In situ Solid-State Reactions Monitored by X-ray Absorption Spectroscopy: Temperature-Induced Proton Transfer Leads to Chemical Shifts

DOI:
[10.1002/chem.201603822](https://doi.org/10.1002/chem.201603822)

Document Version
Accepted author manuscript

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Stevens, J., Walczak, M., Jaye, C., & Fischer, D. A. (2016). In situ Solid-State Reactions Monitored by X-ray Absorption Spectroscopy: Temperature-Induced Proton Transfer Leads to Chemical Shifts. *Chemistry: A European Journal*, 22(44), 15600-15604. <https://doi.org/10.1002/chem.201603822>

Published in:
Chemistry: A European Journal

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.

In situ Solid-State Reactions Monitored by X-ray Absorption Spectroscopy: Temperature-Induced Proton Transfer Leads to Chemical Shifts

Joanna S. Stevens,^[a] Monika Walczak,^[b] Cherno Jaye,^[c] and Daniel A. Fischer^[c]

Abstract: The dramatic colour and phase alteration with the solid-state, temperature-dependent reaction between squaric acid and 4,4′-bipyridine has been probed *in situ* with X-ray absorption spectroscopy. The electronic and chemical sensitivity to the local atomic environment through chemical shifts in the near-edge X-ray absorption fine structure (NEXAFS) reveals proton transfer from the acid to the bipyridine base through the change in nitrogen protonation state in the high-temperature form. Direct detection of proton transfer coupled with structural analysis elucidates the nature of the solid-state process, with intermolecular proton transfer occurring along an acid-base chain followed by a domino effect to the subsequent acid-base chains leading to the rapid migration along the length of the crystal. NEXAFS thereby conveys the ability to monitor the nature of solid-state chemical reactions *in situ*, without the need for *a priori* information or long-range order.

Proton transfer plays an important role in many chemical and biological processes, and has the ability to profoundly impact electronic structure and functional properties of materials. The potential to tune chemical and physical properties of organic materials through varying the degree of proton transfer and molecular interactions has consequently led to advances in crystal engineering for pharmaceuticals,^[1, 2] energetic materials,^[3] organic ferroelectrics,^[4] molecular switches^[5] and optical materials.^[6, 7] Solid-state reactions initiated by external factors such as temperature, light or pressure (chromisms) are also often attributed to intra- or intermolecular proton migration in molecular chemistry.^[8–11]

Detection of whether proton transfer has occurred in solid-state products, and therefore study and elucidation of proton transfer processes, is not trivial as it typically involves the position of a single hydrogen atom. This is compounded in the case of temperature-dependent transitions where collection of data from diffraction techniques becomes increasingly complicated (e.g. difficulties of accurately locating hydrogen with X-ray diffraction, minimum crystal size for single crystal neutron diffraction and potential decomposition or loss of crystallinity) or impossible for solutions with the loss of long-range order (e.g. alteration of tautomer populations).

A pertinent example of dramatic changes through a solid-

state reaction ascribed to proton transfer is the temperature-induced transition observed for the complex of 4,4′-bipyridine (4BPY) and squaric acid (SQU).^[12] Aqueous crystallisation of 4BPY and SQU forms a yellow salt [4BPYH]⁺[SQU][−], along with an additional orange salt (minor product), with the yellow form undergoing an unusual reversible, solid-state colour and phase change at high-temperatures (Scheme 1). An increase in the transition temperature with deuteration suggested proton transfer as a potential explanation, although single crystal X-ray diffraction was unable to determine the proton positions due to the high-temperature involved and single crystal neutron diffraction precluded by the inability to obtain crystals of sufficient size.^[13] Refinement of the powder neutron diffraction pattern of the high-temperature form correlated with a model in which transfer of the remaining squarate hydrogen to 4,4′-bipyridinium occurs, forming a di-salt as the high-temperature red form II [4BPYH₂]²⁺[SQU]^{2−}, although there is no direct evidence for the change in proton location.

X-ray absorption spectroscopy is a powerful technique to study local electronic structure,^[14] and does not require any long-range order (crystallinity is not a requirement such that amorphous materials and solutions can be studied^[15]). By combining atomic and chemical sensitivity through *in situ* measurements of the near edge region (near-edge X-ray absorption fine structure, NEXAFS), this offers an approach for monitoring and understanding of solid phase organic reactions. The alteration in protonation state with the temperature-induced solid-state reaction of 4BPY/SQU is successfully traced here,^[16] enabling unambiguous determination of whether proton transfer occurs. Correlation with visual observations of the phase transition and structural intermolecular bonding allows insight into the nature of the process occurring in the solid-state reaction.

Scheme 1. Yellow (I) and orange (III) salts of 4BPY/SQU from crystallisation, and reversible solid-state reaction to the red di-salt (II) with proton transfer.

[a] Dr. J. S. Stevens
School of Chemical Engineering & Analytical Science
The University of Manchester
Oxford Road, Manchester, M13 9PL, UK
E-mail: joanna.stevens@manchester.ac.uk

[b] Dr. M. Walczak
School of Materials
The University of Manchester
Oxford Road, Manchester, M13 9PL, UK

[c] Dr. C. Jaye, Dr. D. A. Fischer
Material Measurement Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland 20899, USA

Figure 1. Solid-state transformation of the yellow form I salt with heating above 185°C, showing the sequential alteration in colour and structural parameters with the transition to the high-temperature red form II. A video of the transition is available (Supporting Information).

Heating the yellow form I salt^[12, 13] produced by aqueous crystallisation of 4BPY with SQU, [4BPYH]⁺[SQU][−], above 185°C leads to a dramatic colour change to the high-temperature, dark red form II (Figure 1; video available as Supporting Information). The colour transition typically originates at one end of the crystal and progresses rapidly towards the other end (<1 s). Where a substantial structural defect occurs across the crystal, the transformation can begin there, travelling away from it along the length of the crystal (Figure 1). This thermochromism is accompanied by alteration in structural parameters – the crystal lengthens and becomes narrower (by over 15% in both dimensions) – indicating a phase change in addition to colour. The crystal thus appears to bend as the reaction occurs (Figure 1). With cooling below 160°C, the crystals transform back to yellow, although the timescale of this is somewhat slower and dependent on the cooling rate.

While refinement of the neutron diffraction powder pattern after the transition^[13] correlated with a model in which proton transfer is involved (remaining squarate hydrogen to 4,4q bipyridinium) and shows the value of such studies for organic molecular materials, it required foreknowledge of geometrical and thermal parameters from multiple temperature-dependent previous single crystal XRD structures, is particularly time-intensive and is not a direct method.^[13] In order to directly reveal the alteration in protonation states with the thermochromism and thereby probe the solid-state reaction *in situ*, near-edge X-ray absorption fine structure (NEXAFS) spectroscopy is utilized here.

The π^* region of NEXAFS (involving transitions from the core atomic level to the π lowest unoccupied molecular orbitals) is highly sensitive to the local chemical environment of an atom, in particular the chemical state, and has recently been demonstrated to distinguish between hydrogen bonding and proton transfer in pharmaceutical co-crystals and salts.^[16] It is therefore ideally placed to identify the

protonation states in the yellow and red forms of 4BPY-SQU, and only requires ~10 minutes for acquisition of a spectrum. The nitrogen K-edge NEXAFS of the yellow form I at ambient temperature clearly shows two primary peaks at 397.7 and 399.2 eV (Figure 2), representing promotion of an N 1s electron to the first π^* unoccupied molecular orbital. This is followed by the low intensity, secondary π^* resonances from transitions to higher-energy unoccupied π^* orbitals, as well as broader σ^* resonances that are more susceptible to variations in geometric structure^[15, 16] once sufficient energy is absorbed to overcome the ionization potential >405 eV, represented by the step up in intensity (a detailed fit of the data is provided in the Supporting Information).

The lowest energy π^* resonance at 397.7 eV arises from the non-protonated pyridine C=N nitrogen environment (C=N 1s $\rightarrow \pi^*$ transition).^[16] In contrast, that at 399.2 eV is shifted to higher energy with the decrease in electron density at nitrogen arising from the positively charged protonated C=NH⁺ nitrogen (C=NH⁺ 1s $\rightarrow \pi^*$).^[16] The areas under the peaks for C=N and C=NH⁺ provide the ratio of transitions from each species, and are comparable since peak width naturally increases with energy (as it is inversely proportional to the lifetime of the transition).^[14] The chemical shifts and 1:1 area ratio for C=N:C=NH⁺ thus successfully identify the yellow form I as the [4BPYH]⁺[SQU][−] salt.

Figure 2. Nitrogen K-edge NEXAFS of the yellow form I salt [4BPYH]⁺[SQU][−] (top) and proton transfer with *in situ* heating to produce the red form II di-salt [4BPYH]₂²⁺[SQU]₂^{2−} over 185°C (bottom), showing the fitted peak areas for the π^* peaks of interest. A fit of the whole spectra is available in the Supporting Information.

In situ heating of the yellow form I was then performed to trace the transition to the red form II over 185°C. Comparison of the nitrogen spectra reveals the complete loss of the peak originating from non-protonated C=N nitrogen at high-temperature, accompanied by a two-fold increase in area for the signal from protonated nitrogen C=NH⁺ (Figure 2). This shows that both of the 4BPY nitrogen atoms are now protonated, revealing that intermolecular proton transfer has occurred with transfer of the remaining squarate hydrogen atom to the pyridine nitrogen to produce the di-salt

$[4\text{BPYH}_2]^{2+}[\text{SQU}]^2$ as the high-temperature red form. The solid-state reaction is thus unambiguously assigned as arising from acid-base proton transfer.

For the specific case investigated here, examination of the structural patterns within the starting form I crystal structure (from XRD)^[12, 13] shows offset chains of SQU-4BPY (Figure 3). Orientation of the crystal faces revealed the longest edge (length) as the shortest cell axis (*a* axis), shortest edge (depth) as the longest *c* axis and width as the *b* axis.^[12] The SQU-BPY chains are not therefore orientated along the length of the crystal (*a* axis, as represented visually in Figure 3) as might be expected with the observed progression of the colour change as the reaction progresses (Figure 1). Rather, the SQU-BPY chains are located in angled planes through the crystal aligned along the *b* axis (width), with alternating chains pointing in opposite directions (Figure 3). As NEXAFS identified proton transfer as the mechanism behind the solid-state reaction, on initiation of the transition with temperature, migration of the proton thus appears to occur across the intermolecular OHN hydrogen bonds along the first SQU-BPY chain (accompanied by the aforementioned slight structural alterations). This then leads to sequential proton transfer back along the second SQU-BPY chain, and so on, leading to the colour change progressing evenly until the end of the length of the crystal is reached.

Figure 3. (Top) Alternating 4BPY-SQU chains of form I^[13] viewed along the *a* axis and (bottom) BFDH morphology of form I showing orientation of the SQU-BPY chains through the crystal and direction of the proton transfer process.

When the unambiguous detection of proton transfer with NEXAFS is combined with the pattern of intermolecular hydrogen bonding of SQU and BPY occurring in the crystal structure and the movement of the phase change along the crystal, this provides a cohesive picture of the proton transfer process. Cooperative intermolecular proton transfer (molecular displacement/proton hopping) occurs across the OHN hydrogen bonds within the SQU-BPY chain, followed by a rapid, domino-like effect to the subsequent chains.

This study represents the first direct spectroscopic evidence that the dramatic alteration in properties with the solid-state transition to the high-temperature red form of SQU and 4BPY involves proton transfer. The high sensitivity of NEXAFS to local atomic environment clearly distinguishes protonated from unprotonated nitrogen through the increased chemical shift *in situ*, and coupled with optical and structural analysis of the thermochromic phase transformation reveals the nature of the proton transfer process. The simplicity of NEXAFS interpretation without the need for *a priori* information or long-range order shows the ability to for identify and elucidate proton transfer processes in solid-state reactions, and the chemical sensitivity suggests the potential to monitor chemistry reactions in general within organic chemistry schemes, even for amorphous and solution systems.

Experimental Section

Materials

4,4'-bipyridine and squaric acid (3,4-dihydroxy-3-cyclobutene-1,2-dione) were obtained with >99% purity (Sigma-Aldrich, UK). Yellow crystals of form I were formed by dissolving equimolar amounts of 4BPY and SQU in water and leaving to slowly evaporate over a few weeks. The high-temperature, red form II was obtained by heating the yellow form I above 185°C.

Near Edge X-ray Absorption Fine Structure (NEXAFS) Spectroscopy

NEXAFS measurements were performed at the U7a beamline of the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory, NY. Partial electron yield (PEY) spectra for the nitrogen K-edge were collected at the magic angle of 54.7°. *In situ* measurements were recorded as a function of temperature by heating from 25°C to above 200°C in order to trace the transition from the yellow form I to the red, high temperature form II.

Acknowledgements

JSS acknowledges the award of the current University Academic Research Fellowship by The University of Manchester, support from the EPSRC through the Critical Mass Grant EP/I013563/1, and thanks to Sharlinda Binti Sachithanathan for her assistance with the camera optical microscopy setup. Use of the National Synchrotron Light Source, Brookhaven National Laboratory, was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886. Certain commercial names are presented in this manuscript for illustration purposes and do not constitute an endorsement by the National Institute of Standards and Technology.

Keywords: organic solid-state reactions ~ protonation ~ X-ray absorption spectroscopy ~ reaction monitoring ~ acid-base reactions

- [1] *Pharmaceutical Salts and Co-crystals*, 1st ed., The Royal Society of Chemistry, Cambridge, U.K., **2012**.
- [2] N. Schultheiss, A. Newman, *Crystal Growth & Design* **2009**, *95*, 499.
- [3] O. Bolton, A. J. Matzger, *Angewandte Chemie International Edition* **2011**, *50*, 8960.
- [4] S. Horiuchi, R. Kumai, Y. Tokura, *Chemical Communications* **2007**, 2321.
- [5] R. Klajn, *Chemical Society Reviews* **2014**, *43*, 148.
- [6] C. L. Jones, C. C. Wilson, L. H. Thomas, *CrystEngComm* **2014**, *16*, 5849.
- [7] D. Yan, D.-K. Bu, A. Delori, B. Patel, G. O. Lloyd, W. Jones, X. Duan, *Chemistry – A European Journal* **2013**, *19*, 8213.
- [8] M. D. Cohen, G. M. J. Schmidt, S. Flavian, *Journal of the Chemical Society (Resumed)* **1964**, 2041.
- [9] S. Takeda, H. Chihara, T. Inabe, T. Mitani, Y. Maruyama, *Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals* **1992**, *216*, 235.
- [10] M. Tanaka, H. Matsui, J.-i. Mizoguchi, S. Kashino, *Bulletin of the Chemical Society of Japan* **1994**, *67*, 1572.
- [11] K. Nakasuji, K. Sugiura, T. Kitagawa, J. Toyoda, H. Okamoto, K. Okaniwa, T. Mitani, H. Yamamoto, I. Murata, *Journal of the American Chemical Society* **1991**, *113*, 1862.
- [12] M. T. Reetz, S. Höger, K. Harms, *Angewandte Chemie International Edition* **1994**, *33*, 181.
- [13] D. M. S. Martins, D. S. Middlemiss, C. R. Pulham, C. C. Wilson, M. T. Weller, P. F. Henry, N. Shankland, K. Shankland, W. G. Marshall, R. M. Ibberson, K. Knight, S. Moggach, M. Brunelli, C. A. Morrison, *Journal of the American Chemical Society* **2009**, *131*, 3884.
- [14] J. Stöhr, *NEXAFS Spectroscopy*, 2nd ed., Springer-Verlag, Berlin, **1992**.
- [15] J. S. Stevens, A. Gainar, E. Suljoti, J. Xiao, R. Golnak, E. F. Aziz, S. L. M. Schroeder, *Chemistry – A European Journal* **2015**, *21*, 7256.
- [16] J. S. Stevens, L. K. Newton, C. Jaye, C. A. Muryn, D. A. Fischer, S. L. M. Schroeder, *Crystal Growth & Design* **2015**, *15*, 1776.

Entry for the Table of Contents

Layout 1:

COMMUNICATION

Domino effect: An *in situ* solid-state Brønsted acid-base reaction is revealed by chemical shifts in X-ray absorption spectroscopy (XAS). Heating of the squaric acid/4,4q bipyridine system reveals direct evidence of proton transfer with the transition and dramatic alteration in properties, showing XAS can be used to unambiguously identify proton transfer without the need for *a priori* information and monitor organic reactions *in situ*.

Joanna S. Stevens,* Monika Walczak,
Cherno Jaye, Daniel A. Fischer

Page No. – Page No.

**In situ Solid-State Reactions
Monitored by X-ray Absorption
Spectroscopy: Temperature-Induced
Proton Transfer Leads to Chemical
Shifts**