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Claude Sauter, Dominique Housset, Julien Orlans, Raphaël de Wijn, Kévin Rollet, et al.. Nucleating agent crystallophore induces instant protein crystallization. *Crystal Growth & Design*, 2024, 24 (16), pp.6682-6690. 10.1021/acs.cgd.4c00600 . hal-04685502

HAL Id: hal-04685502

<https://hal.science/hal-04685502v1>

Submitted on 4 Sep 2024

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Nucleating Agent Crystallophore Induces Instant Protein Crystallization

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Cite This: *Cryst. Growth Des.* 2024, 24, 6682–6690



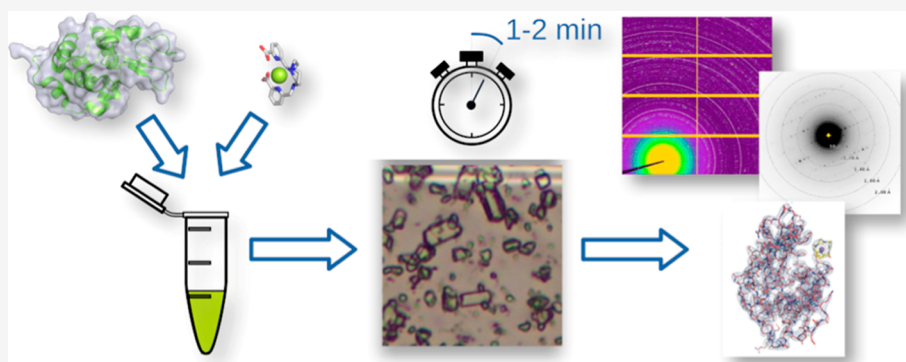
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ABSTRACT: The rapid preparation of homogeneous suspensions of micro- or nanocrystals is a crucial step in serial crystallography. We show how additives, such as the crystallophore (TbXo₄) that acts as a molecular glue by promoting protein–protein interactions, can facilitate sample preparation for both serial synchrotron crystallography (SSX) and micro electron diffraction (3D ED). This lanthanide complex was used here for its nucleating properties to crystallize the hen egg-white lysozyme. SAXS monitoring indicates that crystals grew in a few minutes under low salt conditions, which would not lead to spontaneous nucleation in the absence of TbXo₄. Resulting micro- and nanocrystals were successfully used to determine the structure of the lysozyme–TbXo₄ complex by SSX and 3D ED, illustrating the diffraction quality of the produced crystals and the usefulness of such compounds in the sample preparation pipeline for serial crystallography.

INTRODUCTION

Obtaining well-diffracting crystals is a prerequisite for any diffraction-based experiments. Among the latter, macromolecular crystallography (MX) has provided valuable information at the atomic scale on the architecture of biological molecules, such as active site description, bound ligand interactions, or details of interactions in key interfaces. Conventional MX relies on the use of a single crystal to obtain a complete crystallographic data set. However, to reduce radiation damages during data collection, most of the MX diffraction data collected during the past three decades were performed at cryogenic temperatures.^{1,2} In addition, the averaged “static” structures provided by conventional MX may not be sufficient to fully understand the function of a given macromolecule, in particular, the molecular motions associated with the biological mechanism, such as catalytic mechanisms and associated conformational changes. To observe the macromolecules in motion at all the biologically relevant time scales, i.e., from femtoseconds to a few minutes, we have to measure the diffraction data at room-temperature as the process of crystal cryocooling is too slow (about a ms) to

trap the relevant states. Moreover, triggering synchronized reactions throughout the crystal is more difficult in large samples as the diffusion time of substrates takes longer (about 100 ms for a $30 \times 40 \times 50 \mu\text{m}^3$ sample³) and the penetration depth of light is most often limited to a few microns in the case of light-activated reactions.⁴

Serial crystallography (SX), at X-ray free electron laser facilities (XFELs) or at synchrotrons, provides an elegant way to overcome conventional MX limitations, in particular, for time-resolved (TR) experiments. Indeed, SX is based on the possibility to reconstruct a complete data set from single diffraction frames, with each frame being measured from a small single crystal.

Received: May 1, 2024

Revised: July 26, 2024

Accepted: July 29, 2024

Published: August 9, 2024



The inherent nature of SX data collection drastically reduces the radiation damage issue as it distributes the required X-ray dose over a very large number of micrometer-sized crystals and opens the way to TR data collection at room or physiological temperature. Moreover, at XFELs, the diffraction is produced before the samples are destroyed (i.e., diffraction before destruction paradigm⁵), permitting to outrun radiation damage at each X-ray pulse, potentially producing a damage-free electron density map.

As a result, TR-SX allows us to obtain structural dynamics information and to observe biological macromolecules in action by capturing transient intermediates along a biological pathway.^{6–9}

From an experimental point of view, SX brings new constraints on crystal preparation, as it intrinsically requires a large amount of samples to make sure to collect a complete diffraction data set. Moreover, optimal TR experiments require crystalline samples with a narrow size distribution in order to ensure a uniform triggering of the reaction under study through the entire crystal volume.^{4,10,11}

The ability to generate crystals on-demand may open new opportunities in TR-SX by facilitating rapid cocrystallization with substrates. First, it would enable the preparation of fresh crystals just prior to data collection, hence eliminating the issues associated with sample transportation, such as the control of the temperature, vibrations, or mechanical shocks or light for light-sensitive crystals. It would also reduce the loss of diffraction quality due to crystal aging. Second, it may also limit common soaking issues such as bad substrate/fragment diffusion due to crystal packing or interferences with crystal contacts. Indeed, molecules used for fragment-based drug discovery may be incubated with the protein prior to crystallization, as can the substrates or analogues be added to the crystallization solution, thus ensuring a controlled triggering or inhibition of the targeted reaction.

Recently, Henkel and co-workers proposed a method that combines protein crystallization and data collection in a novel one-step process they named JINXED to perform optimal TR experiments based on serial crystallography.¹² They exploited hen egg-white lysozyme (HEWL) crystals generated with crystallization times of only a few seconds from highly concentrated protein and crystallant solutions.

In 2017, we introduced the crystallophore (TbXo4), a lanthanide complex with both nucleating and phasing properties.¹³ In particular, its unique characteristics of favoring protein crystallization was initially highlighted using a set of eight proteins. The study also showed that the crystallophore induces more crystallization conditions for a given protein and strongly enlarges its crystallization diagram, allowing us to use a less concentrated protein solution.¹³ These nucleating properties were also exploited to grow crystals from protein fractions containing a mixture of several proteins and to produce crystals free of defects showing better diffracting properties.¹⁴ Finally, the addition of the crystallophore to HEWL solubilized in pure water instantly produced larger size particles that were detected by dynamic light scattering. After several weeks, the presence of single crystals was observed in this unusual condition.¹⁵

Altogether, these results prompted us to challenge the nucleating properties of the crystallophore for the minute-scale production of crystals with the appropriate size for either SX experiments or the electron diffraction of 3D nanocrystals (3D ED). As a proof-of-principle, we generated HEWL crystals with

a distribution ranging from the nanometer to the micrometer size, allowing their diffraction quality to be evaluated by means of electron diffraction and synchrotron serial crystallography, respectively. Finally, we used TR small-angle X-ray scattering (TR-SAXS) to determine the time window associated with crystal production assisted by the crystallophore.

MATERIALS AND METHODS

Chemicals. The crystallophore molecule, TbXo4, was kindly provided by Polyvalan (<https://crystallophore.fr>). HEWL was purchased from Roche (cat. no. 10837059001) or from Seikagaku Corp. (Tokyo, Japan, cat. no. 100940) or Sigma-Aldrich (St. Louis, MO, USA, Fluka cat. no. 62970-SG-F). All other chemicals were purchased from Sigma-Aldrich.

Sample Preparation for Diffraction Experiments. The lyophilized HEWL (Roche) was first dissolved in 80 mM sodium acetate pH 4.6 to a final concentration of 80 mg/mL. In a 1:1 ratio, the prepared solution was then mixed with a crystallant solution containing 800 mM NaCl, 80 mM sodium acetate pH 4.6, and 20 mM TbXo4, leading to a final volume of 100 μ L. This batch crystallization resulted in a milky suspension. In the present work, crystallant refers to the precipitating agent according to ref 16.

Sample Preparation for SAXS Experiments. HEWL powders from Seikagaku Corp. or Sigma-Aldrich were dissolved in 50 mM Na acetate at pH 4.5 to prepare stock solutions at 200 and 175 mg/mL, respectively. Lysozyme stock solutions were filtered prior to concentration measurement by UV spectrophotometry and ultracentrifuged at 125,000g prior to SAXS experiments.

SSX Chip Preparation, Data Collection, and Data Processing. After centrifugation for 2 min at 2000g, 5 μ L of HEWL-TbXo4 microcrystals supernatant solution was sealed between two foils of 13 μ m thick Mylar (DuPont) enclosed in a frame of 10 \times 15 mm (SOS chip).¹⁷

Measurements were performed at the ESRF synchrotron facility (Grenoble, France) on ID29 beamline (<https://www.esrf.fr/id29>) using an X-ray photon energy of 11.56 keV (1.072 \AA) with a 1% bandwidth and a beam size of 4 \times 2 μ m² (H \times V). X-ray pulse lengths of 90 μ s at a frame rate of 231.25 Hz were recorded on a JUNGFRU 4 M detector. The sample-to-detector distance was 150 mm. The motorized stage was moved 25 μ m between two X-ray pulses to refresh the sample.

Diffraction patterns were processed using a CrystFEL-v0.10.2 suite.¹⁸ Spot-finding was performed using the Peakfinder8 algorithm.¹⁹ Various indexing algorithms, XGANDALF²⁰ and MOSFLM²¹ were applied to index diffraction frames. Merging was done using partialator.²² The final data set statistics are presented in Table 1.

The HEWL structure was solved by molecular replacement with the PHASER program²³ from the CCP4 suite of programs²⁴ using the 193L PDB entry as a starting model. The top 1 solution had an LLG value of 2274.4 and an *R*-factor of 0.361.

The model was further refined through two rounds of refinement in Phenix.²⁵ The first consisted of adding the Tb ion within the model using an anomalous Fourier synthesis and, in particular, by performing simulated annealing and water molecule search. Prior to the second refinement round, the Xo4 ligand was then added, and the TbXo4 molecule occupancy was adjusted to 0.75 so that terbium *B*-factors fit the ones of the binding residue Asp101. *R*-factors and stereochemistry values are summarized in Table 1.

3D ED Grid Preparation, Data Collection, and Data Processing. The solution of lysozyme nanocrystals was centrifuged for 2 min at 2000 g, and 3 μ L of the supernatant was deposited on a 400 mesh copper grid covered with a Lacey carbon film. The grid was then backside blotted manually with a blotting paper and flash frozen in liquid ethane using a homemade mechanical plunger.

The electron diffraction data were collected on a F20 cryo-electron microscope (FEI) operated at 200 kV and equipped with a hybrid pixel Medipix3RX 512 \times 512 detector. Electron diffraction crystallographic data were collected at -170 $^{\circ}$ C on five different crystals

Table 1. Data Processing and Refinement Statistics for SSX Data Collected on HEWL Microcrystals

	data processing
no. of collected frames	153,600
no. of hits	40,262
indexed patterns	22,622
average dose per pulse (MGy)	0.66
wavelength (Å)	1.072
space group	$P4_32_12$
unit-cell parameters (Å)	$a = b = 78.75, c = 38.20$
resolution range (all. Å) high resolution range	78.75–2.05 (2.08–2.05)
no. observations	2239287 (38381)
no. unique reflections	7990 (380)
multiplicity	280.3 (101.0)
completeness (%)	100 (100)
R_{split}	11.87 (181.81)
$CC_{1/2}$	0.987 (0.213)
CC^*	0.997 (0.593)
$I/\sigma(I)$	5.82 (0.50)
Wilson B factor (Å ²)	41.68
	refinement
resolution range	55.68–2.05 (2.35–2.05)
no. refl. used in refinement	7952 (2575)
no. refl. used for free set	398 (129)
R_{work}	0.1801 (0.2807)
R_{free}	0.2166 (0.3018)
no. of non-hydrogen atoms	1088
macromolecules	1001
ligands	30
solvent	57
average B -factor (Å ²)	44.29
macromolecules	43.39
ligands	68.22
solvent	47.64
σ bond (Å)	0.007
σ angle (°)	0.86
clashscore	7.59

(Table S1). A selected aperture of about 1 μm was inserted into the first image plane of the electron microscope in order to limit the area contributing to the measured diffraction pattern. The HEWL crystals were continuously rotated on an angular wedge ranging from 32 to 46° with 0.1835° per frame (continuous rotation speed set to 5% on the F20 microscope, i.e., 1.468°/s) and an exposure time of 0.125 s/frame. The camera length was set to 730 mm, corresponding to calibrated camera length values of 1285 mm.

All the data sets were processed with the XDS package.²⁶ The five data sets were scaled and merged with XSCALE. The final data set statistics are presented in Table 2.

The HEWL structure was solved by molecular replacement with the PHASER program²³ from the CCP4 suite of programs²⁴ using the 193L PDB entry as a starting model. The top 1 solution had an LLG value of 540 and an R -factor of 0.454. The solution was further refined with Refmac5,²⁷ using electron atomic scattering length tabulated in the atomsf_electron.lib file of CCP4, leading to an R work of 0.202 and an R free of 0.318, with good stereochemistry (r.m.s. bond and angle deviation of 0.06 Å and 1.84°, respectively). At this point, the first peak in the residual $\{F_{\text{obs}} - F_{\text{calc}}\}$ Coulomb potential map (+7.32 σ) was observed at the expected position of the TbXo4 compound (Figure 2A). TbXo4 was thus added to the model and placed in the position and orientation that provided the best fit with the residual Coulomb potential map. Another round of refinement with Refmac5 indicated that the TbXo4 B -factor was significantly higher than those of Trp62, Trp63, and Asp101 side chains, which are in close contact with TbXo4. The occupancy of TbXo4 was then

Table 2. Data Processing and Refinement Statistics for Electron Diffraction Data Collected on HEWL Nanocrystals

	data processing
space group	$P4_32_12$
unit-cell parameters (Å)	$a = b = 78.63, c = 37.91$
wavelength (Å)	0.02508
resolution range (all. Å) high resolution range	55.60–3.21 (3.30–3.21)
no. observations	26621 (837)
no. unique	1817 (123)
multiplicity	33.1 (11.8)
completeness (%)	83.8 (71.5)
R_{sym}	0.709 (1.941)
R_{meas}	0.736 (2.103)
$CC_{1/2}$	0.935 (0.393)
$I/\sigma(I)$	3.79 (0.69)
Wilson B factor (Å ²)	68.7
	refinement
resolution range	50.00–3.21 (3.29–3.21)
no. refl. used in refinement	1633 (102)
no. refl. used for free set	178 (9)
no. non-hydrogen atoms	1031
R -factor	0.219
R_{work}	0.210 (0.310)
R_{free}	0.300 (0.410)
σ bond (Å)	0.003
σ angle (°)	0.987

reduced to 0.75, and a final round of refinement was performed. The final structure included the entire polypeptide chain corresponding to the HEWL and one TbXo4 compound, with acceptable R -factors and stereochemistry (Table 2).

SAXS Sample Environment and Data Collection. TR-SAXS experiments were performed on the SWING beamline at synchrotron SOLEIL (Saint-Aubin, France). The X-ray beam wavelength was set to $\lambda = 0.826$ Å (15 keV). The Eiger X 4 M detector (Dectris) was positioned at a distance of 2037 mm from the sample with the direct beam off-centered. The resulting exploitable q -range was 0.004–0.69 Å⁻¹, where the wave vector is $q = 4\pi \sin \theta/\lambda$ and 2θ is the scattering angle.

Rapid mixing of HEWL solutions with salt and nucleant solutions was performed using a homemade syringe pump, as described in Figure 1. The first syringe (1 mL, Braun Melsungen AG, Germany) contained 50 mM sodium acetate pH 4.5 with or without HEWL and the second contained 50 mM sodium acetate pH 4.5, 400, or 800 mM NaCl, with or without 20 mM TbXo4. Injection lines made of Peek tubes coming from the syringes were coupled to the incubation capillary by a mixing tee (U-466S, Chrom Tech). The incubation capillary was directly plugged into the SAXS cell.

The syringes had an inner diameter of 4.73 mm, hence delivering 17.6 $\mu\text{L}/\text{mm}$ by linear displacement of the step motor. They were filled with 300 μL of solution before each experiment. Rapid solution mixing was carried out by moving the plunger of both syringes by 10.9 mm in 1 min 50 s (0.1 mm/s) to obtain 280 μL of crystallization medium and fill the entire tubing, including the SAXS cell. The evolution of the solution was monitored over 30 min by collecting 180 images with an interval of 10 s and an exposure time of 1 s per image while translating the solution to refresh the sample (displacement step of 0.03 mm at 1 mm/s) after each image.

For each salt condition (final NaCl concentration 200 or 400 mM), a series of measurements were carried out including (i) the acetate buffer only (for buffer subtraction), (ii) control solutions containing either HEWL or TbXo4, and (iii) the full mix to follow the nucleation/growth process. After each experiment, the setup was extensively washed with a 2% (v/v) aqueous solution of Hellmanex (Hellma HmbH, Germany) and water.

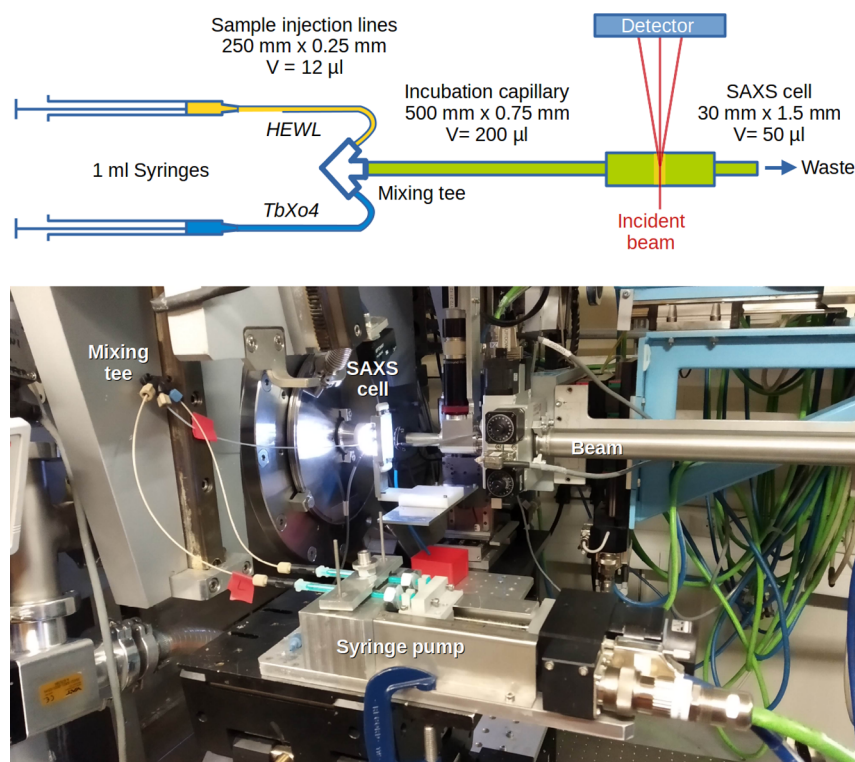


Figure 1. Schematic view and picture of the experimental setup used for TR-SAXS.

Data processing was performed using Foxtrot²⁸ and data analysis with the ATSAS package.²⁹ Graphics were prepared with BioXTAS-RAW.³⁰

Powder diffraction programs were not suitable for Bragg rings indexing due to the large unit cell and limited experimental resolution. Instead, F_{calc} values were generated for the experimental resolution range using Phenix.²⁵ Structure factors were calculated up to a resolution of 12.7 Å ($2\theta = 3.8^\circ$) from a tetragonal HEWL crystal structure collected at room temperature (PDB ID 4NGK; $a = 79.28$ Å, $c = 37.73$ Å, space group $P4_32_12$). Bragg rings overlaid on the SAXS scattering profile were assigned to their corresponding Bragg peaks by the successive refinement of cell parameters by least-squares minimization in an Excel spreadsheet converged to $a = 79.0$ Å and $c = 38.3$ Å.

Raw Data Availability. The raw frames for both SSX and 3D ED experiments have been deposited in Zenodo repository under DOI <https://zenodo.org/doi/10.5281/zenodo.12732930>.

Structural biology software support for IBS was provided by SBGrid.³¹

RESULTS AND DISCUSSION

Rapid HEWL Crystallization. The crystallization of HEWL, a widely used model protein for MX, in the presence of NaCl and acetate buffer at pH 4.5 is a conventional condition to generate well-diffracting crystals. In the present work, the mixing in an Eppendorf tube of a HEWL protein solution prepared in an acetate buffer with a solution containing the crystallophore in the presence of NaCl (see [Materials and Methods](#) section) yielded a dense milky suspension after less than 2 min. This milky suspension that slowly sediments is indicative of a potential massive presence of microcrystals.⁴

Crystal Size Distribution. Few microliters of the produced suspension were first deposited between two glass lamellas for optical visualization. As shown in [Figure 2A](#), crystals with the typical tetragonal shape were clearly visible

with a distribution size ranging from one micron to 20 µm. To characterize even smaller ones, transmission electron microscopy was performed and clearly revealed well-defined crystals with sizes ranging from 200 nm to 1 µm ([Figure 3A](#)). This confirms the effect of TbXo4 on the production of crystalline samples with an ideal size for both 3D ED and serial crystallography, providing an optimal crystal size according to the planned experiments. It should be mentioned that the produced crystals were obtained at a low NaCl concentration (that would not allow spontaneous crystallization) and commonly used HEWL concentration (40 mg/mL) thanks to the TbXo4 properties and were obtained in a batch, facilitating the scaling up to larger volumes. As already mentioned, the crystallophore provides new crystallization conditions from nanoliter vapor diffusion crystallization.¹³ By exploiting these conditions, one can expect to facilitate the sometime difficult transition from nanoscale crystallization to large-scale batch crystallization.^{10,11}

Diffraction Evaluation of Micron-Sized Crystals. A Synchrotron Serial Crystallography (SSX) experiment was performed on the ID29 beamline at ESRF (Grenoble) using a fixed-target approach. To this end, a SOS (sheet-on-sheet) chip was used to present the crystals in front of the beam.¹⁷ The solution containing microcrystals was sandwiched between two Mylar foils leading to random crystal positions. The diffraction data were recorded by defining a raster grid of 25 µm and using a beam size of 4×2 µm². 153,600 detector frames were recorded. Among them, 40,262 contained diffraction (hit rate of 26.2%) and 20,622 of those contained indexable patterns (indexing rate of 51.2%).

The overall data processing resulted in a 2.1 Å resolution data set with 100% completeness and $CC(1/2)$ and $I/\sigma(I)$ of 0.987 and 5.82, respectively ([Table 1](#)). A criterion of $CC^* > 0.5$ was used to define the maximum resolution.

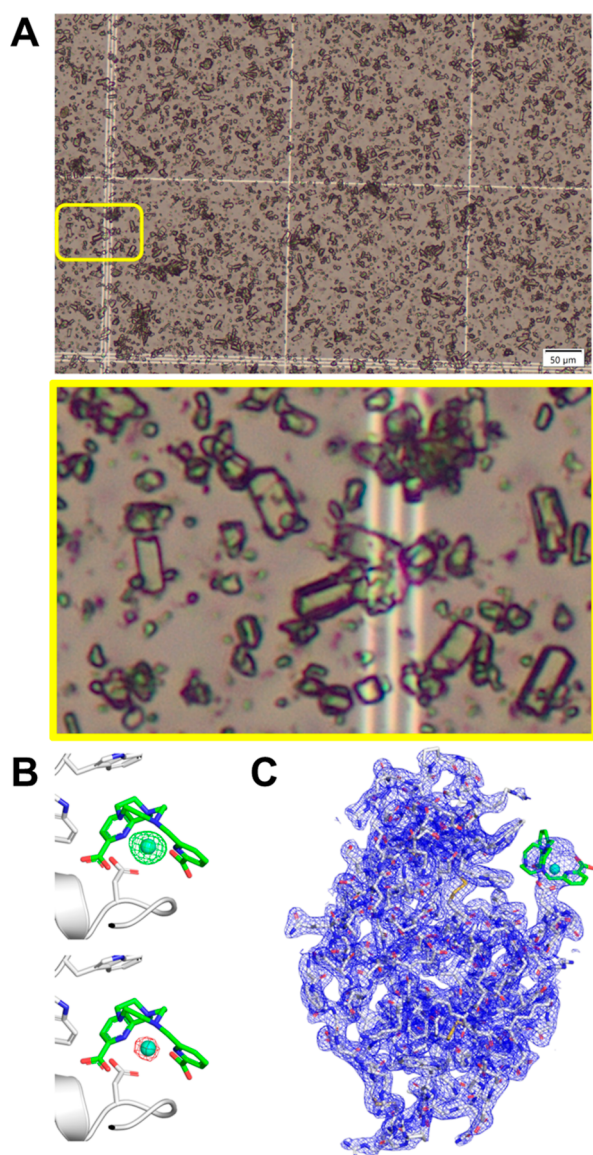


Figure 2. (A) View of the HEWL microcrystals used for the SSX experiments. A close-up (yellow rectangle) is provided. (B) Electron density maps (contour: 7σ level) calculated after molecular replacement; $\{mF_{\text{obs}} - DF_{\text{calc}}\}$ in green (upper) and anomalous Fourier synthesis in red (lower). Refined HEWL (cartoon mode) model with TbXo4 depicted in green (stick mode) was superimposed. (C) Refined HEWL model with $\{2mF_{\text{obs}} - DF_{\text{calc}}\}$ electron density map (contour: 1σ level).

As shown in Figure 2, the molecular replacement performed with Phaser yielded a clear $\{2mF_{\text{obs}} - DF_{\text{calc}}\}$ electron density map (contour level $\sigma = 1.0$). In particular, in the $\{mF_{\text{obs}} - DF_{\text{calc}}\}$ electron density map, the presence of a 18σ peak close to Asp101 confirms the presence of the crystallophore molecule as expected.¹³ This is further confirmed by the anomalous Fourier synthesis exploiting the anomalous signal present within the data. Indeed, at the beam energy used to collect the data (11.56 keV), the terbium f' value is about eight electrons, thus inducing a significant anomalous contribution to the diffracted intensities (Figure 2B).

These results clearly highlight the quality of the TbXo4-generated microcrystals and their usefulness to derive structural information at a high resolution.

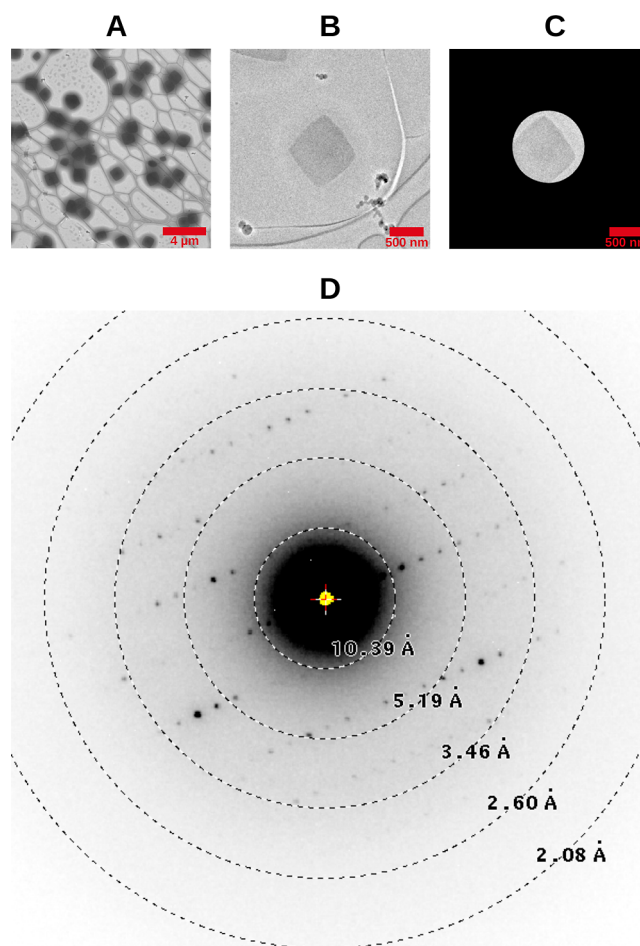


Figure 3. (A) View of the HEWL crystals on the frozen grid that was used for the electron diffraction experiments. The magnification of the F20 electron microscope was set to $\times 800$. (B,C) View of the crystal that was used for the data collection of set no. 5. The magnification of the F20 electron microscope was set to $\times 5000$. View (C) has been taken with the selected aperture diaphragm inserted. (D) Still diffraction pattern of the crystal used for data set no.4, just before launching the continuous rotation.

Diffraction Evaluation of Nanosized Crystals. 3D ED is an emerging diffraction technique allowing us to get structural biology information from nanosized protein crystals.^{32–34} HEWL was the first protein structure to be solved by 3D ED and refined against electron diffraction data.^{35–37} To evaluate the diffraction quality of the nanosized HEWL-TbXo4 crystals, we performed a 3D ED data collection using a F20 cryo-electron microscope from FEI (see Materials and Methods section). On the best grid, the crystal size distribution was moderately heterogeneous, with a majority of crystals resembling square platelets, with edges ranging from 0.5 to $1 \mu\text{m}$ (Figure 3A).

The final merged data set was obtained from five different crystals (Figure 3B,C). The individual data processing resulted in similar diffraction qualities for each sample with, in particular, high resolution comprised between 4 and 3.2 \AA (Supporting Information, Table S1). One example of a diffraction frame is shown in Figure 3D.

The final data set is 83.8% complete and includes data up to 3.21 \AA resolution (Table 2).

After molecular replacement and the first round of refinement, the main peak in the residual $\{F_{\text{obs}} - F_{\text{calc}}\}$ Coulomb

potential map ($+7.32\sigma$) was unambiguously attributed to the terbium atom (Figure 4A). As for the structure derived from

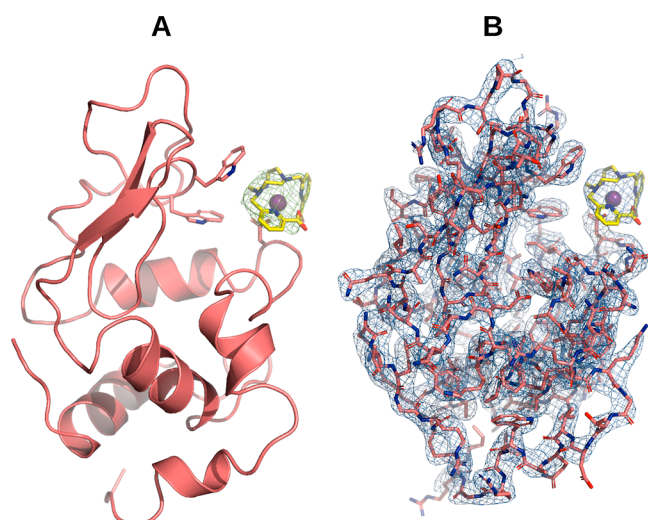


Figure 4. (A) View of the HEWL structure after the first round of Refmac5 refinement during which the crystallophore TbXo4 was not included. The main peak of the residual $\{F_{\text{obs}} - F_{\text{calc}}\}$ Coulomb potential map contoured at the 2.8σ level (depicted in green) is shown, with the model of TbXo4 shown in stick mode fitted into it. (B) View of the $\{2F_{\text{obs}} - F_{\text{calc}}\}$ Coulomb potential map, contoured at the 1.1σ level, after the final round of Refmac5 refinement including the TbXo4 compound.

SSX data, its position close to Asp101 is as expected.¹³ The final fit between the $\{2F_{\text{obs}} - F_{\text{calc}}\}$ Coulomb potential map and the final model is good all along the polypeptide chain as well as for TbXo4 (Figure 4B) showing that TbXo4 generated nanocrystals allow us to get precise structural information. It is worth noting that the occupancy determined for the TbXo4 moiety is the same for both the SSX and the 3D ED data-derived model. This demonstrates the consistency of the data and the reproducibility of the crystals grown in this condition.

CRYSTAL PRODUCTION TIME WINDOW ASSESSED BY SAXS

TR-SAXS was used to monitor the nucleation properties of TbXo4 on HEWL solutions. To perform rapid mixing of the crystallization solution with the HEWL, we assembled an injection system consisting of a syringe pump, a connector (tee-mixer) for the capillary tubes bringing the solutions from the syringes, and a wider capillary tube acting as an incubation chamber connected to the SAXS cell (Figure 1). Several procedures were tested to achieve rapid mixing without creating bubbles in the system. The best compromise consisted of running the motor at 0.1 mm/s, resulting in a mixing step of 1'50" to produce a volume sufficient to fill the entire tubing, including the SAXS cell. The evolution of the solution was then followed for 30 min in capturing one image every 10 s and moving the solution after each image to refresh the sample. Also, the beamline energy was shifted from its standard value (12 keV $-\lambda = 1.033 \text{ \AA}$) to 15 keV to avoid fast capillary fouling with solutions containing TbXo4.

Rapidly after mixing HEWL with 10 mM TbXo4 in 400 mM NaCl, the solution turned snowy in the SAXS cell (Supporting Information, Movie S1). The scattering intensity jumped at $t = 170 \text{ s}$ (Figure 5A) and discrete peaks appeared in the profiles,

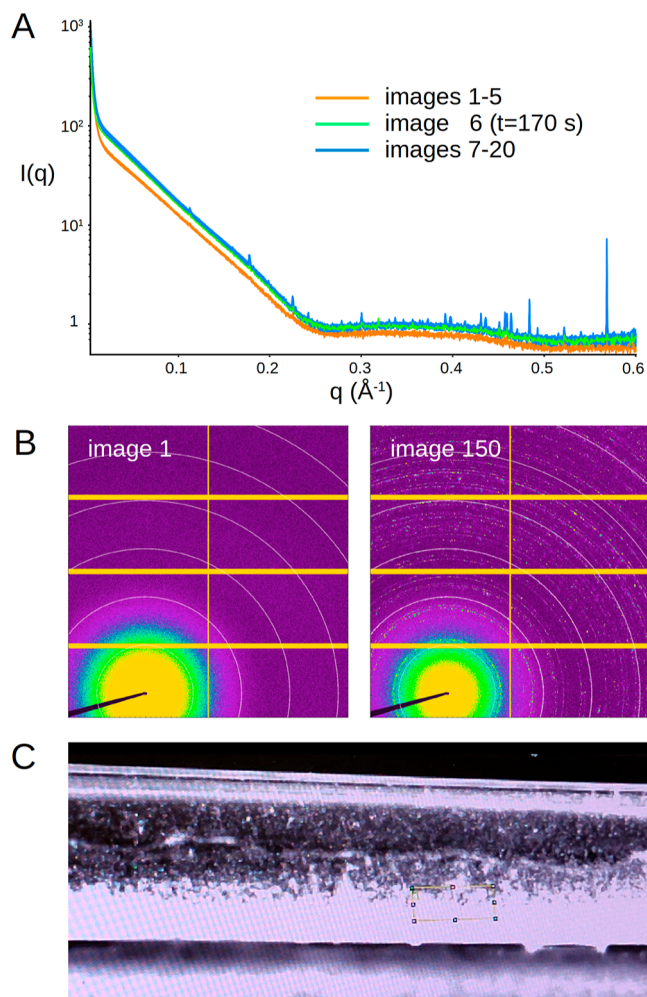


Figure 5. (A) Monitoring of microcrystallization by TR-SAXS. (A) Evolution of SAXS profiles between $t = 120 \text{ s}$ (image 1) just after the mixing step and $t = 380 \text{ s}$ (image 20). The scattering intensity increases and diffraction rings (Bragg rings) appear at $t = 170 \text{ s}$, indicating the formation of microcrystals. (B) First image showing the scattering signal of HEWL solution, which superimposes with diffraction rings generated by microcrystals in the image 150 ($t = 1620 \text{ s}$). White circles correspond to a scattering angle of $q = 0.1, 0.2, 0.3, 0.4, 0.5,$ and 0.6 \AA^{-1} , respectively. (C) View from the beamline camera showing microcrystals settling at the bottom of the SAXS cell. The yellow rectangle symbolizes the X-ray beam.

indicating the formation of a crystalline phase. The cell was then gradually filled with microcrystals (Figure 5C), leading to powder diffraction patterns that intensified over time (Supporting Information, Movie S2). Figure 5B illustrates the initial HEWL scattering signal and its superposition with microcrystal diffraction patterns after 25 min. The analysis of these powder diffraction-like patterns indicates the presence of tetragonal HEWL crystals with unit-cell parameters of $a = 79.0 \text{ \AA}$ and $c = 38.3 \text{ \AA}$ (Supporting Information, Figure S1).

Rapid crystallization did not occur in the time frame of the experiment (30 min) in the absence of TbXo4 or when the NaCl concentration was decreased to 200 mM (data not shown). However, lowering the protein concentration to 67 mg/mL (instead of 100 mg/mL) still led to microcrystallization, although less spectacular (Supporting Information, Movie S3).

CONCLUSIONS

The production of protein crystals requires the generation of a supersaturated state, which is usually achieved by adding a crystallant that reduces the solubility of the protein. In the case of lysozyme, the most common crystallant is NaCl. The higher the crystallant concentration, the higher the supersaturation and the higher the probability of nucleating and growing crystals. This is why batch crystallization with fast mixing of protein with a high crystallant concentration is a very popular way of preparing a sample for SSX which requires hundreds of thousands of microcrystals to determine a crystal structure. However, this kind of highly supersaturated condition is very unstable because it is far from equilibrium and does not guarantee the reproducibility and the homogeneity of microcrystal batches.

An alternative strategy, potentially compatible with lower supersaturation levels, is to promote nucleation with compounds acting as a molecular glue, a concept already validated on HEWL with calixarenes in the presence of 20–30% (w/v) PEG 8000.³⁸ Having observed that TbXo4 was also able to trigger the nucleation and the crystal growth of HEWL even in the absence of any crystallant,¹⁵ we explored the possibility to generate microcrystal batches at low salt concentrations, not by making the protein less soluble but by promoting intermolecular contacts leading to crystal growth. This is exactly what TbXo4 provides, as illustrated by its propensity to generate more hits at lower protein concentration during crystallization screening.¹³

Our results illustrate that TbXo4 is an efficient molecular glue that can initiate fast microcrystal production in a few minutes. SAXS monitoring revealed the presence of diffraction patterns after less than 3 min. However, owing to the large beam size and the strong background from the solution, we cannot exclude that nanocrystals may appear much faster but remain undetectable until they reach a minimal size and density in the SAXS cell. Nevertheless, such microcrystalline samples can be easily and reproducibly prepared on demand. They proved useful for structural analysis by SSX and 3D ED, and they showed a diffraction quality that is fairly homogeneous.

Altogether, when we consider the possibility of promoting instant crystallization with TbXo4, along with its ability to trigger crystallization in different solvent conditions of a screen and generate multiple crystal forms, the crystallophore definitely appears as a promising tool for sample preparation in SSX including TR applications.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.cgd.4c00600>.

Lysozyme data acquisition by 3D ED and integration statistics of individual nanocrystals, SAXS profile averaged over images 135–150 highlighting powder diffraction ring positions as a function of q and 2θ (Miller indices of peaks correspond to tetragonal microcrystals with cell parameters of $a = b = 79.0$ Å and $c = 38.3$ Å), and image 150 showing the superposition of diffuse scattering from the solution and powder diffraction signals from microcrystals (PDF) Evolution of the HEWL—TbXo4 mix over time. The first sequence was recorded after 3 min when micro-

crystals started to appear and sediment at the bottom of the SAXS capillary. The solution was pushed forward every 10 s by the syringe pump to refresh the sample exposed to the X-ray beam symbolized by the yellow rectangle. The second sequence at 12 min after the mix shows increased microcrystal formation and sedimentation (MP4)

Sequence of 150 SAXS images (1 image every 10 s) illustrating the appearance and intensification of diffraction rings with a mix consisting of 100 mg/mL HEWL, 10 mM TbXo4, 400 mM NaCl, and 50 mM Na acetate (pH 4.5) (MP4)

Sequence of 180 SAXS images (1 image every 10 s) illustrating the appearance and intensification of diffraction rings with a mix consisting of 75 mg/mL HEWL, 10 mM TbXo4, 400 mM NaCl, and 50 mM Na acetate (pH 4.5) (MP4)

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Author Contributions

C.S. and E.G. designed and coordinated the project. R.d.W., K.R., P.B., O.M., and E.G. prepared the samples. D.H. and E.G. performed 3D ED experiments. D.H. processed and analyzed 3D ED data. J.O., S.L.R., S.B., D.d.S., and E.G. performed SSX data collection. J.O. and E.G. processed and analyzed SSX data.

C.S., K.R., P.B., J.P., and E.G. performed SAXS data collection. C.S. and P.B. processed and analyzed SAXS data. C.S., D.H., and E.G. wrote the original draft. The final manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Funding

This work was supported by the French Agence Nationale de la Recherche (ANR) through the Project Ln23 (ANR-13BS07-0007-01 to OM and EG) and by the Région Auvergne-Rhône-Alpes through the project Xo4-2.0 (Pack Ambition Recherche 2017 to OM and EG), the French Center for Atomic Research (CEA), the French Centre National de la Recherche Scientifique (CNRS), the University of Strasbourg Institute of Advanced Science (USIAS-W21RSAUT to C.S.), the LabEx consortia "NetRNA" (ANR-10-LABX-0036 NETRNA to C.S.), and a Ph.D funding to K.R. from the French-German University (DFH-UFA grant no. CT-30-19). This work used the platforms of the Grenoble Instruct-ERIC center (ISBG; UAR 3518 CNRS-CEA-UGA-EMBL) within the Grenoble Partnership for Structural Biology (PSB), supported by FRISBI (ANR-10-INBS-0005-02) and GRAL, financed within the University Grenoble Alpes graduate school (Écoles Universitaires de Recherche) CBH-EUR-GS (ANR-17-EURE-0003). The IBS electron microscope facility is supported by the Auvergne-Rhône-Alpes Region, the Fondation pour la Recherche Médicale (FRM), the Fonds FEDER and the GIS-Infrastructures en Biologie Santé et Agronomie (IBiSA).

Notes

The authors declare the following competing financial interest(s): OM and EG declare a potential conflict of interest since they are co-founders of the Polyvalan company that commercializes the crystallophore.

ACKNOWLEDGMENTS

IBS acknowledges integration into the Interdisciplinary Research Institute of Grenoble (IRIG, CEA). The authors thank the following synchrotron facilities and associated scientists for beamtime allocation to the project: beamline ID29 at the European Synchrotron Facility (Grenoble, France) and SWING at SOLEIL synchrotron (project 20211662, Saint-Aubin, France). We thank Emmanuelle Neumann for training on the F20 cryo-electron microscope.

ABBREVIATIONS

MX, macromolecular crystallography; HEWL, hen egg-white lysozyme; SSX, synchrotron serial crystallography; 3D ED, electron diffraction of 3D nanocrystals.

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