Organic synthesis using photoredox catalysis

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Natural photosynthesis is a remarkable chemical machinery that enables our life on earth and delivers a constant stream of oxygen and organic biomass. We should acknowledge this fact with humbleness, especially because we have not been able yet to mimic this process in a reliable way even after decades of intense research. The basic mechanistic principle behind photosynthesis is photoredox catalysis or light-driven charge separation, which leads to an energy harvesting process by taking advantage of the reduction products and filling the holes by a sacrificial electron donor, water. Fortunately, we can use the waste product from this process, oxygen, for breathing.

For applications in organic synthesis, the principles of photoredox chemistry serve as guidelines, i.e., photoinduced electron transfer (PET) kinetics and thermodynamics as expressed in the Rehm–Weller and Marcus equations. For catalytic versions, the photoinduced redox processes require efficient and robust photocatalysts, and in many cases appropriate sacrificial components. In recent years, three major groups of light-absorbing molecules/materials have been (re)investigated, which facilitate a wide range of redox activation from their excited states: transition metal complexes (e.g., the thoroughly investigated Ru(bipy)₃ and other Ru or Ir complexes) with strong MLCT transitions, organic dyes such as xanthene, porphyrine or phthalocyanine dyes (e.g., eosin Y), and colloidal semiconductor particles (e.g., TiO₂) [1-9]. In addition, combinations of light-absorbing materials have been studied such as dye-coated semiconductor nanoparticles. On the substrate side, the focus is on redox-active donor/acceptor molecules, which range from all kind of aromatic, olefinic and carbonyl-type electron acceptor compounds to heteroatom-linked electron donors. The relevance of carbon–carbon bond formation for organic synthesis is also depicted in these processes, and in recent years, enantioselective versions of these processes as well as unusual activation and coupling modes have been developed. In contrast to the “traditional” catalysis areas such as metal-, organo- and biocatalysis, photoredox catalysis (and photocatalysis in general) is a young research field with regard to synthetic applications. The collection of papers in this Thematic Series on organic synthesis using photoredox catalysis shows this convincingly.

It was a great pleasure to act as the editor of this Thematic Series on photochemical reactions, and I would like to thank all...
authors for their excellent contributions and the staff of the Beilstein-Institut for their professional support.

Axel G. Griesbeck

Cologne, April 2014

References


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Abstract
A mild and efficient methodology for the bromination of phenols and alkenes has been developed utilizing visible light-induced photoredox catalysis. The bromine was generated in situ from the oxidation of Br$^-$ by Ru(bpy)$_3^{3+}$, both of which resulted from the oxidative quenching process.

Introduction
Bromophenols serve as important synthetic intermediates for a variety of naturally occurring biologically active compounds and are also important constituents of industrial chemicals [1-5]. Thus, numerous methods were developed for the electrophilic bromination of phenols. The typical approaches include direct electrophilic halogenation by using molecular bromine or N-bromosuccinimide (NBS) [6-8], organometallic catalyst-promoted bromination [9-12], and the oxidative bromination of phenols [13-15]. Nevertheless, most of the methods suffer from several drawbacks such as toxic reagents, harsh conditions, low yields, and low chemo- and regioselectivity. Hence, the development of an environmentally friendly methodology for the bromination of phenols with high chemoselectivity under mild and operationally simple conditions is still appealing.

Recently, an intriguing and promising strategy for the application of photoredox catalysts to initiate single electron transfer processes have been developed [16-22]. Since the pioneering work from the groups of MacMillan [23-25], Stephenson [26-28], Yoon [29-31] and others [32-44] demonstrated the usefulness of Ru(bpy)$_3$Cl$_2$ and its application to various visible-light-induced synthetic transformations, visible-light-photoredox catalysis has emerged as a growing field in organic chemistry and has been successfully applied in a variety of reactions. In the oxidative quenching process [45-47], Ru(bpy)$_3^{2+}$ excited by visible light generates Ru(bpy)$_3^{3+}$, which was oxidized to Ru(bpy)$_3^{5+}$ in the presence of oxidative quenchers. CBr$_4$ is an example of a suitable oxidative quencher and leads to the formation of Br$^-$ and •CBr$_3$. We envision that Ru(bpy)$_3^{3+}$ is a
strong oxidant (1.29 V vs SCE, in CH₃CN) that could sequentially oxidize the resulting Br⁻ (1.087 V vs SCE, in CH₃CN) to generate the bromine for the bromination of phenols and other substrates in situ (Scheme 1), thus avoiding the use of highly toxic and volatile liquid bromine.

Results and Discussion

Our initial investigation was carried out on protected 4-methoxyphenol 1a and CBr₄ in dried CH₃CN in the presence of Ru(bpy)₃Cl₂ (5.0 mol %) with visible light irradiation (blue LEDs, λ_max = 435 nm) for 6 hours. The corresponding 2-bromo-4-methoxyphenol (2a) was obtained in 78% yield (Table 1, entry 1), whereas 3-bromo-4-methoxyphenol was not observed.

The optimization of the reaction conditions were conducted by screening selected solvents and the amount of the photoredox catalyst using 1a as the representative substrate. As can be seen in Table 1, the solvent had a significant effect on the reaction efficiency. The reaction did not work well in DMF, MeOH, THF, CH₂Cl₂, EtOAc, CH₃CN with 10 equivalents of H₂O or 1,4-dioxane (Table 1, entries 5–11). The reaction in CH₃CN and open to air led to the highest yield, 94% (Table 1, entry 4), whereas the reaction conducted under N₂ or O₂, or in DMSO and open to air gave lower yields (Table 1, entries 2, 3, 12). Our final optimization showed that the reaction also provided comparable results when the catalyst loading was reduced to 3% or 1% (Table 1, entry 13). It should be pointed out that an exclusion of either the photocatalyst or the light source did not afford the desired product 2a. Therefore, the reaction conditions of CBr₄ (1 equiv) in dried CH₃CN in the presence of Ru(bpy)₃Cl₂ (5.0 mol %) with visible light irradiation (blue LEDs, λ_max = 435 nm) and open to air were utilized to test the scope of the reaction.

With the optimized conditions in hand, we prepared a variety of phenols which were subjected to the photocatalytic reaction. In general, both electron-withdrawing and electron–donating groups were tolerated as substituents R² in this process. Interestingly, the substrates protected with TMS (trimethylsilyl), TBS (tert-butyldimethylsilyl), MOM (methoxymethyl) and THP (tetrahydropyranyl) groups led to the corresponding bromophenols via a Tandem bromination/deprotection reaction (Table 2, entries 1–8, 12, 13, and 15), among which the cases with substituents at para- and ortho-position afforded 2- and 4-bromophenol, respectively, in good to excellent yields (Table 2, entries 1–5 and 12). The compound substituted with a methoxy group at the meta-position (1b) led to both 2- and 4-bromophenols 2b and 2b’ with a ratio of 2:1 (Table 2, entry 8). Without any substituent at the phenol moiety mono- and dibromophenols were obtained with a ratio of 3:2 (Table 2, entries 6 and 7). Notably, 1-bromonaphthalen-2-ol and 1-bromo-2-methoxynaphthalene could be prepared in good yields with high regioselectivity from TMS and methyl protected naphthalen-2-ol (Table 2, entries 13 and 14). The direct treatment of 3-methoxyphenol under the same reaction conditions afforded 2- and 4-bromo-3-methoxyphenol with a ratio of 3:2 in a synthetically acceptable yield (Table 2, entry 11). Phenols protected with Bn or Ms groups led to 2- and 4-bromophenol derivatives in excellent yields without the loss of Bn or Ms groups (Table 2, entries 9 and 10).
Table 2: Scope of the photocatalytic bromination of phenols.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Product</th>
<th>Yield (%)</th>
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<td></td>
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<td>6</td>
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</table>

<sup>a</sup>Isolated yield based on complete consume of the starting material. <sup>b</sup>Reaction conditions: substrate 1 (0.1 mmol), CBr<sub>4</sub> (0.1 mmol), Ru(bpy)<sub>3</sub>Cl<sub>2</sub> (5 mol %), dried CH<sub>3</sub>CN, blue LEDs (1 W), open to air. <sup>c</sup>Ratio of the isomers in parentheses.
The bromination of phenols could be controlled by the amount of CBr₄. For example, when TMS protected 3-methoxyphenol was treated with 2 equivalents of CBr₄ under similar conditions (Table 2), a dibromophenol product was directly obtained in a high yield (95%) (Scheme 2), which also could be prepared from the same starting materials in two steps (Table 2).

We also conducted a control experiment by reacting stilbene with CBr₄ (1 equiv) in dry CH₃CN in the presence of Ru(bpy)₃Cl₂ (5.0 mol %) with visible-light irradiation (blue LEDs, λ_max = 435 nm) for 72 hours, which led to the anti-1,2-dibromo-1,2-diphenylethane in 92% yield. This result is in accordance with the direct bromination of stilbene from liquid bromine [47]. Based on this result, our protocol provides an easily manageable and environment-friendly pathway to the bromination of alkenes. We further examined the scope of the reaction, and the results are summarized in Scheme 3. The 1,2-dibromo products were obtained in moderate to high yields.

With the success of the bromination of phenols and alkenes, we further focused on the complementary bromination of diketones and cyclization reactions. The treatment of cyclohexane-1,3-dione (5) and (E)-4-(4-methoxyphenyl)but-3-en-1-ol (7) under the same reaction conditions led to 2,2-dibromocyclohexane-1,3-dione (6) and bromofuran compound 8 in 22% and 52% yield, respectively (Scheme 4). This outcome demonstrates the efficiency of the Ru(bpy)_3Cl_2/CBr_4 photocatalytic system. The stereochemistry of the bromofuran compound was determined by 2D NMR spectra.

Conclusion

In summary, we have developed a mild and operationally simple method for the in situ preparation of bromine utilizing a visible-light photoredox catalyst. The reaction proceeds with high chemical yield and regioselectivity for the bromination of phenols and alkenes. Further development of photoredox catalysis in the context of radical chemistry and its application in other reactions are currently underway in our laboratory.
Experimental

General procedure for the bromination of phenols and alkenes

To a 10 mL round bottom flask equipped with a magnetic stir bar were added phenols or alkenes (0.1 mmol), CBr₄ (33 mg, 0.1 mmol), dry CH₃CN (1 mL) and Ru(bpy)₃Cl₂ (3.8 mg, 0.005 mmol). The mixture was irradiated with blue LEDs (1 W) at room temperature open to air until the starting material disappeared completely (monitored by TLC). After the reaction was completed, the solvent was concentrated in vacuo. The residue was purified by flash column chromatography to give the final product.

Bromination of diketones

To a 10 mL round bottom flask equipped with a magnetic stir bar were added 5 (0.4 mmol), CBr₄ (133 mg, 0.4 mmol), dry CH₃CN (2 mL) and Ru(bpy)₃Cl₂ (15 mg, 0.02 mmol). The mixture was irradiated with blue LEDs (1 W) at room temperature open to air until the starting material was largely consumed (monitored by TLC). After the reaction was completed, the solvent was concentrated in vacuo. The residue was purified by flash column chromatography to give the final product 6.

Synthesis of bromofuran

To a 10 mL round bottom flask equipped with a magnetic stir bar were added 7 (0.13 mmol), CBr₄ (43 mg, 0.13 mmol), LiBr (11 mg, 0.13 mmol), dry CH₃CN (1 mL) and Ru(bpy)₃Cl₂ (4.5 mg, 0.006 mmol). The mixture was irradiated with blue LEDs (1 W) at room temperature open to air until the starting material disappeared completely (monitored by TLC). After the reaction was completed, the solvent was concentrated in vacuo. The residue was purified by flash column chromatography to give the final product 8.

Supporting Information

Supporting Information File 1

[http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-53-S1.pdf]

Acknowledgements

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References

Metal and metal-free photocatalysts: mechanistic approach and application as photoinitiators of photopolymerization

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Abstract

In the present paper, the photoredox catalysis is presented as a unique approach in the field of photoinitiators of polymerization. The principal photocatalysts already reported as well as the typical oxidation and reduction agents used in both reductive or oxidative cycles are gathered. The chemical mechanisms associated with various systems are also given. As compared to classical iridium-based photocatalysts which are mainly active upon blue light irradiation, a new photocatalyst Ir(piq)2(tmd) (also known as bis(1-phenylisoquinolinato-NC2'tmd)iridium(2,2,6,6-tetramethyl-3,5-heptanedionate) is also proposed as an example of green light photocatalyst (toward the long wavelength irradiation). The chemical mechanisms associated with Ir(piq)2(tmd) are investigated by ESR spin-trapping, laser flash photolysis, steady state photolysis, cyclic voltammetry and luminescence experiments.

Introduction

Photoredox catalysis is now well-known and largely used in organic synthesis, especially in the development of sustainable radical-mediated chemical processes under very soft irradiation conditions (e.g., household fluorescence or LED bulbs, halogen lamps, sunlight, Xe lamp), e.g., chntioselective alkylation, cycloaddition, etc. [1-14]. Ruthenium- and iridium-based...
organometallic complexes are mostly employed as radical sources: they exhibit an excellent visible-light absorption, long lived excited states and suitable redox potentials and they work through either an oxidation or a reduction cycle [1-12]. To avoid, however, the high cost, potential toxicity and limited availability of these structures, metal-free organic dye compounds (e.g., Eosin-Y, Nile Red, Alizarine Red S, perylene derivative or Rhodamine B etc.) were recently proposed for cooperative asymmetric organophotoredox catalysis [13,14]. Photoredox catalysis was then introduced into the polymer photochemistry field (area) in the very past years (see a review in [15-22]). Indeed, in this area, free-radical photopolymerization (FRP, Scheme 1, reactions 1 and 2), cationic photopolymerization (CP, Scheme 1, reactions 3 and 4), free-radical promoted cationic photopolymerization (FRPCP, Scheme 1, reactions 5–7) or acid and base-catalyzed photocrosslinking (reactions 8 and 9) are initiated using photoinitiators (PI) which generate reactive species (radicals, cations, anions, radical cations, acids, bases). These PIs are often incorporated into multicomponent photoinitiating systems (PIS) where they primarily react with the other concomitant reagents or additives. PIs and PISs have been extensively developed both in industrial R&D and academic laboratories [15-40]. PIs are usually organic molecules that are consumed during the light exposure [15-40]. The use of organometallic compounds as PIs was reported many years ago (see a review in [41]) and reintroduced in some recent papers dealing with, e.g., Cr, Ti, Fe, Rh, W, Pt, Ru, Ir, Zn, Zr-based derivatives [42-44]. On this occasion, it appeared that a photoredox catalysis behavior (allowing a PI regeneration while keeping a high reactivity/efficiency) can be introduced through a suitable selection of the PIs and PISs [45-55].

This approach opened up [45-53] a new way for the design of a novel high performance class of PIs for FRP and FRPCP (where the photoinitiator is now referred as a photoinitiator catalyst PIC). It brings, among others, the following novel properties [45-55]:

- Almost no photoinitiator is consumed.
- Since the spectral photosensitivity extends now from the UV to the visible, laser excitation in the purple, blue, yellow, green or red is feasible.
- Low light intensities (as delivered, e.g., by household lamps and LED bulbs) can be used; this is a catalytic process without loss of efficiency with irradiation.
- Photopolymerization under sunlight becomes reachable.
- The production of the radical or cationic initiating species for the FRP of acrylates or the FRPCP of epoxides, respectively, is quite easy; polymerization of sustainable monomers can also be achieved (e.g., epoxidized soybean oil).
- A possible dual behavior (simultaneous generation of radicals and cations that ensure the formation of, e.g., an epoxy/acylate interpenetrated network IPN) is achieved.

Examples of PICs proposed by us in the photopolymerization reactions are depicted in Figure 1 and Figure 2 (for metal based PICs and metal free PICs, respectively) [45-55]. Their reactivity parameters (redox potentials, excited state lifetimes) are given in the associated references. These PICs are typically used (see below) in combination with various additives (see Figure 3 below) in three-component photoinitiating systems, e.g., based PIC/iodonium salt (or sulfonium salt)/tris(trimethylsilyl)silane (or N-vinylcarbazole) or PIC/amine/alkyl halide. Also, relatively high intensity light sources (Hg, Xe or Hg–Xe lamps, laser diodes) can be obviously employed.
Figure 1: Previously reported PIC (based on metal complexes) [45-52].

Figure 2: Previously reported PIC (metal free organic molecules) [54,55].

However, and with more interest, very soft irradiation conditions (using, e.g., household fluorescence or LED bulbs, halogen lamps or even sunlight) are also suitable to polymerize radical and cationic monomers (see Figure 4 below) under polychromatic or monochromatic lights in the 350–700 nm and to get tack free coatings.

The present paper will i) review the various possible mechanistic schemes using metal and metal free oxidizable or reducible PICs for FRP, CP and FRPCP, ii) show examples of reported PICs, iii) discuss the encountered mechanisms in various PIC based photoinitiating systems, iv) highlight some examples of high performance PISs and v) present the effi-
ciency of a novel PIC in photopolymerization reactions as well as the excited state processes involved in the photoinitiating systems used.

Experimental

i) Compounds: The synthesis of bis(1-phenylisoquinolinato-$N,C^2$)iridium(2,2,6,6-tetramethyl-3,5-heptanedionate) is described below (following a published procedure). All reagents and solvents were purchased from Aldrich or Alfa Aesar and used as received without further purification.

ii) Irradiation sources: Several lights were used: 1) polychromatic light from a halogen lamp (Fiber-Lite, DC-950 – incident light intensity: $I_0 \approx 12$ mW/cm$^2$; in the 370–800 nm range); 2) monochromatic light delivered by a laser diode at 532 nm ($I_0 \approx 100$ mW/cm$^2$) and 3) LEDs at 514 nm.

iii) Free radical photopolymerization (FRP) of acrylates: The experiments were carried out in laminated conditions or under air. The prepared formulations deposited on a BaF$_2$ pellet (25 µm thick) were irradiated (see the irradiation devices). The evolution of the double bond content was continuously followed by real time FTIR spectroscopy (JASCO FTIR 4100) at about 1630 cm$^{-1}$ as in [15].

iv) The ring opening polymerization of epoxides: The photosensitive formulations were deposited (25 µm thick) on a BaF$_2$ pellet under air. The evolution of the epoxy group content was continuously followed by real time FTIR spectroscopy (JASCO FTIR 4100) at about 790 cm$^{-1}$, respectively [15].

v) ESR spin trapping (ESR-ST) experiments: The ESR-ST experiments were carried out using an X-band spectrometer (MS 400 Magnettech). The radicals were produced at room temperature upon a light exposure (see the irradiation devices) under N$_2$ and trapped by phenyl-$N$-tert-butyl nitron (PBN) according to a procedure described in detail in [15]. The ESR spectra simulations were carried out with the PEST WINSIM program.

Results and Discussion

Possible usable strategies for the design of PICs in the photopolymerization area

Oxidizable photoinitiator catalysts

Using oxidizable photoinitiator catalysts, three possibilities can be briefly considered. The simplest first situation is depicted in Scheme 2. Through light excitation in the presence of an electron acceptor (eA), the oxidized form of the photoinitiator catalyst (PIC$^{•+}$) is produced. A E-Z compound should be added to recover the PIC in its ground state and generate a radical and a cation. Suitable E-Z or E-Z$^-$ structures have to be designed.

A second situation is shown in Scheme 3. It consists in using the radical formed from the eA radical anion to recover the PIC. Both a radical and a cation are thus generated. The easiness of the radical $\rightarrow$ cation step as well as the nature of the cationic centers remains connected with the nature of eA. The key point is to find a radical directly formed through this way and that can be easily oxidized by PIC$^{•+}$.

Another situation is encountered in Scheme 4 where the initially formed radical Rad-m (from the decomposition of a suitable electron donor as before) is converted into another radical Rad-1 (upon addition of a convenient radical source), this novel radical being able to favorably react with PIC$^{•+}$. Such a process should be likely more feasible.

According to these different Schemes, both FRP, CP and FRPCP can be initiated from the free radicals and cations generated. In these three situations, as a function of its structure, the PIC radical cation PIC$^{•+}$ can behave as an initiating species.
Reductible photoinitiator catalysts

Scheme 5 shows a situation where the PIC is reduced through a photoinduced electron transfer with an electron donor eD. A suitable B-Y (or B-Y\(^+\)) compound leads to a regeneration of PIC and the formation of a radical and an anion (or a radical and a neutral product). Therefore, FRP can be achieved.

Examples of PICs in the photopolymerization area

Examples of PICs are shown above in Figure 1 and Figure 2. Typical oxidation and reduction agents used in catalytic (oxidation and reduction) cycles are gathered in Figure 3; the monomers that have been polymerized in previous works are given in Figure 4 [45-55].

Oxidizable photoinitiator catalysts

The oxidation of a PIC is quite easily realized. For example, the excitation of Ru(bpy\(_3\))\(^{2+}\) (with bpy = bipyridine) in the presence of an iodonium salt (e.g., Ph\(_2\)I\(^+\)) as eA leads to Ru(bpy\(_3\))\(^{3+}\). However, very few systems involving a E-Z structure or a E-Z anion (as suggested in Scheme 2) and allowing a regeneration of a ground state PIC together with efficient
radical and cationic initiating species for FRP/CP/FRPCP has been reported yet [45-55].

Interestingly, when using a Ru complex as PIC and Ph$_2$I$^+$ salt as eA as above, a phenyl radical Ph$^+$ is formed (Scheme 3). Unfortunately, the oxidation reaction of Ph$^+$ by PIC$^{+\cdot}$ is rather hard [45-52] and such a system does not work. Sulfonium salts were also used as eA but the reactivity is lower than that for iodonium salts (see below) [56].

A typical efficient system based on Scheme 4 involving Ru(bpy)$_3$($^{2+}$ as PIC, Ph$_2$I$^+$ as eA and a silane R$_3$SiH (e.g., tris(trimethylsilyl)silane TTMSS) as Add is detailed in Scheme 6. A phenyl radical is generated (previously noted Rad-m in Scheme 4). A silyl radical R$_3$Si$^\cdot$ (noted Rad-1 above) and a silylium R$_3$Si$^{+}$ are formed through a subsequent Ph$^+$/R$_3$SiH hydrogen abstraction and R$_3$Si$^\cdot$/PIC$^{+\cdot}$ interaction, respectively (the eA serves both as an electron donor and a radical mediator source) [45-52]. The Ph$_2$I$^+$/R$_3$Si$^\cdot$ interaction increases
the yields in both phenyl radicals and silylium species [45-52].
The nature of the PIC is responsible for the absorption properties. Interestingly, whatever the PIC, the nature of the cation is only dependent of the choice of Add. The three-component system behaves here as an efficient dual radical/cation source. Moreover, as already known [57], the introduction of the silane also reduces the oxygen inhibition of the radical stages of the FRP and FRPCP reactions.

Many photoinitiating systems have been designed on the basis of Scheme 6 [45-52]. Ruthenium and iridium-containing PICs are relatively well known and a large variety of derivatives have been recently tested in the photopolymerization area. Thus, more or less successful attempts using Fe, Pt, Ni, Zn-based complexes have been also recently reported [56,58-60].

Other examples of eA and Add are also available. In some cases, a sulfonium salt (e.g., a triphenylsulfonium salt) can be introduced instead of the iodonium salt (Scheme 7) [56].

The silane has been also changed for \(N\)-vinylcarbazole NVK (Scheme 8). The phenyl radical adds to the NVK double bond and the resulting radical is electron rich and can be easily oxidized. NVK is a cheaper additive than silane (\(R_3\)SiH) and exhibits a relatively similar performance in photoinitiating systems of cationic polymerization [45-52,54,55].

Examples of metal-free pure organic PICs for FRP and FRPCP have also been very recently reported [54,55,61,62]. For example, they involve a violanthrone dye Vi [61,62] or an anthracene derivative (e.g. bis[(triisopropylsilyl)ethynyl]-anthracene) [54,55] as PIC, \(Ph_2I^+\) as eA and TTMSS as Add (see the simplified Scheme 9 based on Scheme 6). Using violanthrone-79/\(Ph_2I^+\)/TTMSS allowed, for the first time, the formation of an initiating cationic species under a red laser line exposure at 635 nm. This result was very important as cationic polymerization in these irradiation conditions was not possible previously. Changing Vi or the anthracene derivative for a hydrocarbon (e.g. pyrene, naphthacene, pentacene) allows a tunable absorption of the system from 400 nm to 650 nm: exposure of the hydrocarbon/\(Ph_2I^+\)/TTMSS system to soft purple (405 nm), blue (457, 462 or 473 nm), green (514, 532 nm), yellow (591 nm) or red (630, 635 nm) LED bulbs or laser diodes becomes successful.
In rare examples, the PIC/methyldiethanolamine MDEA/phenacyl bromide R-Br (that usually operates through a reductive cycle; see below) works according to an oxidative cycle (Scheme 10). This is the case when the PIC stands for a truxene-acridinedione derivative Tr-AD (this is one of the possible examples for Scheme 2) [63]. For these PICs, the interaction of the excited states of Tr-AD with R-Br is much more favorable than the interaction with the amine.

Recently, an iridium complex (Ir(ppy)$_3$) (with ppy = 2-phenylpyridine) was proposed for the controlled photopolymerization reactions through a photoATRP process based on a photoredox catalysis approach (oxidative cycle; Scheme 11) [64].

All these described systems, producing radicals, cations or radical cations, allow efficient CP and FRPCP of cationic monomers, FRP of acrylates, simultaneous radical/cationic polymerization of epoxide/acrylate blend. The reactions can be carried out (see in [45-55]) in formulations containing multifunctional synthetic epoxides, acrylates, monomers/oligomers or epoxide/acrylate blends (renewable raw or modified materials are usable to some extent) with lights extending from the UV to the red, using polychromatic or monochromatic light sources, even with low intensity of light emission (sun, household devices).

**Reductible photoinitiator catalysts**

Reported systems based on a reductive cycle are mainly based on Ru complexes [45-53]. Such a reductible PIC was first mentioned in FRP (Scheme 12) in a system composed of a Ru complex as PIC, an amine (methyldiethanolamine, MDEA) as an electron/proton donor and a phenacyl bromide R-Br [45]. In this mechanism, a reduced form of the Ru complex is formed (e.g., Ru(bpy)$_3^{2+}$) and a phenacyl radical is produced upon the subsequent cleavage of the phenacyl halide radical anion. Later on, other amines (N,N-diisopropylethylamine, N,N-dimethylformamide) and bromides (ethyl 2-bromoisobutyrate, benzyl bromide) were proposed for the photocatalytic radical polymerization of various methacrylates [53]. Ir complexes can also be used.

As only carbon centered radicals can be generated in Scheme 12, the change of the phenacyl bromide for a compound being able to generate more efficient radicals towards the addition to double bonds was tentatively achieved in the Ru complex/amine (ethyl diaminoethylbenzoate)/chlorosilane (e.g.,...
Scheme 13: Reaction mechanisms for the Violanthrone/Ru(ligand)$_3^{2+}$/Ph$_2$I$^+$/R$_3$SiH system upon visible lights.

(TMS)$_3$SiCl system (see Scheme 12 and change R-Br and MDEA for (TMS)$_3$SiCl and EDB, respectively); the performance in FRP remains unfortunately rather low [56]. Despite the presence of aminoalkyl and silyl initiating radicals (known as very reactive radicals towards the addition process onto acrylate double bond [65]), a lower reactivity of (TMS)$_3$SiCl towards PIC$^-$ or/and a lower ability of the (TMS)$_3$SiCl$^-$ radical anion to decompose into a silyl radical and a chlorine anion likely play a detrimental role. Bromosilanes might be considered but they are not easily accessible.

Works using metal-free PIC proceeding through a reduction cycle have been recently achieved in FRP for the first time [54,55]: they involve hydrocarbon derivatives (e.g., pyrene, naphtacene, pentacene), an amine (e.g., ethyl dimethylaminobenzoate) and an alkyl halide (e.g., phenacyl bromide); the mechanism is similar to that shown in Scheme 12. As above, a tunable absorption of the system is achieved by carefully selecting the hydrocarbon (the system is sensitive to lights ranging from 300 to 670 nm) [54,55]. Other colored PICs might be dyes (as suggested in experiments for organic synthesis purposes [54-56]) but preliminary experiments using common dyes such as Eosin suggest that their behavior as PICs is not straightforward. The redox processes with organic dyes are not always fully reversible: this plays a detrimental role in the catalytic cycle with a lost of the efficiency through a PIC degradation.

A striking example concerns the use of a Ru complex (Ru(bpy)$_3^{2+}$) as PIC which is reduced here into Ru(bpy)$_3^+$ although as shown above, it usually works through an oxidation cycle [61,62]. A violanthrone derivative (violanthrone-79) is employed as eD and Ph$_2$I$^+$ as B-Y$^+$ (see Scheme 5); TTMSS is added. This multicomponent system works according to the detailed Scheme 12. A phenyl radical is produced from B-Y$^+$ (= Ph$_2$I$^+$). As shown before, the silane ensures the formation of R$_3$Si$^-$ and R$_3$Si$^+$ (Scheme 13), respectively [45-52]. This is presumably the most famous example so far for the generation of an initiating cation under a green laser line at 532 nm; the photosensitivity is extremely high.

A more complicated situation has also been found in some PIC/amine/alkyl halide system where both a reduction and an oxidation cycle simultaneously operate, e.g., in Michler’s ketone derivative MK/amine AH (e.g., MDEA)/chlorotriazine Tz-Cl (Scheme 14) [66].

All these reactions allowed the radical photopolymerization of formulations containing multifunctional synthetic acrylates using UV to red lights delivered by low intensity sources.
A new PIC based on a panchromatic iridium complex and the associated performance in the photopolymerization area

There is still a need for the development of new PICs with i) improved light absorption properties and ii) high reactivity. These new PICs can be highly worthwhile for the use of very soft irradiation conditions. For example, the actual Ir and Ru-based PICs are mainly characterized by a blue light absorption and are operative in the 400–480 nm spectral range, i.e., the well-known and commercially available Ir derivative Ir(ppy)$_3$ (tris[2-phenylpyridinato-C$^2$,N]iridium(III)) is characterized by an intense absorption at 370 nm and exhibits an only moderate absorption at $\lambda > 400$ nm. Among others, the design of green light sensitive Ir complexes is an interesting challenge. This is the reason why the new Ir based PIC (bis(1-phenylisoquinolinato-N,C$^2$)iridium(2,2,6,6-tetramethyl-3,5-heptanedionate) noted Ir(piq)$_2$ (tmd); Figure 5), already synthesized in [67] but never used as PIC in photoinitiating systems is presented here.

Indeed, the visible light absorption properties of Ir(piq)$_2$(tmd) are much better than those of Ir(ppy)$_3$ (Figure 6). Remarkably, Ir(piq)$_2$(tmd) is perfectly adapted for applications under green light exposure (LED bulb at 514 nm or a laser diode at 532 nm) and exhibits an almost panchromatic behavior in the 400–650 nm range.

The PIC/Ph$_2$I$^+/NVK$ system

The photochemical properties of Ir(piq)$_2$(tmd)

A triplet-state lifetime of 1.1 $\mu$s has been determined for Ir(piq)$_2$(tmd) by laser flash photolysis experiments. A relatively similar lifetime (1.3 $\mu$s) was previously measured for $^3$Ir(ppy)$_3$ [68]. Such long lifetimes for triplet states are important in photoredox catalysis to ensure an efficient quenching by the oxidation agents.

Ir(piq)$_2$(tmd) is characterized by an oxidation potential of 0.67 V vs SCE (Figure 7A); its triplet-state energy level ($E_T \sim 2.07$ eV) was determined from absorption/luminescence experiments (Figure 7B). From these data, a favorable $^3$Ir(piq)$_2$(tmd)/Ph$_2$I$^+$ oxidation process can be expected, i.e., the free energy change $\Delta G$ for the corresponding electron transfer is
negative ($\Delta G = -1.2$ eV) as calculated from the classical Rehm–Weller $\Delta G = E_{\text{ox}} - E_{\text{red}} - E_T + C$ where $E_{\text{ox}}$, $E_{\text{red}}$, $E_T$ and $C$ are the oxidation potential of Ir(piq)$_2$(tmd), the reduction potential of Ph$_2$I$^+$, the excited triplet state energy of Ir(piq)$_2$(tmd), and the electrostatic interaction energy for the initially formed ion pair, generally considered as negligible in polar solvents) [69].

This favorable $^3$PIC/Ph$_2$I$^+$ interaction is also in line with a fast photolysis of the PIC observed during the irradiation of Ir(piq)$_2$(tmd)/Ph$_2$I$^+$ (Figure 8). In ESR spin-trapping experiments on irradiated Ir(piq)$_2$(tmd)/Ph$_2$I$^+$ in the presence of phenyl-N-tert-butyl nitroxide (PBN), phenyl radicals are also detected (Figure 9). In the presence of NVK, the formation of Ph-NVK is also observed (the PBN radical adducts are characterized by $a_N = 14.4$ G and $a_H = 2.5$ G, in agreement with previous data [45-52]). All these results are fully consistent with the Scheme 8 presented above. Therefore, Ir(piq)$_2$(tmd) can be used in an oxidative cycle in combination with Ph$_2$I$^+$ and NVK.

The polymerization initiating ability of the Ir(piq)$_2$(tmd)/Ph$_2$I$^+/NVK system

The polymerization profile for the ring-opening polymerization of EPOX using a Ir(piq)$_2$(tmd)/Ph$_2$I$^+/NVK initiating system upon a laser diode at 532 nm is depicted in Figure 10A (it was obtained by a classical procedure already presented in [68]). An excellent polymerization is obtained (~60% of conversion for 700 s of irradiation; tack-free coating); on the opposite, in the same conditions, Ir(ppy)$_3$/Ph$_2$I$^+/NVK leads to a low conversion (<20%) in full agreement with the low absorption of Ir(ppy)$_3$ under green lights (see Figure 6). Remarkably, the consumption of the NVK double bonds, followed in the course of the polymerization (see the conversion of NVK in Figure 10B), is in agreement with the mechanism presented in Scheme 8. These results show the interest of developing new PICs with improved or extended light absorption properties.
The PIC/MDEA/alkyl halide
The performance of the new proposed PIC for a reductive cycle in combination with an amine (MDEA) and an alkyl halide (phenacyl bromide; R–Br) to initiate a radical polymerization has been also checked. In full agreement with Scheme 11, the presence of three components is required. Indeed, Ir(piq)2(tmd)/MDEA/R–Br is very efficient (Figure 11, curve 2) compared to Ir(piq)2(tmd)/MDEA (Figure 11, curve 1).

![Figure 11: (A) Photopolymerization profile of TMPTA; initiating systems: (1) Ir(piq)2(tmd)/MDEA (1%/2%) and (2) Ir(piq)2(tmd)/MDEA/R–Br (1%/2%/3%); laser diode at 532 nm; in laminate.](image)

**Conclusion**
Photoinitiator catalysts PICs appear as a new class of initiating systems usable in different photopolymerization reactions: FRP, CP and FRPCP. The associated systems are characterized by an outstanding photosensitivity; the catalytic pathways ensure a regeneration of the PIC and avoid any lost of reactivity upon irradiation. A bleaching of the sensitizer can be observed in excess of oxidation or reduction agent. In this case the polymerization of thick samples can be carried out. With this bleaching, colorless coatings can also be obtained. The search for new PICs and/or new redox agents might be of high interest as depicted by the present proposal of a new PIC (Ir(piq)2(tmd)). This allows the design of multicomponent photoinitiating systems based on an excellent Ir complex working at λ > 500 nm, a goal that was never achieved before using other available Ir derivatives (e.g., the well known Ir(ppy)3). The development of new catalytic methodologies still remains a huge challenge.

**References**
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Visible-light-induced, Ir-catalyzed reactions of
N-methyl-N-((trimethylsilyl)methyl)aniline with cyclic
α,β-unsaturated carbonyl compounds

Dominik Lenhart and Thorsten Bach*

Abstract
N-Methyl-N-((trimethylsilyl)methyl)aniline was employed as reagent in visible-light-induced, iridium-catalyzed addition reactions to cyclic α,β-unsaturated carbonyl compounds. Typical reaction conditions included the use of one equivalent of the reaction substrate, 1.5 equivalents of the aniline and 2.5 mol % (in MeOH) or 1.0 mol % (in CH₂Cl₂) [Ir(ppy)₂(dtbbpy)]BF₄ as the catalyst. Two major reaction products were obtained in combined yields of 30–67%. One product resulted from aminomethyl radical addition, the other product was a tricyclic compound, which is likely formed by attack of the intermediately formed α-carbonyl radical at the phenyl ring. For five-membered α,β-unsaturated lactone and lactam substrates, the latter products were the only products isolated. For the six-membered lactones and lactams and for cyclopentenone the simple addition products prevailed.

Introduction
The photoinduced electron transfer (PET) of an amine to an excited oxidant followed by the loss of a cationic leaving group allows accessing a broad variety of α-aminoalkyl radicals [1-4]. As first shown by Mariano et al. [5,6] and by Pandey et al. [7] a trimethylsilyl (TMS) group is a suitable electrophilic leaving group for this purpose and addition reactions of α-aminoalkyl radicals to double bonds can be induced by irradiation of α-silylated amines in the presence of sensitizers such as 1,4-dicyanobenzene or 1,9-dicyanoanthracene. Addition reactions of this type have been broadly used for the formation of carbon–carbon bonds [8-22]. In non-silylated tertiary amines, a proton can act as a leaving group and photoinduced addition reactions of tertiary amines to enones are long known [23-28]. Mechanistically, addition reactions of this type can occur as a radical chain reaction because the addition product of the α-aminoalkyl radical is a carbon-centered radical, which can abstract a hydrogen atom from the tertiary amine [29,30]. Notable contributions to the field of direct tertiary amine addi-
tion reactions to enones were made by Hoffmann et al., who established the use of aromatic ketones as suitable PET catalysts for these reactions [31-37]. In Scheme 1, the addition reaction of N,N-dimethylaniline (1) to (5R)-methoxyfuran-2(5H)-one (2) is shown, which proceeds to the intriguing tricyclic product 4 employing 4,4′-bis(dimethylamino)benzophenone (3) as the catalyst [38]. In this case, the amine was used in large excess (15 equiv) and the chiral menthyl group was derived from (−)-menthol. It was later found that the reaction proceeds with a higher yield (73%) if acetone was employed as a co-solvent [39] and that the diastereoselectivity depends both on the stereogenic center at C5 and on the chirality of the menthyl (Men) backbone [40].

Results and Discussion
Addition to cyclic α,β-unsaturated lactones

Our work commenced with attempted addition reactions to the parent furan-2(5H)-one (9) and was conducted with a set of eight visible light lamps (Osram L 8W/640 cool white) [48]. A screen of potential catalysts (see Supporting Information File 2 for further details) in CH2Cl2 as the solvent (c = 0.1 M) revealed that [Ir(ppy)2(bpy)]BF4 (ppy = phenylpyridine; bpy = 2,2′-bipyridine) and [Ir(ppy)2(dbppy)]BF4 (dbppy = 4,4′-di-tert-butyl-2,2′-bipyridine) gave the best results while other iridium catalysts turned out to be inferior. Remarkably, the desired tricyclic product 10 was isolated as the only product while the direct addition product 11 was not observed. Contrary to that, the ruthenium catalyst Ru(bpy)3Cl2 delivered a mixture of both products in a ratio of 77/23. Apart from CH2Cl2, other solvents were tested (see Supporting Information File 2), none of which led to a significant yield improvement. It was observed, however, that the desired reaction was faster in polar solvents such as DMF, DMSO and MeOH. The reaction went to completion in four to five hours while 24 hours were required to reach full conversion in CH2Cl2. The direct addition product was detected as a side product both in DMF (10/11 = 71/29) and in DMSO (82/18). In MeOH, however, only the tricyclic product 10 was formed. A slight yield improvement was observed when raising the catalyst loading in the latter case from 1 mol % to 2.5 mol % while a decrease of the catalyst concentration led to lower yields. The results of the reactions under optimized conditions are provided for CH2Cl2 and MeOH as the solvent (c = 0.1 M) for further details) in CH2Cl2 as the solvent (c = 0.1 M) for further details). In CH2Cl2, DMSO, and MeOH, the results were similar. In DMSO (82/18). In MeOH, however, only the tricyclic product 10 was formed. A slight yield improvement was observed when raising the catalyst loading in the latter case from 1 mol % to 2.5 mol % while a decrease of the catalyst concentration led to lower yields. The results of the reactions under optimized conditions are provided for CH2Cl2 and MeOH as the solvent (c = 0.1 M) for further details). In CH2Cl2, DMSO, and MeOH, the results were similar.

In more recent work [41,42], Nishibayashi et al. showed that iridium complexes can serve as efficient PET catalysts for the addition of α-aminomethyl radicals [43-45] to enones. N-Methyl-N-(trimethylsilyl)methylaniline (5) for example served as substrate for the alkylation of 2-cyclohexenone (6) employing iridium catalyst 7. When using the amine as the limiting reagent and an excess of enone (1.5 equiv) product 8 was obtained in 70% yield.

Based on our interest in photochemically induced addition reactions of α-aminoalkyl radicals [46,47], the potential of iridium catalysis attracted our interest and we wondered whether it would be possible to apply the title compound, N-methyl-N-((trimethylsilyl)methylaniline (5), in addition reactions to other cyclic α,β-unsaturated carbonyl compounds. In particular, we were interested to see whether cyclization reactions as for product 4 would be observed when using α,β-unsaturated lactones and lactams in combination with a silylated amine and an iridium catalyst. In this article, we provide full details of our studies in this field. Seven different substrates were tested as limiting reagents in the addition reactions and the structure of the respective products was elucidated.

Scheme 1: PET-catalyzed addition of N,N-dimethylaniline (1) to furan-2(5H)-one 2 [38] and of N-methyl-N-((trimethylsilyl)methylaniline (5) to 2-cyclohexenone (6) [41].
Scheme 2: Ir-catalyzed formation of tricyclic product 10 by a domino radical addition reaction to α,β-unsaturated lactone 9.

Scheme 3: Ir-catalyzed addition reactions of N-methyl-N-((trimethylsilyl)methyl)aniline (5) to 5,6-dihydro-2H-pyran-2-one (12).

Scheme 4: Ir-catalyzed addition reactions of N-methyl-N-((trimethylsilyl)methyl)aniline (5) to 2-cyclopentenone (15).

Addition to cyclic α,β-unsaturated ketones

Based on the results obtained with five-membered lactone 9, it was surprising to note that the related five-membered enone, 2-cyclopentenone (15), delivered mainly the direct addition product 17 instead of the tricyclic product 16. The reactions (Scheme 4) went to completion within 24 hours (in CH₂Cl₂) and 4.5 hours (in MeOH). As for compounds 13 and 14, a complete separation of the two products was not feasible by column chromatography. A mixture of 16 and 17 was obtained, which was free of impurities and in which the relative ratio of products could be established by ¹H NMR spectroscopy. From a preparative point of view, the result of the reaction in MeOH was more satisfactory because it delivered a combined yield of 67% for both addition products. The relative configuration of compound 16 is tentatively assigned as cis due to the coupling constant between the depicted (Scheme 4) protons (3JHH = 7.0 Hz). The coupling constant is similar to the coupling constant for the known annulated cis-product 10 and is
in agreement with coupling constants recorded for protons in related tricyclic compounds [50,51].

Replacing 2-cyclopentenone (15) by 2-cyclohexenone (6) led to the above-mentioned direct addition product 8 (Scheme 1), as previously reported by Nishibayashi et al. [41]. The yield we obtained when using the ketone as the limiting reagent and 1.5 equiv of the amine was 65%. There was no indication for the formation of a tricyclic product.

### Addition to cyclic α,β-unsaturated lactams

Lactams offer the possibility of reactivity tuning by choosing an appropriate protecting group at the nitrogen atom. Since initial experiments with unprotected pyrrolin-2-one were not promising the respective tert-butyloxycarbonyl (Boc) and 4-toluenesulfonyl (Ts) derivatives 18a and 18b were prepared [52]. In CH2Cl2 as the solvent, the attempted addition reaction of N-methyl-N-((trimethylsilyl)methyl)aniline (5) turned out to be sluggish. With substrate 18a, product 19a was isolated in 23% yield after an irradiation time of 24 hours employing 1 mol % of catalyst 7. With substrate 18b the conversion was 64% after 24 hours at an increased catalyst loading of 2.5 mol %. Compound 19b was isolated in 36% yield (56% based on conversion). Somewhat better results were recorded in MeOH as the solvent (Scheme 5). Irrespective of the protective group, the reaction was complete within six hours and delivered exclusively the tricyclic products 19. The Boc-protected product 19a was obtained in only 30% yield, however; the result indicates that the Boc protecting group is not ideal for reactions in MeOH as the solvent (vide infra). A higher yield (49%) was recorded for the Ts-protected product 19b. The two protons at the ring junction show a similar coupling constant ($3J = 8.1$ Hz for 19a, $3J = 7.9$ Hz for 19b) as the protons in the related lactone 10 suggesting a *cis*-annulation of the two heterocyclic rings.

The instability of Boc-substituted lactams upon irradiation in MeOH solution was also notable in attempted reactions of substrate 20 [53]. With a catalyst loading of 2.5 mol %, the combined yield (10%) of addition products 21 and 22 was disappointingly low at a conversion of 62% after seven hours. The reaction in CH2Cl2 proceeded more smoothly and delivered after an irradiation time of 24 hours the two products 21 and 22 in a combined yield of 44% (Scheme 6). There was no yield improvement if the catalyst loading was increased to 2.5 mol %.

With an excess of α,β-unsaturated lactam 20, the reaction turned out to proceed with higher type selectivity. The domino process was suppressed and the plain addition product 22 was obtained in 75% yield (Scheme 7).

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**Scheme 5:** Ir-catalyzed formation of tricyclic products 19 by a domino radical addition reaction to α,β-unsaturated lactams 18.

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**Scheme 6:** Ir-catalyzed addition reactions of N-methyl-N-((trimethylsilyl)methyl)aniline (5) to α,β-unsaturated lactam 20.

**Scheme 7:** Ir-catalyzed addition reactions of N-methyl-N-((trimethylsilyl)methyl)aniline (5) to α,β-unsaturated lactam 20 with the aniline being the limiting substrate.
The latter result suggested that the previously discussed (Scheme 3) addition reaction to 5,6-dihydro-2H-pyran-2-one (12) might also lead to a single product if performed with the aniline as the limiting agent. To our surprise, however, the relative product ratio remained unchanged when the substrate ratio 5/12 = 1.5/1 was decreased to 1/1.5.

Mechanistically, it is likely that the well-established photoredox cascade between aniline 5 and the photoexcited iridium complex 7 operates [54-58]. Oxidation of the aniline and loss of the trimethylsilyl group leads to an α-aminomethyl radical, which adds to the cyclic α,β-unsaturated carbonyl compound (Scheme 8). The intermediate radical A can undergo immediate reduction presumably by concomitant oxidation of the previously reduced iridium complex (path a), which provides the simple addition products (e.g., 14, 17, 22) [41,42], or it attacks (path b) the adjacent phenyl group to form radical B. The further fate of radical B is likely an oxidation to the tricyclic products (e.g., 10, 19). Upon hydrogen transfer the α,β-unsaturated carbonyl compound would give a cyclic α-acyl radical, which would be capable to re-oxidize the reduced iridium complex thus completing the catalytic cycle. However, we have not been able to substantiate the latter hypothesis, e.g., by isolation of a saturated carbonyl compound.

Interestingly, we did not find a hint for a radical chain pathway, which would include hydrogen abstraction from the starting aniline 5 by intermediate A. The resulting radical would carry a trimethylsilyl group, which would be eventually found in the product. The absence of a trimethylsilyl group in the products indicates that reduction (path a) and cyclization (path b) are more efficient than hydrogen abstraction while hydrogen abstraction has been established as a radical chain propagating step in reactions performed with UV light [5,6,8,11,32,38-40].

**Conclusion**

In summary, it was shown that a photochemical generated aminomethyl radical – produced from N-methyl-N-((trimethylsilyl)methyl)aniline – adds readily not only to the previously reported cyclohexenone but to several cyclic α,β-unsaturated carbonyl compounds. Further reaction of the intermediate α-carbonyl radical was observed with five-membered substrates leading to synthetically interesting tricyclic products. The latter reaction suffers from the fact that oxidation of the putative intermediate B is required, which seems to occur at the expense of the substrate. If a suitable compound was found to adapt the role of an ancillary oxidant, yields could possibly be improved.

**Supporting Information**

**Supporting Information File 1**

Experimental section. [http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-86-S1.pdf](http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-86-S1.pdf)

**Supporting Information File 2**

Tables of all optimization experiments and copies of 1H/13C spectra of PET catalysis products. [http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-86-S2.pdf](http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-86-S2.pdf)

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**References**


![Scheme 8: Cyclization of putative radical A to intermediate B competes with reduction of A to form addition products, such as 14, 17, 22.](http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-86-S1.pdf)
Tailoring of organic dyes with oxidoreductive compounds to obtain photocyclic radical generator systems exhibiting photocatalytic behavior

Christian Ley*, Julien Christmann, Ahmad Ibrahim, Luciano H. Di Stefano and Xavier Allonas

Abstract

The combination of a dye which absorbs the photon, an electron acceptor and an electron donor leading to energy conversion through electron transfer, was the basis of the so called three-component systems. In this paper, an experimental work combining Rose bengal dye with a triazine derivative as electron acceptor and ethyl 4-(dimethylamino)benzoate as electron donor, will underline the benefit of the photocyclic behavior of three-component systems leading to the dye regeneration. A thermodynamic approach of the photocycle is presented, followed by a mechanistic and computational study of ideal photocycles, in order to outline the specific kinetics occurring in so called photocatalytic systems. The simple kinetic model used is enough to outline the benefit of the cyclic system and to give the basic requirements in term of chemical combination needed to be fulfilled in order to obtain a photocatalytic behavior.

Introduction

Among the possible usage of light, the conversion of photons into chemical energy, as stored into radicals or ions, is of great interest. As a part of this research area, the development of photoradical generators (PRG) is still a lively topic that finds applications in triggering bioactivity [1], drug or fragrance release [2-4], microelectronics [5], water catalysis reduction [6-8], and laser imaging [9]. In organic chemistry, the development of new methods for organic synthesis was achieved by use of photolabile protective groups, which could be released under irradiation by light [10,11]. Since many decades in industry, PRG are used in photopolymerization, a field in which the PRG prompt the initiation of the polymerization through a chain
reaction [12]. Photopolymerization was first used over 4000 years ago in the mummification process [13]. During the last decades the number of commercial applications is still continuously increasing. By example, photopolymer applications are found in electronic materials [14], printing materials [15], optical and electro-optical materials [16,17], fabrication of devices and materials [18], adhesives and sealants [19], coatings [20] and surface modifications [21,22].

The great interest in PRG application to free radical polymerization (FRP) has led to the development of two major classes of photoinitiating systems (PIS): Type I and Type II. In Type I PIS, the excited states reached after light absorption undergo a cleavage leading to the production of two initiating radicals [5,23,24]. However, most Type I PIS are only active under UV–blue irradiation [25,26]. To overcome this spectral limitation, Type II PIS were developed. They contain the photosensitizer (PS) which absorbs the light and a coinitiator (Co) which reacts with PS excited states through hydrogen abstraction or electron transfer reaction (see Scheme 1). Numerous dyes were reported as PS [9,27-32]. Hydrogen donor coinitiators could be amines [39,40], ethers [41-43] or thiols [43-45]. Electron transfer coinitiators could be borate salts [46,47], iodonium [48,49] or triazine [32] derivatives. However, if Type II PIS gain sensitivity in the visible part of the electromagnetic spectrum, their efficiency is lower than Type I PIS. To gain more reactivity the so-called three component systems (3-cpt) were developed by adding a redox additive to Type II systems [32,50-52]. A higher yield of initiating radicals is generally claimed in such cases. Moreover, the dye is recovered during the process and is newly available to absorb light, running into a new cycle [9,32]. These photocyclic initiating systems (PCIS), should then present a somehow constant absorbance, leading to constant and efficient absorption of the incident photons. Both features are responsible for the higher efficiency of PCIS [9,31,53-55] in photopolymerization reactions. Therefore, as the dye is regenerated during the photochemical reaction, a catalytic behavior appears, leading to the so-called photocatalytic system.

In this paper an experimental and mechanistic study of Type II PIS will be given and compared with a PCIS. Then, in order to improve the knowledge of PCIS, a thermodynamic and mechanistic approach of PCIS exhibiting an ideal photocatalytic behavior will be presented. The proposed scheme will be used as model to run some computation. This will permit to compare and discuss the advantages, the specificity of this kind of photocyclic systems and outline the important features and conditions which have to be fulfilled in order to obtain high performances for this kind of photocatalytic systems. This ideal approach will permit a better general understanding of the complex kinetics underlying PCIS chemical reactions, allowing a better and simplest selection of chemicals combination.

Results and Discussion

In order to outline this behavior, the photochemical consumption of the dye (i.e., photolysis) was studied in a typical Type II and a 3-cpt PCIS based on the Rose Bengal as dye, and a triazine derivative (TA) as an acceptor (coinitiator). In addition, an amine (ethyl 4-(dimethylamino)benzoate, EDB) was chosen as redox (electron donor) additive for the PCIS (see Scheme 1).

Type II photoinitiating system

In Scheme 2, the typical reaction mechanism of a dye (PS) with an electron acceptor (A) is depicted. After absorption of actinic light (hv), the PS reaches its singlet excited state (1PS*) and after intersystem crossing (kISC), its triplet excited state (3PS*). From both these excited states, an electron transfer can occur from the PS to A (with quenching rate constants 1kq/A and 3kq/A, respectively). The oxidized form of the dye (PS+*) is formed together with the reduced acceptor (A−) which lead to initiating radicals [33,48,49].

As a consequence, the PS is consumed (i.e., photolyzed or bleached) during the photoinduced electron transfer reaction. Thus, according to Beer–Lambert’s law, the absorbance of the system decreases during the reaction: this bleaching could be followed by UV–visible absorption spectroscopy.

Scheme 1: Chemical structures of RB, EDB and TA.
The photolysis of an acetonitrile solution of RB/TA was done within a 1 cm width cell with a monochromatic 532 nm laser diode tuned to 9 mW/cm² intensity. This will correspond to the 9 mW/cm³ computation condition (vide infra). The initial concentration was \([\text{RB}]_0 = 6.5 \times 10^{-5} \text{ mol·L}^{-1}\) (with \(\varepsilon = 31900 \text{ M}^{-1} \cdot \text{cm}^{-1}\) and a length of \(l = 1 \text{ cm}\), this corresponds to an initial absorbance of around 0.2 at 532 nm) and \([\text{TA}]_0 = 10^{-3} \text{ mol·L}^{-1}\). The transmitted laser diode light was real-time recorded. It is thus possible to calculate the optical density \(A(t)\) of the sample, which is then converted into \([\text{RB}]_t\). It can be seen from Figure 1 that a fast decrease of \([\text{RB}]_t\) occurs, so fast that the very beginning is not resolved by the detector. This indicates that the dye is consumed during irradiation, due to the electron transfer to TA. In about 100 s, the absorbance is almost zero indicating a complete consumption of the dye. As a consequence, the absorption spectrum completely vanishes after 5 min of irradiation, confirming the disappearance of the dye (see insert Figure 1). It should be noted that in the same conditions, no photolysis occurs for an acetonitrile solution of neat RB.

To quantify the consumption of the PS, the photolysis quantum yield \((\Phi_{\text{photolysis}})\) was determined. \(\Phi_{\text{photolysis}}\) is defined by the ratio of the initial number of photosensitizer (PS) molecules present \((N_{\text{PS}})\) to the total number of absorbed photons \((N_{\text{abs}})\). It could be expressed by the following equation:

\[
\Phi_{\text{photolysis}} = \frac{N_{\text{PS}}}{N_{\text{abs}}} = \frac{V \cdot [\text{PS}]_0}{V \cdot \int_{0}^{t} \frac{\text{d}A}{\text{d}t} \text{d}t} = \frac{[\text{PS}]_0}{\int_{0}^{t} \frac{\text{d}A}{\text{d}t} \text{d}t}
\]  

(1)

where \(V\) is the volume of the irradiated solution. The absorbed photon concentration is given by:

\[
\int_{0}^{t} \frac{\text{d}A}{\text{d}t} \text{d}t = I_0 \left(1 - 10^{-\alpha(t)}\right) \text{d}t
\]

(2)

where \(I_0\) is the incident light intensity on the cell (9 mW·cm⁻³, i.e., \(4 \times 10^{-5} \text{ einstein·s}^{-1} \cdot \text{cm}^{-3}\)). The experimental measure of the absorbance \(A(t)\) allows the calculation of \(I_{\text{abs}}(t)\) and a numerical integration. Accordingly, the total concentration of absorbed photon is calculated as \(3.43 \times 10^{-4} \text{ mol·L}^{-1}\) for RB/TA. It should be noted here that the missing first 1 second of the fast decay of \(A(t)\) will represent, at maximum, \(1.47 \times 10^{-5} \text{ mol·L}^{-1}\) of absorbed photons (by assuming a constant \(A(t) = 0.2\) during this 1 s). This overestimation represents less than 5% of the total absorbed photons and could be neglected. Then, dividing the initial RB concentration by these values, a photolysis quantum yield of 0.19 for RB/TA is obtained.

**Photocyclic initiating system**

A typical photocyclic initiating system (PCIS) consists of a light absorbing dye (PS), an electron acceptor (A) and an electron donor (D) (Scheme 3). In such systems, upon irradiation phoatoinduced electron transfer reaction between the dye and one of the components, for example A in Scheme 3, gives rise to a radical anion (A⁻) and the oxidized PS (PS•⁺). Then, PS•⁺ can react with the electron donor D (\(k_{\text{red}}\)) to regenerate the PS ground state (photocyclic reaction), leading to the formation of one radical cation D⁺⁺. Generally, A⁻ and D⁺⁺ will give rise to initiating radicals for free radical polymerization, to hydrogen by water reduction or oxygen by water oxidation [6-8], etc. In an ideal case, a photocatalytic behavior is ensured when there is enough redox donor to make the dye surviving during a long period of time. It will be shown below that this behavior has great advantages; the most immediate is the fact that the absorbance of the PCIS is kept constant.

In order to exemplify the behavior of the photocycle involving the dye, the acceptor and the donor, the absorbance of a RB/TA/EDB solution was monitored during irradiation as for the Type II PIS. EDB was chosen as electron donor for the PCIS.
because its reactivity toward $^{3}$PS is low compared to that of TA (vide infra). This ensures that $^{3}$PS will react mainly with TA in an oxidative cycle as proposed in Scheme 3. The solution was irradiated with the same laser diode and same output power. The same initial concentration of RB and TA was realized, and $[EDB]_0$ was fixed to $10^{-3}$ mol·L$^{-1}$. The experimental evolution of the $[RB(t)]$ could be seen on Figure 2.

Compared to the Type II PIS, the behavior is quite different: the absorbance decreases very slowly at the beginning of the process, being almost constant for a couple of seconds. Then, the absorbance slowly decreases due to an increase of the photolysis rate with irradiation time. After 250 seconds, the residual absorbance is zero: in the photocyclic system, the time required for complete consumption of the dye is two times longer than in Type II PIS. This confirms the dye regeneration within a photocycle exhibiting a photocatalytic behavior.

The longer experimental surviving time of RB in the PCIS is in qualitative agreement with the proposed schemes. To quantify the cyclic behavior and to compare clearly Type II and PCIS, the quantum yield of dye photolysis ($\Phi_{photolysis}$) was also determined for RB/TA/EDB. The total concentration of absorbed photons for the PCIS is 0.0139 mol·L$^{-1}$. Dividing the initial RB concentration by this value leads to a photolysis quantum yield of $4.7 \times 10^{-3}$. This extremely low photolysis quantum yield obtained for the PCIS means that more than 210 photons are needed to bleach one dye molecule. The turnover number becomes very high for the PCIS while for the Type II system, only 5 photons are needed to bleach RB. This clearly demonstrates the cyclic regeneration of the dye in the selected three-component combination presented here. As a conclusion, these experimental results clearly confirm the photocyclic behavior of the selected 3-cpt system RB/TA/EDB. However, to get more insight and to understand the benefits of this process, a better understanding of the thermodynamics and the kinetics is necessary.

### Thermodynamics of the PCIS

Obviously, every mixture of an acceptor, a donor and a dye, would not give rise to a photocatalytic behavior. The components should be selected with care in order to get a cyclic behavior instead of competitive parallel reactions [54] where A and D compete to react with the PS excited states. Thus, a thermodynamic approach of the PCIS should help the selection of the candidates. Scheme 4 represents the different electron transfer reaction occurring in the oxidative PCIS according to the mechanism given in Scheme 3.

The first reaction is the electron transfer reaction between the dye ground state and the coinitiator. Its reactivity is governed by the corresponding Gibbs free energy change $\Delta G_{ET}^{GS} = E_{ox}^{PS} - E_{red}^{A}$ where $E_{ox}$ and $E_{red}$ are the half-wave oxidation and reduction potentials for the donor and the acceptor, respectively. $\Delta G_{ET}^{GS}$ must be as high as possible to prevent any dark reaction.

After absorption of light the PS goes into singlet or triplet excited states, in which it becomes both more oxidant and more reducer. As a consequence, electron transfer reaction can occur with the acceptor A (Scheme 3). The reaction must be as much exergonic as possible. The values of the Gibbs free energy...
Scheme 4: Thermodynamics of an oxidative three components PCIS, a) ground state reaction (Δ\(G^0_{ET}\)), b) excited state reaction (Δ\(G^*_{ET}\)), c) back electron transfer (BET, Δ\(G_{BET}\)), d) PS regeneration (Δ\(G_{PS}^{PP*}\)).

Change Δ\(G^*_{ET}\) for photoinduced electron transfer is given by the Rehm–Weller equation [56]: Δ\(G^*_{ET}\) = \(E_{ox}^D - E_{red}^A - E^* + C\), where \(E^*\) stands for the energy of the excited state. The Coulombic term \(C\) is usually neglected in polar solvent. Δ\(G^*_{ET}\) will determine the rate of electron transfer and the dye and the electron acceptor must be chosen such that Δ\(G^*_{ET}\) is negative enough to obtain a high electron transfer rate constant.

The third electron transfer step is the unwanted back electron transfer BET within the contact ion pair (PS•+···A•−) which leads to initial reactants. This one is the more tricky to handle. Δ\(G_{BET}\) is given by −Δ\(G^{GS}_{ET}\) = \(E_{red}^A - E_{ox}^{PS}\). This reaction is generally quite exergonic and the rate compete with the dissociation rate \(k_{dis}\) of the contact ion pair into free solvated species. In practice BET reduce the overall radical generation quantum yields. Some new approaches allow to trigger this reaction [57,58].

The last important step is the dye regeneration. In order for the cycle and for the catalytic behavior to occur, the corresponding Gibbs free energy change Δ\(G_{PS}^{PP*}\) should be negative. If one assumes that the reduction potential of PS•+ is given by the oxidation potential of PS, then Δ\(G_{PS}^{PP*}\) = \(E_{ox}^D - E_{ox}^{PS}\). Thus, in order to achieve an efficient dye regeneration, the choice of the donor D should be carefully done to obtain an exergonic reduction of the oxidized PS.

This approach is also valid to a reductive catalytic cycle where the PS first reacts with the donor D, and then its reduced form is oxidized by the acceptor A. Table 1 summarizes the Gibbs free energy formula for estimation and the potential effect on the photocyclic behavior. The "Wanted values" row gives the values which must be obtained in order to get a possible photocyclic behavior of the selected components. The "Control" row summarizes the effect of the corresponding electron transfer on the PCIS final properties like shelf life, radical quantum yield and dye regeneration. One should also note that as Δ\(G_{BET}\) = −Δ\(G^{GS}_{ET}\) it is always negative even if a positive value is wanted.

Computational studies of PCIS
As seen before, there are four-electron transfer reactions to manage in order to get a working PCIS. Moreover the full mechanistic description becomes more complicate by taking into account that both the oxidative and reductive pathways can be in competition (see Scheme 5). In order to get more insights into the description and comprehension of PCIS, a complete simulation of the photocyclic behavior of RB/TA/EDB was
Table 1: Gibbs free energy of the different electron transfer reactions occurring in a three component PCIS.

<table>
<thead>
<tr>
<th>Gibbs free energy</th>
<th>Wanted values</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta G_{ET}^{GS} = E_{ox}^{PS} - E_{red}^{A} )</td>
<td>( &gt;0 )</td>
<td>Shelf life</td>
</tr>
<tr>
<td>( \Delta G_{ET}^{<em>} = E_{ox}^{PS} - E_{red}^{A} - E^{</em>} + C )</td>
<td>( &lt;0 )</td>
<td>Rate of electron transfer: radical quantum yields</td>
</tr>
<tr>
<td>( \Delta G_{BET} = E_{red}^{A} - E_{ox}^{PS} = -\Delta G_{ET}^{GS} )</td>
<td>( &gt;0 )</td>
<td>Control of back electron transfer: radical quantum yields</td>
</tr>
<tr>
<td>( \Delta G_{ET}^{PS^{*+}} = E_{ox}^{D} - E_{ox}^{PS} )</td>
<td>( &lt;0 )</td>
<td>Regeneration of the PS: photolysis quantum yield</td>
</tr>
</tbody>
</table>

Figure 3: Mechanistic description of photocyclic system involved in the RB/TA/EDB system. The rate constants are defined in the text.

Scheme 5: General photocatalytic cycle occurring in three components photocyclic systems. Two cycles are in competition: on the right side the first reaction occurs with the donor D defining the reductive pathway, while on the left side the primary reaction occurs with the acceptor A leading to the oxidative pathway.

The full kinetic description of the reactions occurring in the complete cycle is displayed in Figure 3, where \( I_{abs} \) is the number of absorbed photons per second; \( k_{des1}, k_{des3} \) are the rate constants of singlet and triplet state deactivation to the ground state, respectively; \( k_{ISC} \) the rate constant of the intersystem crossing from \( ^1PS \) to \( ^3PS; ^1k_{q/A}, ^3k_{q/A} \) the bimolecular electron transfer rate constant of the singlet and triplet excited state of the PS by the acceptor A (donor D), respectively; \( k_{red} \) and \( k_{ox} \) are the rate constants of reduction and oxidation of \( ^3PS^{*} \) and \( ^3PS^{*} \), respectively.

The time evolution of ground state \( ^0PS \), \( ^1PS \), \( ^3PS \) excited state, \( ^3PS^{*}, ^3PS^{*} \), D, A, \( ^3D^{*} \) and \( ^3A^{*} \) are given by the following equations:
Table 2: Thermodynamic and kinetic parameters of the PCIS simulation, \( k_q \): quenching rate constant of excited states.

<table>
<thead>
<tr>
<th>Quencher</th>
<th>( 0^{\text{RB}} )</th>
<th>( 1^{\text{RB}} )</th>
<th>( \Delta G_{\text{ET}} ) (eV)/( k_q ) (M(^{-1})·s(^{-1}))</th>
<th>( RB^{**} )</th>
<th>( RB^{*} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDB</td>
<td>2.07</td>
<td>-0.10/9.0 ( 10^8 )</td>
<td>0.27/4.5 ( 10^4 )</td>
<td>0.42/–</td>
<td>0.12/–</td>
</tr>
<tr>
<td>TA</td>
<td>1.77</td>
<td>-0.40/6.0 ( 10^9 )</td>
<td>-0.03/1.7 ( 10^7 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
which leads to:

\[ k_{\text{ISC}} = \frac{\frac{\Phi_0}{\tau_0}}{2.410^{-9}} \approx 3.410^8 \text{M}^{-1} \cdot \text{s}^{-1} \]

and to

\[ k_{\text{des}} = \frac{1}{\tau_0} - k_{\text{ISC}} = \frac{1}{2.410^{-9}} - 3.3810^8 \approx 7.910^7 \text{M}^{-1} \cdot \text{s}^{-1} \]

At this RB concentration, and in the absence of quencher, the triplet state lifetime was measured around 80 µs, leading to \( k_{\text{des}} = 1.25 \times 10^4 \text{M}^{-1} \cdot \text{s}^{-1} \). The following parameters were used to perform the computation: the continuous incident light intensity \( I_0 \) was fixed to 9 mW·cm\(^{-2}\) at 532 nm (i.e., \( 4 \times 10^{-5} \) einstein·L\(^{-1}\)·s\(^{-1}\)). The initial PS (i.e., RB) concentration was fixed to \([\text{RB}]_0 = 6.50 \times 10^{-6} \text{M}\), with \( \varepsilon = 31900 \text{M}^{-1} \cdot \text{cm}^{-1} \) and a cell length of 1 cm this corresponds to an absorbance of 0.2 at 532 nm, in line with the experiments. The initial concentration of the quenchers were fixed at \([\text{TA}]_0 = 10^{-2} \text{M}\) and \([\text{EDB}]_0 = 10^{-3} \text{M}\) for TA (acceptor A) and EDB (donor D).

**Photophysical cycle**

One must keep in mind that in PCIS, two cycles can occur: the photochemical one which involves the reaction of the dye excited states with chemical reactants, and an internal photophysical. This later is an energy waste, comprising the absorption of light, the deactivation by internal conversion and fluorescence of \( \text{PS} \) to the ground state \( \text{PS} \), the intersystem crossing to \( \text{PS} \), and the deactivation of the \( \text{PS} \) to \( \text{PS} \). In order to achieve high quantum yield for the conversion of the light energy, this photophysical cycle should be avoided as much as possible. This means that the excited states must live as long as possible, the quenching rate constants should be as high as possible (exergonic reaction with high \( k_{q,A} \) and \( k_{q,D} \)), and a high concentration of D and A should be used (high pseudo first order rate constants \( k_{q,A}[\text{A}] \) and \( k_{q,D}[\text{D}] \)). This will prevent the probability of natural excited state deactivation to be high.

**Simulation of Type II photoinitiating system**

The Type II system studied here contains only RB as photosensitizer and an electron acceptor TA (or donor EDB). Both RB/TA and RB/EDB systems were calculated. Figure 4 shows the changes in RB, RB\(^{\bullet+}\), TA, and TA\(^{-\bullet}\) concentrations for the former system.

Two important conclusions are to be outlined. First, the ground state of the dye is quickly bleached: in about 4 seconds it has completely disappeared. Second: the final TA\(^{-\bullet}\) concentration, i.e., the maximum number of initiating radicals produced is equal to the initial ground state RB concentration, i.e., \( 6.50 \times 10^{-6} \text{M}\). The final triazine concentration remains high because only \( 6.50 \times 10^{-6} \text{M} \) of TA have reacted with the dye RB. The same conclusion can be drawn for the RB/EDB computation but with slower rates due to lower reactivity (i.e., \( k_{q,D} \)). As a conclusion, in Type II PIS the limiting component for radical generation is the concentration of the dye.

**Simulation of photocyclic initiating system**

In the photocyclic system, the initial pseudo first-order reaction rates are equal to \( 3k_{q,A}[\text{TA}]_0 = 1.7 \times 10^5 \text{s}^{-1} \) for TA (acceptor A) and \( 3k_{q,D}[\text{EDB}]_0 = 4.5 \times 10^1 \text{s}^{-1} \) for EDB (donor D). This means that the oxidative photocycle preferentially occurs, at least until \( 3k_{q,A}[\text{TA}] > 3k_{q,D}[\text{EDB}] \). The plot of Log(\( 3k_{q,A}[\text{TA}] \)) and Log(\( 3k_{q,D}[\text{EDB}] \)) on Figure 5 show that it is the case for the first 310 sec of the reaction: during this period one can assume that the oxidative pathway is the main reaction.
The evolution of [RB], [TA] and [EDB] displayed on Figure 5 is also very interesting. Two major differences with Type II PIS should be outlined: first, the acceptor TA is totally consumed as its concentration falls to zero. Second, the ground state RB concentration, presents only a slight decrease during 200 s, i.e., as long as enough acceptor TA is present in the solution. This first part of the cycle should be explained by the reduction of the oxidized dye RB$^\text{•+}$, by EDB leading to a recovery of the dye. As soon as no more TA is available (around 250 s) [RB] lowers faster to zero. In this second part the photocatalytic system is reduced to a conventional Type II system, where the dye is consumed during its reaction with the excess of amine EDB. If the TA acceptor is completely consumed this is not the case for the amine present in excess, only one TA equivalent is lost during the first part of the cycle, and [EDB] reduces to 0.9·10$^{-2}$ M. During the second part of the reaction, a more tiny 6.5·10$^{-6}$ M is consumed (i.e. the initial RB concentration, cf. type II PIS) leading to a final EDB concentration of 8.9935·10$^{-3}$ M.

On Figure 6, the evolution of EDB$^\text{•+}$ and TA$^\text{•−}$ concentrations are displayed together with RB. In the first part of the cycle (before 300 s) both radical curves are similar. Then, as soon as TA is consumed, no more TA$^\text{•−}$ is produced and a final concentration of 1·10$^{-3}$ M is reached, i.e. the initial TA concentration. At this stage the EDB$^\text{•+}$ also reaches 1·10$^{-3}$ M. During this second part, the reaction of excess EBD with RB leads to a tiny more 6.5·10$^{-6}$ M for EDB$^\text{•+}$ and to the bleaching of the dye. Thus, the computed final total radical concentration is formally equal to 2.0065·10$^{-3}$ M.

It is worth emphasizing the important points and advantages of photocyclic systems:

1. the dye concentration is kept high for 250 s, this means that the absorbance of the solution is high, leading to a very high photon absorption of the solution during the first part of the cycle;
2. the final radical concentration is very high: 2.0065·10$^{-3}$ M i.e. 150 times the concentration obtained in Type II PIS;
3. the limiting component is no more the dye, but the co-initiator of lowest concentration, in the present case the acceptor TA.

All this phenomena explain the synergistic effect observed in some free radical polymerization.

### Radical and photolysis quantum yields

As for the Type II systems, in order to quantify the catalytic behavior of the dye, the quantum yield of dye photolysis ($\Phi_{\text{photolysis}}$) in PCIS was determined. The radical quantum yield is defined by the ratio of the number of produced radical to the total number of absorbed photons ($N_{\text{abs}}$). It could be expressed by the following equation:

$$\Phi_{\text{photolysis}} = \frac{N_{\text{rad}}}{N_{\text{abs}}} = \frac{V \cdot \left[ A^- + R^\text{•+} \right]}{V \cdot \int I_{\text{abs}} \, dt} = \frac{\int A^- + R^\text{•+}}{\int I_{\text{abs}} \, dt} \tag{4}$$

The calculated quantum yield for Type II RB/TA and photocyclic RB/TA/EDB are given in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>Type II RB/TA</th>
<th>PCIS RB/TA/EDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_{\text{photolysis}}$</td>
<td>0.475</td>
<td>1.55·10$^{-3}$</td>
</tr>
<tr>
<td>$\Phi_{\text{rad}}$</td>
<td>0.475</td>
<td>0.478</td>
</tr>
</tbody>
</table>

In Type II PIS both quantum yields are equal because the amount of radicals formed is equal to the amount of dye photolysed: as a consequence, only about two photons are needed to bleach one dye molecule, corresponding to a very low turnover number. Moreover we can see that the system has an average efficiency: according to $\Phi_{\text{rad}}$ one photon on two is lost for radical generation. For photocyclic system, the picture is somehow different: the photolysis quantum yield falls to 1.55·10$^{-3}$, meaning that more than 600 photons are needed to bleach one dye molecule: the turnover number becomes very high for the PCIS selected for the computation. However, if the photocatalytic behavior is very good, the radical quantum yield present an average value around 0.478, especially if one keep in
mind that it could rise up to two, theoretically. But this is in line
with the low rate constant of electron transfer of RB excited
singlet and triplet states: the wasting photophysical cycle is
comparatively too fast, preventing any efficient chemical
energy escape from the photophysical cycle

However one can see from the experimental results that the
consumption of the dye is longer than awaited for the Type II
PIS, while it is shorter for the photocatalytic system. This is
confirmed by comparing the experimental photolysis quantum
yields to the computed values: the experimental photolysis
quantum yield is higher and the turn over number of the real
photocatalytic system RB/TA/EDB is lower than expected,
while the opposite stands for RB/TA. This should be due to the
fact that the bleaching of the dye is not only a direct conse-
quence of the electron transfer reaction but could be due also to
secondary reactions between the radicals and the dye related
intermediates. As a consequence, the experimental efficiency of
the photocycle is lower than the simulated one. This is clear
from the shape of the two experimental curves where the
consumption of RB in RB/TA is initially fast and then decreases
slower while the opposite stands for the RB/TA/EDB: the
consumption increases due to an increase of radical in the solu-
tion.

Conclusion

In this paper experimental and full mechanistic studies of
Type II PIS and 3-cpt photocatalytic systems were presented
and compared. Some advantages that PCIS bear over classical
Type II systems are: dye regeneration with high possible
turnover (600), high radical production (>10^{-3} M). But these
studies also reveal the importance of component choice: great
care must be taken in order to build photocatalytic radical
generator by combination of three compounds. Especially a
simple thermodynamic approach should help to select the can-
didates as a starting point. If the present paper was focused on
PCIS application for free radical polymerization, it should
be noted that the same type of system bearing the same under-
lying kinetics and mechanisms are used in the field of photo-
catalytic water reduction.

Experimental

Redox potentials were measured by cyclic voltammetry using a
potentiostat (Princeton Applied Research 263A) at a scan rate
of 1 V/s in acetonitrile, with platinum as both working and
auxiliary electrodes, and a saturated calomel reference elec-
trode (KCl in methanol). Measurements were performed in
acetonitrile using 0.1 M of tetrabutylammonium hexafluoro-
phosphate (Aldrich) as supporting electrolyte. The samples
were bubbled with argon for 20 minutes prior to the analysis.
Ferroocene was used as standard [60].

Steady state UV–vis spectra were obtained on a Varian Cary
4000 UV–vis double beam spectrophotometer in 1 cm path
quartz UV grade cell.

Laser flash photolysis experiments (LFP) were carried out
exciting at 532 nm with a nanosecond Nd-YAG laser (Power-
lite 9010, Continuum), operating at 10 Hz. The transient absorp-
tion analysis system (LP900, Edinburgh Instruments) uses a
450 W pulsed Xe arc lamp, a Czerny–Turner monochromator, a
fast photomultiplier, and a transient digitizer (TDS 340,
Tektronix) [61]. The instrumental response was about 7 ns. The
observation wavelength is indicated in each case. Experiments
were performed in acetonitrile under Ar bubbling.

A FluoroMax-4 (Horiba, Jobin-Yvon) spectrophotometer
coupled with a Time-Correlated Single-Photon Counting
(TCSPC) accessory was used to measure the steady-state fluo-
rescence spectra and singlet excited state lifetimes. NanoLEDs
were used as pulsed excitation source leading to a time resolu-
tion of around 200 ps. The measurements were performed in
acetonitrile solutions under argon bubbling at room tempera-
ture. The quenching rate constants k_q of the excited states were
obtained according to the Stern–Volmer analysis where the reci-
procal lifetime is plotted as a function of quencher concentra-
tion: [57]. Chemicals: Rose Bengal extra (RB) and ethyl 4-(dimethyl-
amino)benzoate (EDB) were obtained from Aldrich, 2-(4-
methoxyphenyl)-4,6-bis(trichloromethyl)-1,3,5-triazine (TA)
was gifts from PCAS (France). Their chemical structures are
given in Scheme 1.

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Abstract
Intermolecular [3 + 2] annulation of cyclopropylanilines with alkynes is realized using visible light photoredox catalysis, yielding a variety of cyclic allylic amines in fair to good yields. This method exhibits significant group tolerance particularly with heterocycles. It can also be used to prepare complex heterocycles such as fused indolines.

Introduction
Cyclopropanes have been used as a three-carbon synthon to prepare a diverse array of organic compounds [1-4]. The unusual reactivity, exhibited by cyclopropanes, is largely due to their inherent ring strain that makes cleavage of the C–C bonds facile [5]. A number of methods have been developed to regioselectively cleave cyclopropanes, generating synthetically useful intermediates that can be further manipulated [1-5]. For one subclass of cyclopropanes, cyclopropylamines, the requisite ring opening is often accomplished by one-electron oxidation of the parent amine. This oxidation step can be realized enzymatically [6-8], chemically [9-14], electrochemically [15,16], and photochemically [17-20]. Recently, visible light photoredox catalysis has emerged as a powerful method to manipulate the redox chemistry of organic compounds [21-26]. Amines have been used as an electron donor to reduce the excited state of photocatalysts, while they are oxidized to amine radical cations. Our group and others have taken advantage of this facile redox process and developed a number of synthetic methods that harness the synthetic potential of amine radical cations [21,27,28]. One of the reported methods from our group involves [3 + 2] annulation of cyclopropylanilines with alkynes [29]. We were intrigued by the possibility of extending this annulation method to include alkynes. The immediate benefits of using alkynes include eliminating the diastereoselectivity issue observed in the annulation of monocyclic cyclopropylanilines with alkynes [29].
group into the annihilation product. Furthermore, the synthesis of cyclic allylic amines is non-trivial in general [30]. Herein, we report intermolecular [3 + 2] annihilation of monocyclic cyclopropylanilines with alkynes under visible light photoredox conditions.

Results and Discussion

Biphenylcyclopropylamine 1 and phenylacetylene (2) were chosen as the standard substrates to optimize the catalyst system for the [3 + 2] annihilation with alkynes (Table 1). Similar to the annihilation with alkynes [29], several reactivity patterns were observed. CH$_3$NO$_2$ was far superior to DMF and CH$_3$CN as the solvent (Table 1; entries 1–3). Ru(bpz)$_3$(PF$_6$)$_2$ was a more effective photocatalyst than Ru(bpy)$_3$(PF$_6$)$_2$ (Table 1, entry 4). Air was detrimental to the annihilation reaction (Table 1, entry 5). However, we noticed the annihilation with alkynes was slower than with alkenes, previously reported by our group [29]. To compensate for lower reactivity of alkynes, we investigated commercially available light resources that were stronger than 13 W compact fluorescent lamps (CFLs). 13 W CFLs were used as the light source to mediate the annihilation with alkenes [29]. White 18 W LEDs were found to be more effective for the annihilation with alkynes, resulting in a higher yield (Table 1, entry 6). Control studies showed that both the photocatalyst and light were required, though some background reaction was observed (Table 1, entries 7 and 8).

Table 1: Catalyst screening.

<table>
<thead>
<tr>
<th>Entry$^a$</th>
<th>Catalyst</th>
<th>Light</th>
<th>Solvent</th>
<th>GC yield of 3 [%]$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4a</td>
<td>18 W LED</td>
<td>CH$_3$NO$_2$</td>
<td>82 (80)$^c$</td>
</tr>
<tr>
<td>2</td>
<td>4a</td>
<td>18 W LED</td>
<td>DMF</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>4a</td>
<td>18 W LED</td>
<td>CH$_3$CN</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>4b</td>
<td>18 W LED</td>
<td>CH$_3$NO$_2$</td>
<td>55</td>
</tr>
<tr>
<td>5$^d$</td>
<td>4a</td>
<td>18 W LED</td>
<td>CH$_3$NO$_2$</td>
<td>41</td>
</tr>
<tr>
<td>6</td>
<td>4a</td>
<td>13 W CFL</td>
<td>CH$_3$NO$_2$</td>
<td>68</td>
</tr>
<tr>
<td>7</td>
<td>none</td>
<td>18 W LED</td>
<td>CH$_3$NO$_2$</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>4a</td>
<td>none</td>
<td>CH$_3$NO$_2$</td>
<td>3</td>
</tr>
</tbody>
</table>

$^a$Conditions: 1 (0.2 mmol), 2 (1 mmol), solvent (2 mL), degassed, irradiation at rt for 8 h.
$^b$Dodecane was used as an internal standard.
$^c$Isolated yield by silica gel chromatography.
$^d$The reaction was conducted in the presence of air.
This reactivity trend towards alkynes is consistent with that exhibited in intermolecular addition of nucleophilic carbon-based radicals to alkynes [31-33]. In addition to phenylacetylene, acetylenic methyl ester is a viable annulation partner, leading to annulation products 11–14 in good yields. Heterocycles are frequently used in organic electronic materials [34] and pharmaceuticals [35,36]. Therefore, the ability to incorporate them is usually considered a benchmark for developing new synthetic methods. This method has certainly passed this test as two pairs of heterocycle-containing alkynes underwent the [3 + 2] annulation with cyclopropylanilines uneventfully (15–18). The alkyne moiety at the C2 or C3 position of thiophene or pyridine showed similar reactivity towards the annulation.

Fused indolines are common structural motifs that appear in a number of biologically active alkaloids and pharmaceuticals [37,38]. The [3 + 2] annulation of monocyclic cyclopropylanilines with alkynes provides a fast entry to this motif (Scheme 1). Starting from commercially available 1-bromo-2-iodobenzene (19) and cyclopropylamine, 2-bromo-N-cyclopropylaniline (20) was prepared in 75% yield via the Buch-
wald–Hartwig amination [39,40]. The [3 + 2] annulation of 2-bromo-\( N \)-cyclopropylaniline (20) and phenylacetylene (2) was performed using the optimized catalyst system to provide cyclic allylic amine 21 in 52% yield. The fused indoline motif was formed via an intramolecular Heck reaction under Fu’s conditions [41] to provide a mixture of two olefinic regioisomers 22, which were converted to saturated fused indoline 23 under standard catalytic hydrogenation conditions in a combined yield of 40% from 21.

Mechanistically, the annulation with alkynes probably proceeds through a pathway similar to the one we proposed for the annulation with alkenes (Scheme 2) [29]. The photoexcited Ru(bpz)\(_3\)^2+ oxidizes cyclopropylaniline 24 to the corresponding amine radical cation 25, which triggers the cyclopropyl ring opening to generate distonic radical cation 26. The primary carbon radical of 26 adds to the terminal carbon of alkyne 27 to afford vinyl radical 28. Intramolecular addition of the vinyl radical to the iminium ion of distonic radical cation 28 closes the five-membered ring and furnishes amine radical cation 29. Finally, Ru(bpz)\(_3\)^1+ reduces amine radical cation 29 to the annulation product 30 while regenerating Ru(bpz)\(_3\)^2+. The proposed mechanism accounts for lower reactivity of alkynes towards intermolecular addition of nucleophilic carbon-centered radicals as well as their regiochemistry in the annulation [31-33]. Addition of radicals to alkynes generally occurs at the less hindered carbon, i.e., the terminal carbon.

Conclusion
In summary, we have successfully expanded the [3 + 2] annulation of cyclopropylanilines to include alkynes. This annulation process with alkynes has addressed some limitations existing in the annulation with alkenes. Moreover, the annulation products from alkynes are highly useful synthetic intermediates. Their utility is demonstrated by a four-step synthesis of fused indolines in which the [3 + 2] annulation with alkynes is used to set
up the backbone of indolines. Continued studies in our group will focus on further expanding the scope of the [3 + 2] annulation to include substituted anilines and other types of π-bonds.

Experimental

General procedure for the [3 + 2] annulation of cyclopropylanilines with alkynes: an oven-dried test tube (16 × 125 mm) equipped with a stir bar was charged with [Ru(bpy)3]2(O2)22H2O (2 mol%), cyclopropylaniline (0.2 mmol), alkyne (1.0 mmol), and dry CH3NO2 (2 mL). The test tube was sealed with a Teflon screw cap. The reaction mixture was degassed by Freeze–Pump–Thaw cycles and then irradiated at room temperature with one white LED (18 watts) positioned 8 cm from the test tube. After the reaction was complete as monitored by TLC, the mixture was diluted with diethyl ether and filtered through a short pad of silica gel. The filtrate was concentrated in vacuum and purified by silica gel flash chromatography to afford the desired allylic amine.

Supporting Information

Supporting Information File 1
Experimental procedures, compound characterization, and NMR spectra.
[http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-96-S1.pdf]

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On the mechanism of photocatalytic reactions with eosin Y

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Full Research Paper

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Abstract
A combined spectroscopic, synthetic, and apparative study has allowed a more detailed mechanistic rationalization of several recently reported eosin Y-catalyzed aromatic substitutions at arenediazonium salts. The operation of rapid acid–base equilibria, direct photolysis pathways, and radical chain reactions has been discussed on the basis of pH, solvent polarity, lamp type, absorption properties, and quantum yields. Determination of the latter proved to be an especially valuable tool for the distinction between radical chain and photocatalytic reactions.

Introduction
The ability of natural systems to harness solar energy for the genesis of matter has been fascinating mankind since time immemorial and has stimulated numerous reproduction attempts in the context of chemical synthesis over the last two centuries. The vast majority of photochemical reactions known until the 1980s exploited stoichiometric amounts of a photoactive molecular entity to drive a chemical transformation [1]. Only recently, a steadily growing number of homogeneous transition metal complexes which are redox-active and show absorption in the visible range of the solar spectrum have been demonstrated to catalyze light-driven organic reactions. The use of the pyridyl-based complexes [Ru(bpy)3]2+, [Ir(ppy)3] and [Ir(ppy2)(dtbbpy)]+ for the mediation of redox processes has certainly attracted the most interest, incipiently in photocatalytic reactions of activated organic electrophiles [2-8].

Despite the numerous examples of efficient catalytic photoredox transformations with organometallic dyes known to date, their high price, toxicity profile, and problematic recyclability might limit their more general use especially on
larger scales. However, the recent pursuit of environmentally more benign photoactive catalysts has focused on much cheaper metal-free dyes. Several commercially available fluorescein and xanthene dyes have been successfully applied to photoredox reactions, including radical substitutions at α-amino, β-carbonyl, and aryl moieties [9,10]. Among them, eosin Y, the 2',4',5',7'-tetrabromo derivative of fluorescein, has been most widely employed. The redox potential of the EY*/EY+ pair of 1.1 V (vs. SCE) is experimentally not available as both of the compounds are short-lived intermediates. However, the redox potential can be obtained indirectly via analysis of the thermodynamic cycle involving the energy of the triplet state eosin Y* (T1) (derived from fluorescence measurements) and the energy of the radical cation eosin Y+* (derived from cyclovoltammetric experiments, for more details see Supporting Information File 1). Much effort has been directed at the oxidative quenching of eosin Y* (T1) with suitable electrophiles in order to generate aryl radicals by a light-driven single-electron transfer (SET) process (i.e., one-electron reduction of Ar–X, see Scheme 1). Due to their easy reducibility, arenediazonium salts are especially attractive precursors which constitute versatile alternatives to haloarene-based strategies. They are readily available by diazotization of anilines, no toxic metals are required; the bond cleavage generates gaseous N2 which escapes the reaction mixture. Photoredox reactions with arenediazonium salts are often more selective than traditional methods such as copper(II)-mediated Meerwein arylations [11] or protocols employing stoichiometric iron(II) or titanium(III) reductants in aqueous media [12-14]. This renaissance of arene diazonium chemistry has recently led to various applications of eosin Y to visible light-driven syntheses of biaryls [15], stilbenes [16], benzo[b]thiophenes [17], α-phenylketones [18], phenanthrenes [19], arylsulfides [20] and arylboron pinacolates [21] (Scheme 1).

Numerous mechanistic studies have been performed at reactions with organometallic photocatalysts [3-8], whereas much less attention has been directed at eosin Y-catalyzed reactions. The reductive quenching pathway of eosin Y, which operates in the photooxidation of isoquinolines [9], has been studied in a single report [22]. To the best of our knowledge, related data have not been collected for the much more widely used oxidative quenching. Most literature protocols were interpreted in analogy to the related ([Ru(bpy)3]Cl2)-catalyzed reactions and similar mechanisms were proposed (Scheme 2) [15-21]. These generally commence with the SET between excited eosin Y and the arenediazonium salt I to give aryl radical II. Nucleophilic attack onto reactive II generates the more stable complex III which is prone to back-electron transfer upon oxidative formation of the cationic species IV. Terminal elimination of X+ (mostly a proton) gives the substitution product V. Two general pathways of back-electron transfer can be followed: Path A involves one-electron reduction of the radical cation state of the catalyst. Radical chain propagation (B) can occur when the SET occurs with another molecule of the starting material I. Some attempts have been made to differentiate between radical chain and

![Scheme 1: Oxidative quenching of eosin Y with arenediazonium salts and reactions of the resultant aryl radicals.](image-url)
photocatalysis mechanisms by monitoring the reaction progress after the light sources have been switched off [20]. Clearly, such experiments neglect the existence of short radical chains and thus provide no conclusive evidence of the mechanism.

In general, the thermodynamic feasibility of a redox process is determined by the difference of redox potentials of the two half reactions. The redox potential of most arenediazonium salts (redox pair \( \text{I/II} \), Scheme 2) is close to 0 V vs. SCE [23,24]. The redox potentials of the short-lived adducts \( \text{III/IV} \) are unknown and experimentally not (easily) available. However, it is likely that their potential is greater than 0 V in many cases which makes the radical species \( \text{III} \) a sufficiently strong reductant for arenediazonium salts of type \( \text{I} \). After all, the unambiguous determination of the underlying reaction mechanisms is not possible without further spectroscopic, kinetic, and theoretical experiments. The studied systems are mostly too complex for transient absorption spectroscopy. We have so far failed to obtain any insight from photo-CIDNP NMR experiments. Therefore, we have decided to evaluate the efficiency of the radiation events of several recent literature protocols by recording the quantum yields \( \Phi \) [15-17,19-21]. Furthermore, we have learned along the way that the reactions appear to be strongly dependent on the pH of the solution and the type of lamp used for irradiation. Here, we present a detailed study on the direct consequences of these three major factors for the outcome and mechanism of several recently reported eosin Y-catalyzed aromatic substitution protocols starting from arenediazonium salts [15-21].

**Results and Discussion**

**Effect of pH on the efficiency of eosin Y-mediated photocatalysis**

For better comparison, we have employed identical reagent concentrations and reaction conditions (solvents) as reported in the original papers [15-21]. Dry DMSO was mostly used as solvent, with the exception of the phenanthrene [19] and arylboron pinacolate [21] syntheses which were run in acetonitrile. Much to our surprise, the solutions of eosin Y and arenediazonium salts in acetonitrile were yellow (instead of the usual red colour; see Figure 1, conditions as in [21]) and did not exhibit intense fluorescence (Figure 2, conditions as in [21]). We have suspected this to be a consequence of facile acid–base reactions of the catalyst eosin Y. Indeed, immediate colour change was effected by addition of base (tetra-n-butylammonium hydroxide, TBAOH), and strong fluorescence occurred in the green spectrum. This dramatic pH effect on the spectroscopic properties of eosin Y solutions prompted us to further investigate this behaviour.

The organic dye eosin Y can exist in four different structures in solution: the spirocyclic form \( \text{EY1} \), the neutral \( \text{EY2} \), the monoanionic \( \text{EY3} \), and the dianionic form \( \text{EY4} \) (Scheme 3). Eosin Y contains two relatively acidic protons (\( pK_a 2.0, 3.8 \) in water) [25] which can be easily abstracted to give dianionic EY4. Lack of clarity exists in many publications on photoredox catalysis with regard to the nature of the employed dye. The authors either report the use of “eosin Y, spirit soluble” – which can be EY1 or EY2 according to the Sigma–Aldrich catalogue [26], or claim the use of the free acid EY2. The presence of
stoichiometric amounts of bases, e.g., in eosin Y-catalyzed photo-oxidative transformations with amines [9], results in the quantitative generation of the dianionic form EY4 under the reaction conditions. On the other hand, the SET-generation of aryl radicals from arenediazonium salts by photocatalysis proceeds in the absence of base. The non-aqueous conditions should not provide a significant buffering capacity. Here, the presence of only minute amount of impurities in the solvents or starting materials is sufficient to push the acid–base equilibria of the catalytic amounts of eosin Y in either direction.

The spirocyclic form EY1 contains an interrupted conjugation of the fluorone ring system and thus would be photocatalytically inactive under visible light irradiation. The neutral form EY2 exhibits only weak fluorescence when irradiated with visible light (Figure 2). Studies on related alkylated eosin derivatives suggest that this fluorescent state is very short lived and is therefore also not appropriate for photoredox catalysis [27]. The charged forms EY3 and EY4 are catalytically active, which in turn also means that solutions containing commercial “eosin Y, spirit soluble” would per se not trigger efficient photoredox catalysis. In such cases, catalytic activity as observed in recent publications by König et al. is dependent on the operation of acid–base equilibration (e.g., in DMSO solution) so that the employed eosin Y is converted in situ to the active species EY3 or EY4 [15-18]. Efforts to reproduce the photoredox synthesis of arylboron pinacolates in acetonitrile have so far failed in our hands when irradiating at 535 nm [21]. No product formation was observed, and the UV–vis spectra showed no appreciable absorption at this wavelength. However, the addition of minor quantities of base (TBAOH) to the reaction mixture resulted in strong absorption at 535 nm and good photocatalytic activity under irradiation. The substitution of acetonitrile with DMSO in the same reaction gave strong absorption at 535 nm and allowed the photocatalytic synthesis of the desired arylboronic ester in good yields in the absence of extra base. This discrepancy is most likely associated with the different properties of DMSO and acetonitrile as bases. DMSO is a stronger base than acetonitrile which enhances the acidity of most Brønsted acids in DMSO [28]. These observations lead to the conclusion that photoredox reactions catalyzed by eosin Y (or similar organic dyes) cannot be discussed without strict specification of the employed form of the dye and the reaction conditions. Conclusive mechanistic proposals of visible-light-driven reactions with these dyes also need to address the operation of acid–base equilibria and the pH dependence of absorption properties.

Effect of the light source on the eosin Y-mediated photocatalysis

Another reaction parameter which lacks clarity and consistency among the literature reports is the source of irradiation. Several
groups including ourselves have used commercial narrow-band LEDs with a maximum intensity at 535 nm (green light) [15-18,20]. Other reactions were irradiated with white light from broad-band compact fluorescent lamps (CFL) [19,21]. The determination of quantum yields requires the use of narrow-band light sources due to the variation of the optical density of the samples with the wavelength. Therefore, we have studied the impact of different irradiation types on the course of the photocatalytic reaction. Although the type of CFLs was not specified in the literature [19,21], the majority of commercial CFLs cover similar spectral ranges with the individual UV edge being significantly below 400 nm and with substantial radiation power in the region of 400–500 nm. A similar wavelength distribution is seen in the spectrum of commercial white-colored LEDs (see Supporting Information File 1 for spectrum).

The activation energy of thermal heterolysis of arenediazonium ions is approx. 115 kJ/mol (1.19 eV) [29]. The energy of a photon at the edge of the visible spectrum (400 nm) is 3.1 eV so that such photons carry sufficient energy to heterolyze diazonium ions to give highly electrophilic aryl cations. Moreover, arenediazonium salts are known to form weak charge-transfer complexes with solvent molecules whose absorption tails into the visible range [30]. These observations support the notion that the use of broad-band visible irradiation indeed can have a profound effect on the outcome of a photocatalytic reaction. We have therefore examined if direct absorption of the arenediazonium ions can trigger a productive pathway under irradiation with broad-band light sources even in the absence of the photocatalyst. As representative examples we chose the recently reported syntheses of arylborinic esters [21] and phenanthrenes [19]. The absorption spectrum of a mixture of para-bromobenzenediazonium tetrafluoroborate (p-BrC₆H₄N₂BF₄) and bispinacolato diboron (B₂pin₂) in acetonitrile shows a significant shoulder of a UV-absorption band tailing into the visible part of the spectrum (Figure 3) [30]. At the UV–vis edge (400 nm), the absorbance of the system is still more than 0.1 which translates into 21% of all light being absorbed at this wavelength. When we performed the borylation reaction according to the literature report [21] but without the addition of the photocatalyst eosin Y, 54% yield of the borylation product were obtained by direct photolysis (Scheme 4). These observations are in full accord with a report of direct reaction of thermally generated aryl cations (from arenediazonium salts) with bispinacolato diboron to give the corresponding arylborinic esters [31]. It is thus very likely that direct light-triggered heterolysis of the starting material accounts for substantial amounts of product formation under conditions which were believed to proceed through photocatalytic SET.

A similar behaviour was found in our study of the phenanthrene synthesis [19]. A solution of o-biphenyldiazonium tetrafluoroborate in acetonitrile showed strong absorption between 400–500 nm with all light at the UV–vis edge at 400 nm being completely absorbed. This again indicates that direct photocleavage of the C–N bond might be operating. The cyclization reaction with ethyl propiolate according to the literature protocol [19] but in the absence of eosin Y did not afford any phenanthrene product (Scheme 5). Instead, a Ritter-type reaction proceeded to give the corresponding acetanilide after aqueous work-up which is consistent with the original report by Deronzier from 1984 [32]. The significant overlap of the absorption spectra of the arenediazonium salt recorded before and after the addition of eosin Y (Figure 4) suggests that direct photolysis of the C–N bond could account for the erosion of product yield in the catalytic process due to competitive hetero-

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**Scheme 4** Eosin Y-catalyzed and dye-free photolytic borylation.
ysis of the substrate and subsequent ionic Ritter reaction. This notion was supported by our experiments performed in DMSO where a higher portion of the photocatalyst resides in the active EY3 and EY4 states. Following an otherwise identical protocol, irradiation at 535 nm resulted in the formation of the phenanthrene in 71% yield (cf. literature yield of 53%) [19].

Quantum yields of eosin Y-catalyzed reactions

The determination of quantum yields of light-driven reactions provides valuable insight into the efficiency of the radiative processes and thus can be used for the mechanistic understanding of such processes. The magnitude of quantum yields $\Phi$ also describes how much energy is wasted into thermal dissipation in such systems, which is an especially critical parameter for the evaluation of sustainability of a photocatalytic process. The quantum yield is defined as the efficiency of a photochemical reaction in the studied system:

$$\Phi = \frac{\text{rate of substrate conversion}}{\text{absorbed photon flux}}$$

Theoretically, if a simple photocatalytic process is considered, the quantum yield would be in the range $0 < \Phi \leq 1$. It approaches unity as the efficiency of the photocatalytic step increases. In reality, quantum yields can exceed unity in cases where the products of the photocatalytic reaction induce (radical) chain reactions. Therefore, the determination of quantum yields $\Phi$ provides a meaningful answer to mechanistic ambiguities. For the eosin Y-catalyzed reactions with arene diazonium salts, conclusive answers to the distinction between photocatalytic and radical chain mechanisms can be derived directly from $\Phi$.

A quantification of the photon flux is rather problematic. Recently, devices became available which use solar cells for the direct measurement of photon fluxes [33]. However, chemical actinometry constitutes a prevalent indirect method of photon flux measurement [34]. Several effective chemical actinometers are known for UV spectral studies whereas similar experiments in the visible range are much more limited by the availability of chemical actinometers. Even more challenging are photon flux determinations above 500 nm which marks the spectral cut-off of the commonly used Hatchard–Parker ferrioxalate. None of the chemical actinometers that operate in this region are commercially available. We therefore decided to prepare potassium Reineckate, a robust actinometer for the >500 nm region, according to a literature method [34,35].

Quantum yields $\Phi$ were measured for all aforementioned visible-light-driven reactions in the same solvent, DMSO. Irradiation was performed with a green LED (3.8 W) at 535 nm. All other reaction conditions were adopted from the individual literature reports [15-21]. For more details on the actinometry experiments and quantum yield determinations, see Supporting Information File 1. The observed quantum yields $\Phi$ of the studied reactions varied by almost two orders of magnitude, between 4.7 and 0.075. This already indicates the operation of different mechanisms in these aromatic substitution reactions with arene diazonium salts. The redox potentials of most substituted arene diazonium salts cluster with very little deviation around 0.0 V vs. SCE ($\pm 0.2$ V) [23,24] so that the observed
differences in $\Phi$ can be largely attributed to different mechanistic pathways. Our experiments (Scheme 6) afforded quantum yields of $\Phi > 1$ for the heterobiaryl coupling [15] and the Heck-type olefination with styrene [16], respectively. This indicates that in addition to a photocatalytic path (Scheme 2, A) radical-chain propagation is operating under the reaction conditions (Scheme 2, B). This contrasts with the other reactions where the quantum yields range between 0.6 and 0.075. In the original paper from Deronzier [32], where similar reactions under catalysis of Ru(bpy)$_3^{2+}$ were studied, $\Phi$ values of 0.46–0.78 were reported. Our actinometric experiments of the eosin Y-catalyzed phenanthrene synthesis [19] and photoborylation [21] gave similar quantum yields of 0.35 and 0.60, respectively. This suggests that the photocatalytic pathway is indeed populated (Scheme 2, A). Finally, the benzothiophene synthesis [17] and photothiolation [19] exhibited relatively low quantum yields which could be a consequence of non-productive processes that are responsible for the significant loss of energy. The presence of electron-rich alkylthiolate moieties in both systems could in principle effect reversible redox processes with the catalyst eosin Y which might account for the erosion of $\Phi$.

**Conclusion**

In summary, we have investigated the impact of several reaction parameters on the outcome and mechanism of photocatalytic aromatic substitution reactions of arenediazonium salts in the presence of eosin Y. However, the significance of these data certainly extends to other light-driven reactions that lie beyond

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**Scheme 6:** Quantum yield determinations of selected visible-light-driven aromatic substitutions.
the focus of this study. Eosin Y (and many other organic photocatalysts) undergo rapid acid–base equilibria which significantly alter the photophysical properties. It is therefore of pivotal importance to ascertain the actual nature of the employed dye under the reaction conditions. Experimental details should always be given that specify the employed dye, reagents, solvents, and additives. The use of broad-spectrum lamps in photocatalytic reactions with arenediazonium salts is strongly discouraged as they promote heterolytic C–N bond cleavage toward highly reactive aryl cation species. The standard reaction conditions of many literature reports involve concentrations which are orders of magnitude higher than those employed under the reaction conditions. Experimental and analytical data.

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Direct C–H trifluoromethylation of di- and trisubstituted alkenes by photoredox catalysis

Ren Tomita, Yusuke Yasu, Takashi Koike* and Munetaka Akita*

Abstract

Background: Trifluoromethylated alkene scaffolds are known as useful structural motifs in pharmaceuticals and agrochemicals as well as functional organic materials. But reported synthetic methods usually require multiple synthetic steps and/or exhibit limitation with respect to access to tri- and tetrasubstituted CF₃-alkenes. Thus development of new methodologies for facile construction of Cₛₐₖₑₙ₃–CF₃ bonds is highly demanded.

Results: The photoredox reaction of alkenes with 5-(trifluoromethyl)dibenzo[b,d]thiophenium tetrafluoroborate, Umemoto’s reagent, as a CF₃ source in the presence of [Ru(bpy)₃]²⁺ catalyst (bpy = 2,2’-bipyridine) under visible light irradiation without any additive afforded CF₃-substituted alkenes via direct Cₛₐₖₑₙ₃–H trifluoromethylation. 1,1-Di- and trisubstituted alkenes were applicable to this photocatalytic system, providing the corresponding multisubstituted CF₃-alkenes. In addition, use of an excess amount of the CF₃ source induced double C–H trifluoromethylation to afford geminal bis(trifluoromethyl)alkenes.

Conclusion: A range of multisubstituted CF₃-alkenes are easily accessible by photoredox-catalyzed direct C–H trifluoromethylation of alkenes under mild reaction conditions. In particular, trifluoromethylation of triphenylethene derivatives, from which synthetically valuable tetrasubstituted CF₃-alkenes are obtained, have never been reported so far. Remarkably, the present facile and straightforward protocol is extended to double trifluoromethylation of alkenes.

Introduction

The trifluoromethyl (CF₃) group is a useful structural motif in many bioactive molecules as well as functional organic materials [1-6]. Thus, the development of new methodologies for highly efficient and selective incorporation of a CF₃ group into diverse skeletons has become a hot research topic in the field of organic synthetic chemistry [7-12]. Recently, radical trifluoro-
methylation by photoredox catalysis [13-23] with ruthenium(II) polypyridine complexes (e.g., {Ru(bpy)}$_3^{2+}$ (bpy: 2,2'-bipyridine)), the relevant Ir cyclometalated complexes (e.g., fac-Ir(ppy)$_3$ (ppy: 2-phenylpyridine)) and organic dyes has been developed; the trifluoromethyl radical (CF$_3$) can be easily generated from conventional CF$_3$ radical precursors such as CF$_3$I, CF$_3$SO$_2$Cl and CF$_3$SO$_2$Na through visible-light-induced single-electron transfer (SET) processes [24-32]. On the other hand, we have intensively developed trifluoromethylations of olefins by the Ru and Ir photoredox catalysis using easy-handling and shelf-stable electrophilic trifluoromethylating reagents [33-36] ($^{+}$CF$_3$) such as Umemoto’s reagent (1a, 5-(trifluoromethyl)dibenzo[b,d]thiophenium tetrafluoroborate) and Togni’s reagents 1b (1-(trifluoromethyl)-1λ$_3$2-benziodoxol-3(1H)-one) and 1c (3,3-dimethyl-1,3-dihydro-1λ$_3$2-benziodoxole) [37-41]. It was found that electrophilic trifluoromethylating reagents ($^{+}$CF$_3$) can serve as more efficient CF$_3$ radical sources under mild photocatalytic reaction conditions. In addition, the putative β-CF$_3$ carbocation intermediate formed through SET photoredox processes is playing a key role in our reaction systems (vide infra).

Trifluoromethylated alkenes, especially multi-substituted CF$_3$-alkenes (3,3,3-trifluoropropene derivatives), have attracted our attention as fascinating scaffolds for agrochemicals, pharmaceuticals, and fluorescent molecules (Scheme 1) [3,42-45].

Conventional approaches to CF$_3$-alkenes require multiple synthetic steps [46-54]. In contrast, “trifluoromethylation” is a promising protocol to obtain diverse CF$_3$-alkenes easily. Several catalytic synthetic methods via trifluoromethylation have been developed so far [38,55-62]. Most of these reactions require prefunctionalized alkenes as a substrate (Scheme 2a). Additionally, only a limited number of examples for synthesis of tri/tetra-substituted CF$_3$-alkenes have been reported so far. Recently, the groups of Szabó and Cho described trifluoromethylation of alkenes, leading to trifluoromethylated alkenes but the application to the synthesis of tetrasubstituted CF$_3$-alkenes is not well documented (Scheme 2b) [63,64]. Another straightforward approach is direct C–H trifluoromethylation of alkenes (Scheme 2c). The groups of Loh, Besset, Cahard, Sodeoka and Xiao showed that copper catalysts can induce a C–H trifluoromethylation of alkenes by electrophilic CF$_3$ reagents ($^{+}$CF$_3$) [65-69]. In addition, Cho et al. reported that the reaction of unactivated alkenes with gaseous CF$_3$I in the presence of a Ru photocatalyst, {Ru(bpy)}$_3^{2+}$, and a base, DBU (diazabicyclo[5,4,0]undec-7-ene) produced CF$_3$-alkenes through iodotrifluoromethylation of alkenes followed by base-induced E2 elimination [70]. To the best of our knowledge, however, the development of synthetic methods for tri- and tetrasubstituted CF$_3$ alkenes through C–alkenyl–H trifluoromethylation of simple alkenes have been left much to be desired.

Previously, we reported on the synthesis of CF$_3$-alkenes via sequential photoredox-catalyzed hydroxytrifluoromethylation and dehydration (Scheme 3a) [37] and photoredox-catalyzed trifluoromethylation of alkenylborates (Scheme 3b) [38]. These results prompted us to explore photoredox-catalyzed C–H trifluoromethylation of di- and trisubstituted alkenes (Scheme 3c). Herein we disclose a highly efficient direct C–H trifluoromethylation of di- and trisubstituted alkenes with easy-handling and shelf-stable Umemoto’s reagent 1a by visible-light-driven photoredox catalysis under mild conditions. This photocatalytic protocol allows us easy access to a range of multi-substituted trifluoromethylated alkenes. In addition, our methodology can
Table 1: Optimization of photocatalytic trifluoromethylation of 1,1-diphenylethene 2a. a

<table>
<thead>
<tr>
<th>Entry</th>
<th>Photocatalyst</th>
<th>CF₃ reagent</th>
<th>Solvent</th>
<th>Base</th>
<th>NMR yield (%)</th>
</tr>
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<tr>
<td>1</td>
<td>fac-Ir(ppy)₃</td>
<td>1a</td>
<td>[D₆]-DMSO</td>
<td>K₂HPO₄</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>fac-Ir(ppy)₃</td>
<td>1b</td>
<td>[D₆]-DMSO</td>
<td>K₂HPO₄</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>fac-Ir(ppy)₃</td>
<td>1c</td>
<td>[D₆]-DMSO</td>
<td>K₂HPO₄</td>
<td>47</td>
</tr>
<tr>
<td>4</td>
<td>fac-Ir(ppy)₃</td>
<td>1a</td>
<td>CD₃CN</td>
<td>K₂HPO₄</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>fac-Ir(ppy)₃</td>
<td>1a</td>
<td>CD₃Cl₂</td>
<td>K₂HPO₄</td>
<td>22</td>
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<tr>
<td>6</td>
<td>fac-Ir(ppy)₃</td>
<td>1a</td>
<td>[D₆]-acetone</td>
<td>K₂HPO₄</td>
<td>29</td>
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<tr>
<td>7</td>
<td>fac-Ir(ppy)₃</td>
<td>1a</td>
<td>[D₆]-DMSO</td>
<td>none</td>
<td>81</td>
</tr>
<tr>
<td>8</td>
<td>[Ru(bpy)₃]²⁺PF₆₆⁻</td>
<td>1a</td>
<td>[D₆]-DMSO</td>
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<td>85</td>
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<tr>
<td>9</td>
<td>none</td>
<td>1a</td>
<td>[D₆]-DMSO</td>
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<td>0</td>
</tr>
<tr>
<td>10</td>
<td>[Ru(bpy)₃]²⁺PF₆₆⁻</td>
<td>1a</td>
<td>[D₆]-DMSO</td>
<td>none</td>
<td>0</td>
</tr>
</tbody>
</table>

aFor reaction conditions, see the Experimental section. bIn the dark.
In the reactions of unsymmetrically substituted substrates (2e–h), products were obtained in good to moderate yields but consisted of mixtures of E and Z-isomers. Based on the experimental results, the E/Z ratios are susceptible to the electronic structure of the aryl substituent. Reactions afforded the major isomers, in which the CF$_3$ group and the electron-rich aryl substituent are arranged in E-fashion. In addition, the present photocatalytic reaction can be tolerant of the Boc-protected amino group (2f) or pyridine (2h). Moreover, a substrate with an alkyl substituent, 2,4-diphenyl-4-methyl-1-pentene (2i), was also applicable to this transformation, whereas the reaction of 1,2-disubstituted alkenes such as trans-stilbene provided complicated mixtures of products.

Next, we extended the present C–H trifluoromethylation to trisubstituted alkenes. The reactions of 1,1-diphenylpropene derivatives 2j and 2k (E/Z = 1/1) afforded the corresponding tetrasubstituted CF$_3$-alkenes 3j and 3k in 82% and 59% (E/Z = 74/26) yields, respectively. Triphenylethenes 2l and 2m (only E-isomer) are also applicable to this photocatalytic C–H trifluoromethylation. Remarkably, the E-isomer of 3m is a key intermediate for the synthesis of panomifene, which is known as

---

**Table 2:** The scope of the present trifluoromethylation of alkenes.$^{a,b}$

<table>
<thead>
<tr>
<th>$R^2$</th>
<th>$R^3$</th>
<th>$R^1$</th>
<th>Product</th>
<th>Yield</th>
<th>E/Z Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>CF$_3$</td>
<td>H</td>
<td>3a</td>
<td>82%</td>
<td>89/11</td>
</tr>
<tr>
<td>MeO</td>
<td>CF$_3$</td>
<td>H</td>
<td>3b</td>
<td>81%</td>
<td>91/9</td>
</tr>
<tr>
<td>Cl</td>
<td>CF$_3$</td>
<td>H</td>
<td>3c</td>
<td>53%</td>
<td>17/83</td>
</tr>
<tr>
<td>Br</td>
<td>CF$_3$</td>
<td>H</td>
<td>3d</td>
<td>70%</td>
<td>33/67</td>
</tr>
<tr>
<td>MeO</td>
<td>CF$_3$</td>
<td>H</td>
<td>3e</td>
<td>70%</td>
<td>89/11</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>CF$_3$</td>
<td>H</td>
<td>3f</td>
<td>37%</td>
<td>91/9</td>
</tr>
<tr>
<td>Cl</td>
<td>CF$_3$</td>
<td>H</td>
<td>3g</td>
<td>51%</td>
<td>9/83</td>
</tr>
<tr>
<td>Br</td>
<td>CF$_3$</td>
<td>H</td>
<td>3h</td>
<td>78%</td>
<td>17/83</td>
</tr>
<tr>
<td>MeO</td>
<td>CF$_3$</td>
<td>H</td>
<td>3i</td>
<td>58%</td>
<td>88/12</td>
</tr>
<tr>
<td>Boc</td>
<td>CF$_3$</td>
<td>H</td>
<td>3j</td>
<td>82%</td>
<td>74/26</td>
</tr>
<tr>
<td>Cl</td>
<td>CF$_3$</td>
<td>Me</td>
<td>3k</td>
<td>59%</td>
<td>74/26</td>
</tr>
<tr>
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<td>65%</td>
<td>88/12</td>
</tr>
<tr>
<td>Br</td>
<td>CF$_3$</td>
<td>MeO</td>
<td>3m</td>
<td>53%</td>
<td>88/12</td>
</tr>
</tbody>
</table>

$^a$For reaction conditions, see the Experimental section. $^b$Isolated yields. $^c$NMR yields. $^d$E/Z ratios were determined by $^{19}$F NMR spectroscopy of the crude product mixtures. $^e$2,6-Lutidine (2 equiv) was added as a base.
an antiestrogen drug [71,72]. These results show that the present protocol enables the efficient construction of a CalkenyCF3 bond through direct C–H trifluoromethylation of 1,1-disubstituted and trisubstituted aryl alkenes.

During the course of our study on the C–H trifluoromethylation of 1,1-diarylethenes 2, we found that a detectable amount of bis(trifluoromethyl)alkenes 4 was formed through double C–H trifluoromethylation. In fact, the photocatalytic trifluoromethylation of 2a,b and d with 4 equivalents of Umemoto’s reagent 1a in the presence of 5 mol % of [Ru(bpy)3](PF6)2 with irradiation from blue LEDs for 3 h gave geminal bis(trifluoromethyl)ethene (4a,b and d) in 45, 80 and 24% NMR yields, respectively (Scheme 4). Substituents on the benzene ring significantly affect the present double trifluoromethylation. Reaction of the electron-rich alkene 2b afforded 1,1-anisyl-2,2-bis(trifluoromethyl)ethene (4b) in a better yield than other alkenes 2a and 2d. Additionally, we found that photocatalytic trifluoromethylation of CF3-alkene 3d in the presence of an excess amount of Umemoto’s reagent 1a produced bis(trifluoromethyl)alkenes 4d in a better yield (56% yield) compared to the above-mentioned one-pot double trifluoromethylation of 2d.

A possible reaction mechanism based on SET photoredox processes is illustrated in Scheme 5. According to our previous photocatalytic trifluoromethylation [37-41], the trifluoromethyl radical (·CF3) is generated from an one-electron-reduction of electrophilic Umemoto’s reagent 1a by the photoactivated Ru catalyst, *[Ru(bpy)3]2+.·CF3 reacts with alkene 2 to give the benzyl radical-type intermediate 3’ in a regioselective manner. Subsequent one-electron-oxidation by highly oxidizing Ru species, [RuIII(bpy)3]3+, produces β-CF3 carbocation intermediate 3+. Finally, smooth elimination of the olefinic proton, which is made acidic by the strongly electron-withdrawing CF3 substituent, provides trifluoromethylated alkene 3. Preferential formation of one isomer in the reaction of unsymmetrical substrates is attributed to the population of the rotational conformers of the β-CF3 carbocation intermediate 3+. Our experimental result is consistent with the previous report [71], which described E-selective formation of the tetrasubstituted CF3-alkene 3m via a β-CF3 carbocation intermediate. In the presence of an excess amount of CF3 reagent 1a, further C–H trifluoromethylation of CF3-alkene 3 proceeds to give bis(trifluoromethyl)alkene 4.
Conclusion

We have developed highly efficient C–H trifluoromethylation of alkenes using Umemoto’s reagent as a CF₃ source by visible-light-driven photoredox catalysis. This reaction can be applied to multi-substituted alkenes, especially, 1,1-disubstituted and trisubstituted aryl alkenes, leading to tri- and tetrasubstituted CF₃-alkenes. The present straightforward method for the synthesis of multisubstituted CF₃-alkenes from simple aryl alkenes is the first report. In addition, we can extend the present photocatalytic system to double trifluoromethylation. Further development of this protocol in the synthesis of bioactive organofluorine molecules and fluorescent molecules is a continuing effort in our laboratory.

Experimental

Typical NMR experimental procedure (reaction conditions in Table 1)

Under N₂, [Ru(bpy)₃](PF₆)₂ (1.1 mg, 1.3 μmol), Umemoto’s reagent 1a (8.5 mg, 25 μmol), 1,1-diphenylethylene (2a, 4.3 μL, 25 μmol), SiEt₄ (~1 μL) as an internal standard, and [D₆]-DMSO (0.5 mL) were added to an NMR tube. The reaction was carried out at room temperature (water bath) and irradiation of visible light (placed at a distance of 2–3 cm from 3 W blue LED lamps: \( hν = 425 \pm 15 \) nm).

General procedure for the photocatalytic C–H trifluoromethylation of alkenes (reaction conditions in Table 2)

A 20 mL Schlenk tube was charged with Umemoto’s reagent 1a (102 mg, 0.3 mmol, 1.2 equiv), [Ru(bpy)₃](PF₆)₂ (2.54 mg, 2 mol %), alkene 2 (0.25 mmol), and DMSO (2.5 mL) under N₂. The tube was irradiated for 2 h at room temperature (water bath) with stirring by 3 W blue LED lamps (\( hν = 425 \pm 15 \) nm) placed at a distance of 2–3 cm. After reaction, H₂O was added. The resulting mixture was extracted with Et₂O, washed with H₂O, dried (Na₂SO₄), and filtered. The filtrate was concentrated in vacuo and the residue was purified by flash column chromatography on silica gel (eluent: hexane) to afford the product mixture with 3a and 3i. Further purification by GPC provided pure 3e and 3d.

Procedures for the photocatalytic double C–H trifluoromethylation of 1,1-bis(4-methoxyphenyl)ethylene (2b)

A 20 mL Schlenk tube was charged with Umemoto’s reagent 1a (340 mg, 1.0 mmol, 4 equiv), [Ru(bpy)₃](PF₆)₂ (10.7 mg, 5 mol %), 2b (60 mg, 0.25 mmol), and DMSO (5 mL) under N₂. The tube was irradiated for 3 h at room temperature (water bath) with stirring by 3 W blue LED lamps (\( hν = 425 \pm 15 \) nm) placed at a distance of 2–3 cm. After reaction, H₂O was added. The resulting mixture was extracted with Et₂O, washed with H₂O, dried (Na₂SO₄), and filtered. The filtrate was concentrated in vacuo and the residue was purified by flash column chromatography on silica gel (hexane → hexane/Et₂O = 29:1) to afford 4b as a product mixture with 3b. Further purification by GPC provided pure 4b in 44% isolated yield (42 mg, 0.11 mmol). Isolated yield was much lower than the NMR yield because of the difficulty of separation of 3b and 4b.

Supporting Information

Supporting information features experimental procedures and full spectroscopic data for all new compounds (3c, 3d, 3f, 3g, 3h, 3i, 3k, 4a, and 4d).

Supporting Information File 1

Experimental procedures and NMR spectra. [http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-108-S1.pdf]

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References


And see references therein.

And see references for the bioactivity therein.

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Homogeneous and heterogeneous photoredox-catalyzed hydroxymethylation of ketones and keto esters: catalyst screening, chemoselectivity and dilution effects

Axel G. Griesbeck* and Melissa Reckenthäler

Full Research Paper

Abstract
The homogeneous titanium- and dye-catalyzed as well as the heterogeneous semiconductor particle-catalyzed photohydroxymethylation of ketones by methanol were investigated in order to evaluate the most active photocatalyst system. Dialkoxytitanium dichlorides are the most efficient species for chemoselective hydroxymethylation of acetophenone as well as other aromatic and aliphatic ketones. Pinacol coupling is the dominant process for semiconductor catalysis and ketone reduction dominates the Ti(OiPr)₄/methanol or isopropanol systems. Application of dilution effects on the TiO₂ catalysis leads to an increase in hydroxymethylation at the expense of the pinacol coupling.

Introduction
Stimulated by the principles of sustainable chemical synthesis and the progress in our understanding of catalytic and photoinduced electron-transfer processes, in recent years photoredox catalysis emerged as a new and powerful area for advanced synthesis [1-10]. There are numerous features that characterize an effective photoredox catalytic cycle: light absorption, charge separation, charge transport and annihilation as well as the use of appropriate sacrificial compounds such as electron and hole donors, elements that also appear in the natural photosynthesis, the role model for all applications. Catalysts that can function as light-absorbing and as redox-activating species must combine several features: redox-inactivity in the electronic ground states, optimal absorption properties in the near UV or visible region and appropriate redox activity in the excited states. Many potent
photoredox catalysts with sufficient long-term stability are transition metal complexes with excited MLCT states that can be generated in the visible. Another important group of photocatalytic active compounds are semiconductor particles that absorb in the UV-A and near visible region. The widely used TiO$_2$ has found numerous applications in photochemical water detoxification or surface purification because of its favourable excited-state redox properties [11]. In synthetic applications of semiconductor photocatalysis two clearly distinguishable reaction protocols were designated as type A and B by Kisch and co-workers [12-15]. In the type A process, two different products are formed from the initially formed electron–hole pair, one from the substrate radical cation that is formed from electron transfer to the semiconductor valence band hole, the other from the substrate radical anion that is formed from reduction by the semiconductor conduction band electron. Mostly, one of these steps consumes a sacrificial electron/hole donor. In type B photocatalysis, combination of the radical ions leads to a new product without the need of sacrificial components. The latter process proceeds with a high degree of atom economy [16]. We have recently demonstrated this for the azido-hydroperoxidation of alkenes, a convenient method for the synthesis of 1,2-amino alcohols [17,18]. In the field of C–C coupling reactions, the direct hydroxyalkylation of carbonyl compounds and carbonyl analogs is a demanding task because the α-CH activation of alcohols must occur in the presence of the acidic and nucleophilic hydroxy group. Thus, protection and deactivation of this group is necessary for thermal processes. In contrast to that, photochemical redox activation is possible in the presence of titanium(IV) catalysts [19-22]. As shown in a series of papers by Sato and coworkers, carbonyl compounds 1 as well as imines couple with methanol to give the 1,2-diols or 1,2-amino alcohols, respectively, when irradiated in the presence of stoichiometric or sub-stoichiometric amounts of titanium tetrachloride (Scheme 1). In order to run these reactions to completion, not less than 0.5 equivalents of TiCl$_4$ were necessary which accounts for severe catalyst consumption. Furthermore, the addition of TiCl$_4$ to methanol solutions is cumbersome and it is unclear what species is catalytically active. These processes have thermal counterparts in reduced titanium-mediated chemistry, e.g., the Ti(III)/t-BuOOH-mediated hydroxymethylation of imines [23,24].

In order to evaluate the nature of the active catalytic species in the photochemical homogenous titanium-catalyzed hydroxymethylation and to develop a truly catalytic process, we used a model reaction for catalyst screening (acetophenone/methanol) and applied the optimal homogenous reaction conditions involving titanium catalysis to other ketones and keto esters.

\[ \text{Scheme 1: Photohydroxymethylation of carbonyl compounds and imines.} \]

\[ \text{Scheme 2: Model process: photocatalyzed acetophenone/methanol reaction.} \]
<table>
<thead>
<tr>
<th>catalyst</th>
<th>irr. wave-length (nm)</th>
<th>yield 4 (%)</th>
<th>yield 5 (%)</th>
<th>yield 6 (%)</th>
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<tr>
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<td>–</td>
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<td>–</td>
<td>–</td>
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<td>&lt;5&lt;sup&gt;d&lt;/sup&gt;</td>
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</tr>
<tr>
<td>Ti(OiPr)&lt;sub&gt;3&lt;/sub&gt;/AlCl&lt;sub&gt;3&lt;/sub&gt;&lt;sup&gt;d&lt;/sup&gt;</td>
<td>254</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

<sup>a</sup>0.375 mmol catalyst in methanol (6 mL), 0.75 mmol acetophenone, irradiation time 72 h, rt; <sup>b</sup>isolated yields; <sup>c</sup>trace amounts detected in <sup>1</sup>H NMR; <sup>d</sup>0.75 mmol added in methanol; <sup>e</sup>0.375 mmol cat. in isopropanol.

Scheme 3: Photocatalyzed acetophenone/methanol reaction: types I–III.
Table 2: Substrate variation under optimized conditions.

<table>
<thead>
<tr>
<th>entry</th>
<th>Substrate</th>
<th>TiCl₂(OiPr)₂&lt;sup&gt;a&lt;/sup&gt; yield (%)&lt;sup&gt;c&lt;/sup&gt;</th>
<th>TiO₂ P25&lt;sup&gt;b&lt;/sup&gt; yield (%)&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Ti(OiPr)₄&lt;sup&gt;a&lt;/sup&gt; yield (%)&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>type I</td>
<td>type II</td>
<td>type III</td>
</tr>
<tr>
<td>1</td>
<td>Ph(CO)CH₃</td>
<td>60 (4 [28])</td>
<td>82 (5 [29])</td>
<td>46 (6 [30])</td>
</tr>
<tr>
<td>2</td>
<td>Ph(CO)Ph</td>
<td>28 (7 [31])</td>
<td>71 (8 [24])</td>
<td>50 (9 [32])</td>
</tr>
<tr>
<td>3</td>
<td>2'-F-Ph(CO)CH₃</td>
<td>56 (10)</td>
<td>54 (11)</td>
<td>40 (12 [33])</td>
</tr>
<tr>
<td>4</td>
<td>4'-MeO-Ph(CO)CH₃</td>
<td>–</td>
<td>23 (13 [34])</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>4'-NO₂-Ph(CO)CH₃</td>
<td>19 (14 [35])</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>6</td>
<td>4'-Me-Ph(CO)CH₃</td>
<td>27 (15 [36])</td>
<td>54 (16 [34])</td>
<td>16 (17 [37])</td>
</tr>
<tr>
<td>7</td>
<td>C₉H₇(CO)CH₃</td>
<td>92 (18 [38])</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>8</td>
<td>cyclohexanone</td>
<td>38 (19 [39])&lt;sup&gt;d&lt;/sup&gt;</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

<sup>a</sup>0.75 mmol ketone in methanol (6 mL), 0.5 equiv cat., irradiation time 72 h, λ = 254 nm (TiCl₂(OiPr)₂) and 300 nm (Ti(OiPr)₄), rt; <sup>b</sup>0.75 mmol ketone in methanol (6 mL), 1.4 wt % TiO₂ P25, irradiation time 48 h irradiation, λ = 350 nm, rt; <sup>c</sup>isolated yields; <sup>d</sup>mixture consisting of 9% 1,2-diol and 29% acetalization product with cyclohexanone (20).

Scheme 4: Photohydroxymethylation and subsequent lactonization of keto esters.

Table 3: Photohydroxymethylation of keto esters: 1,2-diol and lactone formation.

<table>
<thead>
<tr>
<th>entry</th>
<th>compound&lt;sup&gt;a&lt;/sup&gt;</th>
<th>R&lt;sup&gt;1&lt;/sup&gt;</th>
<th>R&lt;sup&gt;2&lt;/sup&gt;</th>
<th>n</th>
<th>1,2-diol (%)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>lactone A (%)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>lactone B (%)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>Ph</td>
<td>Me</td>
<td>0</td>
<td>15 (26 [41])&lt;sup&gt;c&lt;/sup&gt;</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>Ph</td>
<td>Et</td>
<td>1</td>
<td>–</td>
<td>56 (28 [42])</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>Me</td>
<td>Et</td>
<td>2</td>
<td>–</td>
<td>54 (29)</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>Me</td>
<td>Et</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>28 (30 [43])</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>Me</td>
<td>Me</td>
<td>4</td>
<td>44 (31)</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

<sup>a</sup>0.75 mmol keto ester in methanol (6 mL), 0.5 equiv TiCl₂(OiPr)₂, irradiation time 72 h, λ = 254 nm, rt; <sup>b</sup>isolated yields; <sup>c</sup>additionally 11% of the corresponding pinacol 27 was formed.

From these results, we reasoned that methanol oxidation is the primary event (e.g., from the DCA results) and acetophenone...
Table 4: Heterogeneous sensitizer variation for model reaction in comparison with optimized homogeneous conditions for model process.

<table>
<thead>
<tr>
<th>entry</th>
<th>catalyst</th>
<th>loading</th>
<th>conversion (%)</th>
<th>yield 4 (%)</th>
<th>yield 5 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TiO₂ P25</td>
<td>2.8 wt %</td>
<td>77</td>
<td>–</td>
<td>66</td>
</tr>
<tr>
<td>2</td>
<td>TiO₂ P25</td>
<td>2.8 wt %</td>
<td>76</td>
<td>–</td>
<td>58</td>
</tr>
<tr>
<td>3</td>
<td>TiO₂ P25</td>
<td>2.8 wt %</td>
<td>96</td>
<td>3</td>
<td>83</td>
</tr>
<tr>
<td>4</td>
<td>TiO₂ P25</td>
<td>2.8 wt %</td>
<td>71</td>
<td>–</td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>TiO₂ P25</td>
<td>2.8 wt %</td>
<td>89</td>
<td>6</td>
<td>79</td>
</tr>
<tr>
<td>6</td>
<td>TiO₂ P25</td>
<td>1.4 wt %</td>
<td>95</td>
<td>1</td>
<td>82</td>
</tr>
<tr>
<td>7</td>
<td>TiO₂ P25</td>
<td>3.3 wt %</td>
<td>81</td>
<td>2</td>
<td>74</td>
</tr>
<tr>
<td>8</td>
<td>TiO₂-pigment</td>
<td>2.8 wt %</td>
<td>89</td>
<td>–</td>
<td>69</td>
</tr>
<tr>
<td>9</td>
<td>zinc white</td>
<td>2.8 wt %</td>
<td>79</td>
<td>–</td>
<td>69</td>
</tr>
<tr>
<td>10</td>
<td>WO₃, &lt;100 nm</td>
<td>2.8 wt %</td>
<td>98</td>
<td>–</td>
<td>70</td>
</tr>
<tr>
<td>11</td>
<td>WO₃, &lt;100 nm</td>
<td>1.4 wt %</td>
<td>95</td>
<td>1</td>
<td>75</td>
</tr>
<tr>
<td>12</td>
<td>Fe₂O₃, &lt;50 nm</td>
<td>2.8 wt %</td>
<td>92</td>
<td>–</td>
<td>75</td>
</tr>
<tr>
<td>13</td>
<td>Fe₂O₃, &lt;50 nm</td>
<td>1.4 wt %</td>
<td>95</td>
<td>–</td>
<td>80</td>
</tr>
<tr>
<td>14</td>
<td>ZnO, 6% Al doped, &lt;50 nm</td>
<td>2.8 wt %</td>
<td>63</td>
<td>–</td>
<td>46</td>
</tr>
<tr>
<td>15</td>
<td>InSnO, &lt;50 nm</td>
<td>2.8 wt %</td>
<td>65</td>
<td>–</td>
<td>45</td>
</tr>
<tr>
<td>16</td>
<td>Ir(ppy)₃</td>
<td>2.5 mol %</td>
<td>91</td>
<td>–</td>
<td>50</td>
</tr>
<tr>
<td>17</td>
<td>Ir(ppy)₃</td>
<td>2.5 mol %</td>
<td>65</td>
<td>–</td>
<td>55</td>
</tr>
<tr>
<td>18</td>
<td>Ir(ppy)₃</td>
<td>0.5 mol %</td>
<td>89</td>
<td>–</td>
<td>82</td>
</tr>
<tr>
<td>19</td>
<td>Ru(bpy)₃Cl₂</td>
<td>2.5 mol %</td>
<td>27</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>Ru(bpy)₃Cl₂</td>
<td>2.5 mol %</td>
<td>95</td>
<td>1</td>
<td>94</td>
</tr>
<tr>
<td>21</td>
<td>Ru(bpy)₃Cl₂</td>
<td>0.5 mol %</td>
<td>96</td>
<td>1</td>
<td>92</td>
</tr>
<tr>
<td>22</td>
<td>none</td>
<td>–</td>
<td>&lt;5%</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

a0.75 mmol acetophenone in methanol (6 mL), irradiation time 24 h, λ = 350 nm, rt; b determined by GC; cλ = 300 nm; d600 mg molecular sieves were added; e100 µL H₂O was added; fIr(ppy)₃ regained from entry 16.

Scheme 5: Model reaction for heterogeneous and dye-sensitized catalysis.

Discussion

Three product-forming routes can be assumed for the three classes of products observed in the study (Scheme 6): hydroxymethylation (route I), pinacolization (route II) and reduction/hydrogenation (route III). The crucial primary step for all processes is methanol oxidation [44]. By using appropriate reaction conditions, every route can be switched on exclusively. Hydroxymethylation is favoured if both hydroxyalkyl radicals are generated in close proximity by a coupled electron transfer/back transfer process. According to this expectation, the optimal conditions for route I are fulfilled for TiCl₃(OR)₂, a species that is capable of oxidizing methanol in the excited state and simultaneously acting as a ground-state Lewis acid that complexes the carbonyl compound. A much weaker Lewis acid such as Ti(OR)₄ is capable of methanol oxidation but prefers hydrogen transfer at the first or second oxidation event. The pinacolization route II is favoured for heterogeneous and dye-catalyzed conditions. Interestingly, the combination of TiO₂ P25 with an organic dye prefers largely the hydrogenation route III [45].
Table 5: Chemoselectivity modification by application of a dilution effect.

<table>
<thead>
<tr>
<th>entry</th>
<th>drop rate</th>
<th>TiO\textsubscript{2} in methanol (30 mL)</th>
<th>reaction time</th>
<th>conversion (%)</th>
<th>yield 4 (%)</th>
<th>yield 5 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1\textsuperscript{a}</td>
<td>0.28 mmol/h</td>
<td>15 mg</td>
<td>18.7 h</td>
<td>92</td>
<td>36</td>
<td>52</td>
</tr>
<tr>
<td>2\textsuperscript{a,b}</td>
<td>0.28 mmol/h</td>
<td>15 mg</td>
<td>18.2 h</td>
<td>82</td>
<td>25</td>
<td>38</td>
</tr>
<tr>
<td>3\textsuperscript{a}</td>
<td>0.21 mmol/h</td>
<td>15 mg</td>
<td>24 h</td>
<td>95</td>
<td>33</td>
<td>55</td>
</tr>
<tr>
<td>4\textsuperscript{a}</td>
<td>0.21 mmol/h</td>
<td>10 mg</td>
<td>24 h</td>
<td>89</td>
<td>13</td>
<td>60</td>
</tr>
<tr>
<td>5\textsuperscript{c}</td>
<td>0.16 mmol/h</td>
<td>10 mg</td>
<td>24 h</td>
<td>96</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>

\textsuperscript{a} 5 mmol acetophenone dissolved in methanol (10 mL) was slowly added to a TiO\textsubscript{2} P25 (15 mg/10 mg) suspension in methanol (30 mL) irradiated (300 nm) at 15 °C; \textsuperscript{b} TiO\textsubscript{2} P25 suspension was cooled to \(-5 \textdegree\) °C; \textsuperscript{c} 3.72 mmol acetophenone dissolved in methanol (10 mL) was slowly added to a TiO\textsubscript{2} P25 (10 mg) suspension in methanol (30 mL) irradiated (300 nm) at 15 °C.

Scheme 5: Photoredox initiated steps on semiconductor particle surfaces, CB, VB = conduction and valence band.

On the surface of the relatively large semiconductor particles, combination events are rare between the hydroxymethyl radical from methanol oxidation and the hydroxyalkyl radical from ketone reduction. Thus, further oxidation of the hydroxymethyl species to give methanol and another hydroxyalkyl radical is feasible. The combination of two hydroxyalkyl radicals is then dictated by diffusion kinetics (Scheme 7). The dilution experiments described in Table 5 indicate that the probability for pinacol formation is reduced by reducing the stationary concentration of the aromatic ketone. It was shown that hydroxymethyl radicals are formed from methanol during the photolysis of TiO\textsubscript{2} in the absence of additional acceptor compounds with formation of hydrogen and eventually formation of formaldehyde [46]. Both hydrogen and formaldehyde were also detected in our experiments by gas-phase analysis. Thus, higher amounts of hydroxymethyl radicals can be produced under lower concentration of the acceptor ketone and the probability of hydroxybenzyl radical dimerization (i.e., route II) is disfavoured under these conditions.

Supporting Information
Supporting Information File 1
Experimental part.
[http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-114-S1.pdf]
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Visible-light photoredox catalyzed synthesis of pyrrolo[2,1-a]isoquinolines via organocatalytic oxidation/[3 + 2] cycloaddition/oxidative aromatization reaction cascade with Rose Bengal

Carlos Vila, Jonathan Lau and Magnus Rueping*

Abstract
Pyrrolo[2,1-a]isoquinoline alkaloids have been prepared via a visible light photoredox catalyzed oxidation/[3 + 2] cycloaddition/oxidative aromatization cascade using Rose Bengal as an organo-photocatalyst. A variety of pyrroloisoquinolines have been obtained in good yields under mild and metal-free reaction conditions.

Introduction
Pyrrolo[2,1-a]isoquinolines constitute the core structure of the natural products family lamellarin alkaloids (Figure 1) [1-4]. These alkaloids display numerous biological activities such as inhibitor of human topoisomerase I by lamellarin D [5] or inhibition of HIV integrase by lamellarin α-20-sulfate [6,7]. Moreover lamellarin I and lamellarin K also showed potential antitumor activities [8,9]. Due to their potential biological activities, the synthesis of pyrrolo[2,1-a]isoquinolines has become a very interesting, important and attractive goal in organic synthesis [10-20]. For example, dipolar [3 + 2] cycloaddition using azomethine ylides [21] is a powerful class of reactions that permits the synthesis of structural complex molecules in a straightforward way and has been used for the efficient synthesis of this type of compounds [22-26]. Recently, several metal mediated syntheses using a [3 + 2] cycloaddition reaction have been described in the literature. Porco Jr. et al. [27] described a silver-catalyzed cycloisomerization/dipolar cycloaddition for the synthesis of the pyrrolo[2,1-a]isoquinolines. Wang and co-workers described a copper catalyzed oxidation/[3 + 2] cycloaddition/aromatization cascade [28]. Also, Xiao disclosed a very elegant oxidation/[3 + 2] cycloaddition/aromatization cascade catalyzed by [Ru(bpy)3]3+ under
irradiation with visible light [29]. In this context, very recently Zhao reported the same reaction using C_{60}-Bodipy hybrids [30] and porous material immobilized iodo-Bodipy [31] as photocatalysts, obtaining in both cases good yields for different pyrrolo[2,1-α]isoquinolines. Finally, Lu presented in 2013 a dirhodium complex for the synthesis of these compounds [32]. Despite these elegant and important syntheses of pyrrolo[2,1-α]isoquinolines through dipolar [3 + 2] cycloaddition, the development of metal-free syntheses using visible light photoredox catalysis with simple organic dyes remained unexplored.

Visible-light photoredox catalysis has emerged as an important field and has attracted increasing attention in recent years [33-42]. Thus, in the last years spectacular advances in visible-light photoredox catalysis have been made and this kind of catalysis has become a powerful tool in organic synthesis. In this context, the use of organic dyes as photoredox catalysts [40-42] has been demonstrated by several groups [43-61] and became a useful alternative to the inorganic photoredox catalysts that are expensive and sometimes toxic. The organic dyes have very important qualities such as being inexpensive, environmentally friendly and easy to handle. As a part of our ongoing research on photoredox catalysis [62-72], we herein present a synthesis of pyrrolo[2,1-α]isoquinolines through an oxidation/[3+2] cycloaddition/aromatization cascade catalyzed by Rose Bengal under irradiation with green LEDs.

**Results and Discussion**

Initially, we focused on the reaction between methyl dihydrosquinoine ester 1a and N-methylmaleimide (2a) catalyzed by Rose Bengal. Although the [3 + 2] cycloaddition occurs smoothly in the presence of Rose Bengal (5 mol %) in acetonitrile under irradiation with visible light, the reaction was not selective affording the dihydrosquinoine 3aa in 35% yield and the hexahydropyrrolo[2,1-α]isoquinoline 4aa in 26% yield, after column chromatography (Scheme 1).

In order to improve the selectivity of the reaction to the aromatized product 3aa, N-bromosuccinimide was added to the reaction mixture when the starting materials were completely consumed [29-31, 73]. In this case the desired product 3aa was obtained in 72% yield (Table 1, entry 1). Other organic dyes such as Rhodamine B or Eosin Y were less efficient compared to Rose Bengal (Table 1, entries 2 and 3, respectively). Several solvents were tested without an improvement in the yield of the product (Table 1, entries 4–9). Finally, after tuning the relative amounts of the reagents, the product 3aa was isolated in 76% yield (Table 1, entry 12).

With the optimal conditions in hand, we examined the substrate scope for the photoreaction catalyzed by Rose Bengal (Scheme 2). Various tetrahydrosquinoines with different...
Table 1: Optimization of the reaction conditions.a

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst</th>
<th>Solvent</th>
<th>Yield (%)b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rose Bengal</td>
<td>CH$_3$CN</td>
<td>72</td>
</tr>
<tr>
<td>2</td>
<td>Rhodamine B</td>
<td>CH$_3$CN</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>Eosin Y</td>
<td>CH$_3$CN</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>Rose Bengal</td>
<td>THF</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>Rose Bengal</td>
<td>CH$_2$Cl$_2$</td>
<td>26</td>
</tr>
<tr>
<td>6</td>
<td>Rose Bengal</td>
<td>toluene</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>Rose Bengal</td>
<td>DMF</td>
<td>65</td>
</tr>
<tr>
<td>8</td>
<td>Rose Bengal</td>
<td>MeOH</td>
<td>52</td>
</tr>
<tr>
<td>9</td>
<td>Rose Bengal</td>
<td>EtOAc</td>
<td>16</td>
</tr>
<tr>
<td>10</td>
<td>Rose Bengal</td>
<td>CH$_3$CN</td>
<td>64</td>
</tr>
<tr>
<td>11</td>
<td>Rose Bengal</td>
<td>CH$_3$CN</td>
<td>60</td>
</tr>
<tr>
<td>12</td>
<td>Rose Bengal</td>
<td>CH$_3$CN</td>
<td>76</td>
</tr>
</tbody>
</table>

aReaction conditions: 1a (0.2 mmol), 2a (0.2 mmol), organic dye (5 mol %), solvent (1 mL), green LEDs irradiation for 24 hours. NBS (1.1 equiv) was added to the reaction mixture and stirring was continued for 1 hour. bYields of the isolated products after column chromatography. c1.25 equiv of 1a was used. d1.25 equiv of 2a was used. e1.1 equiv of 1a was used.

Scheme 2: Evaluation of the substrate scope.
Scheme 3: Evaluation of the substrate scope with activated alkynes.

1. R1 = CO2Me, 1a; R² = H, 6aa
2. R1 = CO2Me, R² = H, 30% yield
3. R1 = CO2Me, R² = CO2Me, 52% yield
4. R1 = CO2Et, R² = CO2Me, 44% yield
5. R1 = CN, R² = CO2Me, 65% yield

electron-withdrawing groups (R²) such as methyl ester (1a),
exteryl ester (1b), tert-butyl ester (1c), cyano (1d) or aromatic
ketone (1e) were reacted with N-methylmaleimide (2a) and
gave the corresponding products 3 in moderate to good yields.
In addition, different N-substituted maleimides were tested
under the optimized reaction conditions to give the corres-
ponding products with good yields. Incorporation of methoxy
groups at C-6 and C-7 in the dihydroisoquinoline core was well
tolerated, affording the corresponding product 3fa in 68% yield.

To demonstrate the synthetic utility of the oxidation/[3 + 2]
cycloaddition/aromatization cascade we examined other diplo-
arophiles such as activated alkynes 5. In this case, the addition
of NBS was not necessary, and the corresponding products 6
were isolated in moderate yields (Scheme 3).

Conclusion

In conclusion, we have developed a metal-free photoredox oxi-
dation/[3 + 2] dipolar cycloaddition/oxidative aromatization
cascade catalyzed by Rose Bengal using visible-light. This
protocol offers a "green" and straightforward synthesis of pyrrolo-
[2,1-a]isoquinolines starting from readily available
maleimides and tetrahydroisoquinolines. Further investigations
to expand the scope and potential of this methodology are
underway in our laboratory.

Supporting Information

Supporting Information File 1
Experimental details and characterization of the synthesized
compounds.
[http://www.beilstein-journals.org/bjoc/content/
supplementary/1860-5397-10-122-S1.pdf]

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Cyclization–endoperoxidation cascade reactions of dienes mediated by a pyrylium photoredox catalyst

Nathan J. Gesmundo and David A. Nicewicz*

Abstract

Triarylpyrylium salts were employed as single electron photooxidants to catalyze a cyclization–endoperoxidation cascade of dienes. The transformation is presumed to proceed via the intermediacy of diene cation radicals. The nature of the diene component was investigated in this context to determine the structural requirements necessary for successful reactivity. Several unique endoperoxide structures were synthesized in yields up to 79%.

Introduction

Endoperoxides are a structurally unique class of naturally-occurring compounds that feature a reactive cyclic peroxide moiety of varying ring sizes (Figure 1). The lability of the endocyclic peroxide O–O bond engenders these compounds with a range of important biological functions, most notably, antimalarial and antitumor activity (e.g., artemisinin, yingzhaosu A and merulin C) [1-4]. From a synthetic standpoint, the installation of the endoperoxide moiety presents a significant challenge due to its susceptibility to reduction and for this reason, is ideally introduced late-stage in target-oriented synthesis. Additionally, many endoperoxide natural products possess architecturally complex frameworks (e.g., artemisinin, yingzhaosu A, muurolan-4,7-peroxide) [5] that pose significant synthetic challenges.

Classical approaches to the introduction of cyclic peroxides typically rely on cycloadditions of alkenes and dienes with singlet oxygen. However, ene processes can often compete, leading to complex mixtures of hydroperoxide adducts [1,6-8]. More recently, cyclization reactions of hydroperoxides with pendant alkenes or alkynes have been developed. Selected examples include Pd(II)-catalyzed hydroalkoxylation reactions of unsaturated hydroperoxides [9], Au(I)-catalyzed endoperoxidation of alkynes [10] and Brønsted acid-catalyzed enantioselective acetalization/oxa-Michael addition cascade reactions of peroxyquinols [11].

While these extant methods are effective at installing the endoperoxide functional group, our interest lay in developing strate-
Figure 1: Selected examples of endoperoxide-containing natural products.

Miyashi:

\[ \text{Ar} = 4-(\text{MeO})\text{C}_6\text{H}_4 \]

\[ \text{Ar} = 4-(\text{MeO})\text{C}_6\text{H}_4 \]

Yoon:

\[ \text{Ar} = 4-(\text{MeO})\text{C}_6\text{H}_4 \]

\[ \text{Ar} = 4-(\text{MeO})\text{C}_6\text{H}_4 \]

We envisioned that the scope of this transformation could be extended to include non-styrenal dienes as well as alternative cyclization modes, provided that a potent single electron oxidant could be identified (\(E_{\text{red}} > +1.5 \text{ V vs SCE}\)). Given the paucity of ground-state single electron oxidants capable of this task, we elected to employ photooxidation catalysts. Additionally, we sought to select visible light-activated organic single electron oxidants that do not readily sensitize singlet oxygen [17-19]. For these reasons, we were attracted to the use of triarylmethylpyrylium salts, as they have excited state reduction potentials in excess of +1.7 V vs SCE (Scheme 2) [20]. In addition, prior work demonstrates that these catalysts are productive in cation radical mediated [4 + 2], [2 + 2], oxygenation, and rearrangement chemistry [21,22]. We also sought to delineate the reactivity of the diene with respect to its structure to better predict the mode of diene cation radical cyclization ([5-endo vs [6-endo]]).
Scheme 2: Diversification strategy for endoperoxide synthesis by single electron transfer. \( E_{\text{red}}^* \) vs SCE [20].

6-endo). Herein is reported an organocatalytic photoredox-mediated strategy for the endoperoxidation of 1,5-dienes using \( ^{1}\text{O}_2 \) to rapidly generate complex endoperoxide frameworks.

Results and Discussion

Reaction optimization

We began our investigation into endoperoxidation conditions with diene 2a as the substrate as it contained both a styene and an aliphatic olefin. Using catalyst 1c in DCM at \(-41 \, ^\circ \text{C}\) under irradiation with 470 nm LEDs afforded endoperoxide 3a in 40% yield after 5 hours (Table 1, entry 1). The observed endoperoxide was attributed to a 5-exo cyclization mode of the diene cation radical followed by capture of molecular oxygen. The use of acetonitrile as solvent gave none of the desired adducts (Table 1, entry 2). Further improvement of the chemical yield of 3a was realized by increasing the reaction concentration

### Table 1: Reaction Optimization and Control Experiments.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Conditions</th>
<th>Conversion</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 mol % 1c, 0.01 M DCM, (-41 , ^\circ \text{C})</td>
<td>100%</td>
<td>40%</td>
</tr>
<tr>
<td>2</td>
<td>2 mol % 1c, 0.01 M MeCN, (-41 , ^\circ \text{C})</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>3</td>
<td>2 mol % 1c, 0.02 M DCM, (-41 , ^\circ \text{C})</td>
<td>100%</td>
<td>63%</td>
</tr>
<tr>
<td>4</td>
<td>1 mol % 1c, 0.05 M DCM, (-41 , ^\circ \text{C})</td>
<td>100%</td>
<td>63%</td>
</tr>
<tr>
<td>5</td>
<td>0.7 mol % 1c, 0.07 M DCM, (-41 , ^\circ \text{C})</td>
<td>100%</td>
<td>70%</td>
</tr>
<tr>
<td>6c</td>
<td>Excluding ( \text{O}_2 )</td>
<td>11%</td>
<td>0%</td>
</tr>
<tr>
<td>7</td>
<td>Excluding hv</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>8</td>
<td>Excluding catalyst 1c</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>9</td>
<td>9-Mes-10-Me-Acr-BF(_4) in place of 1c</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>10d</td>
<td>Rose Bengal in place of 1c</td>
<td>100%</td>
<td>0%</td>
</tr>
</tbody>
</table>

All reactions carried out in oxygen-saturated solvents unless otherwise noted. \(^\text{a}\) \(-41 \, ^\circ \text{C}\) found to be the optimum temperature during initial substrate reaction optimization. \(^\text{b}\) Yields with respect to \((\text{Me}_3\text{Si})_2\text{O}\) \(^1\text{H}\) NMR internal standard. \(^\text{c}\) Reaction carried out under \( \text{N}_2 \) atmosphere in DCM. \(^\text{d}\) Reaction carried out in oxygen-saturated MeOH at room temperature using a white flood lamp.
(Table 1, entries 3–5), resulting in a 70% yield (1H NMR) of the endoperoxide (Table 1, entry 5). In all reactions, substrate conversion was 100%, with the remainder of the mass balance in all cases representing oxidative decomposition pathways. When O2 was excluded from the reaction (Table 1, entry 6), none of the endoperoxide was observed. Not surprisingly, exclusion of light or catalyst 1c from the reaction (Table 1, entries 7 and 8 respectively) resulted in no product formation. Interestingly, when 9-mesityl-10-methylacridinium tetrafluoroborate, which has been used with success in other photooxidation processes [23-26], was used in place of 1c, complete consumption of 2a was observed, but 3a was not produced. Once again only oxidative decomposition pathways seemed active, this time possibly due to superoxide formation. Lastly, to exclude the intervention of a singlet oxygen mechanism, we conducted the reaction in the presence of Rose Bengal. Under these conditions, we observed only 1O2 ene reactivity with the isoprenyl group (65% yield of hydroperoxide), underscoring the unique reactivity garnered by this catalyst system (see Supporting Information File 1 for hydroperoxide characterization). Suitable crystals of 3a provided X-ray confirmation of the endoperoxide structure (Figure 2).

We invoke a mechanism similar to that proposed by Miyashi [12] and Yoon [15] in their respective transformations (Scheme 3). Following excitation of triarylpypylium tetrafluoroborate catalyst 1, one-electron oxidation of the 1,5-diene substrate produces localized cation radical intermediate 4 and pyranyl radical 1*. Cyclization of diene cation radical 4 then forms stabilized distonic cation radical intermediate 5, which is intercepted by O2 to form 6. Single electron reduction, either from 1* to regenerate active catalyst 1 or from another substrate equivalent in a chain process, forms the desired bicyclic endoperoxide.

DFT calculations suggest that the formation of the initial distonic cation radical 5 is exothermic by approximately 3 kcal/mol relative to cation radical 4 [27]. Superficially, this is rationalized by the increased substitution on 5 relative to 4. In addition, the majority of the spin density on 5 is located on the isoprenyl group (DFT-5, Scheme 3). This may be fortuitous as...
stereoselectivity in the oxygen addition step is irrelevant, whereas the opposite scenario involving a benzylic radical inter-
mediate would require a stereospecific addition of oxygen to the same face of the cyclopentane system as the isoprenyl cation in order for endoperoxide formation to occur.

With optimized conditions identified, we sought to examine the scope of the reaction with respect to the diene structure. Miyashi’s 1,5-diene ($2b$; $E_{1/2}^{Ox} = 1.22$ V vs SCE [12]) afforded a 50% yield of the expected endoperoxide along with ~5% of a 1,4-dione, presumably from double oxidative cleavage of the 1,5-diene (Table 2, entry 1). Unfortunately, attempts to move away from $2b$ to less electron-rich dienes such as $2c$, $2d$ and $2e$ (Table 1, entries 2–4), failed to produce any of the desired endoperoxide products and mainly oxidative cleavage adducts were observed.

Table 2: Diene structure investigation for endoperoxidation cascade.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Expected adduct</th>
<th>Yield $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\text{Ar} = 4$-MeO-C$_6$H$_4$</td>
<td>$2b$</td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>$\text{Ar} = 4$-MeO-C$_6$H$_4$</td>
<td>$2c$</td>
<td>0%</td>
</tr>
<tr>
<td>3</td>
<td>$\text{Ar} = 4$-MeO-C$_6$H$_4$</td>
<td>$2d$</td>
<td>0%</td>
</tr>
<tr>
<td>4</td>
<td>$\text{Ar} = 4$-MeO-C$_6$H$_4$</td>
<td>$2e$</td>
<td>0%</td>
</tr>
<tr>
<td>5</td>
<td>$\text{Ar} = 4$-MeO-C$_6$H$_4$</td>
<td>$2a$</td>
<td>66%</td>
</tr>
<tr>
<td>6</td>
<td>$\text{Ar} = 4$-MeO-C$_6$H$_4$</td>
<td>$2f$</td>
<td>32%</td>
</tr>
</tbody>
</table>
Table 2: Diene structure investigation for endoperoxidation cascade. (continued)

<table>
<thead>
<tr>
<th>7</th>
<th>Ar = 2,4-(MeO)₂-C₆H₃</th>
<th>9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Ar = 3,4-(MeO)₂-C₆H₃</td>
<td>0%</td>
</tr>
<tr>
<td>9</td>
<td>Ar = 2-MeO-C₆H₄</td>
<td>16%</td>
</tr>
<tr>
<td>10</td>
<td>Ar = 4-Me-C₆H₄</td>
<td>0%</td>
</tr>
<tr>
<td>11</td>
<td>Ar = 4-Cl-C₆H₄</td>
<td>0%</td>
</tr>
<tr>
<td>12</td>
<td>Ar = 2-furyl</td>
<td>0%</td>
</tr>
</tbody>
</table>

All reactions carried out in oxygen-saturated solvents. Solvents examined: DCM, CHCl₃, MeCN, PhMe, acetone. **Catalysts 1a, 1b, and 1c screened for reactivity with all substrates.**

The geminal dimethyl group (2f) resulted in significantly diminished yields of the endoperoxide adduct, likely due to the lack of a Thorpe–Ingold effect present in 2a. These experiments also demonstrated that the electron-rich arene was necessary for reactivity (cf. 2e and 2f; Table 2, entries 4 and 6). The importance of the electron-rich arene may lie in the necessary distonic cation radical intermediate: the electron-rich arene may provide greater stability to the distonic intermediate formed after 5-exo-trig cyclization, ultimately ensuring it remains to intercept oxygen. A further survey of the styrene component supported this hypothesis. While electron-rich styrenes gave modest amounts of product formation (2f, 2g and 2i; Table 2, entries 6, 7 and 9), styrenes with either weakly donating (4-Me; Table 2, entry 10) or even withdrawing (4-Cl; Table 2, entry 11) functionality furnished none of the expected endoperoxides. In these cases, oxidative degradation was observed as was the case with the highly oxidizable 2-furyl group (Table 2, entry 12). Interestingly, 3,4-dimethoxystyrene-substituted diene 2h also gave none of the desired adduct, which we attributed to lack of charge density on the alkene [28,29].
We next investigated the endoperoxidation cascade by replacing the isoprenyl substituent with a variety of other alkenes. A pendant styrene afforded the desired endoperoxide adduct in 68% yield, albeit with no diastereocontrol (2m, 1:1 dr; Table 3, entry 1). A diene bearing a tetrasubstituted alkene (2n) was reactive in this context, giving polycyclic endoperoxide 3n in 64% yield (6.5:1 dr). The use of 1,2-, 1,1-dialkyl as well as monoalkyl-substituted alkenes appeared to completely disfavor

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Observed product</th>
<th>Yielda</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b</td>
<td><img src="PMP" alt="2m" />Ph</td>
<td><img src="PMP" alt="3m" />Ph</td>
<td>68%, 1:1 d.r.</td>
</tr>
<tr>
<td>2c</td>
<td><img src="PMP" alt="2n" /></td>
<td><img src="PMP" alt="3n" /></td>
<td>64%, 6.5:1 d.r.</td>
</tr>
<tr>
<td>3d</td>
<td><img src="PMP" alt="2o" />Me</td>
<td><img src="PMP" alt="3o" />Me</td>
<td>36%</td>
</tr>
<tr>
<td>4d</td>
<td><img src="PMP" alt="2p" />Me</td>
<td><img src="PMP" alt="3p" />Me</td>
<td>37%</td>
</tr>
<tr>
<td>5d</td>
<td><img src="PMP" alt="2q" />Me</td>
<td><img src="PMP" alt="3q" />Me</td>
<td>27%</td>
</tr>
<tr>
<td>6°</td>
<td><img src="PMP" alt="2r" />Me</td>
<td>–</td>
<td>0%</td>
</tr>
<tr>
<td>7°</td>
<td><img src="PMP" alt="2s" />Me</td>
<td>–</td>
<td>0%</td>
</tr>
</tbody>
</table>

Reactions carried out in oxygen-saturated solvents. aAverage of two isolated yields. b1:1 mixture of separable diastereomers. e6.5:1 mixture of inseparable diastereomers. Presumed major diastereomer shown. dDesired endoperoxide never observed. eMultiple conditions tested, no productive chemistry observed.

![Table 3: Variation of the tethered alkene component.](image)
the endoperoxidation pathway and resulted in the unexpected isolation of \( \alpha \)-allyl ketones (Table 3, entries 3–5) in modest yields. Based on the Miyashi precedent, the formation of these adducts can be rationalized by invoking a formal [3,3]-rearrangement of the initial cation radical intermediate. The competing 6-endo cyclization mode and formation of distonic cation radical 9 ultimately provides access to the more stabilized cation radical 10, which undergoes oxidative cleavage to afford the corresponding \( \alpha \)-allyl ketones (Scheme 4). In the absence of the geminal dimethyl group (2r, 2s), neither the Cope-like reactivity or the endoperoxidation was observed (Table 3, entries 6 and 7).

Lastly, we elected to explore cyclization modes similar to the Yoon work under the developed conditions. Diene 2t was anticipated to undergo 6-exo-trig cyclization to form the necessary distonic cation radical intermediate (Table 4, entry 1). The expected trioxabicyclo[3.3.1]nonane product was formed, albeit

Table 4: Other cyclization modes and substrate designs.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Desired product</th>
<th>Yield ( ^a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1( ^b )</td>
<td>Ar = 4-MeO-C(_6)H(_4) ( 2t )</td>
<td>Ar = 4-MeO-C(_6)H(_4) ( 3t )</td>
<td>16%</td>
</tr>
<tr>
<td>2</td>
<td>Ar = 4-MeO-C(_6)H(_4) ( 2u )</td>
<td>Ar = 4-MeO-C(_6)H(_4) ( 3u )</td>
<td>79%, 5.7:1 d.r.</td>
</tr>
<tr>
<td>3</td>
<td>Ar = 4-MeO-C(_6)H(_4) ( 2v )</td>
<td>Ar = 4-MeO-C(_6)H(_4) ( 3v )</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>4( ^c )</td>
<td>Ph ( 2w )</td>
<td>Ph ( 2w )</td>
<td>0%</td>
</tr>
</tbody>
</table>

Reactions carried out in oxygen-saturated dichloromethane. \(^a\)Average of two isolated yields. \(^b\)Carried out in 0.4 M DCE after solvent and concentration optimization. \(^c\)Catalysts 1a or 1b were also tested but failed to furnish the endoperoxide.
in low yields (16%), where the remainder of the mass balance was attributed to oxidative degradation.

Bis(styrene) 2u afforded the identical fused 1,2-dioxane observed in Yoon’s report in 79% yield (5.7:1 dr). Tethered trisubstituted aliphatic alkene substrate 2v, along with bis(styrene) substrate 2w were unfortunately unsuccessful, producing neither of the desired fused 1,2-dioxane products in appreciable amounts. Degradation pathways were dominant for 2v and mainly unreacted starting material was observed 2w.

Conclusion
In the presence of an organic single electron photooxidant, a variety of dienes were demonstrated to undergo a cyclization/endoperoxidation cascade sequence to form 1,2-dioxanes. In the presence of an organic single electron photooxidant, a cation radical. If available, a Cope-like pathway can compete the putative alkene cation radical to form a more stable distonic oxidizable olefin and an alkene that can efficiently react with novel biologically-active endoperoxides.

Supporting Information
Supporting Information File 1
Experimental procedures and characterization data. [http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-128-S1.pdf]

Supporting Information File 2
X-ray data. [http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-128-S2.pdf]

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References
27. Gaussian 09, Revision D.01; Gaussian, Inc.: Wallingford CT, 2013.
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Visible light photoredox-catalyzed deoxygenation of alcohols

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Full Research Paper

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Keywords:
C–O bond activation; deoxygenation; photochemistry; photoredox catalysis; visible light

Abstract
Carbon–oxygen single bonds are ubiquitous in natural products whereas efficient methods for their reductive defunctionalization are rare. In this work an environmentally benign protocol for the activation of carbon–oxygen single bonds of alcohols towards a reductive bond cleavage under visible light photocatalysis was developed. Alcohols were activated as 3,5-bis(trifluoromethyl)-substituted benzoates and irradiation with blue light in the presence of [Ir(ppy)$_2$(dtb-bpy)](PF$_6$) as visible light photocatalyst and Hünig’s base as sacrificial electron donor in an acetonitrile/water mixture generally gave good to excellent yields of the desired defunctionalized compounds. Functional group tolerance is high but the protocol developed is limited to benzylic, α-carbonyl, and α-cyanoalcohols; with other alcohols a slow partial C–F bond reduction in the 3,5-bis(trifluoromethyl)benzoate moiety occurs.

Introduction
The dwindling supply of hydrocarbons from fossil resources calls for the usage of renewable resources for the synthesis of fine chemicals in the future [1]. This strategy suffers from the relative high degree of functionalization of feedstock materials, which is often not desired in fine chemicals and further leads to compatibility issues in chemical transformations. Carbon–oxygen single bonds are common elements in natural materials and their reduction to non-functionalized carbon–hydrogen bonds decreases complexity and increases compatibility of those materials in further chemical manipulations in accordance with established oil-based protocols developed in the chemical industry during the last century.

A classical radical deoxygenation reaction using over-stoichiometric amounts of highly noxious chemicals [2] is the Barton–McCombie reaction, although nowadays several improved protocols are available [3]. Radical deoxygenations can also be carried out electrochemically [4] or photochemically [5-9]. In all these cases an activation of the hydroxy group is necessary, either via conversion to the corresponding halide or formation of an ester derivative, which consequently generates over-stoichiometric amounts of byproducts. Related to this work, Stephenson et al. elegantly succeeded in the direct deoxygenation of alcohols by their in situ conversion to iodoses using triphenylphosphine and iodine followed by visible light-medi-
ated reduction with amines as stoichiometric sacrificial electron donor and \( \text{fac-Ir(ppy)}_3 \) (ppy = 2-phenylpyridine) as photoredox catalyst (Scheme 1) [10]. This protocol is applicable to a broad range of alcohols. It also greatly advanced the quest to develop sustainable methods for the deoxygenation of alcohols. Yet, several redox steps, i.e., the stoichiometric transformation of triphenylphosphine to triphenylphosphine oxide and iodine to iodide, are required, which appears to be problematic for establishing a sustainable protocol that allows the recycling and reuse of the reagents involved. Herein we report a redox economic deoxygenation method of alcohols in which formation of radicals is achieved under visible light photocatalysis and the auxiliary activation group can be readily recovered and reused.

This method, ultimately requiring only energy and a tertiary amine as stoichiometric reductant, gives high yields after short illumination times under mild conditions for the deoxygenation of benzylic alcohols, α-hydroxycarbonyl, and α-cyanohydrin compounds. Moreover, the selective catalytic monoacylation of diols is possible, thus allowing efficient monodeoxygenations as exemplified in the conversion of (+)-diethyl tartrate to unnatural (+)-diethyl malate.

Results and Discussion

Following the lead of photochemical deoxygenations under UV light irradiation (vide supra) we envisioned carboxylic ester derivatives as substrates for initial test reactions. Benzoate esters were chosen due to the potentially very facile recovery of the benzoic acids used for activation. Through variation of the substitution pattern of benzoates we intended to shift the electrochemical reduction potentials of the substances into a region that could be accessed by common visible light photocatalysts. The substituents should be as inert as possible in order not to interfere with the photochemical reaction itself. Therefore different trifluoromethyl-substituted benzoates were prepared and subjected to cyclovoltammetric measurements. 3,5-Bis(trifluoromethyl)-substituted benzoate 3 showed the most promising reduction potential of the compounds investigated (Scheme 2) and was therefore expected to be most susceptible for an initial photoredox electron transfer that we considered in analogy to the Barton–McCombie technology to be crucial to trigger deoxygenations.

Initial deoxygenation experiments were carried out with either Ru(bpy)_3Cl_2·6H_2O [bpy = 2,2′-bipyridine] or [Ir(ppy)_2(dtbbpy)](PF_6) [ppy = 2-phenylpyridine; dtbbpy = 4,4′-di-tert-

**Scheme 1**: Strategies for the visible light-catalysed deoxygenation of alcohols (reagents needed in (over-)stoichiometric quantities are depicted in blue).
butyl-2,2'-bipyridine] as photocatalysts, Hantzsch ester (diethyl 1,4-dihydro-2,6-dimethyl-3,5-pyridinedicarboxylate) as hydrogen donor, and iPr₂NEt as sacrificial electron donor in DMF (Scheme 3). Light generated from a high power LED was channeled into the reaction solution in a Schlenk tube through a glass rod from above while magnetic stirring and heating was applied from below. This reaction setup is superior compared to conventional ones that are carried out in a vessel with external irradiation: a high light intensity can be achieved for irradiation and reaction temperatures can be manipulated very conveniently by heating in a conventional oil bath while carrying out the photoreaction. Also light pollution is kept to a minimum, which renders the apparatus an optimal device for the fast setup of test reactions.

In agreement with the reduction potentials, 3,5-bis(trifluoromethyl)-substituted benzoate 3 gave the best results in the deoxygenation reaction while esters 1 and 2 led to incomplete reactions after 16 h of irradiation (Table 1). The performance of [Ir(ppy)₂(dtbbpy)][PF₆] was in all cases superior as compared to Ru(bpy)₃Cl₂·6H₂O, possibly due to its increased reduction potential (\(E^0 = -1.51\) V vs \(E^0 = -1.31\) V) [11].

Having identified a promising activation group for deoxygenation in combination with an iridium-based photocatalyst, different solvents and reaction temperatures were examined for the conversion of 3 (Table 2). Gratifyingly, toxic DMF could be replaced with more benign acetonitrile without appreciable decreasing the yield (Table 2, entry 2). The reaction also proceeded in less polar solvents (Table 2, entries 3 and 4), albeit yields were significantly lower. When the reaction was performed at ambient temperature 4 was only formed in 41% yield after 16 h of irradiation (Table 2, entry 5). Control experi-
Table 1: Comparison of different esters and photocatalysts in deoxygenation reaction.

<table>
<thead>
<tr>
<th>Photocatalyst</th>
<th>Compound yield [%](^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ru(bpy)(_3)Cl(_2)·6H(_2)O</td>
<td>5 8 10</td>
</tr>
<tr>
<td><a href="PF(_6)">Ir(ppy)(_2)(dtb-bpy)</a></td>
<td>18 20 85</td>
</tr>
</tbody>
</table>

\(^a\)All yields determined by GC–FID with dodecane as internal standard.

Table 2: Solvent/temperature dependence and control experiments of deoxygenation reaction with 3,5-bis(trifluoromethyl)benzoate 3.\(^a\)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Solvent, modification</th>
<th>Yield (%)(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DMF</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>MeCN</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>DCM</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>THF</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>MeCN, rt</td>
<td>41</td>
</tr>
<tr>
<td>6</td>
<td>MeCN, w/o photocatalyst</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>MeCN, w/o light source</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>MeCN, w/o Hantzsch ester</td>
<td>91</td>
</tr>
<tr>
<td>9</td>
<td>MeCN, w/o iPr(_2)NEt</td>
<td>53</td>
</tr>
</tbody>
</table>

\(^a\)Conditions see Table 1. \(^b\)All yields determined by GC–FID with dodecane as internal standard.

ments suggest that the deoxygenation reaction of 3,5-bis(trifluoromethyl)benzoate 3 is indeed a photochemically mediated process (Table 2, entries 6 and 7): when either the photocatalyst (Table 2, entry 6) or the light source (Table 2, entry 7) was omitted significantly lower yields were obtained. Leaving out Hantzsch ester (Table 2, entry 8) apparently does not impede the deoxygenation while carrying out the reaction without Hünig’s base lowers the yield (Table 2, entry 9), nevertheless, 4 was still formed to a significant extent. These results suggest that Hantzsch ester is not necessary as the hydrogen source but likewise that reductive quenching of the photocatalyst is not exclusively accomplished by Hünig’s base.

We assumed that the mechanism of the deoxygenation reaction involves an electron uptake of the ester moiety from the reductively quenched photocatalyst followed by mesolysis and subsequent hydrogen abstraction (Scheme 4). Quantum mechanical calculations (B3LYP/6-31G*) for benzhydryl 3,5-bis(trifluoromethyl)benzoate (3) revealed that the electron density of the presumed transient radical anion is mainly located at the phenyl moiety of the benzoate – and not in the desired anti-bonding \(\sigma^*(C–O)\) (Scheme 5). Protonation of the radical anion would lead to a neutral radical species, which in the calculations reflects in a shift of electron density towards the C–O bond to be cleaved.

Consequently, a mixture of acetonitrile/water (14:1) was explored as reaction medium, resulting to our delight in dramatically reduced reaction times to achieve full conversion. Starting from bis(trifluoromethyl)benzoates, quantitative formation of the deoxygenated products could be already observed after 20 minutes of irradiation.

A simple iridium-catalyzed hydrogenation mechanism as an alternative for a photochemical pathway of the reaction could be ruled out; in the presence of 5 atm H\(_2\) without irradiation under otherwise unchanged reaction conditions no deoxygenation of the benzoates could be observed even after prolonged reaction times.

Scheme 4: Proposed reaction mechanism with and without additional water.
With the newly optimized reaction conditions at hand different benzylic alcohol derivatives were investigated (Table 3). Uniformly very good isolated yields after short reaction times were achieved in case of dibenzylic alcohol derivatives. Steric bulk (Table 3, entry 2), as well as a broad range of functional groups with different electronic properties, i.e., an electron-donating \( p \)-methoxy substituent (Table 3, entry 3), electron-withdrawing \( p \)-nitro substituent (Table 3, entry 4), ester group containing systems (Table 3, entry 5), chlorinated derivatives (Table 3, entry 6) and electron-deficient heteroaromatic systems (Table 3, entry 7) were well tolerated, giving the corresponding deoxygenated products in analytical pure form in high yields after filtration through a short plug of silica gel. Noteworthy, no reduction of reducible groups such as nitro (Table 3, entry 4) or chloro (Table 3, entry 5) was observed. Moving to monobenzylic alcohols, e.g., replacement of one aromatic group with an alkyl chain resulted in prolonged reaction times but nevertheless acceptable yields of the deoxygenated products (Table 3, entries 8 and 9). With \( \alpha \)-carbonyl-substituted benzylic alcohol derivatives irradiation times could be reduced again and defunctionalized materials were isolated in moderate to good yields (Table 3, entries 10 and 11). Bis(trifluoromethyl)benzoic acid 5 could easily be recovered (>90%) in an acid–base extraction step.

Also bis(trifluoromethyl)benzoates of non-benzylic \( \alpha \)-cyanohydrin 6a and \( \alpha \)-hydroxycarbonyl compounds 6b–e turned out to be amenable for the desoxygenation process (Table 4).

**Table 3: Preparative deoxygenation reactions.**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Product</th>
<th>Yield (%)(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3a(^\text{Ph} \text{Ph})</td>
<td>4a(^\text{Ph} \text{Ph})</td>
<td>95</td>
</tr>
<tr>
<td>2</td>
<td>3b(^\text{Ph})</td>
<td>4b(^\text{Ph})</td>
<td>86</td>
</tr>
<tr>
<td>3</td>
<td>3c(^\text{MeO} \text{Ph})</td>
<td>4c(^\text{MeO} \text{Ph})</td>
<td>87</td>
</tr>
<tr>
<td>4</td>
<td>3d(^\text{O}_2\text{N} \text{Ph})</td>
<td>4d(^\text{O}_2\text{N} \text{Ph})</td>
<td>91</td>
</tr>
</tbody>
</table>
Table 3: Preparative deoxygenation reactions. (continued)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Product</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>EtO₂C₆H₄Ph₃e₄f</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Cl₆H₄Ph₃f₄f</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Py₆H₄Ph₃g₄g</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Ph₃h₃h</td>
<td>66ᵇᶜ</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>N₃i₃i</td>
<td>79ᶜ</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3j₃j</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>3k₃k</td>
<td>67</td>
<td></td>
</tr>
</tbody>
</table>

ᵃIsolated yields of reactions conducted at a 0.2–1.0 mmol scale. ᵇDetermined by GC with dodecane as internal standard. ᶜ16 h reaction time.

Table 4: Preparative deoxygenation reactions of non-benzylic benzoates. ᵃ

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Product</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6a</td>
<td>7a</td>
<td>86</td>
</tr>
<tr>
<td>2</td>
<td>6b</td>
<td>7b</td>
<td>79</td>
</tr>
<tr>
<td>3</td>
<td>6c</td>
<td>7c</td>
<td>14ᵇ</td>
</tr>
</tbody>
</table>
Especially interesting from a preparative point of view, the monodeoxygenation of diethyl tartrate to maleate could be achieved from 6e in excellent yields (Table 4, entry 5). Notably, after screening various Lewis acids (Supporting Information File 1) it was found that 6e could be selectively prepared by copper(II) chloride-catalyzed benzylation of diol 8 with anhydride 9, which in turn can be generated from its acid 5 by treatment with acetic anhydride (Scheme 6).

Since acetic anhydride is technically being produced by thermal dehydration of acetic acid [12], the overall sequence to the benzoylated starting material 6e does not require any type of activation reagents such as thionyl chloride or DCC that are often used for ester formation, but ultimately only requires energy in form of heat. After the photochemical deoxygenation, 3,5-bis(trifluoromethyl)benzoic acid (5) is formed, which can be easily recovered in high yield and from which anhydride 9 can be regenerated as described above.

Attempts to deoxygenate simple alkyl-substituted alcohols (primary, secondary and tertiary) were not successful; for example under typical conditions 3,5-bis(trifluoromethyl)benzoates such as 10 gave 12 where one trifluoromethyl group was completely reduced to a methyl group in 52% yield (Scheme 7). Apparently, electron transfer to the benzoate group is still possible however, the subsequent C–O bond cleavage does not occur, presumably due to the energetically unfavorable primary radical intermediate that would result via the desired cleavage of the C–O bond. Instead, carbon–fluorine cleavage, leading to a benzylic radical, is the preferred pathway.

To unambiguously rule out that the methyl group in 12 originates from a substitution process with acetonitrile as the methyl source, the reaction was carried out in deuterated acetonitrile. No deuterium incorporation was observed which proved that acetonitrile is not responsible for the presence of the methyl group in 12. Performing the reaction in the presence of TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl) gave, beside reduction product 12, adduct 13 which suggests that the methyl group originates from a sequential reduction of the C–F bonds through a radical pathway. In addition a test for fluoride with [Fe(SCN)(H$_2$O)$_5$]$^{2+}$ in an evaporated aliquot of the irradiated reaction mixture was positive. Increasing the amount of Hünig’s base acting as sacrificial electron donor in the initial reduction step of 10 led to full conversion of the starting material and gave 12 as the only reaction product in 77% isolated yield.

For larger scale applications it would be desirable to install the activating benzoate group in situ rather than in a foregoing reaction step. Also, considering its high price the employment of only small amounts of iridium-based catalyst and lower priced triethylamine instead of costly disopropylethylamine would be
desirable. Taking 14 as model compound it could be shown that the overall deoxygenation process can be optimized and simplified in this regard by the in situ formation of the 3,5-bis(trifluoromethyl)benzoate 3a which in turn could then be converted to deoxygenated compound 4a in 91% yield (Scheme 8) in a flow process using a microreactor (see Supporting Information File 1).

**Conclusion**

In summary a protocol for the deoxygenation of benzylic alcohols, α-hydroxycarbonyl and α-cyanohydrin compounds under visible light photocatalysis was developed using 3,5-bis(trifluoromethyl)benzoic anhydride for alcohol activation. Since 3,5-bis(trifluoromethyl)benzoic acid can be recycled and reactivated under redox neutral conditions, and moreover, the in situ activation of alcohols with this auxiliary is possible we envision that an overall continuous process could be developed for the deoxygenation of alcohols by this protocol. That ultimately only requires heat, triethylamine as a sacrificial electron donor and visible light, forming water as the only byproduct. Therefore, we believe that despite the relatively expensive activation of alcohols as 3,5-bis(trifluoromethyl)benzoic acid esters, the deoxygenation protocol described here could become also attractive for large-scale applications.

**Experimental**

General procedure for photochemical deoxygenations: A Schlenk tube was charged with photocatalyst (20 µmol, 2.0 mol %), benzoate (1.00 mmol, 1.00 equiv), sealed with a screw cap and subsequently evacuated and backfilled with N₂ (3×). Solvent (20 mL), Hünig’s base (0.35 mL, 2.0 mmol, 2.0 equiv), and degassed water (1.8 mL, 100 mmol, 100 equiv) were added and the reaction mixture was magnetically stirred until a homogeneous solution was obtained. The reaction mixture was degassed by freeze-pump-thaw (5×) and the screw cap was replaced with a Teflon-sealed inlet for a glass rod, through which irradiation with a 455 nm high power LED took place from above while the reaction was magnetically stirred and heated in an aluminum block from below. After the reaction the mixture was diluted with 100 mL Et₂O, washed with 50 mL 10% Na₂CO₃, 50 mL H₂O, 50 mL brine, and dried over Na₂SO₄. After evaporation the crude mixture was purified by filtration through a short plug of flash silica gel with a mixture of petrol ether and ethyl acetate.

![Scheme 7: Reduction of benzoate moiety in case of non-benzyl alcohols.](image)

![Scheme 8: Optimized conditions for larger scale applications.](image)
Supporting Information

Supporting Information File 1
Experimental details, characterization data and spectra.
[http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-10-223-S1.pdf]

Acknowledgements
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References

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The definitive version of this article is the electronic one which can be found at:
doi:10.3762/bjoc.10.223
Abstract

A visible-light-induced photoredox-catalyzed bromoetherification of alkenols is described. This approach, with CBr₄ as the bromine source through generation of bromine in situ, provides a mild and operationally simple access to the synthesis of β-bromo-tetrahydrofurans and -tetrahydropyrans with high efficiency and regioselectivity.

Introduction

The halocyclization of alkenes provides an excellent synthetic method for halogenated heterocycles [1-3]. In recent years, haloaminocyclization [4,5], halolactonization [6,7] and haloetherification [8,9] of alkenes have received considerable attention from chemists, and various approaches have been made in this area. Initially, the classical synthetic pathway for bromocyclization proceeds utilizing bromine [10]. However, molecular bromine is hazardous and difficult to handle. Further research show that N-bromosuccinimide (NBS) is an effective alternative for the bromocyclization [11-14]. Furthermore, Wei Sun and co-workers disclosed an intriguing strategy to access the haloetherification of alkenols with N-chlorosuccinimide (NCS), leading to the synthesis of β-chlorotetrahydrofurans [15]. Recently we have reported that visible-light-induced photoredox catalysis could serve as a more environmental-friendly alternative reaction system to obtain Br₂ in situ from CBr₄, an oxidative quencher of photoredox catalyst [16-22]. Thus, as part of difunctionalization of alkenes, with our continuous investigations on the photoredox catalytic reactions [16,23-27], herein we report our preliminary studies on visible-light-induced photoredox-catalyzed bromoetherification of alkenols using CBr₄ as the bromine source.

Results and Discussion

Our initial studies were focused on the reaction of alkenol 1a as a model reaction for optimizing the reaction conditions. We were encouraged by the discovery that when 1a, CBr₄ and Ru(bpy)₃Cl₂ were irradiated by blue LEDs in MeCN for
4 hours, trans-β-bromotetrahydrofuran 2a was obtained via 5-endo bromoetherification reaction, although the yield was only 31% (Table 1, entry 2). We have reported the bromoetherification of compound 1a as an example in our previous article [16]. However, considering the value of this strategy for the synthesis of β-bromotetrahydrofurans and -tetrahydropyrans, further research were carried out to optimize the reaction conditions. Moreover, the stereochemistry of the bromotetrahydrofurans compound 2a was misidentified before. Herein, the stereochemistry of the bromotetrahydrofurans compound 2a was determined by NOE spectra, for details see Supporting Information File 1. After a screening of selected solvents, we found solvents had a significant effect on the reaction efficiency (Table 1, entries 1–5). The reaction in DMSO led to the highest yield up to 94% (Table 1, entry 1). In addition, 2 equivalents of CBr₄ were required for the efficient transformation (Table 1, entries 6 and 7). Furthermore, when the catalyst loading was reduced to even 1 mol %, the reaction also gave a comparable result (Table 1, entry 8). It should be pointed out that no reaction was observed in the absence of light or photocatalyst.

With the optimized reaction conditions in hand, various substituted butenols were subsequently investigated for the scope of the reaction. As shown in Table 2, electronically distinct styrenes ranging from electron-rich to electron-deficient

---

**Table 1:** Survey on the photocatalytic bromoetherification of alkenols.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Conditions</th>
<th>Time (h)</th>
<th>Yield (%)³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Standard conditions⁴</td>
<td>4</td>
<td>94</td>
</tr>
<tr>
<td>2</td>
<td>CH₃CN as solvent</td>
<td>4</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>DCM as solvent</td>
<td>12</td>
<td>28</td>
</tr>
<tr>
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<td>THF as solvent</td>
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<td>71</td>
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<td>5</td>
<td>DMF as solvent</td>
<td>22</td>
<td>77</td>
</tr>
<tr>
<td>6</td>
<td>Only 1 equiv CBr₄ was used</td>
<td>6</td>
<td>76</td>
</tr>
<tr>
<td>7</td>
<td>Only 1.5 equiv CBr₄ was used</td>
<td>5</td>
<td>88</td>
</tr>
<tr>
<td>8</td>
<td>Only 1 mol % Ru(bpy)₃Cl₂ was used</td>
<td>7</td>
<td>90</td>
</tr>
</tbody>
</table>

⁴Standard conditions: alkenol 1a (0.2 mmol, 1 equiv), CBr₄ (0.4 mmol, 2 equiv), Ru(bpy)₃Cl₂ (0.006 mmol, 3 mol %) in dry DMSO (0.1 M) irradiated by blue LEDs (1 W); ³isolated yield.

**Table 2:** Photocatalytic bromoetherification of butenols.⁸

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Product</th>
<th>Yield (%)³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R = 4-OMePh</td>
<td>2a</td>
<td>94</td>
</tr>
<tr>
<td>2</td>
<td>R = 3-OMePh</td>
<td>2b</td>
<td>93</td>
</tr>
<tr>
<td>3</td>
<td>R = 2-OMePh</td>
<td>2c</td>
<td>89</td>
</tr>
<tr>
<td>4</td>
<td>R = Ph</td>
<td>2d</td>
<td>88</td>
</tr>
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</table>
Table 2: Photocatalytic bromoetherification of butenols.\(^a\) (continued)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Product</th>
<th>Yield (%)</th>
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</thead>
<tbody>
<tr>
<td>5</td>
<td>(R = 4\text{-MePh})</td>
<td>(2e)</td>
<td>90</td>
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<tr>
<td>6</td>
<td>(R = 3\text{-MePh})</td>
<td>(2f)</td>
<td>85</td>
</tr>
<tr>
<td>7</td>
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<tr>
<td>8</td>
<td>(R = 4\text{-BrPh})</td>
<td>(2h)</td>
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<td>9</td>
<td>(R = 3\text{-BrPh})</td>
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<td>14</td>
<td>(R = 2,5\text{-diOMePh})</td>
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</tr>
<tr>
<td>15</td>
<td>(R = 2\text{-OMe-5-ClPh})</td>
<td>(2o)</td>
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<tr>
<td>16</td>
<td>(R = 2\text{-OMe-naphthalen-1-yl})</td>
<td>(2p)</td>
<td>86</td>
</tr>
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</table>

\(\text{Standard conditions: butenol 1 (0.2 mmol, 1 equiv), CBr}_4 (0.4 \text{ mmol, 2 equiv), Ru(bpy)}_3\text{Cl}_2 (0.006 \text{ mmol, 3 mol \% in dry DMSO (0.1 M) irradiated by blue LEDs (1W) for 4 h; isolated yield.}\)

---

Table 3: Photocatalytic bromoetherification of pentenols.\(^b\)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Product</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(R = 4\text{-OMe})</td>
<td>(2t)</td>
<td>91</td>
</tr>
<tr>
<td>2</td>
<td>(R = 4\text{-Me})</td>
<td>(2u)</td>
<td>87</td>
</tr>
</tbody>
</table>

provided good yields of the desired 5-endo bromoetherification products (Table 2, entries 1–16). Additionally, trisubstituted alkenols were also examined and showed high reactivity (Table 2, entries 17 and 18). The alkenol with geminal dimethyl substituent produced the expected 5-endo bromoetherification product in 90% yield (Table 2, entry 19).

To further demonstrate the general value of this strategy, a number of longer-chain pentenols were prepared and submitted to the optimized reaction conditions. As can be seen in Table 3, various styrenes were reacted efficiently to form the substituted tetrahydropyrans in high yield via 6-endo bromoetherification (Table 3, entries 1 and 2). Furthermore, not only primary alco-
Table 3: Photocatalytic bromoetherification of pentenols. (continued)

<table>
<thead>
<tr>
<th></th>
<th>R</th>
<th>3v</th>
<th>3w</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Me</td>
<td>1:1.1</td>
<td>74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Ph</td>
<td>1:1.3</td>
<td>80</td>
<td></td>
<td></td>
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<tr>
<td>5</td>
<td>Me</td>
<td></td>
<td>84</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*a*Standard conditions: pentenol 1 (0.2 mmol, 1 equiv), CBr₄ (0.4 mmol, 2 equiv), Ru(bpy)₃Cl₂ (0.006 mmol, 3 mol %) in dry DMSO (0.1 M) irradiated by blue LEDs (1 W) for 4 hours; *b*isolated yield.

hols but also secondary alcohols were tolerated using the reaction conditions albeit a mixture of 6-endo and 5-exo bromoetherification products obtained (Table 3, entries 3 and 4). Interestingly, for terminal alkene, the 5-exo bromoetherification product was achieved in 84% yield (Table 3, entry 5).

To add more credence to the involvement of bromine in this protocol, a control experiment was conducted by reaction of alkenol 1a with liquid bromine in DMSO which led to trans-β-bromotetrahydrofuran 2a in 95% yield (Scheme 1). Such a result is in accordance with the case of 1a reacted under the standard reaction conditions of this protocol.

Based upon the above results, the mechanism is proposed as shown in Scheme 2. Firstly, oxidative quenching of the visible-light-induced excited state Ru(bpy)₃²⁺* by CBr₄, generates Br⁻ along with the Ru(bpy)₃³⁺ complex. Then bromine was generated in situ through the oxidation of Br⁻ by Ru(bpy)₃³⁺ [16], sequential reaction with alkene 1a forms the three-membered bromonium intermediate 4 [28]. Finally, intramolecular nucleophilic cyclization furnishes the desired product β-bromotetrahydrofuran 2a.

Conclusion

In summary, we have developed a mild and operationally simple method for the bromoetherification of alkenols with CBr₄ as the bromine source, utilizing visible-light-induced phototoredox catalysis. The reaction proceeds with high efficiency and regioselectivity for the synthesis of β-bromotetrahydrofurans and -tetrahydropyrans.

Experimental

General procedure for the photocatalytic bromoetherification of alkenols

To a 10 mL round bottom flask equipped with a magnetic stir bar were added alkenols 1 (0.2 mmol), CBr₄ (132 mg, 0.4 mmol), Ru(bpy)₃Cl₂ (4.6 mg, 0.006 mmol) and dry DMSO (2 mL). The mixture was irradiated with blue LEDs (1 W) at room temperature without being degassed for 4 hours. Then water was added and the aqueous layer was extracted with ethyl
acetate. The combined organic layers were washed with brine, dried over anhydrous Na₂SO₄ and concentrated. The residue was purified by flash column chromatography to give the final products 2.

**Supporting Information**

Supporting Information File 1

1H and 13C NMR spectra for products.

[http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-11-5-S1.pdf]

**Acknowledgements**

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**References**


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Eosin Y-catalyzed visible-light-mediated aerobic oxidative cyclization of \( N,N \)-dimethylanilines with maleimides

Zhongwei Liang\(^1,2\), Song Xu\(^1,2,3\), Wenyan Tian\(^1,2\) and Ronghua Zhang*\(^1,2\)

**Abstract**

A novel and simple strategy for the efficient synthesis of the corresponding tetrahydroquinolines from \( N,N \)-dimethylanilines and maleimides using visible light in an air atmosphere in the presence of Eosin Y as a photocatalyst has been developed. The metal-free protocol involves aerobic oxidative cyclization via sp\(^3\) C–H functionalization process to afford good yields in a one-pot procedure under mild conditions.

**Introduction**

Over the past several years, visible light photoredox catalysis has become a powerful and promising tool and has been productively used to drive chemical transformations in the field of organic synthesis [1-6]. The approach takes full advantage of visible light, which is clean, abundant, and renewable. The pioneering work in this research area, reported by the groups of MacMillan [7-9], Yoon [10,11], Stephenson [12,13] and others [14-18], has demonstrated that ruthenium and iridium complexes as visible light photoredox catalysts are capable of catalyzing a broad range of useful reactions. A variety of new methods have been developed to accomplish known and new chemical transformations by means of these transition metal-based photocatalysts so far. However, the ruthenium and iridium catalysts usually are high-cost, potentially toxic and not sustainable. Similar to the redox properties of these organometallic complexes, some metal-free organic dyes such as Eosin Y, Rose Bengal, Fluorescein, and Methylene Blue, have shown superiority of their applications as photocatalysts, which are easy to handle, environmentally friendly, inexpensive, and have great potential for applications in visible-light-mediated photoredox reactions [19-27].

More recently, visible-light-induced sp\(^3\) C–H bond functionalization adjacent to nitrogen atoms has been extensively studied and has become a fundamental organic transformation [28-38]. Tertiary amine \( A \) generally generates a nucleophilic \( \alpha \)-amino-
alkyl radical B or an electrophilic iminium ion C via visible-light photoredox catalysis. Unfortunately the research of the α-aminoalkyl radical is limited in photochemical synthesis because it tends to form the iminium ion by one electron oxidation (Scheme 1) [39-41].

In the context of this research background, we investigated the α-aminoalkyl radical route to achieve the aerobic oxidative cyclization of N,N-dimethylanilines with maleimides to form the corresponding tetrahydroquinoline derivatives under organic dye Eosin Y catalysis. Swan and Roy reported the reaction using benzoyl peroxide as catalyst at low temperature as early as 1968 [42]. In 2011, Miura and co-workers achieved this transformation using a copper catalyst and air as the terminal oxidant [43]. Bian and co-workers presented the same reaction using [Ru(bpy)₃]³⁺ as photoredox catalyst under irradiation with visible light next year [44]. Herein, we show an environmentally friendly aerobic oxidative cyclization methodology that avoids the use of metal catalysts and makes full use of air as oxidant.

Results and Discussion

Our investigations for the envisaged protocol commenced with the reaction of N,N-dimethylaniline (1a) (0.5 mmol) with N-phenylmaleimide (2a) (0.25 mmol) in MeCN (3 mL) in the presence of 3 mol % Eosin Y under an air atmosphere (rt). Gratifyingly, the desired product tetrahydroquinoline 3a was obtained in 82% yield after 18 h (Table 1, entry 1). When the molar proportion of 1a and 2a was adjusted to 1:1 and 1:2, the yield of 3a decreased (Table 1, entries 6 and 7). Then, a series of control experiments were carried out, which indicated that Eosin Y, visible light and air are all essential for the reaction (Table 1, entries 8–10).

Next, we optimized the reaction conditions with respect to solvent and catalyst dosage. MeCN was found to be the best solvent (Table 2, entry 1) among DMF, DCE, DCM, DMSO, acetone, dioxane, and MeNO₂. When the amount of Eosin Y was decreased from 3 mol % to 2 mol % or increased from 3 mol % to 4 mol %, the yield of the tetrahydroquinoline product 3a was slightly reduced (Table 2, entries 9 and 10). Thus, the optimum catalyst dosage of Eosin Y was found to be 3 mol %.

With the optimized conditions in hand, the substrate scope of this reaction was examined (Scheme 2). The reaction is mild and tolerates many functional groups. N,N-dimethylaniline and substituted N,N-dimethylanilines incorporating methyl and bromo on the phenyl ring reacted with 2 to afford the corresponding tetrahydroquinolines 3 in good yields. N-arylmaleimides with electron-donating groups such as methyl, methoxy

<table>
<thead>
<tr>
<th>Entry</th>
<th>Organic dye</th>
<th>Oxidant</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Eosin Y</td>
<td>air</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>Rose Bengal</td>
<td>air</td>
<td>67</td>
</tr>
<tr>
<td>3</td>
<td>Methylene Blue</td>
<td>air</td>
<td>trace</td>
</tr>
<tr>
<td>4</td>
<td>Fluorescein</td>
<td>air</td>
<td>trace</td>
</tr>
<tr>
<td>5</td>
<td>Eosin Y</td>
<td>O₂c</td>
<td>77</td>
</tr>
<tr>
<td>6</td>
<td>Eosin Y</td>
<td>air</td>
<td>69d</td>
</tr>
<tr>
<td>7</td>
<td>Eosin Y</td>
<td>air</td>
<td>73e</td>
</tr>
<tr>
<td>8</td>
<td>none</td>
<td>air</td>
<td>n.r.</td>
</tr>
<tr>
<td>9</td>
<td>Eosin Y</td>
<td>air</td>
<td>n.r.f</td>
</tr>
<tr>
<td>10</td>
<td>Eosin Y</td>
<td>none</td>
<td>traceg</td>
</tr>
</tbody>
</table>

aReaction conditions: 1a (0.5 mmol), 2a (0.25 mmol), organic dye (3 mol %), MeCN (3 mL), two 9 W Blue LEDs irradiation under an air atmosphere at rt. bIsolated yield of the product 3a; n.r. = no reaction. cUnder O₂ (1 atm, balloon). d0.25 mmol of 1a and 0.25 mmol of 2a were used. fThe reaction was carried out in the dark. gUnder N₂.
Scheme 2: Substrate scope for aerobic oxidative cyclization of N,N-dimethylanilines with maleimides.
Table 2: Optimization of reaction conditions.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Eosin Y (mol %)</th>
<th>Solvent</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>MeCN</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>DMF</td>
<td>47</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>DCE</td>
<td>71</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>DCM</td>
<td>37</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>DMSO</td>
<td>trace</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>acetone</td>
<td>64</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>dioxane</td>
<td>51</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>MeNO₂</td>
<td>58</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>MeCN</td>
<td>80</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>MeCN</td>
<td>77</td>
</tr>
</tbody>
</table>

*Reaction conditions: 1a (0.5 mmol), 2a (0.25 mmol), solvent (3 mL), two 9 W blue LEDs irradiation under an air atmosphere at rt. bIsolated yield of the product 3a.

On the basis of our observations and literature reported [19,36,38,43,44], a proposed mechanism for the formation of the corresponding tetrahydroquinolines 3 form N,N-dimethyl-anilines 1 and maleimides 2 is depicted in Scheme 3. On absorption of visible light, the ground state of Eosin Y (EY) is induced to its single excited state (1EY*), which moves to its more stable triplet excited state (3EY*) through inter system crossing (ISC) [46,47]. 3EY* may undergo an oxidative or reductive quenching cycle [48-50]. In this mechanism, a single electron transfer (SET) from 1 to 3EY* generates the amine radical cation 4, and at the same time, 3EY* is reduced to the EY•−. In the presence of oxygen, the photoredox catalytic cycle of EY is finished via a SET oxidation, with the production of a superoxide radical anion O₂•−. Deprotonation of 4 generates and electron-withdrawing groups such as chloro, bromo, and N-methylmaleimide all underwent the aerobic oxidative cyclization to give the corresponding products in good yields. When using 4,4′-methylenbis(N,N-dimethylaniline) as the substrate, the reaction occurred only on one side and the yield of the product 3p is 52%. The reaction of N,N,3-trimethylaniline and N-phenylmaleimide resulted in the formation of a mixture of regioisomers 3q1 and 3q2 with 81% combined yield. The major product was the sterically more hindered 3q1 [43-45].
α-aminoalkyl radical 5. Then 5 reacts with 2 to generate radical 6, and the latter then undergoes cyclization to form intermediate 7. Proton and electron transfer from 7 to \( O_2^- \) yields the final product 3 and \( \text{HOO}^- \). The \( \text{HOO}^- \) will be subsequently protonated to yield \( \text{H}_2\text{O}_2 \) as the by-product. \( \text{H}_2\text{O}_2 \) was detected after the reaction was completed by using KI/starch indicator (see the Supporting Information File 1). The involvement of radical pathway was supported by experimental result that the reaction was suppressed in the presence of TEMPO.

Conclusion

In conclusion, we report an efficient metal-free method for the synthesis of corresponding tetrahydroquinolines from \( N,N \)-dimethylanilines and maleimides using molecular oxygen as oxidant and Eosin Y as catalyst under the irradiation of visible light. The protocol is significantly green because it utilizes visible light and atmospheric oxygen as the greenest reagents, and metal-free, cheap Eosin Y with a relatively low loading as the photocatalyst to deliver the product at room temperature in a simple one-pot procedure. This methodology expands the range of substrates in the area of visible light photoredox reactions.

Supporting Information

Supporting Information File 1
Experimental section and characterization of the synthesized compounds.

[http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-11-48-S1.pdf]

Acknowledgements

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References


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Photocatalytic nucleophilic addition of alcohols to styrenes in Markovnikov and anti-Markovnikov orientation

Martin Weiser, Sergej Hermann, Alexander Penner and Hans-Achim Wagenknecht*

Abstract
The nucleophilic addition of methanol and other alcohols to 1,1-diphenylethylene (1) and styrene (6) into the Markovnikov- and anti-Markovnikov-type products was selectively achieved with 1-(N,N-dimethylamino)pyrene (Py) and 1,7-dicyanoperylene-3,4:9,10-tetracarboxylic acid bisimide (PDI) as photoredox catalysts. The regioselectivity was controlled by the photocatalyst. For the reductive mode towards the Markovnikov-type regioselectivity, Py was applied as photocatalyst and triethylamine as electron shuttle. This approach was also used for intramolecular additions. For the oxidative mode towards the anti-Markovnikov-type regioselectivity, PDI was applied together with Ph–SH as additive. Photocatalytic additions of a variety of alcohols gave the corresponding products in good to excellent yields. The proposed photocatalytic electron transfer mechanism was supported by detection of the PDI radical anion as key intermediate and by comparison of two intramolecular reactions with different electron density. Representative mesoflow reactor experiments allowed to significantly shorten the irradiation times and to use sunlight as “green” light source.

Introduction
Photocatalysts are organic or inorganic compounds that couple the physical process of light absorption with a chemical reaction by means of time, space and energetics, in order to catalyse it. With respect to the “green” character of sunlight as unlimited natural light source and the availability of LEDs as cheap and reliable artificial light sources, the research field of photoredox catalysis has tremendously grown over the past decade [1-7]. Transition metal complexes, mainly [Ru(bpy)3]2+ [7], were most often used as photocatalysts, whereas the potential of organic compounds and dyes has not yet been fully exploited [8]. The way towards a really complete organo-type photoredox catalysis has mainly been established for eosin Y as an important alternative for [Ru(bpy)3]2+ [9].

Photocatalytic nucleophilic additions of amines and alcohols to olefins, especially styrenes, became an increasingly important
task due to their potential and versatile applicability in chemical syntheses. Their non-photochemical counterparts require acids, bases or transition metal complexes as catalysts [10]. The first examples of photochemical olefin aminations were reported by Cookson et al. [11] and Kawanisi et al. [12] in the 1960s/70s, and Lewis identified exciplex states as key intermediates [13,14]. The corresponding photohydration worked only if the aromatic olefins as starting material were directly excited by UV light [15,16]. The first approach towards a photocatalytic version of this type of reaction came from Arnold, Maroulis et al. [17,18]. They demonstrated that electron-rich naphthalenes are able to photoinitiate methanol additions to olefins into the Markovnikov orientation and proposed an oxidative electron transfer mechanism for this process [17]. Complementarily, electron-poor naphthalenes yielded the anti-Markovnikov-type addition of cyanide to styrene [18]. Recently, we showed by a library of different chromophores that 1-(N,N-dimethyl-amino)pyrene (Py) can be applied as photocatalyst for the nucleophilic addition of methanol to styrene derivatives into the Markovnikov orientation and proposed an oxidative electron transfer mechanism for this process [17]. Most recently, Nicewicz et al. published the hydrofunctionalization of alkenes to the anti-Markovnikov products by photoredox catalysis using 9-mesityl-10-methylacridinium [20,21]. Herein, we want to present our complementary approach to perform inter- and intramolecular nucleophilic additions of alcohols to styrene derivatives by photocatalysis. The regioselectivity – Markovnikov or anti-Markovnikov – can simply be controlled by the chosen photocatalyst, either Py or 1,7-dicyanoperylene-3,4,9,10-tetracarboxylic acid bisimide (PDI).

Results and Discussion
Photocatalytic complementarity

The photocatalytic complementarity of the two different routes (to the Markovnikov or anti-Markovnikov addition products of styrene derivatives) results from the two types of photoinduced charge transfer initiated by the photoexcited catalyst (Scheme 1). If an electron-poor chromophore is applied, the first step that follows irradiation is an electron transfer leading to one-electron oxidation of the substrate styrene and may involve intermediates such as exciplexes. Nucleophilic attack and loss of the proton of the alcohol yield a radical at the benzylic position that explains the anti-Markovnikov-type selectivity of this photocatalytic process. Back charge transfer to the photocatalyst closes the photocatalytic cycle and subsequent protonation yields the anti-Markovnikov-type addition product. In contrast, an electron-rich chromophore photoinduces an electron transfer onto the substrate. The corresponding radical anion is protonated rapidly to the neutral radical that is the key intermediate to explain the Markovnikov selectivity of this route. Both steps, electron transfer and protonation, could also occur in one proton-coupled electron transfer step. Back electron transfer to the photocatalyst finishes the photocatalytic cycle of this process, and subsequent nucleophilic attack accompanied by deprotonation gives the Markovnikov-type addition product.

Reductive route: Markovnikov regioselectivity

For the reductive mode of photocatalysis towards the Markovnikov-oriented addition products, we recently applied Py as photocatalyst and 1,1-diphenylethylene (1) as test substrate (Scheme 2). It was assumed that inefficient back electron transfer was responsible for low yields of the MeOH addition product 2 and rapid degradation of the photocatalyst Py. This problem could be solved by adding triethylamine which served as electron shuttle between back electron transfer that regenerates the photocatalyst and the final step of product formation. The substrate scope of this optimized photocatalytic conditions revealed that electron-poor α-phenylstyrenes and styrenes are
preferred which further supported the reductive electron transfer mechanism [19].

This photocatalysis was applied also for intramolecular additions. In the particular case of substrate 3, Et₃N as electron shuttle could not be used; it provided a competing nucleophile since the desired nucleophile could not be added in high excess. In order to shift the reaction more towards the intramolecular alternative, the photoredox catalysis was performed in high dilution (2 mM). The product 4 could be identified in 60% yield (Scheme 3).

**Oxidative route: anti-Markovnikov regioselectivity**

For the oxidative mode of photocatalysis towards the anti-Markovnikov-oriented addition products, PDI (Scheme 4) was applied as photocatalyst. Its absorption maximum in CH₂Cl₂ is located at 525 nm that makes it an excellent candidate for photoirradiation by both sunlight and green light-emitting diodes. Furthermore, based on $E_{\text{red}}$(PDI/PDI°) = −0.28 V (measured by cyclic voltammetry, vs SCE, see Supporting Information File 1) and $E_0^0$ = 2.35 eV (see Supporting Information File 1), PDI is an electron deficient chromophore with an excited state oxidation potential of 2.07 V. In combination with the oxidation potential of 1.81 V (vs SCE) [22] for substrate 1 the driving force $\Delta G$ of initial oxidation was estimated by Rehm–Weller to be around 250 meV. In general, irradiations were carried out in quartz glass cuvettes at a constant temperature of 30 °C, using a 250 mW high-power LED ($\lambda$ = 530 nm) as light source while stirring.

This example showed that the addition of Et₃N as electron shuttle was not required in all cases. A more detailed look on the problem of inefficient back electron transfer indicated that loss of polar attraction after rapid protonation of the substrate radical anion might lead to diffusion and separation of the photocatalyst from the intermediate product-forming radical cation. If it was assumed that back electron transfer was a strongly dependant process, the photocatalyst might not be regenerated and hence removed from the catalytic cycle. This scenario could potentially be improved by a substrate binding site on the photocatalyst that keeps the substrate in the vicinity of Py as long as it is required for forward and back electron transfer.

Preliminary experiments with substrate 1 revealed that formation of benzophenone was nearly completely prevented by carefully degassing the reaction mixture. A previous report of Neunteufel and Arnold considered the electron transfer from the catalyst onto the substrate as key step [23]. In agreement with that proposal, the Stern–Volmer plots (see Supporting Information File 1) showed that fluorescence of PDI is significantly quenched in the presence of 1. The critical step, however, seemed to be the back electron transfer that recovers the photocatalyst from the PDI radical anion after nucleophilic addition,
Scheme 4: Proposed mechanism of the anti-Markovnikov-type photocatalytic addition of methanol to 1,1-diphenylethylene (1) and styrene (6) yielding the corresponding products 5 and 7 (ET = electron transfer).

Scheme 4: Proposed mechanism of the anti-Markovnikov-type photocatalytic addition of methanol to 1,1-diphenylethylene (1) and styrene (6) yielding the corresponding products 5 and 7 (ET = electron transfer).

since addition of Ph–SH as electron and proton shuttle helped to significantly accelerated reactions [20,21]. In this respect, oxidative and reductive mode behaved similarly since both types of photocatalysis needed a suitable electron shuttle as additive. Comparison of MeOH addition reactions to substrate 1 in the presence of 0.4 and 1.0 equivalents of Ph–SH as additive showed differences in conversion rates, especially during the first six hours of irradiation (Figure 1). With stoichiometric amounts of Ph–SH full conversion was achieved within six hours, whereas 40 mol % only reached 70% of conversion at that time.

Nucleophilic addition of a variety of alcohols to substrate 1 gave the corresponding products in excellent yields (Table 1). Especially the conversion of 1 with benzyl alcohol was significantly slower, since longer irradiations were needed. Only the addition of phenol failed completely. Since isopropanol and tert-butanol as sterically demanding nucleophiles gave the corresponding addition products in good yields, it was assumed that the acidity of benzyl alcohol, and more significantly of phenol, weakened the nucleophilicity for this type of reaction. Styrene (6) has an oxidation potential of 1.94 V (vs SCE) [22] and, hence, could also be oxidized by the chosen photocatalyst PDI. The corresponding photocatalytic nucleophilic additions to 6 (Table 1) yielded less of each product, which was in agreement with the higher oxidation potential (compared to 1). Here again, the addition of phenol showed no significant amounts of product formation.

We representatively demonstrated the dependency of the performance of photocatalysis with substrate 1 on different PDI concentrations (Figure 2). After three hours, the yields of methanol addition product 5 differed only slightly, but on a longer timescale (12 h and longer) the yields diverged as expected. The reaction with 2 mol % of PDI was finished after 24 h, whereas the reaction with only 1 mol % reached full conversion only after 12 additional hours of irradiation time.
Table 1: Photocatalytic nucleophilic addition of alcohols to 1 and 6.

<table>
<thead>
<tr>
<th>nucleophile</th>
<th>yields (%)(^b) of 5 after 12 h irradiation</th>
<th>substrate 1 yields (%)(^b) of 5 after 24 h irradiation</th>
<th>substrate 6 yields (%)(^b) of 7 after 42 h irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>methanol</td>
<td>69</td>
<td>100</td>
<td>32</td>
</tr>
<tr>
<td>ethanol</td>
<td>75</td>
<td>100</td>
<td>21</td>
</tr>
<tr>
<td>propanol</td>
<td>64</td>
<td>100</td>
<td>24</td>
</tr>
<tr>
<td>butanol</td>
<td>66</td>
<td>100</td>
<td>21</td>
</tr>
<tr>
<td>isopropanol</td>
<td>63</td>
<td>100</td>
<td>19</td>
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<tr>
<td>tert-butanol</td>
<td>78</td>
<td>98</td>
<td>19</td>
</tr>
<tr>
<td>benzyl alcohol</td>
<td>52</td>
<td>84</td>
<td>8(^c)</td>
</tr>
<tr>
<td>phenol</td>
<td>n.d.</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

\(^a\) Reaction conditions: 1 or 6 (25 mM), Ph–SH (12.5 mM), PDI (0.5 mM), in CH\(_2\)Cl\(_2\)/alcohol 3:1 (4 mL), argon atmosphere, 30 °C, 250 mW LED, λ = 530 nm, 1, 6 and products identified and quantified by GC–MS. \(^b\) Averaged yield from at least two independent reactions. As no byproducts have been detected conversion matches yield. \(^c\) Conversion = 24%.

The usage of just 0.2 and 0.5 mol % PDI increased the irradiation time at least to 36 h, and it was considered doubtful if prolonged irradiation would complete the reactions.

During these photocatalytic experiments, the colour of the solution changed from orange to blue after the first seconds of irradiation and turned back to orange just when the reaction was finished. If the irradiation of the photocatalytic sample was stopped it took about an hour until the blue color completely disappeared and obviously the chromophore relaxed back to the ground state. Spectroelectrochemistry measurements (see Supporting Information File 1) revealed that the blue colored intermediate could be assigned to the radical anion of PDI as photocatalyst whose half-lifetime was determined to be approximately 4 min (Figure 3). The appearance of this intermediate strongly supported the proposed electron transfer mechanism of this type of photocatalysis (Scheme 4).

Although the intramolecular additions of substrates 8 and 10 in the presence of PDI as photocatalyst yielded the corresponding products 9 and 11 only in moderate yields (Scheme 5), they additionally support the proposed photocatalytic mechanism (Scheme 4). Comparison of product formation after 18 h showed that the methoxy substituted product 9 was obtained in approximately double yield compared to 11. Obviously, the photooxidation of the electron-rich double bond in substrate 8 by electron transfer occured faster than the one in substrate 10. These results indicate that the initial charge transfer was the rate-limiting step of this photocatalytic process.
Scheme 5: Intramolecular additions of substrates 8 and 10 to demonstrate the effect of different electron densities of the double bond. Reaction conditions: 8 or 10 (25 mM), Ph–SH (12.5 mM), PDI (0.5 mM), in CH₂Cl₂ (4 mL), argon atmosphere, 30 °C, 250 mW LED, λ = 530 nm, 8–11 identified and quantified by GC–MS.

Table 2: Photocatalytic experiments with 1 in flow reactors.

<table>
<thead>
<tr>
<th>setup</th>
<th>yield of 5 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mesoflow reactor 1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>76&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>mesoflow reactor 2&lt;sup&gt;d&lt;/sup&gt;</td>
<td>72&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>sunlight w/o PDI&lt;sup&gt;f&lt;/sup&gt;</td>
<td>0</td>
</tr>
</tbody>
</table>

<sup>a</sup>Reaction conditions: 1 (25 mM), Ph–SH (12.5 mM), PDI (0.5 mM), in CH₂Cl₂:MeOH 3:1, argon atmosphere, reactants identified and quantified by GC–MS.<br><sup>b</sup>Syringe pump with flow rate of 300 µL/h, 220 min, 30 °C, 4 × 250 mW LED, λ = 530 nm.<br><sup>c</sup>Conversion = 88%.<br><sup>d</sup>4 mL, rt, sunlight, 17/04/14, Karlsruhe, 11 a.m. until noon.<br><sup>e</sup>Conversion = 100%.<br><sup>f</sup>1 h, no conversion; 1 month, 51% conversion mainly to benzo-phenone.

The photocatalytic capability of PDI was representatively compared to that of 9-mesityl-10-methylacridinium perchlorate (MesAcr) which was applied by Nicewicz et al. for similar additions [20,21]. After 3 h irradiation at 448 nm by two LEDs (250 mW) in the presence of MesAcr (otherwise identical experimental conditions as those described in Table 1) product 5 was formed in 30% yield, whereas the corresponding reaction with PDI as the photocatalyst yields 49% when PDI is irradiated at 530 nm and 59% when irradiated at 470 nm. These irradiations were performed with the corresponding LEDs and yields were identical with conversions.

Finally, the nucleophilic addition of methanol to 1 using PDI as photocatalyst was representatively executed in two mesoflow reactors, since flow chemistry has significant advantages over batch chemistry, such as easier temperature control, larger surface-to-volume ratio and more efficient photoirradiation. Two setups were used to transfer the reaction to continuous-flow systems. The first mesoflow reactor was equipped with four 250 mW high-power LEDs (λ = 530 nm), a syringe pump, and temperature control to 30 °C. The second one was constructed for exposure to sunlight and consisted of a PTFE tubing to demonstrate applicability of this photocatalysis without need for electricity. Mesoflow experiments were executed using either sunlight, to give 72% yield over only 1 h, or four high-power LEDs, to give 76% yield over 3 h (Table 2). As control that 1 was not excited directly by sunlight, a sample without PDI was set into sunlight and, as expected, yielded no product.

**Conclusion**

The photocatalytic complementarity of the two different routes to either the Markovnikov- or anti-Markovnikov-type nucleophilic alcohol addition to styrene derivatives was accomplished by Py and PDI as photocatalysts. The regioselectivity was controlled by the type of photoinduced charge transfer that was initiated by the photoexcited catalyst. For the reductive mode towards the Markovnikov orientation, Py was applied as photocatalyst. It was previously elucidated that inefficient back electron transfer required the addition of Et₃N as electron shuttle that closed the photocatalytic cycle since back electron transfer occurred more efficiently. The photocatalytic process was used also for intramolecular additions. For the oxidative mode towards the anti-Markovnikov-type regioselectivity, PDI was a highly suitable photocatalyst based on its electrochemical and optical properties. Photocatalytic additions of a variety of alcohols to styrene derivatives gave the corresponding products in good to excellent yields. Similar to the reductive mode, the oxidative nucleophilic addition needed the additive Ph–SH as electron and proton shuttle. The proposed photocatalytic electron transfer mechanism was supported by the observation of the PDI radical anion as key intermediate and by comparison of two intramolecular reactions with different electron density. Representative mesoflow reactor experiments revealed that the irradiation times can be significantly shortened and sunlight can
be used as a “green” light source. The yields of methanol addition using PDI as photocatalyst were higher than those obtained with MesAcr as literature-known photocatalyst. These results provide a good basis to extend this photocatalytic approach to other nucleophilic additions as synthetically valuable olefin functionalizations, including C–C bond forma-

## Experimental

**Materials and methods.** All chemicals were purchased from Aldrich, ABCR and TCI. GC–MS data were recorded on a Varian GC–MS System (gas-phase chromatograph 431-GC, mass spectrometer 210-MS). Absorption spectra were determined with a Perkin Elmer Lambda 750 UV–vis spectrometer. Fluorescence was measured with a Horiba Scientific FluoroMax 4 spectrofluorometer with step width of 1 nm and an integration time of 0.2 s.

**Photocatalytic experiments with Py.** Irradiations have been executed in a 4 mL cuvette equipped with a magnetic stir bar. The samples were prepared with stem solutions and final concentrations of the substrates (25 mM), Ph–SH (12.5 mM) and Py (2 mM) in MeCN. The solution was then degassed using the freeze pump thaw method and afterwards irradiated with a 366 nm LED while stirring. Samples have been taken under argon countercflow to prevent oxygen from getting into the reaction mixture.

**Photocatalytic experiments with PDI.** Irradiations have been executed in a 4 mL cuvette equipped with a magnetic stir bar. The samples were prepared with stem solutions and final concentrations of the substrates (25 mM), Ph–SH (12.5 mM) and PDI (0.5 mM) in either CH2Cl2 or CH2Cl2/alcohol 3:1 mixtures. The solution was then degassed using the freeze pump thaw method and afterwards irradiated with a 530 nm LED while stirring. Samples have been taken under argon countercflow to prevent oxygen from getting into the reaction mixture.

## Supporting Information

### Supporting Information File 1

Spectral data: Cyclic voltammogram of PDI, determination of $E_{00}$ of PDI, Stern–Volmer plots of PDI in the presence of substrate $I$, spectroelectrochemistry of PDI, pictures of the mesoflow setups.

[http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-11-62-S1.pdf]

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## References
