

CrossMark
click for updatesCite this: *Chem. Sci.*, 2017, 8, 654

Chromium photocatalysis: accessing structural complements to Diels–Alder adducts with electron-deficient dienophiles†

Susan M. Stevenson,^a Robert F. Higgins,^b Matthew P. Shores^b and Eric M. Ferreira^{*a}

A chromium-catalyzed, visible light-activated net [4 + 2] cycloaddition between dienes and electron-deficient alkenes is described. Gathered evidence, *via* control experiments, isolated intermediates, and measured redox potentials, points to several converging reaction pathways that afford the cyclohexene adducts, including a photochemical [2 + 2] cycloaddition/vinylcyclobutane rearrangement cascade and a substrate excitation/oxidation sequence to a radical cation intermediate. Notably, the accompanying mechanistic stipulations result in a process that yields regioisomeric compounds from those generated by traditional Diels–Alder cycloadditions.

Received 25th July 2016
Accepted 11th September 2016

DOI: 10.1039/c6sc03303b

www.rsc.org/chemicalscience

Introduction

In the past decade, the renaissance of photoredox catalysis has generated renewed interest in radical cation accelerated reactions initiated through photoinduced electron transfer (PET).¹ Notable examples in the area of radical cation [2 + 2] and [4 + 2] cycloadditions² have utilized metal photoredox catalysts containing Ru³ and Ir⁴ ions, as well as triarylpyrylium salts,⁵ as light-activated single-electron oxidants. In the interest of advancing sustainable chemical transformations,⁶ there has recently been a shift toward developing photocatalysts based on more earth-abundant metals, with particular achievements reported using Cu⁷ and Fe-containing⁸ systems. Our groups have investigated strongly oxidizing polypyridyl and -phenanthrolyl Cr photocatalysts.⁹ We reported that these light-activated Cr(III) complexes ($E_{1/2} = +1.33$ – 1.84 V *vs.* SCE¹⁰) are capable of promoting radical cation Diels–Alder cycloadditions of electron-rich alkenes,^{9b} akin to the Ru-initiated examples from Yoon in 2011.¹¹ Mechanistically, however, the Cr-photocatalyzed cycloaddition differs from the Ru version¹² in that the reaction catalyzed by [Cr(Ph₂-phen)₃](BF₄)₃ favored an oxygen-mediated catalytic cycle over radical chain propagation.^{9c} This unique behavior encouraged us to investigate the synthetic utility of the Cr photocatalysts further.

The radical cation [4 + 2] cycloaddition using Ru or Cr with light was relatively constrained by the requirement of

sufficiently oxidizable alkenes, a common stipulation in these reactions.¹³ Being mindful that photocatalysis has often provided an entry point for the construction of nonintuitive bonds *via* novel reaction manifolds,¹⁴ we wondered whether electron-poor dienophiles *outside of the oxidizable realm* could also yield cycloaddition products. Though electron-poor olefins would typically be expected to participate in [4 + 2] cycloadditions through more conventional, LUMO-lowering activation modes (*e.g.*, thermal, Lewis acid), a photochemical strategy could broaden the range of Diels–Alder cycloadducts attainable, and perhaps offer orthogonal selectivity profiles (*e.g.*, regio-, diastereo-). Herein, we report the Cr-photocatalyzed cycloaddition of electron-poor olefins with dienes (Fig. 1). Experiments implicate multiple operative mechanistic pathways that converge to form the same cycloadducts. Importantly, the described transformation results in Diels–Alder products of *reversed* regioselectivity, yielding “*meta*” adducts as opposed to the “*ortho*” and “*para*” adducts generated under conventional activation.

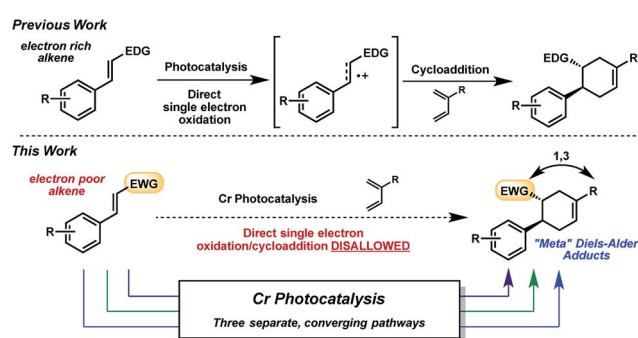


Fig. 1 Photocatalyzed [4 + 2] cycloadditions with electron deficient alkenes.

^aDepartment of Chemistry, University of Georgia, Athens, GA 30602, USA. E-mail: emferreira@uga.edu

^bDepartment of Chemistry, Colorado State University, Fort Collins, CO 80523, USA

† Electronic supplementary information (ESI) available: Experimental procedures, characterization data, electrochemistry data, UV/visible data, NMR spectra. See DOI: 10.1039/c6sc03303b

Results and discussion

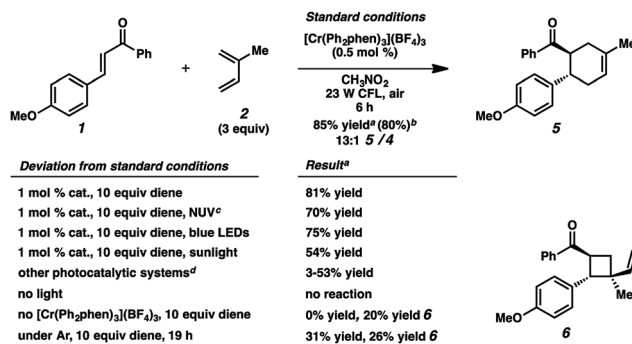
Reaction development

The reactivity of 4-methoxychalcone is illustrative (1, Fig. 2). In intermolecular Diels–Alder cycloadditions using conventional activation, enones of this type routinely require rather forcing conditions and yield predominantly adduct 4.¹⁵ Based on our previous efforts, we reasoned that the cycloaddition of 4-methoxychalcone through a photocatalytic oxidation pathway would be out of the question, as the oxidation potential of enone 1 (+2.00 V, in CH₃NO₂) is too positive to be oxidized by the [Cr(Ph₂phen)₃]³⁺ catalyst ($E_{1/2}^* = +1.33$ V, in CH₃NO₂) in the pathway as described for the electron-rich dienophiles.^{9b,16} Thus, under Cr-photocatalysis conditions, no cycloaddition between 4-methoxychalcone (1) and isoprene (2) should occur.

Surprisingly, however, when enone 1 was exposed to [Cr(Ph₂phen)₃](BF₄)₃ in the presence of isoprene (2) and irradiation with a 23 W compact fluorescent light bulb, cycloadduct 5 was formed in 85% yield (80% isolated yield, Scheme 1). Remarkably, the regioselectivity of this cycloaddition was 13 : 1 favoring the reversed Diels–Alder adduct (5). We found that increased catalyst loading and equivalents of diene did not increase the yield. Near-UV (NUV), blue LEDs, and sunlight also effected this transformation, but optimal results were achieved with the 23 W CFL source. Other photoredox catalysts were less effective (*vide infra*). A control experiment confirmed that no reaction occurred without light. Notably, with light but in the absence of catalyst, vinylcyclobutane 6 was formed in 20% yield, presumably *via* photochemical [2 + 2] cycloaddition between enone 1 and isoprene,¹⁷ but no [4 + 2] products were detected. Lastly, performing the reaction in the absence of air significantly decelerated the formation of cyclohexene 5, while vinylcyclobutane 6 also formed. We had previously found oxygen to be important for Cr-mediated photocatalysis with electron-rich substrates (*vide infra*).^{9b,c,18}

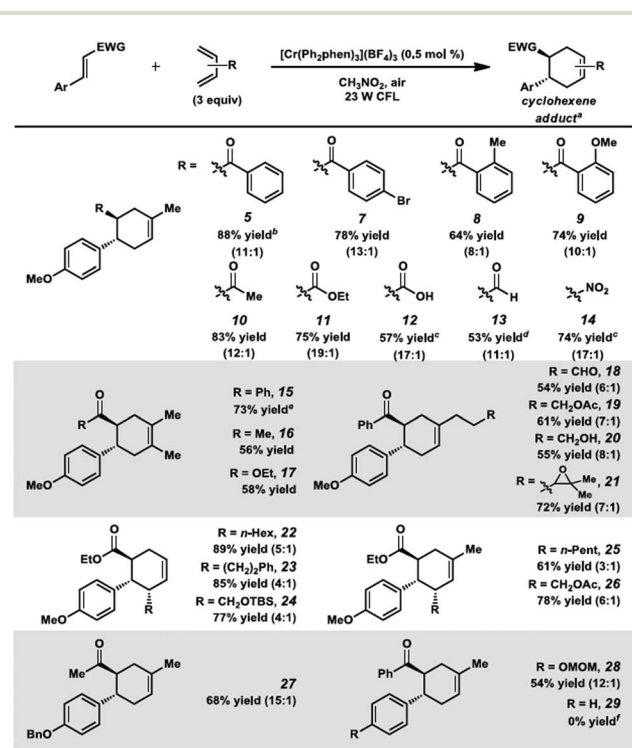
Substrate scope

Encouraged by the success of this reaction, we set out to test the limits of these cycloadditions by examining other electron-poor



Scheme 1 Selected optimization experiments.

olefins (Scheme 2). We were delighted to find this process was successful for a range of cycloaddition partners. Several differentially substituted chalcone derivatives were found to be viable substrates for this transformation (5, 7–9). Other α,β -unsaturated carbonyl compounds reacted in moderate to high yields (10–13). A nitroolefin was also a competent substrate, forming cyclohexene 14 in 74% yield. Consistent with the 4-methoxychalcone case, the transformations with isoprene all proceeded with high levels of regioselectivity (8 : 1 to 19 : 1). Symmetrical 2,3-dimethyl-1,3-butadiene could be used with several of these dienophiles, affording cyclohexenes 15–17 in good yields. Regioselectivity considerations are not applicable for this diene,



^a Isomeric ratio in parenthesis, major isomer is drawn. ^b Gram scale. ^c 1 mol % cat. ^d 9 equiv diene. ^e NUV irradiation was used. ^f A vinylcyclobutane analogous to 6 was formed in 11% yield.

Scheme 2 The Cr-photocatalyzed [4 + 2] cycloaddition between dienes and electron-deficient alkenes-scope.

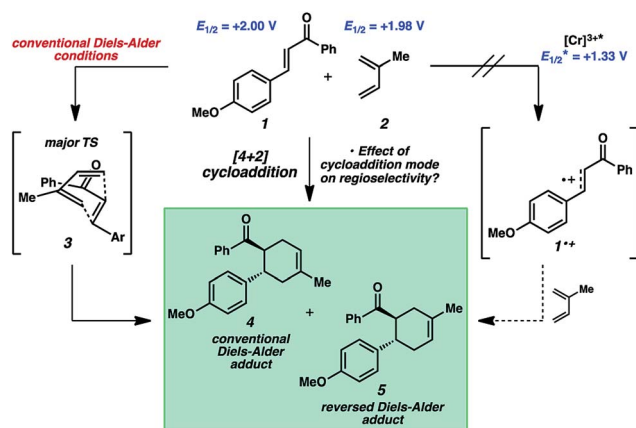


Fig. 2 Cycloaddition reactivity of 4-methoxychalcone.

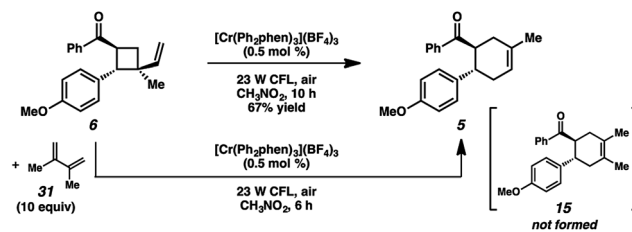


but it is still remarkable that this method circumvents the forcing conditions generally required to obtain these adducts.¹⁹ Differentially substituted dienes were also proficient in this reaction. The cycloaddition conditions were tolerant of a variety of functional groups on the diene (**18–21**, **24**, **26**). In addition, terminally substituted dienes gave cyclohexenes **22–26** in high yields. Somewhat lower regioselectivity ratios were observed, but stereoselectivity was excellent in these processes, as the major constitutional isomer was observed as a single diastereomer.²⁰ Lastly, enones containing different electron-rich aryl groups at the β -position also participated in the reaction (**27**, **28**), although we note here the scope was more limited.²¹ For example, an enone with an electron-neutral arene was not productive in this transformation (**29**).

Mechanistic pathways

We have found in our initial mechanistic studies the potentially operative pathways deviate significantly from the direct oxidative route. As mentioned previously, accounting for reduction potentials it is unlikely that the photoexcited Cr catalyst ($\text{Cr}^{3+*/2+}$ $E_{1/2} = +1.33$ V in CH_3NO_2) could be directly oxidizing 4-methoxychalcone (**1**, $E_{1/2} = +2.00$ V) or isoprene (**2**, $E_{1/2} = +1.98$ V (ref. 22)) to initiate the cycloaddition.²³ Furthermore, all attempts to catalyze the cycloaddition using photocatalysts with more positive excited state reduction potentials, such as $[\text{Ru}(\text{bpy})_3]^{2+}$, triphenylpyrilium, Mes-Acr, or a variety of cyanoarenes and chloranil,²⁴ provided lower yields than $[\text{Cr}(\text{Ph}_2\text{phen})_3](\text{BF}_4)_3$ (see the ESI[†]), indicating that this transformation is likely not proceeding *via* simple direct oxidation of the electron deficient alkene. An energy transfer pathway could also be ruled out since the long-lived excited state of $[\text{Cr}(\text{Ph}_2\text{phen})_3](\text{BF}_4)_3^*$ (38 kcal mol⁻¹) is considerably lower than the transfer energies of either the 4-methoxychalcone (**1**) or isoprene (the triplet excited state energies are both ~ 60 kcal mol⁻¹).²⁵

We thus considered other mechanistic pathways (Fig. 3). One possibility is that the reaction is proceeding through intermediate vinylcyclobutane **6** (*Pathway A*), which we observed when the reaction was performed without catalyst.²⁶ Indeed, when vinylcyclobutane **6** ($E_{1/2} = +1.68$ V in CH_3NO_2) was exposed to the Cr conditions, product **5** was formed in 67% yield as a single isomer (Scheme 3).²⁷ When this rearrangement was performed in



Scheme 3 Rearrangement of vinylcyclobutane **6**.

the presence of excess diene **31**, only the rearrangement product was observed and not the cross-adduct between 4-methoxychalcone and the added diene, confirming that cyclohexene **5** is forming through direct rearrangement of vinylcyclobutane **6** and not through cycloreversion/recombination.^{28,29} Thus, we believe that a cascade pathway involving photochemical [2 + 2] cycloaddition (**1**, $\lambda_{\text{max}} = 340$ nm) followed by single-electron oxidative vinylcyclobutane rearrangement³⁰ is viable and occurring. We note, however, that cyclobutane **6** was formed in only 20% yield without catalyst, while 85% yield of cyclohexene **5** was formed with catalyst in the same duration, suggesting that this [2 + 2]/rearrangement may not be the only mechanistic pathway.

A different route, *Pathway B* offers a means of accessing a reactive enone radical cation (**1**^{•+}, Fig. 3). If *in situ* dimerization of enone **1** occurs,³¹ the resulting dimer (**30**) has a significantly lower reduction potential ($E_{1/2} = +1.40$ V, in CH_3NO_2) than the starting enone. Oxidation could then induce cycloreversion to the radical cation, and interception of this putative radical cation with the diene could afford the cycloaddition product (*via* direct [4 + 2] and/or [2 + 2]/rearrangement).³² Control experiments suggest this pathway is a minor contributor at most. First, enone dimer **30** was found to form in only trace amounts under the standard Cr conditions in the absence of diene. Furthermore, independently synthesized enone dimer **30** subjected to irradiation affords retrocyclobutanation with and without catalyst, but in low yields (Scheme 4). When dimer **30** was exposed to the cycloaddition conditions in place of enone **1**, cyclohexene **5** formed in 20% yield, at least implicating the feasibility of this pathway. Notwithstanding, the low production of dimer **30** and the relatively sluggish cycloreversion suggests a lesser role in the formation of cyclohexene **5**.

An alternative pathway for the generation of **1**^{•+} recognizes that the photoexcited enone (**1**^{*}) will be easier to oxidize than its ground state form (Fig. 3, *Pathway C*). Select reports indicate

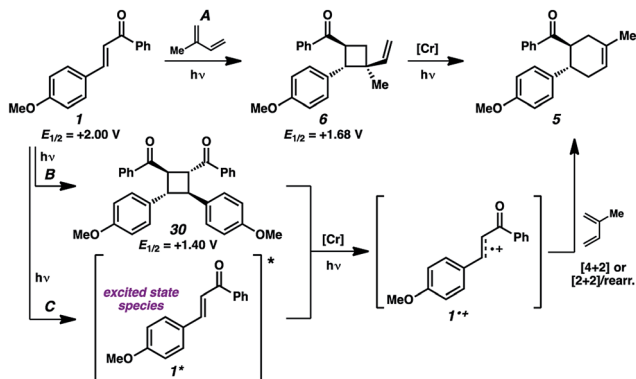
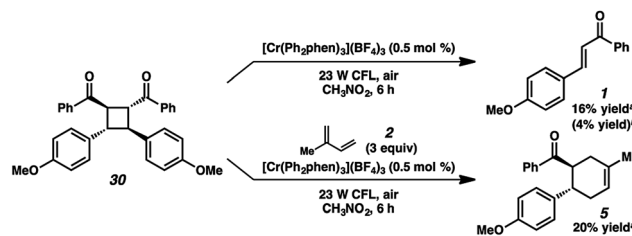


Fig. 3 Possible mechanistic pathways.



^a NMR yield with dodecyl acetate as internal standard. The remainder is recovered **30**.
^b Yield when reaction was performed without catalyst.

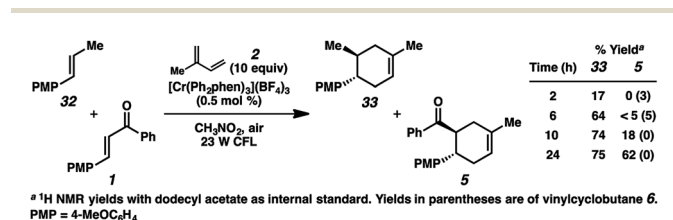
Scheme 4 Cycloreversion of enone dimer **30**.



that the excitation of chalcone derivatives and related α,β -unsaturated carbonyl species lead to excimers³³ and/or charge-transfer complexes,³⁴ which enable single-electron oxidation.³⁵ The oxidation of enone **1*** in this manner would generate radical cation **1**^{•+}, which would proceed to product **5** as described earlier. Here, we note that enone **1** shows weak emission at 443 nm when excited at 340 nm in acetonitrile, from which we estimate an excited state reduction potential ($1^{•+/0*}$) of -0.80 V, which suggests thermodynamic competency for oxidation of **1*** by the photoexcited Cr catalyst. The triplet excited state lifetime of enone **1** was reported to be 23 and 29 ns in heptane and methanol, respectively,^{25a} suggesting this is well within the range of feasibility for oxidation by the long-lived excited state of the Cr catalyst.

Bauld and coworkers have discussed the inhibitory effect of *trans*-anethole on competing radical cation cycloadditions and vinylcyclobutane rearrangements due to its highly oxidizable nature ($E_{1/2} = +1.35$ V (ref. 9c)).^{22,36} Thus, if the cycloaddition of enone **1** and isoprene (**2**) is proceeding through a radical cation (e.g., **1**^{•+}), we would expect the addition of *trans*-anethole to considerably impede the formation of cycloadduct **5**. In accordance with this hypothesis, in a competition experiment using a 1 : 1 mixture of *trans*-anethole (**32**) and enone **1** with excess isoprene, the cycloaddition with enone **1** proceeded only after the majority of **32** was consumed (Scheme 5). The inhibitory effect of alkene **32** may implicate the intermediacy of the enone radical cation (**1**^{•+}) in the overall process.

In an effort to probe the termination step(s) concerning all possible pathways, quantum yield experiments were performed. Since compounds **1**, **6**, and **30** can all be invoked as starting materials or intermediates in the mechanism, each was tested for their photochemical efficiency. At 350 nm excitation, maximum quantum yield values for species **1**, **6**, and **30** were $\Phi = 0.013$, 0.45, and 0.013, respectively. Compounds **1**, **6**, and **30** do absorb light at 350 nm (as does nitromethane), and their equilibria in solution complicate the calculation of an accurate quenching factor. Therefore compound **6**, which showed the largest quantum yield, was excited at 400 nm in the presence of $[\text{Cr}(\text{Ph}_2\text{phen})_3]^{3+}$ in CD_3NO_2 where the maximum quantum yield was $\Phi = 0.93$. Since only $[\text{Cr}(\text{Ph}_2\text{phen})_3]^{3+}$ absorbs light at this wavelength, the quenching factor is assumed to be ~ 1 , giving a chain length value of < 1 . These data corroborate the lack of a predominant radical chain mechanism¹² in the reaction manifold. Moreover, when a deoxygenated sample containing **6** and $[\text{Cr}(\text{Ph}_2\text{phen})_3]^{3+}$ was irradiated at 400 nm in nitromethane, the quantum yield decreased to a maximum value of $\Phi = 0.21$, further implicating this reactivity as photocatalytic instead of photoinitiated, akin to our previous report.^{9c}



Scheme 5 Competition experiment with *trans*-anethole.

The presence of oxygen in this transformation also deserves mention. In our earlier study, we had discussed the roles of O₂ in the cycloaddition using electron-rich alkenes. O₂ was essential, and the absence of it shut down catalysis altogether. Singlet oxygen was formed in these cycloadditions *via* a quench of the long-lived Cr(III) excited state. The singlet oxygen is then reduced to superoxide by Cr(II), and the superoxide then reduces the cycloadduct radical cation. In this specific reaction with electron-deficient alkenes, the effect of O₂ is still beneficial to the overall reaction progress, but not nearly to the same extent as the earlier transformation (*i.e.*, reaction rates are slower, but the cyclohexene product is still formed *via* catalytic turnover). We believe singlet oxygen is formed in these cycloadditions as well. In the analysis of the reaction and the substrate scope, in several cases we noted the formation of a minor byproduct (average <5% yield). We determined this byproduct to be an allylic hydroperoxide, presumably arising from the oxidation of the cyclohexene product by ¹O₂.³⁷ It is possible that we may be amplifying or diminishing specific reaction pathways in the presence of O₂; future studies may elucidate its multifaceted effects.

From the evidence amassed thus far we conclude that this Cr-photocatalyzed cycloaddition using an electron deficient dienophile can occur through several reaction pathways involving photochemical and radical cation processes, all outside of the direct electron transfer or energy transfer pathways. Coincidentally, the operative pathways all converge to the same cyclohexene adducts. Further mechanistic studies are underway.³⁸

Diels–Alder regioselectivity analysis

A hallmark characteristic of the Diels–Alder reaction is its highly predictive regioselective outcomes. An electron-withdrawing group on the dienophile and an electron-donating group on the diene will impact the coefficients of the FMOs so as to dictate the overall regioselectivity of the cycloaddition (*i.e.*, the “*ortho*–*para* rule”). Efforts to reverse this natural regioselectivity of Diels–Alder cycloadditions have been reported, but only a handful of strategies have been successful.^{39,40} These include the incorporation of electronically steering substituents that can be subsequently removed,⁴¹ and catalyzed *vs.* thermal/noncatalyzed cycloadditions that adjust the molecular orbital coefficients of the reactants (e.g., selective coordination of a sterically unhindered carbonyl).⁴² Table 1 depicts an alternative strategy to achieve this unnatural regioselectivity. Example dienes and β -(*para*-methoxyphenyl)nitroethylene were combined using both previously described LiClO₄/CH₃NO₂ conditions⁴³ and our chromium photocatalyzed conditions. As can be seen, these transformations each proceed to afford complementary regiochemistries, where the photocatalyzed reactions occur with high selectivity for the unconventional Diels–Alder adducts. This unconventional regioselectivity tracks consistently with all of the selectivities observed in the cases in Scheme 2. These transformations represent a novel, conditions-based approach to invert the Diels–Alder regioselectivity with reactive diene/dienophile partners.



Table 1 Reversed regioselectivity under Cr-photocatalysis conditions

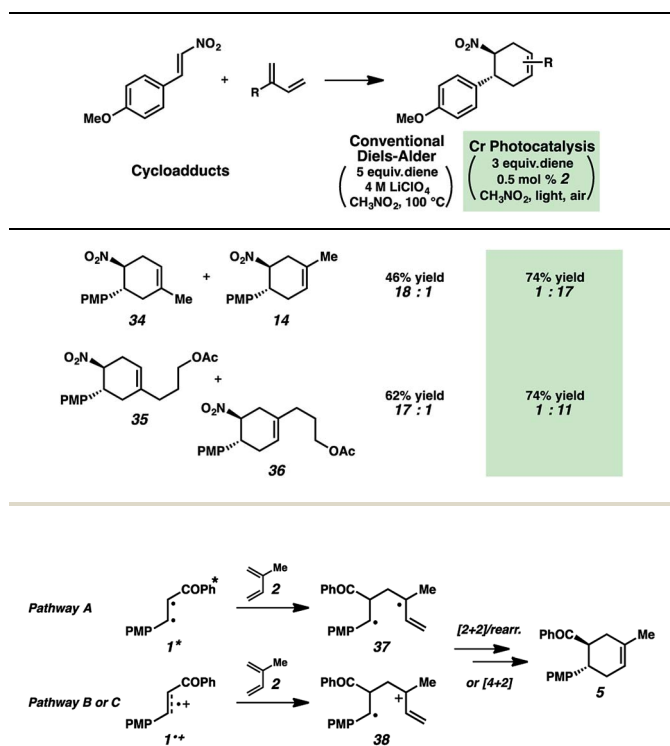


Fig. 4 General regiochemical explanation.

Our hypothesis for the observed regioselectivity is illustrated in Fig. 4, using chalcone 1 and isoprene as an example. Notably, whether the cycloaddition is proceeding through a photochemical “head-to-tail” [2 + 2] cycloaddition⁴⁴ followed by a radical cation vinylcyclobutane rearrangement, or an enone radical cation pathway, the net reversed Diels–Alder regioselectivity should be favored. With isoprene (2), the methyl substituent allows selective generation of the more stable diradical or radical cation intermediate. Presumably, the aryl group also stabilizes this intermediate species to some extent.

Conclusions

The deliberate investigations of photocatalytic manifolds with various components have unlocked new transformations that possess tremendous potential for the chemistry community. We have shown that that the Cr-catalyzed [4 + 2] cycloaddition of dienes with electron-poor alkenes (*i.e.*, outside of the oxidizable realm) can yield cyclohexene adducts, and, perhaps most pertinently, with opposite regioselectivities to those provided *via* the traditional Diels–Alder cycloaddition. In as much as the previous Cr-catalyzed [4 + 2] cycloaddition is a chemoselective complement to the Diels–Alder reaction, this example represents a *regioselective* complement to the transformation. This process is optimally effective using Cr photocatalysis. Mechanistic investigations elucidating the unique impact of Cr, and efforts to expand this chemistry, will be reported in due course.

Acknowledgements

This research was carried out by the Catalysis Collaboratory for Light-activated Earth Abundant Reagents (C-CLEAR), which is supported by the NSF and EPA through the Network for Sustainable Molecular Design and Synthesis program (NSF-CHE-1339674). We acknowledge collaborators Niels Damrauer and Anthony Rappé and their groups for enriching discussions. Sang Lee is acknowledged for experimental assistance.

Notes and references

- For a recent discussion of this topic, see, A. Studer and D. P. Curran, *Angew. Chem., Int. Ed.*, 2016, **55**, 58–102.
- (a) F. Müller and J. Mattay, *Chem. Rev.*, 1993, **93**, 99–117; (b) T. P. Yoon, *ACS Catal.*, 2013, **3**, 895–902; (c) Y. Liu, R. Song and J. Li, *Sci. China: Chem.*, 2016, **59**, 161–170.
- (a) M. A. Ischay, Z. Lu and T. P. Yoon, *J. Am. Chem. Soc.*, 2010, **132**, 8572–8574; (b) M. A. Ischay, M. S. Ament and T. P. Yoon, *Chem. Sci.*, 2012, **3**, 2807–2811; (c) S. Lin, C. E. Padilla, M. A. Ischay and T. P. Yoon, *Tetrahedron Lett.*, 2012, **53**, 3073–3076.
- (a) Z. Ma, X. Wang, X. Wang, R. A. Rodriguez, C. E. Moore, S. Gao, X. Tan, Y. Ma, A. L. Rheingold, P. S. Baran and C. Chen, *Science*, 2014, **346**, 219–224; (b) X. Wang and C. Chen, *Tetrahedron*, 2015, **71**, 3690–3693.
- M. Riener and D. A. Nicewicz, *Chem. Sci.*, 2013, **4**, 2625–2629.
- T. P. Yoon, M. A. Ischay and J. Du, *Nat. Chem.*, 2010, **2**, 527–532.
- For select examples, see: (a) S. E. Creutz, K. J. Lotito, G. C. Fu and J. C. Peters, *Science*, 2012, **338**, 647–651; (b) M. Pirtsch, S. Paria, T. Matsuno, H. Isobe and O. Reiser, *Chem.–Eur. J.*, 2012, **18**, 7336–7340; (c) M. Majek and A. Jacobi von Wangelin, *Angew. Chem., Int. Ed.*, 2013, **52**, 5919–5921; (d) A. C. Hernandez-Perez and S. K. Collins, *Angew. Chem., Int. Ed.*, 2013, **52**, 12696–12700; (e) S. Paria and O. Reiser, *ChemCatChem*, 2014, **6**, 2477–2483; (f) Q. M. Kainz, C. D. Matier, A. Bartoszewicz, S. L. Zultanski, J. C. Peters and G. C. Fu, *Science*, 2016, **351**, 681–684.
- (a) A. Gualandi, M. Marchini, L. Mengozzi, M. Natali, M. Lucarini, P. Ceroni and P. G. Cozzi, *ACS Catal.*, 2015, **5**, 5927–5931; (b) J. Zhang, D. Campolo, F. Dumur, P. Xiao, J. P. Fouassier, D. Gigmes and J. Lalevée, *J. Polym. Sci., Part A: Polym. Chem.*, 2015, **53**, 42–49; (c) J. Zhang, D. Campolo, F. Dumur, P. Xiao, J. P. Fouassier, D. Gigmes and J. Lalevée, *J. Polym. Sci., Part A: Polym. Chem.*, 2016, **54**, 2247–2253.
- (a) A. M. McDaniel, H.-W. Tseng, N. H. Damrauer and M. P. Shores, *Inorg. Chem.*, 2010, **49**, 7981–7991; (b) S. M. Stevenson, M. P. Shores and E. M. Ferreira, *Angew. Chem., Int. Ed.*, 2015, **54**, 6506–6510; (c) R. F. Higgins, S. M. Fatur, S. G. Shepard, S. M. Stevenson, D. J. Boston, E. M. Ferreira, N. H. Damrauer, A. K. Rappé and M. P. Shores, *J. Am. Chem. Soc.*, 2016, **138**, 5451–5464.
- All reduction/oxidation potentials are in V vs. SCE in CH₃CN unless otherwise noted. Those measured in CH₃NO₂ are also vs. SCE.



- 11 S. Lin, M. A. Ischay, C. G. Fry and T. P. Yoon, *J. Am. Chem. Soc.*, 2011, **133**, 19350–19353.
- 12 M. A. Cismesia and T. P. Yoon, *Chem. Sci.*, 2015, **6**, 5426–5434.
- 13 N. L. Bauld, D. J. Bellville, B. Harirchian, K. T. Lorenz, R. A. Pabon, D. W. Reynolds, D. D. Wirth, H.-S. Chiou and B. K. Marsh, *Acc. Chem. Res.*, 1987, **20**, 371–378.
- 14 (a) C. K. Prier, D. A. Rankic and D. W. C. MacMillan, *Chem. Rev.*, 2013, **113**, 5322–5363; (b) J. Xuan and W.-J. Xiao, *Angew. Chem., Int. Ed.*, 2012, **51**, 6828–6838; (c) J. M. R. Narayanam and C. R. J. Stephenson, *Chem. Soc. Rev.*, 2011, **40**, 102–113; (d) R. A. Angnes, Z. Li, C. R. D. Correia and G. B. Hammond, *Org. Biomol. Chem.*, 2015, **13**, 9152–9167.
- 15 For a list of select examples, see the ESI.†
- 16 We note here that in our experience the reduction potentials can be sensitive to the conditions of measurement (solvent, additives, etc.) and thus should only be used as a general guide. Reduction potentials cited from the literature are compiled in the ESI.†
- 17 Intermolecular photochemical [2 + 2] cycloadditions of acyclic chalcone derivatives and related α,β -unsaturated carbonyls are rare due to the propensity of these species for *cis/trans*-isomerization upon photoexcitation. See: (a) S. Poplata, A. Tröster, Y.-Q. Zou and T. Bach, *Chem. Rev.*, 2016, DOI: 10.1021/acs.chemrev.5b00723, in press; (b) P. Margaretha, in *Molecular and Supramolecular Photochemistry*, ed. A. G. Griesbeck and J. Mattay, Marcel Dekker, New York, 2005, vol. 12, ch. 8; (c) A. K. F. Albertson and J.-P. Lumb, *Angew. Chem., Int. Ed.*, 2015, **54**, 2204–2208.
- 18 When the reaction was performed where O₂ was present, we also observed in very minor quantities (average <5% yield) the formation of an allylic hydroperoxide byproduct.
- 19 In sample cases (e.g., 16, 17), this method provided noticeably enhanced dienophile reactivity over conventional activation techniques. See the ESI for an analysis.†
- 20 Relative stereochemistry confirmed by NMR analysis.
- 21 In the interest of synthetic utility, the PMP group can be oxidatively cleaved. See ESI.†
- 22 N. L. Bauld, *Tetrahedron*, 1989, **45**, 5307–5363.
- 23 (a) The reduction potential value is measured based on the emission from the ²E state. In an earlier report on the [Cr(Ph₂Phen)₃]³⁺ complex (ref. 9a), there was an extra emissive feature which was assigned to a ²T₁ state that has a much shorter lifetime. This emission corresponds to a Cr^{3+*/2+} E_{1/2} = +1.42 V in CH₃NO₂, still well below the reduction potentials of the substrates investigated here. To date, there is no observed evidence of the higher energy state (i.e., ⁴T₂) using picosecond spectroscopy, so we believe this ⁴T₂ state is likely insignificant in this photocatalytic system; (b) For a related reference discussing the ⁴T₂ state in Cr(acac)₃-type complexes, see: J. N. Schrauben, K. L. Dillman, W. F. Beck and J. K. McCusker, *Chem. Sci.*, 2010, **1**, 405–410; (c) For a recent example of a Cr(III) complex that takes advantage of strong-field ligands to establish a large energy gap between the ²E/²T₁ and the ⁴T₂ states, see: S. Otto, M. Grabolle, C. Förster, C. Kreitner, U. Resch-Genger and K. Heinze, *Angew. Chem., Int. Ed.*, 2015, **54**, 11572–11576.
- 24 In other examples, triphenylpyrylium, 1,4-dicyanobenzene, and 9,10-dicyanoanthracene have been observed to oxidize chalcone derivatives for intramolecular nucleophilic attack. See: (a) S. Kar and S. Lahiri, *Indian J. Chem.*, 2001, **40B**, 1121–1124; (b) G. Pandey, A. Krishna and G. Kumaraswamy, *Tetrahedron Lett.*, 1987, **28**, 4615–4616; (c) M. J. Climent, H. García, S. Iborra, M. A. Miranda and J. Primo, *Heterocycles*, 1989, **29**, 115–121.
- 25 (a) R. A. Caldwell and M. Singh, *J. Am. Chem. Soc.*, 1983, **105**, 5139–5140; (b) R. A. Caldwell, *J. Am. Chem. Soc.*, 1970, **92**, 3229–3230; (c) A static emission spectrum of 4-methoxychalcone is provided in the ESI.†
- 26 Vinylcyclobutane 6 was also detected in the crude NMR spectra of incomplete reactions.
- 27 The allylic hydroperoxide byproduct (ref. 18) was formed more prominently in this specific experiment, leading to the diminished yield as compared to the full cycloaddition. No rearrangement occurred in the absence of light; trace cyclohexene 5 was formed in the absence of catalyst.
- 28 For examples of cyclobutane cycloreversion, see: (a) F. D. Lewis and M. Kojima, *J. Am. Chem. Soc.*, 1988, **110**, 8664–8670; (b) Ref. 3b; (c) Ref. 5.
- 29 The reverse trapping experiments were also performed. See ESI for details.†
- 30 (a) D. W. Reynolds, B. Harirchian, H.-S. Chiou, B. K. Marsh and N. L. Bauld, *J. Phys. Org. Chem.*, 1989, **2**, 57–88; (b) T. Kim, R. J. Pye and N. L. Bauld, *J. Am. Chem. Soc.*, 1990, **112**, 6285–6290.
- 31 (a) F. Toda, K. Tanaka and M. Kato, *J. Chem. Soc., Perkin Trans. 1*, 1998, 1315–1318; (b) M. D'Auria and A. Vantaggi, *Tetrahedron*, 1992, **48**, 2523–2528; (c) Ref. 24a.
- 32 The bifurcation of [4 + 2] vs. [2 + 2]/VCBR in electron transfer processes has been the subject of intense investigation. See the ESI for a list of select studies.†
- 33 S. Chatterjee, S. Kar, S. Lahiri and S. Basu, *Spectrochim. Acta, Part A*, 2004, **60**, 1713–1718.
- 34 (a) P. Wang and S. Wu, *J. Photochem. Photobiol., A*, 1994, **77**, 127–131; (b) Y. Wang, *J. Phys. Chem.*, 1985, **89**, 3799–3805; (c) R. J. DeVoe, M. R. V. Sahyun and E. Schmidt, *Can. J. Chem.*, 1989, **67**, 1565–1575; (d) S. Kar, S. Aich, S. Basu and S. Lahiri, *Res. Chem. Intermed.*, 1999, **25**, 903–913.
- 35 (a) S. Kar and S. Lahiri, *J. Chem. Soc., Chem. Commun.*, 1995, 957–958; (b) D. P. Kranz, A. G. Griesbeck, R. Alle, R. Perez-Ruiz, J. M. Neudörfel, K. Meerholz and H.-G. Schmalz, *Angew. Chem., Int. Ed.*, 2012, **51**, 6000–6004.
- 36 W. Yueh and N. L. Bauld, *J. Phys. Org. Chem.*, 1996, **9**, 529–538.
- 37 For a review discussing allylic oxidation by ¹O₂, see: H. H. Wasserman and J. L. Ives, *Tetrahedron*, 1981, **37**, 1825–1852.
- 38 In preliminary experiments, we have seen a nonlinear dependence of the light intensity on the overall rate of reactivity. This observation is also consistent with multiple two-photon reaction pathways.



- 39 F. Peng, R. E. Grote, R. M. Wilson and S. J. Danishefsky, *Proc. Natl. Acad. Sci. U. S. A.*, 2013, **110**, 10904–10909.
- 40 The Yoon Ru-catalyzed [4 + 2] cycloaddition using electron-rich alkenes in ref. 11 also relates how the photocatalytic strategy can be used to access regioisomeric Diels–Alder adducts.
- 41 (a) S. Danishefsky, M. P. Prisbylla and S. Hiner, *J. Am. Chem. Soc.*, 1978, **100**, 2918–2920; (b) N. Ono, H. Miyake and A. Kaji, *J. Chem. Soc., Chem. Commun.*, 1982, 33–34.
- 42 (a) B. M. Trost, J. Ippen and W. C. Vladuchick, *J. Am. Chem. Soc.*, 1977, **99**, 8116–8118; (b) Z. Stojanac, R. A. Dickinson, N. Stojanac, R. J. Woznow and Z. Valenta, *Can. J. Chem.*, 1975, **53**, 616–618; (c) J. S. Tou and W. Reusch, *J. Org. Chem.*, 1980, **45**, 5012–5014; (d) P. V. Alston, M. D. Gordon, R. M. Ottenbrite and T. Cohen, *J. Org. Chem.*, 1983, **48**, 5051–5054.
- 43 M. Ayerbe and F. P. Cossío, *Tetrahedron Lett.*, 1995, **36**, 4447–4450.
- 44 E. J. Corey, J. D. Bass, R. LeMahieu and R. B. Mitra, *J. Am. Chem. Soc.*, 1964, **86**, 5570–5583.

