Angewandte Chemie International Edition

Cycloaddition

International Edition: DOI: 10.1002/anie.201505931
German Edition: DOI: 10.1002/ange.201505931

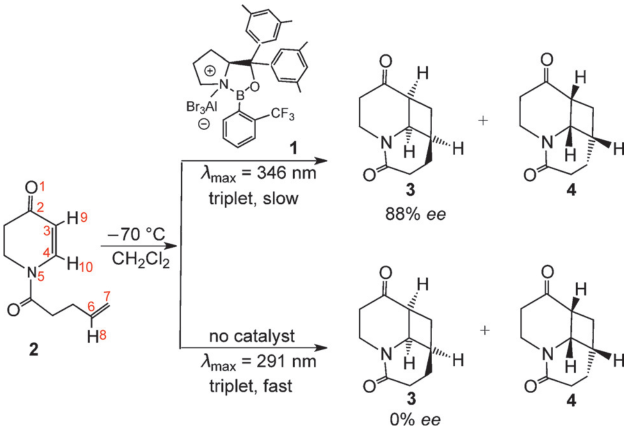
Regulatory Mechanism of the Enantioselective Intramolecular Enone [2+2] Photocycloaddition Reaction Mediated by a Chiral Lewis Acid Catalyst Containing Heavy Atoms

Hongjuan Wang, Xiaoyan Cao, Xuebo Chen, Weihai Fang, and Michael Dolg**

Abstract: *The asymmetric catalysis of the intramolecular enone [2+2] photocycloaddition has been subject of extensive experimental studies, however theoretical insight to its regulatory mechanism is still sparse. Accurate quantum chemical calculations at the CASPT2//CASSCF level of theory associated with energy-consistent relativistic pseudopotentials provide a basis for the first regulation theory that the enantioselective reaction is predominantly controlled by the presence of relativistic effects, that is, spin–orbit coupling resulting from heavy atoms in the chiral Lewis acid catalyst.*

The [2+2] photocycloaddition (PCA) reaction has undergone extensive investigations for more than one hundred years, because it can be widely applied in organic synthesis for the preparation of natural and non-natural products.[1] To extend its application to biologically interesting compounds, substantial efforts have been undertaken to develop practical techniques for the preparation of enantiomers with a high enantiomeric excess (*ee*).[1c,d,2] In contrast to the traditional chiral-auxiliary-based approach,[3] a direct strategy was recently developed and it employs different chiral templates through a noncovalent linking between the catalyst and its substrate. The approach shows an excellent performance in both enantioselectivity and yield, and has the advantage that it is not necessary to first add and then remove the auxiliary.[4] In 2010, the first chiral oxazaborolidine/$AlBr_3$-based Lewis acid catalyst (**1**; Scheme 1) was identified by Bach and co-workers to initiate enantioselective photoreactions of coumarins,[5] although it was originally synthesized and applied by Corey and co-workers to catalyze thermal cycloaddition reactions.[6]

Three years later, interesting advances and even breakthroughs were achieved in the group of Bach by using the same chiral Lewis acid (**1**) to enable the enantioselective intramolecular [2+2] PCA of a typical enone substrate, that is, 5,6-dihydro-4-pyridones.[7] As shown in Scheme 1, the PCA product **3** of 1-(pent-4-enoyl)-2,3-dihydropyridin-4-one (**2**) has been obtained in 84% yield and with 88% *ee* when the unselective background reaction was noticeably suppressed at high catalyst loadings. However, in Bach's complementary experiments, an uncatalyzed [2+2] PCA in the triplet state was found to take place even faster than that with the catalyst–substrate complex upon photoexcitation at $\lambda =$ 366 nm.[8] This result indicates a complicated regulatory mechanism mediated by the chiral Lewis acid and the challenge of suppressing the unselective background reaction.[2c,7] In contrast to the wealth of experimental investigations, extensive theoretical mechanistic studies elucidating the effect of the Lewis acid on the reaction course have not yet been performed and many questions are still open.[2c,7] In this work, we therefore employed a multi-configurational quantum chemical approach associated with relativistic energy-adjusted ab initio pseudopotentials[9] (see the Supporting Information). The aim is to investigate **2** and its coordinated complexes with different Lewis acid catalysts as the first example to elucidate a photocatalytic regulation theory for the enantioselective intramolecular enone [2+2] PCA reaction and the associated mechanism-based design principle for highly selective catalysts.



Scheme 1. Enantioselective intramolecular [2+2] photocycloaddition reaction for **2**, mediated by the chiral Lewis acid **1**.

All absorption maxima of the $S_0 \rightarrow S_{CT}(^1\pi\pi^*)$ transitions for **2**, **2**/BCl_3, and **2**/**1** exhibit a significant feature of charge transfer with the largest oscillator strength, $f = 0.57$–0.66 (see Table 1 and Table S2 in the Supporting Information), as compared with other excitation patterns. According to the population analyses and charge translocation calculations (see Section S2), the photoinitiated charge translocation (PICT) from the C3=C4 moiety to the C2=O1 carbonyl group (see Scheme 1 for atom numbering) has a noticeable

---

[*] Dr. H. Wang, Prof. X. Chen, Prof. W. Fang
Key Laboratory of Theoretical and Computational Photochemistry of Ministry of Education, Department of Chemistry
Beijing Normal University
Xin-wai-da-jie No. 19, Beijing 100875 (China)
E-mail: xuebochen@bnu.edu.cn

Dr. X. Cao, Prof. M. Dolg
Theoretical Chemistry, University of Cologne
Greinstrasse 4, 50939 Cologne (Germany)
E-mail: m.dolg@uni-koeln.de

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201505931.

increase from 0.34 *e* for **2** to 0.43–0.48 e for the **2**/BCl_3 and **2**/**1** complexes. The electron deficiency of boron imposes an electron-withdrawing effect on the carbonyl moiety (C2=O1), and it facilitates charge transfer from the C3=C4 bond to the carbonyl group. Our computational results show that this enhanced charge transfer leads to a considerable bathochromic shift of the absorption maximum of the $^1\pi\pi^*$ bright state from $\lambda = 275$ nm for **2** to $\lambda = 344$–347 nm for **2**/BCl_3 and **2**/**1**. Consistently, a more than 50 nm red-shifted absorption was observed in the high-cross-section transition of **2** in the presence of the Lewis acid.[7,8] In addition, both the present calculations (Table 1) and the previous experiments reveal that the maximum absorption of a versatile class of enones are red-shifted to the same wavelength region no matter what kinds of Lewis acid catalysts were used, for example, $EtAlCl_2$ ($\lambda = 343$ nm), BCl_3($\lambda = 348$ nm), and **1** ($\lambda = 346$ nm).[7,8] As a result, the modification of the PCA reaction allows mild reaction conditions with low excitation energy because of the participation of Lewis acids.[7,8,10]

Table 1: Data for **2**, **2**/BCl_3, and **2**/**1**.

	$\lambda_{\text{ab, max}}$ (Exp.)	f	$E_{\perp}$,np (Exp.)	λ_{em} (Exp.)	SOC S_{NP}/T_{CT}	SOC S_{CT}/T_{CT}	Barrier(**3**/**4**)
2	275 (291)	0.64	84.8 (79.4)	–	66.1	–	3.5/5.4
2/BCl_3	344 (348)	0.66	105.1	422.0	–	0.7	5.0/6.1
2/**1**	347 (346)	0.57	102.9	437 (419)	–	37.4	5.2/15.8

Maximum absorption ($\lambda_{\text{ab,max}}$, nm), oscillator strengths (f), vertical excitation energy of $n \rightarrow \pi^*$ transition ($E_{\perp}$,np, kcal mol^{-1}), wavelengths of fluorescence emission (λ_{em}, nm), and spin–orbit coupling (SOC, cm^{-1}) for **2**, **2**/BCl_3, and **2**/**1** enone–catalyst complexes. The experimental values (Refs. [7,8]) are shown within parentheses for comparison. The barriers (in kcal mol^{-1}) for cycloaddition in the triplet state are given along two reaction pathways towards the product of enantiomer **3** and **4**.

Besides the $^1\pi\pi^*$ bright state, the dark spectroscopic $S_{NP}(^1n\pi^*)$ state, originating from the promotion of one electron of the O1 lone pair to a π^* orbital of the whole conjugated ring, is also modified by the Lewis acid coordination. The vertical excitation energy to the $S_{NP}(^1n\pi^*)$ state of **2** is computed to be 84.8 kcal mol^{-1}. The value for the **2**/**1** complex goes up to 102.9 kcal mol^{-1} and is even about 20.0 kcal mol^{-1} higher than that for the bright $S_{CT}(^1\pi\pi^*)$ state, peaking at $\lambda = 347$ nm (82.3 kcal mol^{-1}). A similar inversion trend of the $^1\pi\pi^*/^1n\pi^*$ energy levels was also found in **2**/BCl_3 upon complexation with a nonchiral Lewis acid (see Table 1). Obviously, the O1–B coordination makes considerable use of the O1 lone pair, thus resulting in a significant energy increase of the $^1n\pi^*$ state. As an important consequence, the $^1n\pi^*$ state population becomes inaccessible energetically and the PCA reaction is therefore solely regulated by the bright $S_{CT}(^1\pi\pi^*)$ state upon photoexcitation of the enone–catalyst complexes at long wavelength ($\lambda => 350$ nm).

Upon high energy excitation ($\lambda < 300$ nm) **2** is populated in the Frank–Condon (FC) region of the $S_{CT}(^1\pi\pi^*)$ state followed by a fast decay to its minimum, S_{CT}-Min, with the concomitant structural changes of weakened O1=C2 (1.21→1.24 Å) and C3=C4 (1.35→1.46 Å) bonds (see Section S5). The removal of the C3=C4 bond constraint in the geometry causes a significant C4–H10 twisting (C2-C3-C4-H10 dihedral angle: 176.1→106.5°) by overcoming a small barrier (3.9 kcal mol^{-1}). As a result, the energy level of the $S_{NP}(^1n\pi^*)$ state is considerably shifted up and eventually intersects with the $S_{CT}(^1\pi\pi^*)$ state at the conical intersection (CI) of S_{CT}/S_{NP}. Following the initial decay associated with C4–H10 twisting, an additional C3–H9 twisting [O1-C2-C3-H9 dihedral angle: −4.2(FC)→68.8°] is further imposed in the structural deformation of the $S_{CT}(^1\pi\pi^*)$ state along a downhill path. This combined torsion of the two C–H bonds leads to another CI between $S_{CT}(^1\pi\pi^*)$ and the ground state, that is, S_{CT}/S_0, which is located at 17.2 kcal mol^{-1} below the FC of the $S_{CT}(^1\pi\pi^*)$ state. Passing through the S_{CT}/S_0 funnel, **2** relaxes to its high vibrational states of the electronic ground state (i.e., hot ground state, S_0*) by the recovery of its geometric structure. Although such excess vibrational energies may be used to surmount the maxima of the racemic cycloaddition reaction pathway in the ground state, an extremely low yield is expected for this process, since the considerably high barriers (48.1/47.2 kcal mol^{-1}) have to be overcome along the paths of the cyclobutane formation towards the two enantiomers (Figure 1 a).

The aforementioned CI (S_{CT}/S_{NP}) provides a bypass channel to funnel the free enone **2** to its dark $S_{NP}(^1n\pi^*)$ state from the bright $S_{CT}(^1\pi\pi^*)$ state. The initial decay in the $S_{NP}(^1n\pi^*)$ state is characterized by the structural recovery of two twisted C–H bonds caused by the relaxation in the $^1\pi\pi^*$ state, thus producing a quasi-planar arrangement in the pyridone ring moiety. This deformation results in a sharp decrease in the energy level of the $S_{NP}(^1n\pi^*)$ state, thus enhancing the mutual interaction between $^1n\pi^*$ and the charge-transfer triplet state, that is, $T_{CT}(^3\pi\pi^*)$. Passing through a downhill path, the spin–orbit coupling (SOC) between the $S_{NP}(^1n\pi^*)$ and $T_{CT}(^3\pi\pi^*)$ states gradually increases and reaches the maximum value (66.1 cm^{-1}) at the singlet-triplet crossing of STC(S_{NP}/T_{CT}). Such strong SOC and the degeneracy of energy levels enable intersystem crossing (ISC) to take place effectively through STC(S_{NP}/T_{CT}). Thus, the nonadiabatic transition of $S_{CT}(^1\pi\pi^*) \rightarrow T_{CT}(^3\pi\pi^*)$ for **2** is smoothly completed through an El-Sayed-type[11] singlet–triplet crossing and the $^1n\pi^*$ intermediate state. Once **2** is populated in the triplet state, the [2+2] PCA reaction is immediately triggered to proceed in a stepwise manner. With the initial formation of the C4–C6 bond in the triplet state overcoming the small barriers (3.5/5.4 kcal mol^{-1}), the energy level in the ground state rapidly increases and approaches the $T_{CT}(^3\pi\pi^*)$ state. This leads to another singlet–triplet crossing between $T_{CT}(^3\pi\pi^*)$ and the ground state, referred to as STC(T_{CT}/S_0), that is verified to have a diradical configuration distributing the unpaired electrons around the C3 and C7 atoms. The existence of STC(T_{CT}/S_0) facilitates the occurrence of spin inversion of the diradical with high efficiency, thus giving rise to an excellent precursor for the subsequent cyclization reaction. Finally, the C3–C7 bond is generated by an ultrafast combination of the diradical in the ground state, thus producing **3** and its enantiomer **4.**

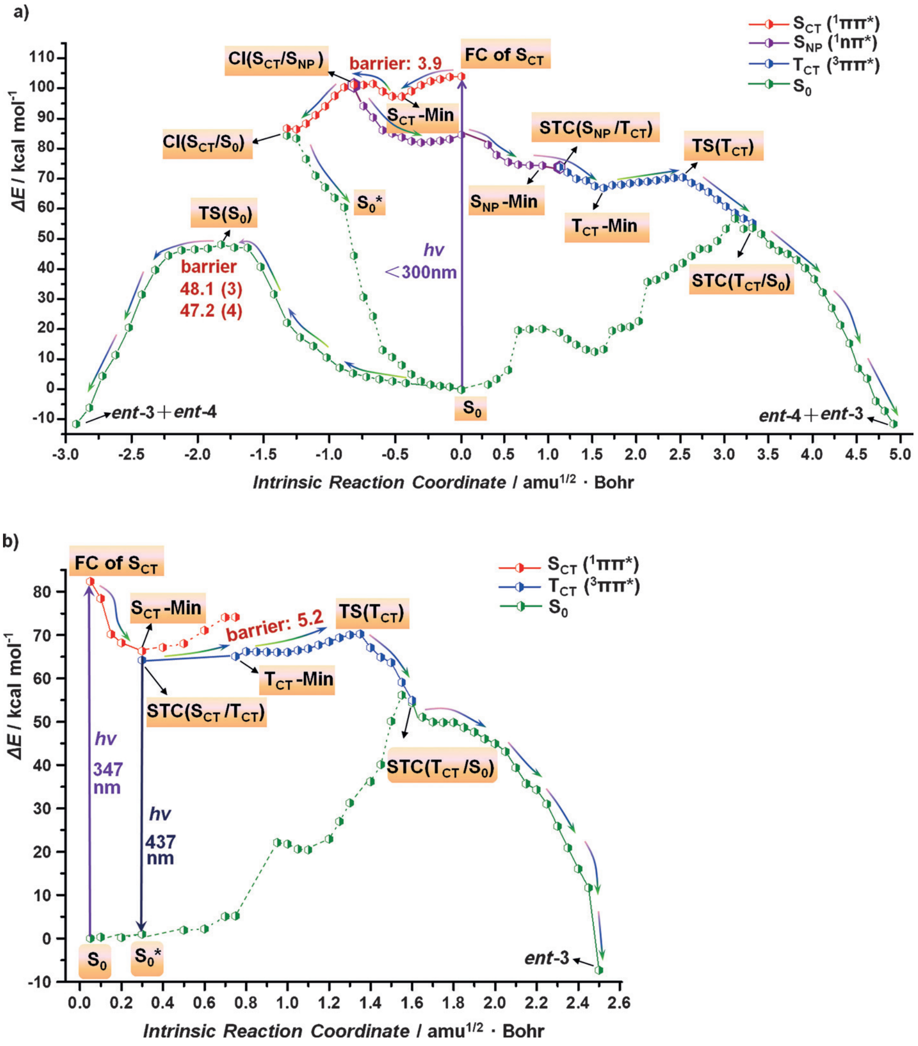


Figure 1. Minimum-energy profiles of the [2+2] photocycloaddition for **2** (a) and the **2**/**1** (b), obtained at the CASPT2//IRC//CASSCF(12e/10o) level of theory. The related [2+2] cycloaddition barriers are given in kcal mol^{-1}. The structures at the highlighted characteristic points of the reaction path are given with their key bond distances in the Supporting Information.

Upon the coordination of **2** with chiral **1** and nonchiral (BCl_3) catalysts, the low-energy excitation ($\lambda \approx 350$ nm) leads to the ultrafast relaxation of enone–catalyst complexes from the FC region of the $S_{CT}(^1\pi\pi^*)$ state to their minima (S_{CT}-Min) with a significant decrease in energy. The adiabatic excitation energies of the $S_{CT}(^1\pi\pi^*)$ state were calculated to red-shift from 97.4 kcal mol^{-1} for **2** to 66.3 and 72.9 kcal mol^{-1} for **2**/**1** and **2**/BCl_3, respectively. This shift is even about 20.0 kcal mol^{-1} lower than the conical intersection of S_{CT}/S_0 for **2** caused by C–H twisting in a high energy level. All these findings suggest that the bright-state decay of enone–catalyst complexes is unlikely to trigger the structural deformation of C–H twisting, but results in an extremely stable minimum of the $S_{CT}(^1\pi\pi^*)$ state with a noticeably weakened C2–O1 (1.29 Å) bond and a reinforced crosslinking between the enone and catalyst (O1-B: 1.59 Å). In addition, the energy level of the $^1n\pi^*$ state is always 20.0–30.0 kcal mol^{-1} higher than $S_{CT}(^1\pi\pi^*)$ from FC to the minimum in the bright excited state. This difference indicates that the $^1n\pi^*$ state has no opportunity to regulate the relaxation in the singlet-excited state of the Lewis acid catalyzed enone. Therefore, the deactivation channel in the singlet state is completely closed upon Lewis acid coordination and the triplet manifold may serve as a potential reaction precursor to deliver the enantioselective product. Consistently, convincing evidence based on experimental observations supports that the Lewis acid catalyzed [2+2] PCA reactions proceed on the triplet hypersurface for the complexed coumarin and dihydropyridone.[4e,8,10c]

2/**1** and **2**/BCl_3 complexes are trapped in deep potential wells once they populate the minima of the $S_{CT}(^1\pi\pi^*)$ state. There are two competitive deactivation channels from S_{CT}-Min, that is, ISC to its triplet state or radiative transition to its ground state by fluorescence emission. Closer energy analyses show that S_{CT}-Min of the **2**/**1** complex has an exceptionally small singlet–triplet gap (2.1 kcal mol^{-1}), which is therefore considered to be the crossing between the $S_{CT}(^1\pi\pi^*)$ and $T_{CT}(^3\pi\pi^*)$ states, referred to as STC(S_{CT}/T_{CT}). In addition, a broad and flat path is determined to relay the following triplet state decay (Figure 1 b). Most importantly, a large SOC of 37.4 cm^{-1} is found over an extended region of STC(S_{CT}/T_{CT}), thus allowing an effective ISC between singlet and triplet states with the same charge-transfer nature as the $\pi\rightarrow\pi^*$ transition. This finding suggests that there exists an anti-El-Sayed-type crossing in the presence of **1**, having heavy bromine atoms, as derived by Shaik et al. as well as Su, and articulated in a two-state reactivity in C–H activation.[11] In contrast, SOC considerably decreases to 0.7 cm^{-1} with a significant singlet–triplet energy splitting (ca., 7.0 kcal mol^{-1}) in the near-degeneracy region of the **2**/BCl_3 complex when **2** is coordinated with the same boron-based catalyst, but without bromine atoms (see Table 1 and Figure S2). All this evidence implies that relativistic effects which result from the presence of heavy atoms play a decisive role in the improvement of the ISC rate and the increase of the PCA yield. This finding is also supported by experimental tests of the Lewis acid catalyzed PCA reaction of coumarin, in which a high yield of 97 % was observed when using $AlBr_3$ as catalyst, whereas $BF_3{\cdot}OEt_2$ gave only a 33 % yield.[5]

It should be pointed out that the increased ISC rate of the $^1\pi\pi^*\rightarrow{}^3\pi\pi^*$ transition induced by the relativistic effects of heavy atoms still cannot compete with that of the El-Sayed rule of an allowed $^1n\pi^*\rightarrow{}^3\pi\pi^*$ conversion in **2**, since the SOC of the **2**/**1** complex (37.4 cm^{-1}) is computed to be much smaller than that of the free enone **2** (66.1 cm^{-1}). This discrepancy of the ISC rates is the reason why the reaction rate for **2**/**1** in the presence of a chiral Lewis acid is slower than that of **2** in the absence of the Lewis acid.[8] For the former case, the strong absorption of the $S_{CT}(^1\pi\pi^*)$ state is initially populated and the ISC of the $^1\pi\pi^*\rightarrow{}^3\pi\pi^*$ transition is the rate-determining step since the $^1n\pi^*$ state population becomes inaccessible energetically. For the latter one, photoexcitation at $\lambda = 366$ nm promotes **2** to its spectroscopic $^1n\pi^*$ state with low oscillator strength ($<10^{-4}$) and the fast ISC of the $^1n\pi^*\rightarrow{}^3\pi\pi^*$ transition regulates the PCA reaction. Considering that fluorescence emission is a slow process with a nanosecond timescale, it cannot compete with the PCA reaction mediated by relativistic effects of the Lewis acid, thus suggesting that fluorescence emission is minor with a low yield.[7] Like the case for **2**, the PCA reaction of the **2**/**1** complex is characterized by a low barrier (5.2 kcal mol^{-1}) in the triplet state and then passes through STC(T_{CT}/S_0) relay towards the major product of **3** in the ground state. However, because of the presence of steric hindrance of **1**, a sizeable barrier (15.8 kcal mol^{-1}) is encountered when the PCA reaction occurs in the opposite direction, thus producing the minor product of **4**, which is the enantiomer of **3**. As an important consequence, a high enantioselectivity is achieved for the PCA reaction.

In summary, extensive theoretical investigations have been performed to provide the first regulatory theory for the influence of a Lewis acid on an enantioselective intramolecular enone [2+2] PCA reaction. The racemic background reaction of the free enone substrate was found to mainly occur in the triplet $\pi\pi^*$ state, which is regulated by the $n\pi^*$ intermediate state by a fast ISC, thus benefiting from an El-Sayed-type singlet–triplet crossing. This unselective background reaction is largely suppressed in the Lewis acid catalyzed reaction by a noticeable energy inversion of the $n\pi^*/\pi\pi^*$ states and the regulatory elimination of the $n\pi^*$ state. The enantioselective PCA reaction has been revealed to be predominantly controlled through an enhanced spin–orbit coupling, caused by relativistic effects resulting from heavy atoms in the chiral Lewis acid catalyst. These mechanistic insights provide useful benchmarks for further studies of PCA reactions mediated by Lewis acids or other catalysts and also may facilitate mechanism-based design for enantioselective catalysts.

Acknowledgements

This work has been supported by the grants NSFC21373029, NSFC21421003, 2011CB808503, and DFG CA 1390/1-1.

Keywords: ab initio calculations · cycloaddition · enantioselectivity · heterocycles · Lewis acids

How to cite: *Angew. Chem. Int. Ed.* **2015**, *54*, 14295–14298
Angew. Chem. **2015**, *127*, 14503–14506

---

[1] a) G. Ciamician, *Science* **1912**, *36*, 385–394; b) B. Alcaide, P. Almendros, C. Aragoncillo, *Chem. Soc. Rev.* **2010**, *39*, 783–816; c) E. Lee-Ruff, G. Mladenova, *Chem. Rev.* **2003**, *103*, 1449–1483; d) J. C. Namyslo, D. E. Kaufmann, *Chem. Rev.* **2003**, *103*, 1485–1537; e) M. A. Ischay, M. E. Anzovino, J. Du, T. P. Yoon, *J. Am. Chem. Soc.* **2008**, *130*, 12886–12887; f) R. Brimioulle, T. Bach, *Angew. Chem. Int. Ed.* **2014**, *53*, 12921–12924; *Angew. Chem.* **2014**, *126*, 13135–13138.

[2] a) G. Talavera, E. Reyes, J. L. Vicario, L. Carrillo, *Angew. Chem. Int. Ed.* **2012**, *51*, 4104–4107; *Angew. Chem.* **2012**, *124*, 4180–4183; b) S. Suárez-Pantiga, C. Hernández-Díaz, E. Rubio, J. M. González, *Angew. Chem. Int. Ed.* **2012**, *51*, 11552–11555; *Angew. Chem.* **2012**, *124*, 11720–11723; c) R. Brimioulle, D. Lenhart, M. M. Maturi, T. Bach, *Angew. Chem. Int. Ed.* **2015**, *54*, 3872–3890; *Angew. Chem.* **2015**, *127*, 3944–3963; d) T. Seiser, T. Saget, D. N. Tran, N. Cramer, *Angew. Chem. Int. Ed.* **2011**, *50*, 7740–7752; *Angew. Chem.* **2011**, *123*, 7884–7896; e) F. de Nanteuil, J. Waser, *Angew. Chem. Int. Ed.* **2013**, *52*, 9009–9013; *Angew. Chem.* **2013**, *125*, 9179–9183.

[3] a) L. M. Tolbert, M. B. Ali, *J. Am. Chem. Soc.* **1982**, *104*, 1742–1744; b) M. Demuth, A. Palomer, H.-D. Sluma, A. K. Dey, C. Krüger, Y.-H. Tsay, *Angew. Chem. Int. Ed. Engl.* **1986**, *25*, 1117–1119; *Angew. Chem.* **1986**, *98*, 1093–1095.

[4] a) K. A. B. Austin, E. Herdtweck, T. Bach, *Angew. Chem. Int. Ed.* **2011**, *50*, 8416–8419; *Angew. Chem.* **2011**, *123*, 8566–8569; b) C. Müller, A. Bauer, M. M. Maturi, M. C. Cuquerella, M. A. Miranda, T. Bach, *J. Am. Chem. Soc.* **2011**, *133*, 16689–16697; c) S. C. Coote, T. Bach, *J. Am. Chem. Soc.* **2013**, *135*, 14948–14951; d) R. Alonso, T. Bach, *Angew. Chem. Int. Ed.* **2014**, *53*, 4368–4371; *Angew. Chem.* **2014**, *126*, 4457–4460; e) R. Brimioulle, H. Guo, T. Bach, *Chem. Eur. J.* **2012**, *18*, 7552–7560; f) M. M. Maturi, M. Wenninger, R. Alonso, A. Bauer, A. Pöthig, E. Riedle, T. Bach, *Chem. Eur. J.* **2013**, *19*, 7461–7472; g) F. Mayr, C. Wiegand, T. Bach, *Chem. Commun.* **2014**, *50*, 3353–3355.

[5] H. Guo, E. Herdtweck, T. Bach, *Angew. Chem. Int. Ed.* **2010**, *49*, 7782–7785; *Angew. Chem.* **2010**, *122*, 7948–7951.

[6] a) D. Liu, E. Canales, E. J. Corey, *J. Am. Chem. Soc.* **2007**, *129*, 1498–1499; b) E. Canales, E. J. Corey, *J. Am. Chem. Soc.* **2007**, *129*, 12686–12687; c) E. J. Corey, *Angew. Chem. Int. Ed.* **2009**, *48*, 2100–2117; *Angew. Chem.* **2009**, *121*, 2134–2151.

[7] R. Brimioulle, T. Bach, *Science* **2013**, *342*, 840–843.

[8] R. Brimioulle, A. Bauer, T. Bach, *J. Am. Chem. Soc.* **2015**, *137*, 5170–5176.

[9] a) A. Bergner, M. Dolg, W. Küchle, H. Stoll, H. Preuss, *Mol. Phys.* **1993**, *80*, 1431–1441; b) M. Dolg, X. Cao, *Chem. Rev.* **2012**, *112*, 403–480.

[10] a) F. D. Lewis, S. V. Barancyk, *J. Am. Chem. Soc.* **1989**, *111*, 8653–8661; b) F. D. Lewis, G. D. Reddy, J. E. Elbert, B. E. Tillberg, J. A. Meltzer, M. Kojima, *J. Org. Chem.* **1991**, *56*, 5311–5318; c) H. Görner, T. Wolff, *Photochem. Photobiol.* **2008**, *84*, 1224–1230.

[11] a) M. A. El-Sayed, *Acc. Chem. Res.* **1968**, *1*, 8–16; b) M. A. El-Sayed, *J. Chem. Phys.* **1963**, *38*, 2834–2838; c) S. S. Shaik, *J. Am. Chem. Soc.* **1979**, *101*, 2736–2738; d) S. S. Shaik, *J. Am. Chem. Soc.* **1979**, *101*, 3184–3196; e) S. S. Shaik, N. D. Epiotis, *J. Am. Chem. Soc.* **1980**, *102*, 122–131; f) M.-D. Su, *J. Org. Chem.* **1996**, *61*, 3080–3087; g) M.-D. Su, *Chem. Phys.* **1996**, *205*, 277–308; h) S. Shaik, D. Danovich, A. Fiedler, D. Schröder, H. Schwarz, *Helv. Chim. Acta* **1995**, *78*, 1393–1407.

Received: June 28, 2015
Revised: August 14, 2015