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Dearomatization-Induced Cycloaddition and Aromatization-Triggered Rearrangement: Synthesis of Vertically Expanded Five-Ring Fused Benzofurans

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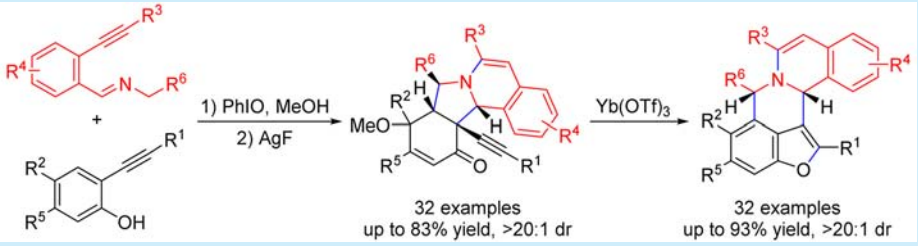
Supporting Information

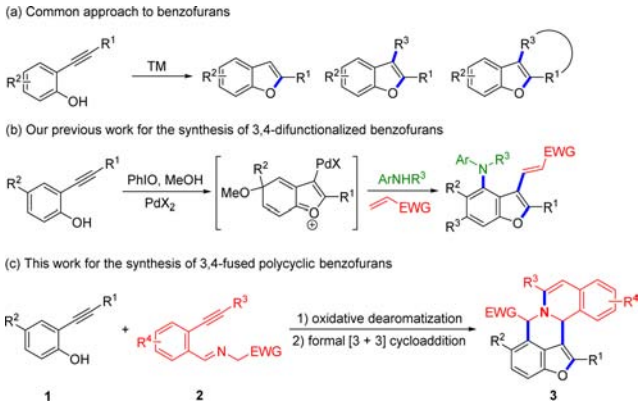


ABSTRACT: A dearomatization strategy has been developed for the efficient construction of vertically expanded five-ring fused benzofurans from *ortho*-alkynylphenols and *ortho*-alkynylarylaldimines. The stepwise procedure comprises a dearomatization-induced silver-catalyzed [3 + 2] cycloaddition followed by an aromatization-triggered ytterbium-catalyzed rearrangement.

Vertically expanded polycyclic aromatic compounds such as 3,4-fused benzofurans are highly valuable synthetic targets because they are the key structural motifs in a number of biologically active substances, such as phenethylamine-type serotonin 5-HT_{2A} receptor agonists.[1,2] Compared with linearly expanded compounds such as 2,3-fused benzofurans, the synthesis of 3,4-fused benzofurans is much more difficult since the direct C-4 functionalization of benzofurans by electrophilic substitution is not feasible. Consequently, a number of elegant tactics including transition metal-catalyzed cascade cyclization,[3] Pictet−Spengler cyclization,[4] photocyclization,[5] phenolic oxidative coupling reaction,[6] and intramolecular Larock annulation[7] have been developed in recent years for the construction of vertically expanded polycyclic structures. However, in many cases, the overall efficiency of these methods is counterbalanced by difficulty in preparing the necessary precursors. *Ortho*-alkynylphenols are however attractive precursors to benzofurans because of their ready accessibility from 2-halophenols and alkynes,[8] but while a wide range of benzofurans can be prepared from *ortho*-alkynylphenols by transition metal-catalyzed cyclization or cascade cyclization/coupling reactions (Scheme 1a),[9] attempts to achieve rapid access to 3,4-fused benzofurans from *ortho*-alkynylphenols appear to have been unsuccessful.

As a continuation of a project focused on the synthesis of biologically active polycyclic aromatic compounds using a dearomatization strategy,[10,11] we have recently developed a method that converts *ortho*-alkynylphenols to 3,4-difunctionalized benzofurans via oxidative dearomatization and a palladium-catalyzed domino reaction.[11b] Mechanistic studies have identified a furan-like organopalladium species as a key intermediate in the conversion (Scheme 1b). Based on this study, we speculated that an intermolecular [3 + 3] dipolar cycloaddition of this kind of intermediate would be possible if a suitable 1,3-dipolar species was sought, and this strategy might be applied in the rapid construction of 3,4-fused benzofurans. This led us to investigate the reaction of *ortho*-alkynylphenols **1** with *ortho*-alkynylarylaldimines[12,13] **2** for the synthesis of vertically expanded five-ring fused benzofurans **3**, which, with

Scheme 1. Synthesis of Benzofurans from *ortho*-Alkynylphenols



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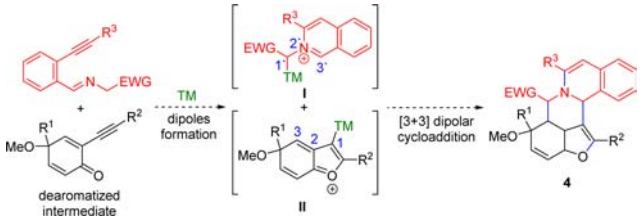
their unique fused bis-heterocyclic structure, might possess potential biological activity.

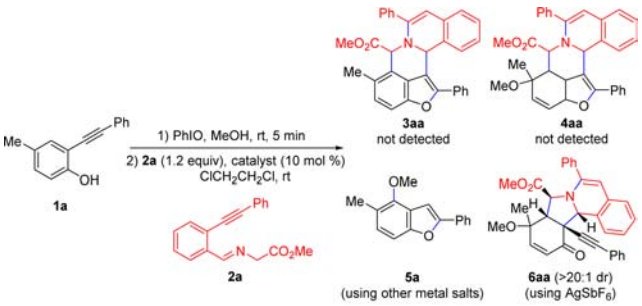
We initially speculated that treatment of the dearomatized intermediate of *ortho*-alkynylphenols and *ortho*-alkynyl-arylaldimines with alkynophilic metal catalysts may lead to the formation of two transition-metal-containing dipoles which may undergo [3 + 3] dipolar cycloaddition (Scheme 2). Subsequent aromatization would complete the construction of compound **3**.

Scheme 2. Envisioned [3 + 3] Dipolar Cycloaddition



However, in preliminary tests of the reactions of the crude dearomatization product of 4-methyl-2-(2-phenylethynyl)-phenol **1a** and 2-phenylethynyl *N*-benzylidene glycinate **2a** in the presence of a series of alkynophilic metal salts, formation of either [3 + 3] cycloaddition product **3aa** or **4aa** was not detected (Scheme 3). Instead, a 4-methoxy substituted

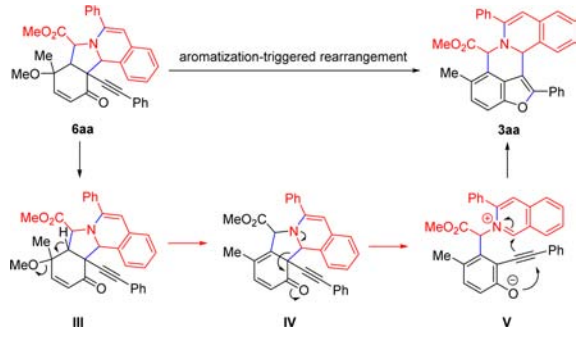
Scheme 3. Preliminary Tests on Screening Catalysts



benzofuran **5a** was isolated as the major product from reactions using Au(I), Au(III), Pd(II), Pt(II), Cu(I), Cu(II), Zn(II), or Rh(I) salts. These experiments indicated that these metal salts prefer to promote a [1,2] methoxy group transfer reaction of intermediate **II** (Scheme 2) instead of the expected [3 + 3] dipolar cycloaddition (for details, see Table S1 in the Supporting Information). Notwithstanding this result, the isolation of a [3 + 2] cycloaddition[14,15] product **6aa** in 58% yield from the $AgSbF_6$-catalyzed reaction encouraged us to continue our investigation since we considered that the desired product could be obtained from an aromatization-triggered rearrangement of compound **6aa**, whose structure was confirmed by single-crystal X-ray diffraction,[16] and diastereoselectivity was determined by ^1H NMR spectroscopy.

As depicted in Scheme 4, we conceived that aromatization of the nonaromatic structure of **6aa** may be a sufficient driving force to generate the intermediate **V** via a retro-Mannich reaction, and subsequent domino nucleophilic cyclization may lead to compound **3aa**. Moreover, only one chiral carbon center in intermediate **V** might remain after the aromatization process. This chiral center might induce a stereoselective nucleophilic

Scheme 4. Aromatization-Triggered Rearrangement Reaction



cyclization to afford **3aa** in high diastereoselectivity. On this basis, we investigated the possibility of this conversion before optimizing the reaction conditions for formation of **6aa**. First, spontaneous rearrangement of **6aa** under thermal conditions was tested, but heating of **6aa** in dichloroethane at 80 °C for 10 h failed to lead to the formation of **3aa**, and instead, slow decomposition of **6aa** via a retro-cycloaddition reaction was observed. A variety of additives were then examined, and some representative results are shown in Scheme 5 (for details, see

Scheme 5. Screening of Additives for the Rearrangement

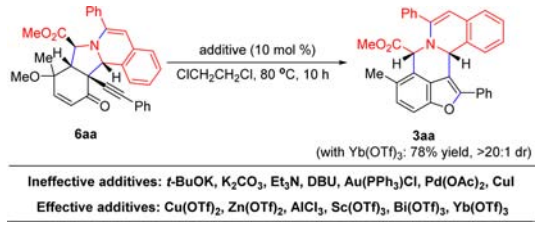
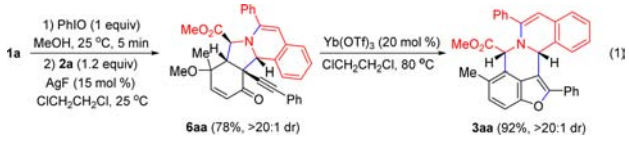


Table S2 in the Supporting Information). While bases or alkynophilic metal salts failed to execute the transformation, many Lewis acids including the Cu(II), Zn(II), Al(III), Sc(III), Bi(III), and Yb(III) salts were able to facilitate the rearrangement. The reaction in the presence of 10 mol % of $Yb(OTf)_3$ gave rise to compound **3aa** in 78% yield with excellent diastereoselectivity (>20:1 dr). The relative stereochemical assignment of **3aa** was based on observed nuclear Overhauser enhancements (NOE).

Further optimization was conducted to improve the efficiency of the cycloaddition/rearrangement process. Among the silver salts that were investigated, silver fluoride proved to be the best catalyst for the [3 + 2] cycloaddition (see Tables S3 in the Supporting Information for details). After screening a range of condition parameters including solvents, temperatures, and the ratio of reagents, the optimum reaction conditions for this process were defined (see Tables S4 in the Supporting Information for details), and the yields of **6aa** and **3aa** were improved to 78% and 92%, respectively (eq 1). Treatment of



compound **6aa** with 10 mol % of AgF in dichloroethane at 80 °C led only to the decomposition of **6aa**, which indicated that

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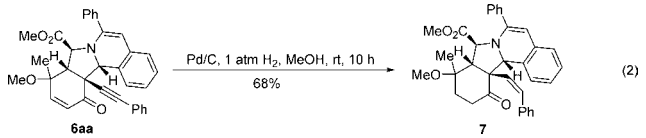
the synthesis of compound **3aa** needs to be carried out in a stepwise manner.

To understand the regioselectivity of [3 + 2] cycloaddition, the dearomatized intermediate of **1a** was isolated. The ^{1}H NMR spectroscopy of this intermediate revealed that the H atom at the C-3 position of 2-alkynyl cyclohexadienone has a higher chemical shift (7.09 ppm) than that of the H atom at the C-5 position (6.79 ppm). This indicates that the C-3 position is more positively charged than the C-5 position, and the nucleophilic cycloaddition might prefer to occur at the C2−C3 double bond to give rise to compound **6aa**. In the control experiments, while no reaction occurred when the dearomatization product was treated with 1 equiv of AgF under the standard cycloaddition conditions, the formation of azomethine ylide was observed when compound **2a** was treated with AgF, and subsequent addition of the dearomatization product to the reaction mixture led to the formation of compound **6aa**. These results indicated that silver salts might work as the alkynophilic metal catalysts to activate the triple bond of 2-phenylethynyl *N*-benzylidene glycinate to facilitate the formation of azomethine ylide for subsequent dipolar cycloaddition. The relative stereochemistry of **6aa** indicated that the [3 + 2] cycloaddition might proceed via a *syn*-addition manner.[17]

Under the optimized conditions, the substrate scope was investigated (Scheme 6). Silver-mediated [3 + 2] cycloaddition was found to proceed with a range of *ortho*-alkynylphenols bearing an aryl, linear or branched alkyl, or cyclopropyl group at the alkynyl moiety as well as those bearing an alkyl or phenyl group at C4 of the phenol ring. The reaction delivered the corresponding product in moderate to good yields with excellent diastereoselectivities (>20:1 dr). Steric hindrance caused by the *tert*-butyl group at the alkynyl moiety or a methyl group at the C5-position of the phenyl ring diminished the yield of compounds **6ga** and **6la**. The same steric hindrance effect was observed in the ytterbium-catalyzed rearrangement of these compounds. A variety of *ortho*-alkynylarylaldimines proved to be suitable reaction partners for the cycloaddition. A range of functional groups on the *ortho*-alkynylarylaldimines were compatible with the reaction conditions. In cross-experiments, a set of products were isolated in moderate yields. In most cases, the ytterbium-catalyzed rearrangement proceeded smoothly, leading to the formation of **3** in moderate to good yields with excellent diastereoselectivities (>20:1 dr). It is noteworthy that, when 3-(4-hydroxy-3-(phenylethynyl)-phenyl) propanoic acid **1m** was used as the substrate, the oxidative dearomatization provided an intermediate containing a spirolactone structure. Under the standard conditions, the corresponding products **3ma**, **3mb**, and **3me**, which contain a free propanoic acid group, were formed in acceptable yields.

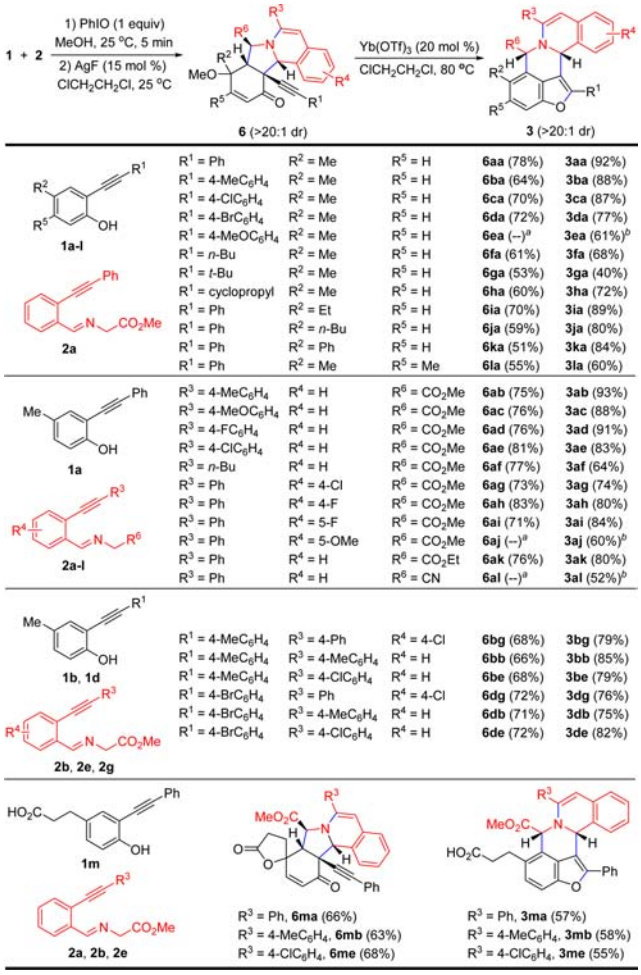
Besides the rearrangement reaction, the reduction of compound **6aa** with Pd/C and hydrogen at room temperature was examined and afforded compound **7** in 68% yield (eq 2).



(2)

In conclusion, we have developed a dearomatization strategy with which to construct vertically expanded five-ring fused benzofurans from *ortho*-alkynylphenols and *ortho*-alkynylarylaldimines. This protocol involves the oxidative dearomatization of *ortho*-alkynylphenols, the silver-catalyzed [3 + 2] cycloaddition with *ortho*-alkynylarylaldimines, and a subsequent ytterbium-catalyzed rearrangement. Application of this strategy in the synthesis of natural products and examination of the biological activities of compounds **3** and **6** are in progress in our laboratory.

Scheme 6. Reaction Scope Investigation



R^1 = Ph	R^2 = Me	R^5 = H	**6aa** (78%)	**3aa** (92%)
R^1 = 4-MeC_6H_4	R^2 = Me	R^5 = H	**6ba** (64%)	**3ba** (88%)
R^1 = 4-ClC_6H_4	R^2 = Me	R^5 = H	**6ca** (70%)	**3ca** (87%)
R^1 = 4-BrC_6H_4	R^2 = Me	R^5 = H	**6da** (72%)	**3da** (77%)
R^1 = 4-$MeOC_6H_4$	R^2 = Me	R^5 = H	**6ea** (--)[a]	**3ea** (61%)[b]
R^1 = *n*-Bu	R^2 = Me	R^5 = H	**6fa** (61%)	**3fa** (68%)
R^1 = *t*-Bu	R^2 = Me	R^5 = H	**6ga** (53%)	**3ga** (40%)
R^1 = cyclopropyl	R^2 = Me	R^5 = H	**6ha** (60%)	**3ha** (72%)
R^1 = Ph	R^2 = Et	R^5 = H	**6ia** (70%)	**3ia** (89%)
R^1 = Ph	R^2 = *n*-Bu	R^5 = H	**6ja** (59%)	**3ja** (80%)
R^1 = Ph	R^2 = Ph	R^5 = H	**6ka** (51%)	**3ka** (84%)
R^1 = Ph	R^2 = Me	R^5 = Me	**6la** (55%)	**3la** (60%)
R^3 = 4-MeC_6H_4	R^4 = H	R^6 = CO_2Me	**6ab** (75%)	**3ab** (93%)
R^3 = 4-$MeOC_6H_4$	R^4 = H	R^6 = CO_2Me	**6ac** (76%)	**3ac** (88%)
R^3 = 4-FC_6H_4	R^4 = H	R^6 = CO_2Me	**6ad** (76%)	**3ad** (91%)
R^3 = 4-ClC_6H_4	R^4 = H	R^6 = CO_2Me	**6ae** (81%)	**3ae** (83%)
R^3 = *n*-Bu	R^4 = H	R^6 = CO_2Me	**6af** (77%)	**3af** (64%)
R^3 = Ph	R^4 = 4-Cl	R^6 = CO_2Me	**6ag** (73%)	**3ag** (74%)
R^3 = Ph	R^4 = 4-F	R^6 = CO_2Me	**6ah** (83%)	**3ah** (80%)
R^3 = Ph	R^4 = 5-F	R^6 = CO_2Me	**6ai** (71%)	**3ai** (84%)
R^3 = Ph	R^4 = 5-OMe	R^6 = CO_2Me	**6aj** (--)[a]	**3aj** (60%)[b]
R^3 = Ph	R^4 = H	R^6 = CO_2Et	**6ak** (76%)	**3ak** (80%)
R^3 = Ph	R^4 = H	R^6 = CN	**6al** (--)[a]	**3al** (52%)[b]
R^1 = 4-MeC_6H_4	R^3 = 4-Ph	R^4 = 4-Cl	**6bg** (68%)	**3bg** (79%)
R^1 = 4-MeC_6H_4	R^3 = 4-MeC_6H_4	R^4 = H	**6bb** (66%)	**3bb** (85%)
R^1 = 4-MeC_6H_4	R^3 = 4-ClC_6H_4	R^4 = H	**6be** (68%)	**3be** (79%)
R^1 = 4-BrC_6H_4	R^3 = Ph	R^4 = 4-Cl	**6dg** (72%)	**3dg** (76%)
R^1 = 4-BrC_6H_4	R^3 = 4-MeC_6H_4	R^4 = H	**6db** (71%)	**3db** (75%)
R^1 = 4-BrC_6H_4	R^3 = 4-ClC_6H_4	R^4 = H	**6de** (72%)	**3de** (82%)

[a]The corresponding products are not stable enough, and the crude products were directly used in the $Yb(OTf)_3$-catalyzed reaction. [b]Total yields over two steps based on compounds **1**.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.6b02329.

Crystallographic data for compound **6aa** (CIF)

Experimental procedures, characterization data, copies of ^{1}H and ^{13}C NMR of new compounds, X-ray diffraction structure and crystallographic data of compound **6aa**, copies of HSQC, HMBC, NOSEY of compound **3aa** (PDF)

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Author Contributions

[§]D.H. and J.C. contributed equally.

Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Marco-Contelles, J.; Carreiras, M. C.; Rodríguez, C.; Villarroya, M.; García, A. G. *Chem. Rev.* **2006**, *106*, 116.

(2) (a) Węcławski, M. K.; Meiling, T. T.; Leniak, A.; Cywiński, P. J.; Gryko, D. T. *Org. Lett.* **2015**, *17*, 4252. (b) Wright, N. E.; Snyder, S. A. *Angew. Chem., Int. Ed.* **2014**, *53*, 3409. (c) Buccini, M.; Piggott, M. J. *Org. Lett.* **2014**, *16*, 2490. (d) Ichiki, M.; Tanimoto, H.; Miwa, S.; Saito, R.; Sato, T.; Chida, N. *Chem. - Eur. J.* **2013**, *19*, 264. (e) Kim, K.; Kim, I. *Org. Lett.* **2010**, *12*, 5314. (f) Ge, H.; Yang, W.; Shen, Y.; Jiang, N.; Guo, Z.; Luo, Q.; Xu, Q.; Ma, J.; Tan, R. *Chem. - Eur. J.* **2010**, *16*, 6338. (g) Boonsri, S.; Karalai, C.; Ponglimanont, C.; Chantrapromma, S.; Kanjana-opas, A. *J. Nat. Prod.* **2008**, *71*, 1173. (h) Fan, C.; Tu, Y.; Song, Z.; Zhang, E.; Shi, L.; Wang, M.; Wang, B.; Zhang, S. *Org. Lett.* **2004**, *6*, 4691. (i) Chambers, J. J.; Parrish, J. C.; Jensen, N. H.; Kurrasch-Orbaugh, D. M.; Marona-Lewicka, D.; Nichols, D. E. *J. Med. Chem.* **2003**, *46*, 3526.

(3) (a) Feng, Y.; Yu, Z. *J. Org. Chem.* **2015**, *80*, 1952. (b) Davis, T. A.; Hyster, T. K.; Rovis, T. *Angew. Chem., Int. Ed.* **2013**, *52*, 14181. (c) Chen, J.; Xie, J.; Bao, D.; Liu, S.; Zhou, Q. *Org. Lett.* **2012**, *14*, 2714. (d) Chang, J.; Kang, H.; Jung, I.; Cho, C. *Org. Lett.* **2010**, *12*, 2016. (e) Satcharoen, V.; McLean, N. J.; Kemp, S. C.; Camp, N. P.; Brown, R. C. D. *Org. Lett.* **2007**, *9*, 1867. (f) Trost, B. M.; Tang, W. *Angew. Chem., Int. Ed.* **2002**, *41*, 2795. (g) Trost, B. M.; Toste, F. D. *J. Am. Chem. Soc.* **2000**, *122*, 11262.

(4) (a) Chen, P.; Bao, X.; Zhang, L.; Ding, M.; Han, X.; Li, J.; Zhang, G.; Tu, Y.; Fan, C. *Angew. Chem., Int. Ed.* **2011**, *50*, 8161. (b) Malachowski, W. P.; Paul, T.; Phounsavath, S. *J. Org. Chem.* **2007**, *72*, 6792. (c) Hu, X.; Tu, Y.; Zhang, E.; Gao, S.; Wang, S.; Wang, A.; Fan, C.; Wang, M. *Org. Lett.* **2006**, *8*, 1823.

(5) Sarma, S. J.; Jones, P. B. *J. Org. Chem.* **2010**, *75*, 3806.

(6) (a) Varghese, V.; Hudlicky, T. *Angew. Chem., Int. Ed.* **2014**, *53*, 4355. (b) Magnus, P.; Sane, N.; Fauber, B. P.; Lynch, V. *J. Am. Chem. Soc.* **2009**, *131*, 16045. (c) Trost, B. M.; Tang, W.; Toste, F. D. *J. Am. Chem. Soc.* **2005**, *127*, 14785. (d) Kodama, S.; Hamashima, Y.; Nishide, K.; Node, M. *Angew. Chem., Int. Ed.* **2004**, *43*, 2659.

(7) (a) Li, L.; Yang, Q.; Wang, Y.; Jia, Y. *Angew. Chem., Int. Ed.* **2015**, *54*, 6255. (b) Kojima, A.; Takemoto, T.; Sodeoka, M.; Shibasaki, M. *J. Org. Chem.* **1996**, *61*, 4876.

(8) (a) Li, Y.; Liu, J.; Witham, C. A.; Huang, W.; Marcus, M. A.; Fakra, S. C.; Alayoglu, P.; Zhu, Z.; Thompson, C. M.; Arjun, A.; Lee, K.; Gross, E.; Toste, F. D.; Somorjai, G. A. *J. Am. Chem. Soc.* **2011**, *133*, 13527. (b) Fischer, J.; Savage, G. P.; Coster, M. J. *Org. Lett.* **2011**, *13*, 3376. (c) Huang, W.; Liu, J.; Alayoglu, P.; Li, Y.; Witham, C. A.; Tsung, C.; Toste, F. D.; Somorjai, G. A. *J. Am. Chem. Soc.* **2010**, *132*, 16771. (d) Tsuji, H.; Mitsui, C.; Ilies, L.; Sato, Y.; Nakamura, E. *J. Am. Chem. Soc.* **2007**, *129*, 11902.

(9) Recent examples, see: (a) Li, J.; Li, C.; Yang, S.; An, Y.; Wu, W.; Jiang, H. *J. Org. Chem.* **2016**, *81*, 2875. (b) Hirner, J. J.; Faizi, D. J.; Blum, S. A. *J. Am. Chem. Soc.* **2014**, *136*, 4740. (c) Liu, J.; Liu, Z.; Liao, P.; Bi, X. *Org. Lett.* **2014**, *16*, 6204. (d) Magnus, P.; Freund, W. A.; Moorhead, E. J.; Rainey, T. *J. Am. Chem. Soc.* **2012**, *134*, 6140. (e) Hachiya, H.; Hirano, K.; Satoh, T.; Miura, M. *Org. Lett.* **2011**, *13*, 3076. (f) Luo, Y.; Wu, J. *Org. Lett.* **2011**, *13*, 5858. (g) Isono, N.; Lautens, M. *Org. Lett.* **2009**, *11*, 1329. (h) Komine, Y.; Kamisawa, A.; Tanaka, K. *Org. Lett.* **2009**, *11*, 2361. (i) Nakamura, M.; Ilies, L.; Otsubo, S.; Nakamura, E. *Angew. Chem., Int. Ed.* **2006**, *45*, 944. (j) Fürstner, A.; Davies, P. W. *J. Am. Chem. Soc.* **2005**, *127*, 15024.

(10) For recent reviews on dearomatization, see: (a) Zi, W.; Zuo, Z.; Ma, D. *Acc. Chem. Res.* **2015**, *48*, 702. (b) Zhuo, C.-X.; Zheng, C.; You, S.-L. *Acc. Chem. Res.* **2014**, *47*, 2558. (c) Zhuo, C.-X.; Zhang, W.; You, S.-L. *Angew. Chem., Int. Ed.* **2012**, *51*, 12662. (d) Roche, S. P.; Porco, J. A., Jr. *Angew. Chem., Int. Ed.* **2011**, *50*, 4068. (e) Pouységu, L.; Deffieux, D.; Quideau, S. *Tetrahedron* **2010**, *66*, 2235. (f) Quideau, S.; Pouységu, L.; Deffieux, D. *Synlett* **2008**, *2008*, 467. (g) Magdziak, D.; Meek, S. J.; Pettus, T. R. R. *Chem. Rev.* **2004**, *104*, 1383. (h) Pape, A. R.; Kaliappan, K. P.; Kündig, E. P. *Chem. Rev.* **2000**, *100*, 2917. (i) Bach, T. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 729.

(11) (a) Han, D.; He, Q.; Fan, R. *Angew. Chem., Int. Ed.* **2015**, *54*, 14013. (b) Han, Z.; Zhang, L.; Li, Z.; Fan, R. *Angew. Chem., Int. Ed.* **2014**, *53*, 6805. (c) Feng, X.; Wang, H.; Yang, B.; Fan, R. *Org. Lett.* **2014**, *16*, 3600. (d) Zheng, C.; Chen, J. J.; Fan, R. *Org. Lett.* **2014**, *16*, 816. (e) Yang, M.; Tang, J.; Fan, R. *Org. Lett.* **2013**, *15*, 3464.

(12) Álvarez-Corral, M.; Muñoz-Dorado, M.; Rodríguez-García, I. *Chem. Rev.* **2008**, *108*, 3174.

(13) (a) Liu, Q.; Wu, Y.; Chen, P.; Liu, G. *Org. Lett.* **2013**, *15*, 6210. (b) Stein, A. L.; Bilheri, F. N.; da Rocha, J. T.; Back, D. F.; Zeni, G. *Chem. - Eur. J.* **2012**, *18*, 10602. (c) Su, S.; Porco, J. A., Jr. *J. Am. Chem. Soc.* **2007**, *129*, 7744. (d) Yanada, R.; Obika, S.; Kono, H.; Takemoto, Y. *Angew. Chem., Int. Ed.* **2006**, *45*, 3822. (e) Asao, N.; Yudha S, S.; Nogami, T.; Yamamoto, Y. *Angew. Chem., Int. Ed.* **2005**, *44*, 5526. (f) Sagar, P.; Fröhlich, R.; Würthwein, E.-U. *Angew. Chem., Int. Ed.* **2004**, *43*, 5694. (g) Kusama, H.; Takaya, J.; Iwasawa, N. *J. Am. Chem. Soc.* **2002**, *124*, 11592.

(14) (a) Adrio, J.; Carretero, J. C. *Chem. Commun.* **2014**, *50*, 12434. (b) Coldham, I.; Hufton, R. *Chem. Rev.* **2005**, *105*, 2765.

(15) Recent examples, see: (a) Zhang, Z.; Xu, B.; Xu, S.; Wu, H.; Zhang, J. *Angew. Chem., Int. Ed.* **2016**, *55*, 6324. (b) Vidadala, S. R.; Golz, C.; Strohmann, C.; Daniliuc, C.-G.; Waldmann, H. *Angew. Chem., Int. Ed.* **2014**, *54*, 651. (c) Li, J.; Zhao, H.; Jiang, X.; Wang, X.; Hu, H.; Yu, L.; Zhang, Y. *Angew. Chem., Int. Ed.* **2015**, *54*, 6306. (d) Walton, M. C.; Yang, Y.; Hong, X.; Houk, K. N.; Overman, L. E. *Org. Lett.* **2015**, *17*, 6166. (e) Liu, H.; Liu, K.; Xue, Z.; He, Z.; Wang, C. *Org. Lett.* **2015**, *17*, 5440. (f) Liu, K.; Teng, H.; Yao, L.; Tao, H.; Wang, C. *Org. Lett.* **2013**, *15*, 2250. (g) Hernández-Toribio, J.; Padilla, S.; Adrio, J.; Carretero, J. C. *Angew. Chem., Int. Ed.* **2012**, *51*, 8854. (h) Yamashita, Y.; Imaizumi, T.; Kobayashi, S. *Angew. Chem., Int. Ed.* **2011**, *50*, 4893. (i) Wang, M.; Wang, Z.; Shi, Y.; Shi, X.; Fossey, J. S.; Deng, W. *Angew. Chem., Int. Ed.* **2011**, *50*, 4897. (j) He, L.; Chen, X.; Wang, D.; Luo, S.; Zhang, W.; Yu, J.; Ren, L.; Gong, L. *J. Am. Chem. Soc.* **2011**, *133*, 13504. (k) López-Pérez, A.; Adrio, J.; Carretero, J. C. *Angew. Chem., Int. Ed.* **2009**, *48*, 340. (l) Wang, C.; Liang, G.; Xue, Z.; Gao, F. *J. Am. Chem. Soc.* **2008**, *130*, 17250.

(16) Crystallographic data for compound **6aa** are available free of charge from the Cambridge Crystallographic Data Centre, accession number CCDC 1494267.

(17) Theory calculations on the pathway of [3 + 2] cycloaddition are currently underway in our laboratory, and these results will be reported in due course.

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