Single-shot 3D structure determination of nanocrystals using femtosecond X-ray free electron laser pulses

Since the first experimental demonstration in 1999 [1], the field of coherent diffractive imaging (CDI) has grown rapidly. CDI has been applied to study a wide range of samples using synchrotron radiation and X-ray free electron lasers (XFELs). Recently, we reported the first experimental demonstration of single-shot 3D structure determination of gold nanocrystals at ~5.5 nm resolution using ~10 femtosecond SACLA pulses [2]. To achieve this, we recorded coherent diffraction patterns from high-index-faceted gold nanocrystals struck by a single SACLA pulse at beamline **BL3**. The high energy of these pulses destroyed the crystals, but in the brief time before their destruction, enough diffracted signal was collected from the crystals to determine their three-dimensional structure. Obtaining a three-dimensional structure from a single view required knowledge and application of the special symmetry present in the nanocrystals. Combined with the unique effect of curvature also intrinsic to the recorded diffraction patterns [3], we reconstructed the 3D structure of each nanocrystal from a single diffraction pattern. Our 3D reconstruction showed, in unprecedented detail, the high-index facets of these nanocrystals.

To further improve the reliability of our results, we combined single-shot diffraction patterns of identical gold nanocrystals. From these, we assembled a 3D diffraction pattern, which produced an average 3D reconstruction. The resolution achieved by this reconstruction is presently limited by the detector geometry. These results present a significant advance in CDI. At a spatial resolution of ~5.5 nm in 3D, these reconstructions enjoy the highest resolution ever achieved by any non-crystallographic 3D X-ray imaging method. As symmetry exists in many nanocrystals and virus particles, this method can be broadly applied to 3D structure studies of other such particles at nanometer resolution on femtosecond time scales. Given a sufficient number of identical nanocrystals, this approach can in principle be used to determine the 3D structure of nanocrystals at atomic resolution.

Figure 1 shows the schematic layout of our experimental setup. SACLA pulses were focused onto a small ~1.5 μm area, producing a total of 126,976 diffraction patterns from which 1,877 high quality patterns were selected. Figure 1 shows a representative high quality single-shot diffraction pattern after data analysis.

Trisoctahedral nanocrystals belong to the crystallographic point group $m\bar{3}m$, consisting two-, three-, and four-fold rotational symmetries along the <011>, <111> and <001> directions respectively, for which there exist a total of 48 symmetry operations used to produce 3D patterns. Using these symmetrized patterns, 3D phase retrieval of

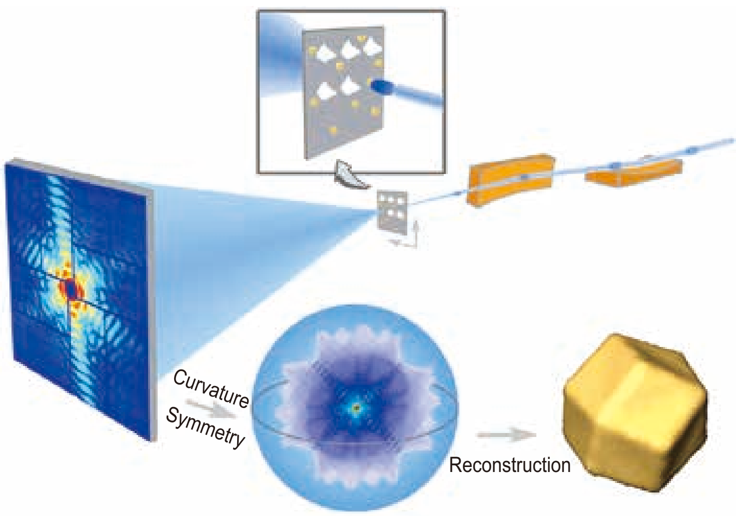

Fig. 1. Schematic layout of the single-shot 3D structure determination using femtosecond XFEL pulses. By using the symmetry of the nanocrystal and the curvature of the Ewald sphere, a 3D diffraction pattern was generated from a single-shot diffraction pattern, from which a 3D reconstruction was computed with a resolution of B5.5 nm.

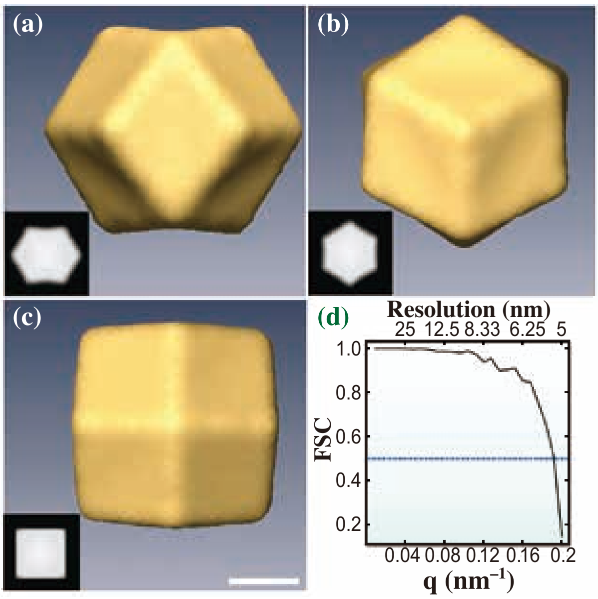

Fig. 2. 3D reconstruction of the single-shot diffraction pattern. **(a-c)** Iso-surface renderings of the final 3D reconstruction along the 2-, 3- and 4-fold rotational symmetry, respectively. The insets show 3.3-nm-thick center-slices of the 3D reconstruction along the corresponding directions. The variation of the electron density inside the nanocrystal is within ±10%, which is mainly due to noise in the single-shot diffraction pattern. **(d)** Fourier shell correction (FSC) comparison between two independently reconstructed gold nanocrystals. Based on the FSC = 0.5 criterion, a 3D resolution of the reconstructions was estimated to be ~5.5 nm.

diffraction patterns was performed, implementing the 3D oversampling smoothness (OSS) algorithm with an additional constraint that incorporates symmetry into the reconstruction [4]. Figures 2(a-c) show the iso-surface renderings along two-, there- and four-fold rotational symmetry of the reconstructed object. The insets in Figs 2(a-c) are central slices perpendicular to each symmetry axis. After determining the relative orientations and aligning the diffraction intensity of six selected high quality diffraction patterns, we assembled a 3D diffraction pattern from 288 symmetrized patterns. Using OSS with symmetry, the average 3D structure of gold nanocrystals was reconstructed. We estimated the 3D resolution of these reconstructions to be 5.5 nm, which is currently limited by the detector geometry arrangement.

To confirm these results, the reconstructed images were compared with the calculated model of trisoctahedral nanocrystals. For trisoctahedron with {661} exposure facets, facet angles α, β and γ shown in Fig. 3(a) are its intrinsic feature, measuring 119.0°, 113.8° and 166.6° respectively. We measured all these parameters for each of the reconstructed particles. Our results indicated that the overall shape and size of these nanocrystals are in good agreement with expected values.

As symmetry exists in many nanocrystals and virus, this method provides a promising way to analyze these particles at nanometer resolution on femtosecond timescales. By recording enough diffraction patterns from identical samples, the 3D reconstruction method can also be used to reconstruct the true 3D structure of weakly scattering objects.

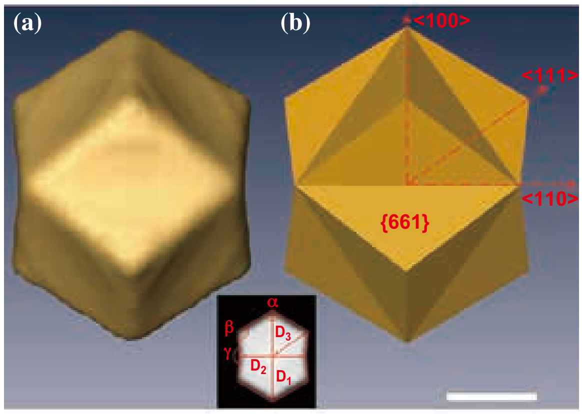

Fig. 3. 3D model of a trisoctahedral gold nanocrystal constructed from a single-shot 3D reconstruction. **(a)** Iso-surface rendering and 3.3-nm-thick central slice (inset) of the nanocrystal along the 2-fold rotational symmetry, of which D1, D2, D3, α, β and γ are six parameters used to characterize the shape, size and facets of the reconstructed nanocrystal. **(b)** 3D model of the concave trisoctahedral nanocrystal constructed from (a), containing exposed high index {661} facets.

H. Jiang[a], J. A. Rodriguez[b], C. Song[c], T. Ishikawa[c] and J. Miao[d,*]

[a] State Key Laboratory of Crystal Materials, Shandong University, China
[b] DOE Institute for Genomics and Proteomics, University of California, USA
[c] RIKEN SPring-8 Center
[d] Dept. of Physics and Astronomy and California NanoSystems Institute, University of California, USA

*E-mail: miao@physics.ucla.edu

References

[1] J. Miao *et al.*: Nature **400** (1999) 342-344.
[2] *R. Xu, H. Jiang, C. Song, J.A. Rodriguez, Z. Huang, C.-C. Chen, D. Nam, J. Park, M. Gallagher-Jones, S. Kim, S. Kim, A. Suzuki, Y. Takayama, T. Oroguchi, Y. Takahashi, Jiadong Fan, Y. Zou, T. Hatsui, Y. Inubushi, T. Kameshima, K. Yonekura, K. Tono, T. Togashi, T. Sato, M. Yamamoto, M. Nakasako, M. Yabashi, T. Ishikawa and J. Miao: Nat. Commun.* **5** *(2014) 4061.*
[3] T. Ishikawa *et al.*: Nat. Photonics **6** (2012) 540.
[4] J.A. Rodriguez *et al.*: J. Appl. Cryst. **46** (2013) 312.