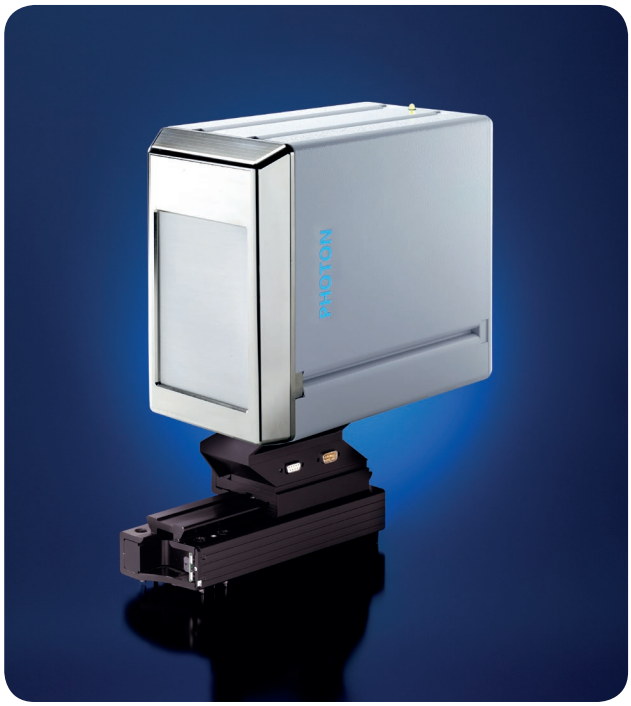

Figure 5: PHOTON II CPAD detector

Instruments used for the comparison:

- D8 VENTURE with Mo IμS 3.0 microfocus source, KAPPA goniometer, and PHOTON II
- D8 QUEST with Ag IμS 3.0 microfocus source, FIXED-CHI goniometer, and PHOTON II
- D8 QUEST with Mo sealed tube, TRIUMPH monochromator, FIXED-CHI goniometer, and PHOTON II (Figure 5)

High-Pressure Data Collection and Processing

Due to the limited accessibility of diffraction data imposed by the geometry of the DAC, it is advisable to collect as much of the reciprocal sphere as possible regardless of the sample's symmetry. High multiplicity will be advantageous during data processing, as it will help improve data quality. Data was acquired using sets of omega and phi scans optimized for the DAC's opening angle and the type of goniometer used. Because the angular sweep of the scan is limited by the DAC's opening angle, the cell was first oriented perpendicular to the conical opening and then scanned in both positive and negative directions by one-half the opening angle; this allows for the best data processing.

The cell used for the experiment was a Diacell Bragg-Mini purchased from Almax easyLab Inc. It was a Merrill-Bassett diamond anvil cell with the following specifications:

- Cell material: stainless steel
- Anvil support material: tungsten carbide
- Pressure mechanism: screw drive
- Top and bottom angle: X-ray, conical 85°
- Diamond anvil, type IIac, Boehler-Almax design 3.3 mm/85°, 16-sided, C = 0.70 mm, (1 0 0)-oriented
- DAC height: 15 mm
- Working distance to sample: 7.5 mm
- Pressures up to 5 GPa
- Pre-indented and drilled (0.20 mm) steel gasket

The Diacell Bragg-Mini is small and light and can be easily mounted on a standard goniometer head (P/N 87-000-088).

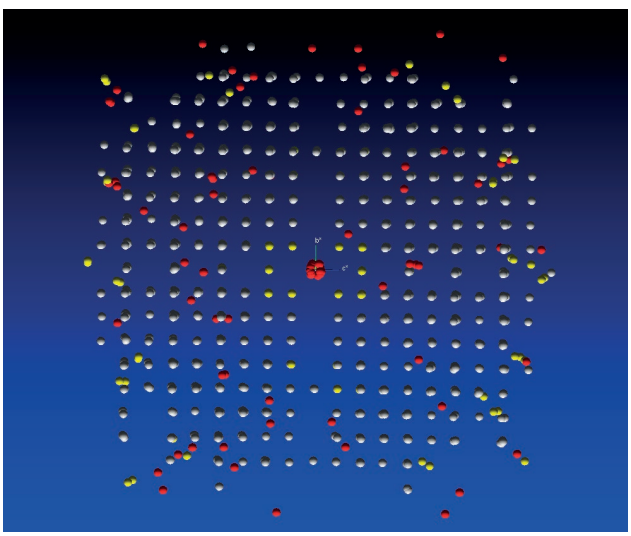

Figure 6: Easy separation of diamond and sample reflections for indexing

The Bruker APEX3 software and hardware provides unique features that were specifically implemented for high-pressure crystallography:

- Component recognition for path planning and collision avoidance
- No blooming prevents artifacts from overexposed diamond reflections
- Tools for excluding powder rings during spot picking
- Powerful indexing methods to identify orientation matrices of the sample and the diamonds (Figure 6)
- Concurrent handling of multiple matrices during data integration
- Concurrent handling of multiple Bravais lattices during data integration

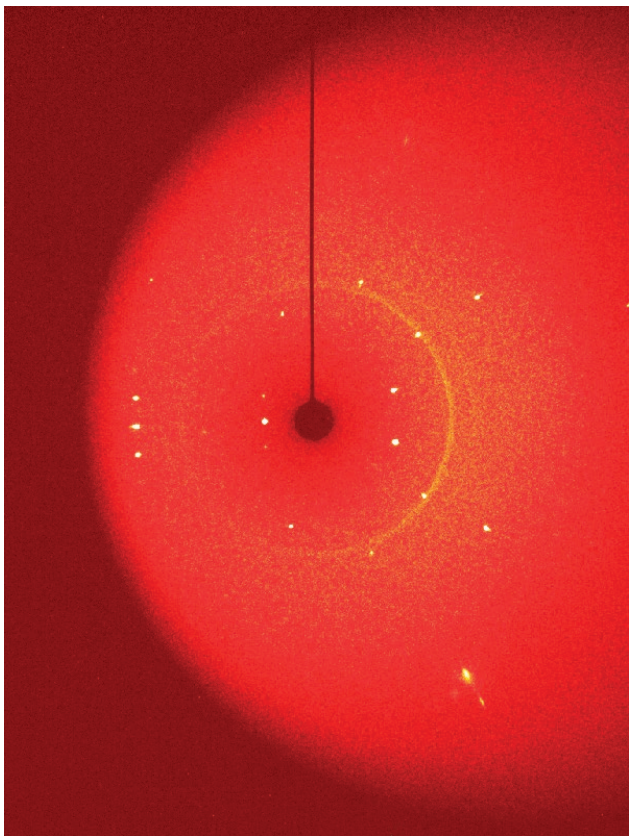

Figure 8: 10 s diffraction image for Mo IμS

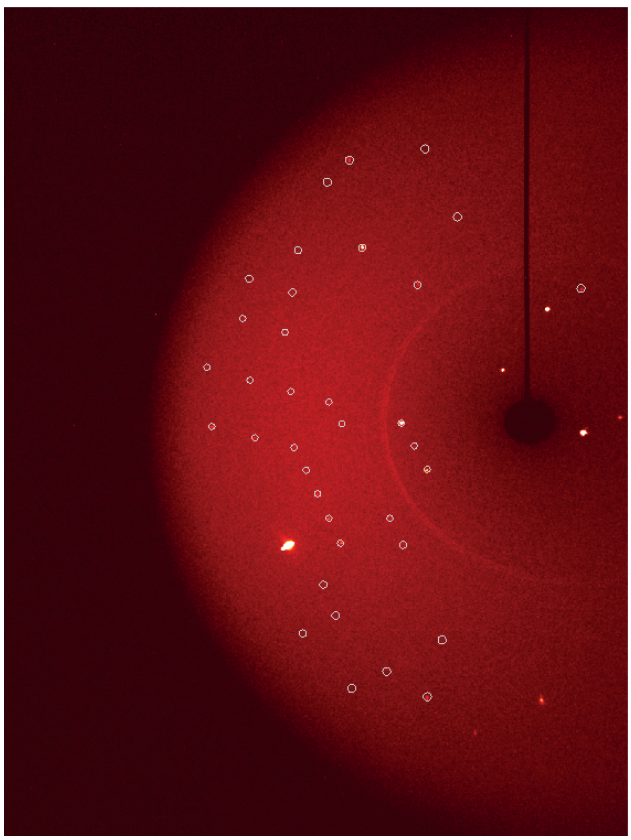

Figure 7: Integration overlay with dynamic mask applied

- Dynamic image mask[8] for modeling the partial shading of the diffraction images by the DAC (figure 7)
- Specialized "best-plane" background treatment of inhomogeneous and rapidly-changing backgrounds
- Scaling plugin with comprehensive interface for analyzing the integrated data and outlier detection
- Interactive model-building and structure refinement based on a creative combination of graphical interface and text-based input.

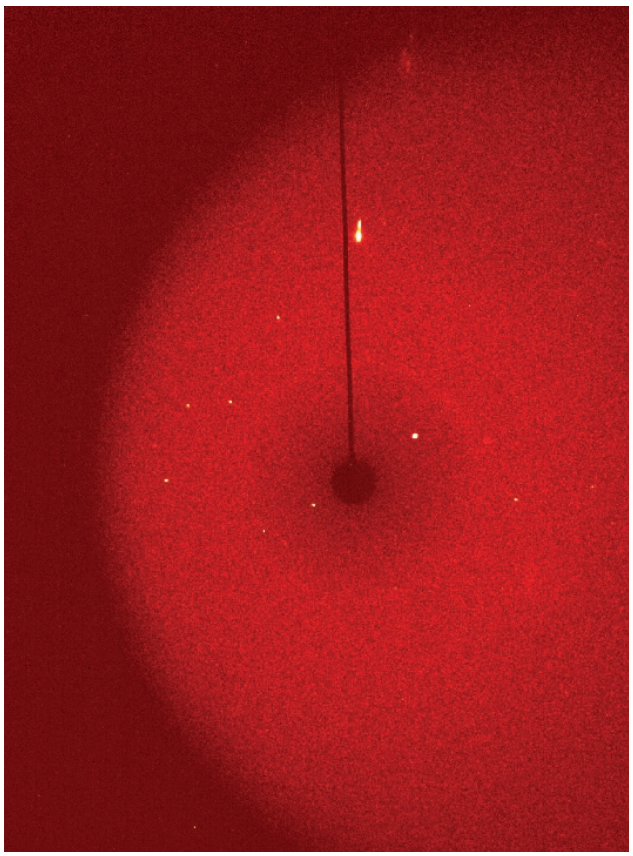

Figure 9: 30 s diffraction image for Ag IμS

Table 1 summarizes the results of five experiments that were carried out with the Ylid crystal. Experiments 1 and 4 are control experiments, standard single-crystal experiments to establish a data quality baseline. The structure reliability criterion, R1, of 2.93% can be achieved with adequate exposure times for the Mo IμS data (1). The higher R1 of 3.87% for the Ag IμS data (4) can be attributed to the relatively short exposure times, which do not fully account for the much lower relative intensity, lower by a factor of about eight, compared to the Mo IμS experiment (1). Exposure times have been adjusted accordingly for the Ag IμS DAC experiment (5).

Data quality similar to that of the control experiments can be achieved with DAC data if collected with Mo or Ag IμS microfocus sources. The small beam almost completely eliminates the adverse effects of diffraction from the gaskets (Figure 8 and Figure 9), and advanced software algorithms deal well with geometry limitations and background effects introduced by the DAC. The Mo IμS experiment (2) provides data that are 35% complete with a R1 of 3.01%, and the result exhibits small and flat residual difference densities. Often high pressure data suffers from low quality and constraints are necessary during anisotropic refinement of a structure. In this case only weak restraints (RIGU) were applied during structure refinement. The Ag IμS experiment (5) provides

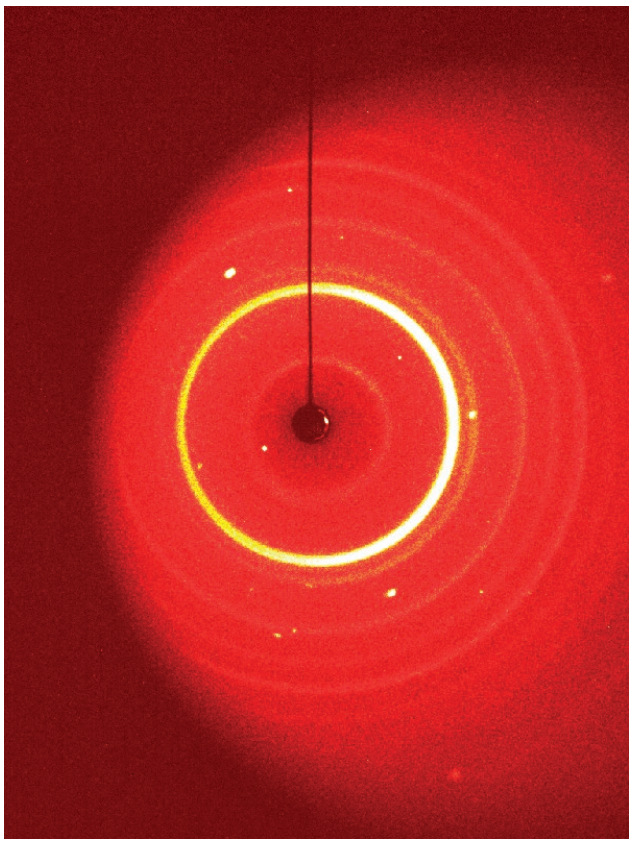

Figure 10:10 s diffraction image for Mo sealed tube with TRIUMPH monochromator

data that are 42% complete with an R1 of 3.2%. As with (1), the residual densities are small and flat. No restraints were applied during structure refinement. The higher completeness for (5) compared to (2) is due to Ag radiation's shorter wavelength and resultant compressed diffraction pattern. As expected, both experiments (2) and (4) required higher multiplicity and longer exposure times to achieve quality of results comparable with the control experiments (1).

Although still satisfactory, the Mo TRIUMPH experiment (3) does not provide the excellent data quality of the IμS microfocus experiments (2) and (5). The large 300 micrometer beam causes diffraction from the gasket and rather high backgrounds (Figure 10) that cannot be completely corrected. R1 is considerably higher, 7.7%. This experiment had the lowest completeness of all the experiments at 30%.

		Experiment				
		1	2	3	4	5
Setup	Source	Mo IμS	Mo IμS	Mo TRIUMPH	Ag IμS	Ag IμS
	Experiment type	<control>	DAC	DAC	<control>	DAC
	Wavelength [Å]	0.7107	0.7107	0.7107	0.5609	0.5609
	Beam diameter [μm]	110	110	300	95	95
	Relative norm. intensity	10.0	8.2	5.2	1.3	1.0
	Goniometer type	KAPPA	KAPPA	FIXED-CHI	FIXED-CHI	FIXED-CHI
	Experiment time [h]	2.51	13.3	9.3	8.3	50.0
	Exposure [s/°]	10/0.5	10,20/0.5	10,30/0.5	10,30/0.5	30,120/0.5
Results	Resolution [Å]	0.8	0.8	0.8	0.8	0.8
	Completeness [%]	99.9	35.2	30.9	99.9	41.9
	Mean multiplicity	7.5	20.3	10.435	9.3	22.8
	Unique reflections	2142	753	660	2150	905
	Observed	1950	666	450	1929	751
	R_{int} [%]	2.25	2.88	6.29	4.51	5.52
	R1 [%]	2.93	3.01	7.74	3.87	3.20
	Difference density [$e^-/Å^3$]	0.24 / -0.24	0.10/ -0.09	0.23/ -0.20	0.30/ -0.22	0.10/-0.11
	Restraints	<none>	RIGU	RIGU	<none>	<none>

Table 1 - Summary of experimental results

Conclusion

Modern D8 QUEST or D8 VENTURE instrumentation equipped with a Mo or Ag IμS microfocus source, PHOTON II CPAD detector, and APEX3 software is an optimum setup for home-lab high-pressure experiments. These systems can collect high-pressure data that yields structures comparable in quality to standard single-crystal experiments.

Author

Dr. Michael Ruf, Bruker AXS Inc., Madison (WI), USA

References

1 F. P. A. Fabbiani, D. R. Allan, W. I. F. David , A. J. Davidson, A. R. Lennie, S. Parsons, Colin R. Pulham, and J. E. Warren Crystal Growth & Design, (2007), 7 (6), 1115–1124

2 F. P. A. Fabbiani and C. R. Pulham, Chem. Soc. Rev., (2006),35, 932-942

3 K. Kurpiewska, K. Lewiński, Cent. Eur. J. Biol. (2010), 5(5), 531–542

4 Dubrovinskaia et al. Sci. Adv. 2016; 2 : e1600341

5 Ilia A. Guzei, Galina A. Bikzhanova, Lara C. Spencer, Tatiana V. Timofeeva, Tiffany L. Kinnibrugh, Charles F. Campana Cryst Growth Des, vol. 8, no. 7, pp. 2411-2418, 2008

6 P. Dera and A. Katrusiak J. Appl. Cryst. (1999). 32, 510-515

7 H. E. King Jr and L. W. Finger J. Appl. Cryst. (1979). 12, 374-378

Bruker AXS GmbH

Karlsruhe · Germany
Phone +49 721 50997-0
Fax +49 721 50997-5654
info.baxs@bruker.com

www.bruker.com