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Photocatalytic Anion Oxidation and Applications in Organic Synthesis

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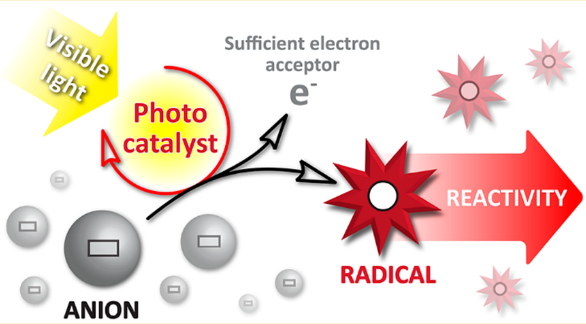
ABSTRACT: Ions and radicals of the same kind differ by one electron only. The oxidation of many stable inorganic anions yields their corresponding highly reactive radicals, and visible light excitable photocatalysts can provide the required oxidation potential for this transformation. Air oxygen serves as the terminal oxidant, or cheap sacrificial oxidants are used, providing a very practical approach for generating reactive inorganic radicals for organic synthesis. We discuss in this perspective several recently reported examples: Nitrate radicals are obtained by one-electron photooxidation of nitrate anions and are very reactive toward organic molecules. The photooxidation of sulfinate salts yields the much more stable sulfone radicals, which smoothly add to double bonds. A two-electron oxidation of chloride anions to electrophilic chlorine species reacting with arenes in aromatic substitutions extends the method beyond radical reactions. The chloride anion oxidation proceeds via photocatalytically generated peracidic acid as the oxidation reagent. Although the number of reported examples of photocatalytically generated inorganic radical intermediates for organic synthesis is still small, future extension of the concept to other inorganic ions as radical precursors is a clear perspective.



INTRODUCTION

A one-electron oxidation converts anions into radicals connecting ionic and radical chemistry. With many inorganic anions readily available, the simple transformation provides access to heteroatom-centered radicals often with high reactivity. However, the use of chemical one-electron oxidizing reagents may not be economical and creates byproducts, and electrochemical oxidation requires a special apparatus and involves a surface reaction at the electrodes. Therefore, visible light-induced homogeneous photooxidation has developed into a useful alternative, generating reactive intermediates in a catalytic fashion using light as a traceless reagent.

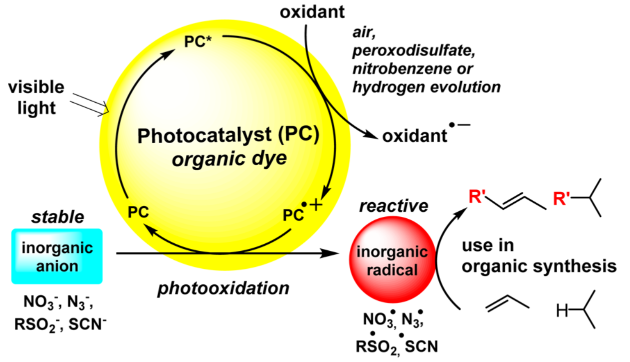


Figure 1. Photocatalytic oxidation of inorganic anions into radicals and their use in organic synthesis.

We focus in this perspective on the visible light-mediated photooxidation of inorganic anions and exclude carbanions (Figure 1). Inorganic anions vary significant in their basicity and therefore require different potentials for their oxidation. We start our survey with the nitrate anion, which needs a strongly photooxidizing acridinium dye for transformation into the nitrate radical. Pseudohalides, like azide or thiocyanate anions, and sulfinates are oxidized at lower potentials. The chemical reactivity of the obtained radicals toward organic molecules depends on the stability of the radical and can vary drastically. The nitrate radical is an example for high reactivity, whereas the sulfur-centered sulfone radicals obtained from sulfinate oxidation react rather selectively. In the last part of this perspective, we extend the oxidation to a two-electron process and discuss the generation of electrophilic chlorine "Cl$^+$" from chloride "Cl$^-$" anions by a photochemical oxidation using in situ-generated peracetic acid as the redox mediator.

The discussed examples of photocatalytic anion oxidation and use of the resulting highly reactive radicals in bond formation or oxidation reactions illustrate the potential of the concept. However, a much larger scope may be envisaged and established over the next few years considering the large variety of inorganic anions that may be suitable starting materials.

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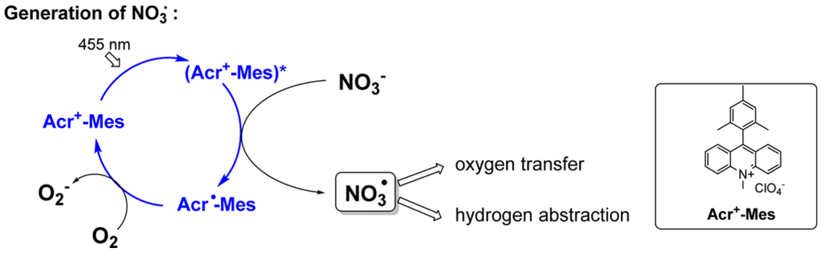
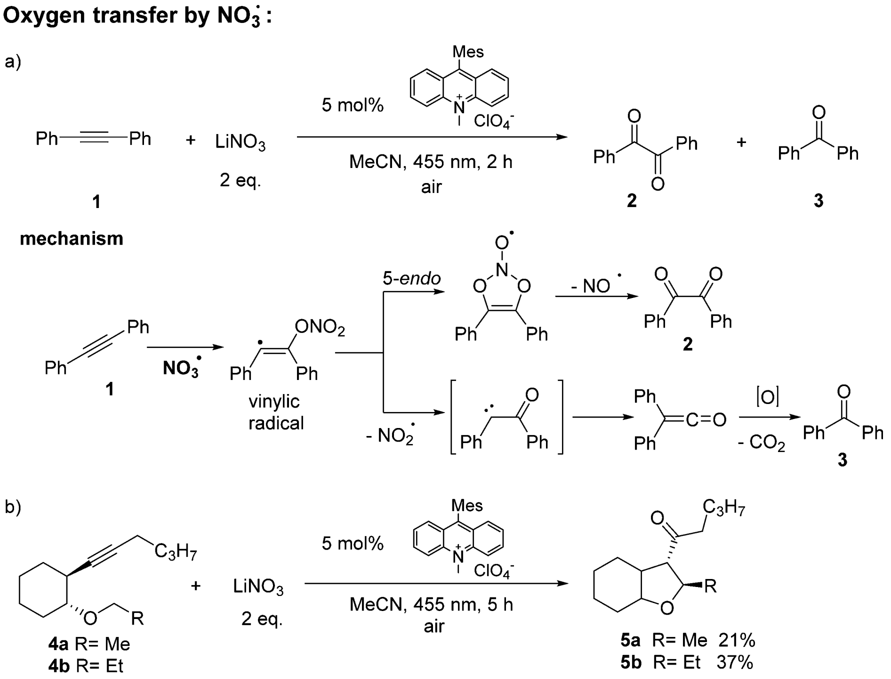


Figure 2. Photoredox-catalyzed oxidation of nitrate ions to $NO_3^\bullet$.

Scheme 1. Oxidation of π-Systems by the Addition of $NO_3^\bullet$: (a) Oxygenation of Diphenylacetylene and (b) Self-Terminating Radical Cascade Reaction



■ NITRATE RADICALS $NO_3^\bullet$ FROM NITRATE ANIONS

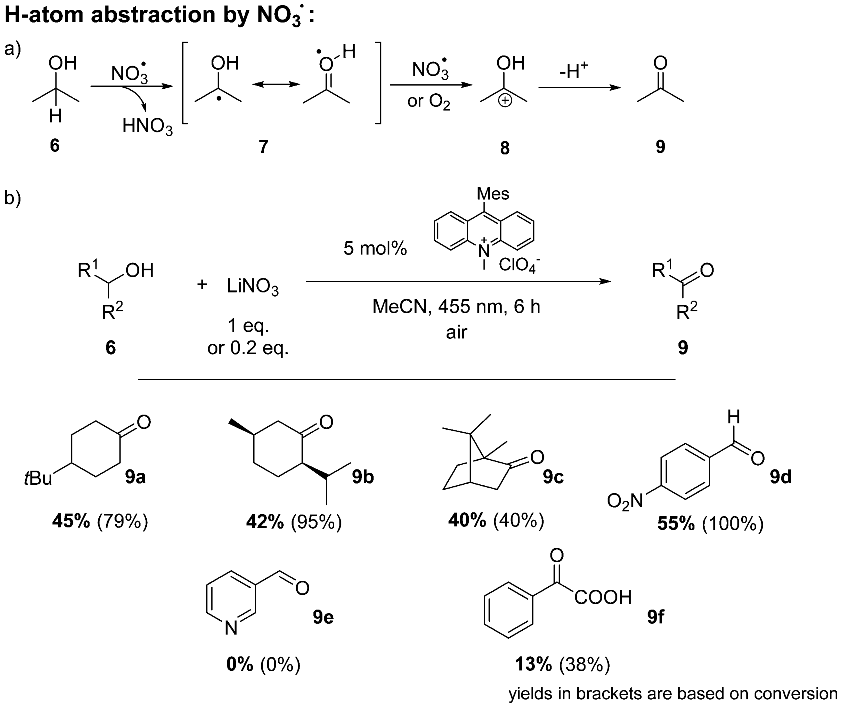
The nitrate radical $NO_3^\bullet$ is a unique oxygen-centered radical with high oxidative power (+2.00 V vs SCE in MeCN) and versatile reactivity.[1] It can undergo electron transfer (ET), add to π systems, or abstract hydrogen atoms (HAT). Moreover, $NO_3^\bullet$ is the most important free radical oxidant in the nighttime troposphere, where it is generated from the atmospheric pollutants nitrogen dioxide and ozone and reacts with volatile organic compounds emitted into the atmosphere.[1a,2] These properties make it an interesting reagent for organic synthesis. However, although transformations in the atmosphere have been widely explored, surprisingly little work has been done to apply $NO_3^\bullet$ to synthetic chemistry.[3] This is mainly caused by its difficult accessibility. Conventional preparation requires toxic gases or UV irradiation of $(NH_4)_2Ce(NO_3)_6$ (CAN), which limits its potential application. The ideal preparation of $NO_3^\bullet$ would be by one-electron oxidation of nitrate anions, which has been reported electrochemically. However, high electrode potentials are necessary and lead to unselective background reactions.[3a]

Using visible light photoredox catalysis to form $NO_3^\bullet$ by catalytic oxidation of readily available NO_3^- overcomes some of these drawbacks and generates the reactive radical under mild conditions in preparative scale. As depicted in Figure 2, a purely organic dye, 9-mesityl-10-methylacridinium perchlorate (Acr$^+$-Mes),[4] can be used as the photocatalyst and oxygen as the terminal oxidant.[5]

Spectroscopic studies on the mechanism of $NO_3^\bullet$ generation revealed that the reaction proceeds by direct oxidation of nitrate ions from the excited singlet state of the photocatalyst with subsequent reoxidation of the reduced catalyst by aerial oxygen. For proving that nitrate ions act as electron donors to the excited state of Acr$^+$-Mes, a 5 μM solution of Acr$^+$-Mes in MeCN was continuously irradiated with 455 nm light under anaerobic conditions. The differential absorption spectrum shows the appearance of the reduced catalyst Acr$^\bullet$-Mes with a maximum at 520 nm[4,6] after irradiation for 120 and 240 s. The signal of Acr$^\bullet$-Mes vanished completely after aeration of the solution as Acr$^\bullet$-Mes is reoxidized to the ground state catalyst Acr$^+$-Mes by oxygen. This is in accordance with the mechanism proposed in Figure 2.

For further investigating how $NO_3^\bullet$ is formed by photoredox catalysis, laser flash photolysis (LFP) and fluorescence quenching were performed to identify the excited state, which is responsible for the oxidation of nitrate ions. The long-lived triplet state with a microsecond lifetime is generally discussed as the reactive state in the majority of the reported oxidative reactions,[7] but judging by the redox potentials (+1.88 V vs SCE for CT[T7a] or +1.45 V vs SCE for LE[T7b]), it does not have the oxidative capacity to oxidize NO_3^-. Indeed, LFP measurements

Scheme 2. (a) Mechanistic Scheme of the Alcohol Oxidation by $NO_3^\bullet$ and (b) Experimental Conditions and Results for the $NO_3^\bullet$-Mediated Oxidation of Alcohols



showed no interaction between the long-lived triplet state and NO_3^-, whereas fluorescence measurements showed quenching of the emission. This clearly indicates a reaction from the singlet state as the triplet states of Acr$^+$-Mes do not emit.[6]

After investigating the mechanism of the photocatalytic generation of $NO_3^\bullet$, the radical was applied for the oxidation of aromatic alkyne **1** (Scheme 1a). The oxidation reaction proceeds by the addition of $NO_3^\bullet$ to the alkyne, yielding either benzil (**2**) or acetophenone (**3**) by loss of CO, and has been described with previous methods for the generation of $NO_3^\bullet$.[3d] This is an example where $NO_3^\bullet$ serves as an oxygen transfer reagent. Using the photocatalytic method with 5 mol % of Acr$^+$-Mes, 0.25 mmol of diphenyl acetylene **1**, and 2 equiv of $LiNO_3$ after 2 h of blue light irradiation (λ_{max} = 455 nm), comparable yields and product ratios were obtained as with the previously described methods.

The developed photocatalytic $NO_3^\bullet$ formation was further applied to the synthesis of tetrasubstituted tetrahydrofurans (Scheme 1b). A reaction is initiated like in the previous example by $NO_3^\bullet$ addition to the triple bond of alkyne **4** and then proceeds via a self-terminating radical cascade.[3b,c] Cyclized product **5** could be obtained in 37% (67% based on conversion) with 45% recovered starting material. The low conversion and resulting low product yield can be rationalized by the observed bleaching of the photocatalyst presumably caused by oxidation of the methyl groups on the mesityl moiety of Acr$^+$-Mes,[8] a known degradation pathway leading to the loss of catalytic activity.[9] Therefore, the yields could be slightly increased by slow addition of Acr$^+$-Mes via a syringe pump.

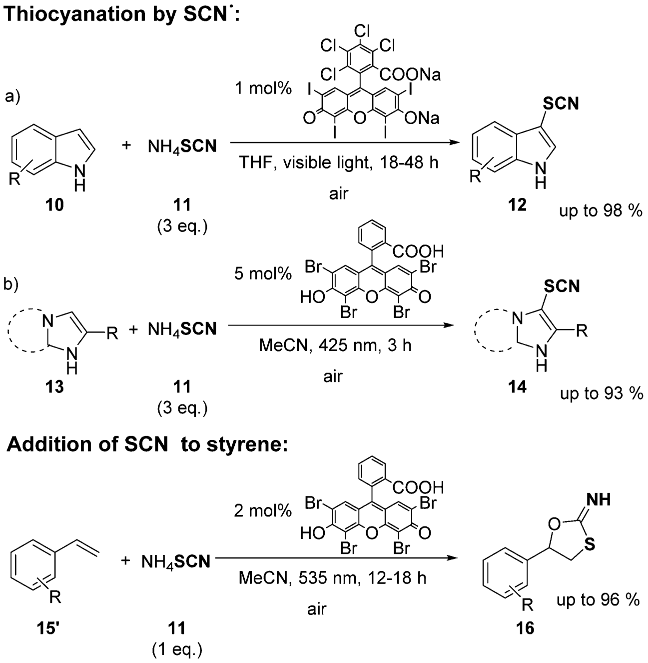
Besides the addition to π systems, $NO_3^\bullet$ can also oxidize substrates by hydrogen atom abstraction.[8,10] This was applied for the catalytic oxidation of nonactivated alcohols (Scheme 2). The reaction proceeds by initial HAT from the alcohol carbon by $NO_3^\bullet$ regenerating NO_3^- (Scheme 2a)[11] that can once more be oxidized to generate another molecule of $NO_3^\bullet$. In this reaction, $NO_3^\bullet$ acts as a redox mediator enabling the oxidation but is not consumed. Thus, nitrate can be used in catalytic amounts. During the reaction, an acidification of the solution is observed but does not affect the reaction. The scope of the alcohol oxidation is depicted in Scheme 2b. Nonactivated alcohols can be converted to the corresponding ketones in good selectivity but with moderate yields as degradation of the catalyst by $NO_3^\bullet$ leads to incomplete conversion. It is worth noting that isomenthol can be converted to isomethone (**9c**) without a change in the configuration of the stereocenter.

The use of photoredox catalysis for the oxidation of abundant nitrate ions provides simple access to highly reactive nitrate radicals and requires only light, air, and an organic dye. This method is a clear advancement to existing methods as it avoids the use of toxic compounds or high electrochemical potentials and demonstrates how reactive radicals can be generated from their corresponding anion by photoredox catalysis.

■ PHOTOCATALYTIC GENERATION OF $SCN^\bullet$

This strategy has also been used to oxidize other rather unreactive inorganic anions, transforming them into reactive radicals. In 2014, Li et al. reported the Rose Bengal-catalyzed thiocyanation of indoles **10** using SCN^-.[12] The reaction proceeds by reductive quenching of the excited state of Rose Bengal by SCN^-, giving $SCN^\bullet$, which subsequently adds to an indole yielding corresponding thiocyanated product **12**. As in the case of $NO_3^\bullet$, molecular oxygen serves as the terminal oxidant. Using this procedure, they synthesized a variety of 3-thiocyanated indoles **12** with yields up to 98%. Later, the groups of Hajra and Yadav used a similar eosin Y-catalyzed process to achieve the thiocyanation and selenocyanation of imidazoheterocycles **13**[13] and the synthesis of 5-aryl-2-imino-1,3-oxathiolanes **16** by addition of $SCN^\bullet$ to styrenes **15′**.[14] All reactions are initiated by the formation of an $SCN^\bullet$ or $SeCN^\bullet$

Scheme 3. SCN• Addition to (a) Indoles, (b) Imidazoles, and (bottom) Styrenes



from the corresponding anion and give access to valuable structures by a mild metal-free catalysis (Scheme 3).

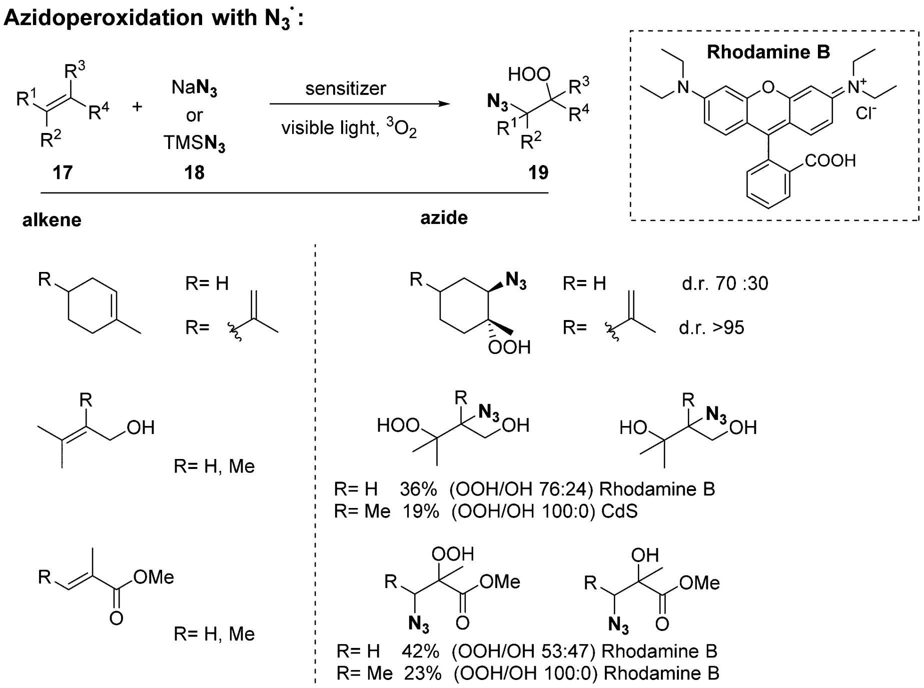
■ PHOTOOXIDATION OF N_3^- TO $N_3^\bullet$

Another interesting radical, which can be generated by oxidation from its corresponding anion, is the azidyl radical $N_3^\bullet$. Organic azides are important precursors in the synthesis of complex molecules as they can be reduced to the amine or used in click reactions.[15] Griesbeck et al. have reported the visible light photocatalytic generation of azidyl radicals from azides in the presence of oxygen using a variety of different sensitizers.[16] The xanthene dye rhodamine B (Scheme 4) proved to be the most efficient sensitizer; however, the nanosized particles of the inorganic semiconductors CdS and TiO_2[17] can also be applied as a photocatalyst in this transformation. The addition of $N_3^\bullet$ to olefins **17** with subsequent trapping of the resulting carbon radical by oxygen leads to 1,2-azidohydroperoxides **19**, which can later be transformed into 1,2-azidoalcohols or 1,2-aminoalcohols. The scope of the reaction includes cycloalkenes, allyl alcohols, and Michael acceptors and is exemplarily shown in Scheme 4.

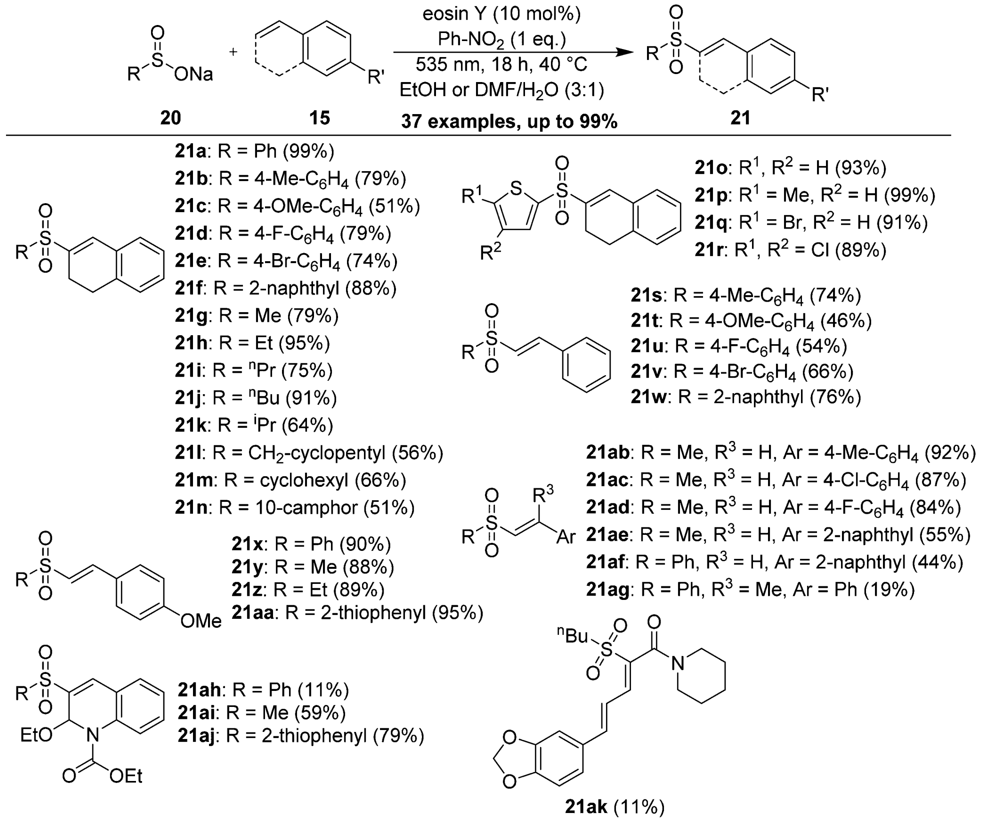
■ OXIDATION OF SULFINATES

Sodium sulfinates are versatile reagents in organic and medicinal chemistry. They are bench stable, easy to handle, moisture-insensitive, and readily available.[18] Compared to sulfonyl chlorides and sulfinic acids, sodium sulfinates are more stable and therefore used preferentially for organic transformations.[18] Sodium sulfinates are prepared from the corresponding sulfonyl chloride by adding sodium sulfite and sodium bicarbonate.[19] Alternatively, sodium sulfinates are obtained by a four step synthesis reported by Baran et al. starting from carboxylic acids.[20] Zinc sulfinates are known as well but currently have relatively few applications.[21] Sulfinates exhibit a dual reactivity as they can react sulfonylative or desulfitative, which was recently summarized by Hamze et al.[18] Baran et al. performed the C−H functionalization of heteroarenes by oxidizing the sulfinate with *tert*-butylhydroperoxide, which reacts under loss of SO_2 to valuable products.[20,22] Nicewicz et al. reported a photoredox-catalyzed desulfitative hydrotrifluoromethylation of styrenes by oxidation of sodium trifluoromethanesulfinate (Langlois reagent).[23] The Langlois reagent reacts always under loss of SO_2.[24] By preserving the SO_2 moiety, vinyl sulfones can be prepared, which are used in organic transformations.[25] They are also of biological importance,[26] for example, as inhibitors for different enzymes.[27]

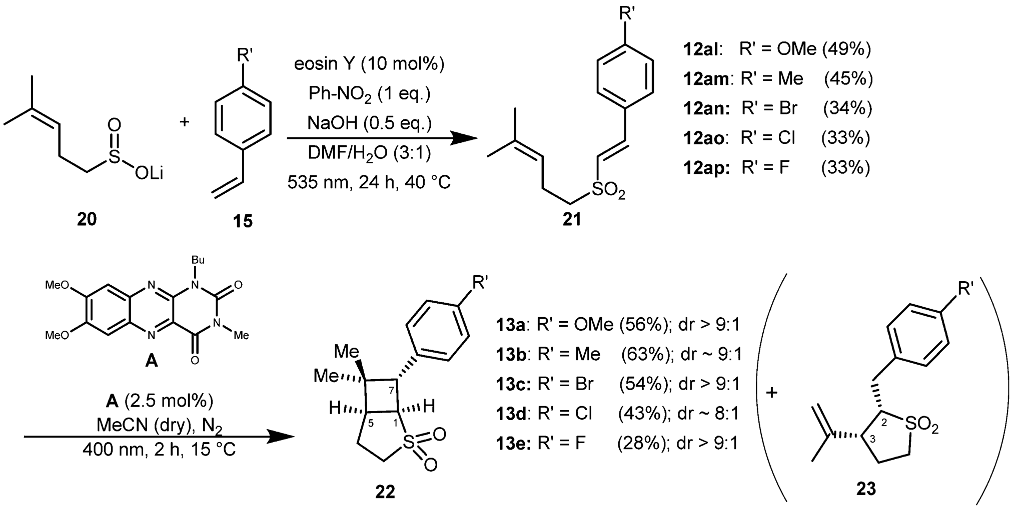
Scheme 4. Azidoperoxidation of Alkenes with Selected Examples



Scheme 5. Scope of Vinyl Sulfones (Isolated Yields)[30,34]



Scheme 6. Synthesis of Complex Cyclic Sulfones 22 and 23 (Isolated Yields)[34]



Vinyl sulfones can be prepared by transition metal-catalyzed reactions of sulfinates with alkenes or alkynes[28] or by decarboxylative sulfonylation reactions with sodium sulfinates.[29] In 2015, our group reported a mild, photoredox-catalyzed synthesis of vinyl sulfones from alkenes and sodium aryl sulfinates.[30] Another approach using visible light photo-oxidation for the synthesis of coumarin derivatives from comparably less stable sulfinic acids with phenyl propiolates was published in the same year.[31] Both methods are limited to aryl vinyl sulfones as the most reported methods. Exceptions are copper-[32] and ammonium iodide-catalyzed syntheses of vinyl methyl sulfones from DMSO with alkenes or alkynes.[33]

To overcome the substrate scope limitation, our group recently extended the original method to sodium alkyl sulfinates.[34] Our eosin Y photoredox-catalyzed sulfonylation protocol enables the metal-free synthesis of alkyl- and aryl vinyl sulfones from sodium and lithium sulfinates.[30,34] The reaction tolerates a wide range of functional groups and has a broad scope with respect to both alkyl- and (hetero)aryl sulfinates and activated alkenes, and the mechanism was studied in detail by transient spectroscopy.

The conditions were first optimized for $[Ru(bpy)_3]Cl_2$. The yield strongly depends on the solvent and increases in protic solvents. Ethanol was selected as the solvent of choice, and only

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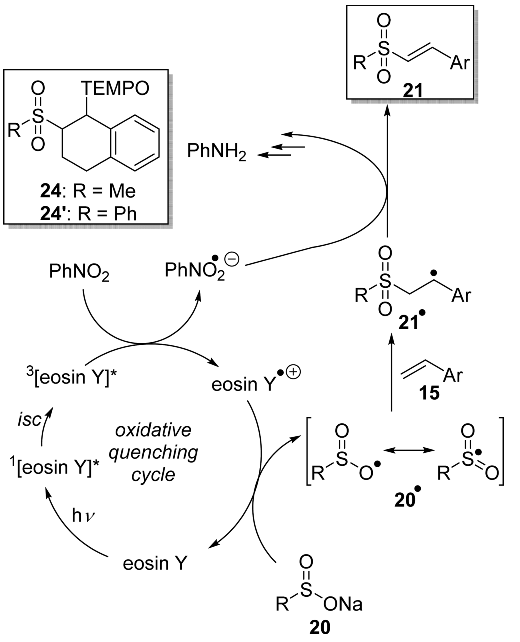
Scheme 7. Confirmed Mechanism for the Eosin Y-Catalyzed Sulfonylation of Alkenes[30,34]



for styrene derivatives was a mixture of DMF and water used because traces of a byproduct were formed with ethanol.[30,34] The reaction conditions were then optimized for the organic dye eosin Y as photocatalysts.[35] The yield increased compared to that with $[Ru(bpy)_3]Cl_2$. Nitrobenzene is the best oxidant for this reaction, but air oxygen works as well with slightly lower yields. The reaction is performed under air, and the oxygen in the air atmosphere acts as a secondary terminal oxidant. Reactions under nitrogen only in the presence of nitrobenzene showed slightly decreased yields. In the absence of any terminal oxidant, it is possible to evolve hydrogen as the only byproduct using $[Co(dmgH)_2(py)Cl]$ as a hydrogen-evolving cocatalyst.[36] The yield of the vinyl sulfone formation under these conditions is comparable to that of the reaction in oxygen atmosphere.

The scope of substrates (Scheme 5) was explored using the general reaction conditions (3 equiv of sulfinate **20**, 1 equiv of alkene **15**, 10 mol % eosin Y, and 1 equiv of nitrobenzene as oxidant). The low reactivity of the sulfone radical makes the method selective for activated alkenes. In total, 37 examples with yields up to 99% were isolated. Aryl, heteroaryl, and alkyl sulfinates were reacted with dihydronaphthalenes, styrenes, and dihydroquinolines. The preservation of the SO_2 moiety was confirmed by X-ray single crystal analysis for compounds **21a**, **21p**, **21q**, **21r**, **21y**, **21ac**, and **21ad**. The mild conditions tolerate electron-withdrawing and -donating groups as well as bromide and chloride substituents, which allow further synthetic modifications. Furthermore, the irreversible receptor antagonist *N*-ethoxycarbonyl-2-ethoxy-1,2-dihydroquinoline (EEDQ)[37] and the alkaloid piperine were used as substrates to give products **21ah–ak**.

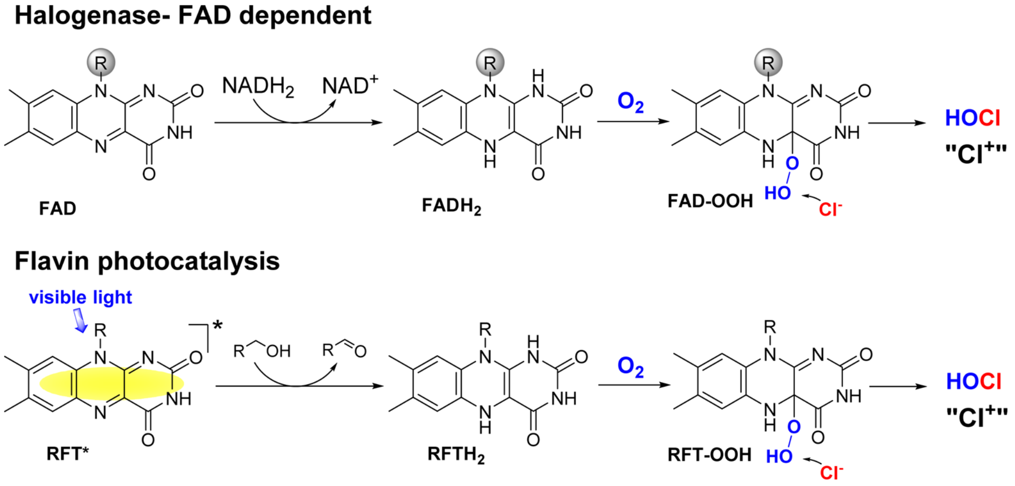
By merging two sequential photocatalytic reactions, complex cyclic sulfones could be synthesized (Scheme 6). The reaction of unsaturated sulfinates with styrene derivatives led to precursors for photocatalyzed intramolecular [2 + 2] cycloadditions **21al–ap**. The method by Cibulka et al.[38] led to a diastereomeric mixture of complex sulfones **22a–e** with five-membered heterocycles **23** as a byproduct.

The proposed mechanism for the eosin Y-catalyzed sulfonylation of alkenes is shown in Scheme 7. Eosin Y is excited by green light irradiation. Oxidative quenching of the triplet state by nitrobenzene produces the radical cation of eosin Y, which was confirmed by transient spectroscopy.[34,39] Oxidation of the sulfinate salt by the eosin Y radical cation yielded the sulfone radical, which reacted with the alkene to form radical intermediate **21•**. After H atom abstraction by the nitrobenzene radical anion, product **21** was obtained. Radical intermediate **21•** was confirmed by trapping with the persistent radical TEMPO, yielding compounds **24** and **24′**.[30,34] The quantum yield was determined to be Φ = 1.3 ± 0.4%, reflecting the comparably long reaction times.

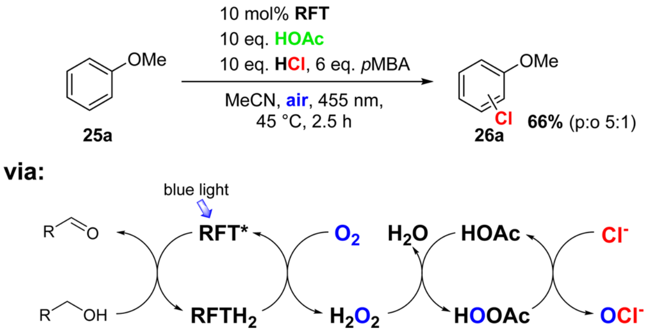
■ OXIDATIVE PHOTOCHLORINATION

The examples in the previous sections have demonstrated how photoredox catalysis can be used to generate radicals from the corresponding inorganic anions by one-electron oxidation. It is also possible to go a step further and generate electrophilic species "X^+", namely "Cl^+", by oxidation from the corresponding anion Cl^-. However, this oxidation is more challenging and

Scheme 8. (top) Simplified Mechanism of the Oxidation of Cl^- by FAD-Dependent Halogenases and (bottom) Analogy to the Proposed Photocatalyzed Biomimetic System



Scheme 9. RFT-Catalyzed Visible Light-Mediated Oxidative Chlorination by in Situ Generation of Peracetic Acid[a]



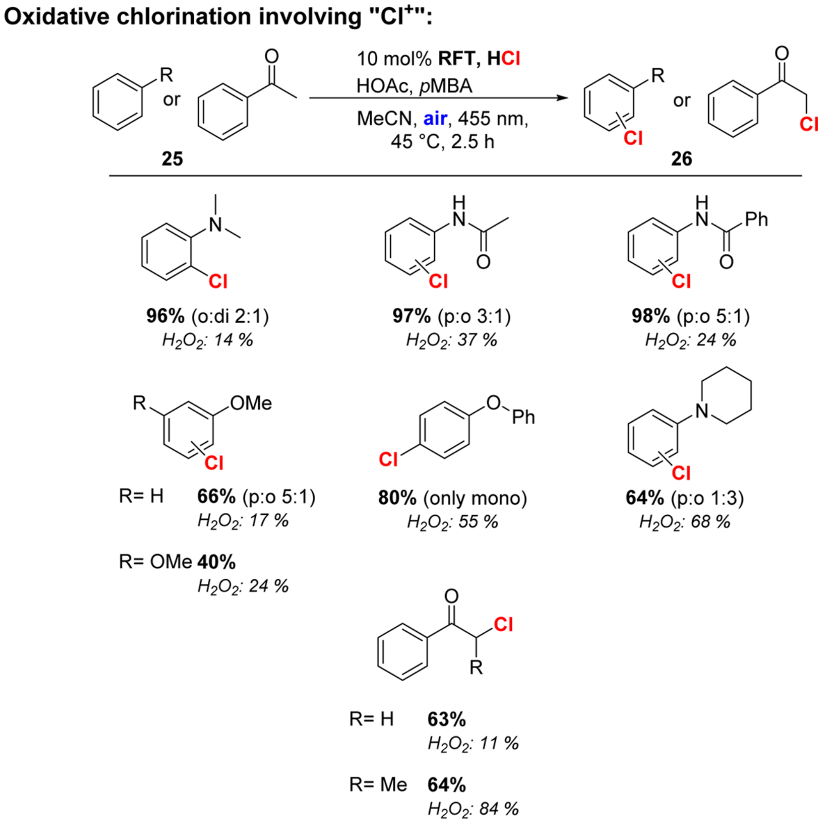
[a] *p*MBA = *para*-methoxy benzyl alcohol.

cannot be realized by two subsequent one-electron oxidation steps, $X^- \rightarrow X^\bullet \rightarrow X^+$, because the resulting radicals $X^\bullet$ are generally too reactive to live long enough for a second oxidation to occur. Moreover, these electrophilic species generally do not exist in their free form. Although there is no free "Cl$^+$" in solution, several reagents provide an electrophilic chlorine atom, such as ^{t}BuOCl, NCS, HOCl, Palau'Chlor,[40] or $Cl_2/AlCl_3$. These reagents are commonly used for electrophilic chlorination. They are synthesized using toxic chlorine gas. Nature is able to perform electrophilic chlorinations starting from chloride anions using enzymatically catalyzed oxidative chlorination.[41] Flavin adenine dinucleotide (FAD)-dependent halogenases efficiently yield aryl halides from halide ions and arenes using O_2 as the oxidant, whereas other families of halogenases (haloperoxidases) rely on H_2O_2 as the oxidant.[41] This oxidative chlorination strategy is very appealing because it produces only water as the byproduct and uses abundant, nontoxic Cl^- as the chlorine source; thus, a variety of chemical oxidative halogenations have been developed.[42] Even though great progress has been made in the area of oxidative bromination, only a few examples are known for chemical oxidative chlorination suffering from drastic conditions and low selectivity[42,43] or they require strong or metal-based stoichiometric oxidants.[44]

Therefore, we have developed a photocatalytic biomimetic system derived from FAD-dependent halogenases.[45] A simplified mechanism of the enzymatic generation of the electrophilic chlorine species HOCl and the analogy to the photocatalytic system is illustrated in Scheme 8. In the photocatalytic process, the biomolecules FAD and $NADH_2$ were replaced by the cheap organic dye riboflavin tetraacetate (RFT) and a benzylic alcohol as the reducing agent.[46] The proposed mechanism proceeds by reduction of RFT to $RFTH_2$ or in the enzyme from FAD to $FADH_2$, respectively. Both reduced species react quickly with oxygen to form the peroxide species RFT-OOH or FAD-OOH. Subsequent attack of Cl^- should lead to the formation of HOCl.

However, the activation by the enzyme is somehow more complex and involves amino acid side chains and ion channels;[41,47] thus, the photocatalytic system requires a mediator, which takes the role of the enzyme binding pocket and overcomes the barrier for the reaction of chloride and the peroxide. A chemical compound that is able to oxidize Cl^- is peracetic acid,[45] which if isolated is highly explosive, but it is

Scheme 10. Scope of the Flavin-Catalyzed Oxidative Chlorination and Comparison to the Direct Addition of H_2O_2[a]



[a] Yields based on conversion.

safely obtained in an equilibrium of acetic acid and H_2O_2.[48] The flavin peroxide RFT-OOH formed in the reaction is reported to quickly release H_2O_2, and thus, the addition of acetic acid enabled the oxidative chlorination of anisole (**25a**) by forming peracetic acid in situ (Scheme 9).

Compared to an enzyme binding pocket, the peracid mediation presents a more general way of activation and allows a broader substrate scope. As depicted in Scheme 10, several electron-rich arenes can be chlorinated in excellent to moderate yields, and acetophenone derivatives can be monochlorinated in the α-position. The addition of H_2O_2 directly gives considerably lower yields compared to the formation by the photocatalytic process as the slow generation of H_2O_2 reduces unselective side reactions and multiple chlorination. The reported visible light photocatalysis allows the oxidation of Cl^- to an electrophilic chlorine using a strategy inspired by an enzymatic system.

■ CONCLUSIONS AND OUTLOOK

Visible light, air oxygen, and a suitable photocatalyst mediating the one-electron oxidation are in many cases sufficient to convert a stable inorganic anion into a highly reactive heteroatom-centered radical that can be used in organic transformations. The simple conditions favor applications in synthesis as expensive and sensitive stoichiometric oxidants or electrochemical setups are avoided. The inorganic radicals undergo, depending on their intrinsic reactivity, C−H abstraction or addition to double bonds or arenes. A much broader scope of the inorganic anions as radical precursors can be imagined than described so far, but many may react only via rather unselective hydrogen atom abstraction due to their high reactivity. There are several challenges ahead extending the method: Many nonbasic anions are currently outside the reachable oxidation potential of visible light photocatalysts, which is at approximately +2.1 V vs SCE. The use of more than one visible light photon for an oxidation process may well extend this range. Consecutive photoinduced electron transfer (conPET)[49] was successfully applied, reaching reduction potentials of up to −2.4 V vs SCE by accumulating the energy of two visible light photons, and a similar process may be used in photooxidations. The high reactivity of photogenerated inorganic radicals leads to unspecific organic transformations. Synergistic catalysis using, for example, radical stabilizing metal complexes may allow more selective reactions. The use of flow chemistry may also be considered as many previous examples have shown the advantage for syntheses involving highly reactive intermediates. The photochemical generation of the radical and its subsequent reaction with an organic substrate can be combined into a single flow process, which also facilitates reactions at larger scale.

Most photooxidations of anions are one-electron processes giving radicals. Our example of converting chloride anions into electrophilic chlorine species demonstrates that an extension of the concept beyond radical chemistry is possible, although the oxidation in this case proceeds via photogenerated peracetic acid. Related photocatalytic oxidative generations of electrophilic species may be envisaged and await future discovery.

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Notes

The authors declare no competing financial interest.

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Burkhard König is a full professor of organic chemistry at the University of Regensburg. His current research interests are the development of synthetic methodologies in photoredox catalysis.

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■ REFERENCES

(1) (a) Wayne, R. P.; Barnes, I.; Biggs, P.; Burrows, J. P.; Canosa-Mas, C. E.; Hjorth, J.; Le Bras, G.; Moortgat, G. K.; Perner, D.; Poulet, G.; Restelli, G.; Sidebottom, H. *Atmos. Environ., Part A* **1991**, *25*, 1−203. (b) Ito, O.; Akiho, S.; Iino, M. *J. Phys. Chem.* **1989**, *93*, 4079−4083.

(2) (a) Pérez-Casany, M. P.; Nebot-Gil, I.; Sánchez-Marín, J.; Tomás-Vert, F.; Martínez-Ataz, E.; Cabañas-Galán, B.; Aranda-Rubio, A. *J. Org. Chem.* **1998**, *63*, 6978−6983. (b) Gong, H.; Matsunaga, A.; Ziemann, P. J. *J. Phys. Chem. A* **2005**, *109*, 4312−4324. (c) Rousse, D.; George, C. *Phys. Chem. Chem. Phys.* **2004**, *6*, 3408−3414.

(3) (a) Shono, T.; Chuankamnerdkarn, M.; Maekawa, H.; Ishifune, M.; Kashimura, S. *Synthesis* **1994**, *1994*, 895−897. (b) Wille, U.; Lietzau, L. *Tetrahedron* **1999**, *55*, 11465−11474. (c) Wille, U.; Lietzau, L. *Tetrahedron* **1999**, *55*, 10119−10134. (d) Wille, U.; Andropof, J. *Aust. J. Chem.* **2007**, *60*, 420−428. (e) Wille, U. *J. Am. Chem. Soc.* **2002**, *124*, 14−15.

(4) Fukuzumi, S.; Kotani, H.; Ohkubo, K.; Ogo, S.; Tkachenko, N. V.; Lemmetyinen, H. *J. Am. Chem. Soc.* **2004**, *126*, 1600−1601.

(5) Hering, T.; Slanina, T.; Hancock, A.; Wille, U.; Koenig, B. *Chem. Commun.* **2015**, *51*, 6568−6571.

(6) Romero, N. A.; Nicewicz, D. A. *J. Am. Chem. Soc.* **2014**, *136*, 17024−17035.

(7) (a) Fukuzumi, S.; Ohkubo, K.; Suenobu, T. *Acc. Chem. Res.* **2014**, *47*, 1455−1464. (b) Benniston, A. C.; Harriman, A.; Li, P.; Rostron, J. P.; van Ramesdonk, H. J.; Groeneveld, M. M.; Zhang, H.; Verhoeven, J. W. *J. Am. Chem. Soc.* **2005**, *127*, 16054−16064.

(8) Baciocchi, E.; Giacco, T. D.; Murgia, S. M.; Sebastiani, G. V. *J. Chem. Soc., Chem. Commun.* **1987**, 1246−1248.

(9) Benniston, A. C.; Elliott, K. J.; Harrington, R. W.; Clegg, W. *Eur. J. Org. Chem.* **2009**, *2009*, 253−258.

(10) (a) Fokin, A. A.; Peleshanko, S. A.; Gunchenko, P. A.; Gusev, D. V.; Schreiner, P. R. *Eur. J. Org. Chem.* **2000**, *2000*, 3357−3362. (b) Mella, M.; Freccero, M.; Soldi, T.; Fasani, E.; Albini, A. *J. Org. Chem.* **1996**, *61*, 1413−1422.

(11) (a) Langer, S.; Ljungstrom, E. *J. Chem. Soc., Faraday Trans.* **1995**, *91*, 405−410. (b) Kyriacou, D. *Modern Electroorganic Chemistry*; Springer-Verlag: Berlin, Heidelberg, 1994.

(12) Fan, W.; Yang, Q.; Xu, F.; Li, P. *J. Org. Chem.* **2014**, *79*, 10588−10592.

(13) Mitra, S.; Ghosh, M.; Mishra, S.; Hajra, A. *J. Org. Chem.* **2015**, *80*, 8275−8281.

(14) Yadav, A. K.; Yadav, L. D. S. *Green Chem.* **2015**, *17*, 3515−3520.

(15) (a) Thirumurugan, P.; Matosiuk, D.; Jozwiak, K. *Chem. Rev.* **2013**, *113*, 4905−4979. (b) Binder, W. H.; Kluger, C. *Curr. Org. Chem.* **2006**, *10*, 1791−1815.

(16) (a) Griesbeck, A.; Steinwascher, J.; Reckenthäler, M.; Uhlig, J. *Res. Chem. Intermed.* **2013**, *39*, 33−42. (b) Griesbeck, A. G.; Lex, J.; Saygin, K. M.; Steinwascher, J. *Chem. Commun.* **2000**, 2205−2206.

(17) Griesbeck, A. G.; Reckenthäler, M.; Uhlig, J. *Photochem. Photobiol. Sci.* **2010**, *9*, 775−778.

(18) Aziz, J.; Messaoudi, S.; Alami, M.; Hamze, A. *Org. Biomol. Chem.* **2014**, *12*, 9743−9759.

(19) (a) Liu, L. K.; Chi, Y.; Jen, K.-Y. *J. Org. Chem.* **1980**, *45*, 406−410. (b) Liu, J.; Zhou, X.; Rao, H.; Xiao, F.; Li, C.-J.; Deng, G.-J. *Chem. - Eur. J.* **2011**, *17*, 7996−7999.

(20) Gianatassio, R.; Kawamura, S.; Eprile, C. L.; Foo, K.; Ge, J.; Burns, A. C.; Collins, M. R.; Baran, P. S. *Angew. Chem., Int. Ed.* **2014**, *53*, 9851−9855.

(21) (a) Fujiwara, Y.; Dixon, J. A.; O'Hara, F.; Funder, E. D.; Dixon, D. D.; Rodriguez, R. A.; Baxter, R. D.; Herlé, B.; Sach, N.; Collins, M. R.; Ishihara, Y.; Baran, P. S. *Nature* **2012**, *492*, 95−99. (b) Fujiwara, Y.; Dixon, J. A.; Rodriguez, R. A.; Baxter, R. D.; Dixon, D. D.; Collins, M. R.; Blackmond, D. G.; Baran, P. S. *J. Am. Chem. Soc.* **2012**, *134*, 1494−1497. (c) Gui, J.; Zhou, Q.; Pan, C.-M.; Yabe, Y.; Burns, A. C.; Collins, M. R.; Ornelas, M. A.; Ishihara, Y.; Baran, P. S. *J. Am. Chem. Soc.* **2014**, *136*, 4853−4856.

(22) (a) Ji, Y.; Brueckl, T.; Baxter, R. D.; Fujiwara, Y.; Seiple, I. B.; Su, S.; Blackmond, D. G.; Baran, P. S. *Proc. Natl. Acad. Sci. U. S. A.* **2011**, *108*, 14411−14415. (b) Zhou, Q.; Gui, J.; Pan, C.-M.; Albone, E.; Cheng, X.; Suh, E. M.; Grasso, L.; Ishihara, Y.; Baran, P. S. *J. Am. Chem. Soc.* **2013**, *135*, 12994−12997. (c) Zhou, Q.; Ruffoni, A.; Gianatassio, R.; Fujiwara, Y.; Sella, E.; Shabat, D.; Baran, P. S. *Angew. Chem., Int. Ed.* **2013**, *52*, 3949−3952.

(23) Wilger, D. J.; Gesmundo, N. J.; Nicewicz, D. A. *Chem. Sci.* **2013**, *4*, 3160−3165.

(24) (a) Lu, Q.; Liu, C.; Peng, P.; Liu, Z.; Fu, L.; Huang, J.; Lei, A. *Asian J. Org. Chem.* **2014**, *3*, 273−276. (b) Lu, Q.; Liu, C.; Huang, Z.; Ma, Y.; Zhang, J.; Lei, A. *Chem. Commun.* **2014**, *50*, 14101−14104. (c) Liu, C.; Lu, Q.; Huang, Z.; Zhang, J.; Liao, F.; Peng, P.; Lei, A. *Org. Lett.* **2015**, *17*, 6034−6037.

(25) (a) Hof, F.; Schütz, A.; Fäh, C.; Meyer, S.; Bur, D.; Liu, J.; Goldberg, D. E.; Diederich, F. *Angew. Chem., Int. Ed.* **2006**, *45*, 2138−2141. (b) Desrosiers, J.-N.; Charette, A. B. *Angew. Chem., Int. Ed.* **2007**, *46*, 5955−5957. (c) Pandey, G.; Tiwari, K. N.; Puranik, V. G. *Org. Lett.* **2008**, *10*, 3611−3614. (d) Ravelli, D.; Montanaro, S.; Zema, M.; Fagnoni, M.; Albini, A. *Adv. Synth. Catal.* **2011**, *353*, 3295−3300. (e) Noble, A.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2014**, *136*, 11602−11605.

(26) (a) Meadows, D. C.; Sanchez, T.; Neamati, N.; North, T. W.; Gervay-Hague, J. *Bioorg. Med. Chem.* **2007**, *15*, 1127−1137. (b) Kerr, I. D.; Lee, J. H.; Farady, C. J.; Marion, R.; Rickert, M.; Sajid, M.; Pandey, K. C.; Caffrey, C. R.; Legac, J.; Hansell, E.; McKerrow, J. H.; Craik, C. S.; Rosenthal, P. J.; Brinen, L. S. *J. Biol. Chem.* **2009**, *284*, 25697−25703.

(27) (a) Palmer, J. T.; Rasnick, D.; Klaus, J. L.; Bromme, D. *J. Med. Chem.* **1995**, *38*, 3193−3196. (b) Frankel, B. A.; Bentley, M.; Kruger, R. G.; McCafferty, D. G. *J. Am. Chem. Soc.* **2004**, *126*, 3404−3405. (c) Liu, S.; Zhou, B.; Yang, H.; He, Y.; Jiang, Z.-X.; Kumar, S.; Wu, L.; Zhang, Z.-Y. *J. Am. Chem. Soc.* **2008**, *130*, 8251−8260.

(28) Taniguchi, N. *Synlett* **2011**, *09*, 1308−1312.

(29) (a) Jiang, Q.; Xu, B.; Jia, J.; Zhao, A.; Zhao, Y.-R.; Li, Y.-Y.; He, N.-N.; Guo, C.-C. *J. Org. Chem.* **2014**, *79*, 7372−7379. (b) Xu, Y.; Tang, X.; Hu, W.; Wu, W.; Jiang, H. *Green Chem.* **2014**, *16*, 3720−3723. (c) Rong, G.; Mao, J.; Yan, H.; Zheng, Y.; Zhang, G. *J. Org. Chem.* **2015**, *80*, 7652−7657.

(30) Meyer, A. U.; Jäger, S.; Hari, D. P.; König, B. *Adv. Synth. Catal.* **2015**, *357*, 2050−2054.

(31) Yang, W.; Yang, S.; Li, P.; Wang, L. *Chem. Commun.* **2015**, *51*, 7520−7523.

(32) (a) Jiang, Y.; Loh, T.-P. *Chem. Sci.* **2014**, *5*, 4939−4943. (b) Chen, J.-Y.; Chen, X.-L.; Li, X.; Qu, L.-B.; Zhang, Q.; Duan, L.-K.; Xia, Y.-Y.; Chen, X.; Sun, K.; Liu, Z.-D.; Zhao, Y.-F. *Eur. J. Org. Chem.* **2015**, *2*, 314−319.

(33) Gao, X.; Pan, X.; Gao, J.; Huang, H.; Yuan, G.; Li, Y. *Chem. Commun.* **2015**, *51*, 210−212.

(34) Meyer, A. U.; Straková, K.; Slanina, T.; König, B. *Chem. - Eur. J.* **2016**, *22*, 8694−8699.

(35) Hari, D. P.; König, B. *Chem. Commun.* **2014**, *50*, 6688−6699.

(36) (a) Troppmann, S.; König, B. *Chem. - Eur. J.* **2014**, *20*, 14570−14574. (b) Zhang, G.; Liu, C.; Yi, H.; Meng, Q.; Bian, C.; Chen, H.; Jian, J.-X.; Wu, L.-Z.; Lei, A. *J. Am. Chem. Soc.* **2015**, *137*, 9273−9280.

(37) Crocker, A. D.; Cameron, D. L. *Clin. Exp. Pharmacol. Physiol.* **1989**, *16*, 545−548.

(38) Mojr, V.; Svobodová, E.; Straková, K.; Neveselý, T.; Chudoba, J.; Dvořáková, H.; Cibulka, R. *Chem. Commun.* **2015**, *51*, 12036−12039.

(39) Meyer, A. U.; Slanina, T.; Yao, C.-J.; König, B. *ACS Catal.* **2016**, *6*, 369−375.

(40) Rodriguez, R. A.; Pan, C.-M.; Yabe, Y.; Kawamata, Y.; Eastgate, M. D.; Baran, P. S. *J. Am. Chem. Soc.* **2014**, *136*, 6908−6911.

(41) Vaillancourt, F. H.; Yeh, E.; Vosburg, D. A.; Garneau-Tsodikova, S.; Walsh, C. T. *Chem. Rev.* **2006**, *106*, 3364−3378.

(42) Podgoršek, A.; Zupan, M.; Iskra, J. *Angew. Chem., Int. Ed.* **2009**, *48*, 8424−8450.

(43) (a) Terent'ev, A. O.; Khodykin, S. V.; Troitskii, N. A.; Ogibin, Y. N.; Nikishin, G. I. *Synthesis* **2004**, *2004*, 2845−2848. (b) Ben-Daniel, R.; de Visser, S. P.; Shaik, S.; Neumann, R. *J. Am. Chem. Soc.* **2003**, *125*, 12116−12117.

(44) (a) Gu, L.; Lu, T.; Zhang, M.; Tou, L.; Zhang, Y. *Adv. Synth. Catal.* **2013**, *355*, 1077−1082. (b) Umland, K.-D.; Mayer, C.; Kirsch, S. F. *Synlett* **2014**, *25*, 813−816. (c) Wang, J.-Y.; Jiang, Q.; Guo, C.-C. *Synth. Commun.* **2014**, *44*, 3130−3138. (d) Cong, Z.; Kurahashi, T.; Fujii, H. *Angew. Chem.* **2011**, *123*, 10109−10113. (e) Vardhaman, A. K.; Barman, P.; Kumar, S.; Sastri, C. V.; Kumar, D.; de Visser, S. P. *Chem. Commun.* **2013**, *49*, 10926−10928. (f) Hansen, P. J.; Espenson, J. H. *Inorg. Chem.* **1995**, *34*, 5839−5844.

(45) Hering, T.; Mühldorf, B.; Wolf, R.; König, B. *Angew. Chem., Int. Ed.* **2016**, *55*, 5342−5345.

(46) (a) Megerle, U.; Wenninger, M.; Kutta, R.-J.; Lechner, R.; König, B.; Dick, B.; Riedle, E. *Phys. Chem. Chem. Phys.* **2011**, *13*, 8869. (b) Lechner, R.; Kümmel, S.; König, B. *Photochem. Photobiol. Sci.* **2010**, *9*, 1367.

(47) Yeh, E.; Blasiak, L. C.; Koglin, A.; Drennan, C. L.; Walsh, C. T. *Biochemistry* **2007**, *46*, 1284−1292.

(48) (a) Klenk, H.; Götz, P. H.; Siegmeier, R.; Mayr, W. In *Ullmann's Encyclopedia of Industrial Chemistry*; Wiley-VCH Verlag GmbH & Co. KGaA, 2000. (b) Zhao, X.; Zhang, T.; Zhou, Y.; Liu, D. *J. Mol. Catal. A: Chem.* **2007**, *271*, 246−252.

(49) (a) Ghosh, I.; Ghosh, T.; Bardagi, J. I.; König, B. *Science* **2014**, *346*, 725−728. (b) Ghosh, I.; König, B. *Angew. Chem., Int. Ed.* **2016**, *55*, 7676.

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