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# Catalytic Supramolecular Photochirogenesis

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**Abstract:** Supramolecular photochirogenesis is a new strategy for circumventing the inherent difficulties encountered in conventional photochirogenesis, i.e. the interactions associated with geometrically less-defined, short-lived excited states, by confining a prochiral substrate(s) in a chiral supramolecular environment(s) prior to photoexcitation. This rather simple, but very successful, strategy has been applied to a variety of chiral photoreactions. However, a stoichiometric, or even excess amount of supramolecular host is often needed to ensure full complexation of the substrate, and achieve the optimum stereochemical outcome. This apparent drawback has recently been removed by introducing a sensitizing moiety to the supramolecular host, or by bathochromically shifting the absorption band of substrate through Lewis acid, or charge-transfer complexation. Recent progress in catalytic supramolecular photochirogenesis will be reviewed.

**Keywords:** photochirogenesis, supramolecular chemistry, chiral photochemistry, catalysis

## 1 Introduction

Photochemical asymmetric synthesis, or *photochirogenesis*, has long been a highly challenging task in modern photochemistry, but has achieved significant progress in the last two decades.[1-4] Traditionally, (non-supramolecular) catalytic photochirogenesis has been accomplished by exploiting chiral photosensitizers, as

exemplified by the first report by Hammond and Cole in 1965 on the enantiodifferentiating photoisomerization of 1,2-diphenylcyclopropane sensitized by a chiral naphthylethylamine derivative.[5] The systematic study on the enantiodifferentiating photoisomerization of cyclooctenes sensitized by chiral (poly)alkyl benzene(poly)carboxylates, as well as the critical role of entropy played at the most crucial stage of enantiodifferentiation, appears to have remarkably boosted research on molecular photochirogenesis.[6-8] However, conventional photochirogenesis with chiral sensitizers is not very efficient in general, affording modest to good enantioselectivities in most cases, except for the one reported recently.[9] This is due to the generally weak interactions, and relatively large conformational freedoms in the exciplex intermediate formed upon interaction of an excited chiral sensitizer with a ground-state substrate. In this context, supramolecular photosensitization, which combines the catalytic nature of photosensitization with the intimate interactions of the supramolecular complex, appears to be highly promising.

Indeed, the most prominent, yet practical advance in this field has been attained in the new interdisciplinary area of supramolecular photochirogenesis, where the supramolecular interactions in both ground and excited states are exploited for manipulating the stereochemical outcomes of photochirogenic reactions.[5,10,11] The photochemical chirality transfer in supramolecular systems can be synergistically controlled not only by reaction kinetics through weak, short-lived excited-state interactions also available in conventional molecular photochirogenesis, but also by complexation thermodynamics through the long-lasting ground-state interactions in the chiral environment. Thus, many of the highly enantioselective photoreactions reported so far were achieved through supramolecular photochirogenic approaches, where cyclodextrins,[12,13] chiral hydrogen-bonding templates,[14] chirally modified zeolites,[15] chiral molecular cages,[16] and chiral aggregates[17,18] were employed as chiral hosts. However, these supramolecular photochirogenic reactions were carried out in the presence of an excess amount of chiral host to gain the optimal

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stereochemical outcomes. This is due to the non-covalent nature of supramolecular complexation, which requires at least a stoichiometric, but often an excess, amount of chiral host to ensure the full complexation of guest substrate and prevent the formation of racemic product from uncomplexed substrate in the bulk solution.

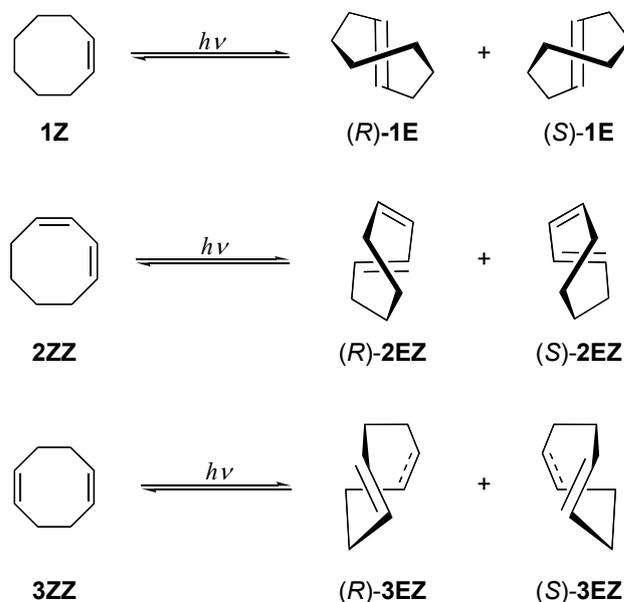
More sensible strategies to accelerate an enantiodifferentiating photoreaction with a sub-stoichiometric amount of chiral host have recently been proposed to achieve catalytic supramolecular photochirogenesis. Complexation of a substrate with a supramolecular host frequently alters the photophysical properties, and photochemical reactivities of the system significantly. Many photoreactions are known to be remarkably expedited upon confinement of substrate in a hydrophobic host cavity due to pre-arrangement, confinement, and/or concentration effects. Furthermore, the non-covalent nature and generally moderate affinity of supramolecular complexation allows the chiral host site/cavity to turn-over by releasing photoproduct, which introduces new substrate, and thus suppresses product-inhibition. However, in supramolecular photochirogenesis, it is more crucial to prevent the non-chirogenic photoreactions that occur to give racemic products outside the chiral cavity. In this review, we will focus on such supramolecular photochirogenic systems that satisfy the following criteria: (1) use of a chiral host in sub-stoichiometric quantity, (2) acceleration of a photochirogenic reaction, and (3) the invention to suppress the non-chirogenic photoreactions that occur outside the chiral supramolecular site/cavity.

## 2 Catalytic Supramolecular Photochirogenesis with Cyclodextrins

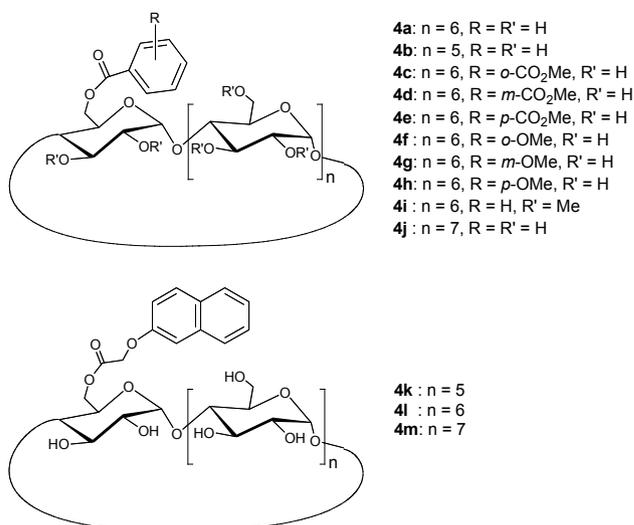
Cyclodextrin (CD), a cyclic oligosaccharide with a hydrophobic cavity and hydrophilic exterior, is one of the most widely studied host molecules. This is due to its immediate availability, good water-solubility, facile chemical modification, and complexation ability for a wide variety of organic guests.[19] Furthermore, CDs are UV-transparent and inherently chiral, facilitating their application to supramolecular photochirogenesis. Indeed, a variety of chiral photoreactions have been studied by using native and modified CDs as chiral hosts.[20]

Photoisomerization of (*Z*)-cyclooctene (**1Z**) mediated by sensitizer-modified CDs (Scheme 1) is the earliest example of an enantiodifferentiating supramolecular photosensitization.[21] Direct photoirradiation of a 1:1 complex of **1Z** with native b-CD at 185 nm gives nearly

racemic **1E** in 0.5–1.5% enantiomeric excess (ee), revealing the poor photochirogenic ability of the native b-CD cavity for **1Z**. [22] In contrast, the supramolecular photoisomerization of **1Z** included and sensitized by a 0.1 equivalent of benzoyl-CD (**4a**) affords **1E** in up to 11% ee.[21] Since then, a series of sensitizer-modified a-, b- and g-CD derivatives **4b–m** (Figure 1) have been prepared for investigating the supramolecular photoisomerization of **1Z**, and cyclooctadienes (**2ZZ** and **3ZZ**) (Scheme 1). [23–31]



**Scheme 1.** Enantiodifferentiating photoisomerization of (*Z*)-cyclooctene (**1Z**) and (*Z,Z*)-1,3- and (*Z,Z*)-1,5-cyclooctadienes (**2ZZ** and **3ZZ**).



**Figure 1.** Sensitizer-appended a-, b-, and g-CDs (**4a–m**) for supramolecular photosensitization.

A nice trick employed in this supramolecular photochirogenic sensitization system is that the sensitizing ability is turned on only when a guest substrate is included in the host cavity. In the absence of guest, the hydrophobic sensitizer moiety is self-included in the CD cavity and cannot transfer excitation energy to substrates outside the cavity, and hence no racemic product is formed in bulk solution. Once a guest substrate is included, the sensitizer moiety is moved to the portal area but is in close contact with the included substrate to facilitate energy transfer and subsequent photoreactions in the chiral environment. This mechanism, in particular its absence of the sensitized photoisomerization in bulk solution, renders this supramolecular photosensitization system catalytic.

In general, b-CD-based sensitizers offer higher enantioselectivities than those based on a- or g-CD due to a cavity size better fitted to cyclooctenes.[23,30] Besides the cavity size, substituent(s) introduced to the benzoate moiety critically affect the supramolecular photosensitization. Thus, the ee of **1E** is significantly enhanced from modest 11% for 6-*O*-benzoyl-b-CD **4a** to 24% for 6-*O*-(methyl phthaloyl)-b-CD **4c** and then to 46% for 6-*O*-(*m*-methoxybenzoyl)-b-CD **4g**, which are in sharp contrast to the much lower ee values obtained with the *o*- and *p*-analogues, **4f** and **4h**. [26,27] These results reveal that even an apparently small difference in structure of the supramolecular host may lead to a significant change in stereochemical outcome and hence the structural optimization of sensitizing host is desirable for obtaining optimal results.

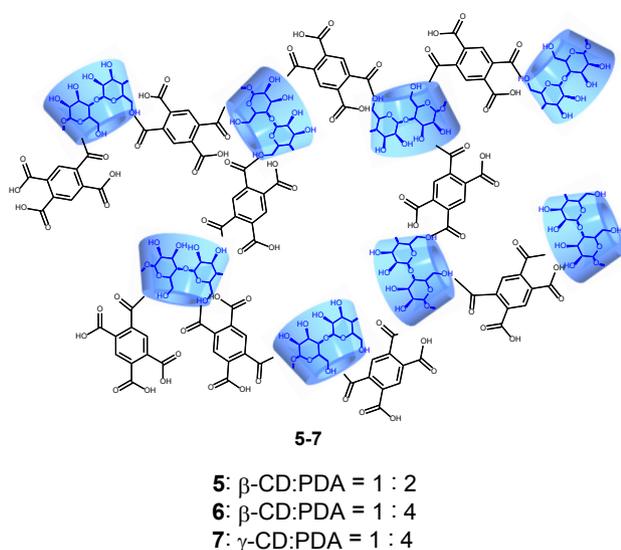
Another interesting aspect of supramolecular photosensitization is the finding that the product's ee is relatively insensitive to change in temperature. This is in keen contrast to the highly temperature-dependent ee values observed upon the conventional photosensitization in isotropic media,[6,32] for which the relatively rigid CD skeleton fixed by the inter-glucoside hydrogen-bonds around the secondary rim is likely to be responsible at least in part. In support of this rationalization, when photosensitization is performed by using permethylated CD derivative **4i**, the skeleton of which is much more flexible due to the broken hydrogen-bonding network, the ee of **1E** greatly varies with temperature to give an antipodal product.[29,33]

Controlling enantiodifferentiating photoisomerization of 1,3-cyclooctadiene **2ZZ** appears to be more difficult, compared to the **1Z** case mentioned above. Thus, the highest ee of **2EZ** reported for the photoisomerization of **2ZZ** with a variety of conventional chiral sensitizers is only 17% even at -110 °C.[34] For better stereochemical

control, supramolecular photosensitization of **2ZZ** with naphthalene-appended a-, b- and g-CDs **4k-m** has been examined in aqueous solutions. b-CD-based sensitizing host **4l** exhibits a much higher affinity to **2ZZ** than a- and g-CD analogues **4k** and **4m**, due to the better size-matching, but affords **2EZ** in mere 4.6% ee upon photoirradiation in aqueous solution,[30] revealing that supramolecular photosensitization does not always lead to better results than conventional molecular photosensitization, and the chiral environment of sensitizing host plays a decisive role.

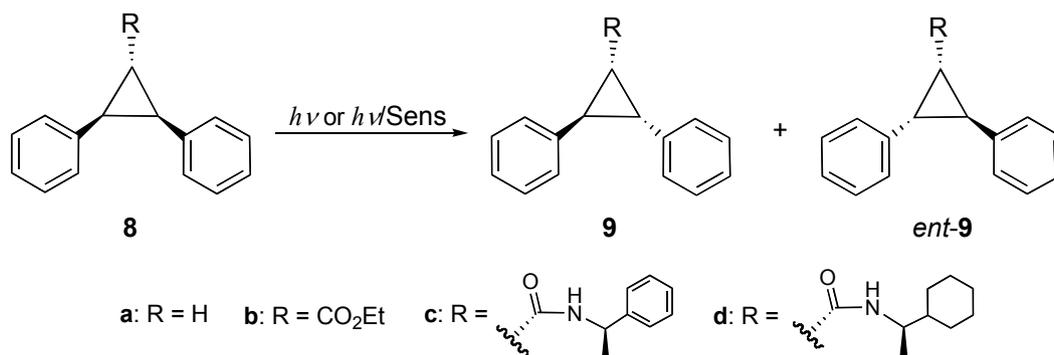
Recently, a series of polymeric CDs crosslinked by pyromellitic dianhydride (**5-7**) (Figure 2), called CD nanosponge (CDNS), have been employed as sensitizing hosts for the enantiodifferentiating photoisomerization of **1Z** and **2ZZ**. [28,35] Upon gradual increase of its concentration in water, CDNS evolves several phases from sol to suspension, flowing gel, and finally rigid gel. Possessing pyromellitate moieties as crosslinkers, CDNS can sensitize the enantiodifferentiating photoisomerizations of **1Z** and **2ZZ** revealing that the ee values of obtained **1E** and **2EZ** critically depend on the phase condition of CDNS, but are consistently optimized at the border of the flowing and rigid gel regions. For example, the ee value of **2EZ** obtained upon photosensitization of **2ZZ** by b-CDNS **6** decreases from 4.7% in sol phase to nearly zero in suspension but revives in flowing gel to reach the maximum of 6.1% at the border to rigid gel. g-CDNS **7** behaves similarly, affording almost racemic **2EZ** in both sol and suspension regions, but the highest 13.3% ee near the border of flowing and rigid gels, is the best ee value ever reported for the supramolecular photoisomerization of **2ZZ**. This phase-dependent photochirogenic behavior is presumably attributed to the alternation of the chiral binding and reaction site for cyclooctenes from the CD cavity in sol phase to the void space surrounded by the exterior walls of CD in gels.

This void space mechanism has been supported by a recent study.[36] Thus, analogous nanosponges prepared from cyclic nigerosyl nigerose, a saucer-shaped cyclic tetrasaccharide with a shallow concave surface, have been examined as sensitizing supramolecular media for the same photosensitization to show very similar photochirogenic behavior, affording generally low ee values of -4% to 6% in aqueous solutions and suspensions but much higher ee values of 22-24% at the border of flowing and rigid gels. These results confirm the positive roles of chiral void space formed upon gelation of the crosslinked saccharide polymer.

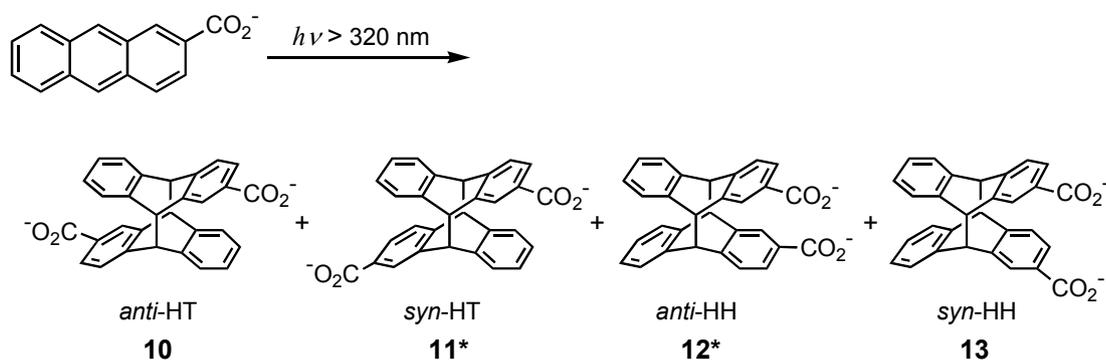


**Figure 2.** CD nanosponges 5-7 prepared by cross-linking  $\beta$ - and  $\gamma$ -CDs with pyromellitic dianhydride (PDA) in 1:2 and/or 1:4 ratios.

Enantio- and diastereodifferentiating photoisomerizations of *cis*-1,2-diphenylcyclopropanes (**8a-d**) mediated by  $\beta$ -CD have been studied comparatively in the solid state and in aqueous solutions with and without a triplet sensitizer added to the system (Scheme 2).[37] Photoirradiation



**Scheme 2.** Enantio- and diastereodifferentiating photoisomerization of *cis*-1,2-diphenylcyclopropane derivatives **8a-d**.



**Scheme 3.** Enantiodifferentiating [4+4] photocyclodimerization of AC.

of a mixture of **8a** and 4-methoxyacetophenone (added as a triplet sensitizer) in the solid state affords the corresponding *trans*-isomer **9a** in 13% ee, while direct irradiation of **8b** in the solid state gives **9b** in comparable 13% ee. Direct irradiation of solid-state complexes of chiral **8c** and **8d** with  $\beta$ -CD affords **9c** and **9d** in better, 28%, and 30% diastereomeric excess (de), respectively, which are much higher than the de of <2% obtained for the same reactions in an aqueous solution, suggesting the crucial role of the conformational freedoms of included substrate in determining the stereochemical outcome.

The enantiodifferentiating [4+4] photocyclodimerization of 2-anthracenecarboxylate (AC) is one of the most comprehensively investigated supramolecular photochirogenic reactions. This reaction gives four stereoisomeric 9,10-bridged cyclodimers **10-13**, of which *syn-head-to-tail* (*syn-HT*) dimer **11** and *anti-head-to-head* (*anti-HH*) dimer **12** are chiral (Scheme 3).

Inclusion complexation of two AC molecules with native  $\gamma$ -CD in aqueous solution greatly accelerates the photocyclodimerization as a result of the pre-arrangement of ACs in a CD cavity to give *syn-HT*-dimer **11** in 46% yield and 41% ee.[12] For better chemical and optical yields, a series of  $\gamma$ -CD derivatives have been prepared and the effects of external factors, such

as solvent, temperature, pressure, and irradiation wavelength, have also been investigated in considerable detail.[38-45] All of these internal and external factors critically affect the stereochemical outcomes of AC photocyclodimerizations, affording chiral cyclodimers **11** and **12** in good to excellent enantioselectivities. Despite the significant acceleration of photocyclodimerization upon complexation, an excess amount of *g*-CD derivative is necessary in most cases for obtaining the best enantioselectivity by minimizing both the amount of free AC in the bulk solution, and the formation of racemic product therefrom. However, this does not immediately mean that catalytic supramolecular photochirogenesis is infeasible for AC photocyclodimerization without using the sensitization technique. Recently, the non-sensitized photocyclodimerization of AC was achieved for the first time by using a catalytic amount (0.1 equivalent) of *g*-CD derivative with a Cu(II)-chelate sidearm.[46] Thus, the Cu<sup>2+</sup> ion chelated by the diamino sidearm of **14-16** (Figure 3) pre-organizes two ACs in HH orientation in the CD cavity

through coordination to the AC's carboxylate anion, while unchelated Cu<sup>2+</sup> in the bulk solution efficiently quenches excited free AC located outside the cavity to prevent the formation of racemic products. The trick in this system is that the chelated Cu<sup>2+</sup> does not quench the excited AC in the CD cavity but manipulates the stereochemical consequence of AC photocyclodimerization to dramatically enhance the chemical yield of the sterically hindered HH-dimers (**12** and **13**) to 80% and the optical yield of **12** to 70% ee.[46]

The competitive enantiodifferentiating polar photoaddition of methanol and water to 1,1-diphenylpropene (**17**) has expanded the scope of sensitized supramolecular photochirogenesis from the unimolecular to bimolecular regime. Upon supramolecular photosensitization by cyanonaphthyl-modified *b*-CD (**20**) in aqueous methanol, **17** affords anti-Markovnikov adducts **18** and **19** via the competitive nucleophilic attack of methanol and water, respectively, to radical cationic **17** (Scheme 4). Methanol-adduct **18** is favored by a factor of

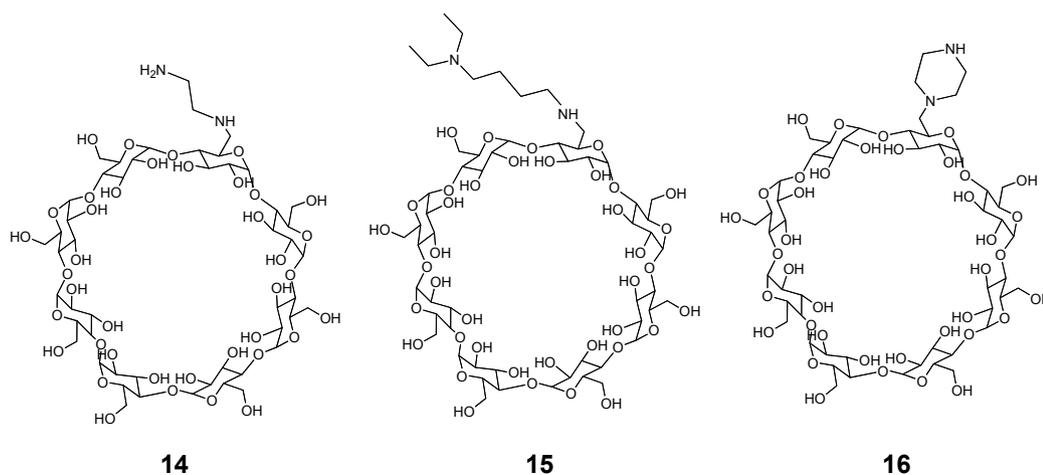
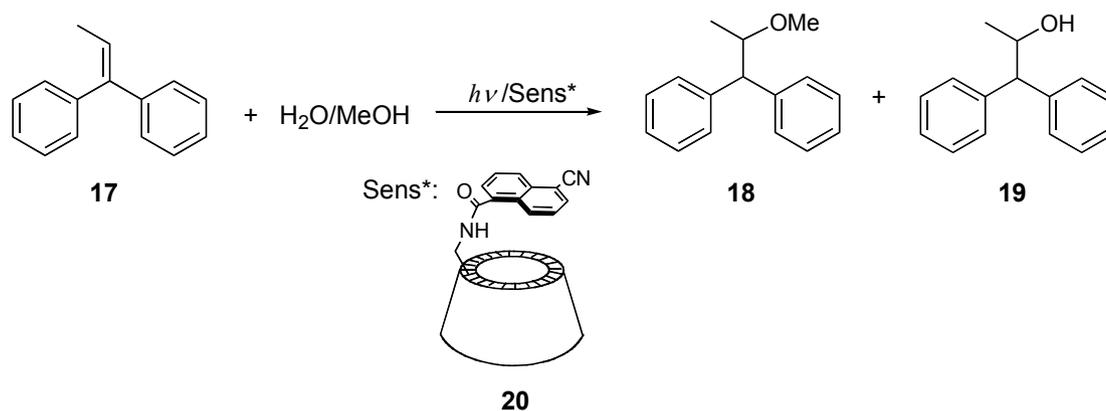


Figure 3. Modified *g*-CDs with a diamino sidearm that chelates to Cu<sup>2+</sup>.



Scheme 4. Photosensitized anti-Markovnikov addition of methanol and water to 1,1-diphenylpropene **17** mediated by cyanonaphthyl-*b*-CD **20**.

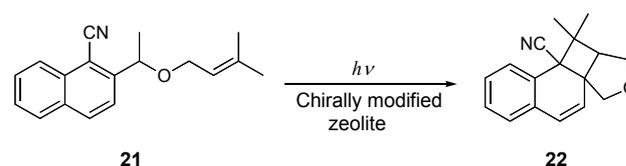
2.5 over water-adduct **19** due to the higher nucleophilicity of methanolic oxygen. In 10% aqueous methanol solution at -10 °C, modest enantioselectivities of 13% and 18% ee are achieved for **18** and **19**, respectively. Interestingly, the ee values and the chiral sense of the photoadducts are also sensitive to environmental variants such as temperature and solvent. Thus, by lowering the temperature, the absolute configuration of product **18** is inverted with the ee value varying from -2.1% at 45 °C to +5.8% at -40 °C.

### 3 Catalytic Supramolecular Photochirogenesis with Chirally-Modified Zeolite

Zeolite supercages have widely been exploited as inorganic hosts for accommodating various organic guests, and for mediating corresponding guest (photo) reactions. Although conventional zeolites are not chiral, chiral nanospace can be created by immobilizing chiral inductors in the supercage. Analogous to CDs, zeolites are UV-transparent (though somewhat scattering) and therefore allow a variety of photoreactions to occur in their supercages. Chiral modification of zeolites is realized by replacing the counter cations on the interior surface of supercage with chiral organic ammonium ions, or by adsorbing neutral chiral organic molecules. Since zeolites are insoluble in most solvents, photoreactions are usually carried out in the solid state or in suspension. The photochirogenesis with chirally modified zeolites often requires an excess amount of chiral inductor to make all the supercages fully modified so as to avoid the formation of racemic photoproduct in the unmodified supercages, while supercages located deep inside the zeolite are relatively difficult to access. The latter factor makes the exchange of photoproduct with substrate slow, leading to

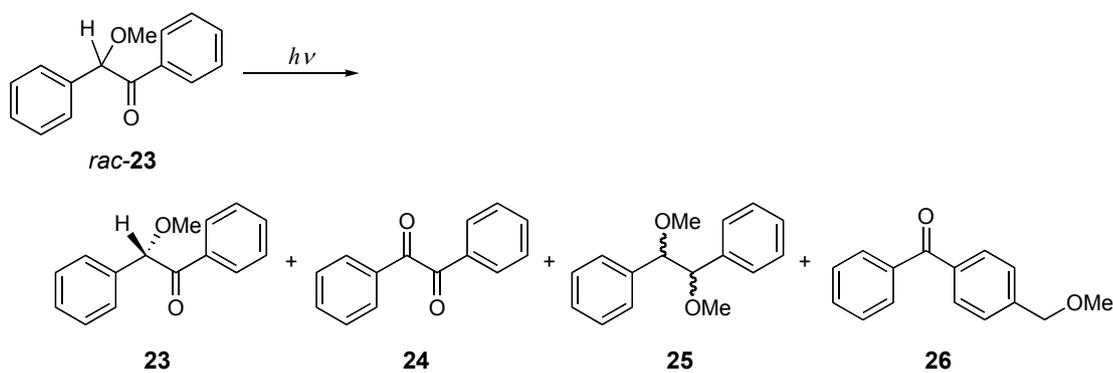
the product inhibition behavior. Therefore, the catalytic photochirogenesis with zeolite host is achieved only by immobilizing chiral sensitizers inside zeolite supercages.

Photoreactions mediated by chirally modified zeolites afford modest to good diastereo- and enantioselectivities. Asymmetric induction upon intramolecular [2+2] photocycloaddition of 1-cyano-2-(1,5-dimethyl-2-oxa-4-hexenyl)naphthalene **21** has been examined in zeolites modified by chiral amine or alcohol (Scheme 5).[47] Irradiation of a slurry sample of **21** adsorbed on dry NaY zeolite modified with L-(+)-diethyl tartrate gives cycloadduct **22** in 10% ee, while the use of L-phenylalaninol as chiral inductor immobilized on the zeolite improved the ee to 15%.



**Scheme 5.** Intramolecular [2+2] photocycloaddition of 1-cyano-2-(5-methyl-2-oxa-4-hexenyl) naphthalene.

Turro *et al.* have studied the deracemization of benzoin methylether **23** upon photolysis in chirally modified zeolites (Scheme 6). The geminate radical pair produced upon the Norrish type I (α-cleavage) reaction of **23** recombines in situ in the chiral supercage to give enantiomerically enriched starting material **23** and para-substituted **26**, or alternatively the benzoyl and methoxybenzyl radicals generated each escape the initial supercage and homodimerize to **24** and **25**. The product distribution obtained upon photolysis in zeolite supercages significantly differs from that in isotropic solutions. In the photolysis of racemic **23** in L-diethyl tartrate-modified NaY zeolite, the formation of geminate recombination products **23**



**Scheme 6.** Norrish type I (α-cleavage) reaction of racemic benzoin methyl ether **23** in chirally modified NaY zeolite.

and **26** is favored, due to the decelerated escape from the supercage, while the photochemical deracemization in the chiral supercage affords **23** in 9.2% ee.[48]

Ramamurthy and coworkers have investigated the diastereodifferentiating *cis-trans* photoisomerization of 2b,3b-diphenylcyclopropane-1a-carboxylates **27** with chiral ester auxiliaries in triplet sensitizer-immobilized LiY, NaY, KY, RbY, and CsY zeolites (Scheme 7).[49] Triplet-sensitized photoisomerization of **27a** adsorbed in 4-methoxyacetophenone-immobilized NaY zeolite affords **28a/29a** in up to 55% de, which is much higher than that obtained in solution phase ( $\leq 5\%$  de).[50]

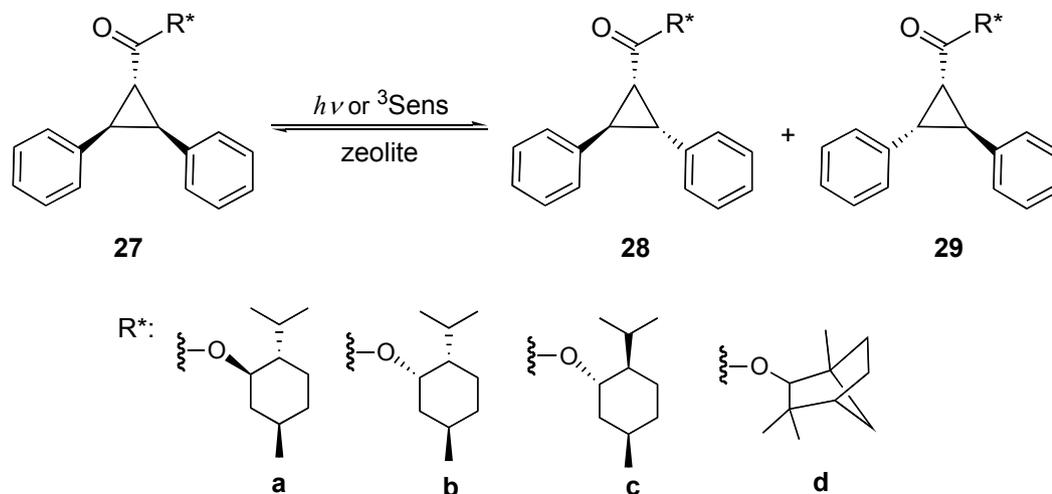
Benzonorbornadiene **30** is photochemically inert upon direct irradiation, but smoothly undergoes the di-p-methane rearrangement to **31** upon triplet sensitization (Scheme 8).[51,52] The use of TIY zeolite as a host accelerates the intersystem crossing of singlet-excited photosubstrate due to the heavy atom effect, facilitating the rearrangement to **31** via the triplet excited state.[53] Thus, the photolysis of **30** within TIY zeolite chirally modified by (+)-ephedrine hydrochloride gives **31** in 14% ee.

To realize the catalytic photochirogenesis with chiral zeolites, Inoue and coworkers have examined the enantiodifferentiating photoisomerization of **1Z** in

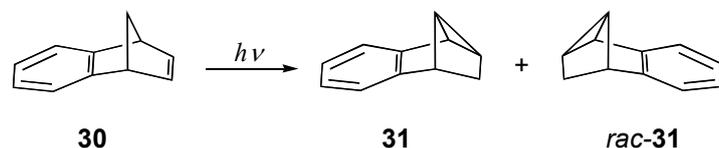
chiral sensitizer-modified zeolite. In sharp contrast to the formation of racemic **1E** upon conventional chiral photosensitization with enantiopure 1-methylheptyl benzoate in isotropic solution, the supramolecular photosensitization with NaY zeolite modified with the same chiral benzoate affords **1E** in a modest but significantly higher ee of 4.5%.[54]

## 4 Catalytic Supramolecular Photochirogenesis with Chiral Templates

The use of a chiral template is a relatively recently emerging supramolecular strategy for mediating asymmetric photochemical reactions. Chiral templates are generally much simpler in chemical structure than conventional chiral hosts, and need to be more sophisticatedly designed for a reasonable balance between binding affinity and steric conflict. The concise structure of chiral templates, as well as the limited number of supramolecular interactions to be considered, allow rational or even *de novo* design, and also the elucidation the chiral differentiation mechanisms in considerable detail. Of the many weak non-covalent interactions, the hydrogen-bonding interaction, which is



**Scheme 7.** Diastereodifferentiating *cis-trans* photoisomerization of 2b,3b-diphenylcyclopropane-1a-carboxylates with chiral auxiliary (R\*).



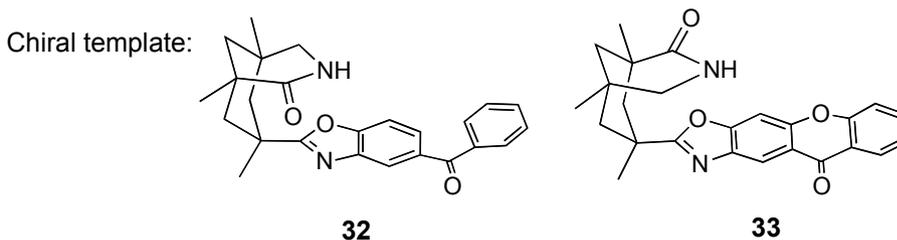
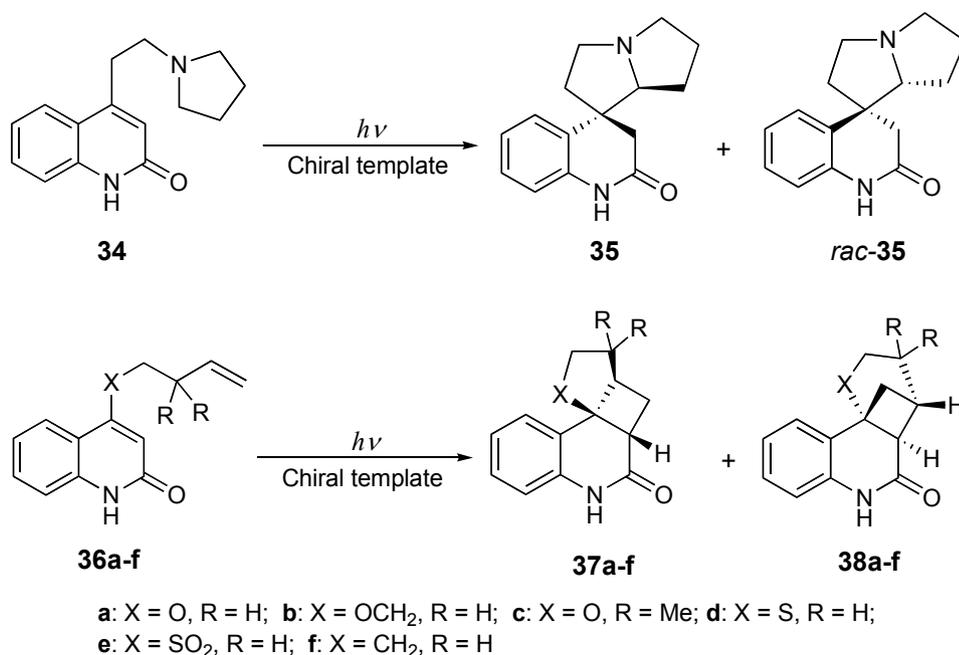
**Scheme 8.** Di-p-methane rearrangement of benzonorbornadiene.

strong and directional, is most frequently employed as a tool for capturing the guest substrate and controlling its orientation, configuration and/or conformation in the supramolecular complex formed.[55,56] Multiple hydrogen-bonding interactions provided by chiral templates can also confine and preorganize substrate(s) to drive photoreactions towards the specific stereochemistry desired.[57-59]

Bach *et al.* have developed a series of Kemp's acid-based chiral templates, such as **32** and **33**, which possess a lactam moiety as a hydrogen-bond donor/acceptor, and an aromatic moiety as both a built-in photosensitizer and a fence to shield one of the enantiotopic faces of an amide-carrying prochiral substrate bound to the template. This dual hydrogen-bonding motif with a sensitizing/shielding aromatic plane enables efficient enantiotopic face-selective binding, and the subsequent photosensitization or photoreaction. Thus, the benzophenone and xanthone moieties in **32** and **33** play dual roles of shielding one of the enantiotopic faces of the complexed substrate

and accepting an electron from the bound substrate upon photoinduced electron transfer (PET).[60,61] Photoirradiation of **34** bound to **32** (Scheme 9) leads to PET from the pyrrolidine nitrogen to the benzophenone moiety of **32**, which is followed by migration of a hydrogen from the carbon  $\alpha$  to the radical cationic pyrrolidine nitrogen. Since one of the enantiotopic faces of quinolone is blocked by the benzophenone moiety, the pyrrolidyl radical can attack the *ipso*-carbon, only from the open face of quinolone to form the spiro skeleton. As a result, the photocyclization of **32** in the presence of 0.1 equivalent of chiral template **32**, gives **35** in 52-64% yield, and in up to 70% ee.

These chiral templates have also been applied to intramolecular [2+2] photocycloaddition of  $\omega$ -alkenyl(oxy)-2-quinolones **36a-f**. [62] Photoirradiation of 4-(3'-butenyloxy)quinolone **36a** in the presence of 0.1 equivalent of **32** results in tricyclic adducts **37a** and **38a** in 75:25 ratio and in 39% and 17% ee, respectively.[63] With xanthone-bearing template **33**, which possesses



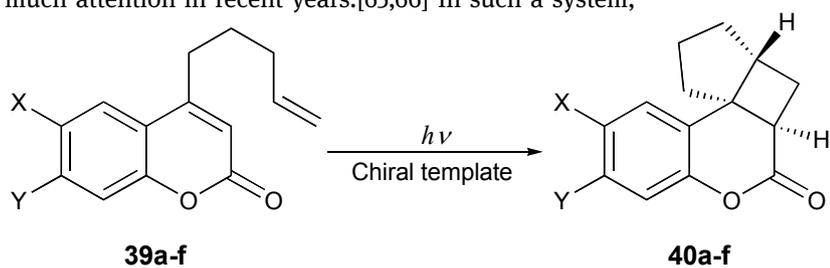
**Scheme 9.** Photocyclization sensitized by chiral templates.

a higher triplet energy and a more effective shielding ability, **37a** and **38a** are given in an excellent ee of 94%. For photocycloaddition of **36b-f**, xanthone-based organocatalyst **33** shows a better enantioselective performance than benzophenone-based **32**, to afford the corresponding cycloadducts in 72–87% ee under the optimized conditions.

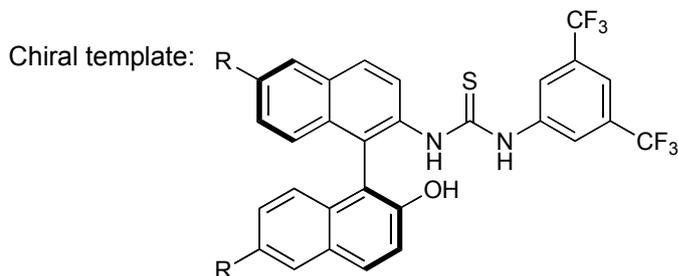
Sivaguru and coworkers have recently reported enantioselective intramolecular photocycloadditions of 4-alkenyl-substituted coumarins **39** catalyzed by a series of chiral binaphthyl-based thioureas **41** (Scheme 10).[64] The thiourea moiety hydrogen-bonds to the carbonyl group of **39**, while the binaphthyl part functions as a built-in chiral photosensitizer. The binding affinities of **39** to **41** are modest, with the combination of **39a** and **41a** showing an association constant of  $84 \text{ M}^{-1}$  in methylcyclohexane. Photoreaction of **39a** with one equivalent of **41b** in a 1:1 toluene/*m*-xylene mixture at  $-78 \text{ }^\circ\text{C}$  affords **40a** in 96% ee. The enantioselectivity of **40a** is held high at 94% ee even when the quantity of catalyst is reduced to 0.1 equivalent but is reasonably reduced to 77% ee with a 0.01 equivalent of **41b**.

## 5 Catalytic Supramolecular Photochirogenesis with Chirally Coordinated Transition Metal Ions

Photochirogenesis via photoredox reaction has attracted much attention in recent years.[65,66] In such a system,



**a:** X = Y = H; **b:** X = Me, Y = H; **c:** X = F, Y = H; **d:** X = OMe, Y = H;  
**e:** X = H, Y = Me; **f:** X = H, Y = F



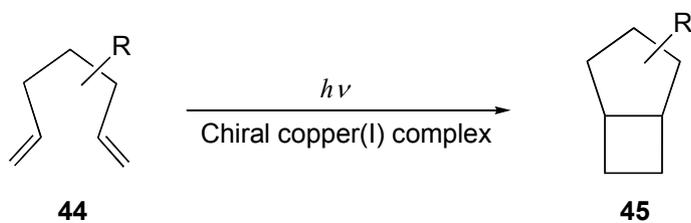
**41a:** R = H  
**41b:** R = CF<sub>3</sub>

the enantioselective photoredox reaction is induced by visible light excitation of a chirally coordinated transition metal ion interacting also with a substrate. For example, intramolecular [2+2] photocycloaddition of *a,w*-alkadienes is greatly accelerated in the presence of copper ion through coordination of the two double bonds to the metal ion. Bach and coworkers have synthesized enantiomeric bicyclo[4.2.0]octane derivatives by using Cu(II)-catalyzed [2+2] photocycloaddition of the corresponding 1,7-heptadienes and the subsequent enantiodifferentiating Baeyer-Villiger oxidations.[67] Mattay *et al.* have examined the intramolecular [2+2] photocycloadditions of 1,6-dienes **44** catalyzed by Cu(I) with chiral oxazoline ligands **42** and **43** (Scheme 11) to obtain **45** in less than 5% ee, most likely due to the low affinity of the Cu(I) complex with the substrate.[68]

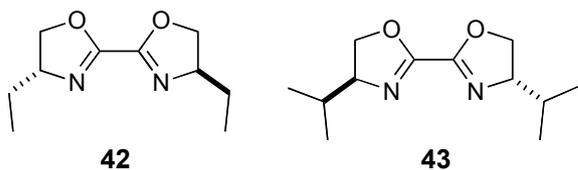
Yoon and coworkers have recently reported a dual catalyst approach to the enantiodifferentiating [2+2] photocycloaddition of *a,b*-unsaturated ketones **46** and **47** (Scheme 12) using a Ru(II) tris(2,2'-bipyridine) complex as a visible light-absorbing PET sensitizer, and a chiral Lewis acid (Gd(III) or Eu(III) triflate) as a stereocontrolling cocatalyst to give the corresponding cyclobutane **48** in 89–93% ee with chiral ligand **50a** and epimeric **49** in 84–97% ee with **50b**.[69]

Meggers and coworkers have reported the enantiodifferentiating photoalkylation of acylimidazole **51** with benzyl bromide **52** catalyzed by a photoredox transition metal complex (Scheme 13).[70] In this

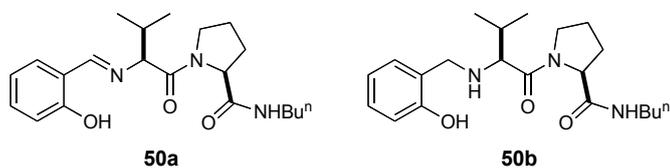
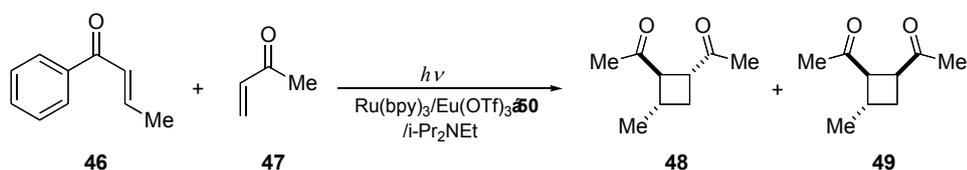
**Scheme 10.** Photocycloaddition of coumarin derivatives using thioureas derived from atropisomeric binaphthyl.



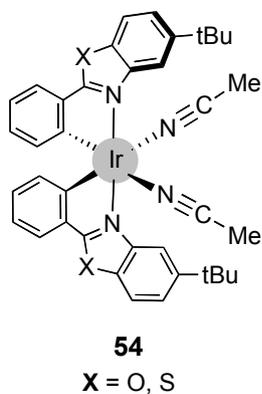
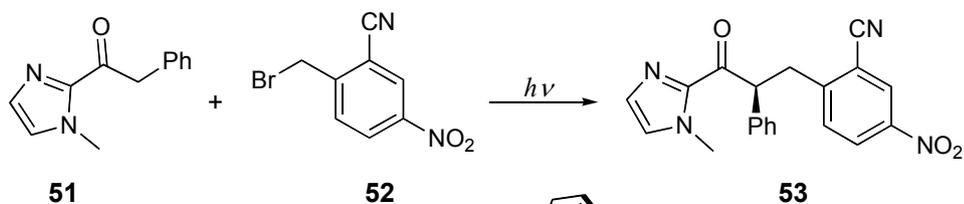
Chiral ligand for Cu(I):



**Scheme 11.** Photocycloaddition of 1,6-dienes **44** to bicyclo[3.2.0]heptanes **45** mediated by Cu(I) complexes with chiral ligands **42** and **43**.



**Scheme 12.** Enantiodifferentiating [2+2] photocycloaddition of **46** and **47** catalyzed by chiral metal complex.



**Scheme 13.** Enantioselective photoredox alkylation of acylimidazole **51**.

photoreaction, Ir(III) complex **54** coordinated by two bidentate ligands in chiral configuration plays triple roles, acting as chiral center, catalyst and photoredox mediator,

to afford alkylation product **53** in up to 99% ee upon visible light irradiation.

## 6 Catalytic Supramolecular Photochirogenesis with Miscellaneous Chiral Sources

Besides the supramolecular photochirogenic systems described above, several interesting chiral supramolecular sensitizers that can catalyze photoreactions have been reported. Inoue and coworkers have studied the enantiodifferentiating photoisomerization of (*Z*)-cyclooctene **1Z** and (*Z,Z*)-1,5-cyclooctadiene **3ZZ** sensitized by planar-chiral paracyclophanes **55a,b** (Figure 4)[9] to realize the planar-to-planar chirality transfer in the excited state. Differing from the conventional point-chiral sensitizers studied previously, the decamethylene bridge in planar-chiral sensitizer **55** effectively shields one of the enantiotopic faces of the paracyclophane sensitizer to render the excited-state interaction with the more enantiotopic face-selective substrate. Under optimized conditions, photosensitizations with **55a** and **55b** afford **1E** in 42% and 43% ee at  $-110\text{ }^{\circ}\text{C}$  and **3EZ** in 87% and 85% ee at  $-140\text{ }^{\circ}\text{C}$ , respectively.

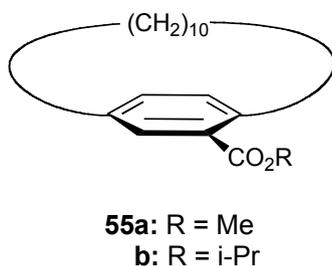


Figure 4. Planar-chiral cyclophane sensitizers **55**.

Enantiodifferentiating photoisomerization of **2ZZ** has been investigated using naphthoyl-curdlan as the supramolecular photosensitizer.[71] Curdlan is a linear glucan composed of 1 $\rightarrow$ 3-linked  $\beta$ -D-glucose units, which is known to form a triple helical structure

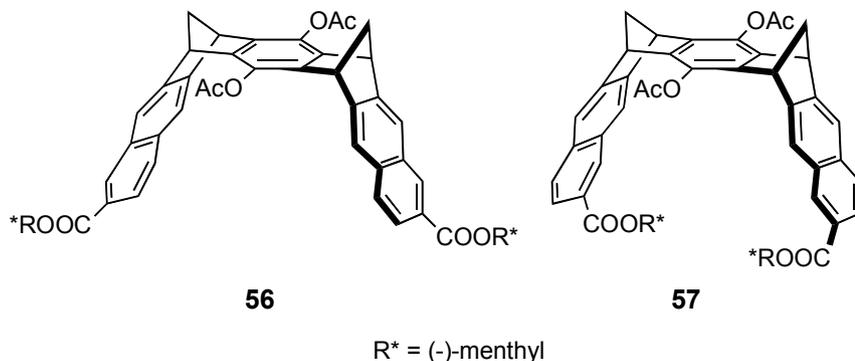
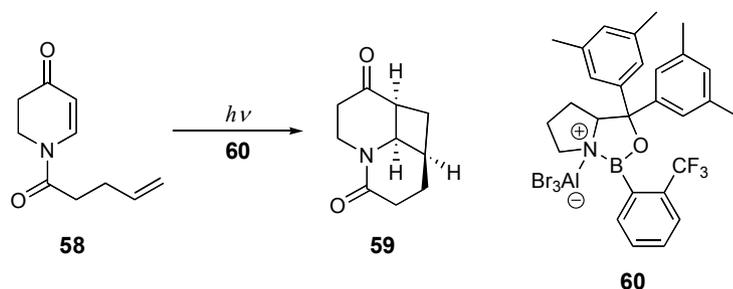


Figure 5. Chiral molecular clips **56** and **57**.

in aqueous solutions. The photoisomerization of **2ZZ** sensitized by naphthoyl-curdlan critically depends on the irradiation time, solvent, phase, temperature, and guest concentration to give **2EZ** in up to 8.7% ee in solution and 11.7% ee in the solid state.

Liquid crystals, including lyotropic poly(*g*-benzyl-L-glutamate) (PBLG) and thermotropic cholesteryl oleyl carbonate, have been employed as chiral photosensitizing supramolecular media for the enantiodifferentiating photoisomerization of **1Z** to evaluate the photochirogenic abilities of the moderately organized media.[72] Although the photoisomerization of **1Z** in liquid crystals affords **1E** mostly in low ee (<5%), it should be noted that lyotropic PBLG gives contrasting results in cholesteric and nematic mesophases, revealing the importance of the mesophase structure. The generally low ee values obtained may indicate however that the chiral 3D structure of the liquid crystal is too large to be sensed by the substrate at the molecular level, and hence the existence of a chiral sensitizer is necessary to afford an appreciable enantioselectivity.

The supramolecular enantiodifferentiating photoisomerization of **2ZZ** and the polar photoaddition of methanol to 1,1-diphenylpropene **17** have been studied by using chiral molecular clips **56** and **57** (Figure 5) as sensitizing hosts. Chiral clip **56** strongly binds the substrates with association constants of  $8800\text{ M}^{-1}$  for **2ZZ** and  $27000\text{ M}^{-1}$  for **17** in 4:1:5 THF-MeOH-H<sub>2</sub>O.[33] The supramolecular complexation by chiral clip facilitates the photoisomerization of **2ZZ** to give a good E/Z ratio of 0.19, while the ee of **2EZ** thus obtained is low (0.7% ee). This result suggests that the inherent chirality of the molecular clip is not effectively transferred to the substrate captured by the two naphthalene moieties. On the other hand, the photoaddition of methanol to **17** sensitized by molecular clips afford only a negligible amount of methanol adduct, suggesting that the electron-transfer photosensitization is discouraged in this sandwiched structure.



**Scheme 14.** Intramolecular [2+2] photocycloaddition of **58** through complexation with chiral Lewis acid **60**.

Recently, Bach and coworkers have proposed a new strategy for catalytic intramolecular [2+2] photocycloaddition of **58** using chiral Lewis acid **60** (Scheme 14).[73] The significant bathochromic shift of >50 nm caused upon complexation of substrate **58** with **60** enables exclusive excitation of the complexed substrate at longer wavelengths, while suppressing the unfavorable photoreaction of uncomplexed **58** to racemic **59**. This strategy is widely applicable to a series of enone derivatives to afford cycloadducts in 80-90% ee at high conversions.

Melchiorre and coworkers have reported a catalytic photochemical  $\alpha$ -alkylation of aldehydes **61**, which is driven by the excitation of a donor-acceptor complex of the chiral enamine derived from the aldehyde with benzyl bromide **62**. [74] As illustrated in Scheme 15, aldehyde **61** first reacts with chiral amine **64** or **65** added as a catalyst (0.2 equivalent) to give the corresponding enamine, which forms a donor-acceptor complex with electron-deficient benzyl bromide **62** in the ground state. Selective photoexcitation of the charge-transfer band of the complex in the visible region induces electron transfer to give radical cationic enamine and **62** radical anion, the latter of which spontaneously decomposes to give a benzyl radical. The radical attacks the radical cationic enamine to afford an iminium cation, which eventually decomposes to the alkylation product in 83%-94% ee, regenerating chiral amine in the presence of one equivalent of 2,6-lutidine.

## 7 Summary and Perspective

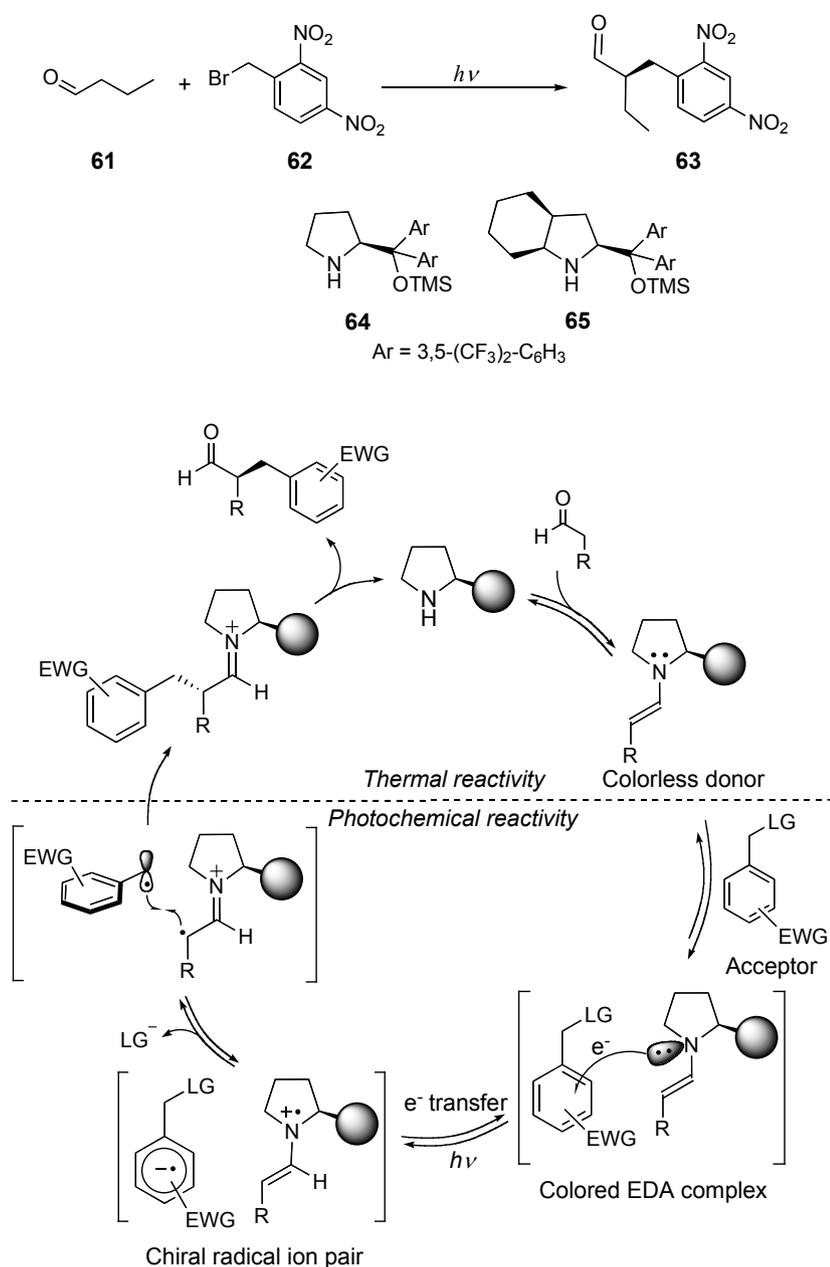
Catalytic supramolecular photochirogenesis has experienced a rapid progress in strategy and methodology particularly in the last decade. The use of a chiral supramolecular host/assembly significantly enhances the local concentration of substrate and the rate and stereoselectivity of the subsequent chiral photoreactions, as a consequence of the complex, and long-lasting supramolecular interactions in the ground and excited states.

One of the major strategies for achieving catalytic photochirogenesis in a supramolecular system is to append a hydrophobic photosensitizing moiety to a transparent chiral host molecule. In such a sensitizing host system, the hydrophobic sensitizer, being embedded in the host cavity, is masked or disabled in the absence of guest substrate. Upon guest inclusion into the host cavity, the sensitizer moiety moves to the host portal but stays in close contact with the included guest, which allows for highly efficient energy or electron transfer, and the subsequent stereodifferentiating chemical process to take place in the chiral supramolecular environment. This method is of high quantum efficiency in principle, and affords good to excellent stereoselectivities as described above.

Non-sensitizing methods have also been developed for catalytic supramolecular photochirogenesis. The most crucial issue in this strategy is to avoid or quench the background photoreactions occurring outside the chiral environment. Background photoreactions can usually be suppressed by adding a transition or heavy metal ion, which coordinates to free substrate in the bulk solution, and quenches its photoreaction by facilitating some intersystem crossing with excited substrate. This method, which consumes part of the available excitation energy, produces inherently low quantum efficiencies.

Better quantum efficiencies unique to this photochemistry can be achieved by increasing the excitation wavelength, which effectively avoids the background reactions of free substrate, through coordination to chiral Lewis acid catalyst, or through charge-transfer complexation with a chiral electron donor/ acceptor, both of which cause bathochromic shifts of the original absorption band of the substrate, to allow exclusive excitation or recovery of the coordinated or complexed substrate, even in the presence of excess substrate.

From a catalytic point of view, if the affinity of photoproduct to the chiral host employed is higher than that of the substrate, product inhibition should occur



**Scheme 15.** Catalytic photochemical  $\alpha$ -alkylation of aldehyde.

to hinder the catalytic use of the supramolecular host. Hence, a modest affinity to substrate, which is lower than that for photoproduct, is favorable in general, or some other technique for efficient removal of photoproduct is needed to design an efficient catalytic supramolecular photochirogenic system.

The catalytic supramolecular photochirogenic systems examined are still limited in number and variety, and the optical (and/or chemical) yields reported are not necessarily satisfactory in some cases, leaving much space for future endeavors. The research in this intriguing

interdisciplinary field of photochemistry, catalysis, asymmetric synthesis, and supramolecular chemistry is certainly fast-growing in number and expanding in area, but we still need to better understand the factors and mechanisms operative in photoreactions occurring in chiral supramolecular environments to construct more efficient chiral supramolecular systems that are applicable to a wider variety of photochirogenic reactions.

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## References

- [1] Yang C., Inoue Y., CRC Handbook of Organic Photochemistry and Photobiology (3rd ed), 2012, pp. 125-176.
- [2] Inoue Y., Ramamurthy V., Chiral Photochemistry, Marcel Dekker, 2004.
- [3] Axel G. Griesbeck, Meierhenrich U.J., Asymmetric photochemistry and photochirogenesis, *Angew. Chem. Int. Ed.*, 2002, 41, 3147-3154.
- [4] Mueller C., Bach T., Chirality Control in Photochemical Reactions: Enantioselective Formation of Complex Photoproducts in Solution, *Aust. J. Chem.*, 2008, 61, 557-564. T. Bach in *Asymmetric Synthesis—The Essentials* (Eds.: S. Bräse, M. Christmann), Wiley-VCH, Weinheim, 2006, pp. 166-170
- [5] Hammond G.S., Cole R.S., Asymmetric induction during energy transfer, *J. Am. Chem. Soc.*, 1965, 87, 3256-3257.
- [6] Inoue Y., Yokoyama T., Yamasaki N., Tai A., An optical yield that increases with temperature in a photochemically induced enantiomeric isomerization, *Nature*, 1989, 341, 225-226.
- [7] Inoue Y., Yokoyama T., Yamasaki N., Tai A., Temperature switching of product chirality upon photosensitized enantio-differentiating cis-trans isomerization of cyclooctene, *J. Am. Chem. Soc.*, 1989, 111, 6480-6482.
- [8] Inoue Y., Matsushima E., Wada T., Pressure and temperature control of product chirality in asymmetric photochemistry. enantiodifferentiating photoisomerization of cyclooctene sensitized by chiral benzenepolycarboxylates, *J. Am. Chem. Soc.*, 1998, 120, 10687-10696.
- [9] Maeda R., Wada T., Mori T., Kono S., Kanomata N., Inoue Y., Planar-to-planar chirality transfer in the excited state. enantio-differentiating photoisomerization of cyclooctenes sensitized by planar-chiral paracyclophane, *J. Am. Chem. Soc.*, 2011, 133, 10379-10381.
- [10] Vallavoju N., Sivaguru J., Supramolecular photocatalysis: Combining confinement and non-covalent interactions to control light initiated reactions. *Chem. Soc. Rev.*, 2014, 43, 4084-4101.
- [11] Yang C., Inoue Y., Supramolecular photochirogenesis, *Chem. Soc. Rev.*, 2014, 43, 4123-4143.
- [12] Nakamura A., Inoue Y., Supramolecular catalysis of the enantiodifferentiating [4+4] photocyclodimerization of 2-anthracenecarboxylate by g-cyclodextrin, *J. Am. Chem. Soc.*, 2003, 125, 966-972.
- [13] Luo L., Liao G.H., Wu X.L., Lei L., Tung C.H., Wu L.Z., g-Cyclodextrin-directed enantioselective photocyclodimerization of methyl 3-methoxyl-2-naphthoate, *J. Org. Chem.*, 2009, 74, 3506-3515.
- [14] Bach T., Grosch B., Strassner T., Herdtweck E., Enantioselective [6p]-photocyclization reaction of an acrylanilide mediated by a chiral host. Interplay between enantioselective ring closure and enantioselective protonation, *J. Org. Chem.*, 2003, 68, 1107-1116.
- [15] Sivaguru J., Natarajan A., Kaanumalle L.S., Shailaja J., Uppili S., Joy A., Ramamurthy V., Asymmetric photoreactions within zeolites: role of confinement and alkali metal ions, *Acc. Chem. Res.*, 2003, 36, 509-521.
- [16] Nishioka Y., Yamaguchi T., Kawano M., Fujita M., Asymmetric [2+2] olefin cross photoaddition in a self-assembled host with remote chiral auxiliaries, *J. Am. Chem. Soc.*, 2008, 130, 8160-8161.
- [17] Ishida Y., Kai Y., Kato S.-y., Misawa A., Amano S., Matsuoka Y., Saigo K., Two-component liquid crystals as chiral reaction media: highly enantioselective photodimerization of an anthracene derivative driven by the ordered microenvironment, *Angew. Chem. Int. Ed.*, 2008, 47, 8241-8245.
- [18] Dawn A., Shiraki T., Haraguchi S., Sato H., Sada K., Shinkai S., Transcription of chirality in the organogel systems dictates the enantiodifferentiating photodimerization of substituted anthracene, *Chem. Eur. J.*, 2010, 16, 3676-3689.
- [19] Rekharsky M.V., Inoue Y., Complexation thermodynamics of cyclodextrins, *Chem. Rev.*, 1998, 98, 1875-1918.
- [20] Yang C., Recent progress in supramolecular chiral photochemistry, *Chin. Chem. Lett.*, 2013, 24, 437-441.
- [21] Inoue Y., Dong S.F., Yamamoto K., Tong L.-H., Tsuneishi H., Hakushi T., Tai A., Inclusion-enhanced optical yield and E/Z ratio in enantiodifferentiating photoisomerization of cyclooctene included and sensitized by b-cyclodextrin monobenzoate, *J. Am. Chem. Soc.*, 1995, 117, 11033-11034.
- [22] Inoue Y., Kosaka S., Matsumoto K., Tsuneishi H., Hakushi T., Tai A., Nakagawa K., Tong L.-H., Vacuum UV photochemistry in cyclodextrin cavities. Solid state Z-E photoisomerization of a cyclooctene-b-cyclodextrin inclusion complex, *J. Photochem. Photobiol., A*, 1993, 71, 61-64.
- [23] Inoue Y., Wada T., Sugahara N., Yamamoto K., Kimura K., Tong L.-H., Gao X.-M., Hou Z.-J., Liu Y., Supramolecular photochirogenesis. 2. enantiodifferentiating photoisomerization of cyclooctene included and sensitized by 6-O-modified cyclodextrins, *J. Org. Chem.*, 2000, 65, 8041-8050.
- [24] Gao Y., Inoue M., Wada T., Inoue Y., Supramolecular photochirogenesis. 3. enantiodifferentiating photoisomerization of cyclooctene included and sensitized by 6-O-mono(o-methoxybenzoyl)cyclodextrin, *J. Incl. Phenom. Macrocycl. Chem.*, 2004, 50, 111-118.
- [25] Gao Y., Wada T., Yang K., Kim K., Inoue Y., Supramolecular photochirogenesis in sensitizing chiral nanopore: Enantiodifferentiating photoisomerization of (Z)-cyclooctene included and sensitized by POST-1, *Chirality*, 2005, 17, S19-S23.
- [26] Lu R., Yang C., Cao Y., Tong L., Jiao W., Wada T., Wang Z., Mori T., Inoue Y., Enantiodifferentiating photoisomerization of cyclooctene included and sensitized by aroyl-β-cyclodextrins: a critical enantioselectivity control by substituents, *J. Org. Chem.*, 2008, 73, 7695-7701.
- [27] Lu R., Yang C., Cao Y., Wang Z., Wada T., Jiao W., Mori T., Inoue Y., Supramolecular enantiodifferentiating photoisomerization of cyclooctene with modified b-cyclodextrins: critical control by a host structure, *Chem. Commun.*, 2008, 374-376.
- [28] Liang W., Yang C., Nishijima M., Fukuhara G., Mori T., Mele A., Castiglione F., Caldera F., Trotta F., Inoue Y., Cyclodextrin nanosponge-sensitized enantiodifferentiating photoisomerization of cyclooctene and 1,3-cyclooctadiene, *Beilstein J. Org. Chem.*, 2012, 8, 1305-1311.

- [29] Fukuhara G., Mori T., Wada T., Inoue Y., Entropy-controlled supramolecular photochirogenesis: enantiodifferentiating *Z-E* photoisomerization of cyclooctene included and sensitized by permethylated 6-O-benzoyl- $\beta$ -cyclodextrin, *Chem. Commun.*, 2005, 4199-4200.
- [30] Yang C., Mori T., Wada T., Inoue Y., Supramolecular enantiodifferentiating photoisomerization of (*Z,Z*)-1,3-cyclooctadiene included and sensitized by naphthalene-modified cyclodextrins, *New J. Chem.*, 2007, 31, 697-702.
- [31] Fukuhara G., Mori T., Wada T., Inoue Y., Entropy-controlled supramolecular photochirogenesis: enantiodifferentiating *Z-E* photoisomerization of cyclooctene included and sensitized by permethylated 6-O-modified  $\beta$ -cyclodextrins, *J. Org. Chem.*, 2006, 71, 8233-8243.
- [32] Inoue Y., Ikeda H., Kaneda M., Sumimura T., Everitt S.R.L., Wada T., Entropy-controlled asymmetric photochemistry: switching of product chirality by solvent, *J. Am. Chem. Soc.*, 2000, 122, 406-407.
- [33] Fukuhara G., Klaerner F.-G., Mori T., Wada T., Inoue Y., Supramolecular complexation and photochirogenesis with inherently chiral molecular clip: enantiodifferentiating photoisomerization of (*Z,Z*)-1,3-cyclooctadiene and polar photoaddition to 1,1-diphenylpropene, *Photochem. Photobiol. Sci.*, 2008, 7, 1493-1500.
- [34] Inoue Y., Tsuneishi H., Hakushi T., Tai A., Optically active (*E,Z*)-1,3-cyclooctadiene: First enantioselective synthesis through asymmetric photosensitization and chiroptical property, *J. Am. Chem. Soc.*, 1997, 119, 472-478.
- [35] Liang W., Yang C., Zhou D., Haneoka H., Nishijima M., Fukuhara G., Mori T., Castiglione F., Mele A., Caldera F., Trotta F., Inoue Y., Phase-controlled supramolecular photochirogenesis in cyclodextrin nanosponges, *Chem. Commun.*, 2013, 49, 3510-3512.
- [36] Wei X., Liang W., Wu W., Yang C., Trotta F., Caldera F., Mele A., Nishimoto T., Inoue Y., Solvent- and phase-controlled photochirogenesis. enantiodifferentiating photoisomerization of (*Z*)-cyclooctene sensitized by cyclic nigerosyl-nigerose-based nanosponges crosslinked by pyromellitate, *Org. Biomol. Chem.* 2015, DOI: 10.1039/C4OB02390K in press.
- [37] Koodanjeri S., Ramamurthy V., Cyclodextrin mediated enantio and diastereoselective geometric photoisomerization of diphenylcyclopropane and its derivatives, *Tetrahedron Lett.*, 2002, 43, 9229-9232.
- [38] Yang C., Fukuhara G., Nakamura A., Origane Y., Fujita K., Yuan D.-Q., Mori T., Wada T., Inoue Y., Enantiodifferentiating [4+4] photocyclodimerization of 2-anthracenecarboxylate catalyzed by 6a,6x-diamino-6A,6X-dideoxy- $\gamma$ -cyclodextrins: Manipulation of product chirality by electrostatic interaction, temperature and solvent in supramolecular photochirogenesis, *J. Photochem. Photobiol. A: Chem.*, 2005, 173, 375-384.
- [39] Yang C., Nakamura A., Fukuhara G., Origane Y., Mori T., Wada T., Inoue Y., Pressure and temperature-controlled enantiodifferentiating [4+4]-photocyclodimerization of 2-anthracenecarboxylate mediated by secondary face- and skeleton-modified  $\gamma$ -cyclodextrins, *J. Org. Chem.*, 2006, 71, 3126-3135.
- [40] Yang C., Nakamura A., Wada T., Inoue Y., Enantiodifferentiating photocyclodimerization of 2-anthracenecarboxylic acid mediated by  $\gamma$ -cyclodextrins with a flexible or rigid cap, *Org. Lett.*, 2006, 8, 3005-3008.
- [41] Yang C., Ke C., Fujita K., Yuan D.-Q., Mori T., Inoue Y., pH-Controlled supramolecular enantiodifferentiating photocyclodimerization of 2-anthracenecarboxylate with capped  $\gamma$ -cyclodextrins, *Aust. J. Chem.*, 2008, 1-4.
- [42] Yang C., Mori T., Inoue Y., Supramolecular enantiodifferentiating photocyclodimerization of 2-anthracenecarboxylate mediated by capped  $\gamma$ -cyclodextrins: critical control of enantioselectivity by cap rigidity, *J. Org. Chem.*, 2008, 73, 5786-5794.
- [43] Yang C., Mori T., Origane Y., Ko Y.H., Selvapalam N., Kim K., Inoue Y., Highly stereoselective photocyclodimerization of a-cyclodextrin-appended anthracene mediated by  $\gamma$ -cyclodextrin and cucurbit[8]uril: a dramatic steric effect operating outside the binding site, *J. Am. Chem. Soc.*, 2008, 130, 8574-8575.
- [44] Yang C., Ke C., Liang W., Fukuhara G., Mori T., Liu Y., Inoue Y., Dual Supramolecular photochirogenesis: ultimate stereocontrol of photocyclodimerization by a chiral scaffold and confining host, *J. Am. Chem. Soc.*, 2011, 133, 13786-13789.
- [45] Yao J., Yan Z., Ji J., Wu W., Yang C., Nishijima M., Fukuhara G., Mori T., Inoue Y., Ammonia-driven chirality inversion and enhancement in enantiodifferentiating photocyclodimerization of 2-anthracenecarboxylate mediated by diguanidino- $\gamma$ -cyclodextrin, *J. Am. Chem. Soc.*, 2014, 136, 6916-6919.
- [46] Ke C., Yang C., Mori T., Wada T., Liu Y., Inoue Y., Catalytic enantiodifferentiating photocyclodimerization of 2-anthracenecarboxylic acid mediated by a non-sensitizing chiral metallosupramolecular host, *Angew. Chem. Int. Ed.*, 2009, 48, 6675-6677.
- [47] Maeda H., Okumura T., Yoshimi Y., Mizuno K., Asymmetric induction in an intramolecular [2+2] photocycloaddition within chirally modified zeolite supercages, *Tetrahedron: Asymmetry*, 2009, 20, 381-384.
- [48] Kaprinidis N.A., Landis M.S., Turro N.J., Supramolecular control of photochemical enantiomeric induction and radical pair recombination in zeolites, *Tetrahedron Lett.*, 1997, 38, 2609-2612.
- [49] Sivaguru J., Sunoj R.B., Wada T., Origane Y., Inoue Y., Ramamurthy V., Enhanced diastereoselectivity via confinement: photoisomerization of 2,3-diphenylcyclopropane-1-carboxylic acid derivatives within zeolites, *J. Org. Chem.*, 2004, 69, 6533-6547.
- [50] Kaanumalle L.S., Sivaguru J., Sunoj R.B., Lakshminarasimhan P.H., Chandrasekhar J., Ramamurthy V., Light-induced geometric isomerization of 1,2-diphenylcyclopropanes included within Y zeolites: role of cation-guest binding, *J. Org. Chem.*, 2002, 67, 8711-8720.
- [51] Edman J.R., Photorearrangement of benzonorbornadiene, *J. Am. Chem. Soc.*, 1969, 91, 7103-7104.
- [52] Hahn R.C., Johnson R.P., Effects of a nitro substituent on di-*p*-methane rearrangements of benzonorbornadiene and its [3.2.1] homolog, *J. Am. Chem. Soc.*, 1977, 99, 1508-1513.
- [53] Joy A., Robbins R.J., Pitchumani K., Ramamurthy V., Asymmetrically modified zeolite as a medium for enantioselective photoreactions: Reactions from spin forbidden excited states, *Tetrahedron Lett.*, 1997, 38, 8825-8828.
- [54] Wada T., Shikimi M., Inoue Y., Lem G., Turro N.J., First photosensitized enantiodifferentiating isomerization by optically active sensitizer immobilized in zeolite supercages, *Chem. Commun.*, 2001, 2001, 1864-1865.

- [55] Mizoguchi J.-i., Kawanami Y., Wada T., Kodama K., Anzai K., Yanagi T., Inoue Y., Enantiodifferentiating photocyclodimerization of 2-anthracenecarboxylic acid using a chiral *N*-(2-hydroxymethyl-4-pyrrolidiny)benzamide template, *Org. Lett.*, 2006, 8, 6051-6054.
- [56] Kawanami Y., Pace T.C.S., Mizoguchi J.-i., Yanagi T., Nishijima M., Mori T., Wada T., Bohne C., Inoue Y., Supramolecular complexation and enantiodifferentiating photocyclodimerization of 2-anthracenecarboxylic acid with 4-aminoproline derivatives as chiral hydrogen-bonding templates, *J. Org. Chem.*, 2009, 74, 7908-7921.
- [57] Bach T., Bergmann H., Harms K., Enantioselective intramolecular [2+2]-photocycloaddition reactions in solution, *Angew. Chem. Int. Ed.*, 2000, 39, 2302-2304.
- [58] Bach T., Bergmann H., Brummerhop H., Lewis W., Harms K., The [2+2]-photocycloaddition of aromatic aldehydes and ketones to 3,4-dihydro-2-pyridones: regioselectivity, diastereoselectivity, and reductive ring opening of the product oxetanes, *Chem. Eur. J.*, 2001, 7, 4512-4521.
- [59] Bach T., Bergmann H., Grosch B., Harms K., Highly enantioselective intra- and intermolecular [2+2] photocycloaddition reactions of 2-quinolones mediated by a chiral lactam host: host-guest interactions, product configuration, and the origin of the stereoselectivity in solution, *J. Am. Chem. Soc.*, 2002, 124, 7982-7983.
- [60] Inoue Y., Synthetic chemistry: Light on chirality, *Nature*, 2005, 436, 1099-1100.
- [61] Bauer A., Westkaemper F., Grimme S., Bach T., Catalytic enantioselective reactions driven by photoinduced electron transfer, *Nature*, 2005, 436, 1139-1140.
- [62] Müller C., Bauer A., Maturi M.M., Cuquerella M.C., Miranda M.A., Bach T., Enantioselective intramolecular [2+2]-photocycloaddition reactions of 4-substituted quinolones catalyzed by a chiral sensitizer with a hydrogen-bonding motif, *J. Am. Chem. Soc.*, 2011, 133, 16689-16697.
- [63] Mueller C., Bauer A., Bach T., Light-driven enantioselective organocatalysis, *Angew. Chem. Int. Ed.*, 2009, 48, 6640-6642.
- [64] Vallavoju N., Selvakumar S., Jockusch S., Sibi M.P., Sivaguru J., Enantioselective organo-photocatalysis mediated by atropisomeric thiourea derivatives, *Angew. Chem. Int. Ed.*, 2014, 53, 5604-5608.
- [65] Narayanam J.M., Stephenson C.R., Visible light photoredox catalysis: applications in organic synthesis, *Chem. Soc. Rev.*, 2011, 40, 102-113.
- [66] Prier C.K., Rankic D.A., MacMillan D.W., Visible light photoredox catalysis with transition metal complexes: applications in organic synthesis, *Chem. Rev.*, 2013, 113, 5322-5363.
- [67] Braun I., Rudroff F., Mihovilovic M.D., Bach T., Synthesis of enantiomerically pure bicyclo[4.2.0]octanes by Cu-catalyzed [2+2] photocycloaddition and enantiotopos-differentiating ring opening, *Angew. Chem. Int. Ed.*, 2006, 45, 5541-5543.
- [68] Langer K., Mattay J., Stereoselective intramolecular copper(I)-catalyzed [2+2]- photocycloadditions. enantioselective synthesis of (+)- and (-)-grandisol, *J. Org. Chem.*, 1995, 60, 7256-7266.
- [69] Du J., Skubi K.L., Schultz D.M., Yoon T.P., A Dual-Catalysis Approach to Enantioselective [2 + 2] Photocycloadditions Using Visible Light, *Science*, 2014, 344, 392-396.
- [70] Huo H., Shen X., Wang C., Zhang L., Röse P., Chen L.-A., Harms K., Marsch M., Hilt G., Meggers E., Asymmetric photoredox transition-metal catalysis activated by visible light, *Nature*, 2014, 515, 100-103.
- [71] Fukuhara G., Imai M., Yang C., Mori T., Inoue Y., Enantiodifferentiating photoisomerization of (*Z,Z*)-1,3-cyclooctadiene included and sensitized by naphthoyl-curdlan, *Org. Lett.*, 2011, 1856-1859.
- [72] Xiao D., Wada T., Inoue Y., Supramolecular enantiodifferentiating photoisomerization of (*Z*)-cyclooctene in lyotropic and thermotropic liquid crystals, *Chirality*, 2008, 21, 110-113.
- [73] Brimiouille R., Bach T., Enantioselective Lewis acid catalysis of intramolecular enone [2+2] photocycloaddition reactions, *Science*, 2013, 342, 840-843.
- [74] Arceo E., Jurberg I.D., Álvarez-Fernández A., Melchiorre P., Photochemical activity of a key donor-acceptor complex can drive stereoselective catalytic  $\alpha$ -alkylation of aldehydes, *Nature Chem.*, 2013, 5, 750-756.