Published in final edited form as:

ACS Catal. 2018 May 4; 8(5): 4473–4482. doi:10.1021/acscatal.8b00821.

Iron-Catalyzed Direct Olefin Diazidation via Peroxyester Activation Promoted by Nitrogen-Based Ligands

Shou-Jie Shen, Cheng-Liang Zhu, Deng-Fu Lu, and Hao Xu*

Department of Chemistry, Georgia State University, 100 Piedmont Avenue Southeast, Atlanta, Georgia 30303, United States

Abstract

We herein report an iron-catalyzed direct diazidation method via activation of bench-stable peroxyesters promoted by nitrogen-based ligands. This method is effective for a broad range of olefins and *N*-heterocycles, including those that are difficult substrates for the existing olefin diamination and diazidation methods. Notably, nearly a stoichiometric amount of oxidant and TMSN₃ are sufficient for high-yielding diazidation for most substrates. Preliminary mechanistic studies elucidated the similarities and differences between this method and the benziodoxole-based olefin diazidation method previously developed by us. This method effectively addresses the limitations of the existing olefin diazidation methods. Most notably, previously problematic nonproductive oxidant decomposition can be minimized. Furthermore, X-ray crystallographic studies suggest that an iron–azide–ligand complex can be generated in situ from an iron acetate precatalyst and that it may facilitate peroxyester activation and the rate-determining C–N₃ bond formation during diazidation of unstrained olefins.

Graphical Abstract

Keywords

iron catalyst; peroxyesters; olefins; *N*-heterocycles; diazidation; diamination

*Corresponding Author: hxu@gsu.edu.

ORCID

Deng-Fu Lu: 0000-0003-1931-9559

Hao Xu: 0000-0001-5029-8392

Notes

The authors declare no competing financial interest.

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acscatal.8b00821.

Experimental procedure, characterization data for all new compounds, and selected NMR spectra (PDF)

Crystallographic information (CIF)

checkCIF/PLATON report (PDF)

INTRODUCTION

Vicinal primary diamines are incorporated in a large number of small-molecule pharmaceuticals and biological probes; therefore, extensive efforts have been devoted to the development of selective and general olefin diamination methods, and a variety of powerful methods have been invented.¹ However, there are still significant synthetic challenges that cannot be fully addressed by these methods. These challenges include the following: (a) it is still difficult to directly convert aliphatic isolated olefins, especially internal olefins, to vicinal primary diamines; (b) methods for selective diamination of highly functionalized olefins have remained underdeveloped; (c) direct diamination of *N*-heterocycles to afford vicinal primary diamines for complex-alkaloid synthesis has been underexplored.²

Alternatively, both stoichiometric³ and catalytic^{4,5} olefin diazidation methods have emerged with unique value. These methods complement the olefin diamination methods and provide a convenient approach to producing synthetically important vicinal primary diamines that are otherwise difficult to obtain. Although an array of olefin diazidation methods have been reported to date,^{3–5} the vast majority of them are predominantly restricted to certain limited types of olefins.^{3,4c,d} Furthermore, many of them involve the usage of a superstoichiometric amount of NaN_3 in acidic media. Additionally, selective diazidation methods for functionalized *N*-heterocycles have been underdeveloped.⁶

In 2015, we reported an iron-catalyzed direct diazidation method for a broad range of olefins, in which an iron catalyst activates TMSN_3 in the presence of bench-stable benziodoxole **1a** to achieve direct olefin diazidation (Scheme 1).^{4a} This reaction occurs at room temperature with low catalyst loading, and it is effective for a wide variety of olefins, including those that are incompatible with the existing methods.³ Notably, the *anti* selectivity for cyclic olefins can be modulated by iron catalysts (dr up to >20:1). Coupled with facile reduction, this method readily provides an array of valuable vicinal primary diamines.

The preliminary mechanistic analysis has revealed that TMSN_3 may reversibly convert the insoluble benziodoxole **1a** to azidoiodinane **1b** and then to a transient iodine(III)–diazide species **1c**, with which an iron catalyst may be oxidized to a high-valent iron–azide species that promotes the stepwise olefin diazidation (Scheme 1).^{4a,b} A variety of control experiments corroborate that the iron–ligand complexes are involved in the rate- and diastereoselectivity-determining C– N_3 bond-forming step in diazidation of unstrained olefins.^{4a}

Identification of the high-valent iron–azide species as a possible reactive intermediate has inspired us to develop a new method that significantly improves upon the reported method. There are two outstanding challenges in this benziodoxolebased diazidation method.

First, in the absence of an olefin, an iron catalyst completely decomposes benziodoxole **1a** together with TMSN_3 in 3 h (eq 1a), presumably through the iron-promoted decomposition of iodine(III)–diazide species **1c**.⁷ In contrast, **1a** is stable toward TMSN_3 in the absence of an iron catalyst in CH_2Cl_2 (eq 1b).⁷ This competing pathway can be particularly problematic for substrates with low reactivity since an excess amount of oxidant **1a** would be necessary

to achieve a synthetically useful yield. Some of these problematic substrates include electronically deactivated allylic esters and carbamates. Therefore, a new catalytic method has yet to be developed such that this nonproductive oxidant–decomposition pathway may be suppressed or even eliminated.

(1a)

(1b)

Next, an excess amount of TMSN_3 (3.6–4.0 equiv) is often applied to achieve high yields in the aforementioned iron-catalyzed olefin diazidation in order to effectively activate benziodoxole **1a**.^{4a} A stoichiometric amount of TMSN_3 (2.0–2.5 equiv) often led to incomplete conversion for certain substrates in the aforementioned method, especially aliphatic isolated olefins. Ideally, nearly a stoichiometric amount of TMSN_3 should be sufficient for a more sustainable and efficient olefin diazidation method.

Herein, we report a new iron-catalyzed direct diazidation method via nitrogen-based ligand-promoted activation of bench-stable peroxyesters that effectively addresses the limitations of the previously developed method (Scheme 2). In this method, nearly a stoichiometric amount of oxidant and TMSN_3 are sufficient for effective diazidation of a broad range of olefins and *N*-heterocycles at room temperature. Notably, a variety of previously difficult substrates are compatible with this new method, some of which include allylic esters and carbamates, β -pinene, highly functionalized indoles, pyrroles that are prone to rapid rearomatization, as well as β,γ -unsaturated ketones.

Compared with the benziodoxole-based method, preliminary mechanistic studies revealed that the previously problematic nonproductive oxidant–decomposition pathway can be effectively suppressed with this new method. X-ray crystallographic studies further suggest that an iron–azide–ligand complex can be generated in situ from an iron acetate precatalyst, and it may facilitate peroxyester activation and the rate-determining C–N₃ bond formation during diazidation of unstrained olefins.

RESULTS AND DISCUSSION

Bench-stable *tert*-butyl peroxyesters have been extensively applied in a variety of oxygen-atom transfer reactions;⁸ however, room-temperature olefin diazidation via ligand-promoted peroxyester activation using nearly a stoichiometric amount of azide source has not been developed.⁹ To explore the possible new reactivity through iron catalysis, we select indene (**2**) as a model substrate in catalyst discovery for both synthetic and mechanistic considerations (Table 1). Extensive exploration of a range of iron catalysts and ligands revealed that the Fe(OAc)₂–bidentate ligand **L1** complex effectively activates bench-stable *tert*-butyl peroxybenzoate **3a** in the presence of TMSN₃ (2.4 equiv) and *i*PrOH (1.2 equiv) and that it catalyzes efficient indene diazidation with excellent dr at room temperature (Table 1).

There are several key observations that are mechanistically important (Table 1). First, the iron-catalyzed peroxyester activation and olefin diazidation are enabled by nitrogen-based ligands: in the absence of a ligand, essentially no reaction was observed and both **2** and **3a** were fully recovered (entry 1). Next, mild proton donors are critical for catalyst turnover and *i*PrOH leads to a more efficient reaction than H₂O (entries 2 and 3). Furthermore, the iron catalyst can activate a range of peroxyesters (entries 4 and 5): a more electron-deficient peroxyester **3c** leads to a faster reaction, and distinct dr values were observed with different peroxyesters (**3b** vs **3c**). These observations suggest that the corresponding carboxylate ligand, presumably generated through the iron-mediated O–O bond cleavage, may be involved in the dr-determining transition state.

To our surprise, the Fe(OAc)₂–tridentate ligand **L2** complex, an effective catalyst in our previously reported benziodoxole-based olefin diazidation method,^{4a} is almost inactive in this reaction: only a small amount of product was observed (entry 6, 6% yield, dr 16:1). Furthermore, another Fe(OAc)₂–tridentate ligand **L3** complex also suffers from low reactivity (entry 7). Interestingly, both the Fe(NTf₂)₂–**L1** and the Fe(NTf₂)₂–**L2** complexes catalyze a rapid reaction; however, the desired indene diazide **4** was isolated in only moderate yields (entries 8 and 9). These results suggest that there may be mechanistic nuances between the Fe(OAc)₂- and the Fe(NTf₂)₂-catalyzed reactions.

Most notably, in the absence of an olefin, the vast majority of **3a** is recovered under the reaction condition (eq 2),⁷ which suggests that the nonproductive oxidant decomposition has been minimized with this new method.

(2)

Upon the discovery of active iron catalysts, we explored this method with a range of unfunctionalized olefins (Table 2). First, we evaluated olefins with electron-rich allylic C–H

bonds which tend to undergo C–H azidation.¹⁰ We observed that both the $\text{Fe}(\text{OAc})_2$ –**L1** and the $\text{Fe}(\text{NTf}_2)_2$ –**L2** complexes are effective for allylsilane diazidation; however, the $\text{Fe}(\text{NTf}_2)_2$ –**L2** catalyst promotes a more rapid reaction with low catalyst loading (entry 1). It is noteworthy that a slight excess of peroxyester **3a** (1.4 equiv) is used to ensure reaction reproducibility since a strong Lewis-acidic $\text{Fe}(\text{NTf}_2)_2$ catalyst is applied. Allylbenzene, a substrate prone to undergo direct C–H azidation, is selectively converted to the corresponding diazide (entry 2). We also observed that this method is effective for isolated olefins, including monosubstituted, 1,1-disubstituted, and *trans*-disubstituted olefins (entries 3–5). Notably, the iron-catalyzed diazidation of (+)-camphene diastereoselectively affords the camphene diazide with excellent dr (entry 6, dr > 20:1).¹¹

Since norbornane diamines are valuable synthetic building blocks and their previous syntheses are less straightforward,¹² we evaluated norbornene in this iron-catalyzed diazidation and discovered that the $\text{Fe}(\text{OAc})_2$ –**L1** complex catalyzes norbornene diazidation with a good overall yield, albeit in moderate dr (entry 7). Gratifyingly, a facile reduction–*N*-Boc protection procedure furnishes the readily separable *N*-Boc norbornane diamines **6a** and **6b** in an excellent overall yield (eq 3).

(3)

This method also proves compatible with styrenyl olefins. We observed that the $\text{Fe}(\text{OAc})_2$ –**L1** complex catalyzes high-yielding diazidation of styrene, α - and β -methylstyrenes, as well as *trans*-stilbene (entries 8–11). Furthermore, the same catalyst also promotes diazidation of indene and dihydronaphthalene with excellent diastereoselectivity (entries 12 and 13).

Both 1,2- and 1,4-allylic primary diamines are important building blocks in synthesis; however, expedient synthesis of 1,4-allylic primary diamines through direct 1,4-diene diamination has been difficult.¹³ Likewise, methods for vicinal diamination of the terminal olefin in a 1,4-diene for primary diamine synthesis have also been underdeveloped.¹⁴ To achieve expedient synthesis of these allylic primary diamines, we explored the iron-catalyzed diazidation with 1,3-dienes (entries 14 and 15). We observed that the $\text{Fe}(\text{OAc})_2$ –**L1** complex catalyzes vicinal diazidation of a phenyl-substituted 1,3-diene and that the $\text{Fe}(\text{NTf}_2)_2$ –**L2** complex rapidly catalyzes alkyl-substituted 1,3-diene diazidation to afford a 1:1 mixture of 1,2- and 1,4-diazides that are in equilibrium, presumably through a facile allylic azide rearrangement.¹⁵ A standard reduction–*N*-Boc protection procedure can convert the diazide mixture **7a/b** to readily separable 1,2- and 1,4-*N*-Boc-diamines **8a** and **8b** (eq 4).

15

(4)

With the success of this new method for selective diazidation of unfunctionalized olefins, we subsequently evaluated a wide variety of *N*-heterocycles as well as highly functionalized olefins (Table 3).

We discovered that both *N*-Troc indole and 3-methyl *N*-Troc indole are excellent substrates and the corresponding *trans*-diazides were isolated as a single diastereomer (entries 1 and 2).⁹ We further observed that the iron catalyst is sufficiently functional group tolerant such that tryptamine carbamate, indole propionic acid, and *N*-Troc dihydroquinoline are all readily converted to the corresponding *trans*-diazides with excellent dr (entries 3–5). Interestingly, the Fe(NTf₂)₂–**L2** complex also catalyzes a previously difficult 1,4-selective *N*-Boc pyrrole diazidation, affording a *trans*-pyrrol diazide with excellent dr (entry 6, dr > 20:1).¹⁶

Highly functionalized terpenes are important building blocks for organic synthesis; however, selective terpene diazidation has been difficult since redox-labile functional groups are less compatible with the vast majority of the existing diazidation methods. Therefore, we further explored this iron-catalyzed method with a range of complex terpenes. We observed that a more electron-rich olefin at the distal position in geranyl acetate can be preferentially functionalized, affording a geranyl diazide (entry 7). Likewise, two olefinic moieties within (–)-carvone can be differentiated, and the azido group is selectively transferred to the less electron-deficient olefin (entry 8). Notably, the labile aliphatic aldehyde group in (±)-citronellal is compatible with the method without detrimental aldehyde oxidation (entry 9). Furthermore, a β,γ-unsaturated ketone can readily undergo diazidation without olefin isomerization (entry 10). Moreover, this method is effective for both electron-deficient methyl cinnamate and electron-rich enamide (entries 11 and 12). It is also compatible with a carboxylic acid functional group without lactone formation (entry 13).

Multifunctional vicinal diamino alcohols and triamines are valuable building blocks for organic synthesis; however, diamination methods for allylic esters and carbamates have not been developed.^{17,18} Additionally, electronically deactivated allylic esters and carbamates present low reactivity under the standard reaction condition in our previously reported method. As a result, we explored the new method with these challenging substrates and discovered that the Fe(NTf₂)₂–**L2** complex catalyzes high-yielding diazidation of these electronically deactivated substrates (entries 14 and 15). A straightforward reduction–protection sequence can thereby afford the functionalized vicinal diamino alcohol **10** and triamine **12** (eqs 5 and 6).

(5)

(6)

The unique synthetic strength of this iron-catalyzed method has inspired us to probe for its mechanistic details with a series of control experiments and to elucidate the similarities and differences between this olefin diazidation method and the previously reported benziodoxole-based method.^{4a}

First, TEMPO radical was introduced in the iron-catalyzed dodecene (**13**) diazidation, and a TEMPO-addition product **14** was observed when either Fe(NTf₂)₂ or Fe(OAc)₂ was used as a catalyst (Scheme 3). Next, we evaluated a substituted vinylcyclopropane **15** with this iron-catalyzed method and isolated the ring-opening product 1,5-diazide **16** in excellent yields with either iron catalyst (Scheme 3). These results suggest that azido radical is likely involved in the first C–N₃ bond-forming step, which may initiate radical addition to an olefin and afford a carbo-radical species.

After the first C–N₃ bond formation, the second C–N₃ bond-forming step can proceed through azido group transfer to either a carbo-radical or a carbocation species. In order to differentiate these two mechanistic possibilities, we explored diazidation of (–)-β-pinene **17** (Scheme 4). Notably, the exocyclic olefin of (–)-β-pinene can be selectively 1,2-difunctionalized using both iron catalysts, which exclusively affords a vicinal diazide **18** with excellent dr (Scheme 4, dr > 20:1). Facile reduction and protonation of **18** furnishes diaminium salt **19**.

To our surprise, neither a ring-contraction nor a ring-fragmentation product (**20a** or **20b**) was detected. Since ring contraction from the (–)-β-pinene scaffold has been well preceded in carbocation-mediated reactions,¹⁹ the absence of **20a** suggests that the second C–N₃ bond formation likely proceeds through a carbo-radical instead of a carbocation species. Additionally, the lack of the ring-fragmentation product **20b** suggests that the rate of the second C–N₃ bond formation is faster than that of carbo-radical fragmentation.

Unlike dodecene (Scheme 3), the diazidation of highly strained (–)-β-pinene in the presence of TEMPO radical affords both the TEMPO-addition product **21** and the diazidation product **18**, which suggests that the second C–N₃ bond-forming step is not rate limiting for this highly strained substrate.

In order to determine which C–N₃ bond-forming step is rate limiting for unstrained olefins, we carried out a few control experiments (Scheme 5). First, we evaluated (*Z*)-hex-3-en-1-ol **22a** in the Fe(NTf₂)₂-catalyzed diazidation with **3a** and identified a significant amount of the isomerization product (*E*)-hex-3-en-1-ol **22b** along with the diazide **23** within 5 min. Notably, both **22a** and **22b** were converted to diazide **23** in a stereoconvergent manner in 2 h. Interestingly, when the Fe(OAc)₂–**L1** complex was used as the catalyst, only the isomerization product **22b** was observed. Notably, the Fe(OAc)₂ catalyst promotes a faster reaction with a more electrondeficient oxidant **3c**: both **22b** and **23** were observed within 2 h. These results suggest that the second C–N₃ bond-forming step is rate limiting in the iron-catalyzed diazidation of unstrained olefins.

Since azido–radical is likely involved in the first C–N₃ bond-forming step, we further investigated the mechanistic details of the ligand-promoted peroxyester activation for azido–radical generation (Scheme 6). We observed that benziodoxole **1a** and TMSN₃ promote isomerization of *cis*-stilbene **24a** to *trans*-stilbene **24b** in the absence of an iron catalyst.^{4a} However, without an iron catalyst, *cis*-stilbene **24a** is completely unreactive toward peroxyester **3a** with TMSN₃ and no isomerization is observed. These results suggest that, unlike the benziodoxole-based method, azido–radical generation is iron catalyst dependent in this new method.

Likewise, in the absence of an olefin, an iron catalyst completely decomposes benziodoxole **1a** with TMSN₃, furnishing *o*-iodobenzoic acid **25** (eq 1a in the Introduction).⁷ However, we observed that the vast majority of peroxyester **3a** is recovered with either iron catalyst in the absence of an olefin using this new method (eq 2).⁷ These observations suggest that the nonproductive peroxyester decomposition pathway can be suppressed in this new method.

The observed electronic effect of a peroxyester over the reaction rate in an Fe(OAc)₂-catalyzed diazidation (Scheme 5) has inspired us to re-evaluate the Fe(NTf₂)₂-catalyzed diazidation of challenging substrates, such as allyl benzoate **26**. As a result, we observed an evidently faster reaction using a more electron-deficient peroxyester **3c** compared with the standard oxidant **3a** (Scheme 7). Since the O–O bond cleavage of electronically distinct **3a/3c** is less likely to be rate limiting (Scheme 5), this result suggests that the carboxylate ligand, presumably generated through the O–O bond cleavage, is likely involved in the rate-determining transition state in both Fe(NTf₂)₂- and Fe(OAc)₂-catalyzed reactions.

Not only can an oxidant affect the diazidation rate, a ligand can also evidently modulate the reactivity. In particular, the observed ligand effect in the Fe(OAc)₂-catalyzed olefin diazidation is mechanistically intriguing: while the Fe(OAc)₂–bidentate ligand **L1** complex is effective for indene diazidation, the Fe(OAc)₂–tridentate ligand **L2** complex is almost inactive (Table 1, entry 6). Since the first C–N₃ bond formation is reversible for diazidation of unstrained olefins, the observed rate retardation with the Fe(OAc)₂–**L2** complex may be attributed to either ineffective peroxyester O–O bond cleavage or inefficient carbo–radical oxidation.

To differentiate these two possibilities, we carried out a few control experiments (Scheme 8). First, we observed that the Fe(OAc)₂–tridentate **L2** complex rapidly catalyzes dodecene

diazidation using benziodoxole **1a**; however, it is completely inactive when *tert*-butyl peroxy 2-iodobenzoate **3d** is used as the oxidant. These results suggest that the inefficient O–O bond cleavage by the Fe(OAc)₂–**L2** complex is likely the reason for the observed low reactivity.

Since the Fe(OAc)₂- and Fe(NTf₂)₂-catalyzed reactions present distinct reactivity profiles (Table 1), we suspect that different active catalytic species may be involved. Therefore, we further studied the coordination chemistry of the Fe(OAc)₂- and Fe(NTf₂)₂-ligand complexes in the presence of TMSN₃ (Scheme 9).

We observed that the gray solution of the Fe(OAc)₂–**L1** complex turned dark when an excess amount of TMSN₃ was introduced. Subsequent ether trituration readily afforded solid **28**, and IR analysis revealed strong azido group absorptions (2041 and 2073 cm⁻¹) shifted to lower energy in comparison to free azide, characteristic of iron–azide complexes (Scheme 9).²⁰ We discovered that **28** is catalytically active for indene diazidation. Interestingly, in the absence of TMSN₃, **28** also promotes the diazidation with essentially the same dr, albeit in a low yield (Scheme 9).²¹ Additionally, **28** promotes diazidation of (*Z*)-hex-3-en-1-ol **22a** in the absence of TMSN₃, which readily affords both the diazidation product **23** and the olefin isomerization product **22b** (Scheme 9).

Extensive exploration of crystallization conditions of **28** afforded solid **29** that is suitable for X-ray crystallographic analysis, which revealed the bridged dimeric structure of solid **29** as Fe^{III}₂(**L1**)₂(N₃)₆ (Scheme 9). We suspect that **28** may be oxidized to afford **29** during crystal growth.²² These experiments suggest that the Fe(OAc)₂ catalysts are converted to iron–azide complexes in their resting state by TMSN₃ and that the iron–azide bond may be involved in the rate-limiting azido group transfer during diazidation of unstrained olefins.

Interestingly, we did not observe the solid formation of the Fe(NTf₂)₂–**L2** complex under the analogous condition, and IR analysis of the resulting viscous oil revealed a lack of characteristic azido group absorptions (Scheme 9). This experiment suggests that the Fe(NTf₂)₂ catalysts may not be converted to the corresponding iron–azide complexes by TMSN₃ in their resting state.

Upon the basis of a variety of collected mechanistic insights, we propose the mechanistic working hypotheses for the Fe(NTf₂)₂- and Fe(OAc)₂-catalyzed olefin diazidation (Scheme 10).

In an Fe(NTf₂)₂-catalyzed reaction (Scheme 10a), an Fe(NTf₂)₂-ligand complex may reductively cleave the O–O bond in a peroxyester **3** to generate a *tert*-butoxyl radical which is associated with a high-valent iron complex **30** with a carboxylate ligand. ^tPrOH presumably facilitates gradual release of HN₃ from TMSN₃, and *tert*-butoxyl radical may thereby be rapidly sequestered by HN₃ to liberate azido radical. The azido radical may readily add to an olefin to afford carbo–radical species **31**. Since the carboxylate ligand is involved in the rate-determining transition state in the Fe(NTf₂)₂-catalyzed diazidation, we propose that TMSN₃ may reversibly convert the iron(III) species **30** to a high-valent iron–azide species **32**, which presumably mediates the rate-determining azido group transfer to

the carbo-radical species **31** and afford the diazidation product.²³ Notably, the Fe(NTf₂)₂-ligand complex can be readily regenerated by the transiently generated TMSNTf₂.

In an Fe(OAc)₂-catalyzed reaction (Scheme 10b), an iron-azide-ligand complex **33** can be generated in situ, which may facilitate the O–O bond cleavage and azido-radical generation in an analogous way. However, the high-valent iron-azide species **34** may directly mediate the rate-limiting azido group transfer to the carbo-radical species **31** and furnish the diazidation product. Subsequently, TMSN₃ may readily convert the iron(II)-carboxylate complex back to the catalytically active iron-azide complex **33** via anion metathesis.

CONCLUSIONS

In conclusion, we have reported an iron-catalyzed direct diazidation method via nitrogen-based ligand-promoted activation of bench-stable peroxyesters. This method significantly improves upon our previously reported, benziodoxolebased method, and it is effective for a broad range of olefins and *N*-heterocycles, including those that are difficult substrates for the existing olefin diamination and diazidation methods. Most notably, nearly a stoichiometric amount of oxidant and TMSN₃ are sufficient for high-yielding diazidation for most substrates. Furthermore, preliminary mechanistic studies were carried out to elucidate the similarities and differences between this new method and the benziodoxole-based diazidation method. It was revealed that, unlike the benziodoxole-based method, azido-radical generation is iron catalyst dependent and the nonproductive oxidant-decomposition pathway can be effectively suppressed using this new method. X-ray crystallographic studies further suggest that an iron-azide-ligand complex can be generated in situ from an iron acetate precatalyst, and it may facilitate peroxyester activation and the rate-determining C–N₃ bond formation for diazidation of unstrained olefins. Our current efforts focus on synthetic applications of this new method for complex molecule synthesis.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This research was supported by the National Institutes of Health (GM110382) and Alfred P. Sloan Foundation (FG-2015-65240). H.X. is an Alfred P. Sloan Research Fellow. We thank Prof. Caleb D. Martin and Ms. Sam Yruegas for X-ray crystallographic analysis of an iron-azide complex **29**. We also thank a referee for the insightful critiques.

References

1. For selected references of olefin diamination methods, see: Chong AO, Oshima K, Sharpless KB. Synthesis of Dioxobis(tert-alkylimido)osmium(VIII) and Oxotris(tert-alkylimido)- osmium(VIII) Complexes. Stereospecific Vicinal Diamination of Olefins. *J Am Chem Soc.* 1977; 99:3420–3426. Bäckvall J-E. Stereospecific Palladium-Promoted Vicinal Diamination of Olefins. *Tetrahedron Lett.* 1978; 19:163–166. Becker PN, White MA, Bergman RG. A New Method for 1,2-Diamination of Alkenes Using Cyclopentadienylnitrosylcobalt Dimer/NO/LiAlH₄. *J Am Chem Soc.* 1980; 102:5676–5677. Bar GLJ, Lloyd-Jones GC, Booker-Milburn KI. Pd(II)-Catalyzed Intermolecular 1,2-Diamination of Conjugated Dienes. *J Am Chem Soc.* 2005; 127:7308–7309. [PubMed: 15898768] Streuff J, Hövelmann CH, Nieger M, Muñoz K. Palladium- (II)-Catalyzed Intramolecular

- Diamination of Unfunctionalized Alkenes. *J Am Chem Soc.* 2005; 127:14586–14587. [PubMed: 16231907] Zabawa TP, Kasi D, Chemler SR. Copper(II) Acetate Promoted Intramolecular Diamination of Unactivated Olefins. *J Am Chem Soc.* 2005; 127:11250–11251. [PubMed: 16089447] Du H, Yuan W, Zhao B, Shi Y. Catalytic Asymmetric Diamination of Conjugated Dienes and Triene. *J Am Chem Soc.* 2007; 129:11688–11689. [PubMed: 17803307] Zhao BG, Peng XG, Cui SL, Shi Y. Cu(I)-Catalyzed Regioselective Diamination of Conjugated Dienes via Dual Mechanistic Pathways. *J Am Chem Soc.* 2010; 132:11009–11011. [PubMed: 20698659] Sibbald PA, Rosewall CF, Swartz RD, Michael FE. Mechanism of *N*-Fluorobenzenesulfonimide Promoted Diamination and Carboamination Reactions: Divergent Reactivity of a Pd(IV) Species. *J Am Chem Soc.* 2009; 131:15945–15951. [PubMed: 19824646] Iglesias Á, Pérez EG, Muñiz K. An Intermolecular Palladium-Catalyzed Diamination of Unactivated Alkenes. *Angew Chem, Int Ed.* 2010; 49:8109–8111. Olson DE, Su JY, Roberts DA, Du Bois J. Vicinal Diamination of Alkenes under Rh- Catalysis. *J Am Chem Soc.* 2014; 136:13506–13509. [PubMed: 25233140] Conway JH, Rovis T. Regiodivergent Iridium(III)-Catalyzed Diamination of Alkenyl Amides with Secondary Amines: Complementary Access to γ - or δ -Lactams. *J Am Chem Soc.* 2018; 140:135–138. [PubMed: 29278330] For selected references of enantioselective olefin diamination methods, see ref 1g and Muñiz K, Barreiro L, Romero RM, Martínez C. Catalytic Asymmetric Diamination of Styrenes. *J Am Chem Soc.* 2017; 139(139):4354–4357. [PubMed: 28277652] Ingalls EL, Sibbald PA, Kaminsky W, Michael FE. Enantioselective Palladium-Catalyzed Diamination of Alkenes Using *N*-Fluorobenzenesulfonimide. *J Am Chem Soc.* 2013; 135:8854–8856. [PubMed: 23734771]
2. For selected recent syntheses of complex alkaloids with 1,2- diaminated N-heterocycles, see: Seiple IB, Su S, Young IS, Lewis CA, Yamaguchi J, Baran PS. Total Synthesis of Palau'amine. *Angew Chem, Int Ed.* 2010; 49:1095–1098. Fleming JJ, Du Bois J. A Synthesis of (+)-Saxitoxin. *J Am Chem Soc.* 2006; 128:3926–3927. [PubMed: 16551097] Ma Z, Wang X, Ma Y, Chen C. Asymmetric Synthesis of Axinellamines A and B. *Angew Chem, Int Ed.* 2016; 55:4763–4766.
 3. For early studies of an iron(II)–iron(III)-mediated stoichiometric olefin diazidation approach using either peroxydisulfate or hydrogen peroxide with NaN_3 , see: Minisci F, Galli R. Influence of the Electrophilic Character on the Reactivity of Free Radicals in Solution Reactivity of Alkoxy, Hydroxy, Alkyl and Azido Radicals in Presence of Olefins. *Tetrahedron Lett.* 1962; 3:533–538. Minisci F. Free-Radical Additions to Olefins in the Presence of Redox Systems. *Acc Chem Res.* 1975; 8:165–171. This stoichiometric approach provides good yield for styrene diazidation; however, it provide modest to moderate yields for diazidation of unfunctionalized aliphatic olefins. For selected references of other stoichiometric diazidation methods for limited types of olefins, see: Fristad WE, Brandvold TA, Peterson JR, Thompson SR. Conversion of Alkenes to 1,2- Diazides and 1,2-Diamines. *J Org Chem.* 1985; 50:3647–3649. Snider BB, Lin H. An Improved Procedure for the Conversion of Alkenes and Glycols to 1,2-Diazides Using $\text{Mn}(\text{OAc})_3 \cdot 2\text{H}_2\text{O}$ in Acetonitrile Containing Trifluoroacetic Acid. *Synth Commun.* 1998; 28:1913–1922. Moriarty RM, Khosrowshahi JS. A Versatile Synthesis of Vicinal Diazides Using Hypervalent Iodine. *Tetrahedron Lett.* 1986; 27:2809–2812. Arimoto M, Yamaguchi H, Fujita E, Nagao Y, Ochiai M. Diazidation of Allylsilanes with a Combination of Iodosylbenzene and Trimethylsilyl Azide, and Synthesis of Allyl Azides. *Chem Pharm Bull.* 1989; 37:3221–3224. Magnus P, Lacour J. New Trialkylsilyl Enol Ether Chemistry. Direct β -Azido Functionalization of Triisopropylsilyl Enol Ethers. *J Am Chem Soc.* 1992; 114:767–769. Chung R, Yu E, Incarvito CD, Austin DJ. Hypervalent Iodine-Mediated Vicinal Syn Diazidation: Application to the Total Synthesis of ($\pm$)-Dibromophakellstatin. *Org Lett.* 2004; 6:3881–3884. [PubMed: 15496054] Sasaki T, Kanematsu K, Yukimoto Y. Heteroaromaticity. LX. Reactions of Medium-Membered- Ring Unsaturated Compounds with Iodine Azide. *J Org Chem.* 1972; 37:890–894. Nocquet-Thibault S, Rayar A, Retaillieu P, Cariou K, Dodd RH. Iodine(III)-Mediated Diazidation and Azidooxyamination of Enamides. *Chem - Eur J.* 2015; 21:14205–14210. [PubMed: 26267539] Kamble DA, Karabal PU, Chouthaiwale PV, Sudalai A. NaIO_4 – NaN_3 -Mediated Diazidation of Styrenes, Alkenes, Benzylic alcohols, and Aryl Ketones. *Tetrahedron Lett.* 2012; 53:4195–4198.
 4. For selected references of catalytic olefin diazidation methods, see: Yuan Y-A, Lu D-F, Chen Y-R, Xu H. Iron-Catalyzed Direct Diazidation for a Broad Range of Olefins. *Angew Chem, Int Ed.* 2016; 55:534–538. Zhu H-T, Arosio L, Villa R, Nebuloni M, Xu H. Process Safety Assessment of the Iron-Catalyzed Direct Olefin Diazidation for the Expedient Synthesis of Vicinal Primary Diamines. *Org Process Res Dev.* 2017; 21:2068–2072. [PubMed: 29353989] For selected catalytic methods for styrene diazidation, see: Fumagalli G, Rabet PTG, Boyd S, Greaney MF. Three-Component

Azidation of Styrene- Type Double Bonds: Light-Switchable Behavior of a Copper Photoredox Catalyst. *Angew Chem, Int Ed*. 2015; 54:11481–11484. Lu M-Z, Wang C-Q, Loh T-P. Copper-Catalyzed Vicinal Oxyazidation and Diazidation of Styrenes under Mild Conditions: Access to Alkyl Azides. *Org Lett*. 2015; 17:6110–6113. [PubMed: 26651361] For more recent examples, see: Peng H, Yuan Z, Chen P, Liu G. Palladium-Catalyzed Intermolecular Oxidative Diazidation of Alkenes. *Chin J Chem*. 2017; 35:876–880. Zhou H, Jian W, Qian B, Ye C, Li D, Zhou J, Bao H. Copper-Catalyzed Ligand-Free Diazidation of Olefins with TMSN₃ in CH₃CN or in H₂O. *Org Lett*. 2017; 19:6120–6123. [PubMed: 29090941] For selected examples of catalytic intramolecular olefin azidation, see: Shen K, Wang Q. Copper-Catalyzed Alkene Aminoazidation as a Rapid Entry to 1,2-Diamines and Installation of an Azide Reporter onto Azaheterocycles. *J Am Chem Soc*. 2017; 139:13110–13116. [PubMed: 28825822] Zhu R, Buchwald SL. Versatile Enantioselective Synthesis of Functionalized Lactones via Copper-Catalyzed Radical Oxyfunctionalization of Alkenes. *J Am Chem Soc*. 2015; 137:8069–8077. [PubMed: 26070105] For a selected review for olefin azidation, see: Wu K, Liang Y, Jiao N. Azidation in the Difunctionalization of Olefins. *Molecules*. 2016; 21:352. [PubMed: 26999085]

5. For an electrochemical diazidation method, see: Fu N, Sauer GS, Saha A, Loo A, Lin S. Metal-Catalyzed Electrochemical Diazidation of Alkenes. *Science*. 2017; 357:575–579. [PubMed: 28798126] See also: Schäfer H. Oxidative Addition of the Azide Ion to Olefins. A Simple Route to Diamines. *Angew Chem, Int Ed Engl*. 1970; 9:158–159.
6. For *N*-heterocycle diazidation, see: refs 3h,4a,b, and 5a.
7. For detailed studies of the iron-catalyzed nonproductive decomposition of 1a, see Supporting Information.
8. For selected references of oxygen atom transfer with peroxyesters, see: Kharasch MS, Sosnovsky G. The Reactions of *tert*-Butyl Perbenzoate and Olefins - A Stereospecific Reaction. *J Am Chem Soc*. 1958; 80:756–756. Gokhale AS, Minidis ABE, Pfaltz A. Enantioselective Allylic Oxidation Catalyzed by Chiral Bisoxazoline-Copper Complexes. *Tetrahedron Lett*. 1995; 36:1831–1834. Kawasaki K, Katsuki T. Enantioselective Allylic Oxidation of Cycloalkenes by Using Cu(II)-Tris(oxazoline) Complex as a Catalyst. *Tetrahedron*. 1997; 53:6337–6350. Sekar G, Datta Gupta A, Singh VK. Asymmetric Kharasch Reaction: Catalytic Enantioselective Allylic Oxidation of Olefins Using Chiral Pyridine Bis(diphenyloxazoline)-Copper Complexes and *tert*-Butyl Perbenzoate. *J Org Chem*. 1998; 63:2961–2967. Sharma A, Hartwig JF. Enantioselective Functionalization of Allylic C–H Bonds Following a Strategy of Functionalization and Diversification. *J Am Chem Soc*. 2013; 135:17983–17989. [PubMed: 24156776]
9. For selected references of ligand-accelerated or ligand-promoted catalysis, see: Jacobsen EN, Marko I, Mungall WS, Schroeder G, Sharpless KB. Asymmetric Dihydroxylation via Ligand-Accelerated Catalysis. *J Am Chem Soc*. 1988; 110:1968–1970. Berrisford DJ, Bolm C, Sharpless KB. Ligand-Accelerated Catalysis. *Angew Chem, Int Ed Engl*. 1995; 34:1059–1070. Wang D-H, Engle KM, Shi B-F, Yu J-Q. Ligand-Enabled Reactivity and Selectivity in a Synthetically Versatile Aryl C–H Olefination. *Science*. 2010; 327:315–319. [PubMed: 19965380] For a recent report of ligand-free, high-temperature diazidation in water, see 4f.
10. For selected references of the iron-catalyzed C–H azidation of electron-rich C–H bonds, see: Sharma A, Hartwig JF. Metalcatalyzed azidation of tertiary C–H bonds suitable for late-stage functionalization. *Nature*. 2015; 517:600–604. [PubMed: 25631448] Karimov RR, Sharma A, Hartwig JF. Late Stage Azidation of Complex Molecules. *ACS Cent Sci*. 2016; 2:715–724. [PubMed: 27800554]
11. For stereochemistry determination, see details in the Supporting Information.
12. For selected references of previous norbornane primary diamine synthesis, see: Bolm C, Schiffrers I, Atodiresei I, Ozcubukcu S, Raabe G. A Novel Asymmetric Synthesis of Highly Enantiomerically Enriched Norbornane-Type Diamine Derivatives. *New J Chem*. 2003; 27:14–17. Maisonia A, Traikia M, Gautier A, Aitken DJ. Control of the Platinum(II) Ligating Properties of Rigid 1,2-Diamines: the Case of *trans*-2,3-Diaminonorbornane. *Tetrahedron Lett*. 2006; 47:8091–8093.
13. For selected references of both catalytic (ref. 13a) and stoichiometric (refs 13b–c) 1,4-diene diamination to afford building blocks other than 1,4-allylic primary diamines, see: Wu Z, Zhang J, Li Y, Zhang W. Pd(II)-Catalyzed Aerobic Intermolecular 1,4-Diamination of Conjugated Dienes: A Regioselective [4 + 4] Annulation for the Construction of Medium-Ring 1,6-Benzodiazocine

Derivatives. *Tetrahedron Lett.* 2017; 58:2640–2643. Akermark B, Bäckvall J-E, Löwenborg A, Zetterberg K. Palladium(II)-Promoted 1,4-Diamination of 1,3-Dienes. Stereochemistry of Amination of a π -Allylpalladium Complex. *J Organomet Chem.* 1979; 166:C33–36. Martínez C, Martínez L, Kirsch J, Escudero-Adán EC, Martín E, Muñoz K. Copper-Mediated 1,4-Diamination of 1,3- Butadienes. *Eur J Org Chem.* 2014; 2014:2017–2021.

14. For palladium-catalyzed vicinal diamination of a more substituted olefin moiety in a 1,3-diene, see: Du H, Zhao B, Shi Y. A Facile Pd(0)-Catalyzed Regio- and Stereoselective Diamination of Conjugated Dienes and Trienes. *J Am Chem Soc.* 2007; 129:762–763. [PubMed: 17243803] For copper catalyst-controlled regioselective vicinal diene diamination of either a more or a less substituted olefin moiety, see ref 1h.
15. For allylic azide rearrangement, see: Feldman AK, Colasson B, Sharpless KB, Fokin VV. The Allylic Azide Rearrangement: Achieving Selectivity. *J Am Chem Soc.* 2005; 127:13444–13445. [PubMed: 16190677] The ratio of **8a/8b** does not match that of **7a/7b**, which is presumably due to the different reactivity of **7a/7b** under the reduction condition controlled by the Curtin–Hammett principle.
16. There are four NMR signals in the ^{13}C NMR spectrum in addition to the ones from *N*-Boc group; therefore, we assign its relative stereochemistry as *trans*.
17. For selected references of synthesis of vicinal diamino alcohols, see: Khayer K, Jenn T, Akhtar M, John R, Gani D. Synthesis of (*R*)- and (*S*)-2,3-Diaminopropyl Sulfate: Mechanism Based Inhibition of Glutamate 1-Semialdehyde Aminomutase. *Tetrahedron Lett.* 2000; 41:1637–1641. Biannic B, Bozell JJ, Elder T. Steric Effects in the Design of Co-Schiff Base Complexes for the Catalytic Oxidation of Lignin Models to *para*-Benzoquinones. *Green Chem.* 2014; 16:3635–3642.
18. For selected references of synthesis of vicinal triamines, see: Busto E, Gotor-Fernández V, Montejó-Bernardo J, García-Granda S, Gotor V. Development of a Chemoenzymatic Strategy for the Synthesis of Optically Active and Orthogonally Protected Polyamines. *Tetrahedron.* 2009; 65:8393–8401. Mitra R, Ganesh KN. Aminomethylene Peptide Nucleic Acid (am-PNA): Synthesis, Regio-/Stereospecific DNA Binding, And Differential Cell Uptake of (α/γ ,R/S)am-PNA Analogues. *J Org Chem.* 2012; 77:5696–5704. [PubMed: 22676429]
19. For selected references of carbocation rearrangements from the β -pinene scaffold, see: Winstein S, Holness NJ. Neighboring Carbon and Hydrogen. XVIII. Solvolysis of the Nopinyl *p*-Bromobenzenesulfonates. *J Am Chem Soc.* 1955; 77:3054–3061. Prakash GKS, Reddy VP, Rasul G, Casanova J, Olah GA. The Search for Persistent Cyclobutylmethyl Cations in Superacidic Media and Observation of the Cyclobutyldicyclopropylmethyl Cation. *J Am Chem Soc.* 1998; 120:13362–13365.
20. For a selected reference of characterized monomeric iron–azide complexes and their IR measurements, see: Grove LE, Hallman JK, Emerson JP, Halfen JA, Brunold TC. Synthesis, X-Ray Crystallographic Characterization, and Electronic Structure Studies of a Di-Azide Iron(III) Complex: Implications for the Azide Adducts of Iron(III) Superoxide Dismutase. *Inorg Chem.* 2008; 47:5762–5774. [PubMed: 18533647]
21. For experimental details, see the Supporting Information.
22. Complex **29** is inactive for olefin diazidation with peroxyesters (**3a–d**); however, it is active for olefin diazidation using beniodoxole **1a**, in which azido–radical generation is non-iron catalyst dependent.
23. For selected references of metal-mediated radical oxidation, see ref 8a and Kharasch MS, Sosnovsky G, Yang NC. Reactions of *tert*-Butyl Peresters. I. The Reaction of Peresters with Olefins. *J Am Chem Soc.* 1959; 81:5819–5824. Kochi JK. Mechanisms of Organic Oxidation and Reduction by Metal Complexes. *Science.* 1967; 155:415–424. [PubMed: 17737550]

Scheme 1.

Iron-Catalyzed Olefin Diazidation with Benziodoxole 1a and the Proposed Mechanistic Working Hypothesis

Scheme 2.

Iron-Catalyzed Olefin Diazidation via Nitrogen- Based Ligand-Promoted Peroxyester Activation

Scheme 3. Mechanistic Experiments To Probe for the Intermediacy of a Carbo-Radical Species^a

^a $\text{Fe(NTf}_2)_2$ (10 mol %), **L2** (10 mol %), **3a** (1.4 equiv), TMSN_3 (2.5 equiv), and $i\text{PrOH}$ (1.2 equiv), TEMPO (1.0 equiv). ^b Fe(OAc)_2 (10 mol %), **L1** (10 mol %), **3a** (1.2 equiv), TMSN_3 (2.4 equiv), $i\text{PrOH}$ (1.2 equiv), and TEMPO (1.0 equiv). ^c $\text{Fe(NTf}_2)_2$ (5 mol %), **L2** (5 mol %), **3a** (1.4 equiv), TMSN_3 (2.5 equiv), and $i\text{PrOH}$ (1.2 equiv). ^d Fe(OAc)_2 (10 mol %), **L1** (10 mol %), **3a** (1.2 equiv), TMSN_3 (2.4 equiv), and $i\text{PrOH}$ (1.2 equiv).

Scheme 4. Iron-Catalyzed Diastereoselective Vicinal Diazidation of (-)- β -Pinene^a

^a $\text{Fe(NTf}_2)_2$ (5 mol %), **L2** (5 mol %), **3a** (1.4 equiv), TMSN_3 (2.5 equiv), and $i\text{PrOH}$ (1.2 equiv). ^b Fe(OAc)_2 (10 mol %), **L1** (10 mol %), **3a** (1.2 equiv), TMSN_3 (2.4 equiv), and $i\text{PrOH}$ (1.2 equiv). ^c Pd/C (10 wt %) in MeOH, 12 h, then $p\text{-TsOH}\cdot\text{H}_2\text{O}$. ^d Fe(OAc)_2 (20 mol %), **L1** (20 mol %), **3a** (1.2 equiv), TMSN_3 (2.4 equiv), and $i\text{PrOH}$ (1.2 equiv), TEMPO (0.5 equiv).

Scheme 5. Control Experiments To Determine the Rate-Limiting Step for Diazidation of Unstrained Olefins^a

^aFe(NTf₂)₂ (5 mol %), L2 (5 mol %), 3a (1.4 equiv), and TMSN₃ (2.5 equiv). ^bOne molar aqueous H₂SO₄, 15 min. ^cFe(OAc)₂ (10 mol %), L1 (10 mol %), 3a (1.2 equiv), and TMSN₃ (2.4 equiv). ^dFe(OAc)₂ (10 mol %), L1 (10 mol %), 3c (1.2 equiv), and TMSN₃ (2.4 equiv).

Scheme 6. Control Experiments To Probe for Mechanistic Insights of Azido-Radical Generation^a

^a**1a** (1.2 equiv), TMSN₃ (4.0 equiv), 2 h. ^b**3a** (1.2 equiv), TMSN₃ (2.4 equiv), and *i*PrOH (1.2 equiv).

Scheme 7. Control Experiments To Corroborate the Involvement of a Carboxylate Ligand in the Rate-Determining C–N₃ Bond-Forming Step for Unstrained Olefins^a

^a $\text{Fe}(\text{NTf}_2)_2$ (10 mol %), **L2** (10 mol %), **3a** (3.0 equiv), TMSN_3 (4.0 equiv), and $i\text{PrOH}$ (0.5 equiv). ^b $\text{Fe}(\text{NTf}_2)_2$ (10 mol %), **L2** (10 mol %), **3c** (3.0 equiv), TMSN_3 (4.0 equiv), $i\text{PrOH}$ (0.5 equiv).

Scheme 8. Control Experiments To Probe for Ligand Effect^a

^a Fe(OAc)_2 (10 mol %), **L2** (10 mol %), **1a** (1.2 equiv), and TMSN_3 (4.0 equiv). ^b Fe(OAc)_2 (10 mol %), **L2** (10 mol %), **3d** (1.2 equiv), TMSN_3 (2.4 equiv), and iPrOH (1.2 equiv).

Scheme 9. Structure–Reactivity Relationship Studies of the $\text{Fe}(\text{OAc})_2$ and $\text{Fe}(\text{NTf}_2)_2$ Catalysts in the Presence of TMSN_3 ^a

^a**28** (10 mol %), **3a** (1.2 equiv), and *i*PrOH (1.2 equiv). ^b $\text{Fe}(\text{OAc})_2$ (10 mol %), **L2** (10 mol %), **3d** (1.2 equiv), TMSN_3 (2.4 equiv), and *i*PrOH (1.2 equiv). ^c**28** (25 mol %) and **3c** (1.2 equiv).

Scheme 10.

Mechanistic Working Hypotheses of the $\text{Fe}(\text{NTf}_2)_2$ - and $\text{Fe}(\text{OAc})_2$ -Catalyzed Olefin Diazidation via Ligand-Promoted Activation of Peroxyesters

Table 1

Catalyst Discovery for Indene Diazidation via Nitrogen-Based Ligand-Promoted Peroxyester Activation

entry ^a	variation from the standard conditions	observations ^{b,c}
1	in the absence of L1	<5% yield <5% conversion
2	in the absence tPrOH	48% yield dr 10:1 59% conversion
3	replace tPrOH with H ₂ O	52% yield dr 10:1 65% conversion in 4 h
4	replace 3a with 3b	75% yield dr 6.7:1 87% conversion in 4 h
5	replace 3a with 3c	87% yield dr 10:1 95% conversion in 1 h
6	replace L1 with L2	6% yield dr 16:1 ca. 10% conversion
7	replace L1 with L3	8% yield dr 7:1 ca. 16% conversion
8	replace Fe(OAc) ₂ with Fe(NTf ₂) ₂ (2.5 mol %)	42% yield dr 4.2:1 68% conversion
9	replace Fe(OAc) ₂ with Fe(NTf ₂) ₂ (2.5 mol %) and replace L1 with L2	52% yield dr 3.5:1 87% conversion

^aReactions were carried out under N₂ and subsequently quenched with saturated Na₂CO₃ solution.^bConversion was measured by ¹H NMR analysis.^cIsolated yield. Standard safety precautions about handling TMSN₃ should be taken; see SI for details.

Table 2

Iron-Catalyzed Peroxyester Activation for Diazidation of Unfunctionalized Olefins

$ \begin{array}{c} \text{R}^1 \quad \text{R}^2 \\ \diagdown \quad \diagup \\ \text{C} = \text{C} \\ \diagup \quad \diagdown \\ \text{R}^3 \end{array} + \text{tBu-O-O-C(=O)Ph} + \text{TMSN}_3 \xrightarrow[\text{CH}_2\text{Cl}_2/\text{MeCN}, 22^\circ\text{C}]{\text{Fe}^{\text{II}} \text{ catalyst/ligand}, \text{tPrOH (1.2 equiv)}} \begin{array}{c} \text{N}_3 \quad \text{R}^1 \\ \diagdown \quad \diagup \\ \text{C} - \text{C} \\ \diagup \quad \diagdown \\ \text{R}^3 \quad \text{N}_3 \end{array} $			
entry ^a	olefins	diazidation products	yield ^b
1 ^c			81%
2 ^c			70%
3 ^c			83%
4 ^c			86%
5 ^c			88%
		<i>dr</i> : 1.3:1	
6 ^d			87%
		<i>dr</i> >20:1	
7 ^d			81%
		<i>dr</i> : 5:1	

entry ^a	olefins	diazidation products	yield ^b
8 ^d			82%
9 ^d			86%
10 ^d		 <i>dr</i> : 1.4:1	92%
11 ^d		 <i>dr</i> : 2:1	89%
12 ^{d,e}		 <i>dr</i> : 10:1	92%
13 ^d		 <i>dr</i> : 12:1	82%
14 ^d			81%

^aReactions were carried out under N₂ unless stated otherwise.

^bIsolated yield.

^cFe(NTf₂)₂ (5 mol %), **L2** (5 mol %), *t*BuOOBz (1.4 equiv), TMSN₃ (2.5 equiv), and *t*PrOH (1.2 equiv).

^dFe(OAc)₂ (10 mol %), **L1** (10 mol %), *t*BuOOBz (1.2 equiv), TMSN₃ (2.4 equiv), and *t*PrOH (1.2 equiv).

^eCatalyst loading (5 mol %).

Table 3

Iron-Catalyzed Peroxyester Activation for Diazidation of *N*-Heterocycles and Highly Functionalized Olefins

$ \begin{array}{c} \text{R}^1 \quad \text{R}^2 \\ \diagdown \quad \diagup \\ \text{C} = \text{C} \\ \diagup \quad \diagdown \\ \text{R}^3 \end{array} + \text{tBu-O-O-C(=O)Ph} + \text{TMSN}_3 \xrightarrow[\text{CH}_2\text{Cl}_2/\text{MeCN}, 22^\circ\text{C}]{\text{Fe}^{\text{II}} \text{ catalyst/ligand}, \text{tPrOH (1.2 equiv)}} \begin{array}{c} \text{N}_3 \quad \text{R}^1 \\ \diagdown \quad \diagup \\ \text{C} - \text{C} \\ \diagup \quad \diagdown \\ \text{R}^3 \quad \text{N}_3 \end{array} $			
entry ^a	olefins	diazidation products	yield ^b
1 ^c		 <i>dr</i> > 20:1	81%
2 ^c		 <i>dr</i> > 20:1	78%
3 ^{c,d}		 <i>dr</i> > 20:1	76%
4 ^{c,e,f}		 <i>dr</i> > 20:1	74%
5 ^c		 <i>dr</i> : 12:1	85%

$ \begin{array}{c} \text{R}^1 \quad \text{R}^2 \\ \diagdown \quad \diagup \\ \text{C} = \text{C} \\ \diagup \quad \diagdown \\ \text{R}^3 \end{array} + \text{tBu-O-C(=O)-Ph} \quad + \quad \text{TMSN}_3 \xrightarrow[\text{CH}_2\text{Cl}_2/\text{MeCN}, 22^\circ\text{C}]{\text{Fe}^{\text{II}} \text{ catalyst/ligand}, \text{tPrOH (1.2 equiv)}} \begin{array}{c} \text{N}_3 \quad \text{R}^1 \\ \diagdown \quad \diagup \\ \text{C} - \text{C} \\ \diagup \quad \diagdown \\ \text{R}^3 \quad \text{N}_3 \end{array} $			
entry ^a	olefins	diazidation products	yield ^b
6 ^c		 <i>dr</i> > 20:1	82%
7 ^c		 <i>dr</i> 1:1	72%
8 ^c		 <i>dr</i> 1:1	67%
9 ^g		 <i>dr</i> 1:1	76%
10 ^c		 <i>dr</i> 1.6:1	84%
11 ^c			72%

$ \begin{array}{c} \text{R}^1 \quad \text{R}^2 \\ \diagdown \quad \diagup \\ \text{C} \\ \diagup \quad \diagdown \\ \text{R}^3 \end{array} + \text{tBu-O-C(=O)-Ph} + \text{TMSN}_3 \xrightarrow[\text{CH}_2\text{Cl}_2/\text{MeCN}, 22^\circ\text{C}]{\text{Fe}^{\text{II}} \text{ catalyst/ligand}, \text{tPrOH (1.2 equiv)}} \begin{array}{c} \text{N}_3 \quad \text{R}^1 \\ \diagdown \quad \diagup \\ \text{C} \\ \diagup \quad \diagdown \\ \text{R}^3 \quad \text{N}_3 \end{array} $			
entry ^a	olefins	diazidation products	yield ^b
12 ^g			91%
13 ^{c,e,f}			73%
14 ^h			85%
15 ^h			77%

^aReactions were carried out under N₂ unless stated otherwise.

^bIsolated yield.

^cFe(NTf₂)₂ (5 mol %), **L2** (5 mol %), ^tBuOOBz (1.4 equiv), TMSN₃ (2.5 equiv), and ^tPrOH (1.2 equiv).

^dTen mol % catalyst was applied.

^eNeither ^tPrOH nor other proton donor was applied.

^fMeI (5.0 equiv) and K₂CO₃ (3.0 equiv).

^gFe(OAc)₂ (10 mol %), **L1** (10 mol %), ^tBuOOBz (1.2 equiv), TMSN₃ (2.4 equiv), and ^tPrOH (1.2 equiv).

^hFe(NTf₂)₂ (10 mol %), **L2** (10 mol %), ^tBuOOBz (3.0 equiv), TMSN₃ (4.0 equiv), and ^tPrOH (0.5 equiv).