


 Cite this: *Chem. Commun.*, 2024, 60, 7033

 Received 30th April 2024,
Accepted 13th June 2024

DOI: 10.1039/d4cc02108h

rsc.li/chemcomm

Herein we describe the stoichiometric and catalytic carbene-transfer reactivity of iron(II) alkoxide complexes with iodonium ylide precursors. Treatment of $\text{PhIC}(\text{CO}_2\text{Me})_2$ with styrene in the presence of catalytic amounts of several different $\text{Fe}(\text{OR})_2(\text{THF})_2$ precursors results in efficient cyclopropanation for a variety of styrenes. Computational and reactivity studies suggest a novel remote metallocarbene/vinyl radical intermediate, $\text{Fe}(\text{OR})_2(\kappa^2\text{-}(\text{O}=\text{C}(\text{OMe}))_2\text{C})$, which could be responsible for the reactive nature of the catalyst.

There is long-standing interest in the chemistry of metallocarbenes, one of the most important functionalities in organometallic chemistry.^{1–15} The reactivity of a metallocarbene is determined by its electronic structure.^{2,15} Common types of metallocarbenes include nucleophilic Schrock carbenes,^{2,3} electrophilic Fischer carbenes,^{2,4} and carbene radicals.^{6–8,15} The reactivity difference between different types of metallocarbenes is most convincingly illustrated *via* their reactions with olefins. Whereas nucleophilic carbenes usually demonstrate olefin metathesis,² both electrophilic and radical carbenes catalyze cyclopropanation.^{4,7,13–15} However, while electrophilic carbenes usually demonstrate two-electron concerted reactivity with olefins, radical carbenes typically exhibit one-electron stepwise reactivity.¹⁵ In addition to their reactions with olefins, metallocarbenes have been previously shown to react with isocyanides to form ketenimines, although this reactivity is generally stoichiometric.^{16–19}

Efficient carbene transfer reactivity mediated by Fe(II) complexes supported by bulky alkoxides†

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We previously reported the synthesis and group-transfer reactivity of middle and late 3d metal complexes in weak-field bis(alkoxide) ligand environments.^{20–30} The reaction of $\text{Co}(\text{OR})_2(\text{THF})_2$ ($\text{OR}=\text{OC}^t\text{Bu}_2\text{Ph}$) with diphenyldiazomethane formed high-valent, low-spin cobalt-carbene $\text{Co}(\text{OR})_2(=\text{CPh}_2)$ with an electronic structure intermediate between cobalt(IV)-alkylidene and carbene(III)-carbene radical.²² One-electron reduction of this compound produced high-spin Co(II) weakly coupled with a carbene radical.²⁷ Both complexes exhibited carbene transfer reactivity with isocyanides.²⁴ In contrast, no substantial carbene transfer reactivity with olefins was observed for $\text{Co}(\text{OR})_2(=\text{CPh}_2)$. The lack of catalytic cyclopropanation reactivity prompted us to turn to the corresponding iron complexes.²⁶ However, no carbene formation *via* N_2 release was observed with $\text{Fe}(\text{OR})_2(\text{THF})_2$. Instead, iron alkoxide complexes reductively coupled diazo compounds through the terminal nitrogens.²⁶ We hypothesized that a different carbene precursor is needed for the formation and carbene transfer reactivity with iron. Herein we describe the reactivity of $\text{Fe}(\text{OR})_2(\text{THF})_2$ and related iron(II) alkoxide complexes with iodonium ylide precursors,³⁰ which are known to serve as precursors for metallocarbene-catalyzed cyclopropanation.³¹ We demonstrate facile carbene transfer to olefins to form cyclopropanes. Mechanistic computational studies suggest the formation of a remote radical carbene $\text{Fe}(\text{OR})_2(\kappa^2\text{-}(\text{O}=\text{C}(\text{OMe}))_2\text{C})$ in which the carbene is coordinated to the metal *via* two ester carbonyls, with the reactive functionality facing away from the metal.

Addition of $\text{PhIC}(\text{CO}_2\text{Me})_2$ ³² to a pale yellow solution of $\text{Fe}(\text{OR})_2(\text{THF})_2$ (**1**) in THF at room temperature led to a color change to orange. ¹H NMR analysis of the reaction mixture in the presence of an internal standard indicated formation of $(\text{MeO}_2\text{C})_2\text{C}=\text{C}(\text{CO}_2\text{Me})_2$ ³³ (**5**) in 78% yield (Fig. 1); formation of PhI was also observed. The formation of **5** was further confirmed by recrystallization (Fig. 1 and ESI†); a closely related structure exhibiting somewhat different cell parameters was recently reported.³⁴ Similarly, the reaction of $\text{PhIC}(\text{CO}_2\text{Ph})_2$ (see ESI†) with **1** led to the formation of $(\text{PhO}_2\text{C})_2\text{C}=\text{C}(\text{CO}_2\text{Ph})_2$

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 † Electronic supplementary information (ESI) available: Experimental procedures, X-ray data collection/refinement details, NMR, IR and GC-MS data, and computational details. CCDC 2351176–2351178. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d4cc02108h>

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Fig. 3 Free energy diagram for cyclopropanation. * indicates transition states that were not located. Unpaired spin up (red) and down (blue) electrons are shown for each intermediate.



Fig. 4 Formation and reactions of the postulated intermediate **4**.

summary of the observed reactivity and proposed mechanism is given in Fig. 4. The key intermediate proposed by DFT calculations is the remote carbene/vinyl radical **4**. It is postulated that **4** forms due to the redox non-innocent nature of $\text{Fe}(\text{OR})_2$ -carbene, which is facilitated by the stability of the delocalized form of the κ^2 -coordinated diester. However, the coordinative unsaturation of the metal center in **4** likely also plays an important role in preventing precedented κ^1 -C coordinated carbene radical derived from $\text{PhIC}(\text{CO}_2\text{Me})_2$.³⁶ Betley and coworkers also proposed the formation of a related vinyl radical derived from α -diazo- β -ketoesters, which led to proximal C–H

bond activation followed by C–O bond formation (C–H alkylation).³⁷ Remote carbenes were also reported for metals with non-coordinating N-heterocyclic carbenes.^{38–41}

The reactive radical nature of **4** is likely responsible for facile formation of olefins ($\text{R}'\text{O}_2\text{C})_2\text{C}=\text{C}(\text{CO}_2\text{R}')_2$ or cyclopropanation (in the presence of styrene). H-atom donors such as cyclohexadiene or 9,10-dihydroanthracene are known to chemically probe ligand-localized unpaired spin density.⁴² These additions to the reaction of **1** with ylide and styrene shut down reactivity (trace products are observed), consistent with the expected catalyst's sensitivity to H-atom donors. The necessity and generality of the κ^2 coordination of the dicarbonyl precursor (prior to PhI elimination) was probed by use of two additional ylides: 2,4-pentanedione-derived (*i.e.* acac-derived) ylide⁴³ and dimedone-derived ylide.⁴⁴ Acac-derived ylide is expected to coordinate to the metal like the diester-derived ylide and therefore should exhibit similar reactivity. As anticipated, the reaction between 2,4-pentanedione-derived ylide, styrene, and **1** (5 mol%) exhibited similar performance, producing the corresponding cyclopropane and olefin.⁴⁵ Due to steric constraints, dimedone-derived ylide is unlikely to coordinate κ^2 to the metal (Fig. 4). No reaction was observed between **1**, dimedone ylide, and styrene (Fig. 1 and ESI†).

The reactivity between **1**, $\text{PhIC}(\text{CO}_2\text{Me})_2$, and isocyanides was also investigated (Fig. 5). No reaction is observed for $\text{PhIC}(\text{CO}_2\text{Me})_2$ and xylyl isocyanide CNXyl ($\text{Xyl} = 2,6\text{-Me}_2\text{C}_6\text{H}_3$). Adding the mixture to a solution of $\text{Fe}(\text{OR})_2(\text{THF})_2$ (1 equiv.) produced a color change to reddish-orange. ^1H NMR suggested that no significant transformation of $\text{PhIC}(\text{CO}_2\text{Me})_2$ took place. We previously reported formation of $\text{Fe}(\text{OR})_2(\text{CNXyl})_2$ (**10**);²¹ it is possible that its stability prevents turnover, which requires substitution of both isocyanides by the ylide. We also previously demonstrated notable differences in the reactivity between aromatic and aliphatic isocyanides; while no turnover (in ketenimine formation) was observed for $\text{Co}(\text{OR})_2(\text{CNXyl})_2$, catalytic reactivity was observed for $\text{Co}(\text{OR})_2(\text{CNAd})_2$ ($\text{Ad} = \text{adamantyl}$).²⁴ Thus, we independently synthesized **10**²¹ and $\text{Fe}(\text{OR})_2(\text{CNAd})_2$ (**11**). As **11** has not been previously reported, it was characterized by X-ray crystallography, NMR and IR spectroscopy, and elemental analysis. Both complexes lacked reactivity with $\text{PhIC}(\text{CO}_2\text{Me})_2$, confirming that the lack of turnover in this reaction is due to the relative stability of the isocyanide complexes.

In summary, we described an efficient cyclopropanation reactivity between ylides and styrenes catalyzed by iron complexes in bulky alkoxide ligand environments. Mechanistic studies suggest that the reaction is mediated by a novel remote



Fig. 5 Reactions between **1**, isocyanides, and $\text{PhIC}(\text{CO}_2\text{Me})_2$.

carbene/vinyl radical intermediate, whose formation is facilitated due to (1) the ability of $[\text{Fe}(\text{OR})_2]$ to coordinate an iodonium ylide precursor in $\kappa^2\text{-O,O}$ -coordination mode, and (2) the propensity of $[\text{Fe}(\text{OR})_2]$ to undergo oxidation to $\text{Fe}(\text{III})$. Future studies will focus on further mechanistic investigations, and additional carbene transfer reactions.

S. G. and R. L. L. are grateful to the National Science Foundation (NSF) for current support through CHE-2348382. Experimental characterization was carried out at Lumigen Instrument Center of Wayne State University. Lakshani W. Kulathungage is a Rumble Fellow. This work made use of the single-crystal XRD that was partially funded by the National Institutes of Health supplement grant #3R01EB027103-02S1.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

There are no conflicts to declare.

Notes and references

- R. A. Moss and M. P. Doyle, *Contemporary Carbene Chemistry*, Wiley, Hoboken, New Jersey, 2013, 1118730267.
- T. Strassner, *Top. Organomet. Chem.*, 2004, **13**, 1–20.
- (a) R. R. Schrock, *Angew. Chem., Int. Ed.*, 2006, **45**, 3748–3759; (b) R. H. Grubbs, *Angew. Chem., Int. Ed.*, 2006, **45**, 3760–3765.
- K. H. Doetz and J. Stendel, *Chem. Rev.*, 2009, **109**, 3227–3274.
- H. M. L. Davies and D. Morton, *Chem. Soc. Rev.*, 2011, **40**, 1857–1869.
- H.-J. Lu, W. I. Dzik, X. Xu, L. Wojtas, B. de Bruin and X. P. Zhang, *J. Am. Chem. Soc.*, 2011, **133**, 8518–8521.
- W. I. Dzik, X. P. Zhang and B. de Bruin, *Inorg. Chem.*, 2011, **50**, 9896–9903.
- S. K. Russell, J. M. Hoyt, S. C. Bart, C. Milsman, S. C. E. Stieber, S. P. Semproni, S. DeBeer and P. J. Chirik, *Chem. Sci.*, 2014, **5**, 1168–1174.
- M. Jia and S. Ma, *Angew. Chem., Int. Ed.*, 2016, **55**, 9134–9166.
- R. R. Schrock and C. Coperet, *Organometallics*, 2017, **36**, 1884–1892.
- A. Chirila, M. B. Brands and B. de Bruin, *J. Catal.*, 2018, **361**, 347–360.
- A. Feliciano, J. L. Vázquez, L. J. Benítez-Puebla, I. Velazco-Cabral, D. C. Cruz, F. Delgado and M. A. Vázquez, *Chem. – Eur. J.*, 2021, **27**, 8233–8251.
- W.-C. C. Lee, D.-S. Wang, Y.-L. Zhu and X. P. Zhang, *Nat. Chem.*, 2023, **15**, 1569–1580.
- W.-C. C. Lee and X. P. Zhang, *Trends Chem.*, 2022, **4**, 850–851.
- R. F. J. Epping, D. Vesseur, M. Zhou and B. de Bruin, *ACS Catal.*, 2023, **13**, 5428–5448.
- R. Aumann and E. O. Fischer, *Angew. Chem., Int. Ed. Engl.*, 1967, **6**, 879–880.
- I. Fernández, F. P. Cossío and M. A. Sierra, *Organometallics*, 2007, **26**, 3010–3017.
- P. Lu and Y. Wang, *Chem. Soc. Rev.*, 2012, **41**, 5687–5705.
- Z. Tang, S. Mandal, N. D. Paul, M. Lutz, J. I. van der Vlugt and B. de Bruin, *Org. Chem. Front.*, 2015, **2**, 1561–1577.
- J. A. Bellow, P. D. Martin, R. L. Lord and S. Groysman, *Inorg. Chem.*, 2013, **52**, 12335–12337.
- J. A. Bellow, M. Yousif, A. C. Cabelof, R. L. Lord and S. Groysman, *Organometallics*, 2015, **34**, 2917–2923.
- J. A. Bellow, S. A. Stoian, J. Van Tol, A. Ozarowski, R. L. Lord and S. Groysman, *J. Am. Chem. Soc.*, 2016, **138**, 5531–5534.
- M. Yousif, D. Wannipurage, C. D. Huizenga, E. Washnock-Schmid, N. J. Peraino, A. Ozarowski, S. A. Stoian, R. L. Lord and S. Groysman, *Inorg. Chem.*, 2018, **57**, 9425–9438.
- A. Grass, N. S. Dewey, R. L. Lord and S. Groysman, *Organometallics*, 2019, **38**, 962–972.
- S. S. Kurup, D. Wannipurage, R. L. Lord and S. Groysman, *Chem. Commun.*, 2019, **55**, 10780–10783.
- A. Grass, S. A. Stoian, R. L. Lord and S. Groysman, *Chem. Commun.*, 2019, **55**, 8458–8461.
- A. Grass, J. A. Bellow, G. Morrison, H.-C. zur Loye, R. L. Lord and S. Groysman, *Chem. Commun.*, 2020, **56**, 8416–8419.
- S. S. Kurup and S. Groysman, *Dalton Trans.*, 2022, **51**, 4577–4589.
- S. S. Kurup, N. M. Woodland, R. L. Lord and S. Groysman, *Molecules*, 2022, **27**, 5751.
- M. S. Yusubov and V. V. Zhdankin, *Curr. Org. Synth.*, 2012, **9**, 247–272.
- C. Zhu, A. Yoshimura, L. Ji, Y. Wei, V. N. Nemykin and V. V. Zhdankin, *Org. Lett.*, 2012, **14**, 3170–3173.
- S. R. Goudreau, D. Marcoux and A. B. Charette, *Org. Synth.*, 2010, **87**, 115–125.
- (a) M. Barfield, T. Gotoh and H. K. Hall, *Magn. Reson. Chem.*, 1985, **23**, 705–709; (b) H. K. Hall and R. C. Daly, *Macromolecules*, 1975, **8**, 22–31.
- I. Litvinov, Experimental Crystal Structure Determination 2022, CCDC 2152148† DOI: 10.5517/ccdc.esd.cc2b7h47.
- B3LYP-D3(BJ)/def2-TZVP/SMD(benzene)//BP86-D3(BJ)/def2-SVP. See ESI† for full computational details.
- R. F. J. Epping, M. M. Hoeksma, E. O. Bobylev, S. Mathew and B. de Bruin, *Nat. Chem.*, 2022, **14**, 550–557.
- Y. Dong, A. T. Wrobel, G. P. Porter, J. J. Kim, J. Z. Essman, S.-L. Zheng and T. A. Betley, *J. Am. Chem. Soc.*, 2021, **143**, 7480–7489.
- A. J. Arduengo, D. Tapu and W. J. Marshall, *Angew. Chem., Int. Ed.*, 2005, **44**, 7240–7244.
- D. M. Khranov, E. L. Rosen, V. M. Lynch and C. W. Bielawski, *Angew. Chem., Int. Ed.*, 2008, **47**, 2267–2270.
- B. Hildebrandt, W. Frank and C. Ganter, *Organometallics*, 2011, **30**, 3483–3486.
- J.-F. Lefebvre, M. Lo, D. Leclercq and S. Richeter, *Chem. Commun.*, 2011, **47**, 2976–2978.
- J. A. Valdez-Moreira, D. C. Wannipurage, M. Pink, V. Carta, P. Moëne-Loccoz, J. Telser and J. M. Smith, *Chem*, 2023, **9**, 2601–2609.
- C. A. Montgomery, I. Jameel, F. Cuzzucoli, T. Chidley, W. S. Hopkins and G. K. Murphy, *Chem. – Eur. J.*, 2022, **28**, e202202029.
- T. A. Gazis, B. A. J. M. Thaker, D. Willcox, D. M. C. Ould, J. Wenz, J. M. Rawson, M. S. Hill, T. Wirthe and R. L. Melen, *Chem. Commun.*, 2020, **56**, 3345–3348.
- G. Adembri, F. De Sio, R. Nesi and M. Scotton, *J. Chem. Soc. C*, 1970, 1536–1540.

