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Intermolecular Photocyclizations of *N*-(ω-Hydroxyalkyl)-tetrachlorophthalimide with Alkenes Leading to Medium- and Large-Ring Heterocycles—Reaction Modes and Regio- and Stereoselectivity of the 1,*n*-Biradicals

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Abstract: A new photocyclization strategy by using intermolecular tandem reactions between *N*-(ω-hydroxyalkyl)-4,5,6,7-tetrachlorophthalimides (**1**, **2**, and **3**) and a series of acyclic and cyclic alkenes is reported. Electron transfer of the triplet-excited phthalimide with the alkene and regioselective trapping of the alkene cation radical by the hydroxyl group at the phthalimide side chain gives a triplet 1,*n*-biradical, which after intersystem crossing (ISC) leads to regio- and diastereoselective synthesis of polycyclic heterocycles with an N,O-containing medium to large ring. Regio- and diastereoselectivity in the cyclizations are clarified by unambiguous steric structure assignments of the products by X-ray diffraction or extensive 2D NMR measurements. The diastereoselectivity is decided by the stereochemical course of the ISC process of the triplet 1,*n*-biradicals. These intermolecular photoreactions also furnish a new strategy to generate triplet 1,*n*-biradicals. Therefore, in photoreactions of **1** and **2** with phenylcyclohexene, the unprecedented stereoselective formation of products by intramolecular hydrogen-atom transfer in the 1,*n*-biradical intermediate was found (**9** and **23**). These facts provide direct verification to the reaction pathways of the 1,*n*-biradicals and give a new insight into the factors deciding reaction-pathway partitioning and stereoselectivity.

Keywords: biradicals · electron transfer · macrocycles · medium-sized rings · stereoselectivity

Introduction

The pursuit of new strategies for the construction of medium and large ring systems is one of the important tasks in organic synthesis.[1] The formation of medium rings (7–9-membered rings) is particularly difficult because of a combination of unfavorable enthalpic and entropic changes during the cyclization process.[2] Even with the powerful ring-closing metathesis (RCM) strategy,[3] successful synthesis of medium-sized rings usually requires rather stringent reaction conditions, such as high dilution of the reactants, high catalyst loading, and a long reaction time. Furthermore, a conformational predisposition in the substrate to bring the two end groups close together is often required.[3c,4]

In recent years, photoinduced cyclization reactions have achieved remarkable success in medium and large-ring synthesis[5] and emerged as an important alternative method to the thermal cyclization reactions. Presently, one of the most successful photochemical synthetic strategies for medium to large rings is based on intramolecular cyclizations of the N-substituted phthalimides initiated by photoinduced electron

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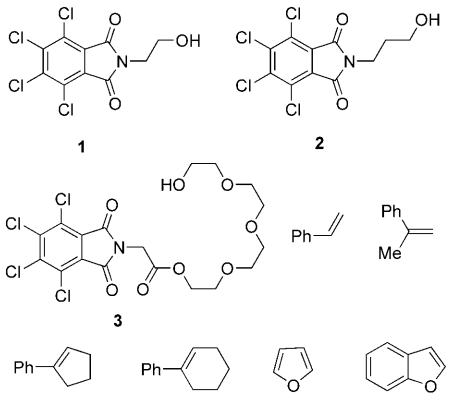
transfer (PET) between the excited phthalimide moiety and a remote electron donor group in the phthalimide side chain. With a benzyl,[6] dialkylamino,[7] alkylthio,[8] alkoxy,[9] or trimethylsilyl[10,11] group as the electron donor, the initial PET event is followed by proton or trimethylsilyl transfer from the donor cation radical to the oxygen atom of the ketyl anion radical to give an 1,*n*-biradical, which then cyclizes to the product with the donor group incorporated into the product. In contrast, when a carboxy anion is used as the donor group, initial PET is followed by decarboxylation to give the 1,*n*-biradical, which on collapse gives a cyclic product without the donor group incorporation.[12,13] In these products, the newly formed medium to large ring is fused with an isoindolone (phthalimidine) skeleton, which is itself an interesting structural motif[14] because of its wide biological activity, occurrence in natural products, and its role as a synthetic intermediate leading to valuable natural and unnatural products. These photocyclization reactions can usually be carried out with a rather high reactant concentration (0.01–0.1 mol L^{-1}) without the need for high dilution conditions. The two terminal groups can be linked by flexible chains rather than a rigid spacer to fix the substrate conformation, as in the thermal cyclizations. These advantages, together with a remarkable synthetic versatility by allowing wide changes in the donor group and the side-chain length and structure make these photoinduced cyclizations efficient tools for diversity-oriented ring synthesis. Another useful photocyclization strategy is based on the intramolecular hydrogen abstraction reaction of a triplet $n\pi^*$ excited carbonyl functionality from a C_γ–H (C_β–H) or a more distant C–H bond (the Norrish Type II—Yang reaction).[15,16] The resulting triplet 1,4- or 1,*n*-biradical, after intersystem crossing (ISC) to the singlet state, cyclizes to the product. Besides synthetic importance, the mechanistic aspects of these intramolecular cyclizations have been under intensive research and have made substantial contributions to our present understanding of the 1,*n*-biradical reactivity and the factors deciding the reaction pathway competition and the cyclization stereoselectivity.[17]

At the same time, photocyclizations based on intermolecular PET reactions have rarely been investigated. A few years ago, we reported the first examples on the photochemical medium and large-ring synthesis by intermolecular PET reactions of *N*-(ω-hydroxyalkyl)-4,5,6,7-tetrachlorophthalimide with alkenes.[18] We envision that, intermolecular photocyclizations offer some special advantages, for example, high dilution conditions is inherently unnecessary due to the intermolecular nature of the reaction, and the wide possibility in changing the phthalimide side chain and the alkene structure enables them to be versatile in constructing polycyclic heterocycles of various ring sizes and structures. In our continuous efforts to develop new photocyclization strategies,[19] we report here photocyclizations of the *N*-(ω-hydroxyalkyl)-4,5,6,7-tetrachlorophthalimides with several acyclic and cyclic alkenes to show their applications in the synthesis of annulated seven-membered oxazepine and the eight-membered oxazocine derivatives, as well as larger ring systems. These N,O-containing medium and large rings are noteworthy synthetic targets. The oxazepines[20] and their fused derivatives[21] have a wide range of biological activity, and form the basis for the skeletons of the holstiine[22] and concavine[23] alkaloids. Also, oxazocine derivatives have medicinally important bioactivity.[24] As a result, the synthesis of oxazepine[25,26] and oxazocine[26f,27] rings and their annulated derivatives has attracted considerable research interest. More importantly, we show that by rendering a new strategy to generate the triplet 1,*n*-biradicals by an intermolecular PET process, these photocyclization reactions have provided a valuable opportunity to gain new insight into the possible reaction modes of the 1,*n*-biradicals and the factors deciding reaction-pathway partitioning and the regio- as well as stereochemistry in these reaction pathways.

Results

Photocyclizations of *N*-(2-hydroxyethyl)-4,5,6,7-tetrachlorophthalimide (1) with alkenes: Photocyclization reactions of **1** with several acyclic and cyclic alkenes were investigated. These gave the[1,4]oxazepino[5,4-*a*]isoindole derivatives in



good yields. Photoreactions of **1** (0.025 mol dm^{-3}) with an excess amount of styrene in benzene afforded a pair of diastereomeric cyclization products, the *cis*-**6** (1*R*,11b*S*; 33%) and the *trans*-**7** products (1*R*,11b*R*; 33%; *cis* and *trans* refer to the steric relationship between the hydroxyl and the phenyl groups). The steric structures of **6** and **7** were determined by X-ray crystallographic analyses (Figure 1). The cyclizations are regioselective, with the alkene's β-carbon atom linking to the side-chain oxygen atom in **1** and the alkene's α-carbon atom linking to the C-1 atom in **1**, leading to the formation of a 1,4-oxazepine ring. Photocyclizations of **1** with 1-phenylcyclopentene under similar conditions proceeded with the same regioselectivity, but this reaction is also stereoselective giving product **8** (3a*R*,12b*R*,12c*R*) (71%) as the sole product as evidenced by X- ray crystallographic analysis.[28] Meanwhile, in the photocyclizations of **1** with 1-phenylcyclohexene, an uncyclized product **9** (13%) and a cyclized product **10** (4a*R*,13b*R*,13c*R*; 52%) were

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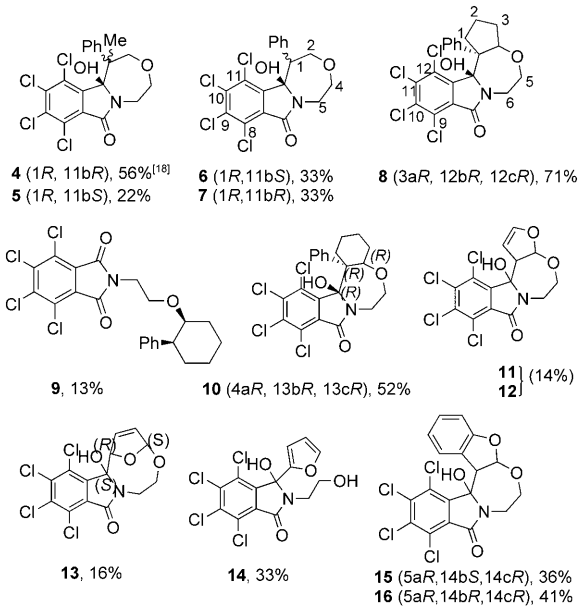

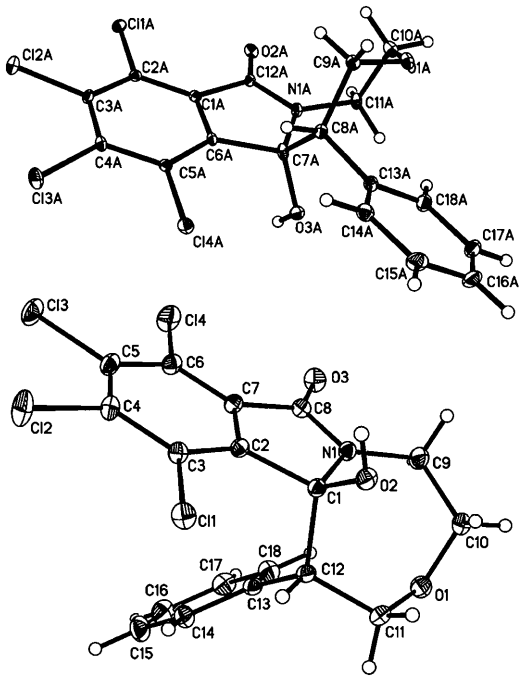

Figure 1. ORTEP drawing of compounds **6** (above) and **7** (below).

formed, with the latter being predominant. A control experiment showed that **10** is a primary product and is not formed by secondary photoreactions of **9** under irradiation. The steric structure of **9** was established by a set of DEPT, H-H COSY, HMQC, HMBC, and NOESY NMR spectroscopic measurements (see the Supporting Information), which show that the phenyl and alkoxy groups in the cyclohexane ring are *cis* to each other. The steric structure of **10** was established by X-ray crystallographic analysis (Figure 2). The molecular packing diagrams of the crystal samples of **6**, **7**, **8**, and **10** show that they are all racemates, each consisting of

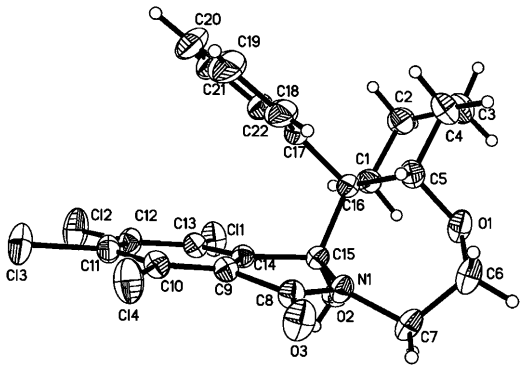

Figure 2. ORTEP drawing of product **10**.

two enantiomers, as illustrated in Figure 3 with compound **10** as an example. Photoreaction of **1** with the heterocyclic alkene furan gave the cyclization products **11**, **12** (total yield

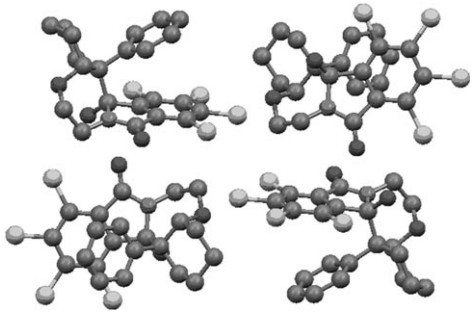

Figure 3. Packing diagram of product **10**.

14%), **13** (16%), and an uncyclized product **14** (33%). Compounds **11** and **12** were obtained as a mixture of diastereomers in a ratio of ≈10:2. In **11** and **12**, the furan's C2 and C3 atoms are linked to the side-chain oxygen and C1 atoms in **1**, respectively, resulting in an acetal structure. In compound **13**, the two α-carbon atoms in the furan are both involved in bond formation with **1**. The crystal structure of **13** is shown in Figure 4. A control experiment showed that, **14** was formed in a secondary photoreaction of **13** under the reaction conditions. In the photoreaction of **1** with benzofuran, two diastereomeric cyclization products **15** (36%) and

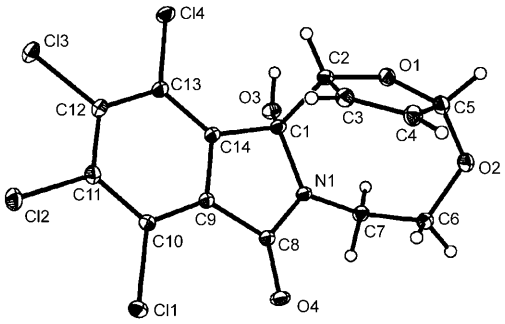

Figure 4. ORTEP drawing of **13**.

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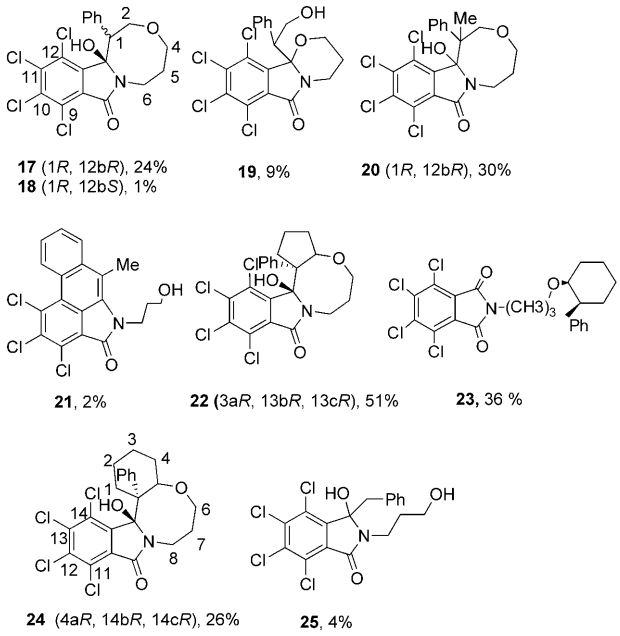
16 (41%) with an acetal structure were formed in comparable yields. DEPT and extensive 2D NMR (H–H COSY, HMQC, HMBC, and NOESY) spectroscopic studies indicated that **15** has a relative configuration of (5a*R*,14b*S*,14c*R*), in which the two methine protons (HC(5a)–C(14c)H) are *cis* to each other. Ground-state geometry optimization of this isomer by DFT/B3LYP/6-31G computation[29] shows that one of the *ortho* protons in the benzene ring of the benzofuran is in the anisotropic shielding area of the tetrachlorobenzene ring in the phthalimide moiety (see the Supporting Information). As a result, its absorption is significantly moved to the upfield area at $\delta = 6.37$ ppm. The ^{1}H NMR spectroscopic coupling constants for the same two protons in **16** are 6.8 Hz, showing that, in this compound, the furan ring is also fused to the seven-membered ring in a *cis* fashion.[30] Therefore, **16** has a (5a*R*,14b*R*,14c*R*) configuration.

Photoreactions of *N*-(3-hydroxypropyl)-4,5,6,7-tetrachlorophthalimide (2) with alkenes: Irradiation of **2** (0.025 mol dm^{-3}) with an excess amount of styrene in benzene afforded two [1,5]oxazocino[4,5-*a*]isoindoles—*trans*-**17**



(24%) and *cis*-**18** (1%; in regard to the steric relationship of the hydroxyl and the phenyl groups), and an oxazinoisoindole product **19** (9%).[31] The crystal structure of **17** is shown in Figure 5. Control experiments showed that, both **17** and **18** are photostable, and photolysis of either **17** or **18** in benzene caused no appreciable decomposition. However, irradiation of *cis*-**18** in the presence of **2** led to the transformation of **18** into **19**. This is why the yield of **18** is low relative to **17**. Similar photoreactions of **2** with α-methylstyrene gave, in addition to the cyclization product **20** (30%, temporarily assigned as a (1*R*,2b*R*) product by spectral comparison with **4**, **5**, **6**, **7**, and with **17**, **18**), a dibenz[*cd*,*f*]indol-4(5*H*)one product **21** (2%). Photoreactions of **2** with 1-phenylcyclopentene gave **22** (3a*R*,13b*R*,13c*R*); 48%) regio- and diastereoselectively (Figure 6), whereas in a similar photolysis of **2** with 1-phenylcyclohexene, the uncyclized **23** (36%) and the cyclized **24** (4a*R*,14b*R*,14c*R*; 26%) (Figure 6) were formed together with a small amount of secondary product **25** (4%).

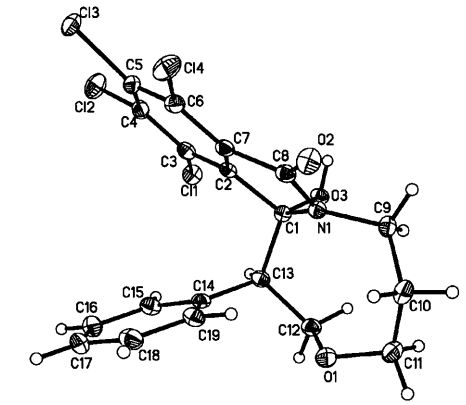


Figure 5. ORTEP drawing of **17**.

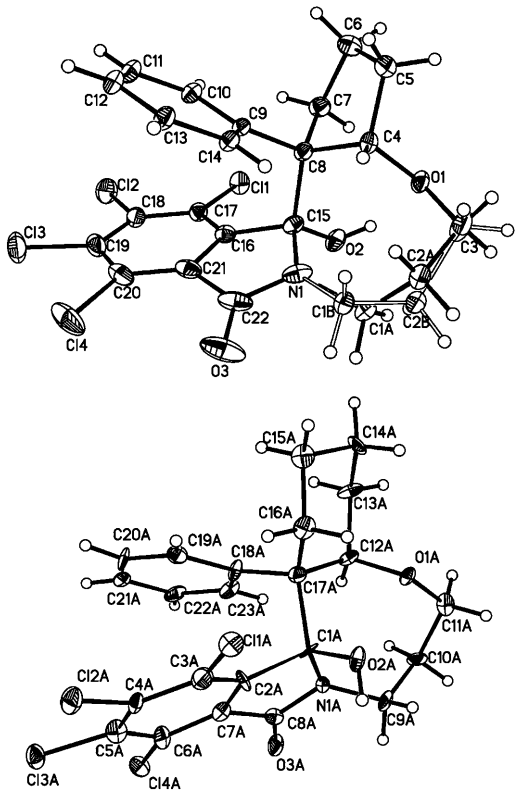


Figure 6. ORTEP drawing of compounds **22** (above) and **24** (below).

Photocyclizations of 2-{2-[2-(2-hydroxyethoxy)ethoxy]ethoxy}ethyl 4,5,6,7-tetrachloro-1,3-dihydro-1,3-dioxo-2*H*-isoindole-2-acetate (3) with alkenes: Photoreactions of **3** with 1-phenylcyclopentene furnished the *trans*-fused cyclization product **26** (3a*R*, 24b*R*,24c*S*) in 17% yield (Figure 7). Simi-

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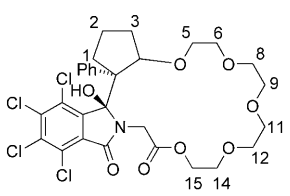
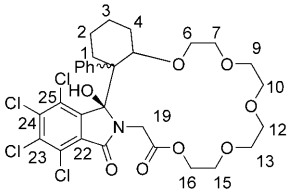
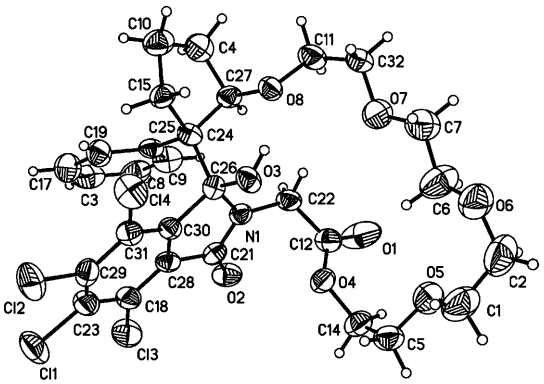


26 (3a*R*, 24b*R*, 24c*S*) 17%



27 (4a*R*, 25b*R*, 25c*S*), 7%
28 (4a*R*, 25b*S*, 25c*R*), 21%



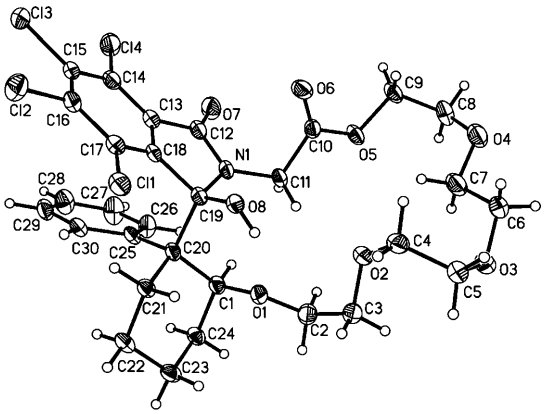
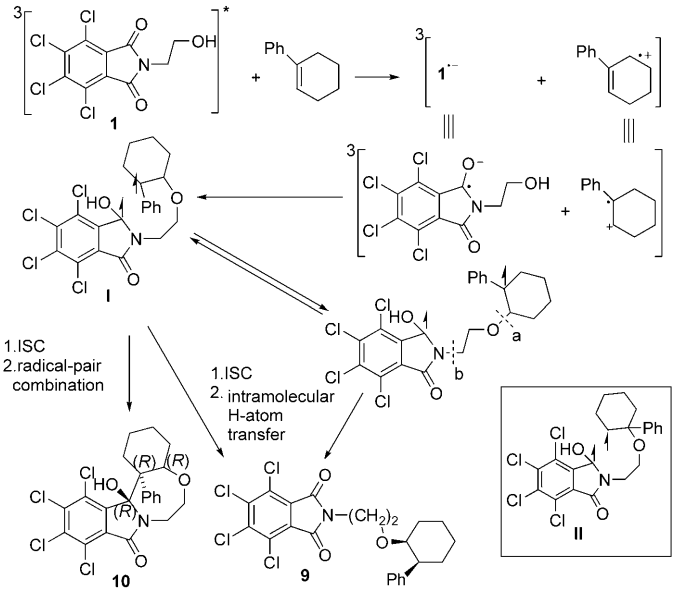


Figure 7. ORTEP drawing of **26** (above) and **27** (below).

lar photoreactions of **3** with 1-phenylcyclohexene, on the other hand, gave the diastereomeric **27** (4a*R*,25b*R*,25c*S*; 7%; Figure 7) and **28** (4a*R*,25b*S*,25c*R*; 21%). The steric structure of **28** is based on a set of NMR spectroscopic measurements (DEPT, H–H COSY, HMQC, HMBC, and NOESY, see the Supporting Information). In these cases, a 19-membered ring is constructed.

Discussion

Photocyclization reaction mechanism: These photocyclization reactions are proposed to be initiated by photoinduced electron transfer (PET) of the triplet excited phthalimide moiety with the alkene (Scheme 1, with the reaction of **1** with 1-phenylcyclohexene as an example). As a model compound for **1**, **2**, and **3**, *N*-methyl-4,5,6,7-tetrachlorophthalimide (TCP) has a half wave reduction potential of −0.95 V



Scheme 1. Proposed photocyclization mechanism.

(SCE, MeCN) as measured by cyclic voltammetry and a triplet energy (E_T) of 67 kcal mol^{-1} as measured by phosphorescence spectral measurements. Therefore, TCP is a stronger excited electron acceptor than triplet excited *N*-methylphthalimide (excited reduction potentials are 1.96 and 1.66 V (SCE) respectively). The absorption maxima of **1** in the UV spectrum is at 237 ($\varepsilon_{max}=67\,937\,M^{-1}cm^{-1}$) and 333 nm ($\varepsilon_{max}=2737\,M^{-1}cm^{-1}$). The free-energy changes for electron transfer between ^{3}TCP* and 1,1-diphenylethene ($E_{1/2}=1.91$ V, SCE, MeCN) and α-methylstyrene ($E_{1/2}=2.13$ V, SCE, MeCN) in benzene are slightly endothermic with ΔG_{ET} of 7.7 and 12.8 kcal mol^{-1}, respectively, as estimated by the Weller equation.[32a] The photocyclizations of N-substituted phthalimides are in most cases in the triplet reaction channel.[32b–d] In contrast to the weekly fluorescent *N*-methylphthalimide, with the internal heavy atom effect of the four chloro atoms, TCP has no measurable fluorescence. We have found that in xanthone ($E_T=74$ kcal mol^{-1}) sensitized photolysis of **1** with 1-phenylcyclohexene, products **9** (21%) and **10** (33%) are both formed. In the xanthone-sensitized photoreaction of **1** with styrene, the same products **6** and **7** are formed. Therefore, we envisage that these photocyclizations proceed at least predominately by the triplet channel. In the triplet ion-radical pair formed in the PET event (Scheme 1), the cation radical of the alkene is intermolecularly captured at the β-carbon atom by the hydroxyl group in the phthalimide side chain, resulting in the formation of an 1,7-biradical (**I** in Scheme 1). Because of the triplet nature, further transformations of this biradical involving bond forming or breaking must be preceded by an intersystem crossing (ISC) leading to its singlet state. By analogy with the much investigated reaction patterns of the triplet 1,4-biradicals typically found in the Norrish Type II–Yang reactions leading to 1-hydroxybutane-1,4-diyl radicals[15–17] and in the Paterno–Büchi reactions leading to 2-oxabutane-

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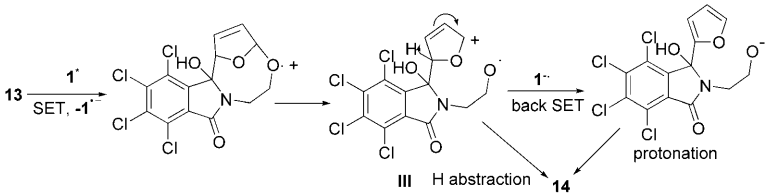
1,4-diyl radicals,[33] three possible decay pathways for the singlet 1,7-biradicals formed in the ISC process can be envisaged: 1) Intramolecular radical-pair combination to give the cyclization products. 2) Intramolecular hydrogen-atom transfer to give uncyclized products. 3) β-Cleavage of one of the σ-bonds next to the two radical centers to give fragmentation products. These transformation pathways for the triplet 1,4-biradicals are now widely accepted. Also, photocyclization reactions via other 1,n-biradicals such as 1,5-,[34] 1,6-,[34,35] and 1,7-[34,36] biradicals and those with even longer chains to intervene the two radical centers[16] have been reported. However, there has been no report as yet that reflects the whole mechanistic pattern for these 1,n-biradicals because it is noted that in the Norrish Type II–Yang reaction, the 1,4-biradical is formed by intramolecular hydrogen abstraction, and a back hydrogen-atom transfer reverts the 1,4-biradical back to the starting material, and this process can only be perceived indirectly by the less-than-unity quantum yield for product formation.[37] In contrast with this situation, in the photocyclizations of **1** and **2** with the alkenes, the 1,7- (such as **I** in Scheme 1) and 1,8-biradicals have a different origin, and intramolecular disproportionation gives products (**9** and **23**) different from the starting materials (**1** or **2** and the alkene). This provides an unprecedented opportunity to directly verify and examine this reaction pathway in the 1,*n*-biradical. The triplet 1,n-biradicals are known to have rather long lifetimes[38] to reach a conformational equilibrium prior to ISC by the side-chain C–C and C–O bond rotations. As a result, ISC may take place in different conformations suitable for ISC. Since once the 1,*n*-biradical transforms to the singlet state, immediate decay by the three competing pathways ensures, and each of these pathways has its own conformational and stereoelectronic requirements, the partitioning of the reaction pathways should be conformation dependent. The cyclization products (**4**–**8**, **10**, etc.) are formed in the singlet 1,7-biradicals derived from the triplet precursor in conformations with the two singly occupied p orbitals close and oriented suitably to each other within bond-forming distance (≈3 Å).[39] Competitive hydrogen-atom transfer can also take place in the same singlet biradicals to give the uncyclized products (**9** and **23**), although the latter products may also be derived from other biradical conformations with the two p orbitals separated by a longer distance.[39c–e] Meanwhile, ISC in the triplet conformations with the two p orbitals located far apart beyond bond-forming distance may result in β-cleavage of the biradical. However, we have not found any products derived from β-cleavage by either pathway (a) or (b) in Scheme 1. We envision that these β-cleavage reactions in the 1,7-biradicals would not be energetically as favorable as that in the 1,4-biradicals in which in conformations with the radical p orbitals overlapping with the σ orbital of the central C–C bond,[40] β-cleavage eliminates the two radical centers to give closed-shell molecules. In contrast, β-cleavage by either way in the 1,7-biradical **I** would give another biradical (a 1,5-biradical here) together with a neutral molecule as primary products.

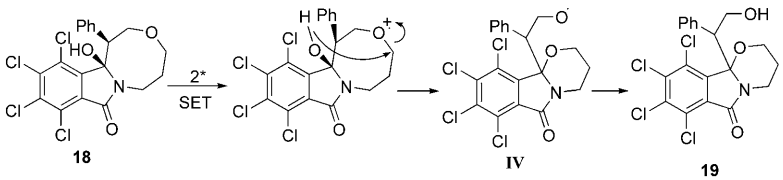
Several byproducts from secondary or side photoreactions were also found in the photocyclizations. Compound **14** is derived from the primary product **13** probably by a secondary PET reaction between an excited **1** (or **13**) with a ground-state **13** (Scheme 2). C–O bond scission in the formed cation radical of **13** leads to a distal cation radical



Scheme 2. Proposed mechanism for the formation of **14**.

III. Deprotonation of the cationic furan moiety and back electron transfer from the anion radical of **1** (or **13**) to the oxygen radical in **III** followed by protonation afford **14**. Alternatively, deprotonation of the cationic furan moiety and hydrogen abstraction of the oxygen radical also give the product (Scheme 2), although we have not found any product derived from the anion radical of **1** (or **13)**.

A possible explanation for why the secondary product **19** is only formed from the photolysis of **18** in the presence of **2**, but not from **17** is that the thermodynamically less stable *cis*-**18** might have lower oxidation potential than *trans*-**17**. This is supported by a DFT computation (B3LYP/6-31G)[30] on their ionization potentials (IP) that shows that the IP of **18** is 0.21 eV lower than that of **17** (see the Supporting Information). SET between exited **2** and **18** leads to the cation radical of **18** (Scheme 3). Intramolecular nucleophilic attack of the hydroxyl group to the α-carbon atom of the oxygen-centered cation radical results in C–O bond cleavage to give **IV**, which on back SET from $\mathbf{2}^{-\bullet}$ followed by protonation or on direct hydrogen abstraction gives **19** (Scheme 3).



Scheme 3. Proposed mechanism for the formation of **19**.

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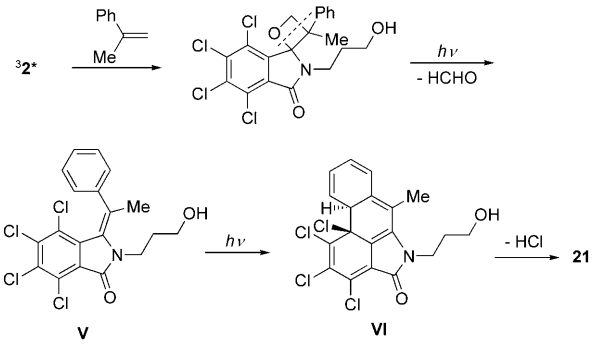
The dibenz[*cd*,*f*]indol-4(5*H*)one product **21** formed in the photoreaction of **2** with α-methylstyrene is most likely derived from the reaction sequence shown in Scheme 4. It is

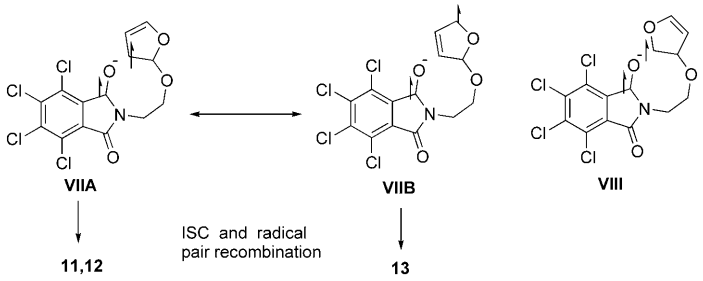


Scheme 4. Proposed mechanism for the formation of **21**.

known that the photoreaction of *N*-methyl-4,5,6,7-tetrachlorophthalimide with styrene derivatives proceeds by the Paterno–Büchi reaction pathway to give spirooxetane products[41] rather than by insertion of the alkene into the phthalimide C(O)–N bond as in the photoreaction of the ring-unsubstituted *N*-methylphthalimide with alkenes.[42] In the photoreaction of **2** with α-methylstyrene, Paterno–Büchi reaction competes with the photocyclization to give a spirooxetane product (Scheme 4). Subsequent photoinduced carbonyl–olefin metathesis of the oxetane product[43] gives **V**. Photoinduced conrotatory electrocyclization in **V** affords **VI** with the H and Cl atoms *trans* to each other. Elimination of hydrogen chloride in **VI** furnishes **21**.

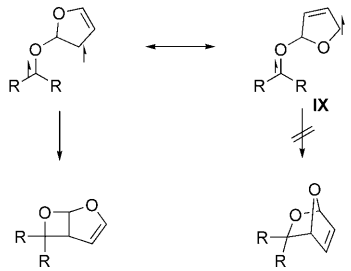
Regioselectivity in the photocyclization reactions: All the photocyclizations described above are highly regioselective. The alkene cation radical is trapped by the hydroxyl group at the phthalimide side chain in an *anti*-Markovnikov fashion so that in the cyclized products, the alkene's β-carbon atom is bonded to the oxygen atom, whereas the α-carbon atom is linked to the phthalimide ketyl carbon atom. This regioselectivity was previously found in cyanoarene-sensitized nucleophilic trapping of the cation radical of aromatic alkenes by alcohol,[44a] water,[19b] and other nucleophiles[44b] and in the alcohol trapping of the alkene cation radical in the intramolecular PET reaction of N-substituted phthalimide derivatives.[45] This selective *anti*-Markovnikov addition of the alcohol to the alkene in the photocyclizations results in the formation of a more stable benzyl radical in the 1,*n*-diradical intermediate (as **I** in Scheme 1) rather than a less stable β-phenylmethylene radical (as **II** in Scheme 1), which indicates thermodynamic control of the trapping reaction owing to the sufficiently long lifetime of the formed triplet 1,*n*-biradical intermediates.[38]

In the photocyclizations with furan and benzofuran, the regioselectivity in products **11**, **12**, **15**, and **16** arises from the trapping of the furan at its α-carbon atom by the hydroxyl group, giving an acetal structure of the cyclization products. This also gives the most stable radical because computational results show that an allylic radical (as **VII** in Scheme 5) is 7 Kcal mol^{-1} more stable than an α-oxymethylene radical (as **VIII** in Scheme 5).[46] This significant difference in radical stability is also the reason for the regioselectivity found in Paterno–Buchi reactions of triplet $n\pi^*$ carbonyl compounds with furan, which give oxetane products with an acetal structure.[47]



Scheme 5. Formation of **11**, **12**, and **13** from biradical intermediates.

The delocalized spin distribution in the allylic radical in **VII** results in two ways of intramolecular radical-pair combination to give products **11**, **12** (via resonance structure **VIIA**), and **13** (via resonance structure **VIIB**). The regioselectivity in **13** has not been found in previously reported photocycloaddition reactions and other PET-induced reactions of furan via a triplet biradical intermediate.[47] It is likely that in such reactions as in the Paterno–Büchi reaction, the short intervening chain between the two radical centers impedes the 1,5-biradical (as **IX** in Scheme 6) to reach an unstrained low energy conformation active for ISC with the two spin-bearing p orbitals orthogonal within bond formation distance. As a result, only the oxetane product (via an 1,4-biradical) is formed. Meanwhile, in the photocyclizations of furan with **1**, the long flexible chain linking the two radical centers allows the occurrence of such an unstrained ISC conformation.



Scheme 6. Biradical intermediates in furan's Paterno–Büchi reaction.

Diastereoselectivity in the photocyclizations: Depending on the structures of the alkenes, two or three stereogenic centers are created during these photocyclizations, leading to diastereomeric cyclization products. The observed degree of diastereoselectivity, however, is quite different from case to

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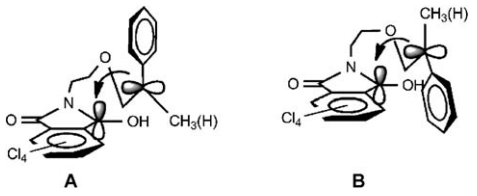
case. For the acyclic terminal alkenes (styrene and α-methylstyrene) in which two new chiral atoms emerge in the cyclization, both diastereomers are formed. In contrast, in the photocyclizations with the cyclic alkenes (1-phenylcyclopentene and 1-phenylcyclohexene) in which three new chiral centers are created, the cyclizations are highly diastereoselective, with only one out of the four possible diastereomers actually formed. Many theoretical[48] and experimental[49] pieces of work have shown that, in a triplet biradical, the ISC efficiency is highly conformation dependent. In an active conformation for efficient ISC, the two spin-bearing *p*-orbitals should be nearly orthogonal to each other. It is believed that, in photocyclization reactions via the intermediacy of triplet 1,*n*-biradicals, it is these active ISC conformations of the biradical that decide the product stereochemistry because once the biradical is switched to the singlet potential energy surface, immediate radical-pair combination takes place, and the product is locked in a stereochemistry inherited from the biradical conformation before ISC, reflecting a stereochemical memory to the conformation of its triplet precursor. This concept has been confirmed in many cases, not only in reactions via a triplet 1,4-biradical (the Norrish type II–Yang[17a–d] and Paterno–Büchi reactions[33,47a–b,49]), but also in photocyclizations via triplet 1,5-,[34] 1,6-,[34,35] and 1,7-[34,36] biradical intermediates.

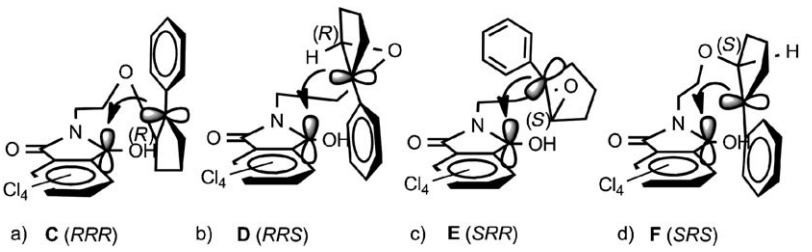
In the reactions of excited **1** with the alkenes, the initial intermediate is a triplet 1,7-biradical. For styrene and α-methylstyrene, the 1,7-biradical has a flexible intervening chain. By inspection of the molecular models, the two active conformations for ISC and subsequent product formation with the benzyl radical placed above (at the *Re* face of) the prochiral phthalimide carbonyl plane are shown in Scheme 7. ISC in conformer **A** by spin inversion (inward rotation of the benzyl horizontal p orbital) gives the *trans*-



Scheme 7. Left) ISC conformation leading to product **4** (or **7**). Right) ISC conformation leading to product **5** (or **6**).

(1*R*,11b*R*) products **4** and **7**, whereas ISC from conformer **B** leads to the *cis*-(1*R*,11b*S*) products **5** and **6**, respectively. It is seen that, for styrene, ISC from both **A** and **B** experiences no significant steric hindrance. Therefore, the two products **6** and **7** are formed in similar yields. In the case of α-methylstyrene, ISC from conformer **A** is still not sterically hindered. However, ISC in **B** by inward rotation of the α-phenylethyl p orbital would bring the methyl to approach the phthalimide plane closely and cause significant steric hindrance between them. The resulting higher energy barrier makes the *cis*-product **5** the minor product (*trans*-**4**/*cis*-**5** 56:22). Two other ISC conformations of the 1,7-biradicals with the benzyl radical center located beneath (at the *Se* face of) the phthalimide carbonyl plane can also be envisioned, these are enantiomeric to **A** and **B**, respectively, and ISC followed by radical-pair combination from these two additional ISC conformations gives the enantiomers of **4**, **5**, **6**, and **7**, respectively, to make each of them a racemate.

In the photocyclizations with the cyclic alkenes 1-phenylcyclopentene and 1-phenylcyclohexene, three new chiral centers are formed in the products, and four pairs of diastereomeric racemers (*RRR–SSS*, *RRS–SSR*, *RSS–SR*, and *RSR–SRS* in terms of the relative configuration of the three chiral atoms C(3a), C(12b), and C(12c) and C(4a), C(13b), and C(13c) for products from 1-phenylcyclopentene and 1-phenylcyclohexene, respectively) may be formed. However, in the reactions of **1** with 1-phenylcyclopentene, only the *RRR–SSS* product **8** is actually found. In this case, in the possible active conformation leading to this (3a*R*,12b*R*,12c*R*) product (**C** in Scheme 8a), in which the two p orbitals are orthogonal to each other within bond-formation distance (≈3 Å), as a result of the orthogonality of the two p orbitals, the 2-phenylcyclopentyl plane is orthogonal to the phthalimide framework, with the phenyl situated upward, and this conformation is not sterically strained. Also, the ISC process in **C** via the 1-phenylcyclopentyl p orbital inward rotation causes no increase in steric hindrance and may benefit from the emerging π–π stacking interaction between the phenyl and the phthalimide framework. The conformers suitable for ISC to give the *RRS* and *SRS* products (conformers **D** and **F** in Scheme 8) are rather similar to conformation **B** in Scheme 7, with a more sterically demanding cyclopentyl ring here to replace the hydrogen atom and methyl group in **B**. Although **D** and **F** are not significantly sterically strained, in these conformers, however, the cyclopentane ring is located above the phthalimide plane. The ISC process by spin inversion in these cases would bring the cyclopentane ring to approach the phthalimide *Re* face and cause severe steric hindrance between the cyclopentane C–



Scheme 8. a) ISC conformation leading to product **8** (3a*R*,12b*R*,12c*R*). b) ISC conformation for a (3a*R*,12b*R*,12c*S*) product. c) ISC conformation for a (3a*S*,12b*R*,12c*R*) product. d) ISC conformation for a (3a*S*,12b*R*,12c*S*) product.

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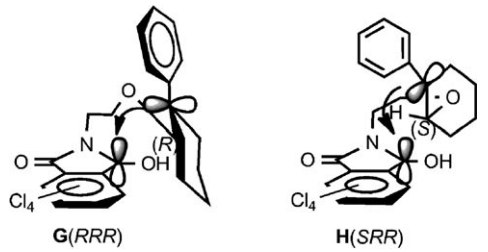
H bonds and the phthalimide framework. This explains why the *RRS* and *SRS* products are not found in the photocyclizations. In the conformation leading to the *SRR* product (**E** in Scheme 8), similar to **C**, the phenyl plane is above the phthalimide ring. However, there is severe steric congestion between one of the phenyl C(*ortho*)–H bonds and the imide side chain (N–$\underline{CH_2}$–CH_2–O), which also causes serious steric hindrance to the ISC process through the 1-phenylcyclohexyl p orbital (and the phenyl) rotation. This is likely the reason for the absence of the *SRR* product.

Photoreactions of **1** with 1-phenylcyclohexene also give only one cyclization product **10** (52%) with the same relative configuration for the three newly formed chiral carbon atoms (4a*R*,13b*R*,13c*R*). The ISC conformation leading to this product (**G** in Scheme 9) is similar to **C** in Scheme 8.



Scheme 9. Left) ISC conformation leading to a (4a*R*,13b*R*,13c*R*) product. Right) ISC conformation for a (4a*S*,13b*R*,13c*R*) product.

The possible active ISC conformations that would lead to the *RRS*, *SRS* products are similar to **D** and **F** in Scheme 8, which would cause severe steric hindrance during the ISC process by bringing the cyclohexane ring to approach the phthalimide plane. The ISC conformation that would lead to an *SRR* product (**H** in Scheme 9) is similar to **E** in Scheme 8, which has significant steric congestion in the static ISC conformation and also causes steric hindrance in the ISC process. At the same time, since in the uncyclized product **9**, the two methine protons in the cyclohexyl are *cis* to each other, this product cannot be formed by hydrogen transfer in the singlet biradical derived by ISC from conformation **G** in competition with cyclization. Neither could it be derived by ISC from a triplet conformation similar to **F** in Scheme 8. ISC from these conformations followed by hydrogen-atom transfer would lead to an uncyclized product with the two cyclohexane methine protons *trans* to each other. Product **9** can be formed, however, from triplet conformations similar to **H** (Scheme 9) and **E** (Scheme 8) albeit with a "looser" geometry with an increased distance between the two spin-bearing p orbitals[39c–e] to ease the steric hindrance both in the static ISC conformation and during the ISC process. ISC followed by hydrogen-atom transfer in one or both of these two types of low-energy conformations delivers the hydrogen atom to the cyclohexyl C2 atom from the opposite side of the alkoxy group to give product **9**.

In the photocyclizations of **2** with the alkenes, a triplet 1,8-biradical is formed as an intermediate. Similar consideration of the active ISC conformations as in the reactions of **1** with the same alkenes can be applied here except that 1) the spacer to link the two spin-bearing p orbitals is slightly more flexible here in the 1,8-biradical and 2) the formation of an eight-membered ring is less feasible than the seven-membered ring because of the unfavorable entropic factor. These two factors explain the parallelism in the diastereoselectivity in the reactions of **1** and **2** with the same alkene. They also provide a rationalization to the fact that in the photoreactions of **2** with 1-phenylcyclohexene, the uncyclized/cyclized product ratio (**23/24** 1.38:1) is higher than in the reactions of **1** (**9**/**10** 1:4).

Conclusion

Intermolecular photocyclization reactions between *N*-(ω-hydroxyalkyl-4,5,6,7-tetrachlorophthalimide and alkenes are achieved by a tandem reaction sequence of photoinduced electron transfer of triplet phthalimide with the alkene, intermolecular nucleophilic trapping of the alkene cation radical, and intramolecular radical-pair combination of the formed 1,*n*-biradical. These photocyclizations lead to the regio- and diastereoselective synthesis of polycyclic heterocycles with a newly formed medium-to-large ring of various structures and are especially efficient in constructing the seven and eight-membered medium-sized rings (oxazepines and oxazocines) from easily accessible starting materials. Regio- and diastereoselectivity in these reactions are clarified on the basis of unambiguous steric structure determination of the products by either X-ray diffraction or extensive 2D NMR spectroscopic measurements. Regioselectivity in the nucleophilic trapping of the alkene cation radical is dictated by the formation of the most stable radical intermediate. This results in a selective addition of the hydroxyl at the β-carbon atom of the styrene derivatives. Diastereoselectivity in the photocyclizations is, on the other hand, decided by the stereochemistry in the active ISC conformations of the triplet 1,*n*-biradical intermediate, which, in turn, is dependent on the structure of the alkene and the phthalimide side chain. The stereoselective formation of the uncyclized products **9** and **23** represents the first examples of the formation of intramolecular hydrogen-atom transfer products that are structurally different from the starting materials, providing a direct verification to this process in the 1,*n*-biradicals. Therefore, as a new strategy to generate 1,*n*-biradicals, these photocyclizations have given new insight into the 1,*n*-biradical reactivity concerning possible reaction pathways and the factors governing the competition and the stereoselectivity in these reactions. These results also demonstrate the synthetic potential of the strategy of using electron acceptors with a side chain bearing a nucleophilic group (such as a hydroxyl) in PET-induced tandem reactions for the construction of polycyclic ring systems.

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Experimental Section

General: Melting points were measured on a Keyi XT3A microscopic melting point apparatus and are uncorrected. ^{1}H NMR spectra were recorded on a Bruker DPX 300 spectrometer with $CDCl_3$ as the solvent unless otherwise specified. ^{13}C NMR spectra were measured on a Bruker Avance-400 spectrometer at 100 MHz with $CDCl_3$ as the solvent. Chemical shifts (δ) are reported in ppm relative to the residual undeuterated solvent signal, and coupling constants (J) are given in Hz. DEPT and 2D NMR measurements were carried out on a Bruker AC-500 spectrometer with $CDCl_3$ as the solvent. IR spectra were taken with a Nicolet NEXUS870 spectrometer for samples in KBr pellets. Mass spectra (EI) were recorded with a VG ZAB-HS spectrometer. Elemental analyses were obtained by using a Heraeus CHN-O-Rapid analyzer. For X-ray crystallographic analysis, the X-ray diffraction intensities and the unit-cell parameters were determined on a Brucker SMART APEXII CCD diffractometer by employing graphite-monochromated ($Mo_{K\alpha}$) radiation ($\lambda = 0.71073$ Å) and operating in the $\omega/2\theta$ scan mode. Data collection and cell refinement were performed with APEX2 software. Structures were solved by direct methods and refined by full-matrix least-squares on F^2 with SHELXTL. Non-hydrogen atoms were refined by anisotropic displacement parameters, and the positions of all hydrogen atoms were fixed geometrically and included in estimated positions by using a riding model.

General procedures for the preparative photolysis of *N*-(ω-hydroxyalkyl)-4,5,6,7-tetrachlorophthalimide with alkenes in benzene solution: The light source was a medium-pressure mercury lamp (500 W) in a glass cooling water jacket to cut off the light of a wavelength shorter than 300 nm. The solution of *N*-(ω-hydroxyalkyl)-4,5,6,7-tetrachlorophthalimide and alkene in benzene was purged with N_2 for 30 min and then irradiated under continuous N_2 purging. The reaction course was monitored by TLC. After the reaction, the solvent was removed under reduced pressure and the residue was separated by flash chromatography on a silica-gel column with petroleum ether/ethyl acetate as the eluent (gradient elution).

Photolysis of *N*-(2-hydroxyethyl)-4,5,6,7-tetrachlorophthalimide (1) with styrene: A solution of **1** (658 mg, 2 mmol) and styrene (2.08 g, 20 mmol) in benzene (80 mL) was photolyzed for 28 h to reach a 100% conversion of **1**. The solvent was removed under reduced pressure and the residue was separated by flash chromatography on a silica-gel column with petroleum ether/ethyl acetate as the eluent to give **6** (287 mg, 33%) and **7** (289 mg, 33%).

8,9,10,11-Tetrachloro-1,4,5,11b-tetrahydro-11b-hydroxy-1-phenyl-[1,4]oxazepino[5,4-*a*]isoindol-7(2*H*)one (1*R*,11b*S*-6): White block solid from chloroform/petroleum ether; m.p. 278–280 °C; IR (KBr): $\tilde{\nu}$ = 3315, 2955, 2849, 1699, 1686, 1495, 1415, 765, 695 cm^{-1}; ^{1}H NMR (300 M, 25 °C, $CDCl_3$): δ = 3.44 (br s, 1H), 3.62–3.72 (m, 2H), 3.81–3.94 (m, 2H), 3.99–4.11 (m, 2H), 4.23 (d, 1H, J = 12 Hz), 7.43–7.48 (m, 3H), 7.52–7.55 ppm (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 41.0, 56.5, 69.0, 71.6, 90.4, 127.0, 127.7, 128.4, 128.8, 129.3, 129.4, 131.6, 135.6, 135.7, 137.9, 145.7, 162.3 ppm; MS m/z (%): 413 [M^+−18] (0.21), 312 (100), 310 (95), 268 (8), 266 (5), 77 (3), 44 (7); elemental analysis calcd (%) for $C_{18}H_{13}Cl_4NO_3$: C 49.92, H 3.03, N 3.23; found: C 49.63, H 3.22, N 3.18.

X-ray structure analysis: $C_{18}H_{13}Cl_4NO_3$; M = 433.09; monoclinic; space group = $Pca2_1$; a = 23.5432(4), b = 10.7804(2), c = 13.3435(2) Å; α = 90, β = 90, γ = 90°; V = 3386.65(10) Å; Z = 8; ρ_{calcd} = 1.699 g cm^{-3}; F(000) = 1760.0; absorption coefficient = 0.719 mm^{-1}; scan range for data collection = 2.31 ≤ θ ≤ 36.02°; 47234 measured reflections, 9201 independent reflections, 8861 reflections with $I > 2\alpha(I)$; R_{int} = 0.0378, 474 refinable parameters, $R[F^2 > 2\alpha(F^2)]$ = 0.0389, wR_2 (F^2) = 0.1014.

8,9,10,11-Tetrachloro-1,4,5,11b-tetrahydro-11b-hydroxy-1-phenyl-[1,4]oxazepino[5,4-*a*]isoindol-7(2*H*)one (1*R*,11b*R*-7): White block solid from chloroform/petroleum ether; m.p. 287–289 °C; IR (KBr): $\tilde{\nu}$ = 3287, 3087, 2958, 2937, 2885, 1689, 1674, 1496, 1419, 1370, 782, 769, 704 cm^{-1}; ^{1}H NMR (300 M, 25 °C, $CDCl_3$): δ = 3.62–3.72 (m, 1H), 4.01–4.08 (m, 3H), 4.19–4.33 (m, 2H), 4.37–4.47 (m, 1H), 4.54 (dd, 1H, J = 13.3, 3.1 Hz), 7.08–7.13 ppm (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 43.8, 50.5, 67.2, 70.6, 92.6, 126.9, 127.5, 127.8, 128.3, 128.4, 135.3, 137.0, 137.5, 143.2, 163.4 ppm; MS m/z (%): 413 [M^+−18] (0.21), 312 (100), 310 (97), 268 (9), 266 (6), 77 (4), 44 (4); elemental analysis calcd (%) for $C_{18}H_{13}Cl_4NO_3$: C 49.92, H 3.03, N 3.23; found: C 49.75, H 3.19, N 3.21.

X-ray structure analysis: $C_{18}H_{13}Cl_4NO_3$; M = 433.09; monoclinic; space group = $P2_1/c$; a = 9.3322(2), b = 9.6937(2), c = 20.3059(4) Å; α = 90, β = 98.2690(10), γ = 90°; V = 1817.85(6) Å; Z = 4; ρ_{calcd} = 1.582 g cm^{-3}; F(000) = 880.0; absorption coefficient 0.670 mm^{-1}; scan range for data collection = 2.21 ≤ θ ≤ 46.45°; 34450 measured reflections, 10932 independent reflections, 9304 reflections with $I > 2\alpha(I)$; R_{int} = 0.0240, 239 refinable parameters, $R[F^2 > 2\alpha(F^2)]$ = 0.0303, wR_2 (F^2) = 0.0842.

Photolysis of 1 with 1-phenylcyclopentene: A solution of **1** (658 mg, 2 mmol) and 1-phenylcyclopentene (1.44 g, 10 mmol) in benzene (80 mL) was photolyzed for 29 h to reach a 99% conversion of **1**. Workup as before gave recovered **1** (7 mg) and product **8** (668 mg, 71%).

9,10,11,12-Tetrachloro-12b-hydroxy-12c-phenyl-1,2,3,3a,5,6,12b,12c-octahydro-8*H*-cyclopenta[6,7][1,4]oxazepino[5,4-*a*]isoindol-8-one (3a*R*,12b*R*,12c*R*-8): White block solid from chloroform/petroleum ether; m.p. 266–268 °C; IR (KBr): $\tilde{\nu}$ = 3319, 3086, 2940, 2866, 1690, 1674, 1500, 1414, 751, 727, 703 cm^{-1}; ^{1}H NMR (300 M, 25 °C, $CDCl_3$): δ = 1.28–1.40 (m, 1H), 1.61–1.73 (m, 1H), 1.91–2.06 (m, 2H), 2.72–2.83 (m, 1H), 2.92 (dd, 1H, J = 13.6, 5.8 Hz), 3.71 (td, 1H, J = 13.4, 5.0 Hz), 4.05 (td, 1H, J = 12.4, 3.7 Hz), 4.33 (dd, 1H, J = 12.5, 4.9 Hz), 4.43 (dd, 1H, J = 14.2, 3.4 Hz), 4.57 (s, 1H), 4.52–4.62 (m, 1H), 7.07 (d, 2H, J = 5.0 Hz), 7.14–7.24 ppm (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 22.8, 31.7, 33.5, 40.9, 65.8, 72.5, 95.46, 95.54, 126.9, 127.0, 127.5, 128.0, 128.6, 128.8, 134.4, 136.8, 138.3, 144.4, 163.9 ppm; MS m/z (%): 453 [M^+−18] (0.16), 298 (77), 296 (58), 268 (6), 144 (100), 129 (88), 128 (46), 115 (33), 44 (4); elemental analysis calcd (%) for $C_{21}H_{17}Cl_4NO_3$: C 53.30, H 3.62, N 2.96; found: C 53.16, H 3.79, N 2.81.

Photolysis of 1 with 1-phenylcyclohexene: A solution of **1** (658 mg, 2 mmol) and 1-phenylcyclohexene (1.58 g, 10 mmol) in benzene (80 mL) was photolyzed for 30 h to reach an 89% conversion of **1**. Workup as above gave recovered **1** (71 mg), **9** (109 mg, 13%) and **10** (452 mg, 52%).

***N*[2-(2-Phenylcyclohexyloxy)ethyl]-4,5,6,7-tetrachlorophthalimide (9)**: White solid from ethyl acetate/petroleum ether; m.p. 160–162 °C; IR (KBr): $\tilde{\nu}$ = 3464, 3031, 2926, 2855, 1709, 1406, 1092, 738, 702 cm^{-1}; ^{1}H NMR (300 M, 25 °C, $CDCl_3$, 500 MHz): δ = 1.21–1.41 (m, 4H), 1.62–1.79 (m, 2H), 1.82–1.92 (m, 1H), 2.42–2.51 (m, 1H), 3.37–3.42 (m, 1H), 3.43–3.47 (m, 2H), 3.49–3.57 (m, 1H), 3.77–3.80 (m, 1H), 3.82–3.90 (m, 1H), 6.51 (t, 1H, J = 7.5 Hz), 6.87 (t, 2H, J = 7.3 Hz), 7.00 ppm (d, 2H, J = 7.3 Hz); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 24.86, 25.97, 31.59, 34.87, 38.7, 50.70, 64.44, 81.91, 124.73, 126.87, 127.39, 127.48, 129.39, 139.45, 145.02, 163.01 ppm; MS m/z (%): 487 [M^++2] (0.12), 312 (41), 310 (30), 158 (100), 130 (25), 91 (56), 44 (1.3); elemental analysis calcd (%) for $C_{22}H_{19}Cl_4NO_3$: C 54.24, H 3.93, N 2.87; found: C 54.06, H 4.12, N 2.68.

10,11,12,13,14-Tetrachloro-2,3,4,4a,6,7,13b,13c-octahydro-13b-hydroxy-13c-phenyl-1*H*,9*H*-cyclohexa[6,7][1,4]oxazepino[5,4-*a*]isoindol-9-one (4a*R*,13b*R*,13c*R*-10): White block solid from chloroform/petroleum ether; m.p. 263–264 °C; IR (KBr): $\tilde{\nu}$ = 3327, 2933, 2860, 1688, 1672, 1468, 1414, 727, 705 cm^{-1}; ^{1}H NMR (300 M, 25 °C, $CDCl_3$): δ = 1.02–1.21 (m, 1H), 1.24–1.41 (m, 1H), 1.61–1.82 (m, 3H), 2.47 (t, 1H, J = 13.7 Hz), 3.04 (d, 1H, J = 13.6 Hz), 3.73–3.97 (m, 2H), 3.92 (s, 1H), 4.19 (dd, 1H, J = 11.7, 5.1 Hz), 4.29–4.49 (m, 2H), 6.90–7.12 (m, 4H), 7.38–7.41 ppm (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 19.6, 22.5, 26.5, 29.7, 41.3, 56.7, 71.1, 85.6, 96.9, 126.2, 127.1, 127.3, 127.7, 128.1, 128.4, 133.9, 136.6, 138.8, 146.2, 164.3 ppm; MS m/z (%): 485 [M^+] (0.23), 312 (19), 298 (70), 296 (53), 158 (100), 130 (43), 129 (64), 115 (46), 91 (29), 77 (8); elemental analysis calcd (%) for $C_{22}H_{19}Cl_4NO_3$: C 54.24, H 3.93, N 2.87; found: C 54.16, H 4.02, N 2.79.

X-ray structure analysis: $C_{22}H_{19}Cl_4NO_3$; M = 487.18; monoclinic; space group = $P2_1/c$, a = 12.7858(6), b = 8.9176(4), c = 19.5307(9) Å; α = 90, β = 104.3210(10), γ = 90°; V = 2157.66(17) Å; Z = 4; ρ_{calcd} = 1.500 g cm^{-3}; F(000) = 1000.0; absorption coefficient = 0.574 mm^{-1}; scan range for data collection = 2.81 ≤ θ ≤ 24.91°; 17683 measured reflections, 5474 independent reflections, 3513 reflections with $I > 2\alpha(I)$; R_{int} = 0.0350, 275 refinable parameters, $R[F^2 > 2\alpha(F^2)]$ = 0.0440, wR^2 (F^2) = 0.1142.

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Photolysis of 1 with furan: A solution of **1** (987 mg, 3 mmol) and furan (4.08 g, 60 mmol) in benzene (120 mL) was photolyzed for 44 h to reach an 83% conversion of **1**. Workup as above gave recovered **1** (166 mg), **11**, **12** (139 mg altogether, 14%), **13** (161 mg, 16%), and **14** (325 mg, 33%).

9,10,11,12-Tetrachloro-12b-hydroxy-3a,5,6,12c-tetrahydrofuro[3′,2′–6,7,1,4] oxazepino[5,4-*a*]isoindol-8(12b*H*)ones (11 and 12): White solid from ethyl acetate/petroleum ether; m.p. 204–206°C; compound **11** was not fully separated from **12**: IR (KBr): $\tilde{\nu}$ = 3373, 2944, 2882, 1695, 1417, 1077 cm^{-1}; ^{1}H NMR (300 M, 25°C, CD_3COCD_3): δ = 2.87–2.99 (m, 2H), 3.10 (t, 1H, J = 10.9 Hz), 3.32–3.43 (m, 2H), 4.07 (d, 1H, J = 3.9 Hz), 5.34–5.39 (m, 1H), 6.02 (d, 1H, J = 4.0 Hz), 6.57 ppm (d, 1H, J = 5.5 Hz); MS m/z (%): 327 [M^+−68] (0.63), 300 (20), 298 (100), 296 (76), 286 (38), 284 (28), 242 (11), 214 (14), 142 (14), 107 (6); elemental analysis calcd (%) for $C_{14}H_9Cl_4NO_4$: C 42.35, H 2.28, N 3.53; found: C 42.12, H 2.45, N 3.47.

10,11,12,13-Tetrachloro-1,6,7,13b-tetrahydro-13b-hydroxy-1,4-epoxy-[1,4]oxazocino[5,4-*a*]isoindol-9(4*H*)one (13): White block solid from chloroform/petroleum ether; m.p. 157–159°C; IR (KBr): $\tilde{\nu}$ = 3504, 3425, 3184, 2929, 1688, 1405, 1059,1010, 726 cm^{-1}; ^{1}H NMR (300 M, 25°C, $CDCl_3$): δ = 3.54–3.62 (m, 1H), 3.77–4.01 (m, 3H), 4.29 (s, 1H), 5.59 (d, 1H, J = 6.1 Hz), 5.69 (s, 1H), 5.90 (d, 1H, J = 6.0 Hz), 6.25 ppm (s, 1H); MS m/z (%): 377 [M^+−18] (1.2), 312 (10), 298 (19), 214 (5), 142 (6), 68 (100); elemental analysis calcd (%) for $C_{14}H_9Cl_4NO_4$: C 42.35, H 2.28, N 3.53; found: C 42.12, H 2.45, N 3.47.

X-ray structure analysis: $C_{14}H_9Cl_4NO_4{\cdot}H_2O$; M = 415.04; monoclinic; space group = $P2_1/c$; a = 7.1888(2), b = 8.7775(2), c = 23.7045(5) Å; α = 90, β = 95.5550(10), γ = 90°; V = 1488.72(6) Å; Z = 4; ρ_{calcd} = 1.852 g cm^{-3}; F-(000) = 840.0; absorption coefficient 0.823 mm^{-1}; scan range for data collection = 2.48 ≤ θ ≤ 45.52°; 37534 measured reflections, 9135 independent reflections, 8061 reflections with $I > 2\alpha(I)$; R_{int} = 0.0256, 243 refinable parameters, $R[F^2 > 2\alpha(F^2)]$ = 0.0316, wR_2 (F^2) = 0.0856.

4,5,6,7-Tetrachloro-3-furan-3-yl-3-hydroxy-2-(2-hydroxyethyl)-2,3-dihydroisoindol-1-one (14): White solid from ethyl acetate/petroleum ether; m.p. 227–229°C; IR (KBr): $\tilde{\nu}$ = 3378, 3258, 1698, 1392, 1033, 753, 731 cm^{-1}; ^{1}H NMR (300 M, 25°C, CD_3COCD_3): δ = 3.06–3.15 (m, 1H), 3.51–3.75 (m, 3H), 6.53 (m, 1H, J = 3.1, 1.8 Hz), 6.90 (d, 1H, J = 2.7 Hz), 7.50 ppm (brs, 1H); MS m/z (%): 377 [M^+−18] (28), 349 (100), 347(72), 323 (42), 321(84), 320(73), 312 (34), 286 (19), 268 (37), 177 (3); elemental analysis calcd (%) for $C_{14}H_9Cl_4NO_4$: C 42.35, H 2.28, N 3.53; found: C 42.33, H 2.29, N 3.49.

Photolysis of 1 with benzofuran: A solution of **1** (654 mg, 2 mmol) and benzofuran (1.18 g, 10 mmol) in benzene (80 mL) was photolyzed for 30 h to reach a 100% conversion of **1**. Workup as above gave **15** (320 mg, 36%) and **16** (365 mg, 41%).

11,12,13,14-Tetrachloro-5a,7,8,14c-tetrahydrobenzofuro[3′2′:6,7]-[1,4]oxazepino[5,4-a]isoindol-10(14*b*H)-one (5a*R*,14b*S*,14c*R*-15): White needles from chloroform/petroleum ether; m.p. 243–245°C; IR (KBr): $\tilde{\nu}$ = 3320, 1700, 1590, 1410, 1365, 1280, 1210, 1175, 1120, 1080, 1020, 750, 715 cm^{-1}; ^{1}H NMR (300 M, 25°C, $CDCl_3$): δ = 3.41–3.50 (m, 1H), 3.75 (t, J = 12.6 Hz, 1H), 3.89 (d, J = 13.2 Hz, 1H), 4.15 (d, J = 14.4 Hz, 1H), 4.26 (brs, 1H), 5.23 (d, J = 7.6 Hz,1H), 5.51 (d, J = 7.3 Hz, 1H,), 6.34 (d, J = 7.7 Hz, 2H), 6.64 (t, J = 7.6 Hz, 1H), 6.87(d, J=7.7 Hz, 1H), 7.13 ppm (t, J = 7.7 Hz, 1H); ^{13}C NMR (100 MHz, 25°C, $CDCl_3$): δ = 29.67, 39.90, 50.76, 62.54, 90.83, 103.48, 109.40, 121.76, 122.01, 122.97, 128.11, 128.55, 129.64, 130.84, 136.84, 138.51, 141.38, 159.66, 162.20 ppm; MS m/z (%): 427 [M^+−18] (0.46), 397(1), 296 (3), 268 (3), 118 (100), 89 (10); elemental analysis calcd (%) for $C_{18}H_{11}Cl_4NO_4$: C 48.35, H 2.48, N 3.13; found: C 48.31, H 2.57, N 3.11.

11,12,13,14-Tetrachloro-5a,7,8,14c-tetrahydrobenzofuro[3′2′:6,7]-[1,4]oxazepino[5,4-*a*]isoindol-10(14*b*H)-one (5a*R*,14b*S*,14c*R*-16): White needles from chloroform/petroleum ether; m.p. 230–231°C; IR (KBr): $\tilde{\nu}$ = 3250, 690, 1590, 1480, 1460, 1370, 1250, 1190, 1090, 990, 880, 750, 670 cm^{-1}; ^{1}H NMR (300 M, 25°C, $CDCl_3$): δ = 3.19–3.26 (m, 1H), 3.47–3.54 (m, 1H), 3.76–3.86 (m, 2H), 4.00 (s, 1H), 4.93 (d, J = 6.8 Hz, 1H), 5.58 (d, J = 6.8 Hz, 1H), 6.94 (d, J = 8.0 Hz, 1H), 7.04 (t, J = 7.4 Hz, 1H), 7.28 (t, J = 7.4 Hz, 1H), 8.02 ppm (d, J = 7.6 Hz, 1H); MS m/z (%): 427 [M^+−18] (0.46), 310 (1), 297 (9), 266 (3), 213 (2), 118 (100), 89 (4); elemental analysis calcd (%) for $C_{18}H_{11}Cl_4NO_4$: C 48.35, H 2.48, N 3.13; found: C 48.29, H 2.61, N 3.09.

Photolysis of *N*-(3-hydroxypropyl)-4,5,6,7-tetrachlorophthalimide (2) with styrene: A solution of **2** (1.029 g, 3 mmol) and styrene (3.12 g, 30 mmol) in benzene (120 mL) was photolyzed for 28 h to reach a 69% conversion of **2**. Workup as above gave recovered **2** (317 mg), **17** (219 mg, 24%), **18** (8 mg, 1%), and **19** (79 mg, 9%).

9,10,11,12-Tetrachloro-1,2,4,5,6,12b-hexahydro-12b-hydroxy-1-phenyl-[1,5]oxazocino[6,5-*a*]isoindol-6(2*H*)one (1*R*,12b*R*-17): White block solid from chloroform/petroleum ether; m.p. 272–274°C; IR (KBr): $\tilde{\nu}$ = 3290, 3084, 2934, 1686, 1673, 1493, 1417, 1117, 763, 706 cm^{-1}; ^{1}H NMR (300 M, 25°C, $CDCl_3$): δ = 2.15–2.21 (m, 1H), 2.41–2.47 (m, 1H), 3.72 (dd, J = 14.7, 11.1 Hz, 1H), 3.96–4.04 (m, 3H), 4.26–4.38 (m, 3H), 5.24 (brs, 1H), 7.09 ppm (s, 5H); MS m/z (%): 370 [M^+−75] (0.16), 324 (2), 298 (2), 104 (100), 78 (3); elemental analysis calcd (%) for $C_{19}H_{15}Cl_4NO_3$: C 51.04, H 3.38, N 3.13; found: C 50.92, H 3.49, N 3.03.

X-ray structure analysis: $C_{19}H_{15}Cl_4NO_3$; M = 447.12. monoclinic; space group = $P2_1/c$; a = 9.6966(3), b = 9.1779(2), c = 21.2134(6) Å; α = 90, β = 95.5040(10), γ = 90°; V = 1879.17(9) Å; Z = 4; ρ_{calcd} = 1.580 g cm^{-3}; F-(000) = 912.0; absorption coefficient 0.651 mm^{-1}; scan range for data collection 2.42 ≤ θ ≤ 41.55°; 18408 measured reflections, 3226 independent reflections, 3016 reflections with $I > 2\alpha(I)$; R_{int} = 0.0238, 248 refinable parameters, $R[F^2 > 2\alpha(F^2)]$ = 0.0254, wR_2 (F^2) = 0.0641.

9,10,11,12-Tetrachloro-1,2,4,5,6,12b-hexahydro-12b-hydroxy-1-phenyl-[1,5]oxazocino[6,5-*a*]isoindol-6(2*H*)-one (1*R*,12b*S*-18): White block solid from chloroform/petroleum ether; m.p. 213–215°C; IR (KBr): $\tilde{\nu}$ = 3412, 1708, 1654, 1430, 727, 696 cm^{-1}; ^{1}H NMR (300 M, 25°C, $CDCl_3$): δ = 1.81–1.93 (m, 3H), 3.47–3.62 (m, 2H), 3.67–3.77 (m, 2H), 4.08–4.19 (m, 1H), 4.26 (d, J = 14.7 Hz, 1H), 4.34–4.40 (m, 1H), 7.12–7.14 (m, 2H), 7.34–7.37 ppm (m, 3H); MS m/z (%): 427 [M^+−18] (0.13), 411 (0.72), 324 (40), 298 (23), 296 (18), 104 (100), 77 (9); elemental analysis calcd (%) for $C_{19}H_{15}Cl_4NO_3$: C 51.04, H 3.38, N 3.13; found: C 51.00, H 3.42, N 3.12.

7,8,9,10-Tetrachloro-3,4-dihydro-10b-(2-hydroxy-1-phenylethyl)-2*H*-[1,3]oxazino[2,3-*a*]isoindol-6(10b*H*)one (19): White block solid from chloroform/petroleum ether; m.p. 199–201°C; IR (KBr): $\tilde{\nu}$ = 3516, 3103, 2965, 2878, 1701, 1396, 1047, 760, 719, 703 cm^{-1}; ^{1}H NMR (300 M, 25°C, $CDCl_3$): δ = 1.98–2.29 (m, 3H), 3.15 (td, 1H, J = 11.7, 4.9 Hz), 3.61 (m, 1H), 3.96 (dd, 1H, J = 10.9, 7.4 Hz), 4.11 (dd, 1H, J = 10.4, 7.3 Hz), 4.31 (t, 1H, J = 6.7 Hz), 4.54 (dd, J = 10.7, 6.5 Hz, 1H), 4.57–4.68 (m, 1H), 6.98–7.00 (m, 2H), 7.11–7.14 ppm (m, 3H); MS m/z (%): 413 [M^+−32] (0.21), 326 (100), 324 (78), 298 (56), 296 (43), 91 (15); elemental analysis calcd (%) for $C_{19}H_{15}Cl_4NO_3$: C 51.04, H 3.38, N 3.13; found: C 50.98, H 3.45, N 3.07.

Photolysis of 2 with α-methylstyrene: A solution of **2** (0.686 g, 2 mmol) and α-methylstyrene (2.36 g, 20 mmol) in benzene (80 mL) was photolyzed for 36 h to reach a 60% conversion of **2**. Workup as above gave recovered **2** (272 mg), **20** (165 mg, 30%), and **21** (8 mg, 2%).

9,10,11,12-Tetrachloro-1,2,4,5,6,12b-hexahydro-12b-hydroxy-1-methyl-1-phenyl[1,5]oxazocino[6,5-*a*]isoindol-6(2*H*)one (1*R*,12b*R*-20): White block solid from ethyl acetate/petroleum ether; m.p. 225–227°C; IR (KBr): $\tilde{\nu}$ = 3294, 3094, 2927, 2875, 1686, 1670, 1412, 729, 697 cm^{-1}; ^{1}H NMR (300 M, 25°C, $CDCl_3$): δ = 1.06 (s, 3H), 1.82–1.92 (m, 1H), 2.41–2.49 (m, 1H), 3.67–3.78 (m, 2H), 3.86 (d, 1H, J = 12.3 Hz), 4.03 (dd, J = 14.9, 5.1 Hz, 1H), 4.08–4.17 (m, 1H), 4.37 (brs, 1H), 4.44 (d, J = 12.3 Hz, 1H), 7.35 ppm (m, 5H); MS m/z (%): 459 [M^+] (1), 326 (100), 324 (75), 298 (66), 296 (48), 118 (77), 105 (44), 103 (38), 91(14), 77 (29); elemental analysis calcd (%) for $C_{20}H_{17}Cl_4NO_3$: C 52.09, H 3.72, N 3.04; found: C 52.01, H 3.62, N 2.95.

1,2,3-Tetrachloro-5-(3-hydroxypropyl)-6-methyldibenz[*cd*,*f*]indol-4(5*H*)one (21): White solid from ethyl acetate/petroleum ether; m.p. 210–211°C; IR (KBr): $\tilde{\nu}$ = 3495, 3093, 2964, 1704, 1689, 1628, 748, 714 cm^{-1}; ^{1}H NMR (300 M, 25°C, $CDCl_3$): δ = 2.08 (t, 2H, J = 5.7 Hz), 2.89 (s, 3H), 3.69 (t, 2H, J = 5.4 Hz), 4.43 (t, 2H, J = 5.9 Hz), 7.69 (t, 1H, J = 7.6 Hz), 7.77 (t, 1H, J = 7.3 Hz), 8.18 (d, 1H, J = 8.2 Hz), 9.77 ppm (d, 1H, J = 8.2 Hz); ^{13}C NMR (100 MHz, CDCl3, 25°C): δ = 14.4, 32.8, 39.80, 58.8, 117.2, 121.1, 123.1, 125.8, 125.9, 126.5, 126.6, 127.8, 129.0, 129.4,

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131.9, 133.5, 134.2, 136.0, 164.4 ppm; MS *m/z* (%): 393 [M^+] (23), 378 (32), 349 (56), 337 (92), 339 (28), 335 (100), 271 (17), 187 (22), 174 (22), 122 (21), 87 (24); elemental analysis calcd (%) for $C_{19}H_{14}Cl_3NO_2$: C 57.82, H 3.58, N 3.55; found C 57.77, H 3.65, N 3.49.

Photolysis of 2 with 1-phenylcyclopentene: A solution of **2** (0.686 g, 2 mmol) and 1-phenylcyclopentene (1.44 g, 10 mmol) in benzene (80 mL) was photolyzed for 28 h to reach an 84% conversion of **2**. Workup as above gave recovered **2** (108 mg) and product **22** (413 mg, 51%).

10,11,12,13-Tetrachloro-13b-hydroxy-13c-phenyl-2,3,3a,5,6,7,13b,13c-octahydro-1*H*,9*H*-cyclopenta[b][1,5]oxazocino[4,5-*a*]isoindol-9-one (3a*S*,13b*S*,13c*S*-22): Colorless plate solid from chloroform/petroleum ether; m.p. 240–242°C; IR (KBr): $\tilde{\nu}$ = 3364, 3092, 2948, 2869, 1705, 1391, 728, 705 cm^{-1}; ^1H NMR (300 MHz, 25°C, $CDCl_3$): δ = 1.32–1.69 (m, 3H), 1.94–2.17 (m, 2H), 2.58–2.72 (m, 2H), 2.96 (dd, 1H, J = 13.9, 7.3 Hz), 3.52 (dd, 1H, J = 14.7, 11.7 Hz), 3.84–3.98 (m, 2H), 4.37 (dd, 1H, J = 14.9, 6.3 Hz), 4.71 (d, 1H, J = 4.5 Hz), 5.71 (s, 1H), 6.94–7.22 ppm (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$, 25°C): δ = 21.4, 27.6, 30.0, 30.7, 38.4, 64.6, 67.5, 85.3, 96.1, 126.7, 127.6, 128.2, 128.6, 129.2, 134.2, 136.6, 137.6, 144.6, 165.6 ppm; MS: *m/z* (%): 485 [M^+] (0.24), 324 (10), 298 (42), 296 (31), 144 (100), 129 (40), 91 (8), 49 (3); elemental analysis calcd (%) for $C_{22}H_{19}Cl_4NO_3$: C 54.24, H 3.93, N 2.87; found: C 54.02, H 4.21, N 2.78.

X-ray structure analysis: $C_{22}H_{19}Cl_4NO_3$; M = 487.18; monoclinic; space group $P21/n$; a = 12.2563(3), b = 9.9236(3), c = 17.2503(4) Å; α = 90, β = 103.2800(10), γ = 90°; V = 2041.99(9) Å; Z = 4; ρ_{calcd} = 1.585 $g\,cm^{-3}$; F(000) = 1000.0; absorption coefficient 0.606 mm^{-1}; scan range for data collection = 2.38 ≤ θ ≤ 40.33°; 41823 measured reflections, 10691 independent reflections, 8451 reflections with $I > 2\alpha(I)$; R_{int} = 0.0309, 294 refinable parameters, $R[F^2 > 2\alpha(F^2)]$ = 0.0389, wR_2 (F^2) = 0.1014.

Photolysis of 2 with 1-phenylcyclohexene: A solution of **2** (0.686 g, 2 mmol) and 1-phenylcyclohexene (2.36 g, 20 mmol) in benzene (80 mL) was photolyzed for 36 h to reach an 88% conversion of **2**. Workup as above gave recovered **2** (79 mg), products **23** (318 mg, 36%), **24** (230 mg, 26%), and **25** (32 mg, 4%).

***N*-[3-(2-Phenylcyclohexyloxy)propyl]-4,5,6,7-tetrachlorophthalimide (23)**: White block solid from chloroform/petroleum ether; m.p. 133–135°C; IR (KBr): $\tilde{\nu}$ = 3470, 2926, 2854, 1772, 1713, 1449, 1403, 1374, 1095, 750, 735, 694 cm^{-1}; ^1H NMR (300 MHz, 25°C, CDCl3): δ = 1.23–1.39 (m, 3H), 1.51 (q, J = 13.0 Hz, 1H), 1.61–1.77 (m, 3H), 1.86 (d, 2H, J = 10.5 Hz), 2.18 (d, 1H, J = 10.4 Hz), 2.41 (td, 1H, J = 12.6, 3.1 Hz), 2.93–3.00 (m, 1H), 3.24–3.31 (m, 1H), 3.37 (dd, J = 6.9, 13.8 Hz, 1H), 3.44–3.50 (m, 2H), 7.10 (t, 1H, J = 7.0 Hz), 7.17 (d, 2H, J = 6.9 Hz), 7.24 ppm (t, 2H, J = 7.3 Hz); ^{13}C NMR (100 MHz, CDCl3, 25°C): δ = 25.0, 26.0, 28.5, 32.2, 33.7, 36.5, 51.2, 66.8, 82.5, 125.9, 127.7, 127.8, 128.0, 129.4, 139.8, 144.7, 163.4 ppm; MS *m/z* (%): 499 [M^+] (0.10), 324 (50), 296 (30), 158 (100), 130 (21), 91 (81), 41 (22); elemental analysis calcd (%) for $C_{23}H_{21}Cl_4NO_3$: C 55.11, H 4.22, N 2.79; found: C 55.09, H 4.28, N 2.74.

11,12,13,14-Tetrachloro-14b-hydroxy-14c-phenyl-1,2,3,4,4a,6,7,8,14b,14c-decahydro-10*H*-cyclohexta[b][1,5]oxazocino[4,5-a]isoindol-10-one (4a*R*,14b*R*,14c*R*-24): White block solid from chloroform/petroleum ether; m.p. 234–236°C; IR (KBr): $\tilde{\nu}$ = 3434, 3091, 2927, 2856, 1700, 1500, 1389, 1089, 745, 729, 692 cm^{-1}; ^1H NMR (300 MHz, 25°C, $CDCl_3$): δ = 1.16–1.38 (m, 3H), 1.60–1.78 (m, 3H), 2.04–2.10 (m, 1H), 2.46 (td, J = 14.1, 2.6 Hz, 1H), 2.58–2.69 (m, 1H), 3.03 (d, J = 14.6 Hz, 1H), 3.53 (t, J = 13.3 Hz, 1H), 3.85–4.01 (m, 2H), 4.27 (dd, J = 14.7, 5.0 Hz, 1H), 4.61 (s, 1H), 5.59 (s, 1H), 6.84 (d, J = 8.0 Hz, 1H), 6.94 (t, J = 7.1 Hz, 1H), 7.05 (t, J = 7.3 Hz, 1H), 7.09 (d, J = 7.2 Hz, 1H), 7.24 ppm (t, J = 7.1 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, 25°C): δ = 19.7, 21.7, 25.9, 26.2, 27.3, 38.7, 56.6, 65.6, 74.9, 98.4, 126.2, 126.4, 126.8, 127.2, 128.1, 128.5, 129.6, 134.0, 136.4, 138.0, 145.0, 166.0 ppm; MS *m/z* (%): 343 (0.84), 298 (22), 296 (16), 158 (100), 130 (40), 129 (60), 115 (27), 91 (21),41 (5); elemental analysis calcd (%) for $C_{23}H_{21}Cl_4NO_3$: C 55.11, H 4.22, N 2.79; found: C 55.12, H 4.28, N 2.74.

X-ray structure analysis: $C_{23}H_{21}Cl_4NO_3$; M = 501.20; triclinic; space group = $P\bar{1}$; a = 10.6774(2), b = 14.8307(3), c = 15.1298(4) Å; α = 95.4770(10), β = 109.2210(10), γ = 106.4500(10)°; V = 2122.08(8) Å; Z = 2; ρ_{calcd} = 1.569 $g\,cm^{-3}$; F(000) = 1032.0; absorption coefficient = 0.586 mm^{-1}; scan range for data collection = 2.78 ≤ θ ≤ 38.53°; 92790 measured reflections, 22157 independent reflections, 17351 reflections with $I > 2\alpha(I)$; R_{int} = 0.0442, 567 refinable parameters, $R[F^2 > 2\alpha(F^2)]$ = 0.0404, wR_2 (F^2) = 0.1199.

4,5,6,7-Tetrachloro-3-hydroxy-3-benzyl-2-(3-hydroxypropyl)isoindolin-1-one (25): White block solid from chloroform/petroleum ether; m.p. 215–216°C; IR (KBr): $\tilde{\nu}$ = 3312, 3032, 2931, 2874, 1691, 1674, 1496, 1421, 1050, 716, 705 cm^{-1}; ^1H NMR (300 MHz, 25°C, $CDCl_3$): δ = 1.89–2.02 (m, 1H), 2.28–2.49 (m, 1H), 3.40 (d, 1H, J = 14.2 Hz), 3.54–3.62 (m, 1H), 3.77–4.08 (m, 4H), 6.73–6.80 (m, 2H), 7.02–7.13 ppm (m, 3H); MS *m/z* (%): 415 [M^+ − 18] (0.65), 326 (100), 324 (91), 298 (77), 296 (56), 91 (21); elemental analysis calcd (%) for $C_{18}H_{15}Cl_4NO_3$: C 49.68, H 3.47, N 3.22; found: C 49.62, H 3.53, N 3.23.

Photolysis 4,5,6,7-tetrachloro-1,3-dihydro-1,3-dioxo-2*H*-isoindole-2-acetic acid 2-{2-[2-(2-hydroxyethoxy)ethoxy]ethoxy}ethyl ester (3) with 1-phenylcyclopentene: A solution of **3** (1.562 g, 3 mmol) and 1-phenylcyclopentene (2.16 g, 15 mmol) in benzene (120 mL) was photolyzed for 32 h to reach a 74% conversion of **3**. Workup as above gave recovered **3** (402 mg) and product **26** (259 mg, 17%).

21,22,23,24-Tetrachloro-1,2,3,3a,5,6,8,9,11,12,14,15,24b,24c-tetradecahydro-24b-hydroxy-24c-phenyl-18*H*-cyclopenta[14,15][1,4,7,10,14,17-pentaoxaazacyclononadecino[16,17-*a*]isoindole-17,20(17*H*,20*H*)dione (3a*R*,24b*R*,24c*S*-26): White solid from ethyl acetate/petroleum ether; m.p. 215–217°C; IR (KBr): $\tilde{\nu}$ = 3386, 3089, 2897, 1732, 1712, 1387, 1088, 756, 731, 703 cm^{-1}; ^1H NMR (300 MHz, 25°C, $CDCl_3$): δ = 1.22–1.47 (m, 2H), 1.79–1.92 (m, 2H), 2.72–2.91 (m, 2H), 3.62–3.87 (m, 14H), 4.30–4.49 (m, 3H), 4.77 (d, J = 11 Hz, 1H), 4.80 (s, 1H), 6.53 (brs, 1H), 6.64 (d, J = 7.9 Hz, 1H), 6.89 (t, J = 7.2 Hz, 1H), 7.11 (t, J = 7.2 Hz, 1H), 7.27 (t, J = 7.2 Hz, 1H), 7.43 ppm (d, J = 7.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, 25°C): δ = 19.3, 25.2, 30.1, 42.8, 64.6, 64.7, 67.2, 68.4, 69.6, 69.9, 70.4, 70.6, 71.0, 88.3, 95.8, 126.0, 127.2, 127.6, 127.7, 128.0, 128.6, 129.0, 134.5, 136.7, 136.9, 144.8, 164.2, 169.0 ppm; MS *m/z* (%): 661 [M^+] (0.02), 520 (2), 372 (29), 370 (56), 368 (58), 334 (12), 298 (51), 296 (54), 145 (100), 129 (50), 91 (47), 45 (42); elemental analysis calcd (%) for $C_{29}H_{31}Cl_4NO_8$: C 52.51, H 4.71, N 2.11; found: C 52.39, H 4.78, N 2.09.

X-ray structure analysis: $C_{29}H_{31}Cl_4NO_8$; M = 663.35; triclinic; space group = $P\bar{1}$; a = 9.4640(19), b = 10.885(2), c = 14.740(3) Å; α = 87.38(3), β = 83.27(3), γ = 80.86(3)°; V = 1488.3(5) Å; Z = 2; ρ_{calcd} = 1.480 $g\,cm^{-3}$; F(000) = 688.0; absorption coefficient = 0.449 mm^{-1}; scan range for data collection = 2.97 ≤ θ ≤ 48.45°; 6219 measured reflections, 5843 independent reflections, 3755 reflections with $I > 2\alpha(I)$; R_{int} = 0.0602, 379 refinable parameters, $R[F^2 > 2\alpha(F^2)]$ = 0.0725, wR_2 (F^2) = 0.2142.

Photolysis of 3 with 1-phenylcyclohexene: A solution of **3** (1.563 g, 3 mmol) and 1-phenylcyclopentene (2.16 g, 15 mmol) in benzene (120 mL) was photolyzed for 66 h to reach a 67% conversion of **3**. Workup as above gave recovered **3** (523 mg), products **27** (92 mg, 7%), and **28** (285 mg, 21%).

22,23,24,25-Tetrachloro-1,2,3,4,4a,6,7,9,11,12,13,15,16,19,25b,25c-hexadecahydro-25b-hydroxy-25c-phenyl-cyclopenta[14,15][1,4,7,10,14,17]pentaoxaazacyclononadecino[16,17-*a*]isoindole-18,21(18*H*,21*H*)dione (4a*R*,25b*R*,25c*S*-27): Block clear solid from ethyl acetate/petroleum ether; m.p. 199–200°C; IR (KBr): $\tilde{\nu}$ = 3342, 3093, 2939, 1757, 1715, 1384, 1202, 1080, 729, 699 cm^{-1}; ^1H NMR (300 MHz, 25°C, $CDCl_3$): δ = 1.22–1.41 (m, 3H), 1.51 (t, J = 13.3 Hz, 1H), 1.67 (d, J = 11.4 Hz, 1H), 1.91 (d, J = 11.3 Hz, 1H), 2.61–2.73 (m, 2H), 3.60–3.93 (m, 14H), 4.22–4.32 (m, 1H), 4.40–4.46 (m, 2H), 4.69 (brs, 1H), 4.79 (d, J = 16.8 Hz, 1H), 6.55 (d, J = 7.9 Hz, 1H), 6.75 (brs, 1H), 6.88 (t, J = 7.2 Hz, 1H), 7.10 (t, J = 7.1 Hz, 1H), 7.29–7.37 ppm (m, 2H); MS *m/z* (%): 675 [M^+] (0.01), 518 (0.06), 458 (0.03), 370 (20), 368 (14), 298 (28), 296 (20), 158 (100), 129 (21), 91 (28); elemental analysis calcd (%) for $C_{30}H_{33}Cl_4NO_8$: C 53.19, H 4.91, N 2.07; found: C 53.12, H 5.03, N 2.03.

X-ray structure analysis: $C_{30}H_{33}Cl_4NO_8$; M = 677.37; triclinic, space group = $P21/n$, a = 18.6856(7), b = 9.3008(4), c = 19.3476(7) Å; α = 90, β = 118.183(2), γ = 90°; V = 2963.8(2) Å; Z = 4; ρ_{calcd} = 1.518 $g\,cm^{-3}$; F(000) = 1408.0; absorption coefficient = 0.453 mm^{-1}; scan range for data collection = 2.47 ≤ θ ≤ 25.15°; 55576 measured reflections, 8781 independent reflections, 5506 reflections with $I > 2\alpha(I)$; R_{int} = 0.0788, 379 refinable parameters, $R[F^2 > 2\alpha(F^2)]$ = 0.0594, wR_2 (F^2) = 0.1515.

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22,23,24,25-Tetrachloro-1,2,3,4,4a,6,7,9,11,12,13,15,16,19,25b,25c-hexadecahydro-25b-hydroxy-25c-phenyl-cyclopenta[14,15][1,4,7,10,14,17]pentaoxaazacyclononadecino[16,17-*a*]isoindole-18,21(18*H*,21*H*)dione (4a*R*,25b*S*,25c*R*-28): White solid from ethyl acetate/petroleum ether; m.p. 185–187 °C; IR (KBr): $\tilde{\nu}$ = 3422, 3261, 2945, 1758, 1718, 1203, 1112, 731, 702 cm^{-1}; ^1H NMR (300 MHz, 25 °C, $CDCl_3$): δ = 1.28–1.93 (m, 6H), 2.13 (d, 1H, J = 12.2 Hz), 2.20 (s, 1H), 2.64 (td, J = 12.7, 2.8 Hz, 1H), 3.42–3.59 (m, 4H), 3.71–3.82 (m, 8H), 4.04–4.10 (m, 1H), 4.39 (d, J = 17.1 Hz, 1H), 4.39–4.51 (m, 1H), 4.69 (d, J = 17.1 Hz, 1H), 5.15 (br s, 1H), 6.40 (d, J = 7.3 Hz, 1H), 6.83 (t, J = 7.2 Hz, 1H), 7.07 (t, J = 7.2 Hz, 1H), 7.19 (d, J = 7.2 Hz, 1H), 7.26–7.29 (m, 1H), 7.81 ppm (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 18.4, 21.8, 23.4, 25.5, 31.0, 44.8, 57.7, 64.1, 65.6, 68.6, 69.7, 70.5, 70.6, 70.7, 71.7, 97.1, 125.8, 127.1, 127.2, 127.3, 128.2, 128.4, 128.9, 129.3, 133.9, 136.0, 137.5, 148.2, 164.8, 168.7 ppm; MS: *m*/*z* (%): 370 (12), 368 (9), 296 (13), 158 (100), 129 (39), 91 (37); elemental analysis calcd (%) for $C_{30}H_{33}Cl_4NO_8$: C 53.19, H 4.91, N 2.07; found: C 53.03, H 5.13, N 2.01.

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[1] a) *Macrocyclic Chemistry: Current Trends and Future Perspectives* (Ed.: K. Gloe), Springer, Dordrecht, **2005**; b) B. Dietrich, P. Viout, J.-M. Lehn, *Macrocyclic Chemistry: Aspects of Organic and Inorganic Supramolecular Chemistry*, VCH, New York, **1993**; c) C. J. Roxburgh, *Tetrahedron* **1995**, *51*, 9767–9822.

[2] a) P. A. Evans, B. Holmes, *Tetrahedron* **1991**, *47*, 9131–9166; b) N. A. Petasis, M. A. Patane, *Tetrahedron* **1992**, *48*, 5757–5821; c) J. O. Hoberg, *Tetrahedron* **1998**, *54*, 12631–12670; d) U. Nubbemeyer, *Top. Curr. Chem.* **2001**, *216*, 125–196.

[3] a) A. Gradillas, J. Pérez-Castells, *Angew. Chem.* **2006**, *118*, 6232–6247; *Angew. Chem. Int. Ed.* **2006**, *45*, 6086–6101; b) I. Nakamura, Y. Yamamoto, *Chem. Rev.* **2004**, *104*, 2127–2198; c) A. Deiters, S. F. Martin, *Chem. Rev.* **2004**, *104*, 2199–2238; d) *Handbook of Metathesis, Vol. 2* (Ed.: H. R. Grubbs), Wiley-VCH, Weinheim, **2003**.

[4] M. E. Maier, *Angew. Chem.* **2000**, *112*, 2153–2157; *Angew. Chem. Int. Ed.* **2000**, *39*, 2073–2077.

[5] For reviews, see a) M. Oelgemöller, A. G. Griesbeck, *J. Photochem. Photobiol. C* **2002**, *3*, 109–127; b) A. G. Griesbeck, A. Henz, J. Hirt, *Synthesis* **1996**, 1261–1276; c) Y. Kanaoka, *Acc. Chem. Res.* **1978**, *11*, 407–413.

[6] Y. Kanaoka, Y. Migita, *Tetrahedron Lett.* **1974**, *15*, 3693–3696.

[7] a) M. Machida, H. Takechi, Y. Kanaoka, *Heterocycles* **1980**, *14*, 1255–1258; b) M. Machida, H. Takechi, Y. Kanaoka, *Heterocycles* **1977**, *7*, 273–276; c) J. D. Coyle, G. L. Newport, *J. Chem. Soc. Perkin Trans. 1* **1980**, 93–96; d) P. H. Mazzocchi, S. Minamikawa, P. Wilson, *J. Org. Chem.* **1979**, *44*, 1186–1188.

[8] See, for examples, a) Y. Sato, H. Nakai, T. Mizoguchi, Y. Hatanaka, Y. Kanaoka, *J. Am. Chem. Soc.* **1976**, *98*, 2349–2351; b) M. Wada, H. Nakai, K. Aoe, K. Kotera, Y. Sato, Y. Hatanaka, Y. Kanaoka, *Tetrahedron* **1983**, *39*, 1273–1279; c) Y. Sato, H. Nakai, M. Wada, T. Mizoguchi, Y. Hatanaka, Y. Kanaoka, *Chem. Pharm. Bull.* **1992**, *40*, 3174–3180; d) A. G. Griesbeck, M. Oelgemöller, J. Lex, A. Haeuseler, M. Schmittel, *Eur. J. Org. Chem.* **2001**, 1831–1843; e) A. G. Griesbeck, M. Oelgemöller, J. Lex, *J. Org. Chem.* **2000**, *65*, 9028–9032; f) U. C. Yoon, S. W. Oh, J. H. Lee, J. H. Park, K. T. Kang, P. S. Mariano, *J. Org. Chem.* **2001**, *66*, 939–943.

[9] a) Y. Kanaoka, Y. Migita, Y. Sato, H. Nakai, *Tetrahedron Lett.* **1973**, *14*, 51–54; b) H. Nakai, Y. Sato, H. Ogiwara, T. Mizoguchi, Y. Kanaoka, *Heterocycles* **1974**, *2*, 621–624.

[10] For reviews, see a) U. C. Yoon, P. S. Mariano, *Mol. Supramol. Photochem.* **2006**, *14*, 179–206; b) U. C. Yoon, P. S. Mariano, *Acc. Chem. Res.* **2001**, *34*, 523–533.

[11] See, for examples, a) D. W. Cho, J. H. Choi, S. W. Oh, C. Quan, U. C. Yoon, R. Wang, S. Yang, P. S. Mariano, *J. Am. Chem. Soc.* **2008**, *130*, 2276–2284; b) U. C. Yoon, H. C. Kwon, T. G. Hyung, K. H. Choi, S. W. Oh, S. Yang, Z. Zhao, P. S. Mariano, *J. Am. Chem. Soc.* **2004**, *126*, 1110–1124; c) U. C. Yoon, Y. X. Jin, S. W. Oh, C. H. Park, J. H. Park, C. F. Campana, X. Cai, E. N. Duesler, P. S. Mariano, *J. Am. Chem. Soc.* **2003**, *125*, 10664–10671; d) U. C. Yoon, S. W. Oh, S. M. Lee, S. J. Cho, J. Gamlin, P. S. Mariano, *J. Org. Chem.* **1999**, *64*, 4411–4418; e) Z. Y. Su, P. S. Mariano, D. E. Falvey, U. C. Yoon, S. W. Oh, *J. Am. Chem. Soc.* **1998**, *120*, 10676–10686; f) X. M. Zhang, S. R. Yeh, S. Hong, M. Freccero, A. Albini, D. E. Falvey, P. S. Mariano, *J. Am. Chem. Soc.* **1994**, *116*, 4211–4220.

[12] For a review, see A. G. Griesbeck, W. Kramer, M. Oelgemöller, *Synlett* **1999**, 1169–1178.

[13] See, for examples, a) A. G. Griesbeck, T. Heinrich, M. Oelgemöller, A. Molis, J. Lex, *J. Am. Chem. Soc.* **2002**, *124*, 10972–10973; b) H. Görner, M. Oelgemöller, A. G. Griesbeck, *J. Phys. Chem. A* **2002**, *106*, 1458–1467; c) A. G. Griesbeck, F. Nerowski, J. Lex, *J. Org. Chem.* **1999**, *64*, 5213–5217; d) A. G. Griesbeck, A. Henz, W. Kramer, J. Lex, F. Nerowski, M. Oelgemöller, K. Peters, E.-M. Peters, *Helv. Chim. Acta* **1997**, *80*, 912–933; e) A. G. Griesbeck, A. Henz, K. Peters, E.-M. Peters, H. G. von Schnering, *Angew. Chem.* **1995**, *107*, 498–500; *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 474–476.

[14] a) I. Takahashi, M. Hatanaka, *Heterocycles* **1997**, *45*, 2475–2499; b) A. Moreau, A. Couture, E. Deniau, P. Grandclaudon, S. Lebrum, *Org. Biomol. Chem.* **2005**, *3*, 2305–2309.

[15] For reviews, see a) P. J. Wagner in *Synthetic Organic Photochemistry, Vol. 12* (Eds.: A. G. Griesbeck, J. Mattay), Marcel Dekker, New York, **2005**, pp. 11–39; b) P. J. Wagner, B.-S. Park in *Organic Photochemistry, Vol. 11* (Ed.: A. Pawda), Marcel Dekker, New York, **1991**, Chapter 4l; c) P. J. Wagner, *Acc. Chem. Res.* **1989**, *22*, 83–91; d) J. C. Scaiano, *J. Photochem.* **1974**, *2*, 81–118; e) N. J. Turro, J. C. Dalton, K. Dawes, G. Farrington, R. Hautala, D. Morton, M. Niemczyk, N. Schore, *Acc. Chem. Res.* **1972**, *5*, 92–101.

[16] a) P. Wessig, O. Mühling in *Synthetic Organic Photochemistry, Vol. 12* (Eds.: A. G. Griesbeck, J. Mattay), Marcel Dekker, New York, **2005**, pp. 41–87; b) S. Abad, F. Bosca, L. R. Domingo, S. Gil, U. Pischel, M. A. Miranda, *J. Am. Chem. Soc.* **2007**, *129*, 7407–7420; c) J. Pérez-Prieto, A. Lahoz, F. Bosca, R. Martinez-Manez, M. A. Miranda, *J. Org. Chem.* **2004**, *69*, 374–381; d) U. Pischel, S. Abad, L. R. Domingo, F. Bosca, M. A. Miranda, *Angew. Chem.* **2003**, *115*, 2635–2638; *Angew. Chem. Int. Ed.* **2003**, *42*, 2531–2534.

[17] For recent references on stereoselective Norrish Type II–Yang reactions, see a) N. Singhal, A. L. Koner, P. Mal, P. Venugopalan, W. M. Nau, J. N. Moorthy, *J. Am. Chem. Soc.* **2005**, *127*, 14375–14382; b) J. N. Moorthy, A. L. Koner, S. Samanta, N. Singhal, W. M. Nau, R. G. Weiss, *Chem. Eur. J.* **2006**, *12*, 8744–8749; c) J. N. Moorthy, S. Samanta, A. L. Koner, S. Saha, W. M. Nau, *J. Am. Chem. Soc.* **2008**, *130*, 13608–13617; d) A. G. Griesbeck, H. Heckroth, *J. Am. Chem. Soc.* **2002**, *124*, 396–403; e) T. Bach, T. Aechtner, B. Neumüller, *Chem. Eur. J.* **2002**, *8*, 2464–2475; f) R. Pedrosa, C. Andrés, J. Nieto, S. del Pozo, *J. Org. Chem.* **2005**, *70*, 1408–1416.

[18] J. Xue, L. Zhu, H. K. Fun, J. H. Xu, *Tetrahedron Lett.* **2000**, *41*, 8553–8557.

[19] a) M. Zhang, H. Y. An, B. G. Zhao, J. H. Xu, *Org. Biomol. Chem.* **2006**, *4*, 33–35; b) Z. F. Lu, J. J. Yue, Y. Zhu, H. W. Hu, J. H. Xu, *Photochem. Photobiol. Sci.* **2009**, *8*, 217–223; c) Y. Zhang, L. Wang, M. Zhang, H. K. Fun, J. H. Xu, *Org. Lett.* **2004**, *6*, 4893–4895.

[20] a) R. Glinka, H. Mikolajewska, PL 137531 B1 9861031, **1986**; b) T. Mukaiyama, T. Takeshi, M. Masaaki, JP 54052089 19790424, **1979**.

[21] See, for examples, a) A. V. Samet, V. N. Marshalkin, K. A. Kislyi, N. B. Chernysheva, Y. A. Strelenko, V. V. Semenov, *J. Org. Chem.* **2005**, *70*, 9371–9376; b) M. M. McGee, S. Gemma, S. Butini, A. Ramunno, D. M. Zisterer, C. Fattorusso, B. Catalanotti, G. Kukreja, I. Fiorini, C. Pisano, C. Cucco, E. Novellino, V. Nacci, D. C. Williams, G. Campiani, *J. Med. Chem.* **2005**, *48*, 4367–4377.

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[22] See, for examples, a) A. Cherif, G. E. Martin, L. R. Soltero, G. Massiot, *J. Nat. Prod.* **1990**, *53*, 793–802; b) E. Wenkert, H. T. A. Cheung, H. E. Gottlieb, M. C. Koch, A. Rabaron, M. Plat, *J. Org. Chem.* **1978**, *43*, 1099–1105; c) N. G. Bisset, J. Bosly, B. C. Das, G. Spiteller, *Phytochemistry* **1975**, *14*, 1411–1414.

[23] A. Arnone, A. Bava, G. Fronza, G. Nasini, E. Ragg, *Tetrahedron Lett.* **2005**, *46*, 8037–8039.

[24] See, for examples, a) S. Seto, J. Asano, *Bioorg. Med. Chem.* **2007**, *15*, 5083–5089; b) S. Seto, *Tetrahedron Lett.* **2004**, *45*, 8475–8478; c) J. K. Mishra, G. Panda, *J. Comb. Chem.* **2007**, *9*, 321–338; d) T. Assoumatine, P. K. Datta, T. S. Hooper, B. L. Yvon, J. L. Charlton, *J. Org. Chem.* **2004**, *69*, 4140–4144.

[25] For a review, see A. Lévai, *Heterocycles* **2008**, *75*, 2155–2185.

[26] For recent examples on oxazepine derivative synthesis, see a) M. Yar, E. M. McGarrigle, V. K. Aggarwal, *Org. Lett.* **2009**, *11*, 257–260; b) L. Guo, B. Li, W. Huang, G. Pei, D. Ma, *Synlett* **2008**, 1833–1836; c) Y. R. Jorapur, G. Rajagopal, P. J. Saikia, R. R. Pal, *Tetrahedron Lett.* **2008**, *49*, 1495–1497; d) C. Hudson, V. S. Murthy, K. G. Estep, G. Gustafson, *Tetrahedron Lett.* **2007**, *48*, 1489–1492; e) H. Ohno, H. Hamaguchi, M. Ohata, S. Kosaka, T. Tanaka, *J. Am. Chem. Soc.* **2004**, *126*, 8744–8754; f) A. R. Katritzky, Y.-J. Xu, H.-Y. He, S. Mehta, *J. Org. Chem.* **2001**, *66*, 5590–5594; g) A. Saba, *Tetrahedron Lett.* **2003**, *44*, 2895–2898.

[27] a) W. Q. Chen, Q. Y. Zhang, B. K. Liu, Q. Wu, X. F. Lin, *Synlett* **2008**, 1829–1832; b) A. Neogi, T. P. Majhi, R. Mukhopadhyay, P. Chattopadhyay, *J. Org. Chem.* **2006**, *71*, 3291–3294; c) M. M. Campbell, D. I. Rawson, A. F. Cameron, *Tetrahedron Lett.* **1979**, *20*, 1257–1260.

[28] H. K. Fun, Y. M. Shen, J. H. Xu, S. Chantrapromma, *Acta Crystallogr. Sect. E* **2007**, *63*, o495–o497.

[29] Gaussian 03, Revision C.02, M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, J. A. Montgomery, Jr., T. Vreven, K. N. Kudin, J. C. Burant, J. M. Millam, S. S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G. A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J. E. Knox, H. P. Hratchian, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, P. Y. Ayala, K. Morokuma, G. A. Voth, P. Salvador, J. J. Dannenberg, V. G. Zakrzewski, S. Dapprich, A. D. Daniels, M. C. Strain, O. Farkas, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. V. Ortiz, Q. Cui, A. G. Baboul, S. Clifford, J. Cioslowski, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, C. Gonzalez, J. A. Pople, Gaussian, Inc., Wallingford CT, **2004**.

[30] In 2,3-disubstituted benzofurans, the *cis* isomer has a *J* value of $\approx$7 Hz for the two protons at C2 and C3, whereas for the *trans* isomer, this *J* value is $\approx$2 Hz, see a) V. V. Dhekne, A. S. Rao, *Synthesis* **1980**, 58–60; b) C. P. Gorst-Allman, P. S. Steyn, *J. Chem. Soc. Perkin Trans. 1* **1987**, 163–168; c) D. R. Arnold, B. J. Fahie, L. J. Lamont, J. Wierzchowski, K. M. Young, *Can. J. Chem.* **1987**, *65*, 2734–2743.

[31] H. K. Fun, S. Chantrapromma, Y. M. Shen, J. H. Xu, *Acta Crystallogr. Sect. E* **2007**, *63*, o2023–o2025.

[32] a) D. Rhem, A. Weller, *Isr. J. Chem.* **1970**, *10*, 259–271; in benzene solution, the free-energy change for electron transfer between the alkene and the phthalimide can be estimated by the equation $\Delta G_{ET} = 23.06[E^{ox}_{1/2} - E^{red}_{1/2} + 0.38] - E^*$ (kcal mol^{-1}), in which $E^{ox}_{1/2}$ and $E^{red}_{1/2}$ are the halfwave oxidation potential of the alkene and the reduction potential of the phthalimide, respectively, and E^* is the excitation energy of the phthalimide (67 kcal mol^{-1} here); b) A. G. Griesbeck, H. Görner, *J. Photochem. Photobiol. A* **1999**, *129*, 111–119; c) K. D. Warzecha, H. Görner, A. G. Griesbeck, *J. Phys. Chem. A* **2006**, *110*, 3356–3363; d) H. Görner, A. G. Griesbeck, T. Heinrich, W. Kramer, M. Oelgemöller, *Chem. Eur. J.* **2007**, *13*, 1530–1538.

[33] A recent review: M. Abe in *CRC Handbook of Photochemistry and Photobiology* (Eds.: W. M. Horspool, F. Lenci), CRC Press, Boca Raton, **2004**, Chapter 62.

[34] A. G. Griesbeck, W. Kramer, A. Bartoschek, H. Schmickler, *Org. Lett.* **2001**, *3*, 537–539.

[35] A. G. Griesbeck, H. Heckroth, H. Schmickler, *Tetrahedron Lett.* **1999**, *40*, 3137–3140.

[36] A. G. Griesbeck, W. Kramer, J. Lex, *Angew. Chem.* **2001**, *113*, 586–589; *Angew. Chem. Int. Ed.* **2001**, *40*, 577–579.

[37] N. C. Yang found that intramolecular disproportionation of the 1,4-biradical may lead to racemization of the $<\iota\tau>\gamma<\iota\tau>$-carbon atom in the starting ketone; a) N. C. Yang, S. P. Elliot, B. Kim, *J. Am. Chem. Soc.* **1969**, *91*, 7551–7553; b) N. C. Yang and S. P. Elliot, *J. Am. Chem. Soc.* **1969**, *91*, 7550–7551.

[38] a) L. J. Johnston, J. C. Scaiano, *Chem. Rev.* **1989**, *89*, 521–547; b) C. Doubleday, Jr., N. J. Turro, J. F. Wang, *Acc. Chem. Res.* **1989**, *22*, 199–205; c) A. G. Griesbeck, M. Abe, S. Bondock, *Acc. Chem. Res.* **2004**, *37*, 919–928.

[39] a) J. R. Scheffer, H. Ihmels, *Tetrahedron* **1999**, *55*, 884–907; b) M. Leibovitch, G. Olovsson, J. R. Scheffer, J. Trotter, *J. Am. Chem. Soc.* **1998**, *120*, 12755–12769; c) E. Cheung, M. R. Netherton, J. R. Scheffer, J. Trotter, *Org. Lett.* **2000**, *2*, 77–80; d) W. Xia, J. R. Scheffer, M. Botoshansky, M. Kaftory, *Org. Lett.* **2005**, *7*, 1315–1318; e) C. Yang, W. Xia, J. R. Scheffer, M. Botoshansky, M. Kaftory, *Angew. Chem.* **2005**, *117*, 5217–5219; *Angew. Chem. Int. Ed.* **2005**, *44*, 5087–5089.

[40] a) F. D. Lewis, T. A. Hilliard, *J. Am. Chem. Soc.* **1970**, *92*, 6672–6674; b) P. J. Wagner, J. M. McGrath, *J. Am. Chem. Soc.* **1972**, *94*, 3849–3851.

[41] H. P. Fu, M. Zhang, H. G. Shi, J. H. Xu, *Res. Chem. Intermed.* **2004**, *30*, 383–395.

[42] a) P. H. Mazzocchi in *Organic Photochemistry, Vol. 5* (Ed.: A. Padwa,), Marcel Dekker, New York, **1981**, pp. 421–471; b) J. D. Coyle, in *Synthetic Organic Photochemistry* (Ed.: W. M. Horspool), Plenum, New York, **1984**, Chapter 4, pp. 259–284.

[43] a) Y. Kubo, M. Suto, T. Araki, *J. Org. Chem.* **1986**, *51*, 4404–4411; b) P. H. Mazzocchi, L. Klingler, M. Edwards, P. Wilson, D. Shook, *Tetrahedron Lett.* **1983**, *24*, 143–146.

[44] a) S. L. Mattes, S. Farid, *J. Am. Chem. Soc.* **1986**, *108*, 7356–7361; b) Z. F. Lu, Y. M. Shen, J. J. Yue, H. W. Hu, J. H. Xu, *J. Org. Chem.* **2008**, *73*, 8010–8015.

[45] K. Maruyama, Y. Kubo, *J. Am. Chem. Soc.* **1978**, *100*, 7772–7773.

[46] a) F. G. Bordwell, X. M. Zhang, *Acc. Chem. Res.* **1993**, *26*, 510, and references therein; b) G. Leroy, M. Sana, C. Wilante, *J. Mol. Struct.* **1989**, *198*, 159–173.

[47] a) A. G. Griesbeck, S. Buhr, M. Fiege, H. Schmickler, J. Lex, *J. Org. Chem.* **1998**, *63*, 3847–3854; b) M. Abe, T. Kawakami, S. Ohata, K. Nozaki, M. Nojima, *J. Am. Chem. Soc.* **2004**, *126*, 2838–2846; c) M. D'Auria, L. Emanuele, R. R. Acioppi in *Advances in Photochemistry, Vol. 28* (Eds.: D. C. Neckers, W. S. Jenks, T. Wolff), Wiley, New York, **2005**, pp. 81–127; d) M. D'Auria, L. Emanuele, R. Racioppi, G. Romaniello, *Curr. Org. Chem.* **2003**, *7*, 1443–1459; e) Y. Zhang, J. Xue, Y. Gao, H. K. Fun, J. H. Xu, *J. Chem. Soc. Perkin Trans. 1* **2002**, 345–353.

[48] a) L. Salem, C. Rowland, *Angew. Chem.* **1972**, *84*, 86–106; *Angew. Chem. Int. Ed. Engl.* **1972**, *11*, 92–111; b) J. Wirz, *Pure Appl. Chem.* **1984**, *56*, 1289–1300; c) L. Carlacci, C. E. Doubleday, Jr., T. R. Furlani, H. F. King, J. W. McIver, Jr., *J. Am. Chem. Soc.* **1987**, *109*, 5323–5329; d) W. Adam, S. Grabowski, R. M. Wilson, *Acc. Chem. Res.* **1990**, *23*, 165–172; e) A. Kutateladze, *J. Am. Chem. Soc.* **2001**, *123*, 9279–9282.

[49] a) A. G. Griesbeck, H. Mauder, S. Stadtmueller, *Acc. Chem. Res.* **1994**, *27*, 70–75; b) A. G. Griesbeck, M. Abe, S. Bondock, *Acc. Chem. Res.* **2004**, *37*, 919–928.

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