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Supramolecular Control of [2+2] Solid State Reactivity

by

Jennifer L. Reid, B.Sc.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Master of Science

Department of Chemistry

Carleton University

Ottawa, ON

August 2001

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acceptance of the thesis

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Chair, Department of Chemistry

Thesis Supervisor

CARLETON UNIVERSITY
2001

This thesis is dedicated to my sister Penny - thanks for all the help and support over the last seven years.

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Abstract

A supramolecular design strategy relying on non-covalent interactions to control [2+2] solid-state reactivity of olefins was followed. Specifically, resorcinol (**R**) and its derivatives were used as templates to steer pyridyl-substituted olefins into reactive alignment. In 20 of the 25 co-crystals involving four different 1,2-bis(*n*-pyridyl)ethylene (**DPE**) substrates and in all 13 (*E*)-1-(4-chlorophenyl)-2-(4-pyridyl)ethylene (**CSP**) and (*E*)-1-(4-bromophenyl)-2-(4-pyridyl)ethylene (**BSP**) co-crystals, similar discrete hydrogen-bonded assemblies were formed between the template and substrate. Structure determinations from single-crystal X-ray diffraction (XRD) were used extensively to determine olefin alignment.

UV irradiation of the co-crystals led to formation of cyclobutane products consistent with the olefin pre-organization in the reactant co-crystals. Solution ^1H NMR spectroscopy, single crystal XRD and ESI⁺-MS were used to determine the product identity, stereochemistry and yield. Room temperature single-crystal XRD identified disorder in co-crystals that reacted despite perpendicular alignment of the olefins.

The potentially single-crystal-to-single-crystal transformation of **44DPE** in the resorcinol (**R**) co-crystal was investigated using ^{13}C CPMAS NMR and powder XRD. ^{13}C CPMAS NMR and PXRD results obtained for irradiated (350 nm) **R·44DPE** co-crystals, suggested that the reaction occurred heterogeneously with disintegration of the crystal.

This supramolecular approach circumvents many of the pitfalls of previous attempts at engineering [2+2] photoreactivity and takes a step closer not only to establishing a potentially general method for aligning olefins in the solid-state, but also towards making the solid-state a viable alternate medium for conducting synthesis.

List of Abbreviations

Abbreviation	Description
44DPE	1,2-bis(4-pyridyl)ethylene
22DPE	1,2-bis(2-pyridyl)ethylene
24DPE	1-(2-pyridyl)-2-(4-pyridyl)ethylene
34DPE	1-(3-pyridyl)-2-(4-pyridyl)ethylene
DPE	dipyridylethylene
CSP	(<i>E</i>)-1-(4-chlorophenyl)-2-(4-pyridyl)ethylene
BSP	(<i>E</i>)-1-(4-bromophenyl)-2-(4-pyridyl)ethylene
XSP	styrylpyridine (either bromo or chloro)
CCB	<i>rcft</i> photoproduct of CSP
BCB	<i>rcft</i> photoproduct of BSP
MeNO₂	nitromethane
CH₂Cl₂	dichloromethane
CHCl₃	chloroform
ESI⁺-MS	electrospray ionization mass spectrometry (positive ion)
UV	ultraviolet
NMR	nuclear magnetic resonance
CPMAS	cross-polarization magic angle spinning
XRD	X-ray diffraction
PXRD	powder X-ray diffraction
T	template
R	resorcinol
MR	5-methoxylresorcinol
CR	4-chlororesorcinol
BR	4-bromoresorcinol
HR	4-hexylresorcinol
DCR	4,6-dichlororesorcinol
OR	5-methylresorcinol (orcinol)
ER	4-ethylresorcinol

A figure depicting the various **R**-based and olefin molecules referred in the above list of abbreviations and throughout this thesis is found in the supplemental section.

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Chapter I: Solid-State Olefin Alignment

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1.0 Introduction

Reaction media play a significant role in controlling the rate of the reaction, product distributions and stereo-chemistry within organic chemistry.¹ In this context, increased efforts have been directed at utilizing what is referred to as organized or constrained media to modify or regulate reactivity. As compared to an isotropic fluid medium where substrates collide in a random fashion, motional freedom is reduced in organized media, increasing both

the rate and selectivity of the reaction. Reminiscent of the action of enzymes, organized media in a lab setting used to this end include: micelles, micro-emulsions, liquid crystals, inclusion complexes, monolayers adsorbed on surfaces and solid phases such as crystals.²

Organic transformations in the solid-state have been known for more than a century³, and have been reported regularly over the last 50 years. Yet in spite of the fact that many organic compounds are crystalline solids under ambient conditions, the solid-state medium is far from a routine choice for carrying out reactions. Arguably, the most extensively investigated transformation within the field of organic solid-state chemistry is the [2+2] photochemical dimerization of olefins. Ultimately, it is the lack of understanding of the factors that direct crystal packing and topochemistry⁴ that prevent the planning and exploitation of organic transformations in the solid-state.

1.1 The Topochemical Principle

Olefins with pendant organic groups have long been recognized⁵ to undergo [2+2] photochemically-promoted dimerizations in the solid-state to form cyclobutane-based products, depending on the relative orientations of the olefins within the reactant crystal lattice. Pioneering studies involving *trans*-cinnamic acids and their derivatives by Schmidt and co-workers⁶ delineated the principles governing photochemically-promoted [2+2] dimerization of olefins in the solid-state. These criteria are referred to as the 'Topochemical Postulate' and correlate the alignment of molecules in the crystal with the stereochemistry of the product, a concept illustrated in Figure 1.1.⁷ Photoactivity correlates with a parallel orientation of neighbouring olefins that are separated by 3.5 to 4.2 Å, whereby the intrinsic

Figure 1.1 *trans*-Cinnamic acid crystallizes in three polymorphic forms, each displaying different solid-state photochemical behaviour. The distances represent the separation between equivalent olefins.⁶

reactivity of the reactants is of secondary importance or sometimes of no consequence at all.⁸

1.2 Benefits of Reaction in the Solid-State

Topochemically controlled organic photoreactions in the solid-state offer increased regio-, stereo-, and enantio-selectivity to desired products as a direct consequence of the strict spatial positioning imparted by the reactant crystal structure.⁹ In addition to providing a quantitative route to a single product rather than the product distributions seen in solution, the solid-state provides a solvent-free medium or ‘cleaner and greener’ organic chemistry. This is schematically illustrated in Figure 1.2.

Along these lines, solid-state [2+2] cycloaddition also offers atom economy.¹⁰ Atom economy refers to how much of the reactants are converted to products. Ideally, all atoms would be incorporated into the products, not only reducing the amount of waste generated but also making more efficient use of raw materials. Cycloaddition reactions such as the Diels-Alder reaction and [2+2] cycloaddition, both in solution and the solid-state, are highly atom efficient with all of the reactant atoms existing in the products.

1.3 Crystal Engineering

Although the requirements for solid-state [2+2] photodimerization are well identified, the design of molecules that will crystallize predictably to allow such reactions to occur has met with limited success. In general, a ‘hit or miss’ approach has largely been used. An approach that allows for some degree of control over the reactivity would, in principle, allow for an exploitation of the benefits associated with the solid-state as a medium for conducting organic transformations. Thus, within the last decade, there has been a surge in interest in

Figure 1.2 Schematic representation of the stereochemical control of photodimerizations in the solid state. Reaction of two *trans* olefins in the solid-state generates (a) the *cis* photo-product or, (b) the *trans* photo-product depending on the relative orientation of the olefins in the reactant lattice.

the field of crystal engineering, an area of supramolecular chemistry (*i.e.* chemistry beyond the molecule).¹¹

Crystal engineering deals with the ability to recognize, understand and exploit intermolecular forces (*e.g.* hydrogen-bonding, π - π stacking) for the rational design of solids, and is therefore of fundamental importance to promote or control solid-state reactivity. To reach the goal of rational design of crystals (*i.e.* prediction of crystal structures), it is now well recognized that it is necessary to have a complete understanding of those intermolecular interactions responsible for organizing molecules and ions in the solid-state.¹² Despite this realization, the successful prediction of crystal structure (*i.e.* space group symmetry) from molecular considerations has remained an elusive target. As a result, we are currently unable to predict whether a molecule, for example, will crystallize favourably for a [2+2] photodimerization to take place. From this observation it is clear that design and prediction of crystal structures *a priori* still remains a formidable challenge in materials science and technology.¹³

1.3.1 Polymorphism of *trans*-Cinnamic Acids

Further contributing to the inability to predict crystal structures is the issue of polymorphism, or the existence of multiple packing arrangements for a single species. In the case of *trans*-cinnamic acids, three polymorphs or packing arrangements have been identified, each showing different [2+2] photochemical behaviour. Identified as the α , β , and γ forms, the molecules of these acids form planar or near-planar hydrogen-bonded pairs across centres of symmetry. The pairs stack parallel to one another, differing in the angle that

the stack axis makes with the normal of the molecular plane, a fact that translates into different distances between equivalent points along the hydrogen-bonded dimers.¹⁴

Head-to-head alignment of the olefins was observed for the β structure with olefin-olefin separations on the order of 3.8 to 4.2 Å, resulting in head-to-head photodimers upon reaction. Similarly, the α structure is also photoactive but the offset or repeat distance (*i.e.* the distance between equivalent double bonds) is much greater than 5.5 Å. Photoactivity in the α structure is a result of the overlap between the olefin in one stack with the centrically related olefin in the next stack, a separation of only 4 Å that leads to the formation of head-to-tail photo-products. In the γ -structure the olefins are photo-inactive (*i.e.* there is no overlap between olefins), with separations of 4.8 to 5.2 Å (see Figure 1.3).

1.4 Single Component Approach

In general, researchers have largely relied upon trial and error for single component systems, with some progress being made towards designing molecules that are pre-organized to assemble in topochemical formation. In this approach, the parent molecule that fails to pack in an arrangement favourable for reaction is intramolecularly substituted with groups that are known to steer the packing such that a reactive alignment of the olefins results. Typical groups which have been incorporated onto the parent molecule framework include halogen atoms (*e.g.* chloro, bromo, fluoro), methylenedioxy, and methoxy groups.¹⁵

1.4.1 Single Component Approach: O-H...O Interactions

Since the reliability of most functional groups used to steer olefins into reactive alignment is doubtful, systems that make use of stronger intermolecular interactions are

Figure 1.3 Schematic representation of the different polymorphs of *trans*-cinnamic acid: (top) β -packing mode, (middle) γ -packing mode and, (bottom) α -packing mode. Blue boxes indicate reactive olefin pairs and d is the separation between equivalent olefins.⁶

desirable, and one such system has been reported.¹⁶ Exploiting hydrogen-bonds, non-covalent forces considerably stronger than halogen-halogen interactions, a 'U' shaped dicarboxylic acid derived from cinnamic acid was shown to self-assemble topochemically in the solid-state. Held together by four O-H...O hydrogen-bonds, the discrete dimers underwent quantitative conversion to the expected topochemical photo-product as illustrated in Figure 1.4.

The success of this method is a direct consequence of the 1,8-substitution pattern of the naphthalene unit which is pre-organized to orient the olefins. As with other intramolecular substitution methods, the steering group is covalently attached to the product and this may limit further derivatization of the product.

1.4.2 Single Component Approach: Halogen Atom Substitution

Monochloro, and especially dichloro, substitution of aromatics were recognized early on for their tendency to steer molecules in crystal lattices into the β -structure (*i.e.* with a short axis of 4 Å) by Cl...Cl interactions.¹² In contrast to the arrangement adopted by pure solid benzene, chloro substitution prevents the aromatics from 'dovetailing' into a herringbone motif, directing the packing arrangement so that the aromatic rings pack in a face-to-face stack.^{12c} This difference is illustrated in Figure 1.5.

Several investigations into the effectiveness of chlorine substitution to coax unreactive solids into the β -packing mode exist, with recent work on coumarins being of particular significance. *Syn* head-to-tail dimers of five different chloro-substituted coumarins were investigated in the solid-state and all were observed to undergo virtually quantitative,

Figure 1.4. Held together by four O-H $\cdots$ O hydrogen bonds, the ‘U-shaped’ di-acid based on cinnamic acid and the solid state photo-product resulting from its irradiation are depicted.¹⁶

Figure 1.5 (a) The face-to-face, π - π stacked alignment of *trans*-(2,4-dichloro)cinnamic acid and, (b) a schematic representation of the stacked vs. herringbone motifs of the above acid and benzene, respectively.¹²

clean photochemical conversion as a direct consequence of their β -packing motif. Previously, it had been observed that coumarins in the solid-state underwent non-topochemical photodimerization, yielding a distribution of products.¹⁷

Although successful, this technique of incorporating steering groups onto the framework of the substrate is limited. The introduction of halogens as steering groups may introduce additional functionality into the reactants that is undesirable. This additional functionality can limit further derivatization of the product, necessitate removal of the substituents and/or purification of the product. A further drawback of utilizing intramolecular substitution is that the forces exploited to align reactive centres are relatively weak, and as a result difficult to control, translating into questionable reliability. These become important considerations if the solid-state is to be considered an alternative route for synthesis.

1.5 Multi-Component Approach

Mixed molecular crystals are homogeneous crystals of at least two chemically distinct substances and, in general, mixed crystals are comprised of molecules of similar shape and size. Held together by intermolecular interactions, crystalline molecular compounds are formed when the intermolecular forces are strong and directional, such as in O-H $\cdots$ O hydrogen-bonds. Two component molecular crystals are often referred to as co-crystals or adduct crystals and examples include hydrogen-bonded co-crystals, donor-acceptor crystals (charge transfer crystals) and host-guest or inclusion crystals. While the investigation of the photochemical behaviour of one component crystals has received considerable attention, the

photoactivity of multi-component crystals is largely unexplored.

1.5.1 Multi-Component Approach: Halogen Atom Substitution

Fluoro substitution of aromatics such that the phenyl groups are perfluorinated has also been recognized to align olefin containing molecules in a topochemical fashion within crystals. Electrostatic π - π interactions between the phenyl and perfluorophenyl groups in a series of stilbene-based molecules were cited as inducing olefin alignment by Grubbs, *et. al.* in 1998 and this is illustrated in Figure 1.6.¹⁸ In each of seven cases reported, face-to-face stacks of alternating phenyl and perfluorophenyl molecules in a 1:1 stoichiometry were observed.

Topochemical olefin alignment and quantitative conversion to the expected cyclobutane-based photodimers was observed in six of the seven cases. Notably, stilbene in its pure crystalline form packs in an edge-to-face arrangement and is not photoactive. Once again topochemical design based upon weak interactions such as electrostatics does not reliably promote desirable or favourable olefin alignment. Additionally, the nature of the products is constrained to being partially fluorinated.

1.5.2 Multi-Component Approach: Cavity-Containing Media

One of the first attempts to use an auxiliary or spectator molecule to induce reactive olefin alignment was reported by Toda.¹⁹ His use of a two-component system held together by O-H...O hydrogen-bonds to engineer photochemically active solids involving the one component diacid of Feldman.¹⁶ In contrast to the Feldman *et. al.* work, this system involves a host-guest complex based upon an acetylenic bridged diol that assembles in the solid-state

(a)

(b)

Figure 1.6 (a) Electrostatic interactions direct the packing of the partially fluorinated stilbene and (b) the topochemical photo-product.¹⁸

to form a cavity inside which two enones reside. The reactivity was attributed to intermolecular interactions and a 90 % conversion to the head-to-tail dimer was exclusively observed (see Figure 1.7a).

Inspection of the packing of the cavity-containing system reveals one O-H...O hydrogen-bond between each substrate and each host molecule, with further stabilization provided by π - π interactions between the phenyl rings of the substrates. In addition to this, the host acetylenic molecule contains one additional dangling OH site capable of participating in hydrogen-bonding. Both the potential for this 'sticky' OH site to participate in further supramolecular interactions and the constraints placed on the shape and size of the substrates by the cavity size, can be regarded as drawbacks to using cavity containing host-guest complexes to steer double bonds into reactive alignment.

1.5.2.1 Cavity Containing Media: Cyclodextrins (CD)

Further efforts to separate the steering groups from the reactive centres have involved the use of the toroidally-shaped cyclodextrins²⁰. Guests included within the cavity of cyclodextrins displaying topochemical behaviour include substituted stilbenes²¹, coumarins²², acenaphthalene²³, anthracene²⁴, and styrylpyridine²⁵. Accelerated reactivity as a result of the inclusion is observed for coumarins, acenaphthalene and anthracene, while for stilbenes and styrylpyridine, reactivity was activated as a consequence of inclusion within a cyclodextrin.

Inclusion of the substituted stilbene, (*E*)-4,4'-bis(dimethylammoniomethyl)stilbene, was investigated in α -, β -, and γ -cyclodextrin, with the first two resulting in the formation of 1:1 complexes whereby the included stilbenes were isolated. In contrast, γ -cyclodextrin

(a)

(b)

Figure 1.7 The host-guest co-crystal system (a) engineered by Toda, whereby the reactants diffuse into a reaction cavity¹⁹ and, (b) γ -cyclodextrin (CD), where the CD is represented schematically by the bucket^{22b}.

displayed a 2:2 host:guest stoichiometry with 98 % conversion to both the *rcctt* and the *rtctt* cyclobutane dimers. *trans*-2-Styrylpyridine was observed to undergo primarily *trans-cis* isomerization while included in α or β -CD's. Inclusion in γ -CD yielded 46 % or 50 % of the expected dimer, in addition to both *cis*- and *trans*- products, depending on whether a 1:1 or 1:2 host:guest ratio was observed (see Figure 1.7b).²⁵

Similarly, the β -CD-coumarin complex was observed to display a 2:3 host:guest ratio²⁶ resulting in 64% conversion to the head-to-head photo-product. From these results it was evident that implementing cavities such as those presented by CD's are unreliable in terms of orienting only two reactants (*i.e.* one and three reactants were also observed). Further, selectivity for only dimerization products was also not observed as *trans-cis* isomerization occurred.

1.5.3 Multi-Component Approach: The Salt Approach

Recent interests of Scheffer²⁷ and co-workers have included the design of photolabile multi-component crystals. Also utilizing pre-organized auxiliary molecules to steer olefins into reactive alignment in the solid-state, they have focussed on the formation of double salts between primarily ethylenediamine (but also other diamines) and a variety of *trans*-cinnamic acids (See Figure 1.8a).

Typically, they observed the formation of the β -truxillic acid photodimer with yields ranging from 0.5 to 84 % in addition to generating both *trans*- and *cis*-cinnamic acids as well. The authors also noted that conversion to the corresponding cyclobutane product(s) does not occur when the *anti*-conformation of the diamines was present, rather [2+2]

photodimerization occurred only when the diamines were in *gauche* conformation.

1.5.4 Multi-Component Approach: Non-Covalent Linkers

Ito *et. al.* exploited the hydrogen-bonding ability of a carboxamide group with a carboxyl group in the solid-state in what they refer to as 'compelled orientational control...using non-covalent linkers'.²⁸ The non-covalent or supramolecular linkers used were a series of dicarboxylic acids, while the substrates were *trans*-cinnamamides, known to afford pure α -truxillamides as solid-state [2+2] photodimerization products in the absence of linkers.

Co-crystallization of the various *trans*-cinnamides with the family of dicarboxylic acids investigated yielded 2:1 mixtures that were all photo-active (*i.e.* olefin-olefin separation of < 4.2 Å), despite 2 of the 8 solids displaying perpendicular olefin alignment (see Figure 1.8b). In general, what was found were discrete hydrogen-bonded assemblies held together by a combination of O-H...N and O-H...O hydrogen-bonds. Irradiation of the solids led to the formation of cyclobutane-based products consistent with the orientation of the olefins relative to one another in the reactant solids.

1.5.5 Multi-Component Approach: Linear Molecular Templates

Recently we reported a method involving linear molecular templates, based on 1,3-dihydroxybenzene (resorcinol - **R**), to enforce topochemical alignment of the olefins of 1,2-bis(4-pyridyl)ethylene (**44DPE**) in the solid-state. A four-component assembly held together by O-H...O hydrogen-bonds, as illustrated in Figure 1.9a, underwent topochemical and quantitative conversion to the corresponding cyclobutane dimer in a [2+2] photo-reaction

(a)

(b)

Figure 1.8 Multi-component approaches to engineering [2+2] reactivity include: (a) Scheffer's use of salts based on ethylenediamine²⁷ and, (b) Ito's use of non-covalent linkers based on dicarboxylic acids and *trans*-cinnamides²⁸.

carried out at 350nm.²⁹ The product tetrapyridyl cyclobutane, illustrated in Figure 1.9b, was readily isolated from the template.

In this arrangement the reactant centres were separated supramolecularly from the steering groups, eliminating the need for intramolecular substitution. Further, this approach exploits the strength and directionality of hydrogen-bonds in the form of a molecule that is pre-organized to enforce the alignment of two sites within a discrete complex for reaction. For this reason it is believed that this approach eliminates the inconveniences of intermolecular forces that have hampered previous topochemical designs and made them unreliable. Additionally the restrictions placed upon the shape and size of the olefins when using a cavity to induce topochemical organization of the reactants was also removed.

1.5.5.1 Linear Molecular Templates: Selection of Template

Our choice of resorcinol, or more precisely, the 1,3-dihydroxy functionality grafted onto an aromatic ring, was based on its ability to induce a stacked alignment of aromatics in the solid-state.³⁰ In particular, a bis(resorcinol)anthracene derivative in the presence of anthraquinone yielded a one-dimensional (1D) polymeric array in which the anthraquinone molecules are separated by 4 Å in a stacked fashion, approximately orthogonal to the anthracene derivative. Illustration of this is found in Figure 1.10.

Held together by way of O-H...O hydrogen-bonds in dimers, the anthraquinone molecules were separated by a distance reminiscent of the Topochemical Principle. This suggested that the parent resorcinol molecule may be able to act as a template, inducing a stacked alignment of olefin-substituted, aromatic, hydrogen-bond acceptors in the solid-state.

(a)

(b)

Figure 1.9 ORTEP representation of the X-ray crystal structure of the hydrogen bonded cyclic array involving (a) **R** and **44DPE** and, (b) **R** and **44CB**. Thermal ellipsoids are shown at a probability of 50 % and dashed lines indicate hydrogen bonds.²⁹

(a)

(b)

Figure 1.10 (a) A 1D hydrogen bonded network based on a bis(resorcinol)anthracene derivative induces a stacked alignment of aromatics and, (b) the parent resorcinol.³⁰

1.5.5.2 Linear Molecular Templates: Selection of Reactant

From the criterion that the reactants must interact with the template by serving as hydrogen-bond acceptors, in addition to the necessity of planarity, it would seem that vinyl pyridines, and related derivatives would be suitable reactants. Pyridines are known to function as hydrogen-bond acceptors in the solid-state, and specifically to interact in an orthogonal fashion with aromatics.³¹ As a starting point, **44DPE** was chosen as a reactant. Notably, **44DPE** is photo-inert in its pure crystalline form³² and therefore reactivity was a direct consequence of utilizing the template approach.

1.6 Thesis Overview

In this chapter, an overview of the literature on inducing reactive [2+2] olefin alignment in the solid-state is described. An attempt has been made to place the preliminary work which has made use of supramolecular interactions to guide reactive olefin alignment within the context of previous work in this area. Application of the solid-state characterization techniques of single crystal X-ray diffraction and solid-state nuclear magnetic resonance spectroscopy leads to a better understanding of the origin of the reactivity in these systems, giving unique insight into the structural and dynamic features.

A subset of derivatives from the resorcinol family has been chosen because they not only function as double hydrogen-bond donors, but it is also well established in its interaction with hydrogen-bond acceptors such as pyridine and its derivatives.³¹ Furthermore, the hydrogen-bond donors are separated by a distance on the order of the olefin separation necessary for topochemical reaction. As mentioned, characterization of these systems relies

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primarily on single crystal XRD to identify olefin alignment and disorder. An introduction to these two techniques and the strengths they possess for structure determination are briefly presented in Chapter 2.

Investigation of the supramolecular interactions between resorcinol and its derivatives with a subset of the homologous family of **DPE** molecules is reported in Chapter 3. Here the dominant characterization technique used was single crystal XRD, and the reliability of utilizing supramolecular interactions to engineer reactivity was developed. In Chapter 4, the nature of the substrate-template interaction was modified for further probing the limits of the reactant diversity. The resulting disorder, and its nature (dynamic or static), has been investigated using room temperature single-crystal XRD. The fifth and final chapter questions whether or not the reaction occurs single-crystal-to-single-crystal or single-crystal-to-poly-crystal for **44DPE** in the resorcinol co-crystal at 350 nm. Solid-state NMR and powder XRD were used to answer this question. Suggestions for further work are also included.

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Chapter II: Physical Techniques

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1.0 Introduction

This chapter outlines the fundamental aspects of two structural techniques: single crystal X-ray diffraction (XRD), and solid-state nuclear magnetic resonance (NMR) spectroscopy. These two techniques can be used to determine structural information that enables a complete understanding of both the alignment of olefins and the effect of UV irradiation on the integrity of the sample.

In particular, the following chapters illustrate the strength of single crystal XRD as it applies to determining olefin alignment in the solid-state, as well as the ability of solid-state NMR to provide information on the effect UV irradiation has on the non-covalent interactions responsible for directing the olefin alignment. Solid-state NMR allows characterization of the microcrystalline photolyzed product and gives information on the physical state of the reactant(s) and product(s).

All of the solid-state NMR data collection and a large part of the analysis reported in this thesis was carried out by Dr. Steven Lang of the Steacie Institute for Molecular Sciences at the National Research Council of Canada. The author's main contribution in the structural characterization of solid-state olefin alignment has been with the XRD work, and therefore this technique is treated with more detail in both this chapter and the balance of the thesis.

1.1 Solid-State Nuclear Magnetic Resonance (NMR) Spectroscopy

^{13}C solid-state NMR studies were carried out for a number of reasons. Since our interests were in the nature of the sample in the solid-state, the orientation information of interest to us would be lost in solution. Simply stated, characterization of our samples without dissolution was important. Thus, spectra were acquired with the sample in the same physical state it was in when photochemical experiments were carried out. Cross-polarization magic angle spinning (CPMAS) experiments were used to investigate whether or not the weak interactions in these samples were destroyed as a result of UV irradiation. ^{13}C CPMAS NMR gives information on the symmetry within the co-crystal environment and comparison of reactant and product spectra was diagnostic.

Solid-state NMR has become a more routinely used solid-state characterization technique as the sources of line broadening in solids have been minimized. In solution the orientation dependant interactions responsible for line broadening in solids (dipolar interactions, chemical anisotropy) are averaged to zero or their isotropic values by rapid random re-orientation. In the solid state, high power decoupling, magic angle spinning and cross-polarization are used to sharpen spectral lines.¹

1.2 Single Crystal X-ray Diffraction (XRD)

Single crystal X-ray diffraction has been described as "...the bedrock structural technique in modern day chemistry..."² Knowledge of the structure of both molecular and non-molecular materials is one of the fundamental aims of chemistry and is essential for a proper understanding of the physical and chemical properties of materials. Of interest is the relative position of the atoms or ions and from this a geometrical statement of the bond lengths and angles, torsion angles, and of particular importance here, non-bonding distances. The detailed pictorial description of the geometry of the compound of interest is, in the case of olefin alignment, one of the primary methods for determining if further investigation of reactivity is merited.

1.2.1 The Origin of X-rays

X-rays were discovered by Röntgen in 1895, and in 1912 von Laue discovered that crystals cause X-rays to diffract, and to a certain extent, established the wave-like nature of X-rays based on interference phenomena, a property associated with waves.

Electromagnetic radiation in the wavelength region of 0.1 to 100 Å, or X-rays, produced in an evacuated X-ray tube by applying an electrical current to a wire filament which ejects electrons. These electrons are then accelerated across a high potential before colliding with the metal target. Much of the electron's kinetic energy is lost as heat radiation but a small proportion generates X-rays. X-rays are generated as a result of the interaction of the incoming electrons with the inner core electrons of the target metal, in which the 1s electrons are ejected. The filling of the vacancy by an electron from either the 2p or 3p sub-

shell results in the emission of nearly monochromatic X-rays with high intensity. The structures reported in this thesis were determined using K_α radiation from a molybdenum source, which has a wavelength of 0.71073 Å.³

1.2.2 Diffraction of X-rays

Bragg demonstrated that measurement of diffraction patterns yielded information on the arrangement of atoms within the unit cell. Further, he treated the diffraction of X-rays by crystals as ‘reflections’ from planes of atoms in the lattice which led to the formulation of Bragg’s Law:

$$2d \sin \theta = n\lambda$$

where d = the spacing between diffraction planes, θ = the angle of the diffracted X-ray beam relative to the plane, λ = the wavelength of the X-ray radiation, and n = the order of the reflection, as illustrated by Figure 2.1. In the diffraction experiment, θ values are measured and since the wavelength of the X-rays are known, d values can be calculated.

In reality a crystal is comprised of many such atomic planes that will diffract incident radiation and the diffraction pattern is sharp, occurring at clearly defined values of θ . Analysis of the single crystal diffraction data enables the determination of the unit cell and the relative arrangement of the atoms, giving a ‘snapshot’ of the solid-state structure of the crystalline material.

1.3 Crystals and Symmetry

The smallest repeatable atomic or molecular arrangement in a crystal is identified as

$$\begin{aligned}
 AB + BC &= n\lambda \\
 AB &= d \sin \theta \\
 BC &= d \sin \theta \\
 AB + BC &= 2d \sin \theta \\
 n\lambda &= 2d \sin \theta
 \end{aligned}$$

Figure 2.1 Bragg construction illustrating the principle of diffraction where d is the spacing between two planes.

the unit cell and repetition of the unit cell in three dimensions defines the solid.⁴ In general the unit cell is defined by six parameters: three axial lengths a , b , and c , that form the edges of a parallelepiped and three interaxial angles, α , β , and γ (see Figure 2.2). Seven three dimensional co-ordinate systems or crystal systems exist, each with different numbers of defining parameters.

Repetition of the unit cells generates a lattice which is either classified as primitive or non-primitive. The primitive lattice contains a single lattice point per unit cell, at the corners of the lattice, while non-primitive lattices, of which there are three, are more complex containing additional lattice points at the centre of either a unit cell or a face(s). Combining the four lattice types with the seven crystal systems, generates 14 possible unique Bravais lattices.

Application of symmetry operations, namely rotation, mirror planes, centre of symmetry, and rotation-inversion, relates the different faces of the crystal that are defined by the Bravais lattice. Relating the faces of the crystal by these symmetry operations results in a total of 32 sets of symmetry operations or transformations, known as the point groups. Combining the 32 point groups with the 14 Bravais lattices gives 230 unique arrangements of the points of the lattice in space. The 230 space groups define the ways in which identical moieties can be arranged in an infinite lattice.

1.4 Determination of Crystal Structures

Once a suitable diffracting crystal is found it is properly mounted and placed on the diffractometer and a preliminary data collection is performed. From the preliminary unit cell

Figure 2.2 The unit cell with defining parameters.

determination the goal is to determine if the crystal diffracts and is single. Further, the preliminary unit cell can be found from the locations of the diffracted peaks. In the event that the crystal is 'good', a full data collection is undertaken and from this data set the structure is solved and refined using various crystallographic software packages.

1.5 Quality of the Structural Data

Several parameters can be used to assess the quality of the data and ultimately the structure itself; three of these parameters will be introduced. The first, the goodness of fit (GooF) parameter, often output by least squares refinement programs, is also referred to as the standard deviation of an observation of unit weight. It is a measure of the agreement between the distribution of the differences between the observed and calculated structure factors ($|F|$) relative to the distribution found based on the weights used in the refinement. A value of 1.0 is expected if the correct weights are in place.⁴

$$GooF = S = \sqrt{\frac{\sum [w(F_{obs}^2 - F_{calc}^2)^2]}{n - p}}$$

Here n is the number of reflections and p is the total number of parameters refined.

A second parameter is the residual index R , which describes the agreement between the observed and calculated reflections on an individual basis:

$$R_1 = \frac{\sum ||F_{obs}| - |F_{calc}||}{\sum |F_{obs}|}$$

where F_{obs} is the observed structural amplitude and F_{calc} is the calculated structural amplitude.⁹

The third and final measure of the data quality analyzed is the wR_2 :⁹

$$wR_2 = \sqrt{\frac{\sum [w(F_{obs}^2 - F_{calc}^2)^2]}{\sum [w(F_{obs}^2)^2]}}$$

Basically, the difference between R_1 and wR_2 lies in the fact that R_1 considers only the most intense diffraction peaks, in fact only those with intensity $I > 2\sigma(I)$, while wR_2 makes use of all the collected data, even the weak diffraction peaks. Historically, R_1 values have been reported with reporting of wR_2 values becoming common place of late. Also important to note is that wR_2 values are typically on the order of at least 2 times R_1 .

In the analysis of the structures reported in this thesis, the GooF, R_1 , and wR_2 , were used simultaneously as measures of the reliability of the resulting structure. However, by far the most important measure of the reliability of structural data is whether it makes chemical and structural sense. From the point of view of a chemist, the relative positions of the atoms are more useful indicators of the data quality.

1.6 Crystallographic Disorder

A common problem in single crystal XRD studies occurs when an atom or group of atoms occupies more than one discrete position or is said to be disordered. Disorder can affect the reliability with which the whole structure can be determined and may lead to increased R values.⁴ In olefin [2+2] reactivity systems, disorder across two sites for the double bonds was observed occasionally and in this thesis the nature of the disorder, either static or dynamic, was of foremost interest. Large thermal parameters and unexpected or

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incongruous bonding distances are often indications that disorder may be present.^{3,4}

1.7 Chapter Summary

Two very powerful structural techniques have been described. The single crystal XRD was used to determine the relative orientations of reactive olefins while CP MAS gave insight into the number of unique nuclear chemical environments that existed in the crystalline samples before and after UV irradiation.

1.8 References

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Chapter III: Di-Pyridines as Substrates

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1.0 Introduction

The encouraging results from the preliminary study¹ involving resorcinol (**R**) and 1,2-bis(4-pyridyl)ethylene (**44DPE**) prompted an extensive study of supramolecular interactions

and template molecules to induce reactive olefin alignment. The primary focus was whether or not this approach to aligning olefins in the solid-state would be reliable. In contrast to previous methods utilizing template-like interactions, modification of the template or reactant should be possible without perturbing the observed reactivity.² As a starting point, modification of the steering component *via* the introduction of functionality onto the **R** core and/or varying the substitution pattern of the reactant **44DPE** was investigated.

Previous solid-state approaches to aligning olefins have suffered from an inability to show that, similar to solution-based chemistry, reactions carried out in the solid-state must display functional group tolerance. Since packing in the solid-state is sensitive to subtle changes in the substitution patterns of molecules, it is not uncommon for members of a homologous family to be structurally different. As a consequence of changes in packing the properties of the molecules (*i.e.* reactivity) are also often altered.³ This lack of reliability results in reluctance towards the use of the solid-state as a reaction medium for synthesis.

Investigation of homologous **DPE** substrates with **R** and its derivatives was carried out to determine to what extent the formation of the discrete four component hydrogen-bonded motif was reproducible. In particular, both symmetric and non-symmetric bipyridyl reactants similar to **44DPE** were examined. From single crystal XRD, the non-covalent intermolecular interactions and the olefin-olefin separations were determined.

2.0 Experimental

2.1 General Details

All reagents, unless otherwise noted, were purchased from Aldrich Chemical Company and used as received, with the exception of **24DPE** which was sublimed under reduced pressure prior to use. ^1H NMR spectra were obtained on a Bruker DRX-400 (^1H 400.13 MHz) 400 MHz NMR spectrometer and ESI⁺-MS analysis was carried out (CB Group, SIMS, NRC) on a VG Quattro I (Micromass) mass spectrometer equipped with a pneumatically-assisted electrospray source, operating in positive mode.

2.2 Single Crystal X-ray Crystallography

Single crystals were individually mounted on the end of a glass fibre and centered on the goniometer of a Siemens SMART CCD diffractometer for data collection. Initial cell constants were calculated from reflections harvested from three sets of 20 or 25 frames. Final cell constants were calculated from reflections obtained from the full data collection. All structures were solved using direct methods. After anisotropic refinement of all non-hydrogen atoms, methine, methyl, methylene, aromatic, and hydroxyl hydrogens were placed by modeling the moieties as rigid groups with idealized geometry, maximizing the sum of the electron density at the calculated hydrogen positions. A summary of the data collection parameters for all of the **DPE** structures collected is given in Tables 3.1-3.4. (All other crystallographic tables are found on the accompanying CD and a list of the structure codes can be found in Table S3.1.) Structure solutions were conducted using SHELXS-96⁴ and refined using SHELXL93⁵, locally implemented on a Pentium-based IBM compatible

Table 3.1 Crystal Data for T-44DPE

	ER (94)	CR (120)	BR (96)	HR (99)	OR (106)	MR (102)	DCR (123)
formula	C ₂₀ H ₂₀ N ₂ O ₂	C ₁₈ H ₁₅ N ₂ O ₂ Cl	C ₁₈ H ₁₅ N ₂ O ₂ Br	C ₂₄ H ₂₈ N ₂ O ₂	C ₁₉ H ₁₈ N ₂ O ₂	C ₁₉ H ₁₈ N ₂ O ₃	C ₁₈ H ₁₄ N ₂ O ₂ Cl ₂
formula weight	320.38	326.77	371.23	376.48	306.35	322.35	361.21
space group	<i>P</i> -1	<i>P</i> -1	<i>P</i> -1	<i>P</i> -1	<i>P</i> 2 ₁ /c	<i>P</i> 2 ₁ /c	<i>P</i> 2 ₁ /n
<i>T</i> , K	173(2)	173(2)	173(2)	173(2)	173(2)	173(2)	173(2)
<i>a</i> , Å	9.3148(6)	7.4672(4)	7.5031(4)	7.6810(5)	9.6511(4)	9.5780(6)	8.5092(3)
<i>b</i> , Å	9.9455(6)	9.3983(5)	9.4782(5)	10.2989(6)	13.4534(6)	11.3862(7)	11.7853(5)
<i>c</i> , Å	10.6598(7)	11.5240(6)	11.6261(6)	13.5102(8)	12.9113(5)	15.0442(10)	16.6610(7)
α , °	62.282(10)	95.8640(10)	96.3440(10)	92.5510(10)	90	90	90
β , °	73.551(10)	90.718(10)	90.3750(10)	98.9160(10)	109.0990(10)	94.3190(10)	99.4570(10)
γ , °	74.202(10)	107.7090(10)	108.3850(10)	99.4630(10)	90	90	90
<i>V</i> , Å ³	826.86(9)	765.58(7)	779.04(7)	1038.76(11)	1584.13(11)	1636.0(2)	1648.11(11)
<i>Z</i>	2	2	2	2	4	4	4
ρ_{calc} , g cm ⁻³	1.287	1.418	1.583	1.204	1.285	1.309	1.453
μ , mm ⁻¹	0.084	0.261	2.650	0.077	0.084	0.090	0.407
# Reflections	9914	9159	9334	11910	18498	11596	19162
# Unique	4155	3945	4011	5310	4100	4224	4265
$2\theta_{\text{max}}$	60	60	60	60	60	60	60
<i>R</i> _{<i>i</i>} (<i>I</i> > 2 σ (<i>I</i>))	0.0546	0.0335	0.0271	0.0423	0.0394	0.0437	0.0284
<i>wR</i> ₂ (all data)	0.1619	0.1009	0.0693	0.1195	0.1204	0.1200	0.0815
Goof on F ²	1.072	1.057	1.000	1.033	1.040	1.023	1.042

Table 3.2 Crystal Data for T-22DPE

	R (132)	ER (93)	CR (121)	BR (97)	OR (122)	MR (91)	DCR (116)
formula	C ₁₈ H ₁₆ N ₂ O ₂	C ₂₀ H ₂₀ N ₂ O ₂	C ₁₈ H ₁₅ N ₂ O ₂ Cl	C ₁₈ H ₁₅ N ₂ O ₂ Br	C ₁₉ H ₁₈ N ₂ O ₂	C ₂₀ H ₂₁ N ₃ O ₃	C ₁₈ H ₁₄ N ₂ O ₂ Cl ₂
formula weight	292.33	320.38	326.77	371.23	306.35	383.40	361.21
space group	<i>P</i> -1	<i>P</i> bca	<i>P</i> -1	<i>P</i> -1	<i>C</i> c	<i>P</i> -1	<i>P</i> 2 ₁ / <i>c</i>
<i>T</i> , K	173(2)	173(2)	173(2)	173(2)	173(2)	173(2)	173(2)
<i>a</i> , Å	7.4833(7)	15.7721(8)	7.6190(4)	7.6253(4)	16.0942(11)	8.0416(6)	9.8398(5)
<i>b</i> , Å	10.0186(10)	11.4022(6)	10.1738(5)	10.1761(5)	12.5373(8)	11.0257(8)	16.5319(8)
<i>c</i> , Å	10.5994(10)	19.5835(10)	11.5295(6)	11.6631(6)	8.2976(6)	11.0950(8)	10.7507(5)
α , °	79.811(2)	90	104.0370(10)	103.5450(10)	90	86.842(1)	90
β , °	73.146(2)	90	104.8270(10)	104.5480(10)	100.9540(10)	85.595(2)	107.727(1)
γ , °	77.686(2)	90	108.5820(10)	108.5880(10)	90	84.153(2)	90
<i>V</i> , Å ³	737.38(12)	3521.8(3)	765.97(7)	780.26(7)	1643.8(2)	974.61(12)	1665.78(14)
<i>Z</i>	2	8	2	2	4	2	4
ρ_{calc} , g cm ⁻³	1.317	1.208	1.417	1.580	1.238	1.306	1.440
μ , mm ⁻¹	0.087	0.079	0.261	2.645	0.081	0.095	0.0402
# Reflections	4073	39692	9147	9320	9613	7023	11958
# Unique	2588	4570	3923	4013	4180	4910	4311
$2\theta_{\text{max}}$	50	60	60	60	60	60	60
<i>R</i> _{<i>i</i>} (<i>I</i> > 2 σ (<i>I</i>))	0.0725	0.0401	0.0342	0.0306	0.0473	0.049	0.0346
<i>wR</i> _{<i>i</i>} (all data)	0.2194	0.1156	0.0991	0.0843	0.1463	0.1457	0.0879
Goof on F ²	1.050	1.043	1.078	1.041	1.027	1.038	1.010

Table 3.3 Crystal Data for T-24DPE

	R (119)	CR (133)	BR (98)	OR (105)	MR (92)	DCR (110)
formula	C ₃₆ H ₃₈ N ₄ O ₄	C ₃₆ H ₃₀ N ₄ O ₄ Cl ₂	C ₃₆ H ₃₀ N ₄ O ₄ Br ₂	C ₃₈ H ₃₆ N ₄ O ₄	C ₃₉ H ₃₉ N ₅ O ₈	C ₃₆ H ₃₀ N ₂ O ₄ Cl ₂
formula weight	584.72	653.54	742.46	612.71	705.75	722.42
space group	<i>P</i> -1	<i>P</i> -1	<i>P</i> -1	<i>P</i> 2 ₁ /c	<i>P</i> 2 ₁ /c	<i>P</i> 2 ₁ /n
<i>T</i> , K	173(2)	173(2)	173(2)	173(2)	173(2)	173(2)
<i>a</i> , Å	10.1822(6)	7.4105(4)	7.4494(8)	18.5692(10)	12.2644(6)	11.1043(6)
<i>b</i> , Å	10.7109(6)	13.7117(7)	13.8301(15)	13.8011(7)	19.3708(10)	19.2698(10)
<i>c</i> , Å	14.4456(8)	16.0279(8)	16.125(2)	12.7404(7)	15.5652(8)	16.1449(8)
α , °	94.5700(10)	92.1010(10)	91.518(2)	90	90	90
β , °	108.4880(10)	93.2740(10)	94.007(3)	91.7600(10)	95.203(10)	105.6800(10)
γ , °	93.7770(10)	103.4020(10)	103.078(2)	90	90	90
<i>V</i> , Å ³	1482.45(15)	1579.58(14)	1612.7(3)	3263.5(3)	3682.6(3)	3326.1(3)
<i>Z</i>	2	2	2	4	4	4
ρ_{calc} , g cm ⁻³	1.310	1.374	1.529	1.247	1.273	1.443
μ , mm ⁻¹	0.087	0.253	2.560	0.082	0.090	0.403
# Reflections	10822	11485	8815	38224	32788	27520
# Unique	7550	8013	5612	8441	5887	8564
$2\theta_{\text{max}}$	60	60	50	60	50	60
<i>R</i> _{<i>i</i>} (<i>I</i> > 2 σ (<i>I</i>))	0.0466	0.0388	0.0793	0.0453	0.0565	0.0373
<i>wR</i> ₂ (all data)	0.1323	0.1099	0.2467	0.1327	0.2102	0.1007
Goof on F ²	0.943	1.048	1.084	1.040	1.078	1.025

Table 3.4 Crystal Data for T-34DPE

	R (138)	BR (107)	MR (137)	CR (136)	DCR (140)
formula	$C_{34}H_{22}N_2O_4$	$C_{36}H_{30}N_4O_4Br_2$	$C_{57}H_{56}N_6O_{10}$	$C_{36}H_{30}N_4O_4Cl_2$	$C_{42}H_{32}N_4O_6Cl_6$
formula weight	402.42	742.46	985.05	653.54	901.42
space group	$P 2_1/c$	$P bca$	$P -1$	$P bca$	$P -1$
T, K	173(2)	173(2)	173(2)	173(2)	173(2)
$a, \text{\AA}$	7.4305(4)	9.4674(5)	10.5788(4)	9.4567(9)	9.2534(10)
$b, \text{\AA}$	27.4322(14)	17.9963(10)	11.0940(5)	17.710(2)	11.2096(12)
$c, \text{\AA}$	8.7033(4)	38.454(2)	22.3645(9)	38.471(4)	19.586(2)
$\alpha, ^\circ$	90	90	90.3830(10)	90	87.754(2)
$\beta, ^\circ$	93.3530(10)	90	94.5690(10)	90	81.529(2)
$\gamma, ^\circ$	90	90	106.3150(10)	90	80.940(2)
$V, \text{\AA}^3$	1771.00(15)	6551.7(6)	2509.87(18)	6442.9(11)	1984.1(4)
Z	4	8	2	8	2
$\rho_{\text{calc}}, \text{g cm}^{-3}$	1.510	1.505	1.303	1.348	1.509
μ, mm^{-1}	0.088	2.520	0.090	0.248	0.488
# Reflections	15514	45492	30099	43419	14250
# Unique	3057	8504	12921	4213	4179
$2\theta_{\text{max}}$	50	60	60	45	45
$R_1 (I > 2\sigma(I))$	0.0667	0.0407	0.0476	0.0489	0.0725
wR_2 (all data)	0.1966	0.0939	0.1315	0.1240	0.2259
GooF on F^2	1.083	0.994	0.952	1.135	1.125

computer. Crystallographic manipulations were performed with the aid of RES2INS⁶ and graphical representations were generated using a combination of RES2INS, Diamond⁷, and Atoms⁸.

2.3 Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) Measurements

TGA measurements were performed using a 2050 Thermogravimetric Analyzer (TA Instruments) with nitrogen as the purge gas at a flow rate of 40 cc/min. The TGA samples (10-20 mg) were ramped from room temperature to 450°C at a rate of 5°C/min in open aluminum pans.

A TA Instruments 2920 Modulated DSC with helium purge gas at a flow rate of 50 cc/min was used to collect DSC measurements. Similarly, the DSC samples (5-10 mg) were ramped from room temperature to 450°C at a rate of 5°C/min in sealed hermetic pans.

Onset temperatures (TGA and DSC) are reported for all co-crystals in the supplemental section.

2.4 Preparation of T·DPE Co-crystals

In general, an equimolar amount of template (T) and DPE was dissolved in a suitable hot solvent or solvent pair and allowed to cool undisturbed under ambient conditions. When CH₂Cl₂ was used as part of a solvent pair, it was added after dissolution during cooling. Crystals suitable for X-ray diffraction were collected and dried under ambient conditions. Tables 3.5-3.8, detail the exact experimental conditions for each of the family of DPE co-crystals prepared.

Table 3.5 Experimental Crystallization Data for **T-44DPE**

	ER	CR	BR	HR	OR	MR	DCR
amount 44DPE	0.181g 0.995 mmol	0.253g 1.39 mmol	0.224g 1.23 mmol	0.204g 1.05 mmol	0.125g 0.687 mmol	0.162g 0.89 mmol	0.204g 1.12 mmol
amount T	0.137g 0.992 mmol	0.200g 1.38 mmol	0.229g 1.21 mmol	0.194g 1.06 mmol	0.089g 0.694 mmol	0.128g 0.89 mmol	0.202g 1.13 mmol
solvent (1:1) volume (mL)	EtOH MeCN 10	EtOH MeNO ₂ 15	EtOH (CH ₃) ₂ CO 30	MeNO ₂ 20	EtOH CH ₂ Cl ₂ 15	EtOH MeNO ₂ 15	EtOH MeNO ₂ 15
yield	0.294g 94 %	0.331g 73 %	0.289g 64 %	0.279g 70 %	0.161g 72 %	0.229g 79 %	0.329g 81 %
crystal habit	yellow needles	colourless blocks	off-white blocks	faint yellow needles	colourless blocks	colourless blocks	faint pink blocks
crystallization time (hours)	12	48	12	72	16	12	17
structure code	jlr94	jlr120	jlr96	jlr99	jlr106	jlr102	jlr123

Table 3.6 Experimental Crystallization Data for **T-22DPE**

	R	CR	BR	ER	OR	MR	DCR
amount 22DPE	0.156g 0.857 mmol	0.100g 0.549 mmol	0.117g 0.643 mmol	0.125g 0.691 mmol	0.144g 0.791 mmol	0.099g 0.544 mmol	0.188g 1.03 mmol
amount T	0.093g 0.845 mmol	0.079g 0.546 mmol	0.124g 0.656 mmol	0.097g 0.683 mmol	0.100g 0.781 mmol	0.077g 0.550 mmol	0.183g 1.02 mmol
solvent (1:1) volume (mL)	MeNO ₂ 20	MeNO ₂ 15	MeNO ₂ 15	EtOH CH ₂ Cl ₂ 20	EtOH MeCN 20	EtOH MeNO ₂ 15	EtOH CH ₂ Cl ₂ 25
yield	0.206g 83 %	0.168g 94 %	0.202g 84 %	0.161g 73 %	0.187g 77 %	0.102g 58 %	0.322g 87 %
crystal habit	colourless blocks	colourless blocks	off-white blocks	pale yellow plates	colourless needles	colourless plates	pale pink needles
crystallization time (hours)	5	12	6	36	72	42	48
structure code	jlr132	jlr121	jlr97	jlr93	jlr122	jlr91	jlr116

Table 3.7 Experimental Crystallization Data for **T-24DPE**

	R	CR	BR	OR	MR	DCR
amount 24DPE	0.322g 1.77 mmol	0.197g 1.08 mmol	0.096g 0.527 mmol	0.199g 1.09 mmol	0.118g 0.648 mmol	0.144g 0.791 mmol
amount T	0.194g 1.76 mmol	0.156g 1.08 mmol	0.099g 0.524 mmol	0.137g 1.10 mmol	0.091g 0.650 mmol	0.144g 0.804 mmol
solvent (1:1) volume (mL)	MeNO ₂ 25	EtOH CH ₂ Cl ₂ 15	EtOH CH ₂ Cl ₂ 20	EtOH 15	EtOH MeNO ₂ 15	EtOH CH ₂ Cl ₂ 20
yield	0.444g 86 %	0.300g 85 %	0.166g 85 %	0.202g 60 %	0.146g 70 %	0.188g 65 %
crystal habit	colourless blocks	colourless needles	colourless blocks	colourless needles	colourless plates	pale red block
crystallization time (hours)	16	48	7	46	55	30
structure code	jlr119	jlr133	jlr98	jlr105	jlr92	jlr110

Table 3.8 Experimental Crystallization Data for **T-34DPE**

	R	CR	BR	MR	DCR
amount 34DPE	0.055g 0.302 mmol	0.060g 0.330 mmol	0.066g 0.363 mmol	0.044g 0.242 mmol	0.066g 0.363 mmol
amount T	0.032g 0.291 mmol	0.048g 0.332 mmol	0.070g 0.370 mmol	0.033g 0.236 mmol	0.064g 0.358 mmol
solvent (1:1) volume (mL)	EtOH CH ₂ Cl ₂ 15	EtOH CH ₂ Cl ₂ 25	EtOH CH ₂ Cl ₂ 25	MeCN 20	EtOH CH ₂ Cl ₂ 30
yield	0.077g 89 %	0.78g 72 %	0.103g 76 %	0.068g 88 %	0.088g 68 %
crystal habit	colourless needles	colourless blocks	colourless blocks	colourless plates	pale red blocks
crystallization time (hours)	48 evaporation	72	72	44 evaporation	11
structure code	jlr138	jlr136	jlr107	jlr137	jlr140

2.5 Photochemistry

Photochemical experiments were carried out using a Rayonet reaction chamber modified for solid samples. Crystalline samples were ground up, sandwiched between two fused silica glass plates and placed in a merry-go-round apparatus within the reaction chamber. Irradiation was carried out for approximately 24 hours at 350nm at temperatures between 37°C and 41°C on 100 to 200mg of sample. The irradiated samples were characterized by solution ^1H NMR spectroscopy and ESI^- -MS spectrometry. A summary of the ^1H NMR results are found in Tables 3.9-3.12 for the co-crystals of **44DPE**, **22DPE**, **24DPE** and **34DPE**, respectively.

2.6 The Photo-products

A summary of the single crystal XRD data for the various co-crystals involving the photo-products is given in Table 3.13 and yield and ESI^- -MS data are given in Table 3.14.

2.6.1 The 44CB Photo-product

The photolyzed microcrystalline **MR·44DPE** was dissolved in 15 mL of EtOH and then 5 mL of toluene was added. Colourless, block-like crystals suitable for X-ray diffraction studies were isolated upon evaporation (24 hours). The photolyzed mixture of **MR·44DPE** was dissolved in 30 mL of CH_3Cl and treated with an aqueous solution of Na_2CO_3 . The **44CB** photo-product was extracted into the organic phase and recovered after removal of the solvent. ^1H NMR spectroscopy and spot TLC indicated both the success and purity of the separation.

Table 3.9 ^1H NMR Data for **T-44CB**

(δ in ppm, multiplicity, number of protons, coupling in Hz)							
	ER (94)	CR (120)	BR (96)	HR (99)	OR (106)	MR (102)	DCR (123)
NCH	8.34, d, 4H, $^3J_{\text{HH}}$ 5.9 Hz	8.34, d, 4H, $^3J_{\text{HH}}$ 5.9 Hz	8.34, d, 4H, $^3J_{\text{HH}}$ 5.8 Hz	8.34, d, 4H, $^3J_{\text{HH}}$ 5.9 Hz	8.60, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz	8.34, d, 4H, $^3J_{\text{HH}}$ 5.8 Hz	8.34, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz
NCHCH	7.22, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz	7.22, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz	7.22, d, 4H, $^3J_{\text{HH}}$ 5.9 Hz	7.22, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz	7.60, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz	7.22, d, 4H, $^3J_{\text{HH}}$ 5.9 Hz	7.22, d, 4H, $^3J_{\text{HH}}$ 6.1 Hz
cyclo- C_2H_4	4.66, s, 2H	4.66, s, 2H	4.66, s, 2H	4.66, s, 2H	7.53, s, 2H	4.66, s, 2H	4.66, s, 2H
Template	9.03, s, 1H	9.93, bs, 1H	9.99, s, 1H	8.97, s, 1H	9.03, s, 2H	9.21, s, 2H	10.22, s, 2H
	8.90, s, 1H	9.46, bs 1H	9.47, s, 1H	8.90, s, 1H	6.01, m, 3H	5.79, t, 3H	7.27, s, 1H
	6.78, d, 1H	7.05, d 1H	7.18, d, 1H	6.76, d, 1H	2.10, s, 3H	3.62, s, 3H	6.66, s, 1H
	6.25, d, 1H	6.43, d, 1H	6.43, d, 1H	6.24, s, 1H			
	6.12, dd, 1H	6.22, dd, 1H	6.18, dd, 1H	6.12, d, 1H			
	2.39, q, 2H			2.37, t, 2H			
	1.05, t, 3H			1.43, m, 2H			
			1.25, bs, 6H				
			0.84, m, 3H				

Where s refers to singlet, d doublet, t triplet, q quartet, dd doublet of doublet, ddd doublet of doublet, ddd doublet of doublet, and m multiplet.

Table 3.10 ¹H NMR Data for T-22CB

(δ in ppm, multiplicity, number of protons, coupling in Hz)				
	R (132)	ER (93)	CR (121)	BR (97)
NCCHCHCHCH	8.34, d, 2H, ³ J _{HH} 4.8 Hz	8.35, d, 2H, ³ J _{HH} 4.8 Hz	8.34, d, 2H, ³ J _{HH} 4.8 Hz	8.34, d, 2H, ³ J _{HH} 4.7 Hz
NCCHCH	7.46, ddd, 2H, ³ J _{HH} 7.7 Hz	7.46, ddd, 2H, ³ J _{HH} 7.6 Hz	7.46, ddd, 2H, ³ J _{HH} 7.6 Hz	7.46, ddd, 2H, ³ J _{HH} 7.6 Hz
NCCH	7.09, d, 2H, ³ J _{HH} 7.8 Hz	7.09, d, 2H, ³ J _{HH} 7.8 Hz	7.09, d, 2H, ³ J _{HH} 7.8 Hz	7.09, d, 2H, ³ J _{HH} 7.8 Hz
NCCHCHCH	7.00, ddd, 2H, ³ J _{HH} 4.8 Hz	7.00, ddd, 2H, ³ J _{HH} 5.0 Hz	6.99, ddd, 2H, ³ J _{HH} 4.8 Hz	6.99, ddd, 2H, ³ J _{HH} 4.9 Hz
cyclo-C ₂ H ₄	4.94, s, 2H	4.95, s, 2H	4.93, s, 2H	4.94, s, 2H
Template	9.16, s, 2H 6.90, t, 1H 6.18, m, 3H	9.01, s, 1H 8.90, s, 1H 6.79, d, 1H 6.26, d, 1H 6.12, dd, 1H 2.40, q, 2H 1.06, t, 3H	9.96, bs, 1H 9.49, bs 1H 7.05, d 1H 6.42, d, 1H 6.22, dd, 1H	10.03, s, 1H 9.51, s, 1H 7.19, d, 1H 6.43, d, 1H 6.19, dd, 1H

Where s refers to singlet, d doublet, t triplet, q quartet, dd doublet of doublet, ddd doublet of doublet, and m multiplet.

Table 3.11 ^1H NMR Data for **T-24CB**

(δ in ppm, multiplicity, number of protons, coupling in Hz)				
	R (119)	CR (133)	BR (98)	OR (105)
NCCHCHCHCH	8.33, m, 3H	8.33, m, 3H	8.34, d, 1H, $^3J_{\text{HH}}$ 4.7 Hz	8.41, d, 1H, $^3J_{\text{HH}}$ 4.7 Hz
NCH			8.32, d, 2H, $^3J_{\text{HH}}$ 6.0 Hz	8.27, d, 2H, $^3J_{\text{HH}}$ 6.0 Hz
NCCHCH	7.50, ddd, 1H, $^3J_{\text{HH}}$ 7.7 Hz	7.50, ddd, 1H, $^3J_{\text{HH}}$ 7.7 Hz	7.50, ddd, 1H, $^3J_{\text{HH}}$ 7.7 Hz	7.55, ddd, 1H, $^3J_{\text{HH}}$ 7.6 Hz
NCHCH	7.22, d, 2H, $^3J_{\text{HH}}$ 5.8 Hz	7.22, d, 2H, $^3J_{\text{HH}}$ 5.8 Hz	7.22, d, 2H, $^3J_{\text{HH}}$ 6.0 Hz	7.16, d, 2H, $^3J_{\text{HH}}$ 6.0 Hz
NCCH	7.12, d, 1H, $^3J_{\text{HH}}$ 7.8 Hz	7.12, d, 1H, $^3J_{\text{HH}}$ 7.8 Hz	7.12, d, 1H, $^3J_{\text{HH}}$ 7.8 Hz	7.19, dd, 1H, $^3J_{\text{HH}}$ 7.8 Hz
NCCHCHCH	7.04, dd, 1H	7.04, dd, 1H	7.04, dd, 1H	7.06, ddd, 1H
4py-(CH) ₄ -2py	4.89, d, 1H, $^3J_{\text{HH}}$ 6.4 Hz 4.69, d, 1H, $^3J_{\text{HH}}$ 6.4 Hz	4.89, d, 1H, $^3J_{\text{HH}}$ 6.2 Hz 4.69, d, 1H, $^3J_{\text{HH}}$ 6.2 Hz	4.90, d, 1H, $^3J_{\text{HH}}$ 6.4 Hz 4.70, d, 1H, $^3J_{\text{HH}}$ 6.4 Hz	4.90, d, 1H, $^3J_{\text{HH}}$ 6.2 Hz 4.70, d, 1H, $^3J_{\text{HH}}$ 6.1 Hz
Template	9.16, s, 2H 6.91, t, 1H 6.18, m, 3H	9.90, bs, 1H 9.44, bs 1H 7.05, d 1H 6.43, d, 1H 6.22, dd, 1H	9.99, s, 1H 9.47, s, 1H 7.19, d, 1H 6.44, d, 1H 6.18, dd, 1H	10.22, s, 2H 7.27, s, 1H 6.66, s, 1H

Where s refers to singlet, d doublet, t triplet, q quartet, dd doublet of doublet, ddd doublet of doublets, and m multiplet.

Table 3.12 ^1H NMR Data for **T-34CB**

$(\delta$ in ppm, multiplicity, number of protons, coupling in Hz)			
	BR (107)	CR (136)	DCR (140)
NHCCCH	8.45, d, 1H, $^3J_{\text{HH}}$ 1.9 Hz	8.45, d, 1H, $^3J_{\text{HH}}$ 1.8 Hz	8.45, bs, 2H
NCH	8.35, d, 2H, $^3J_{\text{HH}}$ 6.0 Hz	8.35, d, 2H, $^3J_{\text{HH}}$ 6.0 Hz	8.35, bd, 4H, $^3J_{\text{HH}}$ 5.3 Hz
NHCCCHCHCH	8.27, dd, 1H, $^3J_{\text{HH}}$ 4.7 Hz	8.27, dd, 1H, $^3J_{\text{HH}}$ 4.6 Hz	8.27, dd, 2H, $^3J_{\text{HH}}$ 3.6 Hz
NHCCCH	7.64, ddd, 1H, $^3J_{\text{HH}}$ 8.0 Hz	7.64, ddd, 1H, $^3J_{\text{HH}}$ 8.0 Hz	7.64, ddd, 2H, $^3J_{\text{HH}}$ 7.9 Hz
NCHCH	7.24, d, 2H, $^3J_{\text{HH}}$ 6.0 Hz	7.24, d, 2H, $^3J_{\text{HH}}$ 6.0 Hz	7.24, d, 4H, $^3J_{\text{HH}}$ 5.9 Hz
NHCCCHCH	7.19, ddd, 1H, $^3J_{\text{HH}}$ 7.8 Hz	7.19, ddd, 1H, $^3J_{\text{HH}}$ 7.8 Hz	7.19, ddd, 2H, $^3J_{\text{HH}}$ 7.8 Hz
4py-(CH) ₄ -3py	4.70, bs, 1H, 4.68, bs, 1H,	4.70, bs, 1H, 4.68, bs, 1H,	4.71, bs, 2H 4.67, bs, 2H
Template	9.98, s, 1H 9.47, s, 1H 7.18, d, 1H 6.43, d, 1H 6.18, dd, 1H	9.90, bs, 1H 9.43, bs 1H 7.05, d 1H 6.43, d, 1H 6.22, dd, 1H	10.22, s, 6H 7.27, s, 3H 6.66, s, 3H

Where s refers to singlet, d doublet, t triplet, q quartet, dd doublet of doublet, ddd doublet of doublet, and m multiplet.

Table 3.13 Crystal Data for Product Co-crystals T·CB

	MR-44CB (108)	BR-22CB (103)	OR-24CB (153)	24CB (151)	DCR-34CB (150)
formula	C ₁₉ H ₁₈ N ₂ O ₃	C ₃₀ H ₂₅ N ₄ O ₂ Br	C ₃₈ H ₄₀ N ₄ O ₆	C ₂₄ H ₂₀ N ₄	C ₄₂ H ₃₂ N ₄ O ₆ Cl ₆
formula weight	322.35	553.45	648.74	364.44	901.42
space group	<i>P</i> 2 ₁ /c	<i>P</i> 2 ₁ /c	<i>P</i> -1	<i>P</i> 2 ₁ /n	<i>P</i> -1
<i>T</i> , K	173(2)	173(2)	173(2)	173(2)	173(2)
<i>a</i> , Å	10.0022(5)	8.7544(4)	8.2912(6)	5.6786(4)	9.3729(7)
<i>b</i> , Å	10.7911(6)	15.3567(8)	11.9492(8)	16.2348(11)	11.0130(8)
<i>c</i> , Å	14.8239(8)	19.7135(10)	17.6696(12)	20.7600(14)	19.8473(14)
α , °	90	90	87.1260(10)	90	89.068(2)
β , °	96.291(1)	100.8140(10)	84.8570(10)	94.499(2)	87.557(1)
γ , °	90	90	72.8120(10)	90	74.251(1)
<i>V</i> , Å ³	1590.38(15)	2603.2(2)	1665.2(2)	1908.0(2)	1970.0(2)
<i>Z</i>	4	4	2	4	2
ρ_{calc} , g cm ⁻³	1.346	1.412	1.294	1.269	1.520
μ , mm ⁻¹	0.092	1.614	0.088	0.077	0.492
# Reflections	10976	29777	18194	13461	13227
# Unique	2795	6733	8531	2499	5144
$2\theta_{\text{max}}$	50	60	60	45	45
<i>R</i> _{<i>i</i>} (<i>I</i> > 2σ(<i>I</i>))	0.0558	0.0388	0.0498	0.0527	0.0449
<i>wR</i> ₂ (all data)	0.1929	0.1045	0.1669	0.1598	0.1151
GooF on F ²	1.086	1.016	1.110	1.064	1.008

Table 3.14 Yield and MS data for the **DPE** irradiated in co-crystals.

Co-crystal	Yield (%)	ESI⁺-MS*
CR·44DPE	100	365.2(34) 183.2(100)
ER·44DPE	13	365.2(3) 183.0(100)
BR·44DPE	97	365.2(49) 183.4(100)
HR·44DPE	91	365.3(13) 183.3(100)
MR·44DPE	100	365.2(20) 183.3(100)
DCR·44DPE	98	365.2(49) 183.2(100)
OR·44DPE	5	365.2(2) 183.2(100)
R·22DPE	95	365.2(44) 183.4(100)
CR·22DPE	88	365.3(45) 183.4(100)
ER·22DPE	80	365.2(47) 183.2(100)
BR·22DPE	81	365.3(37) 183.3(100)
OR·22DPE	0	365.3(1) 183.2(100)
DCR·22DPE	86	365.2(21) 183.2(100)
R·24DPE	95	365.2(45) 183.3(100)
CR·24DPE	100	365.3(18) 183.4(100)
BR·24DPE	92	365.2(13) 183.4(100)
OR·24DPE	95	365.3(13) 183.4(100)
DCR·24DPE	57	365.2(12) 183.3(100)
R·34DPE	0	183.2 (100)
MR·34DPE	0	365.2(1) 183.0(100)
DCR·34DPE	99	365.2(16) 183.3(100)
CR·34DPE	99	365.2(9) 183.1(100)
BR·34DPE	98	365.2(9) 183.2(100)

* M⁺ and M⁺⁺

20 of 25 cases dimerized with 19 of 25 photodimers as expected from the organization of the substrates in the reactant co-crystals.

2.6.2 The 22CB Photo-product

The photolyzed microcrystalline **BR-22DPE** was dissolved in 15 mL of acetone. Off-white, block-like crystals suitable for XRD were isolated after complete evaporation (56 hours). The photolyzed mixture of **BR-22DPE** was dissolved in 30 mL of CH_2Cl_2 and treated with an aqueous solution of Na_2CO_3 . The **22CB** photo-product was extracted into the organic phase and recovered after removal of the solvent. ^1H NMR spectroscopy and spot TLC indicated both the success and purity of the separation.

2.6.3 The 24CB Photo-product

The photolyzed microcrystalline **OR-24DPE** was dissolved in 15 mL of EtOH and then 10 mL of CH_2Cl_2 was added. Colourless, plate-like crystals suitable for X-ray diffraction studies were isolated after 47 hours upon evaporation. The photolyzed mixture of **OR-24DPE** was dissolved in 30 mL of CHCl_3 and treated with an aqueous solution of Na_2CO_3 . The **24CB** photo-product was extracted into the organic phase and recovered after removal of the solvent. ^1H NMR spectroscopy and spot TLC indicated both the success and purity of the separation. A single crystal XRD was also carried out on the isolated product following re-crystallization from CH_2Cl_2 .

2.6.4 The 34CB Photo-product

The photolyzed microcrystalline **DCR-34DPE** was dissolved in 20 mL of EtOH and then 15 mL of CH_2Cl_2 was added. Pale pink, block-like crystals suitable for XRD studies were isolated upon complete evaporation (18 hours).

3.0 Results and Discussion

In general, co-crystallization of **DPE** with either the parent resorcinol (**R**) template or one of its derivatives resulted in the formation of four *inter*-molecular hydrogen-bonds between the pyridine units of **DPE** and the hydroxyl groups of the template molecule. As a consequence of these interactions, assembly of a discrete, cyclic, hydrogen-bonded dimer similar to that reported for **R** and **44DPE** was observed for 20 of the 25 different template-substrate co-crystals. This discrete assembly is depicted schematically in Figure 3.1. Notably, in 20 of the 25 template-substrate co-crystals, the olefins of **DPE** conform to the criteria of the Topochemical Principle (*i.e.* the olefins are aligned parallel) suggesting that the crystalline materials would be photoactive in the solid-state. Relevant hydrogen-bond distances and angles⁹, and olefin-olefin separations¹⁰ for all 25 co-crystals are given in Tables 3.15-3.18 and Tables 3.19-3.20, respectively.

3.1 Supramolecular Control of Reactivity

The process of self-assembly, which involves the single step construction of chemical architecture through the use of non-covalent forces, consists of three steps: component recognition, orientation and structure termination.¹¹ In such a context the various template and substrate components have assembled by way of O-H...N hydrogen-bonds such that the pyridine moieties adopt an approximately orthogonal orientation with respect to the **R**-based units. The dihedral angles between the aromatic unit of the template **R** and the aromatic unit of the substrate **DPE** are collated in Table 3.21, and in 20 of 25 instances the **DPE** olefins

Figure 3.1 Schematic representation of the discrete four-component hydrogen-bonded assemblies formed in **T-DPE** co-crystals.

Table 3.15 *Inter-molecular hydrogen bond distances (Å) and angles (°) for T-44DPE.*

Template	Intermolecular Distances and Angles		
	O...N	H...N	Δ O-H...N
CR (120)	2.743(1)	1.904(5)	176.7(3)
	2.737(1)	1.898(8)	176.5(5)
BR (96)	2.732(2)	1.893(6)	176.8(4)
	2.739(2)	1.900(11)	177.0(7)
ER (94)	2.779(2)	1.943(7)	164.9(5)
	2.778(2)	1.941(9)	173.8(13)
HR (99)	2.776(1)	1.937(4)	177.5(3)
	2.798(1)	1.962(6)	173.7(2)
MR (102)	2.804(2)	1.965(10)	176.9(8)
	2.743(2)	1.904(8)	176.5(5)
OR (106)	2.748(1)	1.911(5)	174.0(4)
	2.749(1)	1.910(4)	177.1(3)
DCR (123)	2.705(1)	1.867(9)	175.5(2)
	2.666(2)	1.817(18)	171.6(16)

Hydrogen bond angles and distances were calculated with the aid of the programs prep96 and parst97.

Table 3.16 *Inter-molecular hydrogen bond distances (Å) and angles (°) for T-22DPE.*

Template	Intermolecular Distances and Angles		
	O...N	H...N	∠ O-H...N
R (132)	2.779(3)	1.957(11)	165.7(4)
	2.807(3)	2.006(11)	159.3(3)
CR (121)	2.775(1)	1.859(22)	179.0(19)
	2.774(2)	1.936(24)	172.6(20)
BR (97)	2.775(2)	1.940(15)	172.4(10)
	2.761(2)	1.964(2)	158.0(1)
ER (93)	2.783(1)	1.952(6)	170.2(2)
	2.757(1)	1.919(7)	175.7(3)
MR (91)	2.774(2)	1.939(10)	172.5(2)
	2.793(2)	1.955(8)	175.1(2)
OR (122)	2.757(4)	1.983(8)	152.7(4)
	2.751(4)	1.930(12)	165.1(11)
DCR (116)	2.731(2)	1.947(25)	172.5(24)
	2.743(2)	1.966(25)	172.6(23)

Hydrogen bond angles and distances were calculated with the aid of the programs prep96 and parst97.

Table 3.17 *Inter-molecular hydrogen bond distances (Å) and angles (°) for T-24DPE.*

Template	Intermolecular Distances and Angles		
	O...N	H...N	∠ O-H...N
R (119)	2.878(4)	2.047(19)	170.2(14)
	2.786(4)	1.964(17)	165.7(12)
	2.738(4)	1.899(17)	176.3(15)
	2.802(4)	1.970(19)	170.8(16)
CR (133)	2.704(2)	1.867(10)	173.9(6)
	2.760(2)	1.921(12)	176.0(10)
	2.748(2)	1.910(12)	174.8(10)
	2.801(1)	1.965(12)	173.1(12)
BR (98)	2.705(9)	1.867(56)	174.7(37)
	2.746(9)	1.928(63)	173.9(64)
	2.800(8)	1.963(66)	164.0(40)
	2.741(10)	1.937(66)	160.0(56)
MR (92)	2.792(2)	1.953(13)	175.9(9)
	2.706(2)	1.868(11)	174.9(7)
	2.762(3)	1.926(19)	173.7(15)
	2.738(3)	1.901(22)	173.6(14)
OR (105)	2.760(2)	1.923(12)	174.1(10)
	2.759(2)	1.920(13)	178.2(11)
	2.820(2)	1.981(11)	176.8(9)
	2.753(2)	1.914(12)	176.3(9)
DCR (110)	2.696(2)	1.857(12)	176.3(9)
	2.722(2)	1.883(9)	177.5(6)
	2.748(2)	1.913(14)	172.7(13)
	2.711(2)	1.875(12)	173.9(9)

Hydrogen bond angles and distances were calculated with the aid of the programs prep96 and parst97.

Table 3.18 *Inter-molecular hydrogen bond distances (Å) and angles (°) for T·34DPE.*

Template	Intermolecular Distances and Angles		
	O...N	H...N	∠ O-H...N
R (138)	2.689	1.869	140.5
CR (136)	2.746(4)	1.912(5)	172.2(5)
	2.736(4)	1.899(5)	174.2(3)
	2.749(3)	1.912(16)	174.8(4)
	2.677(3)	1.839(11)	175.8(4)
BR (107)	2.746(3)	1.907(9)	177.3(7)
	2.747(3)	1.908(5)	177.7(3)
	2.678(3)	1.840(10)	175.6(5)
	2.679(3)	1.931(14)	175.6(3)
MR (137)	2.709	1.875	171.88
	2.807	1.817	174.12
	2.746	1.915	170.23
	2.799	1.960	176.41
DCR (140)	2.718(6)	1.883(34)	172.9(19)
	2.747(6)	1.909(33)	175.2(21)
	2.648(5)	1.845(28)	159.3(24)
	2.640(4)	1.811(17)	168.6(18)

Hydrogen bond angles and distances were calculated with the aid of the programs prep96 and parst97 with the exception of 138 and 137 where RES2INS was used. Errors are not available for 138 or 137.

Table 3.19 Olefin-olefin separations expressed in Å.

	44DPE	22DPE	24DPE	34DPE
R				
CR	3.88	3.89	3.72	3.69 (∞)
BR		3.81 (∞)	3.89	MA 3.60
ER	3.90	3.81 (∞)	3.94	3.64
HR	4.65	3.99		
MR	3.94			
OR	3.66	S 4.07	S/MA 3.89	MA 4.14 (∞)
	3.92	MA 4.15 (∞)	3.90	
DCR	3.78	4.12	4.00	3.75

Olefin...olefin separations are expressed as centre-to-centre distances and calculated using RES2INS.

S-inclusion of solvent

MA-misalignment of olefins (anti-parallel arrangement)

∞ - indicates an infinitely hydrogen bonded assembly

Table 3.20 Adjacent olefin separation expressed in Å.

	44DPE	22DPE	24DPE	34DPE
R		4.39	3.93	4.59
CR	3.93	3.81	3.94	6.27
BR	3.93	3.81	3.94	6.28
ER	6.08	7.41		
HR	5.80			
MR	6.97			4.80
OR	7.21		7.21	
DCR	6.67	7.39	5.65	7.10

Olefin...olefin separations are expressed as centre-to-centre distances and calculated using RES2INS.
S-inclusion of solvent

Table 3.21 Dihedral angles (°) between the aromatic ring of **T** and the pyridyl moiety of **DPE**.

	44DPE	22DPE	24DPE	34DPE
R		97.3 90.2	97.3 92.0 107.9 96.9	~
CR	103.6 108.4	90.8 94.8	104.6 102.5 104.2 98.0	100.4 97.7 117.0 111.3
BR	103.1 108.1	96.8 90.2	104.0 98.8 105.9 102.2	90.5 92.4 115.7 115.3
ER	134.9 125.3	93.4 104.8		
HR	133.3 114.5			
MR	109.6 116.6	~	116.3 99.0 98.9 90.5	~
OR	114.7 102.1	115.5 115.4	104.6 96.4 95.0 91.8	
DCR	104.5 112.9	106.6 103.8	108.3 111.1 105.3 97.3	105.6 108.0 113.2 103.1

Calculated with the aid of Utilty (NRCVax)

~ disordered structures with partial occupancies give a range of angles.

are parallel and eclipsed. Such observations provide further evidence for the utility of a supramolecular approach to rational solid-state engineering of reactivity.

3.2 Photochemical Studies

As stated, when olefins are aligned in the solid-state such that they are parallel and separated by $< 4.2 \text{ \AA}$, UV irradiation induces [2+2] photodimerization. This was observed in 19 of the 25 systems, in which, according to the supramolecular design strategy, a template molecule was used to align the olefins of four of the homologous family of **DPE** molecules in the solid-state. In fact, neither the introduction of functional groups about the periphery of the template nor changes in the location of the hydrogen-bond accepting sites within the reactant appreciably perturbed the solid-state reactivity of the olefins.

3.3 Photochemical Reactivity of the Pure Substrates

In a similar way to *trans*-stilbene, **44DPE**, **22DPE** and **24DPE** are photochemically inactive in their pure states.¹² In contrast, **34DPE** displays solid-state [2+2] photochemical behaviour.¹³ Such observations may be attributed to the crystal structures of the pure compounds of **44DPE**, **22DPE** and **34DPE** as discussed below. With single-crystal data for pure **24DPE** unavailable, photochemical experiments with a microcrystalline sample of **24DPE** indicated its stability towards photodimerization.¹⁴

As illustrated in Figure 3.2, **44DPE** self-assembles in the solid-state such that the molecules pack in layers in which neighbouring molecules lie approximately orthogonal to each other, interacting by way of C-H $\cdots$ N (H(6) $\cdots$ N(1) $2.938 \text{ \AA}$, H(2) $\cdots$ N(1) $2.971 \text{ \AA}$) hydrogen-bonds.¹⁵ Unlike **44DPE**, **22DPE** self-assembles such that a herringbone motif is

Figure 3.2 Space-filling diagrams illustrating the packing of **44DPE**: (a) a single layer and, (b) stacking layers.^{12b}

adopted between neighbouring molecules, stabilized by C-H $\cdots$ π interactions¹⁵, as illustrated in Figure 3.3. Notably, adjacent layers in both **44DPE** and **22DPE** interact by way of face-to-face π - π arene interactions (ring-ring separations of 3.80 Å and 3.81 Å, respectively) such that olefins between layers lie offset by 6.52 Å and 7.21 Å, respectively. With the criteria of the 'Topochemical Principle' not met it is not surprising that [2+2] photodimerization of either pure **44DPE** or pure **22DPE** does not occur in the solid-state.

Unlike both the symmetric **22DPE** and **44DPE**, as well as the non-symmetric **24DPE**, **34DPE** does display [2+2] photoreactivity in its pure crystalline form. As illustrated in Figure 3.4, molecules pack in a head-to-tail fashion with an olefin-olefin separation of 4.39 Å between the olefins of adjacent layers. Despite being beyond the 4.2 Å limit demarcated by the 'Topochemical Principle', **34DPE** dimerizes to yield a cyclobutane-based product consistent with the spatial orientations in the reactant crystal.¹³ Although photoactive in its pure form, the **34DPE** substrate was investigated to explore the diversity and reliability of using **R**-based templates to align olefins. Further, it was hoped access to the head-to-head cyclobutane photo-product, not available from the dimerization of pure solid **34DPE**.

3.3.1 Photochemical Reactivity of the **44DPE** Co-crystals

In contrast to pure **44DPE**, **44DPE** upon co-crystallization with seven different **R**-based molecules was photochemically active in all seven instances. Photolysis of the co-crystals of **44DPE** with the non-symmetric **ER**, **BR**, **CR** and **HR** as well as the symmetric **MR** and **DCR**, as determined by ¹H NMR spectroscopy, resulted in the formation of the *r*-1, *c*-2, *t*-3, *t*-4 cyclobutane dimer of **44DPE** (**44CB**) with yields as summarized in Table 3.14.

Figure 3.3 Space-filling representations based on the single crystal data for pure **22DPE**: (a) top-view of two layers of molecules illustrating the offset packing arrangement of nearest neighbour olefins and, (b) edge-on view of the layers depicting the herringbone motif adopted by the molecules.^{12b}

Figure 3.4 Space-filling representations based on the single crystal data for pure **34DPE**: (a) side-view of a layer of molecules illustrating the offset packing arrangement of nearest neighbour olefins and, (b) edge-on view of the layers depicting the twisted herringbone motif adopted by the molecules.¹³

The *rcctt* photo-product is depicted in Figure 3.5 in addition to the alternate *r*-1, *t*-2, *c*-3, *t*-4 cyclobutane dimer. ESI⁺-MS was used to confirm the presence of the dimerized product as the molecular ion peak at m/z 365.¹⁶

The *rcctt* stereochemistry of **44CB**, suggested by ¹H NMR values reported in the literature¹⁰, was further confirmed by the crystal structure of the photolyzed mixture of **MR** and **44CB**. In a similar way to the assembly of **R** and its derivatives with **44DPE**, **MR** assembles with **44CB** to form a discrete, cyclic hydrogen-bonded array, illustrated in Figure 3.6. Held together by four O-H...N hydrogen-bonds (O(1)...N(1) 2.761(4) Å, O(2)...N(2) 2.649(4) Å), the dihedral angles between the aromatics were found to be 108.8° N(1) and 103.4° N(2). ¹H NMR results indicate that in the seven different **44DPE** co-crystals examined, a solid-state reaction according to the 'Topochemical Principle' occurred.

Interestingly, the co-crystal of **44DPE** with **ER** displayed reactivity despite having an olefin-olefin separation of 4.65 Å, a distance considerably outside the generally accepted topochemical maximum 4.2 Å. As indicated previously, the upper limit of 4.2 Å was established because of a lack of experimental data between 4.2 and 4.7 Å.³ By ¹H NMR the conversion to the corresponding **44CB** in the case of the **ER** co-crystal was determined to be a modest 13%. Additionally it was found that the co-crystal of **44DPE** with **OR**, despite having a topochemical olefin-olefin separation of 3.92 Å, showed only a 5% conversion rate.

Although it was evident that photodimerization had occurred within the co-crystals containing **44DPE**, the possibility that the reaction had taken place between the olefins of adjacent hydrogen-bonded arrays and not necessarily within the cyclic arrays themselves,

(a)

(b)

Figure 3.5 Two possible stereochemical configurations of a cyclobutane dimer are the (a) *cis*-1,2, *cis*-3,4 and, (b) the *trans*-1,2, *trans*-3,4.

Figure 3.6 ORTEP perspectives of the (a) **MR-44DPE** co-crystal and, (b) its photo-product **MR-44CB**. Thermal ellipsoids are shown at a probability of 50 % and dashed lines indicate hydrogen-bonds.

necessitated examination. To rule out these possibilities, further inspection of the crystal structures involving **44DPE** revealed that the olefins of the surrounding cyclic arrays, with the exception of **BR** and **CR**, lie offset and are separated by distances $>5.5 \text{ \AA}$, as summarized in Table 3.20 and illustrated in Figure 3.7. These spatial relationships severely violate the 'Topochemical Principle' and along with the stereochemistry of the **44CB** in the **MR·44CB** co-crystal, strongly suggest that the photochemical reaction has indeed taken place within the cyclic dimers of the co-crystals of **44DPE** with **HR**, **ER**, **MR** and **DCR**.

Similar conclusions as to the nature of the dimerization of the olefins of **44DPE** iso-structural co-crystals of **BR** and **CR** can be drawn, despite the $3.93 \text{ \AA}$ separation that exists between cyclic arrays. Support for this conclusion was found in the dimerization yields and the associated statistics. Random dimerization events would result in the sequestration of single olefins without other olefins within reactive proximity (see Figure 3.8). The maximum yield of dimerization product is $86.5 \% (1 - 1/e^2)$ for cases of random dimerization.¹⁷ On this basis the observed yields of 100 % and 97 %, for the **CR** and **BR** co-crystals, respectively, confirmed that dimerization occurred primarily within the hydrogen-bonded cyclic arrays.

3.3.2 Photochemical Reactivity of the **22DPE** Co-crystals

In contrast to pure **22DPE**, **22DPE** upon co-crystallization with seven different **R**-based molecules was photochemically active in five instances. Photolysis of the co-crystals of **22DPE** with the unsymmetric **ER**, **BR** and **CR** as well as the symmetric **R** and **DCR**, resulted in the formation of the *r*-1, *c*-2, *t*-3, *t*-4 cyclobutane dimer of **22DPE** (**22CB**) with

Figure 3.7 The packing of adjacent assemblies within the **MR-44DPE** co-crystal is such that the olefins of adjacent assemblies are offset and separated by ~ 7.2 Å.

Figure 3.8 Schematic representation illustrating the isolated olefin environment created in random dimerization reactions.¹⁷

yields as summarized in Table 3.14, as determined by ^1H NMR spectroscopy. ESI⁺-MS was used to confirm the presence of the dimerized product as the molecular ion peak at m/z 365.

The *rcctt* stereochemistry of **22CB**, suggested by the ^1H NMR values reported in the literature^{12b}, was further confirmed by the crystal structure of the photolyzed mixture of **BR** and **22CB**. In contrast to the discrete hydrogen-bonded assembly observed for the co-crystal of **MR** with **44CB**, **BR** assembles with **22CB** to form an infinite, 1-D, hydrogen-bonded chain, as illustrated in Figure 3.9b. Tethered by two O-H...N hydrogen-bonds (O(1)...N(1) 2.740(2) Å, O(2)...N(2) 2.709(2) Å), the dihedral angles between the aromatics were found to be 95.0° N(1) and 85.0° N(2). ^1H NMR results indicated that in five of the seven different **22DPE** co-crystals examined, a solid-state reaction according to the 'Topochemical Principle' occurred.

In contrast to the discrete hydrogen-bonded cyclic arrays formed between co-crystals of **44DPE** with **R** and seven of its derivatives, only four of seven co-crystals involving **22DPE** formed similar discrete arrays. Of the four co-crystals involving **22DPE** tethered in a discrete fashion, the one involving **MR** also included a molecule of MeNO₂ and therefore only three of the seven co-crystals displayed the desired assembly pattern.

Rather than displaying the desired discrete four component assembly, co-crystals of **22DPE** with **CR**, **BR** and **OR** formed infinite 1-D hydrogen-bonded chains (see Figure 3.9a). Interestingly, the olefins in the **CR** and **BR** co-crystals displayed topochemical alignment and reacted to form the *rcctt*-**22CB** in conversion rates of 88% and 91%, respectively. In contrast, the **22DPE** olefins in the **OR** co-crystal were aligned in an anti-parallel fashion but still

Figure 3.9 Representations based on the single crystal XRD data illustrating the (a) 1D infinite hydrogen-bonded motif adopted by **BR** and **22DPE** where the hydrogen atoms not participating in hydrogen-bonds have been omitted and, (b) the photo-product: **BR·22CB**.

within the 4.2 Å of the 'Topochemical Principle'. Following the UV irradiation of the crystalline materials, the ^1H NMR analysis of the photolyzed material showed no evidence for [2+2] photodimerization.

Although the ^1H NMR results strongly suggested the dimerization of **22DPE** to the head-to-head **22CB** photo-product in the **R**, **ER** and **DCR** co-crystals, the possibility of reaction between the olefins of adjacent hydrogen-bonded arrays leading to the head-to-tail photo-product was also examined. Further inspection of the packing arrangements of the arrays within the crystal revealed that for **DCR** and **ER** the nearest neighbour olefins were offset and separated by > 7.0 Å, as summarized in Table 3.20. Once again, these spatial relationships violate the 'Topochemical Principle' and along with the stereochemistry of the **22CB** and **BR** co-crystal, strongly suggest that the photochemical reaction has indeed taken place within the cyclic dimers of the co-crystals of **22DPE** with **ER** and **DCR**.

In the case of the **R** co-crystal of **22DPE**, the distance between the olefins of adjacent assemblies was 4.4 Å, a distance outside the experimental limit of 4.2 Å but not without precedent for reaction. With 95% of the **22DPE** converted to **22CB** (*i.e.* more than the 86.5% statistically predicted for random reactions) as determined by ^1H NMR spectroscopy, the conclusion that the reaction occurred primarily between the olefins within hydrogen-bonded arrays seemed reasonable.

3.3.3 Photochemical Reactivity of the 24DPE Co-crystals

Upon co-crystallization with six different **R**-based molecules, **24DPE** displayed [2+2] photochemical reactivity in five of the six instances, in contrast to pure **24DPE** which is

photochemically inactive.¹⁴ Photolysis of the co-crystals of **24DPE** with the non-symmetric **BR** and **CR** and the symmetric **R**, **OR** and **DCR**, resulted in the formation of the *r*-1, *c*-2, *t*-3, *t*-4 cyclobutane dimer of **24DPE** (**24CB**) with yields summarized in Table 3.14, determined by ¹H NMR spectroscopy. ESI⁺-MS was used to confirm the presence of the dimerized product as the molecular ion peak at *m/z*⁺ 365.

The head-to-head *rctt* **24CB** photo-product resulted from photolysis of the co-crystals of **24DPE** with **R**, **BR**, **CR** and **DCR**, while the head-to-tail *rctt* photo-product (see Figure 3.10) resulted from the photolysis of the **OR** co-crystal. Assignment of the stereochemistry of the photo-products was determined by ¹H NMR analysis in conjunction with the crystal structure of both the isolated **24CB** from the photolyzed co-crystal of **24DPE** with **R**, and the crystal structure of **OR·24CB**. ¹H NMR results indicated that in five of the six different **24DPE** co-crystals examined, a solid-state reaction according to the 'Topochemical Principle' occurred.

With an *rctt* geometry, the pure **24CB** assembles into infinite hydrogen-bonded chains tethered by two C-H...N hydrogen-bonds (H(18)...N(1) 2.909(5) Å, H(6)...N(2) 2.905(5) Å) per molecule. Unlike the head-to-head nature of **24CB**, a head-to-tail orientation existed in the **OR·24CB** co-crystal. Tethered by two O-H...N hydrogen-bonds (O(1)...N(1) 2.685(2) Å, O(4)...N(3) 2.673(2) Å), two molecules of **OR** interacted by way of OH...O hydrogen-bonds (O(2)...O(3) 2.761(2) Å, O(2)...O(5) 2.621(2)) and the dihedral angles between the aromatics were 104.6° N(1) and 100.0° N(3). Unlike the discrete assembly of **MR** with **44CB**, **OR** and **24CB** assembled to form an infinite 1D hydrogen-bonded polymer. The

Figure 3.10 A space-filling representation based on the single crystal XRD of the interactions between the **24CB** photo-product with **OR** resulting in an infinite 1D hydrogen-bonded polymer. Two molecules of water, also part of the assembly, have been omitted for clarity.

infinite hydrogen-bonding pattern in the **OR·24CB** co-crystal is similar to that found for the **BR·22CB** co-crystal with the exception that two molecules of water are also incorporated into the structure.

In each of the six different co-crystals involving **24DPE**, discrete four component hydrogen-bonded cyclic arrays resulted, similar to those observed for all of the **44DPE** co-crystals and four of the **22DPE** co-crystals. In a similar fashion to the **22DPE** co-crystal with **MR**, the **24DPE** co-crystal also included a molecule of MeNO_2 and as a consequence of the photochemical behaviour of MeNO_2 ¹⁸, the solid-state photochemistry of the **MR·24DPE** co-crystals was not investigated. Of the five remaining co-crystals involving **24DPE**, all displayed topochemical alignment of the olefins.

Despite the fact that ¹H NMR results strongly suggested that the dimerization behaviour of **24DPE** in each of the five co-crystals investigated occurred between the olefins within a single hydrogen-bonded assembly, the possibility of reaction of the olefins of adjacent hydrogen-bonded assemblies was addressed. Further inspection of the packing arrangements of the arrays within the crystal revealed that for the symmetric **DCR** and **OR**, the nearest neighbour olefins were offset and separated by 5.65 Å and 7.21 Å, respectively, or in other words, well outside the distance criterion of the 'Topochemical Principle'. Additionally, the nearest neighbour olefin in the **DCR** co-crystal were aligned in a head-to-tail fashion such that photodimerization would have generated a cyclobutane product with alternating 4- and 2-pyridyl substituents, rather than the spatial arrangement in the observed product.

For the **BR**, **CR** and **R** co-crystals involving **24DPE**, the distance between the olefins of adjacent assemblies was less than 4 Å in each instance, well within topochemical limits. In a similar manner to the **DCR** and **OR** co-crystals, adjacent assemblies in the **R** co-crystal packed in a head-to-tail fashion and the observed ^1H NMR spectrum allowed for the conclusion that reaction occurred between the olefins within hydrogen-bonded arrays. Unlike the **R** co-crystal, adjacent assemblies in the iso-structural **BR** and **CR** co-crystals of **24DPE** packed such that the olefins of adjacent assemblies were aligned in a head-to-head fashion. With yields of greater than the statistically random maximum of 86.5 %, the conversion of **24DPE** to **24CB** in the co-crystals of **BR** and **CR** was concluded to occur within hydrogen-bonded arrays rather than between the olefins of adjacent assemblies.

3.3.4 Photochemical Reactivity of the 34DPE Co-crystals

Co-crystallization with five different **R**-based molecules, **34DPE** displayed [2+2] photochemical reactivity in three instances. As mentioned previously, **34DPE** is photochemically active in its pure form and UV irradiation leads to the head-to-tail *rcit*-cyclobutane product. It was hoped that utilizing a co-crystal approach that a head-to-head packing arrangement of the olefins could be induced and the head-to-head photo-product accessed.

Photolysis of the co-crystals of **34DPE** with the non-symmetric **CR** and **BR** and the symmetric **DCR** resulted in the formation of the head-to-head *r*-1, *c*-2, *t*-3, *t*-4 cyclobutane dimer of **34DPE** (**34CB**), as illustrated in Figure 3.11, with yields as summarized in Table 3.14. Assembling in a 3:1 ratio (**DCR**:**34CB**), two molecules of **DCR** tethered one molecule

(a)

(b)

Figure 3.11 Based on the single crystal XRD data (a) a space-filling representation of the interaction of **DCR** and **34DPE** and, (b) a ball-and-stick representation of the the photo-product: **DCR·34CB**.

of **34CB** by four O-H...N hydrogen-bonds (O(1)...N(1) 2.709(3) Å, O(2)...N(3) 2.713(4) Å, O(3)...N(2) 2.629(4) Å, O(4)...N(4) 2.653(4) Å), with the dihedral angles between the aromatic ring of **DCR** and the pyridyl rings found to be 99.1° N(1), 106.4° N(2), 92.3° N(3) and 108.3° N(4).

Assignment of the stereochemistry of the photo-products was accomplished by ¹H NMR analysis in conjunction with the crystal structure of the re-crystallized photo-products of **34DPE** with **DCR**. ¹H NMR results indicated that in three of the five **34DPE** co-crystals examined, a solid-state reaction according to the 'Topochemical Principle' occurred. ESI⁻ MS was used to confirm the presence of the dimerized product (molecular ion peak at *m/z*⁻ 365).

Discrete four component hydrogen-bonded cyclic arrays with topochemical alignment of the olefins resulted in the co-crystals of **34DPE** with **BR** and **DCR**. Interestingly, the **DCR·34DPE** co-crystal assembled in a 3:2 stoichiometry rather than a 1:1 stoichiometry. Unlike the **BR** co-crystal, the olefins of **34DPE** in the **CR** co-crystal were aligned in an anti-parallel orientation. Surprisingly, despite the anti-parallel olefin alignment in the **CR·34DPE** co-crystal reaction occurred in virtually quantitative yield.

Similar to the **CR·34DPE** co-crystal, an anti-parallel arrangement of the **34DPE** olefins in the **MR** co-crystal resulted. Self-assembling in a 3:2 (**MR:34DPE**) stoichiometry, an infinite O-H...N hydrogen-bonded polymer resulted. Unlike the three previous co-crystals involving **MR**, the oxygen of the methoxy group was participating in the O-H...N hydrogen-

bonding pattern. The interaction of **R** with **34DPE** also resulted in an infinite 1D hydrogen-bonded polymer, in which the olefins displayed a head-to-tail topochemical alignment.

An examination of the packing arrangement adopted in the **DCR** and **BR** co-crystals revealed that the nearest neighbour olefins belonging to different assemblies were separated by more than 6 Å. It was therefore concluded that reaction had occurred within the hydrogen-bonded assemblies. Furthermore, the nearest neighbour olefins were oriented head-to-tail rather than head-to-head and would have resulted in the formation of a head-to-tail rather than the observed head-to-head dimerization photo-product. In addition, the virtually quantitative conversion allows the conclusion that the reactions took place within the hydrogen-bonded arrays and not in a random fashion.

3.4 Implications for Design

In general, the approximately orthogonal geometry and dimeric face-to-face stacking arrangements adopted by **R** and **44DPE** were observed in the majority of the 25 different co-crystals examined. Further, in 20 of the 25 cases, discrete four component hydrogen-bonded assemblies were formed. This reproducibility suggests that a supramolecular approach to steering olefins into reactive alignment based on **R** or its derivatives was indeed a rational way to design reactive solids. Effectively what has been demonstrated was that most of the time **R** or its derivatives were able 'clip' together two molecules of **DPE** such that they were pre-disposed to undergo [2+2] photodimerization.

Although not every co-crystal combination displayed the discrete topochemical hydrogen-bonding motif, the majority did. Interestingly, some of the co-crystals which did

not conform to this motif often involved substituents about the core of **R** that could participate in additional non-covalent interactions (*e.g.* **MR**, **CR**, **BR**). With an incomplete understanding of the subtle forces that drive crystal packing, this was of little surprise.¹⁹ What was encouraging was the high success rate when compared to the well documented fact that members of a homologous family of molecules are not typically iso-structural.² Despite the small number of non-conforming co-crystals the fact still remained that for the majority of co-crystals examined the introduction of functionality about **R** and the altering of the nature of the substrate did not appreciably perturb the reactivity.

Notably, this approach, although not 100 % reliable, can claim certain advantages over previous attempts to induce reactive solid-state olefin alignment. These advantages include:

- (1) reliability (*i.e.* beyond a 'hit or miss' approach),
- (2) circumventing the need for introduction of additional functionality into the photolyzed product (*e.g.* fluorine),
- (3) eliminating the size constraints of a reaction cavity, and finally,
- (4) application to a wider variety of reactants.

In short, this approach does circumvent many of the pitfalls of previous attempts in this field and takes a step closer to not only establishing a potentially general method for aligning olefins in the solid-state, but also towards making the solid-state a viable alternate medium for conducting synthesis.

4.0 Chapter Three: Conclusions

The discrete hydrogen-bonded motif initially reported¹ to exist between **R** and **44DPE** was found in 80 % of the investigated co-crystals. Guided by supramolecular interactions, photo-reactivity of the four **DPE** substrates was found in 19 systems, typically in excellent yield, resulting in the formation of the expected photo-product. The only anomaly between the photo-product expected from the relative reactant orientations involved **OR** and **24DPE**. DSC measurements did not indicate any phase change behaviour in the temperature range where the reaction was performed at, suggesting possibly the existence of a polymorph and requiring further study of this system.

4.1 Future Work

The single crystal XRD and photochemical experiments described in this chapter have led to a number of new questions. First is the question of the behaviour of the two members of the homologous family of **DPE** substrates not investigated here. The photochemical behaviour of **23DPE** and **33DPE** as co-crystals with **R**-based molecules will complete the investigation of the family of **DPE** molecules. From here the introduction of substituents onto the six different **DPE** substrates is a logical direction. Further along these lines, the possibility of interchanging the hydrogen-bond accepting and donating sites is also of interest in terms of probing not only the limits of this approach, but also its reliability.

Second, preliminary studies involving substrates with multiple reaction centres indicated that it was possible to induce multiple reactions in a single substrate using this supramolecular approach to olefin alignment.¹ This would provide an efficient route to

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macrocycles such as cyclophanes. A third possibility is utilizing the extended aromatic photo-products as electron transfer bridges in multi-nuclear organometallic complexes.

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Chapter IV: Mono-pyridines as Substrates

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1.0 Introduction

With the encouraging results from the studies involving **DPE**, we continued to explore the limits of reactant diversity and further test the reliability of this supramolecular approach to inducing solid-state olefin alignment. The intent was both to modify the substrate by introducing functionality onto it, as well as alter the nature of the template-substrate interaction. It was hoped that this study would further expand the library of substrates able to be aligned in this manner and test the reliability with which a similar non-covalent assembly was formed.

The mono-hydrogen-bond accepting olefins (*E*)-1-(4-chlorophenyl)-2-(4-pyridyl)ethylene (**CSP**) and (*E*)-1-(4-bromophenyl)-2-(4-pyridyl)ethylene (**BSP**) were chosen as substrates. Substituted styrylpyridines (**SP**) were chosen as substrates for several reasons: they were previously described in the literature¹, the photochemical activity of unsubstituted **SPs** in the solid-state was already established², and using monopyridines would determine if a template:substrate ratio of 2:1 would still allow for reactive olefin alignment.

Of particular interest was how the olefin alignment and photoreactivity was affected. In order to compare the behaviour of the **CSP** and **BSP** substrates relative to **DPE**, both symmetric and non-symmetric resorcinol-based (**R**) molecules were used as potential templates. Characterization of the olefin alignment was studied by single crystal XRD, both at low and room temperature.

2.0 Experimental

2.1 General Details

All reagents, unless otherwise noted, were purchased from Aldrich Chemical Company and used as received. ^1H NMR spectra were obtained on a Bruker DRX-400 (^1H 400.13 MHz) 400 MHz NMR spectrometer and ESI^+ -MS analysis (CB Group, SIMS, NRC) was carried out on a VG Quattro I (Micromass) mass spectrometer equipped with a pneumatically-assisted electrospray source, operating in positive mode.

2.2 Single Crystal X-ray Crystallography

Single crystals were individually mounted on the end of a glass fibre and optically centered on the goniometer of a Siemens SMART CCD diffractometer for data collection. Initial cell constants were calculated from reflections harvested from three sets of 20 or 25 frames. Final cell constants were calculated from reflections obtained from the full data collection. All structures were solved using direct methods. After anisotropic refinement of all non-hydrogen atoms, methine, methylene, methyl, aromatic, and hydroxyl hydrogens were placed by modeling the moieties as rigid groups with idealized geometry, maximizing the sum of the electron density at the calculated hydrogen positions. A summary of the data collection parameters for all of the **CSP** and **BSP** structures collected are given in Tables 4.1-4.4. (All other crystallographic tables are found on the accompanying CD and a list of the structure codes can be found in Table S4.1.) Structure solutions were conducted using SHELXS-96³ and refined using SHELXL93⁴, locally implemented on a Pentium-based IBM compatible computer. Crystallographic manipulations were performed with the aid of

Table 4.1 Crystal Data for T-CSP

	ER (126)	CR (85)	BR (112)	R (130)	OR (135)	MR (84)	DCR (134)
formula	$C_{34}H_{30}N_2O_2Cl_2$	$C_{32}H_{23}N_2O_2Cl_3$	$C_{32}H_{23}N_2O_2Cl_2$	$C_{32}H_{26}N_2O_2Cl_2$	$C_{33}H_{28}N_2O_2Cl_2$	$C_{33}H_{24}N_2O_2Cl_3$	$C_{32}H_{24}N_2O_2Cl_4$
formula weight	569.50	575.89	620.35	541.45	555.47	571.47	610.33
space group	$P 2_1/n$	P -1	P -1	P -1	P -1	P -1	P -1
T, K	173(2)	173(2)	173(2)	173(2)	173(2)	173(2)	173(2)
a, Å	8.5725(5)	10.0244(6)	9.9934(9)	9.9260(5)	9.3814(9)	10.2932(10)	10.2066(4)
b, Å	36.722(2)	10.5121(6)	10.6777(9)	10.2028(5)	10.5330(10)	11.4529(12)	10.6414(5)
c, Å	10.7456(4)	13.6189(8)	13.5429(12)	13.8652(7)	15.8596(15)	13.2790(14)	13.9223(6)
α , °	90	100.747(1)	101.254(2)	105.453(1)	105.893(2)	67.607(2)	109.734(1)
β , °	120.720(3)	101.872(1)	100.893(2)	97.863(1)	96.256(2)	80.172(2)	93.281(1)
γ , °	90	94.810(1)	94.868(2)	92.480(1)	107.694(2)	79.142(2)	98.337(1)
V, Å ³	2908.0(3)	1368.6(1)	1380.6(2)	1336.0(1)	1404.0(2)	1413.0(3)	1399.1(1)
Z	4	2	2	2	2	2	2
ρ_{calc} , g cm ⁻³	1.301	1.397	1.492	1.346	1.314	1.343	1.449
μ , mm ⁻¹	0.257	0.369	1.716	0.276	0.265	0.267	0.457
# Reflections	34774	10027	10095	15989	17757	10397	17764
# Unique	7554	6984	7052	6866	7810	7245	7770
$2\theta_{max}$	60	60	60	60	60	60	60
R_i ($I > 2\sigma(I)$)	0.0716	0.0509	0.0598	0.0351	0.0536	0.0688	0.0370
wR ₂ (all data)	0.1986	0.1144	0.1217	0.0971	0.1403	0.1313	0.0926
Goof on F ²	1.008	1.005	0.961	1.065	1.034	0.887	1.023

Table 4.2 Crystal Data for **T·BSP**

	R (89)	ER (128)	CR (88)	BR (113)	MR (87)	DCR (129)
formula	C ₃₂ H ₂₆ N ₂ O ₂ Br ₂	C ₃₄ H ₃₀ N ₂ O ₂ Br ₂	C ₆₄ H ₅₀ N ₄ O ₄ Br ₄ Cl	C ₆₄ H ₅₀ N ₄ O ₄ Br ₆	C ₃₃ H ₂₈ N ₂ O ₃ Br ₃	C ₃₂ H ₂₄ N ₂ O ₂ Br ₂ Cl
formula weight	630.37	658.42	1329.62	1418.54	660.39	699.25
space group	P -1	P 2 ₁ /n	P -1	P -1	P -1	P -1
T, K	173(2)	173(2)	173(2)	173(2)	173(2)	173(2)
a, Å	9.9237(4)	8.5883(5)	13.8926(5)	13.9363(5)	10.2529(4)	10.2574(5)
b, Å	10.2721(5)	37.042(2)	14.4789(5)	14.5847(5)	11.5662(5)	10.6538(5)
c, Å	13.9556(6)	9.7822(5)	14.7013(6)	14.7084(5)	13.6068(6)	14.0583(7)
α, °	105.840(1)	90	78.682(1)	79.293(1)	66.340(1)	109.749(1)
β, °	97.695(1)	108.1650(10)	79.741(1)	79.924(1)	79.777(1)	93.191(1)
γ, °	92.959(1)	90	74.596(1)	74.572(1)	78.554(1)	99.220(1)
V, Å ³	1350.4(1)	2956.9(3)	2770.6(2)	2806.7(2)	1439.9(1)	1417.3(1)
Z	2	4	2	2	2	2
ρ _{calc} , g cm ⁻³	1.550	1.479	1.594	1.679	1.523	1.639
μ, mm ⁻¹	3.034	2.775	3.056	4.345	2.852	3.082
# Reflections	16125	26545	20262	25523	17237	16964
# Unique	6952	5208	14114	9885	7404	7281
2θ _{max}	60	50	60	50	60	60
R _i (<i>I</i> > 2σ(<i>I</i>))	0.0281	0.0694	0.0375	0.0369	0.0316	0.0274
wR ₂ (all data)	0.0697	0.1814	0.0788	0.0657	0.0708	0.0670
Goof on F ²	0.990	1.113	0.938	0.953	0.969	1.038

Table 4.3 Room Temperature Crystal Data for T-CSP

	R (147)	MR (152)	DCR (155)
formula	C ₃₂ H ₂₆ N ₂ O ₂ Cl ₂	C ₃₃ H ₂₈ N ₂ O ₃ Cl ₂	C ₃₂ H ₂₄ N ₂ O ₂ Cl ₄
formula weight	541.45	571.47	610.33
space group	<i>P</i> -1	<i>P</i> -1	<i>P</i> -1
<i>T</i> , K	446(2)	446(2)	446(2)
<i>a</i> , Å	10.0329(9)	10.527(5)	10.3712(11)
<i>b</i> , Å	10.4015(10)	11.549(6)	10.7215(11)
<i>c</i> , Å	10.8410(13)	13.236(6)	13.9579(14)
α , °	105.410(2)	67.703(9)	109.583(2)
β , °	98.430(2)	80.458(10)	93.816(2)
γ , °	92.652(2)	79.238(10)	97.688(2)
<i>V</i> , Å ³	1371.9(2)	1454.6(12)	1438.8(3)
<i>Z</i>	2	2	2
ρ_{calc} , g cm ⁻³	1.311	1.305	1.409
μ , mm ⁻¹	0.269	0.260	0.445
$2\theta_{\text{max}}$	60	60	50
# Reflections	16430	17342	12917
# Unique	7081	7488	5057
<i>R</i> ₁ (<i>I</i> > 2 σ (<i>I</i>))	0.0463	0.0554	0.0577
<i>wR</i> ₂ (all data)	0.1346	0.1571	0.1755
Goof on F ²	0.821	0.766	1.009
Disorder (site occupancies)	85:15 and 85:15	75:25	70:30 and 70:30

Table 4.4 Room Temperature Crystal Data for T·BSP

	R (144)	MR (148)	DCR (154)
formula	C ₃₃ H ₂₆ N ₂ O ₂ Br ₂	C ₃₃ H ₂₄ N ₂ O ₂ Br ₂	C ₃₂ H ₂₄ N ₂ O ₂ Br ₂ Cl ₂
formula weight	630.37	660.39	699.25
space group	<i>P</i> -1	<i>P</i> -1	<i>P</i> -1
T, K	446(2)	446(2)	446(2)
<i>a</i> , Å	9.997(7)	10.4793(6)	10.4291(10)
<i>b</i> , Å	10.462(3)	11.6130(7)	10.7015(11)
<i>c</i> , Å	13.952(8)	13.5581(8)	14.0996(14)
α , °	105.88(3)	66.6080(10)	109.652(2)
β , °	97.99(3)	80.2240(10)	93.633(2)
γ , °	93.04(4)	78.7120(10)	98.570(2)
<i>V</i> , Å ³	1383.5(13)	1477.27(15)	1454.5(3)
<i>Z</i>	2	2	2
ρ_{calc} , g cm ⁻³	1.513	1.485	1.597
μ , mm ⁻¹	2.962	2.780	3.004
# Reflections	16622	17763	17338
# Unique	7182	7611	7494
$2\theta_{\text{max}}$	60	60	60
R_1 ($I > 2\sigma(I)$)	0.0384	0.393	0.0437
wR_2 (all data)	0.1096	0.1056	0.0983
GooF on F ²	0.930	0.869	0.0783
Disorder (site occupancies)	none	76:24	70:30 and 85:15

RES2INS⁵ and graphical representations were generated using a combination of RES2INS, Diamond⁶, and Atoms⁷.

2.3 Thermal Gravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) Measurements

TGA measurements were done using a 2050 Thermogravimetric Analyzer (TA Instruments) with nitrogen as the purge gas at a flow rate of 40 cc/min. The TGA samples (10-20 mg) were ramped from room temperature to 450°C at a rate of 5°C/min in open aluminum pans. A TA Instruments 2920 Modulated DSC with helium purge gas at a flow rate of 50 cc/min was used to collect DSC measurements. Similarly, the DSC samples (5-10 mg) were ramped from room temperature to 450°C at a rate of 5°C/min in hermetically sealed pans. Onset temperatures are reported for all co-crystals in the supplemental section.

2.4 Synthesis of (*E*)-1-(4-halophenyl)-2-(4-pyridyl)ethylene (XSP where X=Cl or Br)

Both **XSP** substrates were synthesized by Perkin condensation⁸ of freshly distilled 4-methylpyridine with the appropriate 4-halobenzaldehyde in refluxing acetic anhydride (80°C) for 18 hours. Upon heating, the clear, colourless solution turned yellow and subsequently resulted in a black tarry liquid which was then diluted with 100 mL of water. Upon alkalization with 1.0 M NaOH, the solution turned milky white and a brown solid precipitated. The recovered precipitate was then dried under vacuum, extracted with hexanes and isolated. Evaporation of the solvent resulted in a yellow solid which was then sublimed under reduced pressure to yield either **CSP** or **BSP**.

2.4.1 Synthesis of (*E*)-1-(4-chlorophenyl)-2-(4-pyridyl)ethylene (CSP)

4-Methylpyridine (8.3 mL, 0.085 mol) and 4-chlorobenzaldehyde (11.949 g, 0.085 mol) were condensed to yield: 6.600 g, 0.031 mol, 36 % (crude **CSP**); 5.280 g, 0.024 mol, 28 % (pure **CSP**). Suitable crystals for single crystal XRD measurement were collected from the sublimator and characterization by ¹H NMR gave chemical shifts similar to those reported in the literature.¹

2.4.2 Synthesis of (*E*)-1-(4-bromophenyl)-2-(4-pyridyl)ethylene (BSP)

4-Methylpyridine (11.0 mL, 0.113 mol) and 4-bromobenzaldehyde (20.919 g, 0.113 mol) were condensed to yield: 12.344 g, 0.047 mol, 42 % (crude **BSP**); 8.324 g, 0.032 mol, 28 % (pure **BSP**). Suitable crystals for single crystal XRD measurement were collected from the sublimator and characterization by ¹H NMR gave chemical shifts similar to those reported in the literature.¹

2.5 Preparation of T·XSP Co-crystals

In general, an equimolar amount of template (**T**) and **XSP** were dissolved in a suitable hot solvent or solvent pair and allowed to cool undisturbed under ambient conditions. When CH₂Cl₂ was used as part of a solvent pair, it was added after dissolution during cooling. Crystals suitable for X-ray diffraction were collected and dried under ambient conditions. Table 4.5 and 4.6 give details of the exact experimental conditions used for growth of the co-crystals of **CSP** and **BSP**.

2.6 Photochemistry

Photochemical experiments were carried out using a Rayonet reaction chamber

Table 4.5 Experimental Crystallization Data for T·CSP

	R	CR	BR	ER	OR	MR	DCR
amount CSP	0.248g 1.15 mmol	0.156g 0.726 mmol	0.188g 0.874 mmol	0.126g 0.586 mmol	0.133g 0.619 mmol	0.222g 1.03 mmol	0.119g 0.553 mmol
amount T	0.128g 1.16 mmol	0.106g 0.733 mmol	0.166g 0.878 mmol	0.080g 5.80 mmol	0.076g 0.613 mmol	0.146g 1.04 mmol	0.100g 0.559 mmol
solvent (1:1) volume (mL)	EtOH CHCl ₃ 20	EtOH CHCl ₃ 20	EtOH CHCl ₃ 20	EtOH CHCl ₃ 20	EtOH CHCl ₃ 20	EtOH CHCl ₃ 20	EtOH CHCl ₃ 30
yield	0.350g 93 %	0.213g 77 %	0.306g 86 %	0.100g 49 %	0.144g 70 %	0.333g 90 %	0.149g 65 %
crystal habit	colourless blocks	colourless blocks	colourless blocks	yellow	colourless blocks	colourless blocks	beige blocks
crystallization time (hours)	18	32	34	17	44	17	11
structure code	jlr130	jlr85	jlr112	jlr126	jlr135	jlr84	jlr134

Table 4.6 Experimental Crystallization Data for T·BSP

	R	CR	BR	ER	MR	DCR
amount BSP	0.189g 0.727 mmol	0.155g 0.596 mmol	0.178g 0.685 mmol	0.169g 0.650 mmol	0.208g 0.800 mmol	0.232g 0.892 mmol
amount T	0.079g 0.718 mmol	0.086g 0.595 mmol	0.130g 0.688 mmol	0.090g 0.651 mmol	0.111g 0.793 mmol	0.160g 0.894 mmol
solvent (1:1) volume (mL)	EtOH CH ₂ Cl ₂ 20	EtOH CH ₂ Cl ₂ 20	EtOH CH ₂ Cl ₂ 20	EtOH CH ₂ Cl ₂ 20	EtOH CH ₂ Cl ₂ 20	EtOH CH ₂ Cl ₂ 30
yield	0.220g 82 %	0.194g 80 %	0.256g 83 %	0.178g 69 %	0.269g 87 %	0.311g 79 %
crystal habit	colourless blocks	colourless blocks	colourless blocks	colourless blocks	colourless blocks	beige blocks
crystallization time (hours)	22	26	26	48	22	12
structure code	jlr89	jlr88	jlr113	jlr128	jlr87	jlr129

modified for solid samples. Crystalline samples were ground up and sandwiched between two fused silica glass plates which were placed in a merry-go-round apparatus within the reaction chamber. Irradiation was carried out for approximately 24 hours at 350nm at temperatures between 37°C and 41°C (100 to 200 mg sample). The irradiated samples were characterized by ^1H NMR and ESI⁻-MS. Yield and MS data for each of the irradiated samples are summarized in Table 4.7 while ^1H NMR data is summarized in Tables 4.8- 4.9.

2.7 The Photo-products

A summary of the single crystal XRD data for the various co-crystals involving the photo-products is given in Table 4.10.

2.7.1 The CCB Photo-product

The photolyzed microcrystalline **R•CSP** was dissolved in 20 mL of EtOH and to this 0.5 mL of benzene was added. Colourless, block-like crystals suitable for XRD studies were isolated upon evaporation (48 hours). The **CCB** photo-product was then isolated by dissolving the photolyzed mixture of **R•CSP** in 30 mL of CHCl_3 and treating it with an aqueous solution of Na_2CO_3 . The **CCB** photo-product was then extracted into the organic phase and recovered after removal of the solvent. ^1H NMR spectroscopy and spot TLC indicated both the success and purity of the separation. The ^1H NMR chemical shifts were identical to those reported for the photo-products (minus the template resonances).

2.7.2 The BCB Photo-product

The photolyzed microcrystalline **R•BSP** was dissolved in 20 mL of EtOH and to this 0.5 mL benzene was added. Colourless, block-like crystals suitable for X-ray diffraction

Table 4.7 Yield and MS data for the **XSP** in irradiated co-crystals.

Co-crystal	Yield (%)	ESI⁺-MS*
R·CSP	95	431.1(35) 216.0(100)
MR·CSP	92	431.1(12) 216.0(100)
ER·CSP	86	431.1(16) 216.2(100)
BR·CSP	98	431.1(28) 216.2(100)
CR·CSP	99	431.1(32) 216.2(100)
OR·CSP	100	431.1(25) 216.1(100)
DCR·CSP	86	431.1(23) 216.0(100)
R·BSP	97	521.1(21) 262.2(80)
MR·BSP	82	521.1(18) 262.2(91)
ER·BSP	0	262.2(96)
CR·BSP	96	521.1(22) 262.2(88)
BR·BSP	93	521.1(18) 261.2(100)
DCR·BSP	38	521.1(4) 262.2(95)

* M⁺ and M⁺⁺

In 12 of 13 co-crystals, photodimerization occurred with formation of the expected photo-product.

Table 4.8 ¹H NMR Data for T-CCB

(δ in ppm, multiplicity, number of protons, coupling in Hz)							
	R(130)	CR (85)	BR (112)	ER (126)	OR (135)	MR (84)	DCR (134)
NCH	8.32, d, 4H, ³ J _{HH} 5.9 Hz	8.33, d, 4H, ³ J _{HH} 5.9 Hz	8.33, d, 4H, ³ J _{HH} 5.9 Hz	8.33, d, 4H, ³ J _{HH} 5.9 Hz	8.33, d, 4H, ³ J _{HH} 5.5 Hz	8.33, d, 4H, ³ J _{HH} 5.9 Hz	8.33, d, 4H, ³ J _{HH} 5.9 Hz
NCHCH o-CH (Ph) m-CH (Ph)	7.19-7.25, m, 12H	7.20-7.26, m, 12H	7.20-7.26, m, 12H	7.18-7.25, m, 12H	7.20-7.26, m, 12H	7.18-7.25, m, 12H	7.18-7.25, m, 12H
Py-(CH) ₄ -Ph	4.58, bs, 4H	4.58, bs, 4H	4.58, bs, 4H	4.58, bs, 4H	4.58, bs, 4H	4.58, bs, 4H	4.59, bs, 4H
Template	9.17, s, 2H	9.91, bs, 1H	10.01, s, 1H	9.01, s, 1H	9.03, s, 2H	9.18, s, 2H	10.24, s, 2H
	6.91, t, 1H	9.43, bs 1H	9.49, s, 1H	8.91, s, 1H	6.00, s, 3H	5.79, d, 3H	7.27, s, 1H
	6.28, m, 3H	7.05, d 1H	7.18, d, 1H	6.79, d, 1H	2.10, s, 3H	3.62, s, 3H	6.66, s, 1H
		6.42-6.43, m, 1H	6.44, d, 1H	6.25, d, 1H			
		6.20-6.23, m, 1H	6.19, dd, 1H	6.12, dd, 1H			
				2.40, q, 2H			
				1.06, t, 3H			

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Where s refers to singlet, d doublet, t triplet, q quartet, dd doublet of doublet, ddd doublet of doublet of doublets, and m multiplet.

Table 4.9 ^1H NMR Data for T-BCB

(δ in ppm, multiplicity, number of protons, coupling in Hz)					
	R (89)	CR (88)	BR (113)	MR (87)	DCR (129)
NCH	8.33, d, 4H, $^3J_{\text{HH}}$ 6.1 Hz	8.33, d, 4H, $^3J_{\text{HH}}$ 6.1 Hz	8.33, d, 4H, $^3J_{\text{HH}}$ 5.9 Hz	8.33, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz	8.33, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz
C_6H_4	7.36, d, 4H, $^3J_{\text{HH}}$ 8.4 Hz	7.36, d, 4H, $^3J_{\text{HH}}$ 8.4 Hz	7.36, d, 4H, $^3J_{\text{HH}}$ 8.4 Hz	7.36, d, 4H, $^3J_{\text{HH}}$ 8.3 Hz	7.36, d, 4H, $^3J_{\text{HH}}$ 8.3 Hz
NCHCH	7.20, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz	7.20, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz	7.20, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz	7.20, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz	7.20, d, 4H, $^3J_{\text{HH}}$ 6.0 Hz
C_6H_4	7.17, d, 4H, $^3J_{\text{HH}}$ 8.4 Hz	7.17, d, 4H, $^3J_{\text{HH}}$ 8.4 Hz	7.17, d, 4H, $^3J_{\text{HH}}$ 8.4 Hz	7.17, d, 4H, $^3J_{\text{HH}}$ 8.4 Hz	7.17, d, 4H, $^3J_{\text{HH}}$ 8.4 Hz
Py-(CH) $_4$ -Ph	4.57, bs, 4H	4.57, bs, 4H	4.57, bs, 4H	4.57, bs, 4H	4.56, bs, 4H
Template	9.15, s, 2H 6.91, t, 1H 6.18, m, 3H	9.91, bs, 1H 9.43, bs 1H 7.05, d 1H 6.43, d, 1H 6.21, dd, 1H	10.01, s, 1H 9.49, s, 1H 7.18, d, 1H 6.44, d, 1H 6.19, dd, 1H	9.20, s, 2H 5.84, s, 1H 5.79, s, 2H 3.62, s, 3H	10.22, s, 2H 7.27, s, 1H 6.66, s, 1H

Where s refers to singlet, d doublet, t triplet, q quartet, dd doublet of doublet, ddd doublet of doublet, and m multiplet.

Table 4.10 Crystal Data for XSP Photo-products

	R·CCB (139)	R·BCB (143)
formula	$C_{36}H_{26}N_2O_2Br_2$	$C_{36}H_{30}N_4O_4Br_2$
formula weight	541.45	630.37
space group	<i>C</i> 2/c	<i>P</i> -1
<i>T</i> , K	173(2)	173(2)
<i>a</i> , Å	38.240(4)	7.8446(14)
<i>b</i> , Å	9.4629(9)	9.7501(13)
<i>c</i> , Å	14.9714(14)	19.843(4)
α , °	90	75.86(2)
β , °	98.193(3)	80.03(2)
γ , °	90	68.36(2)
<i>V</i> , Å ³	5362.3(9)	1362.1(4)
<i>Z</i>	8	2
ρ_{calc} , g cm ⁻³	0.275	1.537
μ , mm ⁻¹	0.069	3.008
# Reflections	23381	9848
# Unique	4727	3575
$2\theta_{\text{max}}$	50	45
R_1 ($I > 2\sigma(I)$)	0.0670	0.0378
wR_2 (all data)	0.1776	0.0815
GooF on F ²	1.069	0.947

studies were isolated upon evaporation (48 hours). The **BCB** photo-product was then isolated by dissolving the photolyzed mixture of **R•BSP** in 30 mL of CHCl_3 and treating it with an aqueous solution of Na_2CO_3 . The **BCB** photo-product was then extracted into the organic phase and recovered after removal of the solvent. ^1H NMR spectroscopy and spot TLC indicated both the success and purity of the separation. The ^1H NMR chemical shifts were identical to those reported for the photo-products (minus the template resonances).

3.0 Results and Discussion

In general, co-crystallization of **BSP** or **CSP** with either the parent **R** template, or one of its derivatives, resulted in the formation of two *inter*-molecular hydrogen-bonds between the pyridine units of the **SP** molecules and the two hydroxyl groups of the **R**-based molecule. As a consequence of these interactions, the assembly of a discrete hydrogen-bonded three-component array and in several cases the further packing of two three-component assemblies into a six-component 'super-assembly' resulted. The olefins of the discrete three-component arrays interacted in a head-to-head fashion while the two three-component assemblies making up the 'super-assembly', also oriented in a head-to-head fashion, as depicted in Figure 4.1.

Seven different template-substrate co-crystals involving **CSP** and six different template-substrate co-crystals involving **BSP** were investigated. A mixture of topochemical and non-topochemical alignment of the olefins was observed for both substrates. The olefins in all 13 co-crystals were within topochemical distance (<4.2 Å apart) and in 8 of the co-crystals the olefins were aligned parallel. This suggested that 8 of the co-crystals would exhibit the desired solid-state photo-reactivity. Relevant hydrogen-bond distances and angles, in addition to the olefin-olefin separations⁹ for all 13 co-crystals are given in Tables 4.11-4.12 and Tables 4.13-4.14, respectively.

3.1 Supramolecular Control of Reactivity

In a similar architecture to that observed for the bis(pyridyl)ethylene (**DPE**) substrates, **R** and its derivatives self-assembled by way of $\text{O-H}\cdots\text{N}$ hydrogen-bonds with **CSP** and **BSP**. Once again the template and substrate components have assembled such that the

(a)

(b)

Figure 4.1. Space-filling representations based on the single crystal XRD data for **CR-CSP**, illustrating (a) the three-component hydrogen-bonded assembly formed in all **SP** co-crystals and, (b) the orientation of two three-component assemblies to form a 'super-assembly'.

Table 4.11 *Inter-molecular hydrogen bond distances (Å) and angles (°) for T·CSP.*

Template	<i>Inter-molecular Distances and Angles</i>		
	O...N	H...N	Δ O-H...N
CR (85)	2.715(2)	1.875(5)	177.8(4)
	2.672(2)	1.834(7)	175.4(6)
BR (112)	2.720(4)	1.883(8)	174.0(5)
	2.667(4)	1.829(12)	175.3(10)
ER (126)	2.712(4)	1.879(4)	171.0(3)
	2.755(4)	1.918(4)	174.2(3)
R (130)	2.737(1)	1.900(4)	174.3(4)
	2.688(1)	1.849(2)	176.1(1)
MR (84)	2.732(4)	1.898(13)	171.6(10)
	2.713(4)	1.922(17)	156.4(16)
OR (135)	2.747(3)	1.907(5)	177.5(4)
	2.754(3)	1.915(9)	177.1(6)
DCR (134)	2.688(2)	1.851(6)	173.7(3)
	2.686(2)	1.846(3)	178.0(1)

Hydrogen bond angles and distances were calculated with the aid of the programs prep96 and parst97.

Table 4.12 *Inter-molecular hydrogen bond distances (Å) and angles (°) for T·BSP.*

Template	<i>Inter-molecular Distances and Angles</i>		
	O...N	H...N	Δ O-H...N
CR (88)	2.733(3)	1.898(4)	172.5(7)
	2.684(2)	1.846(7)	176.0(8)
	2.720(3)	1.880(4)	177.7(7)
	2.719(3)	1.880(6)	177.2(8)
BR (113)	2.723(4)	1.885(7)	175.0(12)
	2.721(4)	1.893(10)	168.3(12)
	2.680(4)	1.841(12)	177.1(13)
	2.737(4)	1.901(7)	173.9(12)
ER (128)	2.647(9)	1.849(26)	158.2(23)
	2.723(9)	1.896(17)	167.9(12)
R (89)	2.695(2)	1.856(2)	176.6(2)
	2.736(2)	1.899(4)	174.0(4)
MR (87)	2.735(2)	1.900(5)	172.5(4)
	2.749(2)	1.909(6)	177.8(4)
DCR (129)	2.702(2)	1.925(25)	174.7(25)
	2.691(2)	1.853(4)	175.2(2)

Hydrogen bond angles and distances were calculated with the aid of the programs prep96 and parst97.

Table 4.13 Olefin-olefin separations expressed in Å.

	CSP	BSP
R	3.98 (MA)	4.02 (MA)
CR	3.92	4.01 3.95
BR	3.90	4.00 4.05
ER	3.92	3.94
MR	3.93 (MA)	3.90 (MA)
OR	3.75	
DCR	4.09 (MA)	4.13 (MA)

Olefin...olefin separations are expressed as centre-to-centre distances and calculated using RES2INS.
MA-misalignment of olefins (anti-parallel arrangement)
No structure was determined for **OR·BSP**.

Table 4.14 Adjacent olefin separation expressed in Å.

	CSP	BSP
R	4.67 HT	4.76 HT
CR	4.61 HT	5.77 HT 5.16 HT
BR	4.59 HT	5.72 HT 5.58 HT
ER	4.86 HH	4.87 HH
MR	3.88 HT	3.92 HT
OR	4.74 HT	
DCR	4.00 HT	4.09 HT

Olefin...olefin separations are expressed as centre-to-centre distances and were calculated using RES2INS.

HT indicates a head-to-tail arrangement between the olefins of adjacent assemblies.

HH indicates a head-to-head arrangement between the olefins of adjacent assemblies.

No structure was determined for **OR·BSP**.

pyridine moieties adopt an approximately orthogonal orientation with respect to the aromatic rings of the **R**-based units. The dihedral angles between the aromatic ring of **R** and the aromatic rings of the substrate **SP** are collated in Tables 4.15, and 8 of 13 have parallel and eclipsed olefin alignment. In some of the template-substrate co-crystals the aromatics deviated substantially from the orthogonal orientation. Such observations increased the reactant diversity to which this supramolecular approach to rational solid-state engineering of olefin alignment can be applied.

3.2 Photochemical Studies

As previously demonstrated, solid-state parallel-aligned olefins separated by less than 4.6 Å, undergo a [2+2] dimerization reaction when irradiated with UV light. For the seven **SP** co-crystals satisfying these criteria, the alignment of the olefins of both **BSP** and **CSP** was a direct consequence of the supramolecular design strategy employing a template. Surprisingly, the six **SP** co-crystals that contained perpendicularly aligned olefins but within the topochemical distance, also reacted. This result was also ascribed to the use of the supramolecular design strategy in the form of a template for bringing the olefins within reactive proximity.

Reducing the number of hydrogen-bond accepting sites on the substrate from two to one, the template-to-substrate ratio changed from 1:1 to 1:2. Despite this alteration, a similar architecture to that observed for the family of **DPE** molecules examined in the previous chapter, in addition to similar [2+2] photo-reactivity, was found. Further, the introduction of functional groups about the periphery of the template did not perturb the solid-state

Table 4.15 Dihedral angles (°) between the aromatic ring of **T** and the pyridyl moiety of **SP**.

	CSP	BSP
R	105.1 96.0	95.4 105.7
CR	106.9 112.4	118.0 106.1 99.4 115.6
BR	107.5 114.5	101.5 108.4 105.5 109.4
ER	99.9 92.6	108.3 94.5
MR	119.0 105.9	105.8 120.6
OR	96.1 98.0	
DCR	125.9 107.0	126.7 106.7

Calculated with the aid of Utilty (NRCVax).

Table 4.16 Halogen-Halogen Distances and Contacts for **CSP** and **BSP** in Å.

	CSP	BSP
R	3.84	3.69
CR	3.67	3.46 3.70
BR	3.64	3.50 3.69
ER		
MR	3.40	3.52
OR		
DCR	3.55	3.54

Calculated with the aid of RES2INS.

Numbers indicated in brackets refer to RT data collections.

The sum of the van der Waals radii for Cl and Br are 3.60 and 3.90 Å, respectively.^{13,15}

reactivity of the olefins.

3.3 Photochemical Reactivity of the Pure Substrates

In a similar way to **44DPE**, **22DPE**, and **24DPE**, **CSP** and **BSP** are photochemically inactive in their pure states. Photochemical inactivity was deduced from the crystal structure of pure **CSP**, and photochemical experiments with **BSP**. As illustrated in Figure 4.2, **CSP** self-assembles in the solid-state such that the molecules adopt a herringbone configuration, stacked in a head-to-head fashion. Stabilized by C-H $\cdots\pi$ interactions¹⁰, the dihedral angle between the pyridyl and phenyl moieties is 99.7°. The nearest neighbour olefins lie offset by 4.83 Å and are not eclipsed, either in a parallel or a perpendicular arrangement. It was not surprising then that **CSP** in the solid-state does not undergo [2+2] photodimerization. Unlike **CSP**, crystallographic information on pure **BSP** was unavailable and photochemical experiments indicated that it does not display [2+2] photo-activity in the solid-state.¹¹

3.4 Aligned Substrates

CSP and **BSP** were co-crystallized with various symmetric and non-symmetric resorcinol-based molecules. Co-crystals of both substrates with the non-symmetric, ortho-substituted **ER**, **BR** and **CR**, and the symmetric, meta-substituted **OR**¹², aligned the substrate olefins in a parallel, eclipsed arrangement.

3.4.1 Photochemical Reactivity of the Aligned CSP Substrates

In contrast to pure **CSP**, co-crystallization with four **R**-based molecules induced [2+2] solid-state photochemical activity. Photolysis of these four **CSP** co-crystals resulted in the formation of the head-to-head *r*-1, *c*-2, *t*-3, *t*-4 cyclobutane photo-product (**CCB**) as

Figure 4.2 Space-filling representations based on the single crystal data for pure CSP: (a) top-view of a layer of molecules illustrating the head-to-head packing and, (b) edge-on view of the layer depicting the herringbone motif adopted by the molecules.

determined by ^1H NMR spectroscopy, with yields as summarized in Table 4.7. ESI⁺-MS confirmed the presence of the dimerized product (molecular ion at m/z^+ 432).

The *rcit* stereochemistry of **CCB** was confirmed by the crystal structure of the **R·CCB** co-crystal. Each molecule of **CCB** was tethered by two different molecules of **R**, forming the discrete hydrogen-bonded array illustrated in Figure 4.3 and held together by two O-H...N hydrogen-bonds (O(1)...N(1) 2.691(4) Å, O(2)...N(2) 2.745(4) Å). The dihedral angles between the aromatic ring of **R** and the pyridyls were found to be 110.8° N(1) and 111.2° N(2). ^1H NMR results indicated that in each of the four olefin aligned **CSP** co-crystals, a solid-state reaction according to the ‘Topochemical Principle’ occurred. Indeed, in each of the four different co-crystals the olefins were within the established 4.2 Å topochemical distance criteria.

Interestingly, the four co-crystals were not iso-structural, a fact that was evident from the way in which the hydrogen-bonded three-component arrays further oriented in the crystal lattice. In the case of **CSP** with both **BR** and **CR**, two hydrogen-bonded three-component arrays packed to form a six-component ‘super-assembly’. Unlike the **BR** and **CR** co-crystals, the symmetric **OR** and non-symmetric **ER** did not display the ‘super-assembly’ packing motif. The Cl-Cl distances between the associated assemblies are summarized in Table 4.16.¹³

The possibility that the reaction could have taken place between the olefins of adjacent hydrogen-bonded three-components rather than the olefins within a hydrogen-bonded three-component was examined. Inspection of the packing within the four crystal

(a)

(b)

Figure 4.3 The discrete four-component assembly of $R \cdot CCB$, based on the single-crystal XRD data, is represented in (a) ORTEP and, (b) space-filling format. Thermal ellipsoids are shown at 50 % probability and dashed lines indicate hydrogen-bonds.

structures involving topochemical alignment of the olefins of **CSP** indicated that the adjacent olefins lie offset and separated by a distance greater than 4.6 Å (distances and angles summarized in Table 4.13), as illustrated in Figure 4.4. The spatial relationship of the olefins between assemblies (head-to-tail) and the head-to-head stereochemistry of the photo-product, supported the conclusion that the photochemical reaction occurred between the olefins within the same three-component hydrogen-bonded assembly. Further support for this conclusion lay in the high degree of conversion to the *rcitt*-cyclobutane photo-product. Of the four crystalline samples displaying topochemical olefin alignment, three were virtually quantitative in conversion to **CCB**, indicating non-random dimerization.¹⁴

3.4.2 Photochemical Reactivity of the Aligned BSP Substrates

Also in contrast to pure **BSP**, co-crystallization of **BSP** with the three of the four **R**-based templates that yielded topochemical alignment in the case of **CSP**, induced [2+2] solid-state photochemical activity. Characterization of the photolysis products of the three **BSP** co-crystals by ¹H NMR spectroscopy indicated the formation of the head-to-head *r*-1, *c*-2, *t*-3, *t*-4 cyclobutane dimer of **BSP** (**BCB**) with yields as summarized in Table 4.7. The **BCB** photo-product was confirmed by ESI⁺-MS (molecular ion at *m/z*⁺ 521).

Similar to **CCB**, the stereochemistry of **BCB** was confirmed through the re-crystallization of the photolyzed product of the **R**·**BSP** mixture. Each molecule of **BCB** was anchored by two different molecules of **R**, generating a discrete four-component hydrogen-bonded array isostructural with that observed for **R**·**CCB** and is illustrated in Figure 4.5. Tethered by two O-H...N hydrogen-bonds (O(1)···N(1) 2.678(5) Å, O(2)···N(2) 2.712(5) Å),

(a)

(b)

Figure 4.4 (a) A space-filling and (b) ORTEP representation of the assemblies in the **BR·CSP** co-crystals: adjacent olefins lie offset and are ~ 4.6 Å apart (a box indicates the olefins of adjacent assemblies). ORTEPs are shown at 50% probability with dashed arrows indicating hydrogen-bonds.

Figure 4.5 ORTEP representation of the interaction of the cyclobutane products with **R** for the co-crystals of (a) **R·CCB** and, (b) **R·BCB**. Thermal ellipsoids are given at 50 % probability and dashed lines represent hydrogen-bonds.

the dihedral angles between **R** and the pyridyls were found to be 108.8° N(1) and 108.6° N(2). ¹H NMR results indicated that in each of the four olefin aligned **BSP** co-crystals, a solid-state reaction according to the 'Topochemical Principle' occurred. Indeed, in each of the three co-crystals, the olefins were well within the established 4.2Å topochemical distance criteria.

Like the four aligned co-crystals involving **CSP**, those involving **BSP** were a mixture of hydrogen-bonded three-component assemblies and super-assemblies of two three-component assemblies. The three-component assemblies formed between **BSP** and **BR** or **CR** were oriented in a head-to-head fashion with halogen-halogen distances¹⁵ as summarized in Table 4.16. The **ER** co-crystal did not display a similar packing motif, nor possess any short Br...Br contacts. Moreover, the **ER·BSP** co-crystal, despite possessing olefins that were oriented topochemically, did not undergo [2+2] photo-reaction.¹¹

For similar reasons as those outlined for **CSP** (*e.g.* violation of the topochemical distance criteria, head-to-head orientation, yields greater than the statistical maximum for random dimerization), the reaction was concluded to have occurred between the olefins within the hydrogen-bonded three-components rather than between the olefins of adjacent three-component assemblies.

3.5 Mis-aligned Substrates

CSP and **BSP** were co-crystallized with the symmetric **R** and **DCR** and the non-symmetric **MR**. Each of these three **R**-based molecules oriented the **CSP** and **BSP** substrate olefins in a perpendicular fashion but within topochemical distance. Not without precedent,

photochemical reactivity was observed in each of these six different co-crystals.¹⁶

3.5.1 Photochemical Reactivity of the Mis-aligned CSP Substrates

Figure 4.6 illustrates parallel vs. perpendicular olefin alignment. Three-component hydrogen-bonded assemblies resulted, where O-H...N interactions between the **R** derivatives and **CSP** were found. The three-component assemblies formed between either **R**, **MR** or **DCR** with **CSP** further oriented in a head-to-head fashion generating the same discrete, six-component 'super-assembly' observed in the **BR** and **CR** co-crystals of **CSP**. Relevant hydrogen-bond distances and halogen-halogen distances are summarized in Tables 4.11 and 4.12, and 4.16, respectively.

Surprisingly, UV irradiation led to the formation of the *rcitt*, head-to-head photo-product suggested by the relative orientations of **CSP** molecules within the unreacted materials. Yields were all determined to be greater than 85 % by ¹H NMR spectroscopy and are summarized in Table 4.7. The *rcitt* photo-product was identified by comparison with the ¹H NMR spectra obtained from the photo-products of the aligned co-crystals. ESI⁺-MS confirmed the presence of the dimerized product with the parent ion peak at *m/z*⁺ 432.

As mentioned previously, the crystal structure of the photolyzed **R**·**CSP** material confirmed the *rcitt* stereochemical assignment of the photo-products. In each of the three misaligned co-crystals dimerization between olefins of adjacent assemblies would have led to the formation of a head-to-tail photo-product, not to the observed head-to-head photo-product. This provided further evidence that the reaction occurred within the hydrogen-bonded assemblies. With the understanding that the reaction occurred between the olefins

Figure 4.6 Stick representations based on the single crystal XRD data presenting the cases of (a) the parallel aligned olefins of the **BR·CSP** co-crystal and, (b) the perpendicular aligned olefins of **R·CSP** co-crystal.

within a three-component assembly, molecular disorder was investigated using the room temperature single crystal XRD data.

3.5.2 Photochemical Reactivity of the Mis-aligned BSP Substrates

In a similar way to the misaligned co-crystals of **CSP** with **MR**, **R** and **DCR**, co-crystals of **BSP** with these **R**-based molecules resulted in a misalignment of the **BSP** olefins. The three-component, hydrogen-bonded motif was maintained and each of the three co-crystals displayed perpendicular olefin alignment, though meeting the topochemical distance criterion.

Through O-H...N interactions between the hydroxyl groups of the **R**-based molecule and the pyridyl moiety of **BSP**, the three-component assemblies further associated generating discrete, six-component assemblies or super-assemblies containing short Br...Br contacts.¹⁵ This super-assembly formation was observed in the three misaligned co-crystals involving **CSP** and the four aligned co-crystals, two involving **BSP** and two involving **CSP**. Relevant hydrogen-bond distances and halogen-halogen contacts, are summarized in Tables 4.11 and 4.12, and 4.16, respectively.

Photolysis of the mis-aligned co-crystals led to the formation of the *rcrt* head-to-head photo-product. Yields are summarized in Table 4.7, and ESI⁺-MS confirmed the presence of the dimerized product (molecular ion at m/z^+ 521). The co-crystals were examined for disorder at room temperature using single crystal XRD.

3.6 Room Temperature Single-crystal XRD Studies

Since the crystal structures reported were solved from data collected at -100°C but

(a)

(b)

Figure 4.7 Schematic representations illustrating the (a) two aligned parallel orientations and, (b) the two perpendicular aligned cases in disordered co-crystals. Olefins in red are occupied 0.15 and olefins in black are occupied 0.85.

the temperature in the reaction chamber during the irradiation was approximately +40°C, it was necessary to redetermine the crystal structure at room temperature (closer to the actual reaction conditions). Single-crystal XRD data would provide information concerning atomic disorder but not information about the dynamic or static nature of the disorder. Redetermination of the six crystal structures involving **BSP** and **CSP** with **R**, **MR** and **DCR** at room temperature, indicated that there was disorder in 5 of 6 systems. With the exception of **R-BSP**, the co-crystals in which the perpendicularly aligned olefins underwent photo-reaction exhibited disorder about two positions in either one or both of the double bonds per hydrogen-bonded assembly. A summary of the site occupancies for each of the disordered olefins can be found in Tables 4.3 and 4.4

For the room temperature **CSP** co-crystals, 85:15 and 75:25 disorder in one and two of the double bonds was determined for both the **R** and **MR** co-crystals, respectively. An 85:15 disorder in one double bond means that an average 85 % of the olefins occupied one position and 15 % occupied the alternate position. If the 15 % occupied double bond happened to be aligned with the second double bond that was not disordered, a maximum of 15 % of the olefins would be in position to react. A site occupancy of 70:30 for both of the olefins in the **DCR** co-crystal was found.

In the case that both olefins in a pair were disordered, four possible olefin arrangements existed, as illustrated in Figure 4.7. For two of the orientations the olefins are aligned parallel and adding the number of aligned cases for each orientation indicated the number of olefin pairs able to react. So for two olefins with occupancies of 0.15 and 0.85

in one position and 0.85 and 0.15 occupancies in the other aligned position, the maximum number of olefins that are positioned to react is 30 %. This analysis applies if the disorder was static or if the atoms were moving between two positions (*i.e.* dynamic disorder). Whereas a static disorder would limit the overall conversion rate to 30 % and 25 % in the **R** and **MR** co-crystals, respectively, the observed 97 % and 82 % strongly suggested that the disorder was dynamic in nature. For the **DCR** co-crystal a static disorder would allow a maximum conversion rate of 60 % and the observed 38 % conversion does not permit a conclusion of dynamic disorder.

The **BSP** co-crystals with **MR** and **DCR** displayed 76:24 disorder across one double bond¹⁷ and 85:15 and 70:30 disorder across both double bonds, respectively. With observed yields of 92 % and 86 % for the **MR** and **DCR** co-crystals, respectively, the maximum allowed static yields of 24 % and 45 % suggested a dynamic rather than static disorder. Unlike both the **MR** and **DCR** co-crystals with **BSP** and the three **CSP** co-crystals with perpendicularly aligned olefins, no evidence for disorder in the co-crystal of **R·BSP** at room temperature was found. Despite the initially perpendicular olefin alignment and no crystallographic evidence for disorder at room temperature, a conversion rate of 95 % was observed in the **R·BSP** co-crystal.¹⁸

3.7 Implications for Design

The objective of the work presented in this chapter was to further probe the limits of reactant diversity and investigate both the template-to-reactant ratio and the effect it had on the reproducibility of the non-covalent interactions to induce olefin alignment. Despite

results that were initially viewed as anomalies, the studies carried out using substituted **SP** substrates have suggested that focussing on olefin proximity rather than specific olefin orientation might be a better goal.

In general, the loosely classified orthogonal geometry between the **R**-based molecules and **XSP** and the dimeric face-to-face stacking of the substrates was similar to that observed in the study of **DPE** as substrates. Indeed, the three-component O-H...N hydrogen-bonded assemblies formed in the **XSP** co-crystals were analogous to the four component **DPE** assemblies. Additional interactions between the three-component **BSP** assemblies were novel and a consequence of the short halogen-halogen contacts. Misalignment was not concluded to be a consequence of the halogen-halogen interactions since both parallel and perpendicular alignment of the olefins were noted in co-crystals where these interactions were absent.

Effectively, what has been demonstrated is the reliability of the 1,3-dihydroxy substitution pattern of aromatics to steer or 'clip' olefins into reactive proximity. Although the parallel eclipsed olefin alignment was dominant in the **DPE** co-crystals, it was not as frequent in the **XSP** co-crystals; reactivity was observed in 12 of 13 systems or 92 % of the time.

4.0 Conclusions

The supramolecular interactions responsible for reliably generating the discrete three-component hydrogen-bonded motif served to further expand the diversity of the reactants to which this approach can be applied. In addition, reducing the template-to-substrate ratio

from 1:1 to 1:2 did not perturb the reactivity of the substrates and illustrated that the ability to bring olefin containing substrates into reactive proximity may be more important than the relative orientation of the olefins.

4.1 Future Work

A theoretical study of the energy differences between parallel and perpendicular aligned olefins in co-crystals may lend further credit to the idea that proximity rather than geometry can dictate reactivity.

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17. In this case there are two possible olefin pair orientations, one aligned parallel and the other perpendicular.

18. DSC measurements do not indicate any phase transitions below ~220°C.

Chapter V: A Single-Crystal Transformation Investigation

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1.0 Introduction

Preliminary results¹ on the **R·44DPE** system not only raised the question of whether or not a supramolecular approach to engineering solid-state [2+2] reactivity was reliable but also whether or not the photodimerization proceeds in a single-crystal-to-single-crystal or single-crystal-to-polycrystalline fashion. As one of the most extensively studied topochemical reactions, several [2+2] photocycloaddition examples of single-crystal-to-single-crystal behaviour exist.²

Typically, however, UV promoted [2+2] cycloaddition reactions proceed heterogeneously (single-crystal-to-polycrystalline) with destruction of the crystal itself.³ Interestingly, solid-state 1,6-polymerizations of triacetylene and 1,4 dimerizations of diolefins are noted for their homogeneous conversion to products in the solid-state.⁴ With the integrity of the crystal maintained over the course of the entire reaction, these polymerizations occur homogeneously.

The key to successful single-crystal-to-single-crystal conversion involves the use of 'tail-end radiation' (wavelengths >540 nm).^{2b,5} The crystal lattice has a low absorptivity for such radiation, and therefore the light penetrates more easily to the interior of the crystal. This means that a solid solution of products and reactants exists throughout the crystal. The energy of radiation is smaller with greater wavelengths, meaning that the molecular and/or atomic motion causing the disruption of the atomic positions is reduced.^{3c} However, with smaller wavelength radiation, complete reaction occurs at the surface, and the interior sites are blocked from incident irradiation.

It was of interest to determine if the reaction of **44DPE** within the **R·44DPE** co-crystal occurred heterogeneously or homogeneously. Specifically, the integrity of the hydrogen-bonded assemblies over the course of irradiation was examined. As a starting point, 350 nm irradiation was used. The similar way in which **44DPE** and **44CB** were anchored by **R** suggested to us that the reaction might be occurring homogeneously and consequently a study of this system at 350 nm rather than longer wavelengths was undertaken. ¹³C CPMAS spectra and PXRD patterns of the photolyzed material were compared with that of the reactant and re-crystallized **R·44DPE** solids and the nature of the photoreaction at 350 nm determined.

2.0 Experimental

2.1 General Details

Co-crystals of **R-44DPE** and **R-44CB** were prepared as described in the literature.⁶ The photolysis was carried out for 24 hours at 350nm in a Rayonet reaction chamber.

2.2 Cross-Polarization Magic Angle Spinning (CPMAS) Experiments

¹³C CPMAS spectra were collected at either 50 or 75 MHz using Tecmag or Bruker AMX300 spectrometers, respectively. Samples were spun at 3-5 kHz in zirconia rotors. The probes for both spectrometers were made by Doty Scientific. For the 50 MHz spectra, a 7mm diameter rotor was used and for the 75 MHz spectra a 5mm diameter rotor was used. In both cases, a sweep width corresponding to 500ppm was used. The ¹H 90° pulse length was 4.75μs on the 7mm probe and 3.75μs on the 5mm probe. Scan repetition delay times of 100-120s were found to be necessary to rid spectra of obvious saturation effects. Proton T₁ values were not measured and in general a 2ms contact time was used. On one sample, contact times of 8ms and 500μs were tried, with no improvement in the signal-to-noise ratio.

2.3 Powder X-ray Diffraction (PXRD) Experiments

Powder diffraction patterns for **R-44DPE**, **R-44CB** and the irradiated sample of **R-44DPE** were collected on a Scintag X2 powder diffractometer ($10^{\circ} \leq 2\theta \leq 100^{\circ}$, 0.02° step interval, 2 second count time per data point).

3.0 Results and Discussion

Comparing the crystal structures of **R-44DPE** and **R-44CB** the question arose as to whether or not the [2+2] photo-cycloaddition reaction occurred homogeneously in the solid-state at 350 nm. Despite the change in crystal system between the reactant and re-crystallized co-crystals (triclinic to monoclinic), the possibility that the reactants were simply 'pinched' together as a result of the irradiation without any disruption of the hydrogen-bonding seemed possible (See Figure 1.9).¹ Since irradiation of the co-crystal was carried out on a microcrystalline sample rather than single crystals, it was necessary to perform and compare characterizations of all the materials in the powdered form.

Inspection of the PXRD patterns from the three samples (reactant, irradiated and re-crystallized) revealed the appearance and disappearance of diffraction peaks (see Figure 5.1), indicating that the three solids were not the same material.⁷ On the basis of the PXRD patterns of the irradiated and re-crystallized solids it was therefore concluded, that the two were polymorphs. ¹³C CPMAS experiments carried out on these three samples further supported the conclusion that the two solids were polymorphs and that the reaction did not proceed single-crystal-to-single-crystal, as the two spectra were quite distinct. The NMR spectra are illustrated in Figure 5.2 with both literature⁸ and observed chemical shifts given in Table 5.1. An explanation of the assignment nomenclature can be found in Figure 5.3.

The high resolution ¹³C CPMAS NMR spectra clearly show the conversion of monomer to dimer with the appearance of two overlapping peaks at 44 and 48 ppm, corresponding to the cyclobutane carbon atoms (literature $\delta = 46$ ppm). Splitting of this

Figure 5.1 PXRD patterns for (a) the reactant **R•44DPE** co-crystals, (b) **R•44DPE** after 24 hours of UV irradiation and, (c) the re-crystallized photo-product **R•44CB**.

Figure 5.2 High resolution ^{13}C CPMAS spectra for (a) **R-44DPE** (200 MHz), (b) **R-44DPE** after 24 hours UV irradiation at 350nm (200 MHz) and, (c) **R-44CB** (300 MHz), the re-crystallized photo-product. The magic angle spinning frequency was 5kHz. * indicates a spinning side band.

Figure 5.3 Atom labelling scheme used in the ^{13}C CPMAS experiments for (a) **R**, (b) **44DPE** and, (c) **44CB**.

Table 5.1 Chemical Shifts for **R-44DPE** before irradiation and after re-crystallization. Literature⁸ chemical shifts for **R**, **44DPE** and **44CB** in solution are also given. All shifts are given in ppm.

		Literature	R-44DPE	R-44CB
R	T1	158.75	162	162
	T2	102.78	102	101
	T3	106.8	106	107
	T4	129.92	130	131
44DPE	R1	150.2	148	
	R2	121.2	125	
	R4	121.8	120	
	R3	143.2	143	
	R6	130.4	127	
44CB	P1, P6	150.5		151
	P2, P5	123.2		125
	P3	147.8		148
	P4	46.0		43 (*)

resonance suggested that there were two different cyclobutane carbon atom environments in the photolyzed material. However, the ^{13}C spectrum of the re-crystallized material showed only a single resonance at $\delta = 46$ ppm. The decrease in the sharpness of the peaks of the pyridyl carbon atoms, and the increase in the multiplicity of these resonances, provides further support for the conclusion that there was a lowering of the crystal symmetry as a result of the photo-reaction. Overall, the results seem to suggest that the cycloaddition in the **R·44DPE** co-crystal did not occur homogeneously but rather heterogeneously at 350 nm.⁹

3.1 Future Work

The results described in this final chapter require further investigation in order to determine the general nature of the photochemical reactions studied. Further studies on the **R·44DPE** system using greater wavelength radiation should be undertaken, in addition to indexing of the PXRD patterns to confirm that the solids are in fact different.

In addition, study of the **MR·44DPE** co-crystals at 350 nm would be of interest. The difference between the **MR·44DPE** and **R·44DPE** co-crystals is that the crystal system from irradiated to re-crystallized material is maintained for **MR·44DPE**, from monoclinic to monoclinic rather than triclinic to monoclinic, respectively. Further, the cell parameters of the two **44DPE** co-crystals differ only marginally. Maintaining the same crystal system suggests that there might be less atomic disruption in the **MR·44DPE** co-crystal as a result of the irradiation and the reaction may, in fact, be single-crystal-to-single-crystal.

4.0 Overall Thesis Conclusions

In this thesis, the use of supramolecular interactions to induce reactive olefin alignment in the solid-state was investigated, primarily using single-crystal XRD to determine the spatial orientations of the olefins. Using this technique, the pre-disposition of the olefins to undergo [2+2] photodimerization in the solid-state was analyzed. Functionality was introduced into the systems and the substrates were altered in order to probe the reliability of this supramolecular approach to aligning olefins. The results obtained demonstrated the reproducibility of the **R**-based templates to interact with the substrates in a similar hydrogen-bonded motif with topochemical olefin alignment. Typically very high to virtually quantitative conversion to the expected photo-products was observed. These results further confirmed the generality of this approach to inducing reactive olefin alignment, while circumventing many of the drawbacks associated with previous work in this area.

A combined ^{13}C CPMAS and PXRD study of the transformation of **44DPE** to **44CB** within the **R** co-crystal was done to understand if the transformation occurred in a heterogeneous or homogeneous fashion. The results seem to suggest that the transformation at 350 nm was heterogenous, occurring in a single-crystal-to-polycrystalline fashion. The irradiated material and the re-crystallized solids appeared to be polymorphs. Further experiments are necessary to determine if this transformation can be implemented single-crystal-to-single-crystal.

4.1 References

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9. Single-crystals that are irradiated turn opaque after exposure for approximately 1 hour.

Supplemental Information

Figure S1. Depictions of the (a) 44DPE, (b) 22DPE, (c) 34DPE, (d) 24DPE and, (e) XSP, where X = Cl or Br, substrates.

Figure S2. Depictions of the (a) symmetric mono-substituted **R**, **OR**, **MR**, (b) the non-symmetric **ER**, **BR**, **CR**, **HR**, and the, (c) symmetric di-substituted **DCR** templates.

Table S1 Structure Key for the Reactant **DPE** Co-crystals.

	44DPE	22DPE	24DPE	34DPE
R		132	119	138
CR	120	121	133	136
BR	96	97	98	107
ER	94	93		
HR	99			
MR	102	91	92	137
OR	106	122	105	
DCR	123	116	110	140

Table S2 Structure Key for **XSP** Co-crystals. Room temperature codes are bracketed.

	CSP	BSP
R	130 (147)	89 (144)
CR	85	88
BR	112	113
ER	126	128
MR	84 (152)	87 (148)
OR	135	
DCR	134 (155)	129 (154)

Table S3 Structure Key for the Photo-products of the **DPE** and **XSP** Co-crystals.

Contents	Structure Number
MR·44CB	108
BR·22CB	103
OR·24CB	153
24CB	151
DCR·34CB	150
R·CCB	139
R·BCB	143

Table S4 Tabulation of TGA and DSC Data for Reactant **DPE** co-crystals.

Co-crystal	TGA (°C)	DSC (°C)
CR·44DPE	221	245
ER·44DPE	198	184
BR·44DPE	214	242
HR·44DPE	206	133
MR·44DPE	167	207
DCR·44DPE	160	252
OR·44DPE	208	186
R·22DPE	196	90
CR·22DPE	185	132
ER·22DPE	192	100
BR·22DPE	180	140
OR·22DPE	177	122
DCR·22DPE	162	145
R·24DPE	174	69
CR·24DPE	174	144
BR·24DPE	174	150
OR·24DPE	176	146
DCR·24DPE	185	153
R·34DPE	209	114
MR·34DPE	137	101
DCR·34DPE	200	198
CR·34DPE	194	142
BR·34DPE	181	149

Table S5 Tabulation of TGA and DSC Data for Reactant **SP** co-crystals.

Co-crystal	TGA (°C)	DSC (°C)
R·CSP	218	150
MR·CSP	210	145
ER·CSP	202	148
BR·CSP	192	178
CR·CSP	199	178
OR·CSP	217	134
DCR·CSP	196	210
R·BSP	161	222
MR·BSP	207	149
ER·BSP	203	140
CR·BSP	189	189
BR·BSP	190	191
DCR·BSP	206	208

Figure S3. Schematic representation of the photoreaction set-up.