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Catalyst-controlled selective synthesis of pyridines and pyrroles

Yaojia Jiang\textsuperscript{a} and Cheol-Min Park\textsuperscript{b}\textsuperscript{*}

We have developed a dual reaction manifold that enables selective synthesis of both pyridines and pyrroles from common substrates \(\alpha\)-diazo oxime ethers. The strong propensity of 1,3-dienyl nitrenes for 4\(\pi\)-electrocyclization to give pyrroles could be diverted to 6\(\pi\)-electrocyclization via 1,6-hydride shift or prototropic isomerization leading to exclusive formation of pyridines by employing metal nitrene complexes derived from \(\alpha\)-diazo oxime ethers under Rh(II) catalysis. The reaction mechanism was studied by deuterium labeling experiment. Furthermore, an orthogonal catalytic system has been identified that promotes selective formation of 1\(H\)-pyrroles from the same substrates by redirecting the reactivity of vinyl 2\(H\)-azirine intermediates.

Metal nitrenes have drawn considerable interest due to their diverse reactivity.\textsuperscript{1-5} Catalytic C–H amination based on metal nitrenes has recently emerged as a powerful tool that allows introduction of nitrogen functionality onto inert C–H bonds and efficient access to a variety of synthetically important amino compounds.\textsuperscript{6-13} Meanwhile, through a disparate mechanism, metal nitrenes derived from aryl and vinyl azides have shown to provide facile access to indoles and other fused N-heterocycles,\textsuperscript{14-19} which comprise core motifs in pharmaceuticals, natural products, and functional materials.\textsuperscript{20-22} Recently, Driver et al. reported synthesis of pyrroles and indoles by metal-catalyzed rearrangement of 1,3-dienyl azides and aryl azides, respectively.\textsuperscript{23, 24}

Cascade reactions offer great advantages for organic synthesis with respect to reduction of wastes, step efficiency, and alleviating time and efforts in handling intermediates.\textsuperscript{25-29} In this regard, we have described a catalytic cascade synthesis of pyrroles from \(\alpha\)-diazo oxime ethers under Rh(II) catalysis.\textsuperscript{30} Encouraged by these results, we became interested in the reactivity of 1,3-dienyl nitrenes as a platform for N-heterocycle synthesis, which could be readily accessible from \(\alpha\)-diazo oxime ethers via \textit{in situ} formation of 2\(H\)-azirines. These nitrene intermediates could potentially participate in two alternative pathways: a) 4\(\pi\)-electrocyclization,\textsuperscript{24, 31} b) 6\(\pi\)-electrocyclization via 1,6-hydride shift or prototropic isomerization. However, the strong propensity of 1,3-dienyl nitrenes for 4\(\pi\)-electrocyclization to give pyrroles intrigued us whether modulation of the reactivity of nitrenes with an optimal transition metal catalyst may lead to alteration of their chemoselectivity toward 6\(\pi\)-electrocyclization to provide pyridines.\textsuperscript{32-45} In addition, challenges include the identification of catalysts with the ability to catalyze sequential formation of metal carbenes and nitrenes from \(\alpha\)-diazo oxime ethers in the consecutive catalytic cycle. Furthermore, the development of a catalytic platform that allows exclusive formation of either pyridines or pyrroles\textsuperscript{46-53} from common substrates is highly desirable. Herein, we describe the successful development of such a reaction manifold [Eq. (1)].

\begin{align*}
\begin{array}{c}
\text{R}^1 \text{N}=\text{N} \text{O} \text{R}^2 \\
\text{R}^3 \text{H} \\
\text{R}^4 \text{H}
\end{array}
\xrightarrow{\text{Rh(II) catalyst}}
\begin{array}{c}
\text{N} \\
\text{R}^5 \text{H} \\
\text{R}^6 \text{H}
\end{array}
\end{align*}

We began our exploration for the synthesis of pyridines by screening various metal salts employing \(\alpha\)-diazo oxime ether 1a as a substrate (Table 1).\textsuperscript{53-56} The use of Cu(OTf)\textsubscript{2} gave pyridine 2a in moderate yield, while Ag and Co catalysts resulted in the formation of a mixture of pyridine 2a and pyrrole 3a (entries 1–3). To further optimize the selectivity for pyridine, we examined Rh(II) complexes bearing ligands with different steric and electronic attributes (entries 4–7) and found that Rh(II) complexes with both electron-withdrawing and sterically bulky ligands gave moderate yields. Gratifyingly, Rh(OAc)\textsubscript{2} provides pyridine 2a in 73\% yield. Oxidation of dihydropyridine appears to be rapid as no observation of dihydropyridine.

With the optimized reaction conditions in hand, we proceeded to survey the scope of the reaction (Table 2). First, we examined the regioselectivity of the reaction by employing substrate 1b bearing two different substituents (R\textsubscript{2} and R\textsubscript{3}). Subjection of 1b bearing methyl and isobutyl groups to the reaction conditions led to the formation of 2b as a single isomer.
in which C-N bond formation occurred at the methyl group, which is syn to the nitrene. To our surprise, 1d bearing p-bromobenzyl group in place of isobutyl group gave 2d resulting from the reaction at the benzyl site. This observation clearly rules out a reaction mechanism based on direct C-H insertion because of the geometric constraint, which prevents the nitrene from reacting at the benzyl site without prior isomerization. The potential isomerization during the formation of 2H-azirine intermediate was ruled out by examination of the alkene isomerization and substituent shift leads to the formation of 1 undergos rearrangement to give vinyl azirine isomerization and substituent shift leads to the formation of 1 undergos rearrangement to give vinyl azirine.

A variety of fused bicyclic pyridines are readily prepared in good yields by incorporating desired size of rings onto alkenes (Table 2, 2e–g). We also examined the tolerability of R1 group and found that various types of substituents could be accommodated (2h–k). The reaction with substrates bearing electron-rich aryl (1h) and heteroaryl (1i) groups proceeded smoothly to give the corresponding pyridines in 72% and 64%, respectively. Also, those with vinyl and alkyl groups reacted well to give pyridines (2j and 2k, respectively). Different esters can be prepared by employing corresponding oxime ethers. Thus, pyridine with benzyl ester (2i) could be prepared in good yield by using benzyl oxime ether.

Next, we explored the feasibility of the synthesis of pyrroles from the same substrates α-diazo oxime ethers. Thus, a successful catalyst would promote multiple sequential rearrangements initiated by generation of carbenoid A, which undergoes rearrangement to give vinyl azirine B. Subsequent isomerization and substituent shift leads to the formation of 1H-pyrrrole 3a (Scheme 2). Due to the competitive formation of 2H-pyrrrole 3a*, it is crucial for a catalyst to promote migration of the gem-substituents on intermediate C. While conversion was sluggish with Ni(0) providing the 2H-azirine intermediate as the major product (Table 3, entry 1), a substantially improved result was obtained by the use of Ni(II) catalysts along with concomitant formation of 3a* (entry 2, 62%). While addition of various ligands did not significantly improve the yield, we were gratified to find that the use of NiCl2 with PPh3 as ligand gave 3a in 82% yield (entry 8).

With the optimized conditions in hand, we surveyed the substrate scope of the synthesis of pyrroles (Table 4). Overall, the pyrrole formation proceeded smoothly with good to excellent yields. First, we examined the migratory aptitude of the geminal substituents of the intermediate 2H-pyrrroles. While substrates bearing similar primary alkyl substituents resulted in the formation of a mixture (3b and 3bb), selective migration was observed with more disparate substituents such as ligand gave 3a in 82% yield (entry 8).

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as aryl groups smoothly undergo migration over alkyl groups (3g–j). It is noteworthy that indole 3h was obtained by spontaneous oxidation. Likewise, alkene groups participate in selective migration (3k). Examination of electronic influence on the migratory aptitude revealed that migration of electron deficient substituents is disfavored (3l vs. 3n). Also, the reaction with heterocyclic substrate proceeds selectively to provide the pyrrole with heterocyclic substituent (3n). The reaction also proceeded well with various types of substituents for R^1 such as aryl, heteroaryl, and alkyl groups (3o–r).

In summary, a dual reaction manifold that allows selective synthesis of both pyridines and pyrroles from common substrates α-diazo oxime ethers has been developed. Mechanistic study indicates the pyridine formation is initiated by 1,6-hydride shift or prototropic isomerization depending on the type of substituents. The reaction scope of these transformations demonstrates that a variety of diverse structures of these important N-heterocycles are readily accessible from α-diazo oxime ethers with high efficiency.

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