Communication

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General and Practical KOMe/Disilane-Mediated Dehalogenative Deuteration of (Hetero)Arylhalides

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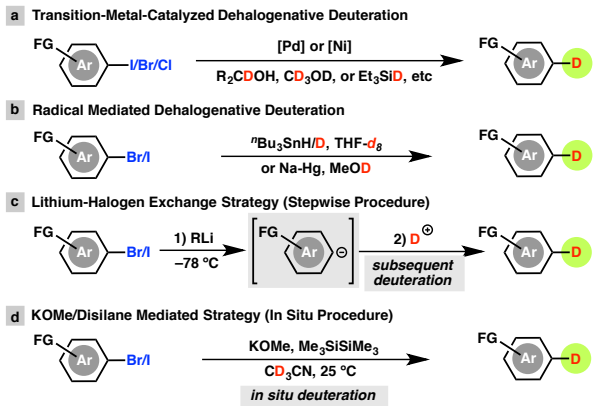
Supporting Information Placeholder

ABSTRACT: Herein we describe a general, mild and scalable method for deuterium incorporation by potassium methoxide/hexamethyldisilane-mediated dehalogenation of arylhalides. With CD_3CN as a deuterium source, a wide array of heteroarenes prevalent in pharmaceuticals and bearing diverse functional groups, are labeled with excellent deuterium incorporation (>60 examples). The *ipso*-selectivity of this method provides precise access to libraries of deuterated indoles and quinolines. The synthetic utility of our method has been demonstrated by the incorporation of deuterium into complex natural and drug-like compounds.

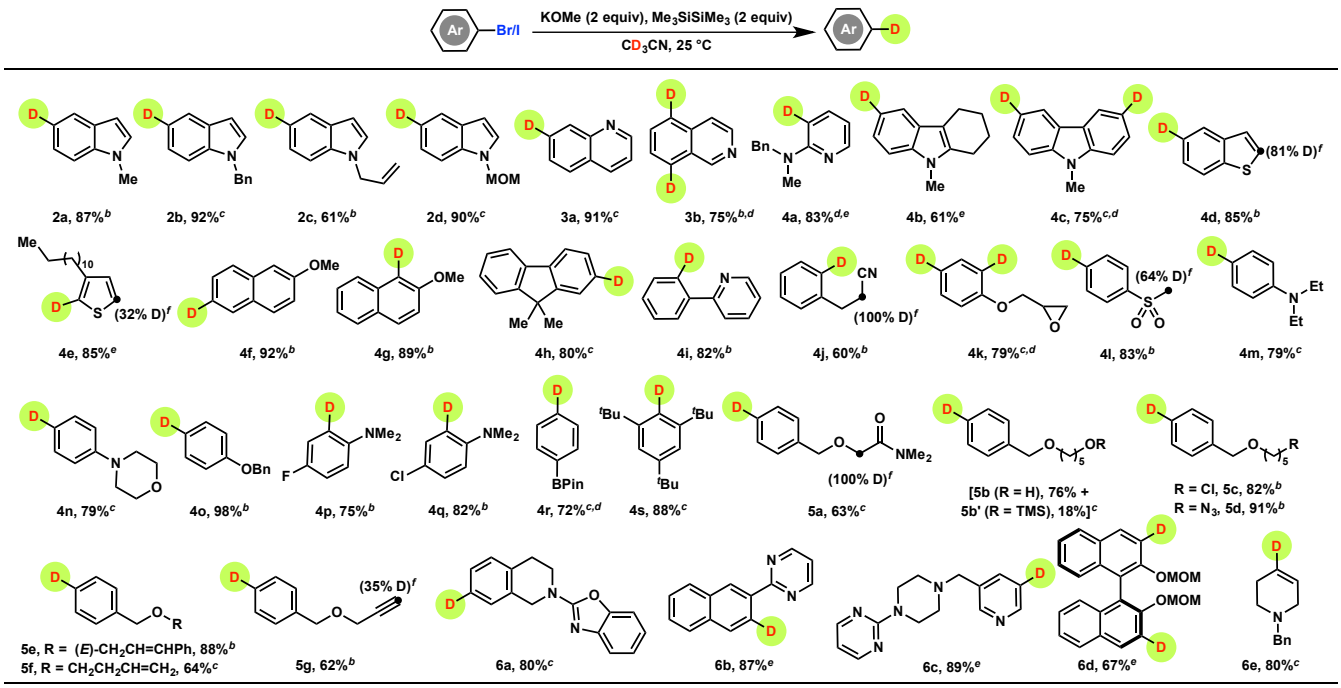
Deuteration has found widespread applications in chemistry and related fields, such as organic synthesis,[1] mechanistic studies,[2] quantitative analyses,[3] and pharmaceutical discoveries and developments.[4] Deuterium labeling techniques are broadly utilized as efficient tools for optimization of metabolic stability and toxicity of drugs.[5] Moreover, introducing deuterium into active pharmaceutical ingredients may enhance their pharmacokinetic and pharmacodynamics properties.[6] Therefore, deuterium incorporation is clinically meaningful and has the potential to enable new drug discovery.[4]

Development of efficient methods for deuteration has recently attracted much attention.[7,8] Dehalogenative deuteration of widely available arylhalides is a convenient way to access versatile deuterated products. A number of methods enabling such transformation have been reported and widely used,[7–10] such as lithium-halogen exchange,[9] transition-metal-catalyzed dehalogenative reduction,[10a–f] and organotin[10g] or sodium amalgam[10h] mediated halogen abstraction (Scheme 1a – c). However, the necessities of precious metal catalysts/ligands, toxic tin reagents, or highly reactive alkyllithium reagents under cryogenic conditions disadvantage the applications of those protocols. Crucially, one of the major challenges and potential limitations in halogen/lithium exchange is the poor tolerance of functional groups.[9] Alternatively, direct hydrogen isotope exchange (HIE) was found to be a straightforward strategy,[11] and great advances were made recently by the Chirik[11f] and Macmillan[11g] groups using iron and iridium photoredox catalysis respectively. Although these are powerful methods, achieving precise site-selectivity and high deuterium incorporation is still challenging. Therefore, general and mild methods with broad substrate scope, precise selectivity, and excellent deuterium incorporation are highly desirable. Recently, we have developed a simple dehalogenative deuteration strategy using a combination of potassium methoxide (KOMe) and hexamethyldisilane ($Me_3SiSiMe_3$) in CD_3CN at room temperature (Scheme 1d). This mild method works well with arylhalides and alkenylhalides, and tolerates a wide range of functionalities. Moreover, deuteration can be easily controlled as the *ipso*-deuteration products are formed in a site-specific manner. Herein we wish to report the preliminary studies of this methodology.[12]

Scheme 1. Deuterium Incorporation with Arylhalides.



Scheme 2. Substrate Scope Studies[a]



[a]Reactions were conducted on 0.5 mmol scale. [b]With 20 equiv of CD_3CN. [c]With 50 equiv of CD_3CN. [d]With KOMe (4 equiv) and $Me_3SiSiMe_3$ (4 equiv). [e]0.2 mmol scale with 1 mL CD_3CN. [f]Proton/deuterium exchange ratio of acidic protons with CD_3CN.

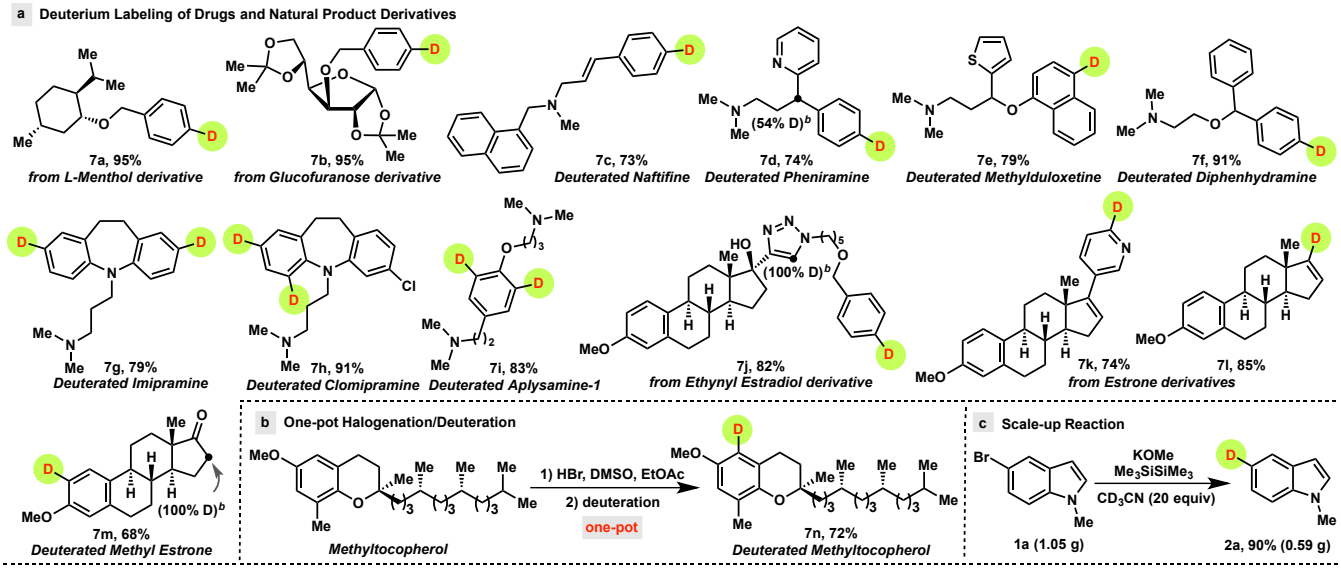
Our investigations started with 1-methyl-5-bromoindole (**1a**) as a model substrate. Extensive optimization experiments identified that treatment of **1a** with KOMe, $Me_3SiSiMe_3$, and a relatively cheap deuterium source–CD_3CN (20 equiv) led to the desired product **2a** in excellent yield (see Table S1 in SI for condition optimizations and discussions). Iodoindole shows similar reactivity, but chloroindole or fluoroindole is completely inert. It is worth noting that the reaction occurs at room temperature with exclusively deuterium incorporation and without the formation of silylation byproducts.[13]

With the optimized conditions in hand, we next turned our efforts to investigate the scope of substrates (Scheme 2). 5-Bromoindoles with various *N*-protecting groups such as Me, Bn, allyl, and MOM, all provided the corresponding deuterated products (**2a** – **2d**) in 61 – 92% yield. Many other pharmaceutically important heterocyclic scaffolds, including quinoline (**3a**), isoquinoline (**3b**), pyridine (**4a**), (tetrahydro)carbazole (**4b** and **4c**), benzothiophene (**4d**), and thiophene (**4e**), all provided the deuterated heterocycles in moderate to good yield (61 – 91 %). Naphthalenes and fluorene were also compatible delivering the corresponding products (**4f**, **4g** and **4h**) smoothly. Next, we explored the electronics effect of substituents on arylbromides. Diverse functionalities such as pyridine (**4i**), nitrile (**4j**), epoxide (**4k**), sulfone (**4l**), amine (**4m**), morpholine (**4n**), benzyloxy (**4o**), were all well tolerated and offered access to deuterium derivatives in 60 – 98% yield. Products **4p** and **4q** were obtained without affecting the chloride and fluoride. In particular, boronate (Bpin) containing product **4r** was successfully synthesized in 72% yield which allows the streamline derivatizations of this deuterated moiety. Surprisingly, the debromination proceeded efficiently even with a sterically-encumbered substrate (2,4,6-tri-tertbutyl-benzyl bromide) to give product **4s** in 88% yield.

To further elaborate the functional group compatibility of this chemistry, a variety of oxygen-tethered benzyl bromides were prepared and subjected to the standard conditions (**5a** – **5g**). To our delight, substrates with a side chain containing amide (**5a**), free alcohol (**5b**), chloride (**5c**), azide (**5d**), internal or terminal olefins (**5e** and **5f**), and terminal alkyne (**5g**) all underwent debrominative deuteration smoothly resulting in the corresponding products in 62 – 94% yield. Interestingly, a free alcohol was partially protected in situ to form silyl ether as well (i.e., **5b**, see SI).[14] In addition, benzooxazole, pyrimidine, and piperiazine containing deuterated compounds (**6a** – **c**) were also successfully accessed in 80% – 89% yield. Finally, the reactions with methoxymethyl-protected (*S*)-3,3'-dibromo-BINOL and alkenylbromide furnished products **6d** and **6e** in 67% and 80% yield, respectively.

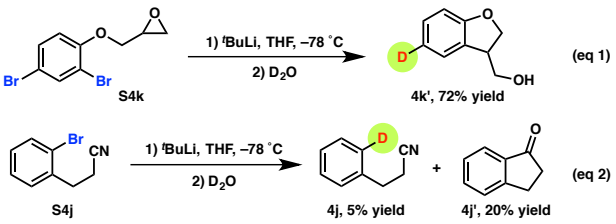
Several additional points regarding the substrate scope investigations are noteworthy. Sensitive functionalities that are incompatible with alkyl lithium, such as epoxide, nitrile, quinoline, pyrimidine etc, are well tolerated. For instance, treatment of epoxide **S4k** and nitrile **S4j** under halogen/lithium exchange conditions resulted in cyclized **4k'** and **4j'** as the major products (eqs 1 and 2). A direct comparison with previously strategies demonstrated that

Scheme 3. Deuterium Incorporation into Pharmaceutically important molecules and Scale-up Reaction[a]



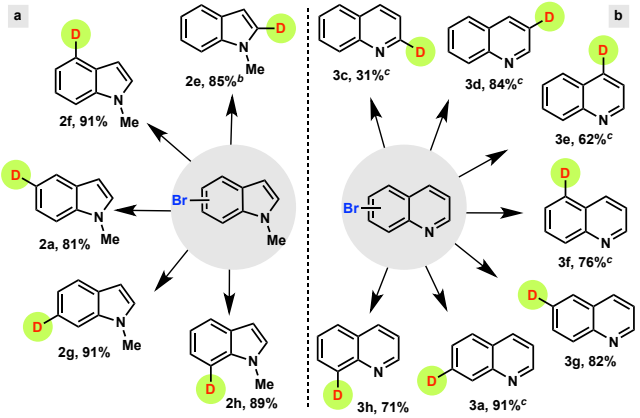
[a]See SI for the detailed reaction conditions. [b]Proton/deuterium exchange ratio of acidic protons with CD_3CN.

our chemistry not only allows a broad substrate scope but also offers a positional complement to recently reported two-step procedure of phosphorium salt formation/deuteration of pyridines and diazines[12a] (see Scheme S1 in SI for the comparison results with halogen-lithium exchange, transition-metal catalysis, and sequential phosphoration/deuteration). Secondly, substrates bearing acidic protons (i.e., α-position of nitrile, amide, and sulfone) undergo proton/deuterium exchange with CD_3CN. Finally, with respect to known limitations, monosubsituted or 1,2-disubstituted linear alkenylbromides gave eliminated alkynes without formation of the desired deuterated products.



The promising functional group tolerance and mild reaction conditions of this protocol enable its application to the deuteration of pharmaceuticals and natural product derivatives (Scheme 3a). Introducing deuterium into menthol (**7a**) and glucofuranose (**7b**) derivatives were successfully realized in excellent yields. Deuterated naftifine (**7c**), pheniramine (**7d**), methylduloxetine (**7e**), diphenhydramine (**7f**), imipramine (**7g**), clomipramine (**7h**), aplysamine (**7i**) were achieved from the corresponding bromide precursors in 73 – 91% yield. A triazole derivative of estradiol (**7j**) was accommodated and deuterium was introduced in 82% yield. Additionally, deuterated estrone analogs (**7k** – **7m**) were readily synthesized in 68 – 85% yield. In the case of estrone **7m**, the carbonyl group adjacent to a quaternary carbon was compatible. Moreover, a formal isotopic exchange of the original C–H bond of methyltocopherol (**7n**) was realized by performing both the bromination[15a] and deuteration in a one-pot fashion to eliminate the need for isolation of the bromo-precursors (Scheme 3b). Finally, we were delighted to find that the reaction was amenable to scale up using 20 equivalent of deuterium source without loss of efficiency (Scheme 3c).

Scheme 4. Combinatorial Synthesis of Libraries of Deuterated Indoles (a) and Quinolines (b)[a]



[a]Reactions were conducted on 0.5 mmol scale with 20 equiv of CD_3CN. [b]With *N*-Me-2-I-indole as substrate. [c]With 50 equiv of CD_3CN.

Precise deuteration of the specific bond of interest is necessary for methods to be useful in drug discovery and mechanistic studies. Such a highly selective deuteration is still a significant challenge for the HIE processes.[11] In contrast, given the availability of diverse arylhalides,[15] site-specifically introducing deuterium into target molecules could be rapidly accessed by our methodology. To showcase this feature, pinpoint incorporation of deuterium into privileged heterocycles was carried out. Starting from

bromo- or iodo-precursors, a library of deuterated indoles (**2a**, and **2e** – **2h**) were synthesized in moderate to good yield (81 – 91%) with excellent deuterium incorporation (Scheme 4a). Similarly, quinolones (**3a**, and **3c** – **3h**) were successfully labeled (from C2 to C8) in 31 – 91% yield (Scheme 4b).

A number of synthetic methods with potassium alkoxides and organosilanes have been reported involving the intermediacy of either radicals or silyl anions.[13,16] We first considered the possibility of a radical pathway. The addition of TEMPO, which is able to shut down the silyl radical addition,[16e] has little effect to the deuteration reaction (see Scheme S2a in SI). Moreover, when a radical probe substrate 1-bromo-2-(but-3-en-1-yl)benzene was used, *ipso*-debromination product was obtained in 54% yield exclusively without the observation of radical cyclization reaction (Scheme S2b).[17] Those results indicate that a free radical species is less possible. Inspired by previous studies reporting silyl substitutions of aryl halides by Ito et al[18] and Strohmann et al,[19] a putative mechanism involving an anionic pathway is proposed to be active under our reation conditions (Scheme S2c). The mixture of KOMe and $Me_3SiSiMe_3$ may slowly generate trimethylsilyl anion or a nucleophilic hypervalentsilane species,[16] which attacks the aryl bromide to form an aryl carbanion.[18] The transient carbanion is instantaneously trapped by the large excess of CD_3CN to provide the desired deuterated product. Detailed studies aimed at understanding mechanism will be carried out to further probe this hypothesis.

In summary, a general KOMe/disilane-mediated *ipso*-dehalogenative deuteration reaction in CD_3CN was developed. This method features operationally simple procedures, mild reaction conditions, readily available reagents, and good functional group tolerance. A diverse range of valuable deuterated (hetero)arenes, natural products, and pharmaceuticals were isotopically labeled with excellent deuterium incorporation and specificity. Further mechanistic studies are currently ongoing.

ASSOCIATED CONTENT

The Supporting Information is available free of charge on the ACS Publications website.

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

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Notes

The authors declare no competing financial interest. A provisional patent has been filed.

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REFERENCES

(1) (a) Miyashita, M.; Sasaki, M.; Hattori, I.; Sakai, M.; Tanino, K. *Science* **2004**, *305*, 495. (b) Quasdorf, K. W.; Huters, A. D.; Lodewyk, M. W.; Tantillo, D. J.; Garg, N. K.; *J. Am. Chem. Soc.* **2012**, *134*, 1396.

(2) (a) Wiberg, K. B. *Chem. Rev.* **1955**, *55*, 713. (b) Simmons, E. M.; Hartwig, J. F. *Angew. Chem. Int. Ed.* **2012**, *51*, 3066.

(3) Selected example, see: Bergner, G.; Albert, C. R.; Schiller, M.; Bringmann, G.; Schirmeister, T.; Dietzek, B.; Niebling, S.; Schlücker, S.; Popp, J. *Analyst* **2011**, *136*, 3686.

(4) For a seminal report, see: (a) Belleau, B.; Burba, J.; Pindell, M.; Reiffenstein, J. *Science* **1961**, *133*, 102. For selected reviews, see: (a) Timmins, G. S. *Expert Opin. Ther. Pat.* **2014**, *24*, 1067. (b) Harbeson, S. L.; Tung, R. D. *MedChem. News* **2014**, 8. (c) Mullard, A. *Nat. Rev. Drug Discov.* **2016**, *15*, 219. (d) Harbeson, S. L.; Tung, R. D. *Annu. Rep. Med. Chem.* **2011**, *46*, 403. (e) Gant, T. G. *J. Med. Chem.* **2014**, *57*, 3595.

(5) (a) Helfenbein, J.; Lartigue, C.; Noirault, E.; Azim, E.; Legailliard, J.; Galmier, M. J.; Madelmont, J. C. *J. Med. Chem.* **2002**, *45*, 5806. (b) Shao, L.; Hewitt, M. C. *Drug News Perspect.* **2010**, *23*, 398. (c) Elmore, C. S.; Bragg, R. A. *Bioorg. Med. Chem. Lett.* **2015**, *25*, 167.

(6) Selected examples: (a) Morgan, A. J.; Nguyen, S.; Uttamsingh, V.; Bridson, G.; Harbeson, S.; Tung, R.; Masse, C. E. *J. Labeled Comp. Radiopharm.* **2011**, *54*, 613. (b) Sharma, R.; Strelevitz, T. J.; Gao, H.; Clark, A. J.; Schildknegt, K.; Obach, R. S.; Ripp, S. L.; Spracklin, D. K.; Tremaine, L. M.; Vaz, A. D. N. *Drug Metab. Dispos.* **2012**, *40*, 625. (c) Stringer, R. A.; Williams, G.; Picard, F.; Sohal, B.; Kretz, O.; McKenna, J.; Krauser, J. A. *Drug Metab. Dispos.* **2014**, *42*, 954.

(7) For reviews, see: (a) Atzrodt, J.; Derdau, V.; Fey, T.; Zimmerman, J. *Angew. Chem. Int. Ed.* **2007**, *46*, 7744. (b) Atzrodt, J.; Derdau,V.; Kerr, W. J.; Reid, M. *Angew. Chem. Int. Ed.* **2018**, *57*, 3022.

(8) A particularly attractive method was established by Wood and co-workers using D_2O as the deuterium source, see: (a) Spiegel, D. A.; Wiberg, K. B.; Schacherer, L. N.; Medeiros, M. R.; Wood, J. L. *J. Am. Chem. Soc.* **2005**, *127*, 12513. For a recent example, see: (b) Soulard, V.; Villa, G.; Vollmar, D. P.; Renaud, P. *J. Am. Chem. Soc.* **2018**, *140*, 155.

(9) (a) Bailey, W. F.; Patricia, J. J. *J. Organomet. Chem.* **1988**, *352*, 1. (b) Yus, M. *Chem. Soc. Rev.* **1996**, *25*, 155. (c) Yus, M. *Synlett* **2001**, *8*, 1197. (d) Reich, H. J. *J. Org. Chem.* **2012**, *77*, 5471.

(10) For a review of metal-mediated reductive hydrodehalogenation: (a) Alonso, F.; Beletskaya, I. P; Yus, M. *Chem. Rev.* **2002**, *102*, 4009. For selected examples of transition-metal catalyzed dehalogenative deuteration: (b) Desmarets, C.; Kuhl, S.; Schneider, R.; Fort, Y. *Organometallics* **2002**, *21*, 1554. (c) Janni, M.; Peruncheralathan, S. *Org. Biomol. Chem.* **2016**, *14*, 3091. (d) Kuriyama, M.; Hamaguchi, N.; Yano, G.; Tsukuda, K.; Sato, K.; Onomura, O. *J. Org. Chem.* **2016**, *81*, 8934. (e) Donald, C. S.; Moss, T. A.; Noonan, G. M.; Roberts, B.; Durham, C. E. *Tetrahedron Lett.* **2014**, *55*, 3305. (f) Johansen, S. K.; Sørensen, L.; Martiny, L. *J. Label Compd. Radiopharm.* **2005**, *48*, 569. For selected examples of radical mediated dehalogenative deuteration: (g) Mutsumi, T.; Iwata, H.; Maruhashi, K.; Monguchi, Y.; Sajiki, H. *Tetrahedron* **2011**, *67*, 1158. (h) Miura, Y.; Oka, H.; Yamano, E.; Morita, M. *J. Org. Chem.* **1997**, *62*, 1188, and ref 8. For a recent example of hydrodehalogenation of haloarenes by NaH/LiI: (i) Ong, D. Y.; Tejo, C.; Xu, K.; Hirao, H.; Chiba, S. *Angew. Chem. Int. Ed.* **2017**, *56*, 1840.

(11) Selected examples: (a) Klei, S. R.; Golden, J. T.; Tilley, T. D.; Bergman, R. G. *J. Am. Chem. Soc.* **2002**, *124*, 2092. (b) Esaki, H.; Ito, N.;

Sakai, S.; Maegawa, T.; Monguchi, Y.; Sajiki, H. *Tetrahedron* **2006**, *62*, 10954. (c) Zhou, J.; Hartwig, J. F. *Angew. Chem. Int. Ed.* **2008**, *47*, 5783. (d) Ma, S.; Villa, G.; Thuy-Boun, P. S.; Homs, A.; Yu, J.-Q. *Angew. Chem. Int. Ed.* **2014**, *53*, 734. (e) Li, W.; Wang, M.-M.; Hu, Y.; Werner, T. *Org. Lett.* **2017**, *19*, 5768. (f) Yu, R. P.; Hesk, D.; Rivera, N.; Pelczer, I.; Chirik, P. J. *Nature* **2016**, *529*, 195. (g) Loh, Y. Y.; Nagao, K.; Hoover, A. J.; Hesk, D.; Rivera, N. R.; Colletti, S. L.; Davies, I. W.; MacMillan, D. W. C. *Science* **2017**, *358*, 1182. (h) Valero, M.; Weck, R.; Güssregen, S.; Atzrodt, J.; Derdau, V. *Angew. Chem. Int. Ed.* **2018**, *57*, 8159.

(12) During the preparation of this manuscript, three different strategies for deuteration/tritiation were reported independently. (a) For a two-step procedure for the selective deuteration/tritiation of pyridines and diazines: Koniarczyk, J.; Hesk, D.; Overgard, A.; Davies, I. W.; McNally, A. *J. Am. Chem. Soc.* **2018**, *140*, 1990. (b) For a radical dehalogenative deuteration reaction with porous CDSe nano sheet as catalyst: Liu, C.; Chen, Z.; Su, C.; Zhao, X.; Gao, Q.; Ning, G.-H.; Zhu, H.; Tang, W.; Leng, K.; Fu, W.; Tian, B.; Peng, X.; Li, J.; Xu, Q.-H.; Zhou, W.; Loh, K. P. *Nat. Commun.* **2018**, *9*, 80. (c) For a palladium (II)-mediated tritiation: Yang, H.; Dormer, P. G.; Rivera, N. R.; Hoover, A. *J. Angew. Chem. Int. Ed.* **2018**, *57*, 1883.

(13) For nucleophilic silylation of aryl halides: (a) Brook, A. G.; Wolfe, S. *J. Am. Chem. Soc.* **1957**, *79*, 1431. (b) Shippey, M. A.; Dervan, P. B. *J. Org. Chem.* **1977**, *42*, 2654. For direct C–H silylation: (c) Postigo, A.; Rossi, R. A. *Org. Lett.* **2001**, *3*, 1197. (d) Toutov, A. A.; Liu, W.-B.; Betz, K. N.; Fedorov, A.; Stoltz, B. M.; Grubbs, R. H. *Nature*, **2015**, *518*, 80.

(14) (a) Firouzabadi, H.; Karimi, B. *Syn. Commun.* **1993**, *23*, 1633. (b) Hudrlik, P. F.; Arango, J. O.; Hijji, Y. M.; Okoro, C. O.; Hudrlik, A. M. *Can. J. Chem.* **2000**, *78*, 1421. (c) Weickgenannt, A.; Oestreich, M. *Chem. Asian. J.* **2009**, *4*, 406.

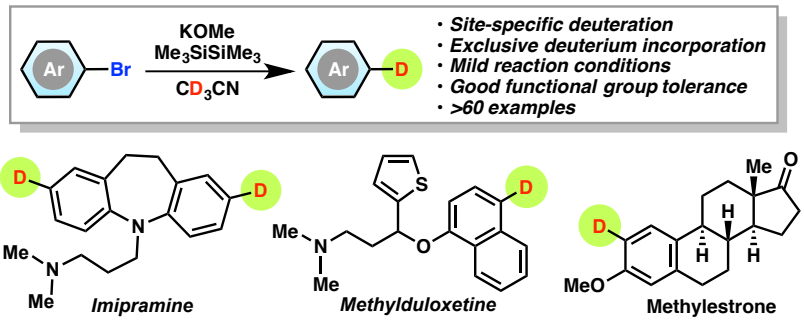
(15) A large number of functional group rich and diverse arylhalides are commercially available or readily prepared. For selected regioselective halogenation methods: (a) Song, S.; Sun, X.; Li, X.; Yuan, Y.; Jiao, N. *Org. Lett.* **2015**, *17*, 2886. (b) Wengryniuk, S. E.; Weickgenannt, A.; Reiher, C.; Strotman, N. A.; Chen, K.; Eastgate, M. D.; Baran, P. S. *Org. Lett.* **2013**, *15*, 792. (c) Sun, K.; Lv, Y.; Wang, J.; Sun, J.; Liu, L.; Jia, M.; Liu, X.; Li, Z.; Wang, X. *Org. Lett.* **2015**, *17*, 4408. (d) Kumar, L.; Mahajan, T.; Sharma, V.; Agarwal, D. D. *Ind. Eng. Chem. Res.* **2011**, *50*, 705. For a recent review, see: (e) Petrone, D. A.; Ye, J.; Lautens, M. *Chem. Rev.* **2016**, *116*, 8003.

(16) (a) Corriu, R. J. P.; Guérin, C.; Henner, B.; Wang, Q.-J. *Organometallics*, **1991**, *10*, 2297. (b) Lachance, N.; Gallant, M. *Tetrahedron Lett.* **1998**, *39*, 171. (d) Chuit, C.; Corriu, R. J. P.; Reye, C.; Young, J. C. *Chem. Rev.* **1993**, *93*, 1371. (e) Liu, W. -B.; et al., *J. Am. Chem. Soc.* **2017**, *139*, 6867. (f) Zhang, L.; Yang, H.; Jiao, L. *J. Am. Chem. Soc.* **2016**, *138*, 7151. (g) Smith, A. J.; Young, A.; Rohrbach, S.; O'Connor, E. F.; Allison, M.; Wang, H.-S.; Poole, D. L.; Tuttle, T.; Murphy, J. A. *Angew. Chem. Int. Ed.* **2017**, *56*, 13747.

(17) (a) Newcomb, M.; Curran, D. P. *Acc. Chem. Res.* **1988**, *21*, 206. (b) Yasuda, H.; Uenoyama, Y.; Nobuta, O.; Kobayashi, S.; Ryu, I. *Tetrahedron Lett.* **2008**, *49*, 367.

(18) (a) Yamamoto, E.; Izumi, K.; Horita, Y.; Ito, H. *J. Am. Chem. Soc.* **2012**, *134*, 19997. (b) Uematsu, R.; Yamamoto, E.; Maeda, S.; Ito, H.; Taketsugu, T. *J. Am. Chem. Soc.* **2015**, *137*, 4090.

(19) (a) Daschlein, C.; Bauer, S. O.; Strohmann, C. *Eur. J. Inorg. Chem.* **2011**, 1454. (b) Strohmann, C.; Bindl, M.; Fraaß, V. C.; Hörnig, J. *Angew. Chem. Int. Ed.* **2004**, *43*, 1011.



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