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Potassium *tert*-Butoxide-Promoted Acceptorless Dehydrogenation of N-Heterocycles

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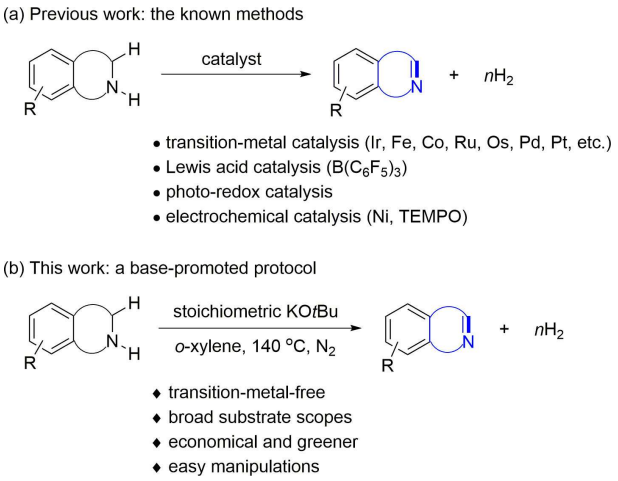
Abstract: Potassium *tert*-butoxide-promoted acceptorless dehydrogenation of N-heterocycles was efficiently realized for the generation of N-heteroarenes and hydrogen gas under transition-metal-free conditions. In the presence of KO*t*Bu base, a variety of six- and five-membered N-heterocyclic compounds efficiently underwent acceptorless dehydrogenation to afford the corresponding N-heteroarenes and H_2 gas in *o*-xylene at 140 °C. The present protocol provides a convenient route to aromatic nitrogen-containing compounds and H_2 gas.

Keywords: acceptorless dehydrogenation; N-heterocycles; potassium *tert*-butoxide; transition-metal-free; dihydrogen

Saturated N-heterocycles as liquid organic hydrogen carriers (LOHCs) have recently been paid more and more attention for acceptorless dehydrogenation (AD) and releasing H_2 gas.[1] Without energy loss, hydrogen-rich LOHCs can not only be stored for a long time, but can also be transported over long distances. Acceptorless dehydrogenation of saturated N-heterocycles avoids the use of stoichiometric oxidants or sacrificial hydrogen acceptors, and has demonstrated potential applications in the field of organic hydrogen storage materials.[2] Hydrogen gas release from saturated N-heterocycles is thermodynamically unfavored due to its endothermicity, but it is entropically favored.[3] Although dehydrogenation of N-heterocycles by means of external oxidants or sacrificial hydrogen acceptors has been well documented,[4] acceptorless dehydrogenation is strongly desired because of the atom-economy requirement and potential application for hydrogen storage (Scheme 1a). In this regard, Fujita and Yamaguchi, et al. reported the dehydrogenation of tetrahydroquinoline derivatives by Cp*Ir(III) complex catalysts.[5] Xiao and co-workers applied cyclometalated iridium complex catalysts and trifluoroethanol solvent in the dehydrogenation reaction of N-heterocycles under relatively mild conditions.[6] Jones, et al. reached the same goal by means of Fe(II)[7a] and Co(II)-PNP[7b] complex catalysts. Crabtree group reported nickel(II)-mediated electrochemical dehydrogenation of N-heterocycles.[8] Other structurally defined iridium,[9] ruthenium,[10] and osmium[11] complex catalysts have also been developed in this area. Paradies and Grimme,[12a] and Kanai,[12b] independently reported



Scheme 1. Acceptorless dehydrogenation of N-heterocycles.

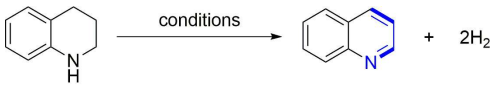
$B(C_6F_5)_3$-catalyzed acceptorless dehydrogenation of N-heterocycles. Photoredox catalysis has also been applied as an effective strategy to execute the same processes.[13] TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl) was used as an effective organo-electrocatalyst for the same goal.[14] Heterogeneous transition-metal catalysts have recently been used for reversible dehydrogenation/hydrogenation of N-heterocycles.[15] There have been some recent publications on acceptorless dehydrogenative coupling of N-heterocycles.[16] However, due to the involvement of transition metals and other specialized catalysts and/or additives, the existing dehydrogenation protocols are often expensive or not very environmentally friendly.

It has been well known that strong bases such as NaOH and KOH can promote Meerwein-Pondorf-Verley-Oppenauer redox reactions of carbonyl compounds and alcohols.[17] Stoichiometric KO*t*Bu base can mediate radical arene C–H/C–I (Br) cross-coupling in the presence of an amine or N-heteroarene as the catalyst or additive.[18] 20 mol% KO*t*Bu was documented to inhibit iron(II)-catalyzed acceptorless dehydrogenation of 1,2,3,4-tetrahydroquinaldine,[7a] while 10 mol% KO*t*Bu exhibited a positive effect on iron nanoparticle-catalyzed acceptorless dehydrogenation of N-heterocycles.[15a] KO*t*Bu (20 mol%) catalyzed the hydrogenation of ketones, and the reaction exhibited the first-order kinetics with respect to the ketone substrate, hydrogen, and the base catalyst.[18d]

During the ongoing investigation of acceptorless dehydrogenation of N-heterocycles,[10c] we found that a base could facilitate acceptorless dehydrogenation of 1,2,3,4-tetrahydroquinoline to form quinoline and H_2 gas in the absence of a transition-metal catalyst. Intrigued by such an unexpected base effect, we explored base-mediated dehydrogenation of a variety of N-heterocycles. Herein, we disclose KO*t*Bu-promoted acceptorless dehydrogenation of N-heterocycles under transition-metal-free conditions (Scheme 1b).

Initially, the reaction conditions were screened by using 1,2,3,4-tetrahydroquinoline (**1a**) as the model substrate. It is noteworthy that the glasswares and magnetos were new for these experiments, and the solvents were dried, distilled, and degassed prior to use. Under a nitrogen atmosphere, treatment of **1a** with 3.0 equiv. of organic base DBU (1,8-diazabicyclo [5.4.0]undec-7-ene) in *o*-xylene at 140 °C for 48 h afforded quinoline (**2a**) in 10% yield (Table 1, entry 1). DABCO (1,4-diazabicyclo[2.2.2]octane), K_2CO_3, and Cs_2CO_3 could not further improve the reaction efficiency. Alkali metal hydroxides NaOH, KOH, and CsOH enhanced the yield to 23–41% (Table 1, entries 2–4). Altering the base to sodium methoxide or ethoxide remarkably increased the yield of **3a** to 66–69%. Sodium *tert*-butoxide further improved the reaction to form **3a** (72%), while the yield was sharply dropped to 19% in the case of using

Table 1. Screening of reaction conditions.[a]



Entry	Base	Base Amount [equiv]	Time [h]	Yield[b] [%]
1	DBU	3.0	48	10
2	NaOH	3.0	48	23
3	KOH	3.0	48	31
4	CsOH	3.0	48	41
5	NaOMe	3.0	48	69
6	NaOEt	3.0	48	66
7	LiO*t*Bu	3.0	48	19
8	NaO*t*Bu	3.0	48	72
9	LDA	3.0	48	0
10	KO*t*Bu	3.0	48	99
11	KO*t*Bu	2.5	48	99
12	KO*t*Bu	2.0	48	76
13	KO*t*Bu	0.5	48	23
14	KO*t*Bu	0.1	48	5
15	KO*t*Bu	2.5	36	75
16	**KO*t*Bu**	**3.0**	**36**	**99 (92)**[c]
17[d]	KO*t*Bu	3.0	48	16
18	**KO*t*Bu**[e]	**3.0**	**36**	**99 (93)**[c]
19[f]	KO*t*Bu	3.0	36	99

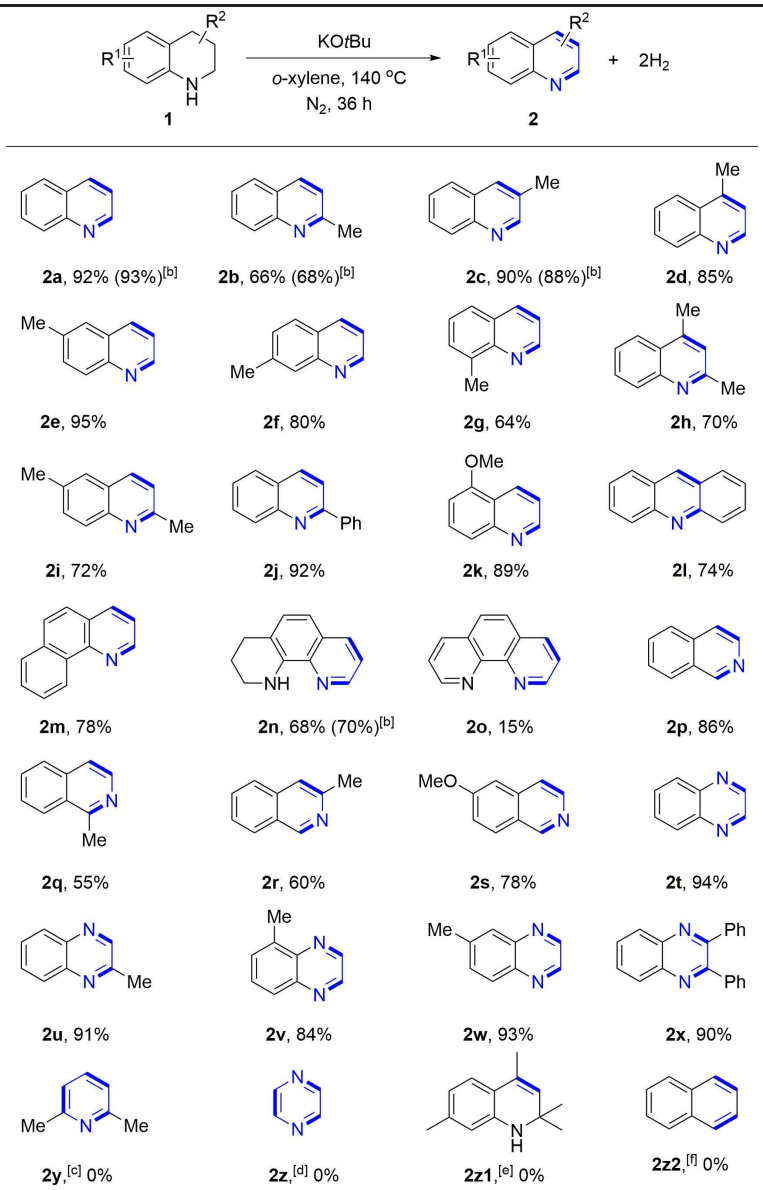
[a] Conditions: **1a** (0.5 mmol), base, *o*-xylene (2 mL), 140 °C, 0.1 MPa N_2. LDA = lithium diisopropylamide.[b] Determined by GC analysis.[c] Isolated yield given in parentheses.[d] 110 °C.[e] Using 99.99% KO*t*Bu. [f] The reaction was conducted under an air atmosphere.

LiO*t*Bu base (Table 1, entries 5–8). LDA (lithium diisopropylamide) showed a remarkable negative lithium ion effect, which completely inhibited the dehydrogenation reaction of **1a** (Table 1, entry 9). The highest yield (99%) was achieved in the presence of KO*t*Bu base (Table 1, entry 10). Both the base loading and reaction time were further optimized, leading to **3a** in 92% isolated yield (Table 1, entries 10–16). Due to the possible coordination of KO*t*Bu to the dehydrogenation product, stoichiometric KO*t*Bu was required.[18] Lowering temperature to 110 °C or conducting the reaction in refluxing toluene dramatically diminished the product yield (Table 1, entry 17). By comparison to 99% KO*t*Bu, high purity (99.99%) KO*t*Bu was applied in the same reaction, resulting in a similar result (Table 1, entry 18). The reaction also smoothly proceeded under an air atmosphere (Table 1, entry 19), but for safety it was carried out for screening of conditions under a nitrogen atmosphere. It is noteworthy that H_2 gas was formed as the only byproduct which was detected by a THERMO^{Star} gas analyzer (see the ESI for details).

Under the optimal conditions, the scope of six-membered N-heterocycles (**1**) was explored (Table 2).

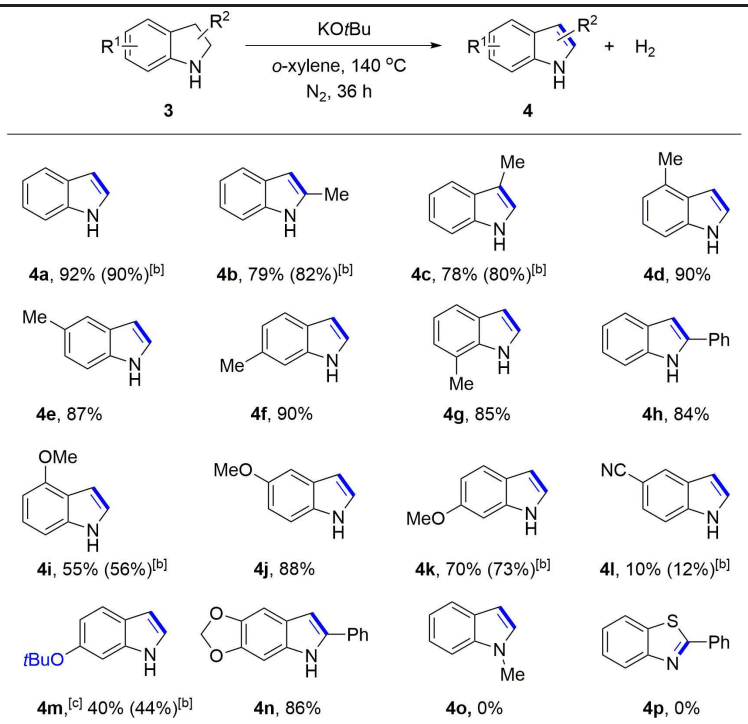
The reactivities of methyl-substituted N-heterocyclic substrates, that is, 2-, 3-, 4-, 6-, 7-, and 8-methyl-1,2,3,4-tetrahydroquinolines (**1b–g**), varied to afford the corresponding dehydrogenation products **2b-g** (64–95%), and the 2- and 8-positioned methyl groups exhibited an obvious steric effect on the yields of **2b** (66%), **2g** (64%), **2h** (70%), and **2i** (72%). However, 2-phenyl-1,2,3,4-tetrahydroquinoline (**1j**) reacted well to give **2j** (92%), and the 2-phenyl group did not exhibit a steric effect. This result is presumably attributed to the coordination interaction between potassium cation and the 2-aryl ring.[18b] 5-Methoxy-1,2,3,4-tetrahydroquinoline (**1k**) also reacted well to form the target product 5-methoxyquinoline (**2k**) in 89% yield. 9,10-Dihydroacridine and 1,2,3,4-tetrahydrobenzo[*h*]quinoline underwent the reaction to give the target products acridine (**2l**, 74%) and benzo[*h*]quinoline (**2m**, 78%) in good yields. The dehydrogenation reaction of 1,2,3,4,7,8,9,10-octahydro-1,10-phenanthroline (**1n**) led to 1,2,3,4-tetrahydro-1,10-phenanthroline (**2n**) in 68% yield, but the corresponding perdehydrogenated product 1,10-phenanthroline (**2o**) was not detected in the reaction mixture. In a separate dehydrogenation reaction of **2n**, compound **2o** was

Table 2. Dehydrogenation of six-membered N-heterocycles (**1**).[a]



[a] Conditions: **1** (0.5 mmol), 99% KO*t*Bu (1.5 mmol), *o*-xylene (2 mL), 0.1 MPa N_2, 140 °C, 36 h. Yields refer to the isolated products.[b] Using 99.99% KO*t*Bu.[c] Using 2,6-dimethylpiperidine (**1y**).[d] Using piperazine (**1z**).[e] Using 2,2,4,7-tetramethyl-1,2,3,4-tetrahydroquinoline (**1z1**).[f] Using 1,2,3,4-tetrahydronaphthalene (**1z2**).

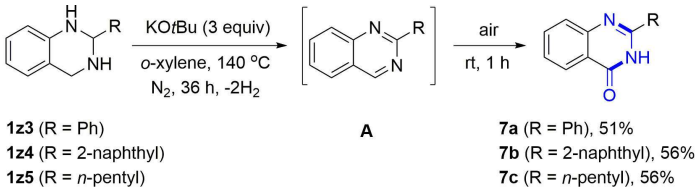
Table 3. Dehydrogenation of five-membered N-heterocycles (**3**).[a]



[a] Conditions: **3** (0.5 mmol), 99% KO*t*Bu (1.0 mmol), *o*-xylene (2 mL), 0.1 MPa N_2, 140 °C, 36 h. Yields refer to the isolated products.[b] Using 99.99% KO*t*Bu.[c] Using 6-chloroindoline (**3 m**).

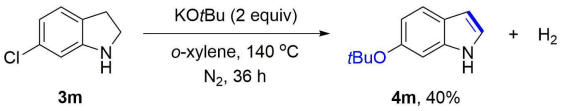
only obtained in 15% yield because it was unstable under the strong basic conditions,[18e] implicating that the possible strong coordination of the quinolinyl nitrogen atom of the substrate to potassium cation diminishes the interaction between the K^+ ion and the aliphatic anionic nitrogen in the reaction intermediate, which thus reduces the reaction efficiency of **2 n**. Tetrahydroisoquinoline (**1 p**) also efficiently reacted to form the corresponding product isoquinoline (**2 p**, 86%), whereas the *α*-methyl groups exhibited a steric effect on the yields of 1- and 3-methylisoquinolines **2 q** (55%) and **2 r** (60%), respectively. 6-Methoxy-isoquinoline (**2 s**) was obtained in a good yield (78%). The dehydrogenation reactions of tetrahydroquinoxalines **1 t-x** smoothly proceeded to give the corresponding quinoxaline products (**2 t–x**) in 84–94% yields, and only in the case of using 5-methyl-tetrahydroquinoxaline (**1 v**) a slight steric effect affected the formation of **2 v** (84%). Unfortunately, 2,6-dimethylpiperidine (**1 y**), piperazine (**1 z**), and 2,2,4,7-tetramethyl-1,2,3,4-tetrahydroquinoline (**1z1**) could not react to yield the corresponding dehydrogenation products 2,6-dimethylpyridine (**2 y**), pyrazine (**2 z**), and 2,2,4,7-tetramethyl-1,2-dihydroquinoline (**2z1**), suggesting the crucial role of both the benzo moiety[1a] and the NH-CH functionality in the N-heterocycle substrates. It is noteworthy that electron-withdrawing groups such as CF_3, CN, and CO_2Et, etc. on the benzo moiety of the substrates dramatically diminished the reaction efficiency. Halogen substituent (F, Cl, or Br) bearing N-heterocycles underwent both *tert*-butoxylation and dehydrogenation under the standard conditions, but no *tert*-butoxylation/dehydrogenation product could be successfully isolated. As a comparison, 1,2,3,4-tetrahydronaphthalene (**1z2**) did not react under the stated conditions, further suggesting the crucial role of an NH-CH functionality in the substrates.

Next, the protocol generality was extended to the dehydrogenation of indolines. The reaction conditions were simply modified by using 2 equiv. of KO*t*Bu base (see the ESI for details). Under the optimal conditions, indole derivatives were efficiently obtained and H_2 gas was formed as the only byproduct (Table 3). The dehydrogenation reaction of indoline (**3 a**) afforded indole (**4 a**) in 92% yield. It should be noted that Jiao, et al. reported that trace amount of dioxygen facilitated the dehydrogenation of 2-cyclopropylindoline in the presence of large excess of KO*t*Bu base (12 equiv), and under the dioxygen-free conditions by means of a small N_2 flow with a positive pressure the indoline dehydrogenation reaction could be excluded.[19] However, when indoline (**3 a**) was used as the substrate under a slight N_2 flow with a positive pressure, the efficient formation of indole (**4 a**, 91%), was not affected, excluding the effect of air or O_2. All the 2-, 3-, 4-, 5-, 6-, and 7-methylindolines (**3 b–g**) efficiently underwent the ac-



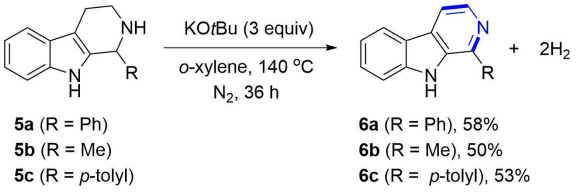
Scheme 2. Synthesis of quinazolin-4(3*H*)-one derivatives.

ceptorless dehydrogenation reaction to give the target products **4b–g** in 78–90% yields. The 2- and 3-methyl groups on the five-membered N-heterocyclic ring exhibited a steric effect on the yields of **4b** (79%) and **4c** (78%), respectively, while the methyl substituents on the aryl ring did not show an obvious substituent effect. 2-Phenylindoline (**3h**) also underwent the reaction efficiently, giving compound **4h** (84%). Dehydrogenation of 4-methoxyindoline (**3i**) produced 4-methoxy-1*H*-indole (**4i**) in 55% yield, while 5-methoxy promoted the reaction to form 5-methoxy-1*H*-indole (**4j**, 88%). However, 6-methoxyindoline (**3k**) reacted much less efficiently than **3j**, affording compound **4k** (70%). 5-Cyanoindoline (**3l**) was sluggish under the stated conditions, and its reaction only resulted in 5-cyanoindole (**4l**) in a low yield (10%). Unexpectedly, 6-chloroindoline (**3m**) underwent a *tert*-butoxylation/dehydrogenation cascade to form **4m** in 40% yield [Eq. (1)]. It was noticed that all the fluoro-, chloro-, and bromo-substituted tetrahydroquinolines underwent the dehydrogenation reaction inefficiently due to the side *tert*-butoxylation reaction. 6-Phenyl-6,7-dihydro-5*H*-[1,3]dioxolo[4,5-*f*]indole (**3n**) exhibited an excellent reactivity to generate the dehydrogenation product **4n** in 86% yield. 1-Methylindoline (**3o**) stayed unchanged under the standard conditions, suggesting the indispensable role of an N–H functionality in the N-heterocycle substrates. The reaction of 2-phenyl-2,3-dihydrobenzothiazole (**3p**) was complicate that no target product could be isolated, presumably due to its decomposition under the strong basic conditions. It is noteworthy that 99.99% KO*t*Bu also promoted the dehydrogenation of indolines, giving the results comparable to those using 99% KO*t*Bu.



(1)

Then, the synthetic protocol was applied for the synthesis of potentially useful N-heteroarenes. Drug development-relevant *β*-carboline is an important motif in many synthetic compounds and natural products. Thus, 1,2,3,4-tetrahydro-*β*-carbolines **5**[20] were subjected to the standard dehydrogenation conditions, affording the corresponding 1-substituted-9*H*-pyrido[3,4-*b*]indoles **6** in 50–58% yields [Eq. (2)], which provides a concise and green route to *β*-carboline derivatives by comparison to the transition-metal-catalyzed procedures.[21] This methodology was

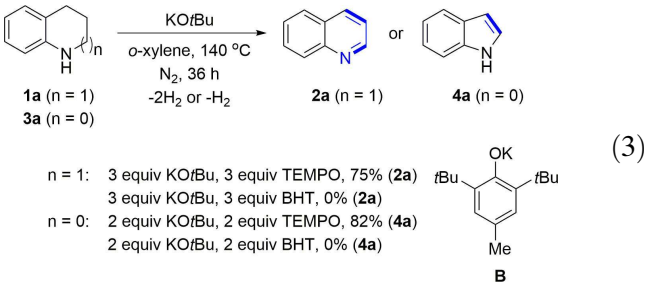


(2)

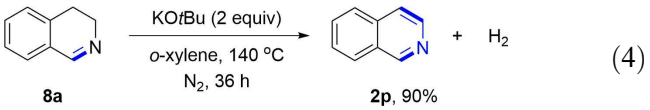
further utilized for the one-pot synthesis of quinazolin-4(3*H*)-ones **7** in 51–56% yields (Scheme 2). 2-Phenylquinazolin-4(3*H*)-one (**7a**) is a useful *β*-glucuronidase inhibitor,[14] and compounds **7b** and **7c** exist in many natural products and synthetic molecules with diverse biological activities.[22] It should be noted that the desired dehydrogenation products, that is, quinazolines **A**, could not be successfully isolated due to their easy oxidation in air under the strong basic conditions. In our hands, the resultant reaction mixtures were allowed to be stirred in air at room temperature for 1 h before they were subjected to work-up, and quinazolin-4(3*H*)-one derivatives **7** were then isolated by silica gel column chromatography.

To gain insights into the dehydrogenation process, mechanistic studies were conducted. When radical scavenger TEMPO was added in the reaction mixture of 1,2,3,4-tetrahydroquinoline (**1a**) or indoline (**3a**) under the standard conditions, the product yield was slightly decreased, suggesting that a radical pathway can be excluded [Eq. (3)].[14] In the presence of 2~3 equiv. of BHT (2,6-di-*tert*-butyl-4-methylphenol), the same dehydrogenation reactions could not occur because BHT readily reacted with KO*t*Bu to form *t*BuOH and potassium phenoxide **B** which could not promote the dehydrogenation of **1a** or **3a** under the stated conditions. It has been well known that imines are usually formed or considered as the reaction intermediates in a typical dehydrogenation process of N-heterocycles.[1] Thus, 3,4-dihydroisoquinoline (**8a**), the imine generated from tetrahydroisoquinoline (**1p**), was treated under the similar basic conditions, giving isoquinoline (**2p**) in 90% yield [Eq. (4)]. In a similar fashion, imine 2,3-diphenyl-1,2-dihydroquinoxaline (**8b**) reacted to yield 2,3-diphenylquinoxaline (**2x**, 92%) as the product [Eq. (5)]. These results have

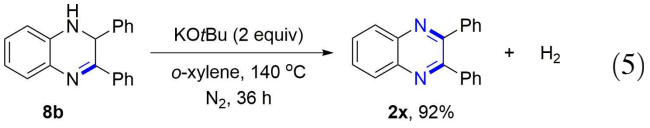
suggested that in the whole dehydrogenation process partially dehydrogenated imine species may be the key reaction intermediates,



(3)

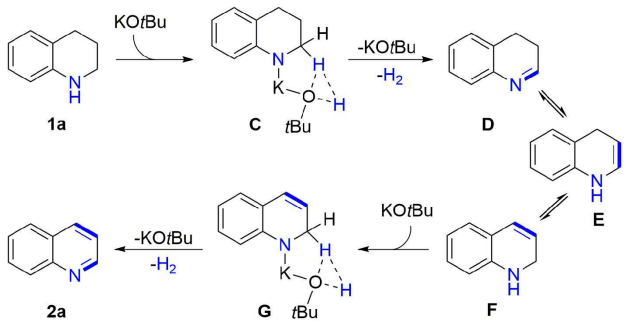


(4)



(5)

A plausible mechanism is proposed in Scheme 3.[7,18] Initially, KO*t*Bu base deprotonates 1,2,3,4-tetrahydroquinoline (**1a**) to form the corresponding potassium amide which interacts with *in-situ* generated *tert*-butyl alcohol by coordination and hydrogen bonding, establishing transition state **C**. Imine intermediate 3,4-dihydroquinoline (**D**) is then produced with regeneration of KO*t*Bu base and release of H_2 gas. Isomerization of intermediate **D** to 1,2-dihydroquinoline (**F**) *via* enamine 1,4-dihydroquinoline (**E**) is thermodynamically favored.[1d,14] Subsequently, the resultant aromatic amine species reacts with KO*t*Bu base again to form the potassium amide which undergoes the second dehydrogenation process through transition state, affording entropically favored aromatic N-heterocyclic compound **2a** and H_2 gas. It is noteworthy that potassium cation may execute coordination



Scheme 3. Proposed mechanism.

to the benzo functionality of the substrate[18a,b] to enhance its dehydrogenation reactivity. It is noteworthy that 1,2,3,4-tetrahydronaphthalene could not undergo the dehydrogenation reaction under the standard conditions (Table 2), suggesting the necessity of a nitrogen atom in the substrate to coordinate potassium *tert*-butoxide.

In conclusion, we have developed a highly efficient transition-metal-free protocol to access diverse N-heteroarenes through base-promoted acceptorless dehydrogenation of N-heterocycles. The present methodology has also demonstrated a potential application for the synthesis of drug development-relevant *β*-carboline and quinazolin-4(3*H*)-one derivatives. Due to easy manipulations, readily available reactants, and transition-metal-free conditions, the present work offers a simple and applicable method for acceptorless dehydrogenation of N-heterocycles to access N-heteroarenes and H_2 gas.

Experimental Section

Synthesis of Quinoline (2 a)

Under a nitrogen atmosphere, a mixture of 1,2,3,4-tetrahydroquinoline (1a) (67 mg, 0.50 mmol) and KO*t*Bu (168 mg, 1.5 mmol) in *o*-xylene (2 mL) was stirred at 140 °C for 36 h. After cooled to ambient temperature, 30 mL saturated aqueous NH_4Cl was added and the mixture was extracted with ethyl acetate (3 × 10 mL). The combined extracts were dried over anhydrous Na_2SO_4, filtered, and evaporated all the volatiles under reduced pressure. The resultant residue was subjected to purification by silica gel column chromatography (eluent: petroleum ether (60–90 °C)/ethyl acetate = 7:1, v/v) to afford quinoline (2 a) as a yellow oil (60 mg, 92%).

Acknowledgements

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References

[1] a) Q. Yin, M. Oestreich, *Angew. Chem. Int. Ed.* **2017**, *56*, 7716–7718; *Angew. Chem.* **2017**, *129*, 7824–7826; b) Z. X. Giustra, J. S. A. Ishibashi, S.-Y. Liu, *Coord. Chem. Rev.* **2016**, *314*, 134–181; c) C. Gunanathan, D. Milstein, *Science* **2013**, *341*, 1229712; d) X. X. Li, Z. X. Wang, *Sci. China Chem.* **2012**, *55*, 1991–2008; e) G. E. Dobereiner, R. H. Crabtree, *Chem. Rev.* **2010**, *110*, 681–703.

[2] a) G. A. Filonenko, R. van Putten, E. J. M. Hensen, E. A. Pidko, *Chem. Soc. Rev.* **2018**, *47*, 1459–1483; b) P. Preuster, C. Papp, P. Wasserscheid, *Acc. Chem. Res.* **2017**, *50*, 74–85; c) R. H. Crabtree, *ACS Sustainable Chem. Eng.* **2017**, *5*, 4491–4498.

[3] a) R. H. Crabtree, *Energy Environ. Sci.* **2008**, *1*, 134–138; b) P. Jessop, *Nat. Chem.* **2009**, *1*, 350–351.
[4] a) W. Y. Zhou, Q. Y. Tao, F. A. Sun, X. B. Cao, J. F. Qian, J. Xu, M. Y. He, Q. Chen, J. L. Xiao, *J. Catal.* **2018**, *361*, 1–11; b) Y. J. Zhang, S. F. Pang, Z. H. Wei, H. J. Jiao, X. C. Dai, H. L. Wang, F. Shi, *Nat. Commun.* **2018**, *9*, 1465. c) Y.-Q. Huang, H.-J. Song, Y.-X. Liu, Q.-M. Wang, *Chem. Eur. J.* **2018**, *24*, 2065–2069; d) S. M. Chen, Q. Q. Wan, A. K. B. Tawiah, *Angew. Chem. Int. Ed.* **2016**, *55*, 9345–9349; *Angew. Chem.* **2016**, *128*, 9491–9495; e) X. J. Cui, Y. H. Li, S. Bachmann, M. Scalone, A.-E. Surkus, K. Junge, C. Topf, M. Beller, *J. Am. Chem. Soc.* **2015**, *137*, 10652–10658.
[5] a) R. Yamaguchi, C. Ikeda, Y. Takahashi, K.-i. Fujita, *J. Am. Chem. Soc.* **2009**, *131*, 8410–8412; b) K.-i. Fujita, Y. Tanaka, M. Kobayashi, R. Yamaguchi, *J. Am. Chem. Soc.* **2014**, *136*, 4829–4832; c) K.-i. Fujita, T. Wada, T. Shiraishi, *Angew. Chem. Int. Ed.* **2017**, *56*, 10886–10889; *Angew. Chem.* **2017**, *129*, 11026–11029.
[6] J. J. Wu, D. Talwar, S. Johnston, M. Yan, J. L. Xiao, *Angew. Chem. Int. Ed.* **2013**, *52*, 6983–6987; *Angew. Chem.* **2013**, *125*, 7121–7125.
[7] a) S. Chakraborty, W. W. Brennessel, W. D. Jones, *J. Am. Chem. Soc.* **2014**, *136*, 8564–8567; b) R. B. Xu, S. Chakraborty, H. M. Yuan, W. D. Jones, *ACS Catal.* **2015**, *5*, 6350–6354.
[8] O. R. Luca, D. L. Huang, M. K. Takase, R. H. Crabtree, *New J. Chem.* **2013**, *37*, 3402–3405.
[9] a) D. F. Brayton, C. M. Jensen, *Chem. Commun.* **2014**, *50*, 5987–5989; b) M. G. Manas, L. S. Sharninghausen, E. Lin, R. H. Crabtree, *J. Organomet. Chem.* **2015**, *792*, 184–189; c) A. Vivancos, M. Beller, M. Albrecht, *ACS Catal.* **2018**, *8*, 17–21.
[10] a) S. Muthaiah, S. H. Hong, *Adv. Synth. Catal.* **2012**, *354*, 3045–3053; b) I. Dutta, S. Yadav, A. Sarbajna, S. De, M. Hölscher, W. Leitner, J. K. Bera, *J. Am. Chem. Soc.* **2018**, *140*, 8662–8666; c) Q. F. Wang, H. N. Chai, Z. K. Yu, *Organometallics* **2018**, *37*, 584–591.
[11] a) M. A. Esteruelas, V. Lezáun, A. Martínez, M. Oliván, E. Oñate, *Organometallics* **2017**, *36*, 2996–3004; b) M. L. Buil, M. A. Esteruelas, M. P. Gay, M. Gómez-Gallego, A. I. Nicasio, E. Oñate, A. Santiago, M. A. Sierra, *Organometallics* **2018**, *37*, 603–617.
[12] a) A. F. G. Maier, S. Tussing, T. Schneider, U. Flörke, Z.-W. Qu, S. Grimme, J. Paradies, *Angew. Chem. Int. Ed.* **2016**, *55*, 12219–12223; *Angew. Chem.* **2016**, *128*, 12407–12411; b) M. Kojima, M. Kanai, *Angew. Chem. Int. Ed.* **2016**, *55*, 12224–12227; *Angew. Chem.* **2016**, *128*, 12412–12415.
[13] a) S. Kato, Y. Saga, M. Kojima, H. Fuse, S. Matsunaga, A. Fukatsu, M. Kondo, S. Masaoka, M. Kanai, *J. Am. Chem. Soc.* **2017**, *139*, 2204–2207; b) K.-H. He, F.-F. Tan, C.-Z. Zhou, G.-J. Zhou, X.-L. Yang, Y. Li, *Angew. Chem. Int. Ed.* **2017**, *56*, 3080–3084; *Angew. Chem.* **2017**, *129*, 3126–3130; c) M. F. Zheng, J. L. Shi, T. Yuan, X. C. Wang, *Angew. Chem. Int. Ed.* **2018**, *57*, 5487–5491; *Angew. Chem.* **2018**, *130*, 5585–5589.
[14] Y. Wu, Hong Yi, A. Lei, *ACS Catal.* **2018**, *8*, 1192–1196.
[15] a) G. Jaiswal, V. G. Landge, D. Jagadeesan, E. Balaraman, *Nat. Commun.* **2017**, *8*, 2147; b) C. Deraedt, R. Ye, W. T. Ralston, F. D. Toste, *J. Am. Chem. Soc.* **2017**, *139*, 18084–18092; c) Y. H. Han, Z. Y. Wang, R. R. Xu, W. Zhang, W. X. Chen, L. R. Zheng, J. Zhang, J. Luo, K. L. Wu, Y. Q. Zhu, C. Chen, Q. Peng, Q. Liu, P. Hu, D. S. Wang, Y. D. Li, *Angew. Chem. Int. Ed.* **2018**, *57*, 11262–11266; *Angew. Chem.* **2018**, *130*, 11432–11436.
[16] a) D. Talwar, A. Gonzalez-de-Castro, H. Y. Li, J. L. Xiao, *Angew. Chem. Int. Ed.* **2015**, *54*, 5223–5227; *Angew. Chem.* **2015**, *127*, 5312–5316; b) C. J. Zhou, Z. D. Tan, H. F. Jiang, M. Zhang, *ChemCatChem* **2018**, *10*, 2887–2892.
[17] a) Q. Xu, J. H. Chen, H. W. Tian, X. Q. Yuan, S. Y. Li, C. K. Zhou, J. P. Liu, *Angew. Chem. Int. Ed.* **2014**, *53*, 225–229; *Angew. Chem.* **2014**, *126*, 229–233; b) L. J. Allen, R. H. Crabtree, *Green Chem.* **2010**, *12*, 1362–1364.
[18] a) C.-L. Sun, Z.-J. Shi, *Chem. Rev.* **2014**, *114*, 9219–9280; b) C.-L. Sun, H. Li, D.-G. Yu, M. Yu, X. Zhou, X.-Y. Lu, K. Huang, S.-F. Zheng, B.-J. Li, Z.-J. Shi, *Nat. Chem.* **2010**, *2*, 1044–1049; c) L. Zhang, H. Yang, L. Jiao, *J. Am. Chem. Soc.* **2016**, *138*, 7151–7160; d) A. Berkessel, T. J. S. Schubert, T. N. Müller, *J. Am. Chem. Soc.* **2002**, *124*, 8693–8698; e) S. Zhou, G. M. Anderson, B. Mondal, E. Doni, V. Ironmonger, M. Kranz, T. Tuttle, J. A. Murphy, *Chem. Sci.*, **2014**, *5*, 476–482.
[19] H. Yang, D.-Z. Chu, L. Jiao, *Chem. Sci.*, **2018**, *9*, 1534–1539.
[20] W. Q. Jiang, X. Q. Zhang, Z. H. Sui, *Org. Lett.* **2003**, *5*, 43–46
[21] S. Eagon, M. O. Anderson, *Eur. J. Org. Chem.* **2014**, *2014*, 1653–1665.
[22] Z. Wang, X. Wu, L. Wang, J. Zhang, J. Liu, Z. Song, Z. Tang, *Bioorg. Med. Chem. Lett.* **2016**, *26*, 2589–2593.

