

## REVIEW

View Article Online

View Journal | View Issue

Cite this: *Org. Chem. Front.*, 2020, **7**, 896

## Recent progress in C(aryl)–C(alkyl) bond cleavage of alkylarenes

Peng-Fei Dai,<sup>a,b</sup> Hua Wang,<sup>b</sup> Xian-Chao Cui,<sup>b</sup> Jian-Ping Qu<sup>id</sup> \*<sup>a</sup> and Yan-Biao Kang<sup>id</sup> \*<sup>b</sup>

Cleavage of the C(aryl)–C(alkyl)  $\sigma$ -bond is important both in academy and industry as it holds the potential to provide straightforward access to a variety of targets from readily available chemical feedstocks such like alkylarenes. However, C(aryl)–C(alkyl) bonds of alkylarenes remain intact under most conventional reaction conditions. In this review, we highlight the results of recent C(aryl)–C(alkyl) bond cleavages that have been induced by homogeneous transition metal reagents, by oxidative cleavages, and by rearrangement.

Received 3rd December 2019,  
Accepted 22nd February 2020

DOI: 10.1039/c9qo01438a

rsc.li/frontiers-organic

## 1. Introduction

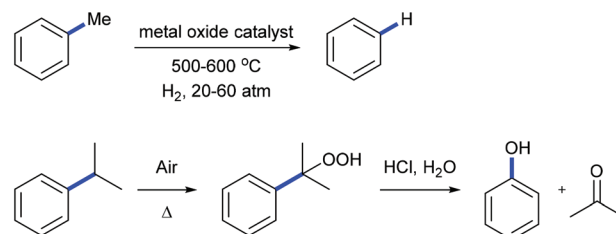
Alkylarenes are products from the coal or petrochemical industries. Transformations of these chemicals by cleaving the C(aryl)–C(sp<sup>3</sup>)  $\sigma$ -bond provide straightforward access to a variety of feedstocks and therefore are important both in academy and industry. Toluene hydrodealkylation is one of the industrial application examples for C(aryl)–C(sp<sup>3</sup>) bond cleavage. Toluene and hydrogen are compressed to pressures between 20 and 60 atmospheres and are heated to temperatures between 500 and 600 degrees centigrade in the presence of a metal oxide catalyst leading to the formation of benzene *via* C(aryl)–C(sp<sup>3</sup>)  $\sigma$ -bond cleavage (Scheme 1, above).<sup>1</sup> Another example is the cumene–phenol process (or the Hock process) which produces over nine million tonnes of phenol per year.<sup>2</sup> Oxidation of cumene under heating forms a cumene radical which bonds with an oxygen molecule to give cumene hydroperoxide. The hydroperoxide is then hydrolysed in an acidic medium (the Hock rearrangement) to give phenol and acetone (Scheme 1, below). Several modifications using a catalytic amount of *N*-hydroxyphthalimide or derivatives to perform this reaction under mild conditions are also known.<sup>3</sup>

Although over the past few decades, several strategies towards C–C bond cleavage,<sup>4</sup> such as using a small ring system to release the ring strain,<sup>5</sup> using the driving force of the aromaticity in a prearomatic system,<sup>6</sup> or using a carbonyl group or a cyano group to activate,<sup>7</sup> have been established, transformations directly from non-polar, unstrained, unactivated alkylarenes remain rare because of the inertness and thermo-

dynamic stability of the C(aryl)–C(sp<sup>3</sup>) bond in alkylarenes resulting from the high bond dissociation energy. Moreover, the C(aryl)–C(sp<sup>3</sup>) bonds in alkylarenes are surrounded by more C–H and C–C bonds and thus suffer from steric hindrances. In 1993, Milstein and co-workers reported the first example of insertion into an unstrained C(aryl)–C(sp<sup>3</sup>)  $\sigma$ -bond of a diphosphinoxylene in solution with the assistance of metal precoordination without using strain relief or aromatization as a driving force (Scheme 2, 1 to 4).<sup>8</sup> The competing C–H activation process (1 to 2) was observed. Later, a catalytic version of this process was reported by using [{Rh(coe)<sub>2</sub>Cl}]<sub>2</sub> (coe = cyclooctene) either under H<sub>2</sub> pressure or with an excess of triethoxysilane with 4–106 turnovers.<sup>9</sup>

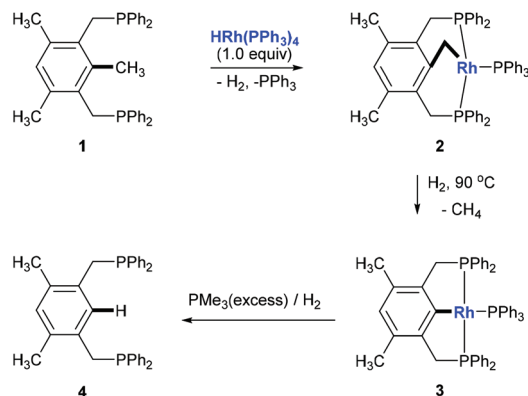
Replacing one of the phosphine ligands with a less steric hindered nitrogen ligand provided a lower activation barrier of the C–C insertion than of the C–H insertion and allowed the C(aryl)–C(sp<sup>3</sup>) insertion to take place even at –30 °C.<sup>10</sup> Other transition metal complexes such as platinum, ruthenium, osmium and nickel complexes towards C(aryl)–C(sp<sup>3</sup>) bond cleavage have also been demonstrated using similar PCP systems.<sup>11</sup>

Recently, the combination of homogeneous transition metal reagents with the assistance of monodentate ligands has



Scheme 1 Hock rearrangement and hydrogenation of toluene.

<sup>a</sup>Institute of Advanced Synthesis, School of Chemistry and Molecular Engineering, Nanjing Tech University, Nanjing 211816, China. E-mail: ias\_jpqu@njtech.edu.cn<sup>b</sup>Department of Chemistry, University of Science and Technology of China, Hefei, Anhui 230026, China. E-mail: ybkang@ustc.edu.cn

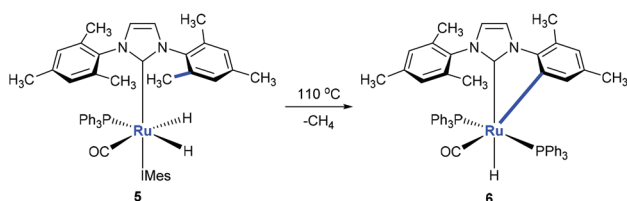


**Scheme 2** C(aryl)–C(sp<sup>3</sup>) bond cleavage by rhodium.

provided a powerful tool for the cleavage of C(aryl)–C(alkyl)  $\sigma$ -bonds in alkylarenes *via* a direct or stepwise C–C bond insertion pathway. Moreover, several strategies using oxidative cleavage or rearrangement as a driving force to cleave the inert C(aryl)–C(sp<sup>3</sup>) bonds of alkylarenes have also been demonstrated. In this mini-review, we will focus on the discussion of these recent publications and four parts will be included. In the first part, we will briefly summarize the cleavage of C(aryl)–C(sp<sup>3</sup>) bonds *via* a C(aryl)–C(sp<sup>3</sup>) insertion using homogeneous transition metal reagents in the presence of monodentate ligands. In the second part, we will discuss the cleavage of C(aryl)–C(alkyl) bonds of alkylarenes, except for methylarenes, through the combination of an oxidative amination and a rearrangement in the absence of any directing groups. In the third part, we will introduce the recent results in the cleavage of C(aryl)–C(methyl) bonds using tandem oxidation/decarboxylative transformations. Finally, miscellaneous C(aryl)–C(sp<sup>3</sup>) bond cleavage of alkylarenes *via* alkyl or aryl migrations will be highlighted.

## 2. Monodentate ligand chelation-assisted C(aryl)–C(sp<sup>3</sup>) bond cleavage

Monodentate ligands such as N-heterocyclic carbenes (NHCs) could assist the C(aryl)–CH<sub>3</sub> bond cleavage. Whittlesey and co-workers reported a cleavage of the C(aryl)–CH<sub>3</sub> bond of 1,3-dimesitylimidazol-2-ylidene (IMes) in the presence of Ru(PPh<sub>3</sub>)<sub>3</sub>(CO)H<sub>2</sub> (Scheme 3).<sup>12</sup> The methyl group on ruthenium



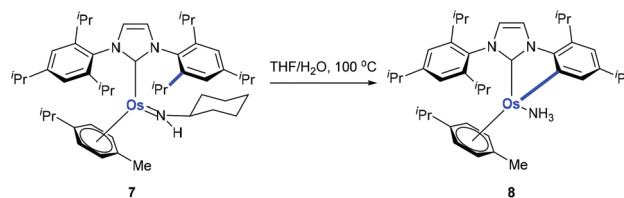
**Scheme 3** Activation of the C(aryl)–CH<sub>3</sub> bond in N-heterocyclic carbene using ruthenium complexes.

complex **5** is eliminated with the hydride to release methane forming ruthenium complex **6** at the same time.

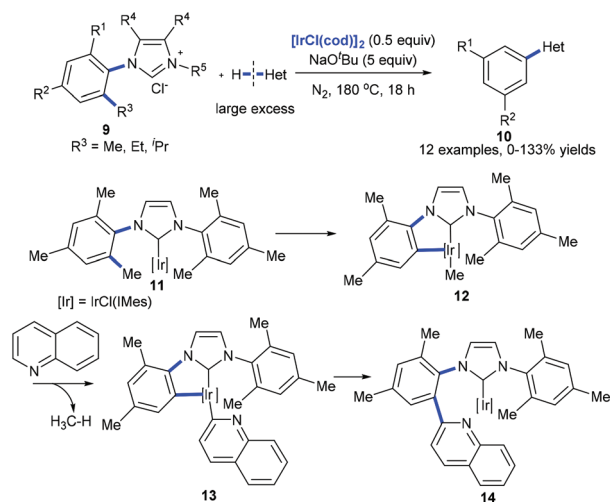
Using osmium-amido complex **7**, Esteruelas and co-workers demonstrated that an isopropyl group of 1,3-bis(2,6-diisopropylphenyl)imidazolylidene could be activated and it involves a  $\beta$ -elimination, an imine dissociation, a C(aryl)–CH<sub>3</sub> bond activation, a reductive elimination, and ammonia coordination processes (Scheme 4).<sup>13</sup>

Recently, Tobisu *et al.* demonstrated the iridium-mediated arylation of quinolones with **9**. The cleavage of a nonpolar, unstrained C(aryl)–C(alkyl) bond on N-heterocyclic carbene iridium complex **11** was proposed to occur generating complex **12** that reacted with quinolones with the release of methanes. The subsequent reductive elimination of **13** forms complex **14**, which would lead to the coupling product **10** (Scheme 5).<sup>14</sup>

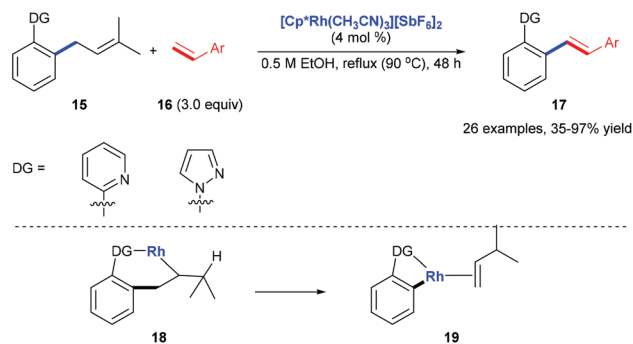
Pyridyl or pyrazolyl groups were also demonstrated as nitrogen monodentate ligands for C(aryl)–C(alkyl) bond cleavage. Kakiuchi and co-workers reported a transformation of allyl groups in allylbenzenes **15** into alkenyl groups **17** *via* a rhodium-catalysed C–C bond cleavage.<sup>15</sup> Pyridyl and pyrazolyl groups in allylbenzenes work as a directing group for the  $\beta$ -carbon elimination of alkyl rhodium complex **18** to form **19** (Scheme 6).



**Scheme 4** Activation of the C(aryl)–*i*Pr bond in N-heterocyclic carbene using an osmium complex.



**Scheme 5** Iridium-mediated arylation of various heteroarenes by activation of the C(aryl)–alkyl bond in N-heterocyclic carbene complexes of iridium.



**Scheme 6** Deallylative alkenylation of allylbenzene derivatives **15** with styrene derivatives **16**.

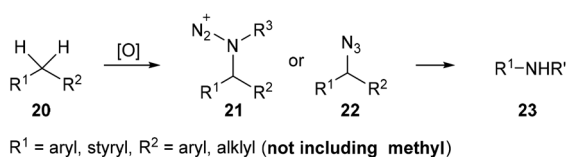
### 3. C(aryl)–C(sp<sup>3</sup>) bond cleavage via tandem oxidative amination/rearrangement

#### 3.1. Tandem oxidative amination/rearrangement mediated by DDQ and azide

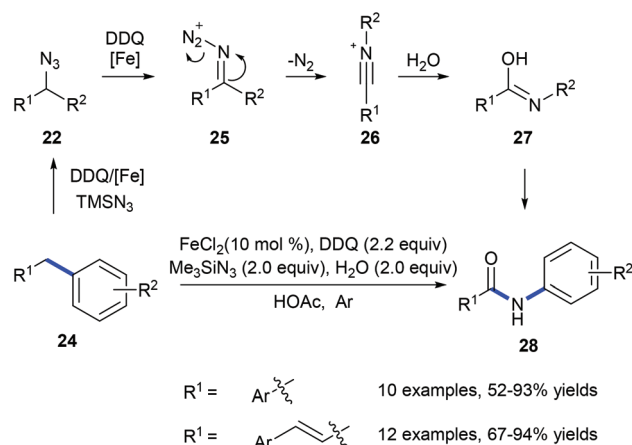
Nitrogen containing organic compounds such as amides and amines are important moieties in organic syntheses and in biological and pharmaceutical compounds. Recently, Jiao *et al.* developed a tandem oxidative substitution/rearrangement strategy to prepare amides or amines **23** from alkylarenes **20** via amination intermediates **21** and **22** (Scheme 7). Besides, the substituent on the  $\alpha$ -methyl on the alkylarenes is necessary for these reactions, while methylbenzene derivatives are inert under these reaction conditions.

In 2011, Jiao and co-workers reported a transformation of benzyl hydrocarbons **24** into the corresponding amides **28** using a tandem iron-catalyzed oxidative substitution/rearrangement reaction (Scheme 8).<sup>16</sup> In wet protonic acid, iron-assisted oxidative addition with TMSN<sub>3</sub> in the presence of DDQ formed **25** which subsequently undergoes a highly chemoselective Beckmann rearrangement followed by hydrolysis resulting in the formation of amide **28**. Six- and seven-membered rings could also be converted into the corresponding lactams in good yields. However, in the case of the reaction of fluorene, phenanthridine was produced suggesting that the desired lactam undergoes dehydration.

On the other hand, on using a copper catalyst in the presence of dry acetonitrile, the oxidative substitution of **29** or electron-rich alkylarenes could also lead to Beckmann-type aryl migration from the carbon atom to the nitrogen atom to gene-



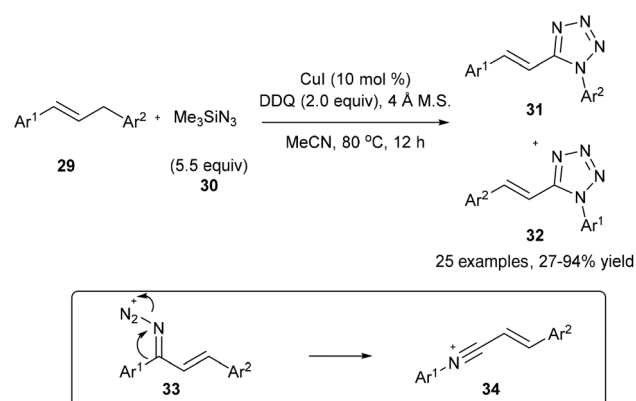
**Scheme 7** Transformation of alkylarenes into amides or amines via a tandem oxidative substitution/rearrangement reaction.



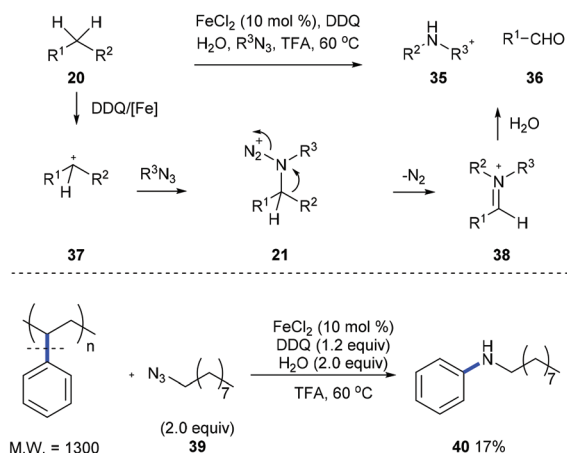
**Scheme 8** Transformation of the benzyl hydrocarbons **24** into amides **28**.

rate intermediate **34**; the following nucleophilic addition and cyclization with another azide finally lead to the desired tetrazole product **31** or **32** in good yields (Scheme 9).<sup>17</sup>

Later, Jiao *et al.* developed an iron-catalyzed cleavage of unactivated C(aryl)–C(alkyl) bonds on diarylmethanes or alkylarenes **20** using stable long chain alkyl azides to form arylamines **35** and aldehyde **36** (Scheme 10).<sup>18</sup> Intermediate **21**, generated from the nucleophilic attack of **37** by organic azide, is proposed, and it undergoes a Schmidt-type rearrangement involving the release of nitrogen and the *trans*-aryl group migration and leads to the formation of iminium **38**. When a mixture of alkyl benzenes was subjected to the standard reaction conditions, a single *N*-alkylaniline was obtained in a moderate yield demonstrating the potential for applying this method to the conversion of a crude mixture of benzyl hydrocarbons from the oil and coal industry. Moreover, a commercially available polystyrene sample and waste polystyrene foam were both used to test the potential of this method in the degradation of polymers and they performed well, giving *N*-nonylaniline **40** in 17% yield.



**Scheme 9** Transformation of **29** into tetrazoles **31** and **32**.

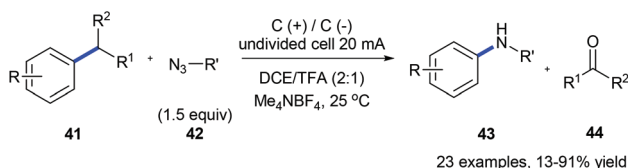


**Scheme 10** Direct synthesis of arylamines through C(aryl)–C(sp<sup>3</sup>) bond cleavage.

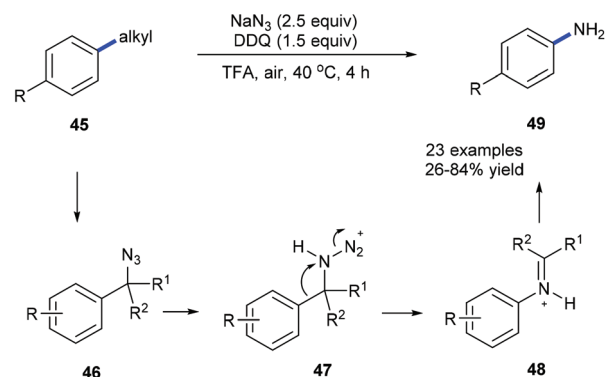
The same group also reported an electrochemical C–C amination of alkylarenes **41** for the synthesis of anilines **43** using graphite plates as electrodes in an undivided cell without any external catalyst or oxidant (Scheme 11).<sup>19</sup> The substrate is first oxidized on the anode generating a radical cation which is deprotonated to give a benzyl radical. The benzyl radical further undergoes oxidation forming an intermediate cation which could be nucleophilically attacked by organic azide **42** producing the Schmidt-type intermediate. This method is efficient for a variety of alkylarenes except for substrates with strong electron-withdrawing groups.

Using NaN<sub>3</sub>, DDQ and TFA, anilines **49** could be prepared from the corresponding alkylarenes **45** or benzyl alcohols under mild conditions *via* a dealkylating C–C amination (Scheme 12).<sup>20a</sup> Alkyl groups such as ethyl, *i*-propyl, benzyl, cyclohexyl, and *n*-butyl could be selectively cleaved and replaced by amine. Secondary benzyl alcohols could also be converted into the corresponding substituted anilines. A Schmidt-type rearrangement pathway including intermediates **46**–**48** was proposed. Utilization of oxygen as an alternative environmentally benign oxidant is also developed. To demonstrate the utility of this method the depolymerization of lignin was also studied by using model compounds obtaining the desired products in moderate yields.

Using organic azide, DDQ and TFA, the allylic C(aryl)–C(alkyl) bond of **50** could be cleaved under metal-free conditions *via* a 1,2-aryl or alkyl migration producing the corres-



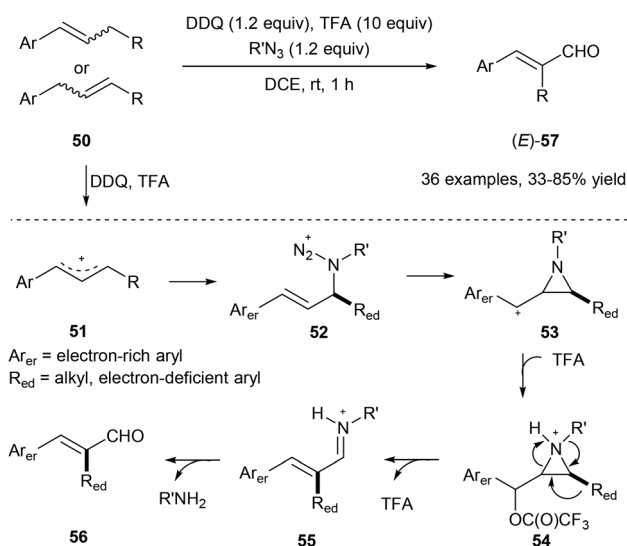
**Scheme 11** Electrochemically oxidative C(sp<sup>2</sup>)–C(sp<sup>3</sup>) bond cleavage of alkylarenes for aniline synthesis.



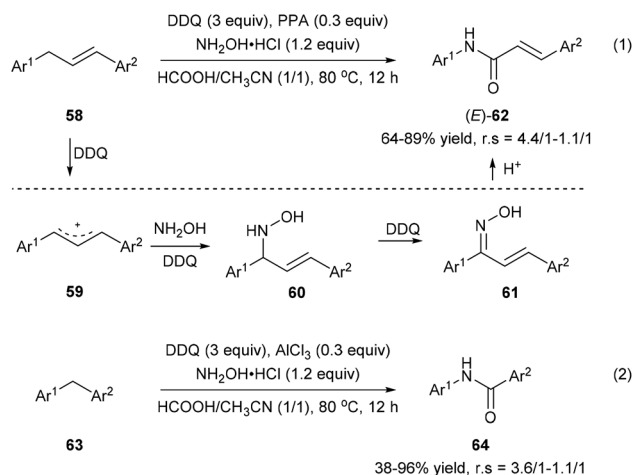
**Scheme 12** Transformation of alkylbenzene derivatives **45** into anilines **49** through site-directed C(aryl)–C(sp<sup>3</sup>) bond cleavage.

ponding *E*-cinnamyl aldehydes **57** regio- and stereoselectively (Scheme 13).<sup>21</sup> Alkyl azides work as a traceless reagent in this transformation by generating an azido cation intermediate **52** and finally turning into alkyl amines. In this transformation, *E* products are obtained in all cases, regardless of the geometry of the starting olefins.

Zhang *et al.* also developed an oxidative amination/rearrangement of 1,3-diarylpropenes **58** or diarylmethanes **63** utilizing hydroxylamine as a nucleophile in the presence of DDQ and an acid (PPA or AlCl<sub>3</sub>). The initial single-electron transfer process between **58** and DDQ produces benzyl cation **59** followed by the attack of hydroxylamine giving rise to **60**. Oxidation of **60** by DDQ affords ketoximes **61**, which convert into the corresponding amides **62** and **64** *via* a Beckmann rearrangement in the presence of an acid with 38–96% yields and 4.4/1–1.1/1 regioselectivities (Scheme 14).<sup>22</sup>



**Scheme 13** Transformation of **50** into cinnamyl aldehydes **57** through selective allylic C–C bond cleavage.



**Scheme 14** Transformation of 1,3-diarylpropenes **58** and diaryl-methanes **63** into amides via oxidative amination/rearrangement.

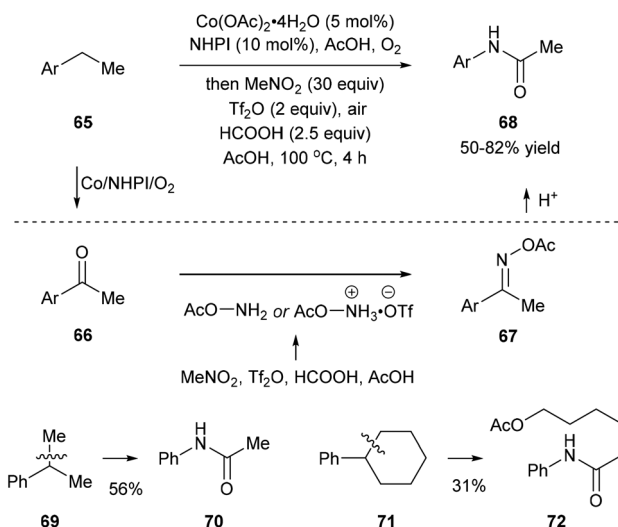
### 3.2. One-pot oxygenation/amination/rearrangement using nitromethane

Recently, Jiao and co-workers reported an activation of nitromethane that utilizes triflic anhydride, formic acid, and acetic acid, and this method provides a nitrogen donor instead of azides for the amination of ketones or aldehydes. When they subjected ethylbenzenes **65** to the classic oxidation conditions using the  $\text{Co}/\text{NHPI}/\text{O}_2$  system, the corresponding ketones **66** were generated *in situ*, and the following addition of triflic anhydride, formic acid, and acetic acid afforded **67**. Hydrolysis of **67** gave rise to the corresponding dealkylated amides **68**. When cumene **69** and cyclohexylbenzene **71**, important feed-stock materials, were subjected to the protocol, secondary amides **70** and **72** were obtained through oxidative  $\beta$ -scission of alkyl chains. Reactions with substituted methylarenes were also investigated but they provided primary benzamides without  $\text{C}(\text{aryl})\text{--C}(\text{alkyl})$  bond cleavage (Scheme 15).<sup>23</sup>

## 4. Cleavage of the $\text{C}(\text{aryl})\text{--CH}_3$ bond via tandem oxidation/decarboxylative transformations

Using amination/rearrangement strategies, great success has been achieved in the scission of the  $\text{C}(\text{aryl})\text{--C}(\text{alkyl})$  bond in ethylarenes, cumene, cyclohexylbenzenes, *etc.*, but demethylative  $\text{C}(\text{aryl})\text{--CH}_3$  bond cleavage of inert methylarenes has been less reported.

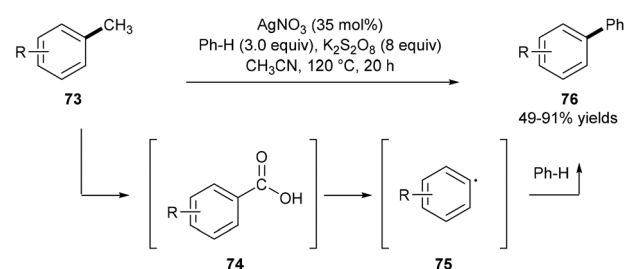
Kim and co-workers reported a one-pot demethylative coupling reaction between inert methylarenes **73** and benzenes using substoichiometric silver nitrate in the presence of an excess amount of the potassium persulfate oxidant under heating. Observations of benzyl hydrogen sulfate, benzaldehyde, and benzoic acid by GC analysis, control experiments, and detection of carbon dioxide by GC-MS analysis suggest that this process involves a radical oxidation of methyl-



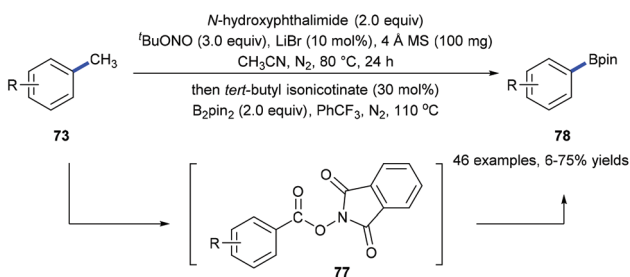
**Scheme 15** Preparation of amides via a one-pot oxygenation/amination/rearrangement of alkylarenes using nitromethane.

arenes **73** to substituted benzoic acids **74** and a following decarboxylative coupling with benzenes. A two-electron oxidative transfer  $\text{Ag}(\text{I})/\text{Ag}(\text{III})$  system for the generation of the free radical  $\text{SO}_4^{\cdot-}$  is proposed based on the studies by XANES and EXAFS analyses (Scheme 16).<sup>24</sup>

Recently, we have developed a site-selective  $\text{C}(\text{aryl})\text{--CH}_3$  bond cleavage/borylation reaction<sup>25</sup> by using a sequential tandem strategy (Scheme 17).<sup>26</sup> Methyl groups of a variety of arenes **73** and biologically active natural products could be



**Scheme 16** Demethylative coupling between methylarenes **73** and benzenes.



**Scheme 17** Sequential radical demethylative  $\text{C}(\text{aryl})\text{--C}(\text{CH}_3)$  bond cleavage and borylation.



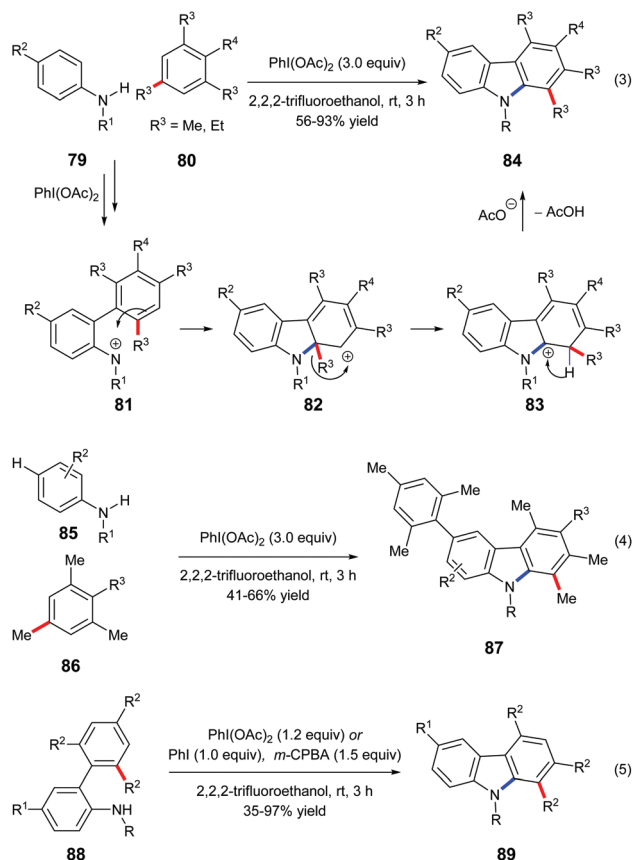
selectively cleaved and replaced by boryl groups under directing group-free and transition metal-free conditions. An *N*-hydroxyphthalimide-ester **77** was isolated from the first step of the standard conditions. It was proposed to be the key intermediate which converted into the corresponding boronate **78**<sup>25a</sup> through a decarboxylative borylation (Scheme 17).

## 5. Miscellaneous C(aryl)–C(alkyl) bond cleavage via alkyl or aryl migrations

Miscellaneous C(aryl)–C(alkyl) bond cleavage of alkylarenes involving alkyl or aryl migrations has been reported by using a hypervalent iodine(III) reagent or a cationic *N*-heterocyclic carbene copper catalyst giving the corresponding product in good yields.

### 5.1 Hypervalent iodine(III)-mediated rearrangement

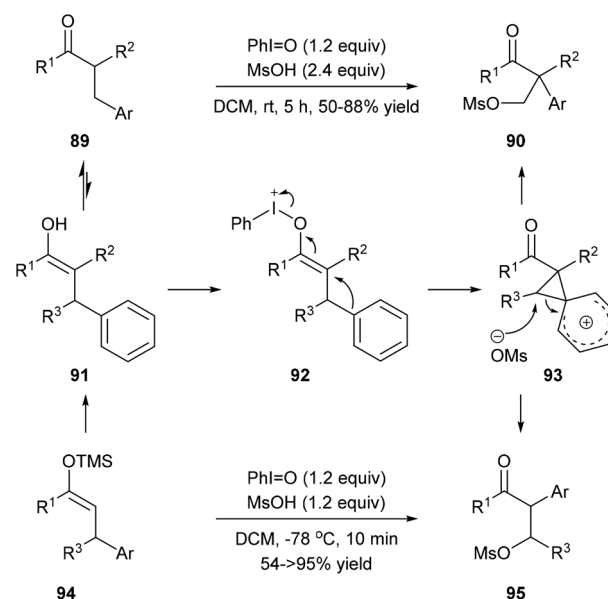
Mal *et al.* reported a one-pot carbazole synthesis *via* an intermolecular annulation between aryl sulfonamides **79** and substituted mesitylenes or 1,3,5-triethylbenzene **80**. The hypervalent iodine(III) reagent  $\text{PhI}(\text{OAc})_2$  prompted the formation of nitrenium ion **81** from sulfonamide, and the following electrophilic aromatic substitution led to carbenium intermediate



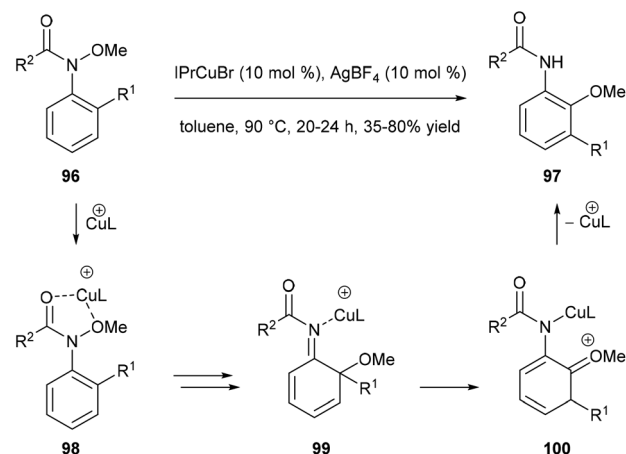
Scheme 18  $\text{PhI}(\text{OAc})_2$  prompted alkyl migration.

**82** which underwent alkyl migration forming a more stable cationic intermediate **83** (Scheme 18, eqn (3)).<sup>27a</sup> When *N*-sulfonylanilides **85** with hydrogen at the *para*-position to the sulphonamide group were subjected to the standard conditions, *para*-arylated carbazoles **87** were obtained (Scheme 18, eqn (4)). An intramolecular reaction of **88** has also been reported by the same research group (Scheme 18, eqn (5)).<sup>27b</sup>

Maulide and co-workers found that a hypervalent iodine(III) reagent could induce a C(aryl)–C(alkyl) bond cleavage  $\alpha$ -arylation of dicarbonyl compounds **89** that possess an aryl group in the  $\beta$ -position of ketones or ketone-derived silyl enol ethers **94** that feature an aryl group in the allylic position (Scheme 19). They proposed that a fragmentation of enolonium **92** could be triggered by a nucleophilic attack of the neighbouring arene to generate phenonium intermediate **93**.



Scheme 19 Hypervalent iodine(III) induced aryl migration.



Scheme 20 Copper catalysed domino rearrangement of *N*-methoxyanilines **96**.

Ring opening of **93** by weakly nucleophilic triflate accounts for the formation of the C(aryl)–C(alkyl) bond cleavage products **90** and **95**.<sup>28</sup>

## 5.2 Copper-catalysed domino rearrangement

Nakamura and co-workers reported a catalytic domino rearrangement of *N*-methoxyanilines **96** that bear an electron-donating alkyl group (Scheme 20). The cationic copper catalyst was found to participate in the [1,3]-migration of the methoxy group from **98** to **99** and the [1,2]-migration of the alkyl group from the *ortho* to the *meta* position (from **99** to **100**). This provides a method for the preparation of multisubstituted 2-aminophenol derivatives **97** from readily accessible *N*-methoxyanilines **96**.<sup>29</sup>

## 6. Summary and outlook

The C(aryl)–C(alkyl)  $\sigma$ -bond in alkylarenes is one of the least reactive functional groups; however, its cleavage could be realized by elaborating the reaction system. In this mini-review, we have highlighted the advances in the cleavage of C(aryl)–C(alkyl)  $\sigma$ -bonds of alkylarenes using a transition-metal insertion in the presence of directing groups, a tandem oxidative amination/rearrangement, tandem oxidation/decarboxylative transformations, and alkyl or aryl migrations. The development of new strategies towards C(aryl)–C(alkyl) bond cleaving functionalization may lead to the invention of new selective and efficient processes for the utilization of alkylarenes which are available or chemical raw materials from the coal and petrochemical industries.

## Conflicts of interest

There are no conflicts to declare.

## Note from RSC Publishing

This article was originally published with the incorrect page numbers. This is the corrected, final version. The Royal Society of Chemistry apologises for these errors and any consequent inconvenience to authors and readers.

## Acknowledgements

We thank the National Natural Science Foundation of China (21602001, 21922109, 21672196, and 21831007), the Start-Up Funding from Nanjing Tech University (39837134), and the Fundamental Research Funds for the Central Universities of China (WK2060190086) for financial support.

## Notes and references

- 1 R. Schmidt, *et al.*, *Hydrocarbons*, in *Ullmann's Encyclopedia of Industrial Chemistry*, Wiley-VCH, 2015.
- 2 (a) "Phenol": M. Weber, M. Weber and M. Kleine-Boymann, *Ullmann's Encyclopedia of Industrial Chemistry*, Wiley-VCH, Weinheim, 2004; (b) Noncatalyzed radical chain oxidation: cumene hydroperoxide: M. Weber, J.-B. G. Daldup and M. Weber, *Liquid Phase Aerobic Oxidation Catalysis: Industrial Applications and Academic Perspectives, First Edition*, ed. S. S. Stahl and P. L. Alsters, Wiley-VCH, Weinheim, 2016.
- 3 (a) R. Nakamura, Y. Obora and Y. Ishii, Selective One-Pot Synthesis of Various Phenols from Diarylethanes, *Chem. Commun.*, 2008, 3417–3419; (b) K. Chen, P. Zhang, Y. Wang and H. Li, Metal-free Allylic/Benzylic Oxidation Strategies with Molecular Oxygen: Recent Advances and Future Prospects, *Green Chem.*, 2014, **16**, 2344–2374; (c) E. M. Yarkina, E. A. Kurganova, A. S. Frolov, N. V. Lebedeva and G. N. Koshel, Aerobic Liquid-Phase Oxidation of *para-t*-Butylcumene to Hydroperoxide, *Pet. Chem.*, 2019, **59**, 1245–1248.
- 4 (a) *C–C Bond Activation*, ed. G. Dong, Springer-Verlag, Berlin, Heidelberg, 2014; (b) Catalysis in C–C activation: H. Li and Z.-J. Shi, *Homogeneous Catalysis for Unreactive Bond Activation*, ed. Z.-J. Shi, Wiley-VCH, Weinheim, 2016; (c) *Cleavage of Carbon–Carbon Single Bonds by Transition Metals*, ed. M. Murakami and N. Chatani, Wiley-VCH Verlag GmbH, Weinheim, 2016.
- 5 (a) K. C. Bishop III, Transition Metal Catalyzed Rearrangements of Small Ring Organic Molecules, *Chem. Rev.*, 1976, **76**, 461–486; (b) M. Rubin, M. Rubina and V. Gevorgyan, Transition Metal Chemistry of Cyclopropenes and Cyclopropanes, *Chem. Rev.*, 2007, **107**, 3117–3179; (c) T. Seiser and N. Cramer, Enantioselective Metal-Catalyzed Activation of Strained Rings, *Org. Biomol. Chem.*, 2009, **7**, 2835–2840; (d) A. Masarwa and I. Marek, Selectivity in Metal-Catalyzed Carbon–Carbon Bond Cleavage of Alkylidenecyclopropanes, *Chem. – Eur. J.*, 2010, **16**, 9712–9721; (e) T. Seiser, T. Saget, D. N. Tran and N. Cramer, Cyclobutanes in Catalysis, *Angew. Chem., Int. Ed.*, 2011, **50**, 7740–7752; (f) C. Aïssa, Transition-Metal-Catalyzed Rearrangements of Small Cycloalkanes: Regioselectivity Trends in  $\beta$ -Carbon Elimination Reactions, *Synthesis*, 2011, **21**, 3389–3407; (g) B.-L. Lu, L. Dai and M. Shi, Strained Small Rings in Gold-Catalyzed Rapid Chemical Transformations, *Chem. Soc. Rev.*, 2012, **41**, 3318–3339; (h) D. J. Mack and J. T. Njardarson, Recent Advances in The Metal-Catalyzed Ring Expansions of Three- and Four-Membered Rings, *ACS Catal.*, 2013, **3**, 272–286; (i) I. Marek, A. Masarwa, P. O. Delaye and M. Leibeling, Selective Carbon–Carbon Bond Cleavage for the Stereoselective Synthesis of Acyclic Systems, *Angew. Chem., Int. Ed.*, 2015, **54**, 414–429; (j) T. Kondo, Ruthenium- and Rhodium-Catalyzed Strain-Driven Cleavage and Reconstruction of the C–C Bond, *Eur. J. Org. Chem.*, 2016, 1232–1242; (k) G. Fumagalli, S. Stanton and J. F. Bower, Recent Methodologies that Exploit C–C Single-Bond Cleavage of Strained Ring Systems by Transition Metal Complexes, *Chem. Rev.*, 2017, **117**, 9404–9432.

- 6 (a) R. C. Hemond, R. P. Hughes and H. B. Locker, Competitive C-H and C-C Activation in the Reaction of Pentamethylcyclopentadiene with Decacarbonyldimanganese, *Organometallics*, 1986, **5**, 2391–2392; (b) R. H. Crabtree, R. P. Dion, D. J. Gibboni, D. V. McGrath and E. M. Holt, Carbon-Carbon Bond Cleavage In Hydrocarbons By Iridium Complexes, *J. Am. Chem. Soc.*, 1986, **108**, 7222–7227; (c) H. Suzuki, Y. Takaya and T. Takemori, Selective Carbon-Carbon Bond Cleavage of Cyclopentadiene on a Trinuclear Ruthenium Pentahydride Complex, *J. Am. Chem. Soc.*, 1994, **116**, 10779–10780; (d) C. T. To and K. S. Chan, Carbon–Carbon Bond Activation by Group 9 Metal Complexes, *Eur. J. Org. Chem.*, 2019, 6581–6591.
- 7 (a) M. E. van der Boom and D. Milstein, Cyclometalated Phosphine-Based Pincer Complexes: Mechanistic Insight in Catalysis, Coordination, and Bond Activation, *Chem. Rev.*, 2003, **103**, 1759–1792; (b) C.-H. Jun, C. W. Moon, H. Lee and D.-Y. Lee, Chelation-Assisted Carbon–Carbon Bond Activation By Rh(I) Catalysts, *J. Mol. Catal. A: Chem.*, 2002, **189**, 145–156; (c) C.-H. Jun and J. H. Lee, Application of C–H and C–C Bond Activation in Organic Synthesis, *Pure Appl. Chem.*, 2004, **76**, 577–587; (d) M. Tobisu and N. Chatani, Catalytic Reactions Involving The Cleavage Of Carbon–Cyano And Carbon–Carbon Triple Bonds, *Chem. Soc. Rev.*, 2008, **37**, 300–307; (e) J. E. M. N. Klein and B. Plietker, Iron-Catalysed Carbon-Carbon Single Bond Activation, *Org. Biomol. Chem.*, 2013, **11**, 1271–1279; (f) F. Chen, T. Wang and N. Jiao, Recent Advances in Transition-Metal-Catalyzed Functionalization of Unstrained Carbon–Carbon Bonds, *Chem. Rev.*, 2014, **114**, 8613–8661; (g) A. Dermenci, J. W. Coe and G. Dong, Direct Activation Of Relatively Unstrained Carbon–Carbon Bonds In Homogeneous Systems, *Org. Chem. Front.*, 2014, **1**, 567–581; (h) M. H. Shaw and J. F. Bower, Synthesis And Applications of Rhodacyclopentanones Derived from C–C Bond Activation, *Chem. Commun.*, 2016, **52**, 10817–10829; (i) D.-S. Kim, W.-J. Park and C.-H. Jun, Metal–Organic Cooperative Catalysis in C–H and C–C Bond Activation, *Chem. Rev.*, 2017, **117**, 8977–9015.
- 8 (a) B. Rybtchinski and D. Milstein, Metal Insertion into C–C Bonds in Solution, *Angew. Chem., Int. Ed.*, 1999, **38**, 870–883; (b) M. Gozin, A. Weisman, Y. Ben-David and D. Milstein, Activation of a Carbon-carbon Bond in Solution by Transition-metal Insertion, *Nature*, 1993, **364**, 699–701.
- 9 S.-Y. Liou, M. E. van der Boom and D. Milstein, Catalytic Selective Cleavage of a Strong C–C Single Bond by Rhodium in Solution, *Chem. Commun.*, 1998, 687–688.
- 10 M. Gandelman, A. Vigalok, L. J. W. Shimon and D. Milstein, A PCN Ligand System. Exclusive C–C Activation with Rhodium(I) and C–H Activation with Platinum(II), *Organometallics*, 1997, **16**, 3981–3986.
- 11 (a) M. E. van der Boom, H.-B. Kraatz, L. Hassner, Y. Ben-David and D. Milstein, Carbon-Carbon vs Carbon-Hydrogen Bond Activation by Ruthenium(II) and Platinum(II) in Solution, *Organometallics*, 1999, **18**, 3873–3884; (b) R. M. Gauvin, H. Rozenberg, L. J. W. Shimon and D. Milstein, Synthesis and Structure of New Osmium-PCP Complexes. Osmium-Mediated C–C Bond Activation, *Organometallics*, 2001, **20**, 1719–1724; (c) M. E. van der Boom, S.-Y. Liou, L. J. W. Shimon, Y. Ben-David and D. Milstein, Nickel Promoted C–H, C–C and C–O Bond Activation in Solution, *Inorg. Chim. Acta*, 2004, **357**, 4015–4023; (d) M. E. van der Boom, H.-B. Kraatz, Y. Ben-David and D. Milstein, Activation of a Non-Strained C–C Bond with Platinum(II), *Chem. Commun.*, 1996, 2167–2168.
- 12 (a) R. F. R. Jazzar, S. A. Macgregor, M. F. Mahon, S. P. Richards and M. K. Whittlesey, C–C and C–H Bond Activation Reactions in N-Heterocyclic Carbene Complexes of Ruthenium, *J. Am. Chem. Soc.*, 2002, **124**, 4944–4945; (b) R. A. Diggle, S. A. Macgregor and M. K. Whittlesey, Computational Study of C–C Activation of 1,3-Dimesitylimidazol-2-ylidene (IMes) at Ruthenium: The Role of Ligand Bulk in Accessing Reactive Intermediates, *Organometallics*, 2008, **27**, 617–625.
- 13 T. Bolano, M. L. Buil, M. A. Esteruelas, S. Izquierdo, R. Lalrempuia, M. Olivan and E. Onate, C–C Bond Activation of the NHC Ligand of an Osmium-Amido Complex, *Organometallics*, 2010, **29**, 4517–4523.
- 14 S. Sakurai and M. Tobisu, Iridium-Mediated Arylation of Quinoline via the Cleavage of Carbon–Carbon and Carbon–Nitrogen Bonds of 1,3-Dimesitylimidazol-2-ylidene, *Organometallics*, 2019, **38**, 2834–2838.
- 15 S. Onodera, S. Ishikawa, T. Kochi and F. Kakiuchi, Direct Alkenylation of Allylbenzenes via Chelation-Assisted C–C Bond Cleavage, *J. Am. Chem. Soc.*, 2018, **140**, 9788–9792.
- 16 C. Qin, W. Zhou, F. Chen, Y. Ou and N. Jiao, Iron-Catalyzed C–H and C–C Bond Cleavage: A Direct Approach to Amides from Simple Hydrocarbons, *Angew. Chem., Int. Ed.*, 2011, **50**, 12595–12599.
- 17 F. Chen, C. Qin, Y. Cui and N. Jiao, Implanting Nitrogen into Hydrocarbon Molecules through C–H and C–C Bond Cleavages: A Direct Approach to Tetrazoles, *Angew. Chem., Int. Ed.*, 2011, **50**, 11487–11491.
- 18 C. Qin, T. Shen, C. Tang and N. Jiao, FeCl<sub>2</sub>-Promoted Cleavage of the Unactivated C–C Bond of Alkylarenes and Polystyrene: Direct Synthesis of Arylamines, *Angew. Chem., Int. Ed.*, 2012, **51**, 6971–6975.
- 19 Y. Adeli, K. Huang, Y. Liang, Y. Jiang, J. Liu, S. Song, C.-C. Zeng and N. Jiao, Electrochemically Oxidative C–C Bond Cleavage of Alkylarenes for Anilines Synthesis, *ACS Catal.*, 2019, **9**, 2063–2067.
- 20 (a) J. Liu, X. Qiu, X. Huang, X. Luo, C. Zhang, J. Wei, J. Pan, Y. Liang, Y. Zhu, Q. Qin, S. Song and N. Jiao, From Alkylarenes to Anilines via Site-directed Carbon–carbon Amination, *Nat. Chem.*, 2019, **11**, 71–77; (b) A. Xia, X. Qi, X. Mao, X. Wu, X. Yang, R. Zhang, Z. Xiang, Z. Lian, Y. Chen and S. Yang, Metal-Free Aerobic Oxidative Selective C–C Bond Cleavage in Heteroaryl-Containing Primary and Secondary Alcohols, *Org. Lett.*, 2019, **21**, 3028–3033.



- 21 J. Liu, X. Wen, C. Qin, X. Li, X. Luo, A. Sun, B. Zhu, S. Song and N. Jiao, Oxygenation of Simple Olefins through Selective Allylic C-C Bond Cleavage: A Direct Approach to Cinnamyl Aldehydes, *Angew. Chem., Int. Ed.*, 2017, **56**, 11940–11944.
- 22 J. Qiu and R. Zhang, DDQ-Promoted Direct Transformation of Benzyl Hydrocarbons to Amides *via* Tandem Reaction of the CDC Reaction and Beckmann Rearrangement, *Org. Biomol. Chem.*, 2013, **11**, 6008–6012.
- 23 J. Liu, C. Zhang, Z. Zhang, X. Wen, X. Dou, J. Wei, X. Qiu, S. Song and N. Jiao, Nitromethane as A Nitrogen Donor in Schmidt-Type Formation of Amides and Nitriles, *Science*, 2020, **367**, 281–285.
- 24 A. K. Singh, M.-G. Kim, H.-J. Lee, R. Singh, S. H. Cho and D.-P. Kima, Direct Aryl-Aryl Coupling without Pre-Functionalization Enabled by Excessive Oxidation of Two-Electron Ag(I)/Ag(III) Catalyst, *Adv. Synth. Catal.*, 2018, **360**, 2032–2042.
- 25 (a) W.-M. Cheng, R. Shang, B. Zhao, W.-L. Xing and Y. Fu, Isonicotinate Ester Catalyzed Decarboxylative Borylation of (Hetero)Aryl and Alkenyl Carboxylic Acids through N-Hydroxyphthalimide Esters, *Org. Lett.*, 2017, **19**, 4291–4294; (b) C. Li, J. Wang, L. M. Barton, S. Yu, M. Tian, D. S. Peters, M. Kumar, A. W. Yu, K. A. Johnson, A. K. Chatterjee, M. Yan and P. S. Baran, Decarboxylative Borylation, *Science*, 2017, **356**, eaam7355; (c) A. Fawcett, J. Pradeilles, Y. Wang, T. Mutsuga, E. L. Myers and V. K. Aggarwal, Photoinduced Decarboxylative Borylation of Carboxylic Acids, *Science*, 2017, **357**, 283–286; (d) D. Hu, L. Wang and P. Li, Decarboxylative Borylation of Aliphatic Esters under Visible-Light Photoredox Conditions, *Org. Lett.*, 2017, **19**, 2770–2773.
- 26 P.-F. Dai, X.-S. Ning, H. Wang, X.-C. Cui, J. Liu, J.-P. Qu and Y.-B. Kang, Cleavage of C(aryl)-CH<sub>3</sub> Bonds in the Absence of Directing Groups under Transition Metal Free Conditions, *Angew. Chem., Int. Ed.*, 2019, **58**, 5392–5395.
- 27 (a) S. Maiti and P. Mal, Dehydrogenative Aromatic Ring Fusion for Carbazole Synthesis via C–C/C–N Bond Formation and Alkyl Migration, *Org. Lett.*, 2017, **19**, 2454–2457; (b) A. Bal, S. Maiti and P. Mal, Iodine(III)-Enabled Distal C-H Functionalization of Biarylsulfonanilides, *J. Org. Chem.*, 2018, **83**, 11278–11287.
- 28 J. Li, A. Bauer, G. D. Mauro and N. Maulide,  $\alpha$ -Arylation of Carbonyl Compounds through Oxidative C-C Bond Activation, *Angew. Chem., Int. Ed.*, 2019, **58**, 9816–9819.
- 29 Y. Ishida, I. Nakamura and M. Terada, Copper-Catalyzed Domino [1,3]/[1,2] Rearrangement for the Efficient Synthesis of Multisubstituted *ortho*-Anisidines, *J. Am. Chem. Soc.*, 2018, **140**, 8629–8633.