Article

Photocatalytic Deoxygenation of Sulfoxides using Visible Light: Mechanistic Investigations and Synthetic Applications

Aimee K Clarke, Alison Parkin, Richard John Kenneth Taylor, William Paul Unsworth, and James A Rossi-Ashton

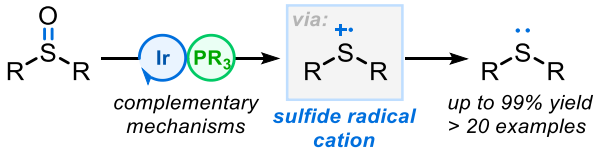
ACS Catal., **Just Accepted Manuscript** • DOI: 10.1021/acscatal.0c00690 • Publication Date (Web): 17 Apr 2020

Photocatalytic Deoxygenation of Sulfoxides using Visible Light: Mechanistic Investigations and Synthetic Applications

Aimee K. Clarke,‡ Alison Parkin, Richard J. K. Taylor,* William P. Unsworth* and James A. Rossi-Ashton‡*

Department of Chemistry, University of York, Heslington, York, U.K., YO10 5DD

Supporting Information Placeholder



ABSTRACT: The photocatalytic deoxygenation of sulfoxides to generate sulfides facilitated by either Ir[(dF(CF$_3$)ppy)$_2$(dtbbpy)]PF$_6$ or *fac*-Ir(ppy)$_3$ is reported. Mechanistic studies indicate a radical chain mechanism operates, that proceeds via a phosphoranyl radical generated from a radical/polar crossover process. Initiation of the radical chain was found to proceed via two opposing photocatalytic quenching mechanisms, offering complementary reactivity. The mild nature of the radical deoxygenation process enables the reduction of a wide range of functionalized sulfoxides, including those containing acid-sensitive groups, in typically high isolated yields.
KEYWORDS: *sulfoxide, deoxygenation, reduction, radical, visible light, photoredox catalysis, sulfide radical cation*

The deoxygenation of sulfoxides to generate sulfides is a fundamental transformation in organic synthesis[1] and biochemistry.[2] Established methods to convert sulfoxides into sulfides[3] involve the use of low-valent metallic species,[4] metal hydride reagents,[5] halide ions[6] and phosphorus compounds.[7] However, these reaction systems can suffer from potential disadvantages, including the use of expensive and/or toxic reagents, difficult work up procedures and the use of harsh reaction conditions, which often limits their functional group tolerance. Consequently, this is an area of continued research and new, efficient procedures for the reduction of sulfoxides into their corresponding sulfides are desirable.

Over the past decade, photoredox catalysis has evolved into a vitally important method able to address long-standing challenges in synthetic chemistry,[8] in large part due to the mild conditions by which reactive radicals can be generated. However photocatalytic methods for the deoxygenation of sulfoxides have rarely been explored.[9] The cleavage of C–O bonds via β-scission of phosphoranyl radicals was initially recognized in the early 1970's by Bentrude,[10] and since then, the groups of Zhu,[11]Doyle[12] and Rovis[12] have extended the synthetic application of this strategy to incorporate photoredox catalysis (Figure 1A), establishing valuable methods for the deoxygenation of alcohols and carboxylic acids. More recently this work was extended to include cleavage of N–O bonds by Yang,[13] and also by Schmidt,[14] who employed more traditional radical initiation methods.

Inspired by these works, we speculated that direct cleavage of S=O bonds could be accomplished via a polar/radical crossover process between phosphine radical cations, generated from a photocatalyst (PC) initiator, and sulfoxides, resulting in the mild deoxygenation of sulfoxides (Figure 1B). Based on existing phosphoranyl radical studies (Figure 1A) and the reported oxidation potentials of sulfides (*e.g.* diphenyl sulfide {$E_{1/2}$ = +1.43 V versus saturated calomel electrode [SCE]})[15] relative to those of phosphines (*e.g.* PPh_3 {$E_{1/2}$ = +0.98 V versus SCE}),[12] a radical chain mechanism was postulated[16] (Figure 1C, see next page for a description).

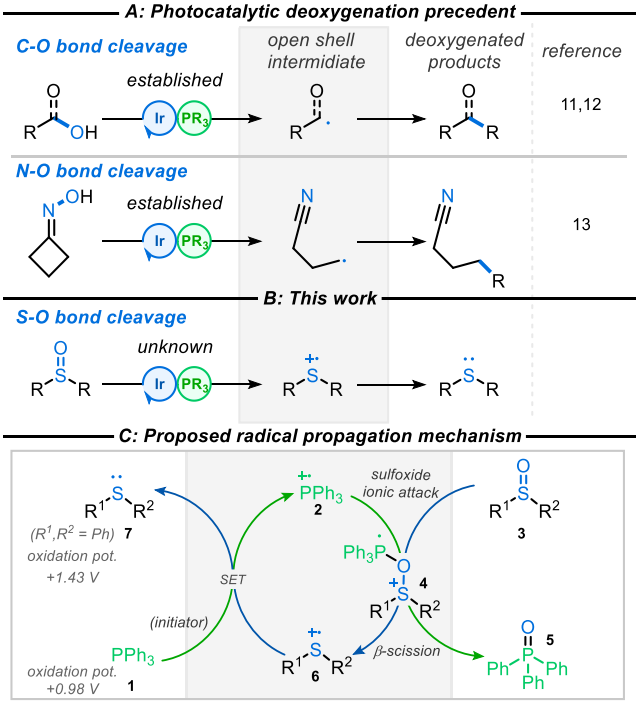
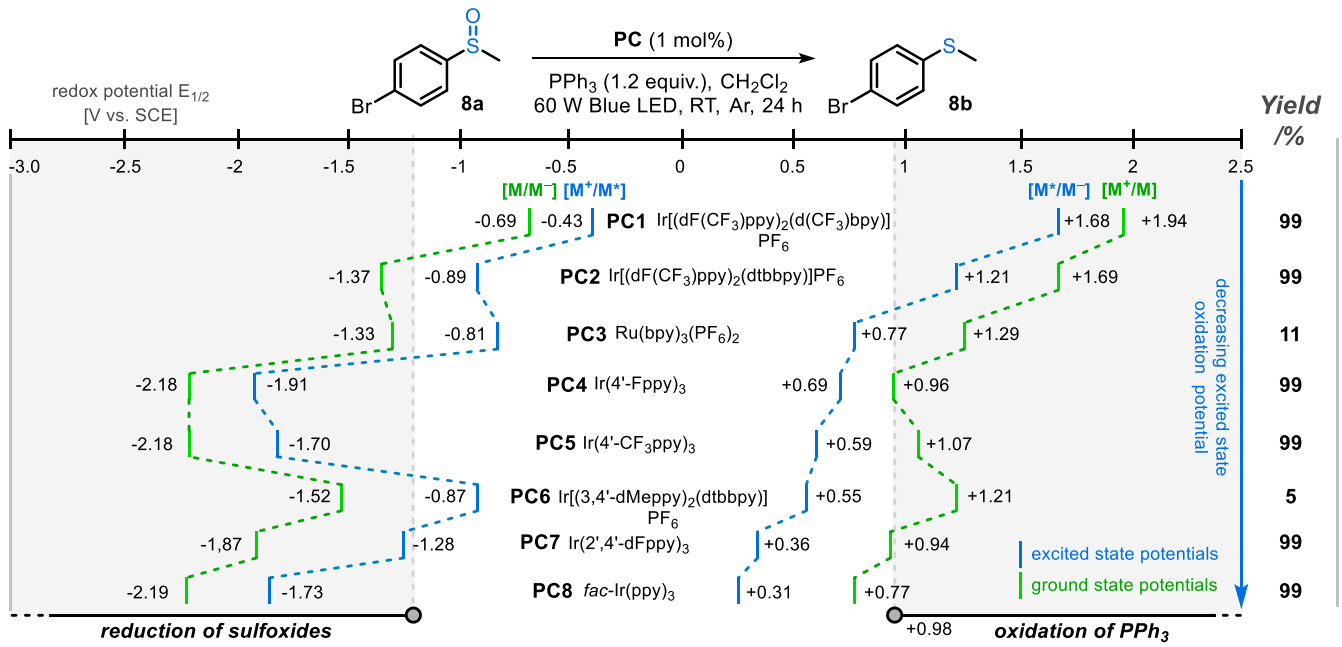


Figure 1. Photocatalytic deoxygenation methods

Scheme 1. Photocatalyst initiator screening

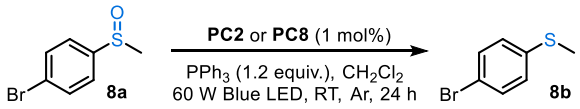


We postulated that initiation of a radical chain deoxygenation process could be promoted by single electron oxidation of PPh_3 **1**, using a suitably oxidizing photocatalyst (*initiator*)[17] to afford a catalytic amount of phosphine radical cation **2**. Polar nucleophilic addition of sulfoxide **3** to radical cation **2** would generate phosphoranyl radical **4**, which upon β-scission would afford sulfide radical cation **6** and triphenylphosphine oxide **5**. Finally, reduction of the sulfide radical cation **6** by PPh_3 **1** would afford the desired sulfide **7**, as well as propagating the radical chain via regeneration of phosphine radical cation **2**. Herein, we describe the realization of this radical chain process for the high yielding deoxygenation of sulfoxides under mild, visible light-driven reaction conditons.[18]

Studies began by surveying the ability of a series of photocatalyst initiators (**PC1**–**8**, Scheme 1) to promote the reduction of 4-bromophenyl methyl sulfoxide **8a** into sulfide **8b**, using PPh_3 as the terminal reductant and CH_2Cl_2 as the solvent, irradiating with a 60 W blue LED light[19] under an argon atmosphere. In line with related literature,[11,12] both **PC1** and **PC2**, which have excited state oxidation potentials (M^*/M^-) greater than that of PPh_3 ($E_{1/2}$ = +0.98 V versus SCE), afforded sulfide **8b** in excellent yields.[20] Moreover, **PC3** and **PC6**, which have excited state oxidation potentials lower than PPh_3, resulted in much lower yields of sulfide **8b** (11% and 5% respectively) as expected. However, PCs possessing a far lower oxidation potential than PPh_3 (*e.g.* **PC7–8**; the PCs that we originally considered to be the *least likely* to promote effective deoxygenation of **8a**) unexpectedly promoted the formation of sulfide **8b** in high yield. We noticed that all four PCs (**PC4–5** and **PC7–8**) able to initiate the reaction effectively despite their low excited state oxidation potentials have relatively high excited state reduction potentials (M^+/M^*). In contrast, the PCs with relatively low excited state oxidation *and* reduction potentials (*i.e.* **PC3** and **PC6**, for which both potentials are within the white area in Scheme 1) did not perform well in the reaction. These observations suggested that two mechanistic pathways may be viable, based on either a reductive or oxidative photocatalyst quenching cycle, with the route taken dependent on the redox potentials of the PC initiator used.

To probe this possibility further, comparative control reactions were conducted, with $Ir[(dF(CF_3)ppy)_2(dtbbpy)]PF_6$ (**PC2**) chosen as a representative oxidizing photocatalyst, and *fac*-$Ir(ppy)_3$ (**PC8**) as a representative reducing photocatalyst. In the absence of PC and light (entries 2 and 3, Table 1) no reaction occurred in either system. In the absence of PPh_3 no reaction occurred when employing the oxidizing **PC2**, although contrastingly, a small amount of conversion into sulfide **8b** was observed when employing the reducing **PC8**. TEMPO drastically suppressed the efficiency of both reaction systems, supporting a free-radical reaction pathway (entry 5); triphenylphosphine oxide was the major product formed in these TEMPO reactions, presumably via the pathway described by Bentrude *et al.*[10] Both reactions could be performed in other solvents or under an atmosphere of air but a reduction in yield was generally observed (entries 6–8). Other readily available phosphines, phosphites and phosphinites were also able to promote sulfoxide reduction, albeit in reduced yield compared with PPh_3 (entries 9–11).

Table 1. General reaction conditions optimization[a]

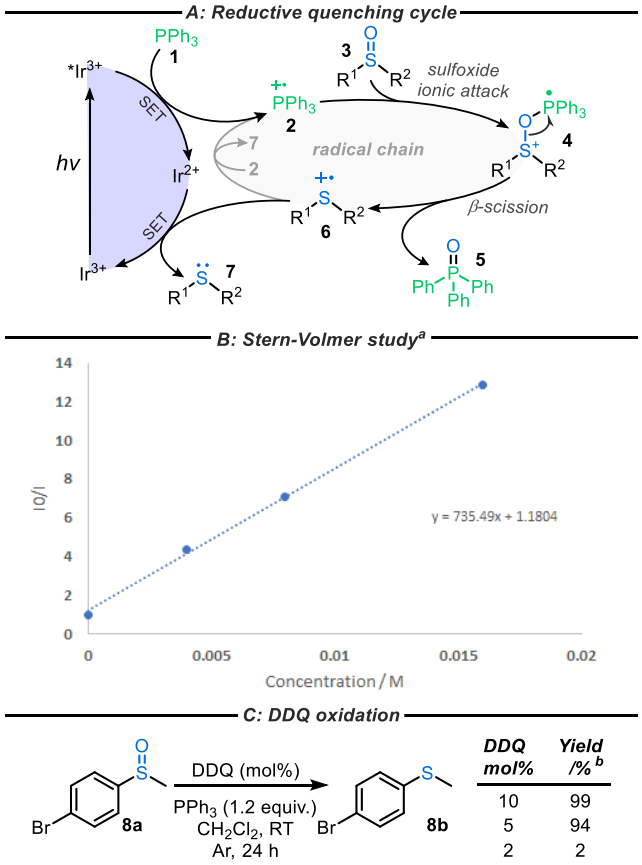


Entry	Deviation from standard conditions	Yield (PC2) / %	Yield (PC8) / %
1	none	99	99
2	no PC	0	0
3	no light	0	0
4	no PPh_3	0	9
5	3 equiv. of TEMPO	2	3
6	under air	69	46
7	THF	85	69
8	toluene	44	99
9	PCy_3	48	33
10	PPh_2OEt	68	5
11	$P(OPh)_3$	28	8

[a]Reaction conditions: **8a** (0.20 mmol), **PC2** or **PC8** (1 mol%), PPh_3 (0.24 mmol) in CH_2Cl_2 (1.0 mL) at RT, 24 h. ^1H NMR yields reported based on a trimethoxybenzene internal standard.

Mechanistically, the single electron oxidation of PPh_3 by the most oxidizing catalysts (*e.g.* **PC1** and **PC2**, Scheme 1) is an established concept.[11,12] Consequently, the initiation of the radical chain cycle when using such oxidizing PCs is proposed to occur via reductive quenching of the excited state PC, to generate the key phosphorus radical cation **2** required to initiate the proposed radical chain mechanism (Scheme 2A). To support this, Stern-Volmer quenching studies were conducted, confirming that the emission of the excited state **PC2** is quenched by PPh_3 (Scheme 2B). Furthermore, when DDQ, an organic oxidant, was used in sub-stoichiometric amounts (≥5 mol%) in place of the PC, sulfide **8b** was produced in excellent yields (Scheme 2C), further supporting the notion that the generation of phosphorus radical cation **2** promotes an efficient radical chain process, as is depicted in Figure 1C.

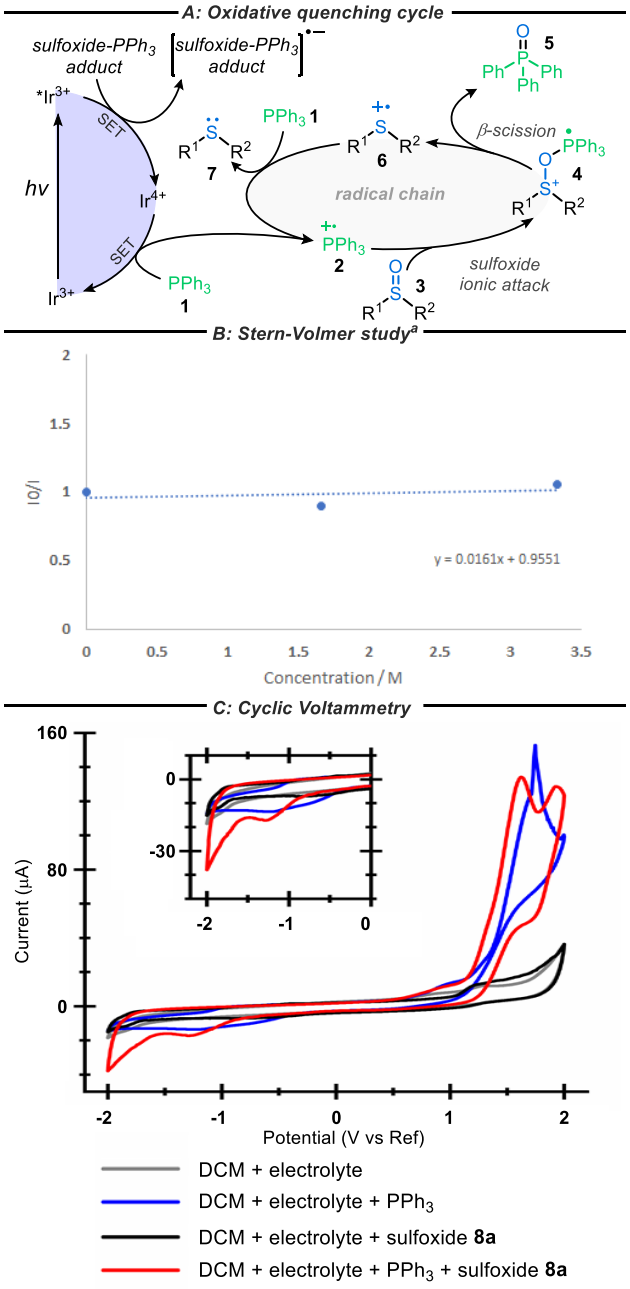
Scheme 2. Initiation via phosphine oxidation (PC2)



[a]Stern-Volmer quenching study of $Ir[(dF(CF_3)ppy)_2(dtbbpy)]PF_6$ with PPh_3 in degassed CH_2Cl_2. [b] ^1H NMR yields reported based on a trimethoxybenzene internal standard.

In contrast, PCs possessing lower oxidation potentials (M^*/M^-) such as *fac*-$Ir(ppy)_3$ (**PC8**), should not be able to oxidize PPh_3, which is supported by the absence of emission quenching of the excited state of **PC8** by PPh_3 (see Supporting Information). It has also been documented that sulfoxides such as DMSO are unable to quench the emission of **PC8**.[21] Nonetheless, contrary to these observations, which suggest that no reaction should occur, it was found that DMSO can be reduced to DMS in high yield (99%) when reacted with **PC8** and PPh_3 under our standard reaction conditions (for conditions see Table 1). We initially postulated that this may be a result of energy transfer from the excited state of **PC8** to the sulfoxide,[22] thus forming an excited state sulfoxide species able to undergo deoxygenation. The low yielding deoxygenation of **8a** in the absence of PPh_3 (see earlier control reactions, entry 4, Table 1) offers some support for this hypothesis, and the direct deoxygenation of sulfoxides under UV irradiation has also be reported.[23] However, we could find no evidence of emission quenching of the excited state of **PC8** by either sulfoxides **8a** or **18a** in Stern-Volmer quenching studies (in line with literature precedent).[21] Furthermore, if energy transfer is involved, it is not clear why the redox properties of the various PCs would have such a pronounced influence on the observed reactivity. Based on these observations, it was considered more likely that initiation is mediated by a redox process. It is also clear from the synthetic results that the phosphine plays a key role in the reaction. Thus, an alternative mechanism was postulated, in which PPh_3 and the sulfoxide interact to form an adduct which can initiate the radical chain mechanism via an initial oxidative quench of the PC (Scheme 3A).

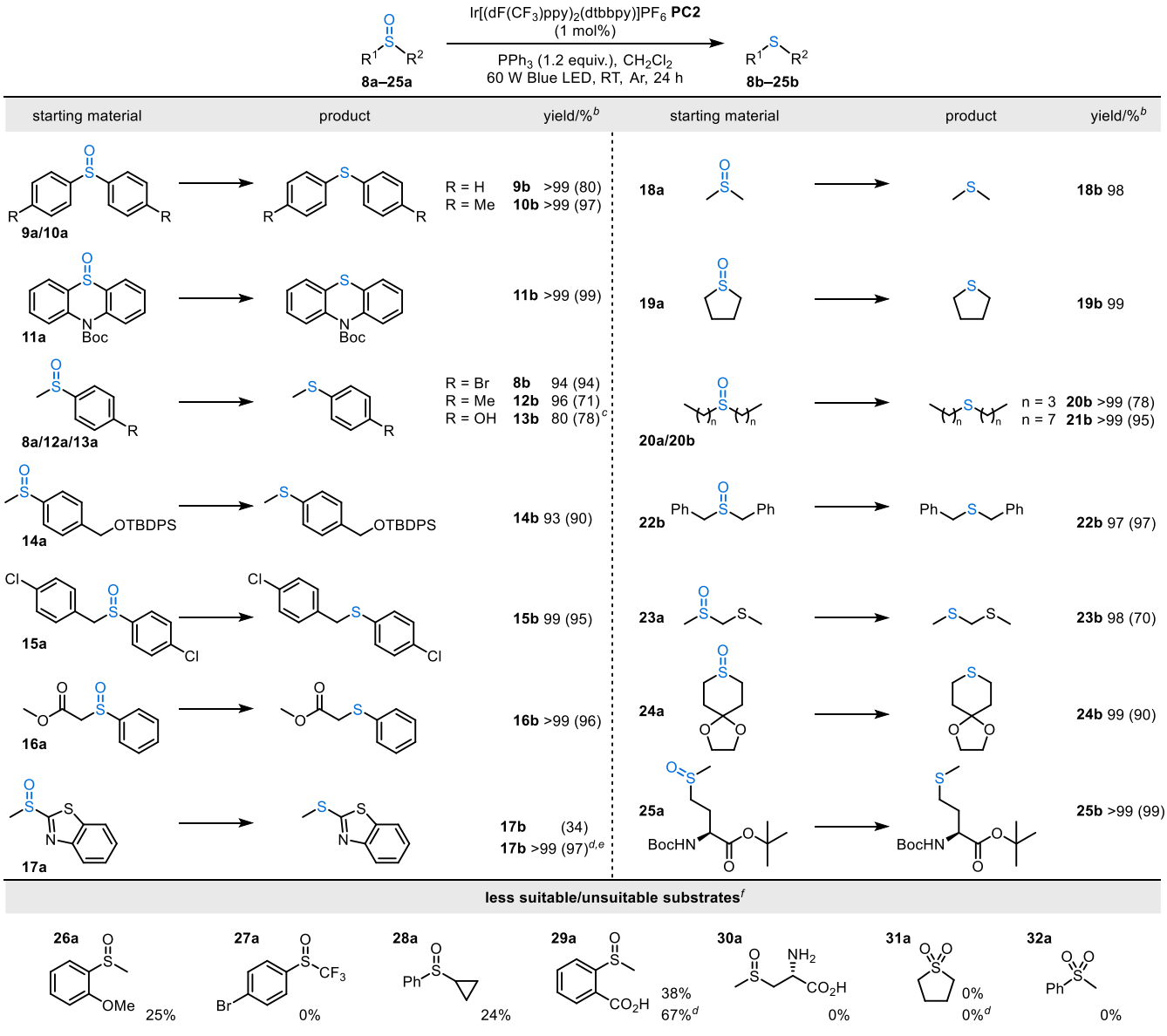
Scheme 3. Initiation via adduct reduction (PC8)



[a]Stern-Volmer quenching study of *fac*-$Ir(ppy)_3$ with 1:1 solution of sulfoxide **8a**:PPh_3 in degassed CH_2Cl_2.

This alternative mechanism would proceed via an electron transfer from the excited state PC to a sulfoxide-PPh_3 adduct, thus accessing a ground state Ir^{4+} complex (M^+/M, Scheme 1). This Ir^{4+} species (which is considerably more oxidizing than the corresponding $*Ir^{3+}$ state) could afford the key phosphine radical cation **2** via phosphine oxidation (**1** → **2**), thus enabling the earlier proposed radical chain reaction to proceed. Following sulfoxide attack (**2** → **4**) and β-scission (**4** → **6**) the resultant sulfide radical cation **6** could then undergo reduction in a number of ways: (1) reaction with PPh_3, thus regenerating phosphine radical cation **2** and propagating the radical chain (depicted in Scheme 3A); (2) reaction with the reduced sulfoxide-PPh_3 adduct; (3) reaction with the excited state PC to form the oxidizing ground state Ir^{4+} complex, which would then go on to propagate initiation via phosphine oxidation (**1** → **2**) (2 and 3 are not depicted in Scheme 3A). We first sought to identify the formation of the proposed sulfoxide-PPh_3 adduct spectroscopically, but regrettably, no evidence for phosphine-sulfoxide interaction was evident using $^1H/^{31}P$ NMR or UV-Vis spectroscopy (see Supporting Information). Stern-Volmer quenching studies also revealed that a 1:1 mixture of PPh_3 and sulfoxide **8a** did not quench the emission of excited state *fac*-Ir(ppy)$_3$ (**PC8**), even at concentrations far greater than that found in the reaction (Scheme 3B). We therefore turned to cyclic voltammetry to see if we could observe a reduction potential consistent with oxidative quenching of the excited state of **PC8**. More encouragingly, a unique reduction process was observed (with onset potential of approx. –0.8 V vs Ag/AgCl) when both the sulfoxide and PPh_3 were present in solution, that was absent when either of these reagents was omitted (Scheme 3C). This electrochemical data certainly suggests that the redox chemistry of the sulfoxide and PPh_3 is affected by the presence/absence of the other. At present, these findings still leave some questions unanswered (most pertinently, what the structure of the hypothetical sulfoxide-PPh_3 adduct could be) but the synthetic and mechanistic results do support the notion that an alternative mechanism for deoxygenation operates, when a PC with a sufficiently reductive potential is used.

Scheme 4. Substrate scope of sulfoxide to sulfide reduction[a]



[a]Reaction conditions: sulfoxide (0.30 mmol), Ir[(dF(CF$_3$)ppy)$_2$(dtbpy)]PF$_6$ (1 mol%), PPh_3 (0.36 mmol) in CH_2Cl_2 (1.5 mL) at RT, 24 h.[b] ^1H NMR yields reported based on a trimethoxybenzene internal standard; isolated yields of products after column chromatography are reported in parentheses.[c] 1 mol% Ir[(dF(CF$_3$)ppy)$_2$(d(CF$_3$)bpy)]PF$_6$ (**PC1**) and 4 d reaction time employed.[d] 1 mol% *fac*-Ir(ppy)$_3$ (**PC8**).[e] 48 h reaction time employed.[f] Yields of the corresponding sulfide observed by ^1H NMR spectroscopy based on a trimethoxybenzene internal standard are presented.

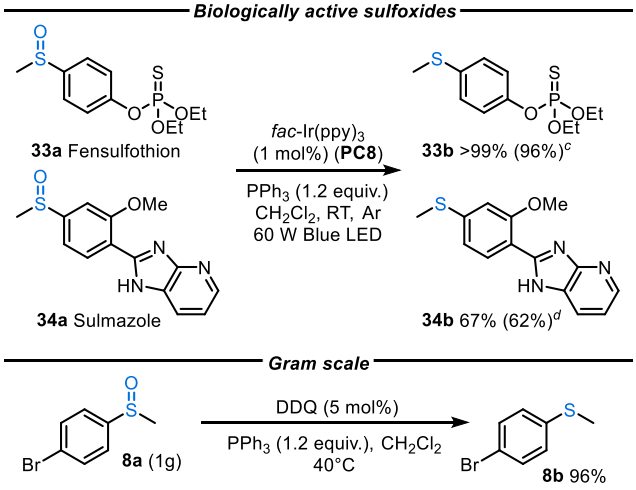
Next, attention turned to probing the synthetic utility of the deoxygenation. A preliminary substrate screen was conducted, from which the relatively oxidizing photocatalyst **PC2** was identified as the most broadly effective PC (see Supporting Information) and was taken on into further substrate scoping studies (Scheme 4). Diaryl sulfoxides **9a**–**11a** were all well tolerated; notably sulfoxide **11a**, incorporating an acid-sensitive Boc group, was converted into its sulfide **11b** in 99% yield. Various sulfoxides bearing a single functionalized aryl group also worked well, including halogenated systems (*e.g.* **8b**, **15b**). Sulfoxide **14a**, which contains an acid-labile silyl ether, was also an excellent substrate for this transformation, providing the corresponding sulfide **14b** in 90% yield.

Importantly, the freedom to vary the PC (and in particular, to vary its redox properties) allows the deoxygenation to be performed on a wide range of substrates. For example, when using the most oxidizing photocatalyst Ir[(dF(CF$_3$)ppy)$_2$(d(CF$_3$)bpy)]PF$_6$ (**PC1**), we were pleased to discover that sulfoxide **13a**, which contains an unprotected alcohol, afforded sulfide **13b** in 78% yield, which was a significant improvement upon the yield using **PC2**.[24] Sulfoxide **17a** also reacted poorly with **PC2** under the optimised conditions (34% conversion), with this attributed to competing oxidation of the benzothiazole moiety in this substrate. To address this, we tested the deoxygenation of sulfoxide **17a** using the less oxidizing *fac*-Ir(ppy)$_3$ photocatalyst **PC8**, and gratifyingly, the corresponding sulfide **17b** was isolated in near-quantitative yield, further demonstrating the value of having complementary synthetic protocols based on both oxidizing and reducing catalysts (see Supporting Information for more comparisons between the reactivity of **PC2** and **PC8**).

Sulfoxide reduction was also performed on a wide range of dialkyl sulfoxides with varying alkyl chain lengths; all reactions progressed cleanly to furnish the desired linear (**18b**, **20b**, **21b**) and cyclic (**19b**) sulfide products in excellent yields. Acetal protecting groups are also well tolerated by this procedure, with sulfide **24b** generated in 90% yield. Complete reduction of sulfoxide **25a** derived from *N*-Boc-protected methionine was also achieved, furnishing the corresponding sulfide **25b** in 99% isolated yield. A list of low yielding or unreactive substrates are presented at the bottom of Scheme 4 (**26a**–**32a**). We believe that the low reactivity of these substrates can generally be attributed to poor solubility of the sulfoxide starting material in CH_2Cl_2 or low nucleophilicity of the sulfoxide/sulfone starting material. Interestingly, aryl carboxylic acid-containing sulfoxide **29a** undergoes deoxygenation when using **PC2** (38% yield), but incomplete conversion of the sulfoxide starting material is observed alongside the formation of a side product.[25] When performing the deoxygenation reaction using **PC8**, the corresponding sulfide is formed cleanly in a 67% yield, with the remaining mass balance composed of unreacted sulfoxide. In all the above scoping studies, the only byproduct formed is triphenylphosphine oxide, and no discernible side products were isolated except where explicitly stated.

Finally, to further demonstrate the functional group tolerance and utility of the procedure, the deoxygenation of a sulfoxide-containing agrochemical (**33a**) and drug molecule (**34a**) was investigated (Scheme 5). In these examples, low to moderate yields of sulfide products were observed when using **PC2**, under a range of conditions. However, upon switching to **PC8** (with a greater reduction potential), far superior reactivity was observed. Thus, agrochemical agent Fensulfothion **33a**, which contains a phosphorothioate moiety, was cleanly reduced to its corresponding sulfide **33b** in 96% isolated yield. Furthermore, Sulmazole **34a**, a cardiotonic drug containing an imidazopyridine ring, was converted into sulfide **34b** in 62% yield under the same conditions; this was a more challenging substrate due to its limited solubility in a range of solvents.

Scheme 5. Biologically active sulfoxide reduction[a,b]



[a]Reaction conditions: sulfoxide (0.30 mmol), *fac*-Ir(ppy)$_3$ (1 mol%), PPh$_3$ (0.36 mmol) in CH_2Cl_2 (1.5 mL) at RT. [b] ^{1}H NMR yields reported based on a trimethoxybenzene internal standard and isolated yields of products after column chromatography are shown in parentheses.[c] 48 h reaction time. [d] 24 h reaction time.

Scalability can be a concern in photoredox catalyzed processes, with an increased photon flux needed for large scale photochemical reactions. Advances in flow chemistry technology have come a long way in addressing this problem, however larger scale photochemical reactions are still typically less straightforward to achieve experimentally compared to the scale up of thermal reactions.[26] To demonstrate that this phosphine radical cation strategy can easily be adopted by researchers who do not have access to the necessary equipment to perform photochemical flow reactions, deoxygenation of sulfoxide **8a** was performed on a 1 g scale, using DDQ as the radical chain initiator, affording sulfide **8b** in 96% yield, with the rest of the mass balance consisting of unreacted sulfoxide **8a**.

In conclusion, this study shows that phosphine radical cations can interact with sulfoxides via a polar/radical crossover mechanism. This novel reactivity could provide a basis for the development of new chemistry, exemplified here by our photocatalytic sulfoxide deoxygenation protocol. Using this mild, visible light-driven method, a wide array of functionalized sulfoxides can be reduced to the corresponding sulfides, including substrates containing acid-sensitive functional groups that are often incompatible with the acidic conditions typically utilized in established methods for sulfoxide reduction. Complementary protocols based on a range of both oxidizing or reducing photocatalysts, that operate via different mechanistic pathways, further increase the range of substrates that can be accommodated.

ASSOCIATED CONTENT

AUTHOR INFORMATION

Corresponding Author

*william.unsworth@york.ac.uk
*richard.taylor@york.ac.uk
*james.rossiashton@york.ac.uk

Author Contributions

‡These authors contributed equally.

Notes

The authors declare no competing financial interest

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Experimental procedures and characterization data for all new compounds (PDF)

ACKNOWLEDGMENT

The authors would like to thank the EPSRC (A.K.C. EP/R013748/1), the University of York (J.A.R.-A., W.P.U.) and the Leverhulme Trust (for an Early Career Fellowship, ECF-2015-013, W.P.U.) for financial support. We are also grateful for the provision of an Eleanor Dodson Fellowship (to W.P.U.) by the Department of Chemistry, University of York. We also thank Dr. James R. Donald, Dr. Michael J. James, Prof. Robin Perutz, Dr. Richard E. Douthwaite and Prof. Anne-Kathrin Duhme-Klair for insightful discussions and Mr. Alex Derry for help with preliminary work.

REFERENCES

1. (a) Kunieda, N.; Nokami, J.; Kinoshita, M. Stereoselective reactions of (+)-(R)-α(*p*-tolylsulfinyl)acetophenone with alkyl Grignard reagents in ethyl ether. *Chem. Lett*. **1974**, *3*, 369–372. (b) Solladié, G. Asymmetric synthesis using nucleophilic reagents containing a chiral sulfoxide group. *Synthesis*, **1981**, 185–196. (c) Kosugi, H.; Konta, H.; Uda, H. Highly diastereoselective reduction of chiral β-ketosulphoxides under chelation control: application to the synthesis of (R)-(+)-*n*-hexadecano-1,5-lactone. *J. Chem. Soc. Chem. Commun*. **1985**, 211–213. (d) Solladié, G.; Demailly, G, Greck, C. Reduction of β-hydroxysulfoxides: Application to the synthesis of optically active epoxides. *Tetrahedron Lett*. **1985**, *26*, 435–438. (e) Kosugi, H.; Watanabe, Y.; Uda, H. Lewis acid-mediated carbon–carbon bond forming reaction using the pummerer rearrangement products from chiral β-hydroxy sulfoxides. *Chem. Lett*. **1989**, *18*, 1865–1868. (f) Carreño, M. C. Applications of sulfoxides to asymmetric synthesis of biologically active compounds. *Chem. Rev*. **1995**, *95*, 1717–1760.
2. (a) Debaun, J. R.; Menn, J. J. Sulfoxide reduction in relation to organophosphorus insecticide detoxification. *Science*, **1976**, *191*, 187–188. (b) Ejiri, S.-I.; Weissback, H.; Brot, N. Reduction of methionine sulfoxide to methionine by *Escherichia coli*. *J. Bacteriol*. **1979**, *139*, 161–164. (c) Yoneyama, K.; Matsumura, F. Reductive metabolism of heptachlor, parathion, 4,4′-dichlorobenzophenone, and carbophenothion by rat liver systems. *Pestic. Biochem. Sci*. **1981**, *15*, 213–221. (d) Brot, N.; Weissbach, H. The biochemistry of methionine sulfoxide residues in proteins. *Trends Biochem. Sci*. **1982**, *7*, 137–139. (e) Surur, A. S.; Schulig, L.; Link, A. Interconnection of sulfides and sulfoxides in medicinal chemistry. *Arch. Pharm. Chem. Life Sci*. **2019**, 325. DOI: 10.1002/ardp.201800248
3. (a) Madesclaire, M. Reduction of sulfoxides to thioethers. *Tetrahedron* **1988**, *44*, 6537–6580. (b) Shiri, L.; Kazemi, M. Deoxygenation of sulfoxides. *Res. Chem. Intermed*. **2017**, *43*, 6007–6041.
4. (a) Mikami, K.; Noujima, A.; Mitsudome, T.; Mizugaki, T.; Jitsukawa, K.; Kaneda, K. Highly efficient gold nanoparticle catalyzed deoxygenation of amides,sulfoxides, and pyridine *N*-oxides. *Chem. Eur. J*. **2011**, *17*, 1768–1772. (b) García, N.; García- García, P.; Fernández-Rodríguez, M. A.; Rubio, R.; Pedrosa, M. R.; Arnáiz, F. J.; Sanz, R. Pinacol as a new green reducing agent: molybdenum-catalyzed chemoselective reduction of sulfoxides and nitroaromatics. *Adv. Synth. Catal*. **2012**, *354*, 321–327. (c) García, N.; García- García, P.; Fernández-Rodríguez, M. A.; García, D.; Pedrosa, M. R.; Arnáiz, F. J.; Sanz, R. An unprecedented use for glycerol: chemoselective reducing agent for sulfoxides. *Green Chem*. **2013**, *15*, 999–1005.
5. (a) Chasar, D. W. Quantitative reduction of sulfoxides. *J. Org. Chem*. **1971**, *36*, 613–614. (b) Drabowiz, J.; Mikolajczyk, M. A mild and efficient reduction of sulphoxides by means of lithium alanate and titanium(IV) chloride. *Synthesis* **1976**, 527–528. (c) Harrison, D. J.; Tam, N. C.; Vogels, C. M.; Langler, R. F.; Baker, R. T.; Decken, A.; Westcott, S. A. A gentle and efficient route for the deoxygenation of sulfoxides using catecholborane (HBcat; cat = 1,2-$O_2C_6H_4$). *Tetrahedron Lett*. **2004**, *45*, 8493–8496. (d) Zhang, J.; Gao, X.; Zhang, C.; Zhang, C.; Luan, J.; Zhao, D. Mild and efficient deoxygenation of sulfoxides to sulfides using $HfCl_4$/KBH_4 system. *Synth. Commun*. **2010**, *40*, 1794–1801.
6. (a) Aida, T.; Furukawa, N.; Oae, S. Catalytic reduction of dimethyl sulfoxide and other sulfoxides with bromine - hydrobromic acid system. *Tetrahedron Lett*. **1973**, *14*, 3853–3856. (b) Landini, D.; Maia, A. M.; Rolla, F. Racemization of sulphoxides with halide ions anchimerically assisted by a carboxy-group. The different behaviour of chloride and bromide ions. *J. Chem. Soc., Perkin Trans. 2* **1976**, 1288–1291. (c) Firouzabadi, H.; Karimi, B. Efficient deoxygenation of sulfoxides to thioethers and reductive coupling of sulfonyl chlorides to disulfides with tungsten hexachloride. *Synthesis* **1999**, 500–502. (d) Shimizu, M.; Shibuya, K.; Hayakawa, R. Chemoselective deoxygenation of sulfoxides with titanium tetraiodide. *Synlett* **2000**, 1437–1438. (e) Yoo, B. W.; Choi, K. H.; Kim, D. Y.; Choi, K. I.; Kim, J. H. Mild and efficient reduction of sulfoxides to sulfides with titanium tetrachloride–indium system. *Synth. Commun*. **2003**, *33*, 53–57. (f) Iranpoor, N.; Firouzbadi, H.; Shaterian, H. R. A new approach to the reduction of sulfoxides to sulfides with 1,3-dithiane in the presence of electrophilic bromine as catalyst. *J. Org. Chem*. **2002**, *67*, 2826–2830.
7. (a) Castrillón, J. P. A.; Szmant, H. H. Reduction of sulfoxides by triphenylphosphine and carbon tetrachloride. *J. Org. Chem*. **1965**, *30*, 1338– 1339. (b) Szmant, H. H.; Cox, O. The acid-catalyzed reaction of triphenylphosphine with sulfoxides. *J. Org. Chem*. **1966**, *31*, 1595–1598. (c) Kikuchi, S.; Konishi, H.; Hashimoto, Y. The deoxygenation of sulfoxide mediated by the Ph_3P/Lewis acid combination and the application to the kinetic resolution of racemic phosphines using optically active sulfoxide. *Tetrahedron* **2005**, *61*, 3587–3591. (d) Hua, G.; Woollins, J. D. The syntheses of sulfides by deoxygenation of sulfoxides using Woollins' reagent. *Tetrahedron Lett*. **2007**, *48*, 3677–3679. (e) Bahrami, K.; Khodaei, M. M.; Arabi, M. S. TAPC-promoted oxidation of sulfides and deoxygenation of sulfoxides. *J. Org. Chem*. **2010**, *75*, 6208–6213. (f) Jang, Y.; Kim, K. T.; Jeon, H. B. Deoxygenation of sulfoxides to sulfides with thionyl chloride and triphenylphosphine: Competition with the Pummerer reaction, *J. Org. Chem*. **2013**, *78*, 6328–6331. (g) Zhao, X.; Zheng, X.; Yang, B.; Sheng, J.; Lu, K. Deoxygenation of sulphoxides to sulphides with trichlorophosphane. *Org. Biomol. Chem*. **2018**, *16*, 1200–1204 and references therein.
8. (a) Prier, C. K.; Rankic, D. A.; MacMillan, D. W. C. Visible light photoredox catalysis with transition metal complexes: applications in organic synthesis. *Chem. Rev*. **2013**, *113*, 5322–5363. (b) Romero, N. A.; Nicewicz, D. A. Organic photoredox catalysis. *Chem. Rev*. **2016**, *116*, 10075–10166. (c) Shaw, M. H.; Twilton, J.; MacMillan, D. W. C. Photoredox catalysis in organic chemistry. *J. Org. Chem*. **2016**, *81*, 6898–6926.
9. Suzuki, K.; Jeong, J.; Yamaguchi, K.; Mizuno, N. Photoredox catalysis for oxygenation/deoxygenation between sulfides and sulfoxides by visible-light-responsive polyoxometalates. *New J. Chem*. **2016**, *40*, 1014-1021.
10. Bentrude, W. G. Phosphoranyl radicals: Their structure, formation, and reactions. *Acc. Chem. Res*. **1982**, *15*, 117–125.
11. (a) Zhang, M.; Xie, J.; Zhu, C. A general deoxygenation approach for synthesis of ketones from aromatic carboxylic

acids and alkenes. *Nat. Commun*. **2018**, *9*, 3517–3527. (b) Ruzi, R.; Ma, J.; Yuan, X.-A.; Wang, W.; Wang, S.; Zhang, M.; Dai, J.; Xie, J.; Zhu, C. Deoxygenative arylation of carboxylic acids by aryl migration. *Chem. Eur. J*. **2019**, *25*. 12724-12729.

12. Stache, E. E.; Ertel, A. B.; Rovis, T.; Doyle, A. G. Generation of phosphoranyl radicals via photoredox catalysis enables voltage–independent activation of strong C–O bonds. *ACS Catal*. **2018**, *8*, 11134–11139.
13. Xia, P.-J.; Ye, Z.-P.; Hu, Y.-Z.; Song, D.; Xiang, H.-Y.; Chen, X.-Q.; Yang, H. Photocatalytic, phosphoranyl radical-mediated N-O cleavage of strained cycloketone oximes. *Org. Lett*. **2019**, *21*, 2658–2662.
14. Lardy, S. W.; Schmidt, V. A. Intermolecular radical mediated anti-markovnikov alkene hydroamination using *N*-hydroxyphthalimide. *J. Am. Chem. Soc*. **2018**, *140*, 12318–12322.
15. Fukuzumi, S.; Shimoosako, K.; Suenobu, T.; Watanabe, Y. Mechanisms of hydrogen-, oxygen-, and electron-transfer reactions of cumylperoxyl radical. *J. Am. Chem. Soc*. **2003**, *125*, 9074–9082.
16. Studer, A.; Curran, D. P. The electron is a catalyst. *Nature Chem*. **2014**, *6*, 765-773.
17. Teegardin, K.; Day, J. I.; Chan, J.; Weaver, J. Advances in Photocatalysis: A Microreview of Visible Light Mediated Ruthenium and Iridium Catalyzed Organic Transformations. *Org. Process Res. Dev*. **2016**, *20*, 1156-1163.
18. For pre-existing methods to generate sulfide radical cations, see: (a) Fasani, E.; Freccero, M.; Mella, M.; Albini, A. The role of SET in the deprotection of (thio)ketals under photosensitization by π-acceptors. *Tetrahedron* **1997**, *53*, 2219–2232. (b) Yokoi, H.; Hatta, A.; Ishiguro, K.; Sawaki, Y. Formation of σ- and π-type dimer radical cations by the photochemical one-electron oxidation of aromatic sulfides. *J. Am. Chem. Soc*. **1998**, *120*, 12728–12733. (c) Vath, P.; Falvey, D. E. Photoinduced C−C bond cleavage in dithiane−carbonyl adducts: A laser flash photolysis study. *J. Org. Chem*. **2001**, *66*, 2887–2890. (d) Korzeniowska-Sobczuk, A.; Hug, G. L.; Carmichael, I.; Bobrowski, K. Spectral, kinetics, and theoretical studies of radical cations derived from thioanisole and its carboxylic derivative. *J. Phys. Chem. A* **2002**, *106*, 9251–9260. (e) Baciocchi, E.; Giacco, T. D.; Elisei, F.; Gerini, M. F.; Lapi, A.; Liberali, P.; Uzzoli, B. Steady-state and laser flash photolysis study of the carbon−carbon bond fragmentation reactions of 2-arylsulfanyl alcohol radical cations. *J. Org. Chem.* **2004**, *69*, 8323–8330. (f) Baciocchi, E.; Giacco, T. D.; Elisei, F.; Lapi, A. Sulfur radical cations. kinetic and product study of the photoinduced fragmentation reactions of (phenylsulfanylalkyl)trimethylsilanes and phenylsulfanylacetic acid radical cations. *J. Org. Chem.* **2006**, *71*, 853–860. (g) Bettoni, M.; Giacco, T. D.; Stradiotto, M.; Elisei, F. Photoinduced one-electron oxidation of benzyl methyl sulfides in acetonitrile: Time-resolved spectroscopic evidence for a thionium ion intermediate. *J. Org. Chem*. **2015**, *80*, 8001–8008.
19. When sulfoxide **8a** was irradiated with a 3 W blue LED light using **PC2** and conditions seen in Scheme 1, sulfide **8b** was formed in 65% yield based on a trimethoxybenzene internal standard.
20. Examination of the reaction mixture for the conversion of **8a** into **8b** using **PC2** revealed that 1 mol% of **PC2** remained which was determined using ^{1}H NMR spectroscopy with a trimethoxybenzene internal standard. Furthermore, ^{19}F NMR spectroscopy revealed no new ^{19}F signals after the reaction, suggesting that the catalyst did not degrade or form aggregates during the course of the reaction (see Supporting Information).
21. Liu, W.-Q.; Lei, T.; Song, Z.-Q.; Yang, X.-L.; Wu, C.-J.; Jiang, X.; Chen, B.; Tung, C.-H.; Wu, L.-Z. Visible Light Promoted Synthesis of Indoles by Single Photosensitizer under Aerobic Conditions. *Org. Lett*. **2017**, *19*, 3251-3254
22. Strieth-Kalthoff, F.; James, M. J.; Teders, M.; Pitzer, L.; Glorius, F. Energy transfer catalysis mediated by visible light: principles, applications, directions. *Chem. Soc. Rev*. **2018**, *47*, 7190-7202.
23. (a) Archer, R. A.; Kitchell, B. S. A Photochemical rearrangement of sulfoxide. *J. Am. Chem. Soc*. **1966**, *88*, 3462-3463. (b) Schultz, A. G.; DeBoer, C. D.; Schlessinger, R. H. Photodesulfurization of a Sulfoxide. *J. Am. Chem. Soc.* **1968**, *90*, 5314-5315. (c) Gurria, G. M.; Posner, G. H. Photochemical deoxygenation of aryl sulfoxides. *J. Org. Chem*. **1973**, *38*, 2419-2420.
24. When **PC2** was used to reduce sulfoxide **13a** a diminished isolated yield of 59% was observed.
25. When using **PC2**, an aldehyde-containing side product was observed in a 10% yield, by ^{1}H NMR spectroscopy (using a trimethoxybenzene internal standard). Presumably, this aldehyde side product forms through a similar mechanism as that described in reference 12.
26. Cambié, D.; Bottecchia, C.; Straathof, N. J. W.; Hessel, V.; Noël, T. Applications of continuous-flow photochemistry in organic synthesis, material science, and water treatment. *Chem. Rev*. **2016**, *116*, 10276-10341.