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Journal

Journal of the American Chemical Society, 146(41)

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Publication Date

2024-10-08

DOI

10.1021/jacs.4c09377

Peer reviewed

Cascade Photoreaction in Crystals: A Phase Change Caused by a Dewar Benzene Quantum Chain Triggers a Topochemical [2 + 2] Photodimerization

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Cite This: *J. Am. Chem. Soc.* 2024, 146, 27988–27992



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ABSTRACT: Crystals undergoing tandem reactions where the first transformation enables the second one are rare. Using photoreactive Dewar benzene 3,4,5,6-tetramethyl-1,2-dicarboxylic diacid (**DB**) as a hydrogen-bonding template for the $[2\pi+2\pi]$ photodimerization of *trans*-4,4'-bipyridyl-ethenes (**BPE**), we obtained crystals **DB**:**BPE**:**NT** with a **DB**:**BPE** = 2:1 stoichiometry with double bonds at a nonreactive distance of 5.957 Å. Exposure to UV light resulted in valence bond isomerization to Hückel benzene 3,4,5,6-tetramethyl-1,2-dicarboxylic acid (**HB**) by a quantum chain reaction that triggered the sought-after topochemical $[2\pi+2\pi]$ photodimerization reaction. Notably, crystals **HB**:**BPE**:**T** with the Hückel benzene isomer and **BPE** adopted a 2:2 stoichiometry and displayed an efficient topochemically templated photodimerization reaction.

The scope of photochemical reactions in crystals^{1–3} continues advancing rapidly. Examples include mechanistic,^{4–6} methodological,⁷ and synthetic applications,⁸ as well as the transduction of molecular-level structural changes into macroscopic mechanical action.⁹ While reactive intermediates provide reliable means to engineer unimolecular rearrangements,¹⁰ the use of supramolecular templates provides a robust strategy to engineer bimolecular reactions in crystals.¹¹ A relatively unexplored frontier entails the design of crystals with competing¹² and/or sequential cascade reactions^{13,14} where one reaction enables another.^{15,16} Herein we report a design intended to display two distinct and consecutive photoreactions using a reliable unimolecular rearrangement and MacGillivray's supramolecular templating strategy.^{7,11}

As shown in [Scheme 1](#), we selected a photoreactive 3,4,5,6-tetramethyl-Dewar benzene-1,2-dicarboxylic acid¹⁷ (**DB**, [Scheme 1b](#)) that transforms into 3,4,5,6-tetramethyl-Hückel benzene-1,2-dicarboxylic acid (**HB**),¹⁸ and *trans*-4,4'-bipyridyl-ethylene (**BPE**), which forms $[2\pi+2\pi]$ dimer **BPED** ([Scheme 1b](#)). As shown in [Scheme 1c](#), we envisioned hydrogen-bond complexes **DB**:**BPE**:**T** and **HB**:**BPE**:**T**, with the “T” encoding their ability to template the dimerization of **BPE** (blue ellipses) into the corresponding **BPED** dimers (green objects). We also expected the Dewar benzene (black ellipses) in **DB**:**BPE**:**T** and **DB**:**BPED**:**T** to undergo valence-bond isomerization to form Hückel benzene (red circles) complexes **HB**:**BPE**:**T** and **HB**:**BPED**:**T**. Given that Dewar benzenes undergo efficient quantum chain reactions giving multiple products per photon absorbed,^{19–21} we expected rapid isomerization of **DB** to be followed by a slower of **BPE** dimerization ([Scheme 1c](#), thick arrows). Quantum chains depend on adiabatic reactions, where the photoproduct is formed in the excited state (**DB*** → **HB***) and can transfer its excitation to a new reactant that continues the chain (**HB***+**DB** → **HB** + **DB***). Termination occurs

when either excited state decays. We have shown that quantum chains in crystals are facilitated by exciton delocalization in the energy transfer step.²²

While dual reactivity was observed, it took place by an unexpected cascade reaction.^{14,15} Crystals of **DB** and **BPE** formed the CHCl_3 -containing *nontemplating* (**NT**) 2:1 complex, **DB**:**BPE**:**NT**, which does not enable the desired topochemical dimerization ([Scheme 1d](#) and [Figure 1a](#)). However, photoisomerization of the Dewar benzene in **DB**:**BPE**:**NT** and loss of solvent (see below), led to a new *templating* phase **HB**:**BPE**:**T**(I) that enabled dimerization to final product **HB**:**BPED**:**T**(I). By contrast, crystallization of **HB** and **BPE** formed the 2:2 *templating* complex, **HB**:**BPE**:**T**, with photodimerization taking place in a single crystal-to-single crystal manner.

Samples of **DB** were prepared as reported previously,¹⁷ **HB** by photoisomerization of **DB**, and **BPE** was obtained from commercial sources. Crystalline complexes were grown by slow evaporation from a 1:3:3 mixture of MeOH, CHCl_3 and hexane. Single crystal X-ray analysis of crystals grown from **HB** and **BPE** confirmed the templating 2:2 stoichiometry with the double bonds at a distance of 3.717 Å in **HB**:**BPE**:**T** ([Figure 1b](#), [Scheme 1c](#)). By contrast, **DB** and **BPE** assembled into the *nontemplating* complex **DB**:**BPE**:**NT** with a 2:1 stoichiometry with one CHCl_3 molecule per asymmetric unit, and double bonds at a distance of 5.957 Å, which is well beyond the

Received: July 10, 2024

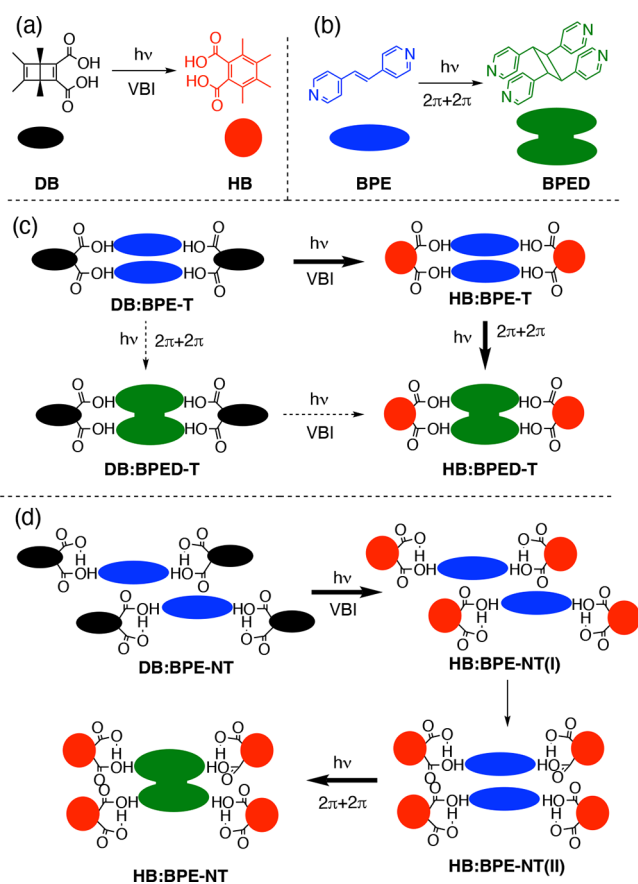
Revised: September 30, 2024

Accepted: October 1, 2024

Published: October 8, 2024



Scheme 1



topochemically allowed limit of ca. 4.2 Å (Figure 1a, Scheme 1d).

Differences in complexation between DB and HB (Figure 1a/b) can be traced to their hydrogen bonding characteristics in relation to those of phthalic acid in Figure 1c. The latter is distinguished by a strong intramolecular H-bond that increases its acidity to $pK_a = 2.92$,^{23a} a value that is lower than that of protonated pyridinium ($pK_a = 5.20$)^{23b} that results in proton transfer. With only one acidic site available for complexation, phthalic acid is unable to template two BPEs and forms a 2:1 complex. In contrast, the methyl groups at positions 3 and 5 in HB disfavor the intramolecular H-bond and make the two carboxylic acids available for neutral $C(O)O-H\cdots N$ H-bonds that help form the templating 2:2 complex (Figure 1b). The bent structure of DB mitigates the steric repulsion between methyl and carboxyl acids, such that they can engage in intramolecular H-bond and proton transfer ($ArC(O)O-H\cdots O = C(Ar)O^+H-N$) and, like phthalic acid, form nontemplating 2:1 complexes with BPE (Figures 1a/c).²⁴ Importantly, a pyridinium nitrogen was confirmed in DB:BPE-NT by a characteristic ^{15}N CP/MAS NMR shift of 212 ppm (Figure S18).²⁵

Photochemical experiments were carried out with dry powders between glass slides and as hexane suspensions of submicron sized crystals using a medium pressure Hg lamp with a $\lambda > 340$ nm filter. Suspensions were obtained by grinding single crystals and suspending them in hexane, knowing that crystals with sizes approaching the excitation wavelength (ca. 200–500 nm) are exposed to light more homogeneously and react more efficiently.²⁶ Irradiation of HB:BPE-T for 24 h

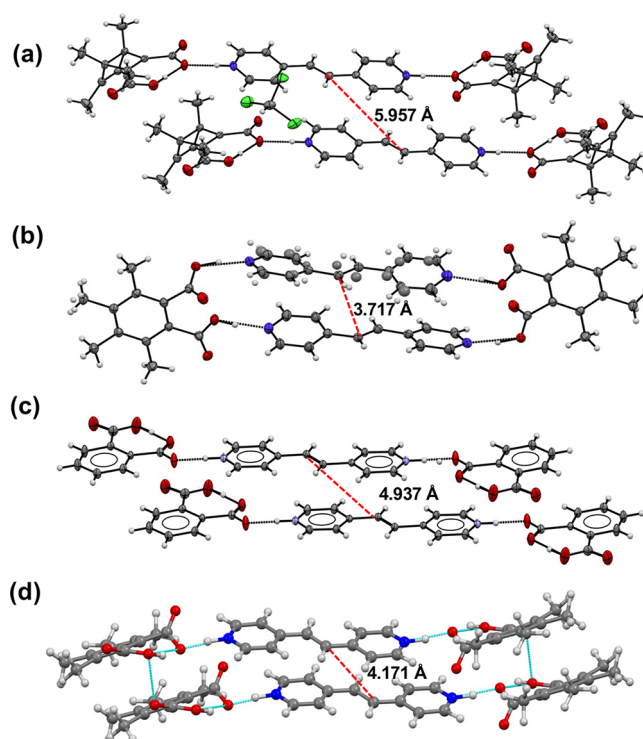


Figure 1. X-ray structures with distance between the BPE double bonds of (a) the DB:BPE-NT 2:1 complex with $CHCl_3$. (b) HB:BPE-T 2:2 complex. (c) Reported 2:1 Complex of phthalic acid and BPE.²⁴ (d) Calculated structure of intermediate phase of HB:BPE-T(I) that allows for a topochemical reaction.

proceeded to 94% in a clean solid-to-solid reaction (SI, Figure S12).^{27,28} PXRD analysis showed a decrease in the peaks assigned to the reactant (Figure 2, black stars) with the

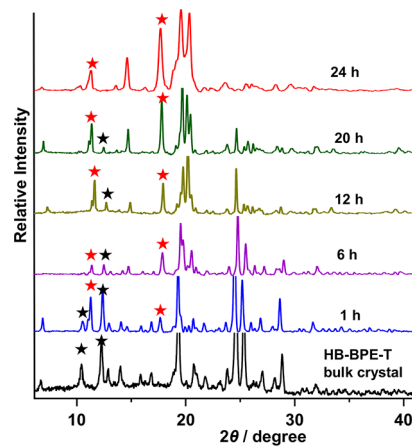


Figure 2. Photoreaction of a microcrystalline suspension of HB:BPE-T monitored by PXRD with selected peaks of the reactant (black asterisks) and product phase (red asterisks) indicated.

concomitant growth of peaks assigned to the product (HB:BPED-T, red stars). Notably, this transformation is a single crystal-to-single crystal reaction (page S31 and Figure S40). The time evolution of a microcrystalline suspension of DB:BPE-NT exposed to UV light was significantly more complex as shown by 1H NMR, solid state ^{13}C CP/MAS NMR (SI, Figure S15), and PXRD.

As shown in Figure 3, while isomerization of Dewar benzene reaches ca. 60% in 15 min, the [2 + 2] photoisomerization

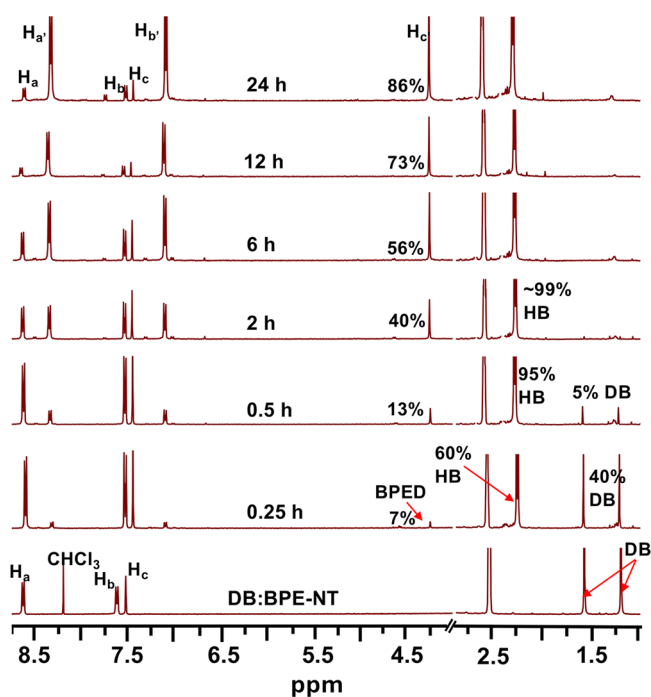


Figure 3. ^1H NMR analysis (400 MHz, 298 K, $\text{DMSO}-d_6$) of the solid-state double photoreaction of complex DB:BPE-NT showing the formation of both HB and BPED.

proceeded to ca. 7%. A decrease in the methyl signals of DB at $\delta = 1.19$ and 1.54 is accompanied by an increase of HB at $\delta = 2.20$ and 2.21 . While isomerization was nearly complete (ca. 95%) after another 15 min, dimerization only advanced to 13%. The growth and accumulation of the BPED product was determined by integration of the cyclobutane hydrogens at $\delta = 4.67$. After 24 h, the dimerization improved to ca. 86% yield.

There was a striking difference between reactions carried out with dry and suspended solids (SI, Figure S14). Red circles and black squares in Figure 4 show the rapid formation of HB

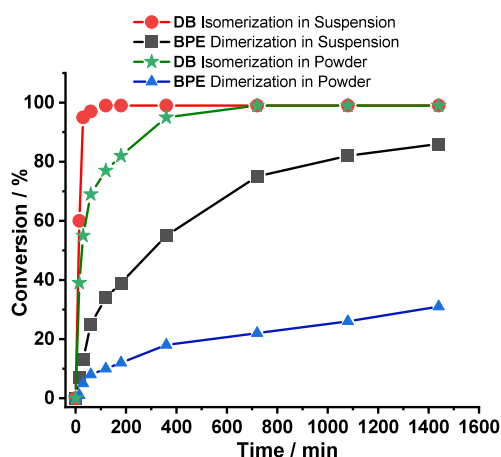


Figure 4. Reaction of DB to HB and dimerization of BPE to BPED in nanocrystalline suspension are colored red and green, respectively. Results from analogous experiments carried out with dry solids are shown in black for HB and blue for BPED.

and BPED with suspended solids. Sluggish reactions in dry powders are shown as green stars and blue triangles. Importantly, the loss of CHCl_3 from crystals of DB:BPE-NT results in a new phase where the efficient reactivity of DB remains, but the yield of BPED declines (SI, Figure S11). This provides a plausible explanation for the low dimerization efficiency with dry DB:BPE-NT (Figure 4, blue triangles). Regardless, these results suggest that fast isomerization of DB leads to structural changes that make an otherwise unfavorable dimerization reaction possible. Knowing that optically dense nanocrystalline suspensions make it possible to measure the quantum yield of solid-state reactions using calibrated chemical actinometers,^{24,29} we determined the quantum yield of DB isomerization to be $\Phi = 22$, in agreement with previous observations for nonsensitized reactants.¹⁹ By contrast, the quantum yield for the photodimerization of BPE was estimated to be $\Phi = 0.42$ (SI, page S26).

Evidence for product-induced phase changes in Scheme 1d was obtained by solid-state ^{13}C CP/MAS NMR and PXRD. The ^{13}C CP/MAS NMR spectra of DB, BPE and DB:BPE-NT (Figure 5) confirmed that the spectrum of the complex is

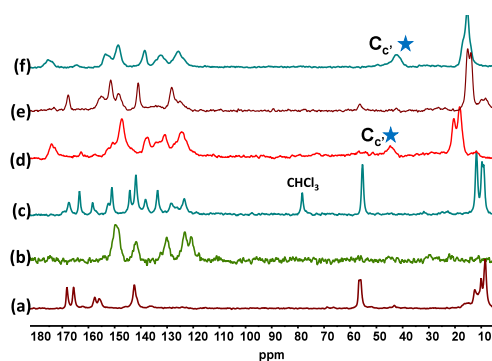


Figure 5. Solid state ^{13}C CP/MAS NMR spectra (150 MHz, 298 K) of (a) DB, (b) BPE, (c) DB:BPE-NT (2:1), (d) DB:BPED-T(I) (2:1) after 24 h irradiation, (e) HB:BPE-T (2:2), and (f) HB:BPED-T after 24 h irradiation.

different from the ones of the components. Carbonyl signals at $\delta = 163$ and 167 reflect the intramolecular hydrogen bond present in both DB diacid (Figure 5a) and DB:BPE-NT complex (Figure 5c). Broad aromatic signals in the spectrum of BPE (Figure 5b) shift and sharpen in DB:BPE-NT, where a new signal at $\delta = 78.3$ ppm corresponds to the CHCl_3 in the lattice. Changes observed after the loss of CHCl_3 are shown in Figure S16. The Dewar benzene isomerization results in the disappearance of the quaternary carbon at 55.2 ppm and formation of the broad cyclobutane dimer signal at 42 ppm in HB:BPED-T(I) (Figure 5d) and HB:BPED-T (Figure 5e). Different product phases are obtained from two consecutive reactions in HB:BPED-T(I) (Figure 5d) or a single dimerization in HB:BPED-T (Figure 5f).

A detailed evolution of the PXRD from the crystal phases involved as a function of reaction shows that changes occurring within the first 15 min are relatively modest despite 60% isomerization of DB to HB (Figure 6). We propose that the first reaction occurs within the original, metastable phase of the reactant.²² The yield of HB jumps to 95% after another 30 min, and some of the most intense peaks of the original phase disappear. It is beyond this conversion that new peaks begin to grow, marking the evolution of the first reaction metastable

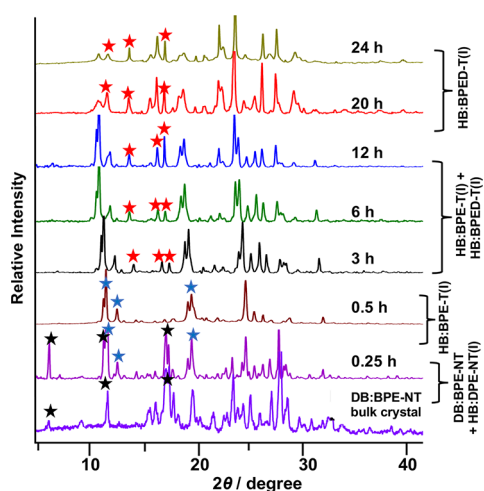


Figure 6. PXRD of photoreaction of DB:BPE-NT with $\lambda > 340$ nm illustrating the solid phases that occur and coexist as a function of reaction progress. Suggested phase identities (Scheme 1d) are on the right.

phase **HB:BPE-NT(I)** into the templating (T) topotactic phase of the first photoproduct, **HB:BPE-T(I)**. The new phase grows within ca. 12 h as the two consecutive reactions are completed and transforms into the final product phase **HB:BPED-T(I)**.

Key to this interpretation is that rearrangement from **HB:BPE-NT(I)** to **HB:BPE-T(I)** changes the distance of the double bonds from unreactive to reactive, while keeping a favorable parallel orientation. Support for this hypothesis was obtained by density functional theory (DFT) calculations using the CP2K v2023.1 software package with the PBEsol-D3 functional and the DZVP-MOLOPT-SR-GTH basis set to model phases **DB:BPE-NT**, **HB:BPE-NT(I)** and **HB:BPE-T(I)** using a periodic boundary condition. We started with the crystal structure coordinates of solvate **DB:BPE-NT** (CHCl_3), transformed Dewar into Hückel benzene, and optimized the structure to emulate solvated complex **HB:BPE-NT(I)** (CHCl_3). Next we removed the solvent and allowed the structure to relax in all three dimensions under no constraints to generate a model for **HB:BPE-T(I)**, where the double bonds are at a distance of 4.171 Å, as required for topochemical dimerization (Figure 1d). Experimental support was obtained from the good match observed between the PXRD simulated from calculated and experimental phases (Figures S30 and S31), which includes a sample of pure **HB:BPE-NT(I)** obtained by irradiation of **DB:BPE-NT** at 0 °C with no dimerization but CHCl_3 trapped in the metastable crystal, and a sample of pure **HB:BPE-T(I)** obtain by spontaneous loss of solvent at ambient temperature.

In conclusion, a design intended to form a dual-reactivity hydrogen-bonding complex between a Dewar benzene-1,2-dicarboxylic diacid and *trans*-4,4'-bipyridyl ethylene unexpectedly formed a 2:1 complex with the two double bonds at a distance well beyond the 4.2 Å limit required for topochemical control. However, a remarkably fast quantum chain reaction from Dewar to Hückel benzene resulted in a spontaneous phase change that brought the double bonds close together and enabled the $[2\pi+2\pi]$ photodimerization in a rare example of a solid-state cascade reaction.¹⁵ This work highlights the potential of extending the number of components and reactions under crystal control.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/jacs.4c09377>.

Experimental and computational details; characterization data; spectroscopic data (NMR, IR, UV–Visible); PXRD and SC-XRD refinement details; Cartesian coordinates (PDF)

Accession Codes

CCDC 2327769–2327770 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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<https://pubs.acs.org/doi/10.1021/jacs.4c09377>

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank the National Science Foundation for support through grants CHE-2154210(MAGG) and CHE040014 from the Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support (ACCESS) program (K.N.H. and J.-R.S.). We also thank NAWA Bekker Programme #BPN/BEK/2021/1/00116 (Poland) for support to K.A.K.

REFERENCES

- (1) Akhtaruzzaman; Khan, S.; Dutta, B.; Kannan, T. S.; Kole, G. K.; Hedayetullah Mir, M. H. Cocrystals for photochemical solid-state reactions: An account on crystal engineering perspective. *Coord. Chem. Rev.* **2023**, *483*, 215095.
- (2) Leyva, E.; de Loera, D.; Espinosa-González, C. G.; Noriega, S. Physicochemical Properties and Photochemical Reactions in Organic Crystals. *Current Org. Chem.* **2019**, *23*, 215–255.
- (3) Biradha, K.; Santra, R. Crystal engineering of topochemical solid state reactions. *Chem. Soc. Rev.* **2013**, *42*, 950–967.
- (4) Morimoto, K.; Kitagawa, D.; Bardeen, C. J.; Kobatake, S. Cooperative Photochemical Reaction Kinetics in Organic Molecular Crystals. *Chem.—Eur. J.* **2023**, *29*, No. e202203291.
- (5) Sankaranarayanan, J.; Bort, L. N.; Mandel, S. M.; Che, P.; Krause, J. A.; Elwood, E.; Brooks, E. E.; Tsang, P.; Gudmundsdottir, A. D. Orbital-Overlap Control in the Solid-State Reactivity of β -Azido-Propiophenones: Selective Formation of cis-Azo-Dimers. *Org. Lett.* **2008**, *10*, 937–940.
- (6) Kuzmanich, G.; Vogelsberg, C. S.; Maverick, E. F.; Netto-Ferreira, J. C.; Scaiano, J. C.; Garcia-Garibay, M. A. Reaction Mechanism in Crystalline Solids: Kinetics and Conformational Dynamics of the Norrish Type II Biradicals from a-Adamantyl p-Methoxyacetophenone. *J. Am. Chem. Soc.* **2012**, *134*, 1115–1123.
- (7) Friščić, T.; Elacqua, E.; Dutta, S.; Oburn, S. O.; MacGillivray, L. R. Total Syntheses Supramolecular Style: Solid-State Construction of [2.2] Cyclophanes with Modular Control of Stereochemistry. *Cryst. Growth Des.* **2020**, *20* (4), 2584–2589.
- (8) Dotson, J. J.; Liepuoniute, I.; Bachman, L. J.; Hipwell, V. M.; Khan, S. I.; Houk, K. N.; Garg, N. K.; Garcia-Garibay, M. A. Taming Radical Pairs in the Crystalline Solid State: Discovery and Total Synthesis of Psychotriadin. *J. Am. Chem. Soc.* **2021**, *143*, 4043–4054.
- (9) Naumov, P.; Chizhik, S.; Panda, M. K.; Nath, N. K.; Boldyreva, E. Mechanically Responsive Molecular Crystals. *Chem. Rev.* **2015**, *115*, 12440–12490.
- (10) Garcia-Garibay, M. A. Engineering Carbene Rearrangements in Crystals: From Molecular Information to Solid State Reactivity. *Acc. Chem. Res.* **2003**, *36*, 491–498.
- (11) MacGillivray, L. T.; Papaefstathiou, G. S.; Friščić, T.; Hamilton, T. D.; Bučar, D.-K.; Chu, Q.; Varshney, D. V.; Georgiev, I. G. Supramolecular control of reactivity in the solid state: from templates to ladderanes to metal–organic frameworks. *Acc. Chem. Res.* **2008**, *41*, 280–291.
- (12) Hipwell, V. M.; Garcia-Garibay, M. A. Mechanistic Studies of Adamantylacetophenones with Competing Reaction Pathways in Solution and in the Crystalline Solid State. *J. Org. Chem.* **2019**, *84*, 11103–11113.
- (13) The photodimerization of α -santonin was the first reaction in crystals ever documented. It required the ring contraction of two adjacent molecules, a Diels–Alder reaction an intramolecular $[2\pi+2\pi]$ cycloaddition. For a summary please see: Natarajan, A.; Tsai, C. K.; Khan, S. I.; McCarren, P.; Houk, K. N.; Garcia-Garibay, M. A. The Photoarrangement of α -Santonin is a Single-Crystal-to-Single-Crystal Reaction: A Long-Kept Secret in Solid State Organic Chemistry Revealed. *J. Am. Chem. Soc.* **2007**, *129*, 9846–9847.
- (14) Yelgaonkar, S. P.; MacGillivray, L. R. Supramolecular Catalysis via Organic Solids: Templates to Mechanochemistry to Cascades. In *Supramolecular Catalysis*; van Leeuwen, P. W. N. M., Raynal, M., Eds.; Wiley-VCH GmbH, 2022. DOI: 10.1002/9783527832033.ch27.
- (15) Li, C.; Campillo-Alvarado, G.; Swenson, D. C.; MacGillivray, L. R. Photoreactive salt cocrystal: $N^+ \cdots H \cdots N$ hydrogen bond and cation– π interactions support a cascade-like photodimerization of a 4-stilbazole. *CrystEngComm* **2021**, *23*, 1071–1074.
- (16) Raju, C.; Ramteke, G. R.; Jose, K. V. J.; Sureshan, K. M. Cascading Effect of Large Molecular Motion in Crystals: A Topotactic Polymorphic Transition Paves the Way to Topochemical Polymerization. *J. Am. Chem. Soc.* **2023**, *145*, 9607–9616.
- (17) Koster, J. B.; Timmermans, G. J.; Van Bekkum, H. Reaction of the Tetramethylcyclobutadiene-Aluminum Chloride Complex with Dienophilic Esters. *Synthesis* **1971**, *1971*, 139–140.
- (18) Ferrar, L.; Mis, M.; Dinnocenzo, J. P.; Farid, S.; Merkel, P. B.; Robello, D. R. Quantum amplified isomerization in polymers based on triplet chain reactions. *J. Org. Chem.* **2008**, *73*, 5683–5692.
- (19) Turro, N. J.; Ramamurthy, V.; Katz, T. J. Energy Storage and Release. Direct and sensitized photoreactions of Dewar benzene and prismane. *Nouv. Journal de Chimie* **1978**, *1*, 363–365.
- (20) Rivera, E.; Paul, I.; Fajardo, J., Jr; Garcia-Garibay, M. A. Quantum Chain Amplification in Nanocrystalline Dewar Benzenes by Intramolecular Sensitization. *Chem. Science* **2023**, *14*, 5802–5810.
- (21) Paul, I.; Konieczny, K. A.; Chavez, R.; Garcia-Garibay, M. A. Reaction amplification with a gain: Triplet exciton-mediated quantum chain using mixed crystals with a tailor-made triplet sensitizer. *Proc. Nat. Acad. Sci.* **2024**, *121*, No. e2401982121.
- (22) Kuzmanich, G.; Gard, M.-N.; Garcia-Garibay, M. A. Photonic Amplification by a Singlet State Quantum Chain Photocarbonylation Reaction in Crystalline Diarylcyclopropanones. *J. Am. Chem. Soc.* **2009**, *131*, 11606–11614.
- (23) (a) Bang, D.-Y.; Lee, I.-K.; Lee, B.-M. Toxicological characterization of phthalic acid. *Toxicol. Res.* **2011**, *27*, 191–203. (b) Krygowski, T. M.; Szatylowicz, H.; Zachara, J. E. How H-bonding modified molecular structure and p-electron delocalization in the ring of pyridine/pyridinium derivatives involved in H-bond complexation. *J. Org. Chem.* **2005**, *70*, 8859–8865.
- (24) Devogelaer, J.-J.; Brugman, S. T. J.; Meeke, H.; Tinnemans, P.; Vlieg, E.; de Gelder, R. Cocrystal design by network-based link prediction. *CrystEngComm* **2019**, *21*, 6875–6885.
- (25) Marek, R.; Lycka, A.; Kolehmainen, E.; Sievanen, E.; Tousek, J. ^{15}N NMR Spectroscopy in Structural Analysis: An Update (2001–2005). *Curr. Org. Chem.* **2007**, *11*, 1154–1205.
- (26) (a) Veerman, M.; Resendiz, M. J. E.; Garcia-Garibay, M. A. Large-Scale Photochemical Reactions of Nanocrystalline Suspensions: A Promising Green Chemistry Method. *Org. Lett.* **2006**, *8*, 2615–2617. (b) Chin, K. K.; Natarajan, A.; Gard, M. N.; Campos, L. M.; Shepherd, H.; Johansson, E.; Garcia-Garibay, M. A. Organic Molecular Nanocrystals: Triplet–Triplet Absorption, Phosphorescence, and Circular Dichroism of Chiral Crystals of Benzophenone. *Chem. Comm* **2007**, 4266–4268.
- (27) Choi, T.; Cizmeciyan, D.; Khan, S. I.; Garcia-Garibay, M. A. An Efficient Solid-to-Solid Reaction via a Steady-State Phase-Separation Mechanism. *J. Am. Chem. Soc.* **1995**, *117*, 12893–12894.
- (28) De Loera, D.; Stopin, A.; Garcia-Garibay, M. A. Photoinduced and Thermal Denitrogenation of Bulky Triazoline Crystals: Insights into Solid-to-Solid Transformation. *J. Am. Chem. Soc.* **2013**, *135* (17), 6626–6632.
- (29) Park, J. H.; Chung, T. S.; Hipwell, V. M.; Rivera, E.; Garcia-Garibay, M. A. Laser Flash Photolysis and Quantum Yield Studies of Radical Pairs in Nanocrystalline Suspensions of a-Phenyl-Substituted Ketones: Sorting Out the Contributions from Singlet and Triplet States. *J. Am. Chem. Soc.* **2018**, *140*, 8192–8197.