



On the influence of water on THz vibrational spectral features of molecular crystals

Sergey Mitryukovskiy, Danny Vanpoucke, Theo Hannotte, Melanie Lavancier, D. Hourlier-Bahloul, Goedeke Roos, Romain Peretti

► To cite this version:

Sergey Mitryukovskiy, Danny Vanpoucke, Theo Hannotte, Melanie Lavancier, D. Hourlier-Bahloul, et al.. On the influence of water on THz vibrational spectral features of molecular crystals. 2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz), Aug 2022, Delft, Netherlands. 10.1109/IRMMW-THz50927.2022.9896035 . hal-03835255

HAL Id: hal-03835255

<https://hal.science/hal-03835255>

Submitted on 15 May 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

On the influence of water on THz vibrational spectral features of molecular crystals

Sergey Mitryukovskiy,¹ Danny E. P. Vanpoucke,² Théo Hannotte,¹ Mélanie Lavancier,¹ Djamila Hourlier,¹ Goedeke Roos³ and Romain Peretti^{1*}

¹Institut d'Electronique de Microélectronique et de Nanotechnologie, Université Lille, CNRS, 59652 Villeneuve d'Ascq, France. E-mail: romain.peretti@univ-lille.fr

²IMO, Hasselt University, 3590 Diepenbeek, Belgium.

³ Univ. Lille, CNRS, UMR 8576 - UGSF - Unité de Glycobiologie Structurale et Fonctionnelle, F-59000 Lille, France

Abstract—The collective vibrations in molecular crystals can be probed using terahertz spectroscopy, providing unique characteristic spectral fingerprints. However, the association of the spectral features to the crystal conformation, crystal phase and its environment is a difficult task. We present a combined computational-experimental study on the incorporation of water in lactose molecular crystals, and show how simulations can be used to associate spectral features in the THz region to crystal conformations and phases. Furthermore, we also show that water does not play only a perturbative role but fully participates in the emergence of the THz vibrations

I. INTRODUCTION

The nanoscale structure of molecular assemblies plays a major role in many (μ)-biological mechanisms. Molecular crystals are one of the most simple of these assemblies and are widely used in a variety of applications ranging from pharmaceuticals and agrochemicals, to nutraceuticals and cosmetics. Water molecules play an essential role in their structural and functional properties.

THz spectra include information of both water of crystallization and the host crystal structure making THz-TDS very sensitive to dehydration. During dehydration, THz spectroscopy will precisely monitor both the loss of water of crystallization and the eventual molecular rearrangement. This could then be further extended to study systems where multiple solid-state forms appear as a result of dehydration.

The purpose of this communication is to go a step further in understanding the role of water in molecular crystals; we present a detailed study of the THz spectrum of one of the most used and thought-to-be-simple materials by the THz community, namely alpha-lactose monohydrate because it is the golden standard in the community [5, 2].

II. RESULTS

To deepen our understanding of the role of water and to validate the simulation results, an experimental setup was developed. It allows the heating and temperature control of the samples, and thus provides the possibility for the dehydration. In our experiments, our samples go through two phase-transitions. We observed the spectral signatures of three different “metastable” crystal phases (stable in N₂ atmosphere, namely, the α -lactose monohydrate (α -LM or phase 1), and two other phases, hereafter called phase 2 and 3) in agreement with the predictions by calculations and mass-spectroscopy tests. We analysed our spectrum by fitting our time traces thanks to a software fit@tds and a method explained elsewhere [7, 6, 8]. The spectra are shown in fig 1.

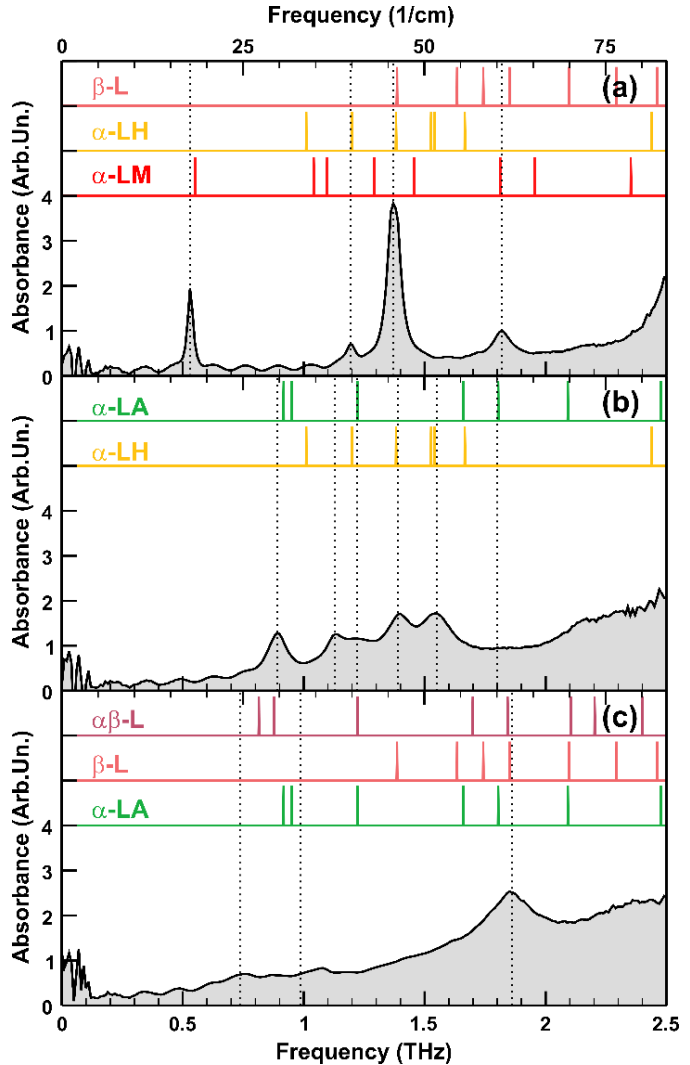


Figure 1: Comparison of calculated low THz vibrational modes at the Γ -point (colour vertical lines) to spectra of the three experimentally obtained morphologies (black curves), (a)-(c) – phases 1-3, correspondingly. The vertical dotted lines indicate the position of the experimentally fitted modes.

For a better interpretation of these spectra we performed DFT calculations. The gas phase single molecule approach for spectral modelling is insufficient for the THz range, as this concerns long ranged vibrational modes. We consequently pursued periodic boundaries DFT calculations. The frequency of the modes found in these calculations are given in fig 1 without further scaling.

Here, one can see that the phase identification is far from obvious and that the simple: $X \rightarrow Y \rightarrow Z$ phase transformation picture, is hard to maintain. It appears the seemingly distinct phases and transformations in reality involve mixtures and/or additional intermediate phases. For example, the alpha-lactose monohydrate sample – widely used in the community for test purposes – cannot be explained by only one single crystal phase.

Secondly, our spectra show drastic changes with decreasing water content. From experimental work [3], these spectral changes could be attributed to the appearance/disappearance of the absorption peaks upon hydration. Thanks to the DFT calculations, we show that although the water molecules have a larger freedom of motion than the carbohydrates, one cannot separate the vibrations of the carbohydrate lattice from the vibrations of the water molecules. Consequently, these water molecules and associated hydrogen bonds do not only play a perturbative role, but also participate in the formation of the vibration. More importantly, the water molecules' impact is not related to their donor-acceptor role, instead their presence loosens the hydrogen bridges between the lactose molecules allowing long ranged collective modes to emerge. They can be seen as having a lubricating role, allowing the motion of several rigid pieces together.

CONCLUSION

In this work [4], we provide a first step by proposing a credible explanation for the well-known lactose spectrum. Using periodic DFT simulations of lactose molecular crystals, the role of water in the observed lactose THz spectrum is clarified, presenting both direct and indirect contributions. By integrating our results, we come to the clear conclusion that the alpha-lactose monohydrate system is more complex than generally thought.

In addition, this work aims to further stress the importance of good and accurate periodic DFT calculations. In contrast to the mid infrared spectroscopic range where the vibrations are localized around one or several molecular bonds, in the THz range, the vibrational modes are delocalized among several molecules. They form what one can call “phonons of the molecular crystal”, making the use of periodic calculations inevitable, as was also pointed out by Banks *et al.* [1]. The clear corollary of this conclusion is that different crystal structures will give rise to different THz spectra. One can exploit this property experimentally and use THz spectroscopy to probe and discriminate the crystalline structure of a molecular crystal sample.

Even though THz spectroscopy exists already more than two decades, we believe that we are still experiencing its infancy. Further work and combination with other experimental and theoretical techniques will be needed to bring it to its full potential and to allow for its straightforward application on more complex structures such as protein crystals or even

protein structures like amyloids or viral capsids.

REFERENCES

- [1] Peter A. Banks, Luke Burgess, and Michael T. Ruggiero. The necessity of periodic boundary conditions for the accurate calculation of crystalline terahertz spectra. *Phys. Chem. Chem. Phys.*, 23(36):20038–20051, 2021.
- [2] ER Brown, W Zhang, LK Viveros, EA Mendoza, Y Kuznetsova, SRJ Brueck, KP Burris, RJ Millwood, and CN Stewart. High-resolution thz spectroscopy of biomolecules and bioparticles: Concentration methods. In *Terahertz and Mid Infrared Radiation: Detection of Explosives and CBRN (Using Terahertz)*, pages 7–18. Springer, 2014.
- [3] Y Listiohadi, JA Hourigan, RW Sleight, and RJ Steele. Moisture sorption, compressibility and caking of lactose polymorphs. *International journal of pharmaceuticals*, 359(1-2):123–134, 2008.
- [4] Sergey Mitryukovskiy, Danny E. P. Vanpoucke, Yue Bai, Théo Hannotte, Mélanie Lavancier, Djamila Hourlier, Goedeke Roos, and Romain Peretti. On the influence of water on thz vibrational spectral features of molecular crystals. *Phys. Chem. Chem. Phys.*, 24(10):–, 2022.
- [5] Kai-Erik Peiponen, Axel Zeitler, and Makoto Kuwata-Gonokami. *Terahertz spectroscopy and imaging*, volume 171. Springer, 2012.
- [6] R. Peretti, S. Mitryukovskiy, F. Kevin, and J. Lampin. Retrieving material and metamaterial parameters directly from time-domain spectroscopy time trace. In *2018 43rd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, pages 1–2, Sept 2018.
- [7] Romain Peretti, Martin Micica, Sergey Mitryukovskiy, Kevin Froberger, Sophie Eliet, Mathias Vanwolleghem, and Jean-François Lampin. Modeling and parameter retrieving in time domain spectroscopy of material and metamaterial. In *Nonlinear Optics and its Applications 2018*, volume 10684, page 106840P. International Society for Optics and Photonics, 2018.
- [8] Romain Peretti, Sergey Mitryukovskiy, Kevin Froberger, Anis Mebarki, Sophie Eliet, Mathias Vanwolleghem, and Jean-François Lampin. Thz-tds time-trace analysis for the extraction of material and metamaterial parameters. *IEEE Transactions on Terahertz Science and Technology*, 9(2):136–149, March 2019.