How small a molecular crystal can be? Looking for Hidden Crystalline Aggregates in Dissolving Benzoic Acid Nanoparticles

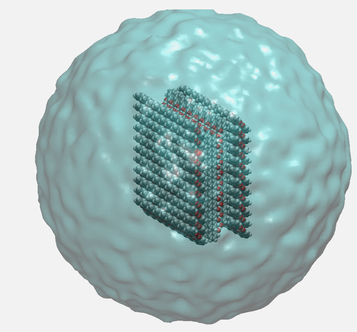
Margherita Vacchini[a], Giovanni Macetti[a], Stefano Righi[a], Leonardo Lo Presti[a]
[a]Department of Chemistry, Università degli Studi di Milano, Milano, Italy
e-mail: margherita.vacchini@unimi.it

Aim

Answering this question would reveal molecular-scale matter behaviour [1]. However, nanocrystals emerging from their liquid matrix are too small to be detected by standard crystallographic techniques [2].

The aim of work is to investigate **dissolution kinetics of a crystalline nanoparticle of benzoic acid (BZA)** embedded in its liquid to find **persistent aggregates** that may conserve some amount of translational symmetry close to the end of the dissolution process. These aggregates could provide a reasonable model for the elusive entities that are sometimes referred to as "**crystal embryos**".

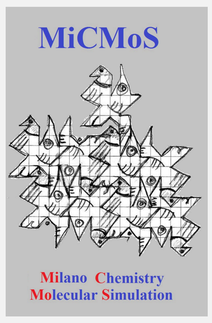
Methods



Molecular Dynamics (MD) simulations were performed using the **Lennard–Jones–Coulomb (LJC) force field**, which has already been successfully employed to describe liquid benzoic acid (BZA) [3]. MD simulations of BZA nanoparticles embedded in their liquid were performed at **high degree of undercooling** (T = 300 K, ~ 100 K of undercooling) in order to slow down dissolution kinetics to investigate intermolecular interactions.

All the computational work was carried out on the **MiCMoS platform**, developed in our group [4,5].

MiCMoS v2.4 User's Manual, May 2025.



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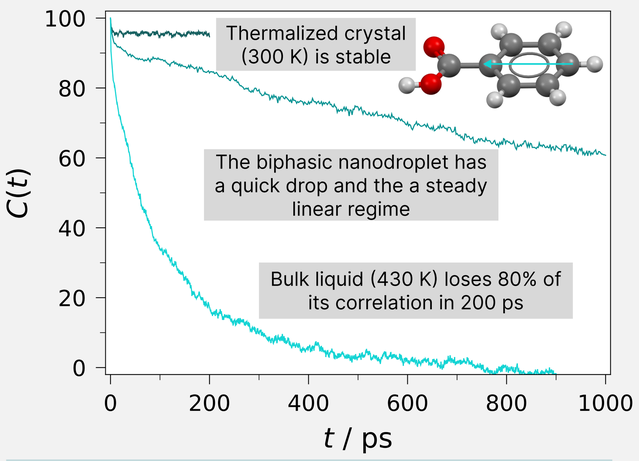
1. Tentative order descriptors

Despite the high degree of undercooling, **the nanoparticle invariably melts.**



This can be seen from the C(t) trend over time.

Rotational correlation function *C(t)*:

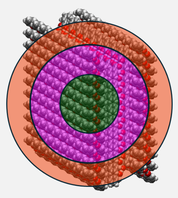
$$C(t) = \frac{\sum_{k=1}^{N_{\mathrm{mol}}} \mathbf{u}_k(t) \cdot \mathbf{u}_k(t=0)}{N_{\mathrm{mol}}}$$

Expected dissolution time **~ 7 ns** (from exponential fitting)

Results

As the nanoparticle melts, the system continuously changes its composition.

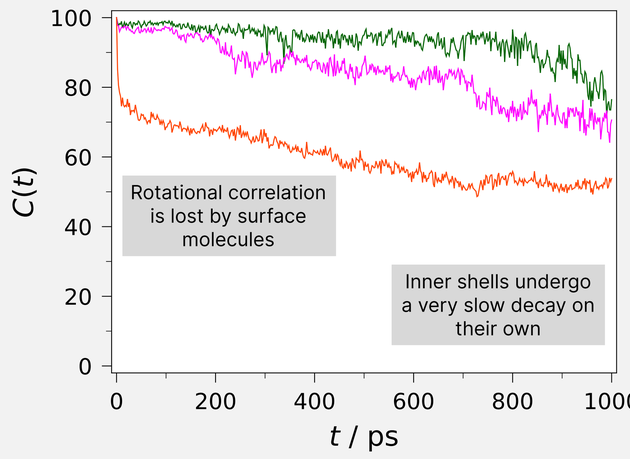
To follow its dynamics, it is mandatory to define **quantitative descriptors for crystallinity**:



shells.f90 algorithm: partitions the volume of the nanoparticle into ~ 10 spherical shells each 4 Å thick and computed the corresponding C(t)

At least three mechanisms account for the overall crystallinity loss of the nanoparticle:

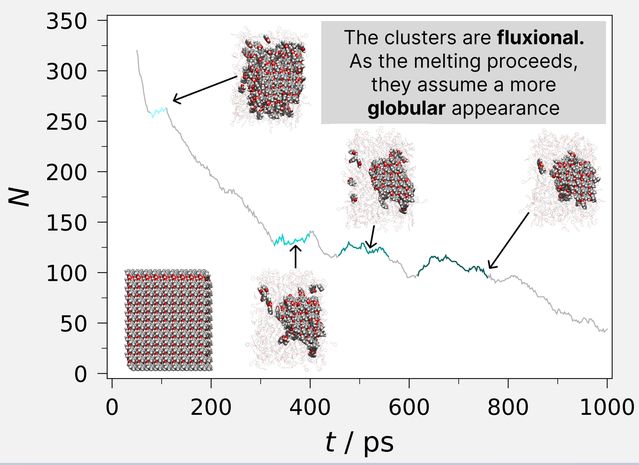
Surface melting → Detaching of molecules from the surface → Bulk melting



2. Crystallinity criterion

To highlight **molecular clusters** that conserve their **crystalline order** a **crystallinity criterion** was employed.

A molecule is "**crystalline**" if its **C(t) > 90%** and **D(t) > 10 Å²** on running averages over 50 ps

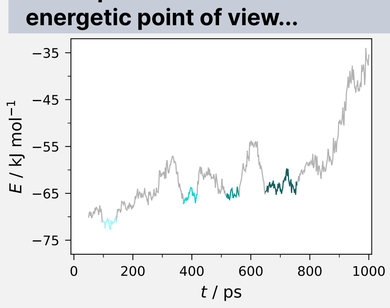


Four stationary states are found with length up to **100-140 ps**

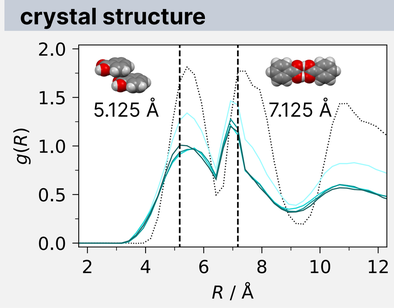
Translational diffusion function *D(t)*:

$$D(t) = \frac{1}{6t} \cdot \frac{\sum_{k=1}^{N_{\mathrm{mol}}} |\mathbf{r}(t) - \mathbf{r}(0)|^2}{N_{\mathrm{mol}}}$$

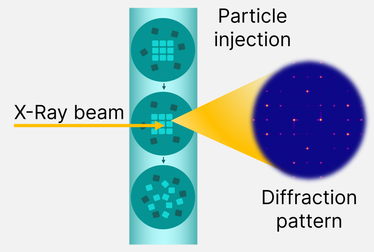
Plateaux in size find **correspondence** also **from energetic point of view...**



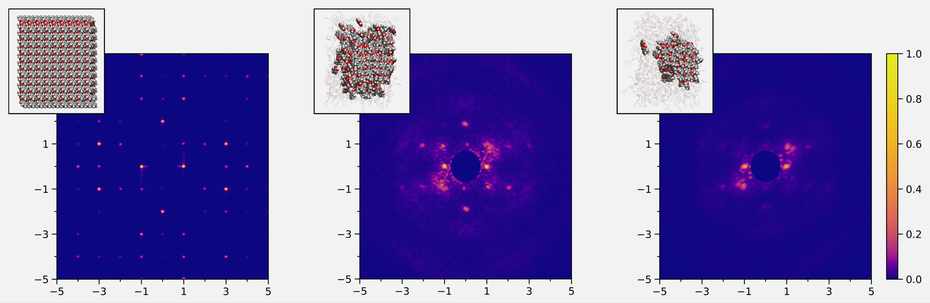
... and are reminiscent of bulk crystal structure



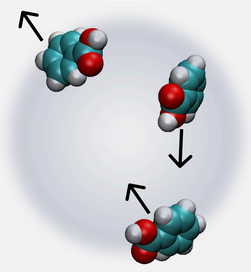
The **MiCMoS routine *Difscat*** was employed to **simulate X-Ray images from the average structures of partially ordered BZA clusters** to see if, hypothetically, these **~3 nm** clusters could be detected from nanodiffraction experiments.



As the nanoparticle melts, **Bragg peaks fade** away and **diffuse scattering features emerge**



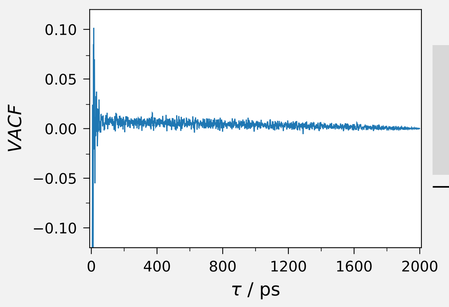
3. Future work



Velocities Autocorrelation Function (VACF):

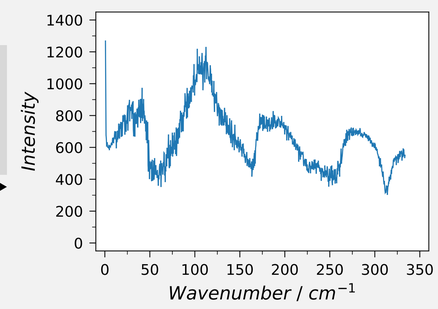
$$C(\tau) = \frac{\sum_{\tau=1}^{\tau_{max}} \frac{1}{NFRAMES-\tau} \cdot \left[\frac{1}{N_{mol}} \sum_{i=1}^{N_{mol}} \boldsymbol{v}_i(t_0) \cdot \boldsymbol{v}_i(t) \right]}{C(0)}$$

Investigating **collective modes through Fourier analysis** would shed light on complex processes like dissolution.



Fourier Transform (FT):

$$\widetilde{C(\tau)} = \sum_{n=0}^{N-1} C(\tau) \cdot e^{-2\pi i \frac{kn}{N}}$$



Conclusions

In this work, we performed classical MD simulations of a benzoic acid (BZA) nanoparticle to identify (partially) crystalline, persistent supramolecular aggregates. We developed a **cheap crystallinity criterion** and **found various stationary regimes**. Found clusters may produce **neatly recognizable Bragg reflections**, which remain detectable even for **supramolecular aggregates down to ~3 nm large**. Experiments aiming at detecting such elusive structures could be possible in practice but need to be accurately designed. **[6]**

References

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