Visible-Light Photocatalysis

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Intermolecular [3+2] Cycloaddition of Cyclopropylamines with Olefins by Visible-Light Photocatalysis**

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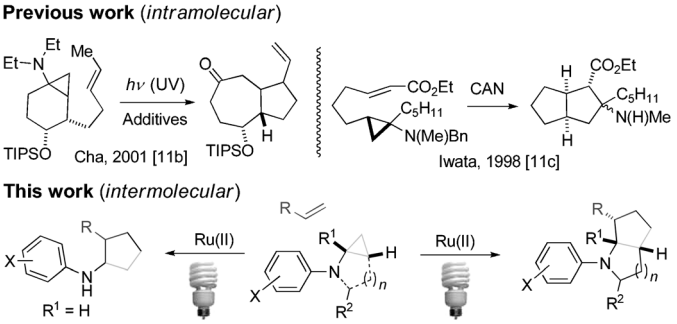
Solar energy is clean, abundant, and more importantly, renewable. As such, any reaction that efficiently harvests and converts solar energy into chemical energy is more important than ever as the world turns to its scientists to meet the challenge of environmental sustainability. Visible light (390–750 nm) accounts for 43% of the overall solar spectrum. However, many organic molecules are unable to absorb visible light efficiently, thereby limiting the use of visible light in organic synthesis. A possible solution to this problem involves the use of visible-light photoredox catalysts such as ruthenium[1] or iridium[2] polypyridyl complexes to channel energy from visible light into organic molecules. The groups of MacMillan,[3] Yoon,[4] Stephenson,[5] Akita,[6] and others[7] have recently published seminal works on visible-light-promoted C–C bond-formation reactions catalyzed by these complexes. Amines are often used as a sacrificial electron donor to reduce the photoexcited Ru^{II} and Ir^{III} complexes to Ru^{I} and Ir^{II} complexes.[8] Recently, amines have been also explored as a substrate in these processes.[9] We were intrigued by the potential of using amines as both the sacrificial donor and the substrate, thus making the process more atom economical.

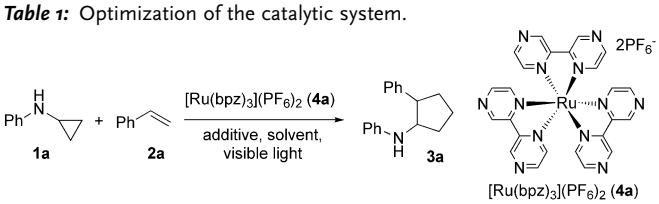
We envisioned a class of amines that are capable of initializing a downstream irreversible reaction upon oxidation by the photoexcited Ru^{II} or Ir^{III} complexes. Cyclopropylamines have been shown to undergo irreversible opening of the cyclopropyl ring upon their oxidation to the nitrogen radical cations. Based on this mode of action, cyclopropylamines have been used to probe amine oxidation in biological systems.[10] Cyclopropylamines have seen limited use in organic synthesis to date.[11] All these applications focus on intramolecular reactions, except the formation of the endoperoxides.[11a] Furthermore, the generation of nitrogen radical cations requires UV light with a photosensitizer or a strong oxidant (e.g., ceric ammonium nitrate), thus limiting the substrate scope and/or the type of the products being formed. Since visible-light photocatalysis has been shown to be a mild and chemoselective method to oxidize amines, we envisioned that new transformations of cyclopropylamines catalyzed by a Ru^{II} or Ir^{III} polypyridyl complex could be developed (Scheme 1). Herein we report an intermolecular [3+2] cycloaddition of olefins with mono- and bicyclic cyclopropylanilines under visible light photocatalysis.



Scheme 1. [3+2] Cycloaddition of cyclopropylamines with olefins. Bn = benzyl, CAN = ceric ammonium nitrate, TIPS = triisopropylsilyl.

Cyclopropylaniline **1a** and styrene **2a** were chosen as the model substrates to optimize the reaction conditions (Table 1). Using a 13W GE fluorescent lightbulb, irradiation of a solution of **1a** and **2a** in CH_3NO_2 with $[Ru(bpz)_3](PF_6)_2 \cdot 2H_2O$[12,13] (**4a**) and air afforded the desired cyclopentane product **3a** as a 1:1 mixture of *cis* and *trans* isomers in 21% yield (Table 1, entry 1). Degassing the reaction mixture

Table 1: Optimization of the catalytic system.



Entry	Conditions[a]	*t* [h]	Conv. of **1a** [%][b]	Yield of **3a** [%][b]
1	**4a** (2 mol%), Air, CH_3NO_2	12	100	21
2	**4a (2 mol%), CH_3NO_2**	**3**	**100**	**96**
3	without **4a**, CH_3NO_2	12	25	16
4	**4a** (2 mol%), CH_3NO_2, lightbulb off	12	35	9
5	**4b** (2 mol%), CH_3NO_2	12	100	79
6	**4c** (2 mol%), CH_3NO_2	12	100	73

[a] Reaction conditions: **1a** (0.2 mmol, 0.1 M in degassed CH_3NO_2), **2a** (1 mmol), irradiation with a 13 W fluorescent lightbulb at RT.
[b] Measured by GC using dodecane as an internal standard. bpz = 2, 2′-bipyrazine.

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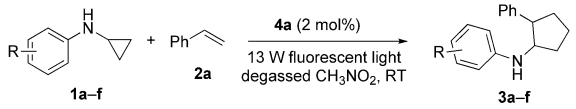
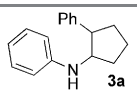
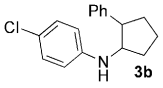
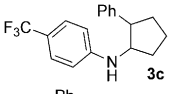
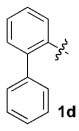
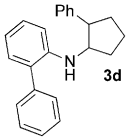
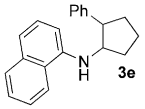
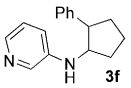
minimized the decomposition of cyclopropyl amine[14] and dramatically improved the yield of **3a** to 96% (Table 1, entry 2). Control studies showed that both the catalyst **4a** (Table 1, entry 3) and light (entry 4) with a suitable wavelength range were necessary for efficient conversion into **3a**. Other photoredox catalysts such as $[Ru(bpy)_3](PF_6)_2$ (**4b**; Table 1, entry 5) and $[Ir(dtbbpy)(ppy)_2]PF_6 \cdot H_2O$[15] (**4c**; Table 1, entry 6) were not as effective in the cycloaddition as **4a**. The effectiveness of the catalysts correlates with the redox potentials of $Ru^{II}*/Ru^{I}$ and $Ir^{III}*/Ir^{II}$.[16] Catalyst **4a**, which has the highest redox potential among the three, gave the highest yield of **3a**.

Having identified **4a** in degassed CH_3NO_2 as the optimal catalytic system, we next sought to apply it to other monocyclic cyclopropylamines (Table 2). The catalytic system was generally effective for secondary cyclopropylanilines, which were prepared by the Buchwald–Hartwig amination[17] or Cu-catalyzed amination[18] of cyclopropylamine. An aryl group, which lowers the redox potential of the amine, is necessary for the initial oxidation to occur.[19] Substitution on the aromatic ring is tolerated (Table 2, entries 2 and 3). Cyclopropylamines substituted with other arenes such as biphenyl and naphthalene worked equally well in the cycloaddition (Table 2, entries 4 and 5). Cyclopropylamines substituted with pyridine also worked well albeit taking a longer time to complete the cycloaddition (Table 2, entry 6). The six cyclopropylanilines either failed to show any diastereoselectivity (**1a–c** and **1f**) or gave modest diastereoselectivity (**1d** and **1e**, d.r. = 3:2) in the cycloaddition with styrene. Tertiary cyclopropylanilines were found to be ineffective in the cycloaddition, possibly because the ring opening was too slow to be competitive.[20]

To address the issue of lack of the diastereoselectivity in the cycloaddition with monocyclic cyclopropylamines, we subsequently applied the optimized reaction conditions to bicyclic cyclopropylamines, which could impart a steric bias toward the cycloaddition. Bicyclic cyclopropylamines **5a–f** were readily prepared from their corresponding amides by the Kulinkovich–de Meijere reaction.[11a,21] In contrast to monocyclic tertiary cyclopropylanilines, bicyclic tertiary cyclopropylanilines **5a–f** successfully underwent the cycloaddition with styrene (**2a**) to provide fused saturated heterocycles **6a–f** in synthetically useful yields and diastereoselectivities (Table 3). The drastic difference in reactivity between these two classes of cyclopropylamines was likely as a result of the higher ring strain in the bicyclic compounds. Bicyclic cyclopropylamines **5a–c** afforded 5,5-fused bicyclic heterocycles **6a–c** in 69–77% yields with diastereomeric ratios (d.r.)

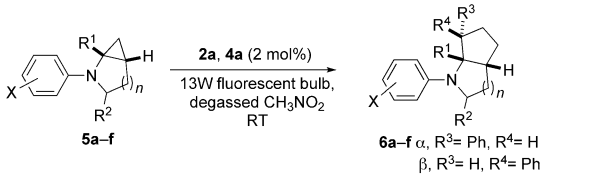
Table 2: [3+2] Cycloaddition of styrene (**2a**) with monocyclic cyclopropylamines (**1**).[a]

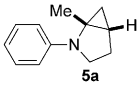
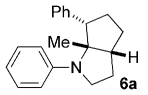
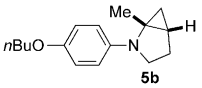
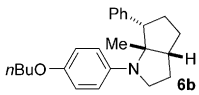
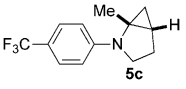
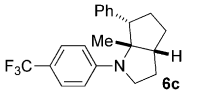
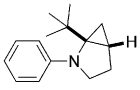
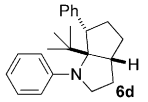
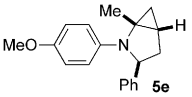
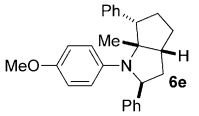
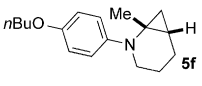
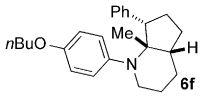


Entry	Substrate	Product	*t* [h]	Yield [%][d]
1[b]	**1a**, R = H	 **3a**	3	87
2[b]	**1b**, R = 4-Cl	 **3b**	6	82
3[b]	**1c**, R = 4-CF_3	 **3c**	4	82
4[c]	 **1d**	 **3d**	24	80
5[c]	 **1e**	 **3e**	6	75
6[b]	 **1f**	 **3f**	48	71

[a] Reaction conditions: substrate (0.2 mmol, 0.1 M in degassed CH_3NO_2), **2a** (1 mmol), **4a** (2 mol%), irradiation with a 13 W fluorescent lightbulb at RT. [b] d.r. = 1:1 and [c] d.r. = 3:2 as determined by ^1H NMR spectroscopy of crude products. [d] Yield of the combined isomers after isolation.

Table 3: [3+2] Cycloaddition of styrene (**2a**) with bicyclic cyclopropylamines **5**.[a]



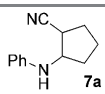
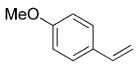
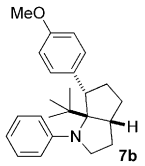
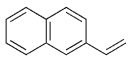
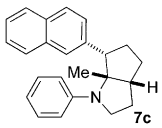
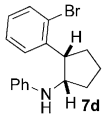
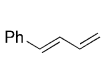
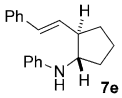
Entry	Substrate	Product[b]	*t* [h]	Yield [%][c] d.r.[d]
1	 **5a**	 **6a**	5	77 4:1
2	 **5b**	 **6b**	8	74 5:1
3	 **5c**	 **6c**	36	69 5:1
4	 **5d**	 **6d**	12	28 (64)[e] >25:1
5	 **5e**	 **6e**	6	72 3:1
6	 **5f**	 **6f**	12	58 4:1

[a] Reaction conditions: **5a–f** (0.2 mmol, 0.1 M in degassed CH_3NO_2), **2a** (1 mmol), **4a** (2 mol%), irradiation with a 13 W fluorescent lightbulb at RT. [b] Only the major diastereoisomer shown. [c] Combined yields of the two isomers after chromatography. [d] Determined by ^1H NMR analysis of the crude products (α/β). [e] Based on recovered **5d**.

ranging from 4:1 to 5:1 (Table 3, entries 1–3). Replacement of the methyl group of **5a** by a *tert*-butyl group dramatically increased the diastereoselectivity as only a single diastereomer of **6d** was obtained (Table 3, entry 4). However, the cycloaddition was much slower than that of **5a–c**. Additionally, the five-membered ring of [3.1.0] bicyclic cyclopropylamines was tolerated in the cycloaddition, as **5e** reacted as well as **5a–c** with only a slightly diminished diastereoselectivity (Table 3, entry 5). Furthermore, [4.1.0] bicyclic cyclopropylamine **5f** participated in the cycloaddition in a similar fashion to **5a–c** to afford 6,5-fused bicyclic heterocycles **6f** in 58% yield with a d.r. of 4:1 (entry 6). The relative configurations of **6a–f** were established by NMR spectroscopy. The relative configuration of compound **6d** was further confirmed by X-ray crystallography (see the Supporting Information).[22]

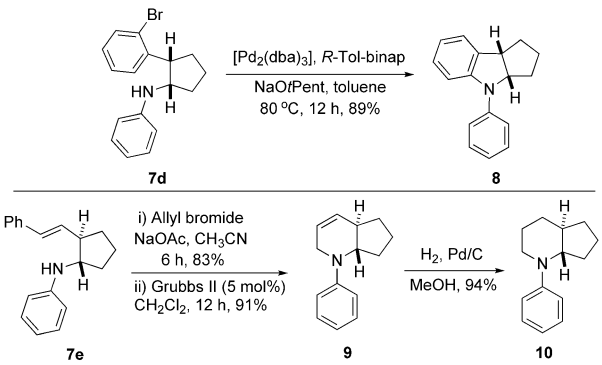
Given the success of the cycloaddition with styrene, we turned our attention to other olefins to explore the potential of this method (Table 4). Terminal olefins substituted with electron-withdrawing groups underwent the cycloaddition with mono- and bicyclic cyclopropylamines, while internal olefins failed to do so. Acrylonitrile gave a lower yield of the cycloaddition product (**7a**) than styrene (Table 4, entry 1). The introduction of a methoxy group to the benzene ring (Table 4, entry 2; **7b** versus **6d**) or replacement of the phenyl ring in styrene by a larger naphthalene group (Table 4, entry 3; **7c** versus **6a**) had little effect on the yield and d.r. of the cycloaddition. Substitution of the *ortho* hydrogen of styrene by bromine rendered the cycloaddition modestly diastereoselective, with the *cis* isomer of **7d** being favored (Table 4, entry 4). Moreover, the conjugated diene, 1-phenyl-1,3-butadiene participated in the cycloaddition, which occurred only at the terminal double bond to provide cyclopentane **7e** with the *trans* isomer being favored (Table 4, entry 5).

Table 4: Scope of olefins in the [3+2] cycloaddition.

Entry	Substrate	Olefin	Product[a]	*t* [h]	Yield [%][b] d.r.[c]
1[d]	**1a**		 **7a**	2	52 1:1
2	**5d**		 **7b**	12	30 (67)[e] >25:1
3	**5a**		 **7c**	6	72 3:1
4	**1a**		 **7d**	6	82 2:1
5	**1a**		 **7e**	6	40 2:1

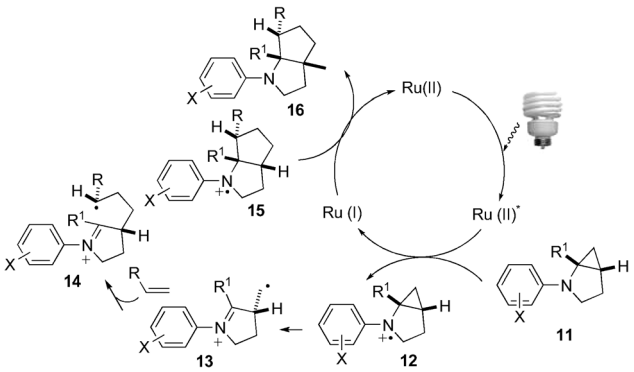
[a] Only the major diastereoisomer shown. [b] Combined yield of the two isomers after chromatography. [c] Determined by ^{1}H NMR analysis of the crude products. [d] Two isomers shown. [e] Based on recovered **5d**.

The cyclopentane products obtained from the cycloaddition with monocyclic cyclopropylamines are useful building blocks for preparing fused heterocycles (Scheme 2).[23] For example, the major isomer of **7d** was subjected to the Pd-catalyzed Buchwald–Hartwig amination reaction to furnish fused indoline **8**[24] in 89% yield. Separately, the major isomer of **7e** was converted into octahydro-1*H*-cyclopenta[*b*]pyridine **10**[25] in 71% overall yield over three steps. This sequence is complementary to the [3+2] cycloaddition of bicyclic cyclopropylamines with olefins (see above).



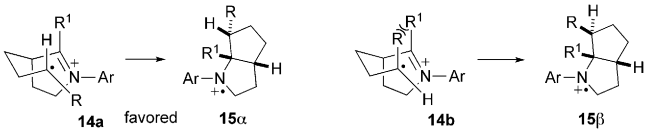
Scheme 2. Synthesis of indoline and octahydro-1*H*-cyclopenta[*b*]pyridine. dba = dibenzylideneacetone, Tol-binap = 2,2′-bis(di-*p*-tolylphosphanyl)-1,1′-binaphthyl.

A possible catalytic cycle is shown in Scheme 3. Upon irradiation, the Ru^{II} complex enters the photoexcited state and cyclopropylamine **11** is oxidized to the nitrogen radical cation **12** with the concomitant formation of Ru^{I}. The nitrogen radical cation **12** subsequently undergoes ring opening to generate β-carbon radical iminium ion **13**, which then adds intermolecularly to the olefin ("Giese Reactions")[26] to produce the stabilized radical **14**. The intramolecular addition of the stabilized radical to the iminium ion furnishes the nitrogen radical cation **15** with the formation of a cyclopentane ring; this compound is reduced by Ru^{I} to complete the catalytic cycle.



Scheme 3. Proposed catalytic cycle.

The diastereoselectivity for the cycloaddition can be rationalized by analogy to the Beckwith–Houk model,[27] which has been used to predict the diastereoselectivity for the cyclization of hexenyl radicals (Scheme 4). Between the two chair transition states **14a** and **14b**, **14a** is expected to be more favorable because it avoids the steric interaction between R and R^1 that occurs in **14b**.



Scheme 4. Diastereoselectivity model.

In summary, we have developed a visible-light-mediated [3+2] cycloaddition of alkenes with cyclopropylamines catalyzed by $[Ru(bpz)_3](PF_6)_2 \cdot 2H_2O$ (**4a**). The method features excellent regiocontrol with respect to the alkene. A variety of functional groups are tolerated and the reactions occur under mild reaction conditions. The configuration at the carbon bearing R^1 in **11** is preserved in **16**. Diastereoelectivity is high when the cyclopropylamine is bicyclic. Further investigation of the diastereoselectivity of the cycloaddition and its application to other C–C bond-forming reactions is ongoing and will be reported in due course.

Experimental Section

A representative procedure: $[Ru(bpz)_3](PF_6)_2 \cdot 2H_2O$ **4a** (3.6 mg, 0.004 mmol, 2 mol%) and phenyl cyclopropylamine **1a** (26 mg, 0.2 mmol) were added to a screw-capped oven-dried test tube equipped with a stir bar. The tube was evacuated and backfilled with nitrogen before styrene (110 μL, 1.0 mmol) and CH_3NO_2 (2 mL) were added. The reaction mixture was degassed by the freeze-pump-thaw method and then irradiated at room temperature by a 13 W fluorescent lightbulb for 3 h. After the reaction was complete (monitored by TLC), the mixture was filtered through a short pad of silica gel and eluted with Et_2O (10 mL). The solution was concentrated and the residue was purified by flash chromatography on silica gel (1.5% Et_2O in hexane) to afford **3a** (42 mg, 87%) as a colorless 1:1 mixture of *cis* and *trans* isomers.

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[1] a) A. Juris, V. Balzani, F. Barigelletti, S. Campagna, P. Belser, A. von Zelewsky, *Coord. Chem. Rev.* **1988**, *84*, 85–277; b) K. Kalyanasundaram, M. Grätzel, *Coord. Chem. Rev.* **1998**, *177*, 347–414; c) K. Kalyanasundaram, *Coord. Chem. Rev.* **1982**, *46*, 159–244.

[2] a) M. S. Lowry, S. Bernhard, *Chem. Eur. J.* **2006**, *12*, 7970–7977; b) L. Flamigni, A. Barbieri, C. Sabatini, B. Ventura, F. Barigelletti, *Top. Curr. Chem.* **2007**, *281*, 143–204.

[3] a) P. V. Pham, D. A. Nagib, D. W. C. MacMillan, *Angew. Chem.* **2011**, *123*, 6243–6246; *Angew. Chem. Int. Ed.* **2011**, *50*, 6119–6122; b) H.-W. Shih, M. N. V. Wal, R. L. Grange, D. W. C. MacMillan, *J. Am. Chem. Soc.* **2010**, *132*, 13600–13603; c) D. A. Nagib, M. E. Scott, D. W. C. MacMillan, *J. Am. Chem. Soc.* **2009**, *131*, 10875–10877; d) D. A. Nicewicz, D. W. C. MacMillan, *Science* **2008**, *322*, 77–80.

[4] a) A. E. Hurtley, M. A. Cismesia, M. A. Ischay, T. P. Yoon, *Tetrahedron* **2011**, *67*, 4442–4448; b) Z. Lu, M. Shen, T. P. Yoon, *J. Am. Chem. Soc.* **2011**, *133*, 1162–1164; c) M. A. Ischay, Z. Lu, T. P. Yoon, *J. Am. Chem. Soc.* **2010**, *132*, 8572–8574; d) T. P. Yoon, M. A. Ischay, J. Du, *Nat. Chem.* **2010**, *2*, 527–532; e) J. Du, T. P. Yoon, *J. Am. Chem. Soc.* **2009**, *131*, 14604–14605; f) M. A. Ischay, M. E. Anzovino, J. Du, T. P. Yoon, *J. Am. Chem. Soc.* **2008**, *130*, 12886–12887.

[5] a) L. Furst, J. M. R. Narayanam, C. R. J. Stephenson, *Angew. Chem.* **2011**, *123*, 9829–9833; *Angew. Chem. Int. Ed.* **2011**, *50*, 9655–9659; b) J. W. Tucker, J. M. R. Narayanam, P. S. Shah, C. R. J. Stephenson, *Chem. Commun.* **2011**, *47*, 5040–5042; c) J. D. Nguyen, J. W. Tucker, M. D. Konieczynska, C. R. J. Stephenson, *J. Am. Chem. Soc.* **2011**, *133*, 4160–4163; d) C. Dai, J. M. R. Narayanam, C. R. J. Stephenson, *Nat. Chem.* **2011**, *3*, 140–145; e) J. M. R. Narayanam, C. R. J. Stephenson, *Chem. Soc. Rev.* **2011**, *40*, 102–113; f) L. Furst, B. S. Matsuura, J. M. R. Narayanam, J. W. Tucker, C. R. J. Stephenson, *Org. Lett.* **2010**, *12*, 3104–3107; g) J. W. Tucker, J. D. Nguyen, J. M. R. Narayanam, S. W. Krabbe, C. R. J. Stephenson, *Chem. Commun.* **2010**, *46*, 4985–4987; h) J. W. Tucker, J. M. R. Narayanam, S. W. Krabbe, C. R. J. Stephenson, *Org. Lett.* **2010**, *12*, 368–371; i) J. M. R. Narayanam, J. W. Tucker, C. R. J. Stephenson, *J. Am. Chem. Soc.* **2009**, *131*, 8756–8757.

[6] T. Koike, M. Akita, *Chem. Lett.* **2009**, *38*, 166–167.

[7] a) M.-H. Larraufie, R. Pellet, L. Fensterbank, J.-P. Goddard, E. Lacote, M. Malacria, C. Ollivier, *Angew. Chem.* **2011**, *123*, 4555–4558; *Angew. Chem. Int. Ed.* **2011**, *50*, 4463–4466; b) M. Neumann, S. Fuldner, B. Konig, K. Zeitler, *Angew. Chem.* **2011**, *123*, 981–985; *Angew. Chem. Int. Ed.* **2011**, *50*, 951–954; c) M. Rueping, S. Zhu, R. M. Koenigs, *Chem. Commun.* **2011**, *47*, 8679–8681; d) R. S. Andrews, J. J. Becker, M. R. Gagne, *Org. Lett.* **2011**, *13*, 2406–2409; e) Y. Su, L. Zhang, N. Jiao, *Org. Lett.* **2011**, *13*, 2168–2171; f) T. Maji, A. Karmakar, O. Reiser, *J. Org. Chem.* **2011**, *76*, 736–739; g) Y. Chen, A. S. Kamlet, J. B. Steinman, D. R. Liu, *Nat. Chem.* **2011**, *3*, 146–153; h) R. S. Andrews, J. J. Becker, M. R. Gagne, *Angew. Chem.* **2010**, *122*, 7432–7434; *Angew. Chem. Int. Ed.* **2010**, *49*, 7274–7276; i) K. Zeitler, *Angew. Chem.* **2009**, *121*, 9969–9974; *Angew. Chem. Int. Ed.* **2009**, *48*, 9785–9789; j) L. Zhou, H. Yang, P. Wang, *J. Org. Chem.* **2011**, *76*, 5873–5881.

[8] a) P. J. DeLaive, B. P. Sullivan, T. J. Meyer, D. G. Whitten, *J. Am. Chem. Soc.* **1979**, *101*, 4007–4008; b) P. J. DeLaive, T. K. Foreman, C. Giannotti, D. G. Whitten, *J. Am. Chem. Soc.* **1980**, *102*, 5627–5631.

[9] a) A. G. Condie, J. C. Gonzalez-Gomez, C. R. J. Stephenson, *J. Am. Chem. Soc.* **2010**, *132*, 1464–1465; b) M. Rueping, D. Leonori, T. Poisson, *Chem. Commun.* **2011**, *47*, 9615–9617; c) M. Rueping, C. Vila, R. M. Koenigs, K. Poscharny, D. C. Fabry, *Chem. Commun.* **2011**, *47*, 2360–2362; d) Y.-Q. Zou, L.-Q. Lu, L. Fu, N-J. Chang, J. Rong, J.-R. Chen, W.-J. Xiao, *Angew. Chem.* **2011**, *123*, 7309–7313; *Angew. Chem. Int. Ed.* **2011**, *50*, 7171–7175; e) J. Xuan, Y. Cheng, J. An, L.-Q. Lu, X.-X. Zhang, W.-J. Xiao, *Chem. Commun.* **2011**, *47*, 8337–8339; f) D. P. Hari, B. Konig, *Org. Lett.* **2011**, *13*, 3852–3855.

[10] For selected recent applications: a) Q. Sun, R. Zhu, F. W. Foss, Jr., T. L. Macdonald, *Chem. Res. Toxicol.* **2008**, *21*, 711–719; b) B. Zhong, R. B. Silverman, *J. Am. Chem. Soc.* **1997**, *119*, 6690–6691; c) M. A. Cerny, R. P. Hanzlik, *J. Am. Chem. Soc.* **2006**, *128*, 3346–3354.

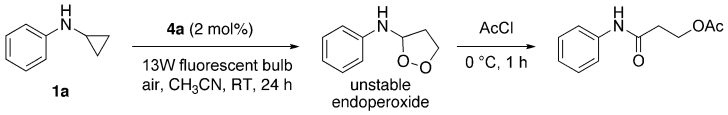
[11] For selected applications: a) C. Madelaine, Y. Six, O. Buriez, *Angew. Chem.* **2007**, *119*, 8192–8195; *Angew. Chem. Int. Ed.* **2007**, *46*, 8046–8049; b) H. B. Lee, M. J. Sung, S. C. Blackstock,

J. K. Cha, *J. Am. Chem. Soc.* **2001**, *123*, 11322 – 11324; c) Y. Takemoto, S. Yamagata, S. Furuse, H. Hayase, T. Echigo, C. Iwata, *Chem. Commun.* **1998**, 651 – 652; d) J. Lee, J. U. Sun, S. C. Blackstock, J. K. Cha, *J. Am. Chem. Soc.* **1997**, *119*, 10241 – 10242; e) L. Larquetoux, J. A. Kowalska, Y. Six, *Eur. J. Org. Chem.* **2004**, 3517 – 3525; f) L. Larquetoux, N. Ouhamou, A. Chiaroni, Y. Six, *Eur. J. Org. Chem.* **2005**, 4654 – 4662; g) J. Lee, S. Berritt, C. K. Prier, M. M. Joullié, *Org. Lett.* **2011**, *13*, 1083 – 1085.

[12] M. Zhu, N. Zheng, *Synthesis* **2011**, 2223 – 2236.

[13] a) D. P. Rillema, G. Allen, T. J. Meyer, D. Conrad, *Inorg. Chem.* **1983**, *22*, 1617 – 1622; b) R. J. Crutchley, A. B. P. Lever, *J. Am. Chem. Soc.* **1980**, *102*, 7128 – 7129.

[14] Upon irradiation of **1a** in the presence of **4a** (2 mol%) and air, an unstable endoperoxide was formed. On treatment with AcCl, it was converted into a stable amide.



[15] J. D. Slinker, A. A. Gorodetsky, M. S. Lowry, J. Wang, S. Parker, R. Rohl, S. Bernhard, G. G. Malliaras, *J. Am. Chem. Soc.* **2004**, *126*, 2763 – 2767.

[16] Redox potentials: (II)*/(I) versus Ag/AgCl: $[Ru(bpz)_3]$, 1.31 ev; $[Ru(bpy)_3]$, 0.77 ev; (III)*/(II) versus Ag/AgCl, $[Ir(dtbbpy)(ppy)_2]$, 0.76 ev.

[17] W. Cui, R. N. Loeppky, *Tetrahedron* **2001**, *57*, 2953 – 2956.

[18] D. Ma, Q. Cai, H. Zhang, *Org. Lett.* **2003**, *5*, 2453 – 2455.

[19] a) G. J. Kavarnos, N. J. Turro, *Chem. Rev.* **1986**, *86*, 401 – 449; see the Supporting Information for the cyclic voltammetry measurement.

[20] X. Li, M. L. Grimm, K. Igarashi, N. Castagnoli, Jr., J. M. Tanko, *Chem. Commun.* **2007**, 2648 – 2650.

[21] C. Madelaine, A. K. Buzas, J. A. Kowalska-Six, Y. Six, B. Crousse, *Tetrahedron Lett.* **2009**, *50*, 5367 – 5371.

[22] CCDC 839339 (**6d**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

[23] Selected recent applications of fused heterocycles: a) M. Y. Chang, H. Y. Tai, Y. L. Chen, *Tetrahedron* **2011**, *67*, 7673 – 7680; b) G. S. Welmaker, J. E. Sabalski, *Tetrahedron Lett.* **2004**, *45*, 4851 – 4854; c) S. Ito, H. Miura, S. Uchida, M. Takata, K. Sumioka, P. Liska, P. Comte, P. Pechy, M. Gratzel, *Chem. Commun.* **2008**, 5194 – 5196.

[24] O. Miyata, N. Takeda, Y. Kimura, Y. Takemoto, N. Tohnai, M. Miyatac, T. Naito, *Tetrahedron* **2006**, *62*, 3629 – 3647.

[25] R. A. Bunce, D. M. Herron, J. R. Lewis, S. V. Kotturi, *J. Heterocycl. Chem.* **2003**, *40*, 113 – 120.

[26] a) B. Giese, *Angew. Chem.* **1983**, *95*, 771 – 782; *Angew. Chem. Int. Ed. Engl.* **1983**, *22*, 753 – 764; b) Ž. Čeković, R. N. Saičić, *Tetrahedron Lett.* **1986**, *27*, 5893 – 5896; c) R. N. Saičić, Ž. Čeković, *Tetrahedron* **1990**, *46*, 3627 – 3640.

[27] D. C. Spellmeyer, K. N. Houk, *J. Org. Chem.* **1987**, *52*, 959 – 974.

