

# HOKKAIDO UNIVERSITY

Title	Use of Imidazo[1,5-a]pyridin-3-ylidene as a Platform for Metal-Imidazole Cooperative Catalysis: Silver-Catalyzed Cyclization of Alkyne-Tethered Carboxylic Acids		
Author(s)	Vishal Kumar, Rawat; Kosuke, Higashida; Masaya, Sawamura		
Citation	Advanced Synthesis & Catalysis, 363(6), 1631-1637 https://doi.org/10.1002/adsc.202001515		
Issue Date	2021-03-16		
Doc URL	http://hdl.handle.net/2115/84394		
Rights	This is the peer reviewed version of the following article: Advanced synthesis & catalysis Volume363, Issue6 March 16, 2021 Pages 1631-1637, which has been published in final form at https://onlinelibrary.wiley.com/doi/10.1002/adsc.202001515. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Self-Archiving.		
Туре	article (author version)		
File Information	Advanced Synthesis & Catalysis 363-6_1631-1637.pdf		

6

Instructions for use

DOI: 10.1002/adsc.202((will be filled in by the editorial staff))

## Use of Imidazo[1,5-*a*]pyridin-3-ylidene as a Platform for Metal-Imidazole Cooperative Catalysis: Silver-Catalyzed Cyclization of Alkyne-Tethered Carboxylic Acids

Vishal Kumar Rawat,<sup>a</sup> Kosuke Higashida,<sup>a,b,\*</sup> and Masaya Sawamura<sup>a,b,\*</sup>

[E-mail: sawamura@sci.hokudai.ac.jp, higashida@icredd.hokudai.ac.jp]

<sup>b</sup> Institute for Chemical Reaction Design and Discovery (WPI-ICReDD), Hokkaido University, Sapporo 001-0021, Japan

Received: ((will be filled in by the editorial staff))

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.201######.((Please delete if not appropriate))

Abstract. Silver complexes with 5-(4-(tert-butyl)-1Himidazol-1-yl)-imidazo[1,5-a]pyridin-3-ylidene ligands were synthesized as metal-imidazole acid-base cooperative catalysts. Single crystal XRD analysis revealed that the silver atom was located in the vicinity of the imidazole ring and that cationic silver complexes formed dimers through coordination between the silver metal and the imidazole pendant. These cationic silver complexes served as catalysts for cyclization of alkyne-tethered carboxylic acids. NMR experiments indicated that the dimeric cationic silver complex dissociated to a monomer upon protonation of the imidazole moiety, resulting in coordination of an acetonitrile to the silver atom. DFT calculations supported the acid-base cooperative action of the silver-imidazole for the efficient alkyne-carboxylic acid cyclization.

**Keywords:** Silver catalyst; Cooperative catalysis; *N*-Heterocyclic carbene; Cyclization

N-Heterocyclic carbenes (NHCs) are strong σdonating ligands, and their transition metal complexes have been widely investigated as catalysts for reaction development due to their robustness and tunability.<sup>[1]</sup> To date, a broad spectrum of NHC ligands with different electronic and steric properties have been synthesized and evaluated. Imidazo[1,5-a]pyridin-3ylidene (Figure 1a) is an NHC scaffold with a rigid bicyclic framework, introduced independently by Lassaletta<sup>[2]</sup> and Glorius.<sup>[3]</sup> Since the substituent at the C5 position of the imidazo[1,5-a]pyridin-3-ylidene projects into the catalytic environment around the NHC-bound metal center, it is expected that ligand modification at this position would have great impact on the nature of the catalyst not only through steric effect but also through a coordinative interaction. In fact, imidazo[1,5-a]pyridin-3-ylidene ligands have been modified at the C5 position with sterically bulky aromatic rings, <sup>[4]</sup> coordinative substituents, <sup>[5]</sup> chiral auxiliaries, <sup>[6]</sup> and other substituents. <sup>[7]</sup>

Therefore, we envisioned that imidazo[1,5*a*]pyridin-3-ylidene could be used as a robust template for producing acid-base cooperative catalysts<sup>[8]</sup> by locating a Lewis acidic transition metal center and a basic functional group such as imidazole at the C3 carbene carbon and the C5 position, respectively (Figure 1b). More specifically, we chose the 4-(tertbutyl)-1H-imidazol-1-yl group as the rigid basic substituent at the C5 position so as to spatially separate the Lewis acidic center and the basic center in the catalytic region. Here, we report the synthesis of protonated precursors for such imidazo[1,5-a]pyridinligands. their conversion 3-ylidene to the corresponding silver(I) complexes, and their application to the silver-catalyzed cyclization of alkyne-tethered carboxylic acids (Figure 1c).<sup>[9,10]</sup>



**Figure 1.** General chemical diagrams for a) imidazo[1,5-*a*]pyridin-3-ylidene metal complexes and b) Lewis acidbase cooperative catalysts with an imidazo[1,5-*a*]pyridin-3ylidene platform. c) Cyclization of alkyne-tethered carboxylic acids through Lewis acid-base cooperative catalysis.

<sup>&</sup>lt;sup>a</sup> Department of Chemistry, Faculty of Science, Hokkaido University, Sapporo 060-0810, Japan

The synthesis of 5-(4-(tert-butyl)-1H-imidazol-1yl)-imidazo[1,5-a]pyridinium salt as an NHC precursor is outlined in Scheme 1. Acetal protection of commercially available 6-bromo-2pyridinecarboxaldehyde gave 2-bromo-6-(1) (diethoxymethyl)pyridine (2) in 96% yield. The 4-(tert-butyl)-1H-imidazolyl substituent was introduced through copper-catalyzed coupling between 2 and 4-(tert-butyl)-1H-imidazole to give 2-(4-(tert-butyl)-1H-imidazol-1-yl)-6-(diethoxymethyl)pyridine (3) in 79% yield. In this coupling, using benzotriazole<sup>[11]</sup> as a ligand for the copper catalyst was crucial for obtaining 3 in a reasonable yield. After removing the acetal protection under acidic conditions, reductive amination with 2,4,6-trimethylphenylmethylamine or 2,6-diisopropylphenylmethylamine followed by Nformylation<sup>[12]</sup> produced the corresponding N-aryl formamides (4a: R = 2,4,6-trimethylphenyl; 4b: R =2,6-diisopropylphenyl). Next. dehvdrative cyclization<sup>[2]</sup> of **4a** and **4b** furnished 5-(4-(*tert*-butyl)-1*H*-imidazol-1-yl)-imidazo[1,5-*a*]pyridinium salts 5a (69%) and **5b** (66%), respectively. The chloride anions on the imidazolium salts 5a and 5b were replaced with a weakly coordinating PF<sub>6</sub> anion through salt metathesis with KPF<sub>6</sub>, yielding **6a** and **6b** in 86% and 85% yields, respectively.



Scheme 1. Synthesis of NHC precursors 5 and 6. (a) TsOH·H<sub>2</sub>O (7 mol%), HC(OEt)<sub>3</sub> (1.2 equiv), EtOH, r.t., 3 h; (b) CuI (10 mol%), benzotriazole (20 mol%), 4-(*tert*-butyl)-1*H*-imidazole (1 equiv), KO'Bu (1.4 equiv), DMSO, 110 °C, 14 h; (c) 1 M HCl aq., acetone, 60 °C, 3 h; (d) RNH<sub>2</sub> (1.2 equiv), AcOH (1 equiv), NaBH(OAc)<sub>3</sub> (1.5 equiv), DCM, r.t., 14 h; (e) HCOOH (excess), Ac<sub>2</sub>O (excess), THF, 0 °C, 3 h; (f) POCl<sub>3</sub> (1.3 equiv), toluene, 100 °C, 38 h; (g) KPF<sub>6</sub> (2 equiv), H<sub>2</sub>O, r.t., 18 h.

Silver(I) chloride complexes **7a** and **7b** bearing the 5-(4-(tert-butyl)-1H-imidazol-1-yl)-imidazo[1,5a]pyridin-3-ylidene framework were synthesizedthrough the reaction of Ag<sub>2</sub>O and imidazolium salts**5a** or**5b**in 84% and 82% yields, respectively (Scheme 2).Single crystals of**7a**and**7b**suitable for XRD analysiswere grown from DCM/Et<sub>2</sub>O and DCE/Et<sub>2</sub>O solutions,respectively. XRD analysis gave the mononuclearstructures of complexes**7a**and**7b**. An ORTEPdrawing of**7a**is shown in Scheme 2 (see SupportingInformation for ORTEP drawing of**7b**). As expected, the silver atom is located in the vicinity of the imidazole ring uncoordinated to the N(4) atom.



Scheme 2. Synthesis of neutral silver complexes 7a and 7b. ORTEP drawing of 7a is described with 50% probability thermal ellipsoids. Hydrogen atoms are omitted for clarity.

Cationic silver(I) complexes 8a and 8b were prepared from imidazolium salts 6a and 6b, respectively. Specifically, the reaction between Ag<sub>2</sub>O and the imidazolium salts (6a or 6b) in acetonitrile at 50 °C for 38 hours gave the desired complexes 8a and 8b in 69% and 68% yields, respectively (Scheme 3). XRD analysis of single crystals of 8a and 8b obtained through recrystallization from a DCM/Et<sub>2</sub>O solution indicated that both complexes existed as dimers with intermolecular coordination between the pendant imidazole and the silver atom (see Supporting Information for ORTEP drawings for 8a and 8b). The average C<sub>carbene</sub>-Ag interatomic distance was 2.08 Å for both 8a and 8b, which is comparable to those for known silver NHC complexes.  $^{[13]}$  In the  $^{13}C{^{1}H}$ NMR spectra of 8a and 8b in CD<sub>2</sub>Cl<sub>2</sub>, resonances for the carbone carbon bound to the silver metal were observed as a pair of doublets at 167.3 ppm  ${}^{1}J({}^{13}C ^{107}$ Ag) = 287.1 Hz,  $^{1}J(^{13}C-^{109}Ag) = 248.5$  Hz} for 8a and at 167.3 ppm { ${}^{1}J({}^{13}C-{}^{107}Ag) = 289.0 \text{ Hz}, {}^{1}J({}^{13}C-{}^{107}Ag) = 289.0 \text{ Hz}, {}^{1}J({}^{13}C-{}^{10}Ag) = 289.0 \text{ Hz}, {}^{1}J({}^{1}C-{}^{10}Ag) = 289.0 \text{ Hz}, {}^{1}J({}^{1}C-{}^{10}Ag) = 289.0 \text{ Hz}, {}^{1}J({}^{1}C-{}^{10}Ag) = 289.0 \text{ Hz}, {}^{1}J($  $^{109}$ Ag) = 249.5 Hz} for **8b**. The appearance of C-Ag coupling indicated that dissociation of the silver metal from the carbene is much slower than the NMR time scale. [14,15]



Scheme 3. Synthesis of silver complexes 8a and 8b.

Next, we evaluated the neutral and cationic silver complexes **7a**, **7b**, **8a**, and **8b** (2 mol% Ag) for catalytic activity in the cyclization of 6-phenylhex-5ynoic acid (**9a**) in acetonitrile at 80 °C for 15 hours. When we applied the cationic complex (**8a**) with the N(1)-mesityl-substituted NHC ligand, the starting material was fully consumed to afford 6-exo-dig lactonization product **10a** in 98% isolated yield with exclusive Z-selectivity (Table 1, entry 1). Meanwhile, the cyclization of **9a** with **8a** in toluene, 1,4-dioxane, and 1,2-dichloroethane gave only trace amounts of the product (see Supporting Information). The cationic silver complex (8b) having the NHC ligand subsituted with a bulkier N(1)-aryl group (2,6-diisopropylphenyl) was much less active, yielding (Z)-10a in only 21% yield (entry 3). The neutral silver chloride complexes 7a and 7b gave only a trace or none of the cyclization product (entries 4 and 5). In accordance with the literature, <sup>[9]</sup> Ag<sub>2</sub>CO<sub>3</sub> as a basic silver complex also promoted this cyclization to give 10a (83%), albeit with lower efficiency than 8a (entry 6). Using ligandfree cationic silver(I) salt AgPF<sub>6</sub> as a catalyst resulted in only 12% yield (entry 8).

Combinations of AgPF<sub>6</sub> and conventional NHC ligands such as IMes  $(L1)^{[16]}$  and IPr  $(L2)^{[17]}$  gave 10a in 27% and 16% yields, respectively (Table 1, entries 9 and 10). Imidazo[1,5-a]pyridin-3-ylidene ligand L3 with a phenyl group at the C5 position gave even lower yield (13%, entry 11). The addition of 1phenylimidazole (11) as an exogenous organic base to the reaction systems with L1, L2, or L3 led to substantial increases in the yield of 10a to 62%, 44%, or 18%, respectively (entries 12-14). These results suggest cooperative action of the cationic silver center and the imidazole derivative (11) as a Lewis acid and Brønsted base, respectively. Furthermore, a comparison of these results with those for the cationic silver complex (8a) with the imidazole-functionalized NHC ligand (entry 1) confirms that the expected acidbase cooperative catalysis with the intramolecularly arranged cationic Ag center and imidazole moiety has been achieved.

Table 1. Silver-Catalyzed Cyclization of 9a

0

Ph	O cataly	st (xx mol% on Ag Iditive (2 mol%) <sub>3</sub> CN, 80 °C, 15 h	) Ph	
9a			10a	
entry	catalyst	additive	yield [%] <sup>[a]</sup>	
(xx mol% Ag)				
1	<b>8a</b> (2)	none	98 <sup>[b]</sup>	
2	<b>8a</b> (1)	none	94 <sup>[c]</sup>	
3	<b>8b</b> (2)	none	21	
4	<b>7a</b> (2)	none	trace	
5	<b>7b</b> (2)	none	0	
6	$Ag_2CO_3(2)$	none	83	
7	$Ag_2CO_3(1)$	none	25 <sup>[d]</sup>	
8	$AgPF_{6}(2)$	none	12	
9	$AgPF_{6}(2)$	L1	27	
10	$AgPF_{6}(2)$	L2	16	
11	$AgPF_{6}(2)$	L3	13	
12	$AgPF_{6}(2)$	L1+11	62	
13	$AgPF_{6}(2)$	L2+11	44	
14	$AgPF_{6}(2)$	L3+11	18	

Reaction conditions: 9a (0.10 mmol) and Ag catalyst (1-2 mol% on Ag atom) in CH<sub>3</sub>CN (0.5 mL) at 80 °C for 15 h. 11: 1-Phenylimidazole. [a]Yield was determined by <sup>1</sup>H NMR analysis using 1,3,5-trimethoxybenzene as an internal standard. [b]Isolated yield. [c]Reaction over 50 h. [d]Reaction over 30 h.



The catalyst loading could be reduced to 1 mol% on the Ag atom using 8a as the catalyst for the reaction of 9a over an extended reaction time (50 h) with the product yield nearly unchanged (Table 1, entry 2). In contrast, the reaction of 9a catalyzed by the reduced amount of Ag<sub>2</sub>CO<sub>3</sub> (1 mol% Ag) remained at only 25% even with the extended reaction time (entry 7). A timecourse profile for the Ag<sub>2</sub>CO<sub>3</sub>-catalyzed reaction indicated that Ag<sub>2</sub>CO<sub>3</sub> was more active than 8a but lost its activity at 10 h (see Supporting Information for time-yield profiles). Thus, the NHC ligand (8a) with the basic pendant is useful for maintaining the activity of the cationic silver catalyst.

With the optimal conditions in hand using 8a as the acid-base cooperative catalyst, the scope of alkynetethered carboxylic acids (9) was explored (Table 2). Both electron-donating (-OMe; 9b) and withdrawing groups (-NO<sub>2</sub> and -CN: 9c,d) were competent substituents at the para position of the aromatic ring of the phenylacetylene derivatives to afford the cyclized products 10b-d in high yields (94-99%, entries 1-3). Terminal alkyne 9e was less reactive (25%, entry 4). 5-Phenyl-4-pentynoic acid (9f) underwent 5-exo-dig with cyclization exclusive regioand stereoselectivities to produce  $(Z)-\gamma$ benzylidenebutyrolactone (10f) in 93% yield (entry 5). The reaction of 2-(phenylethynyl)benzoic acid (9g) occurred preferentially in 5-exo-dig cyclization mode to afford (Z)-3-benzylideneisobenzofuran-1(3H)-one (10g) as the major product, while the competitive 6endo-dig cyclization formed the corresponding  $\delta$ lactone (1%) as an inseparable by-product (entry 6). 4-Nonynoic acid **9h** was transformed to an E/Z mixture (13/87) of the corresponding  $\gamma$ -lactone 10h in 88% yield (entry 7). Similar erosion of stereoselectivity on the cyclization of 9h was reported for other silver(I) and gold(I) catalytic systems.<sup>[9b,18]</sup> Monomethyl malonate derivatives 9i and 9j were suitable substrates for the exo cyclization, giving the corresponding six-(10i) and five-membered (10j) lactones in 87% and 84% yields, respectively (entries 8 and 9). Twofold cyclization of dodeca-5,7-divnedioic acid 9k occurred cleanly to furnish the bislactone 10k in 98% yield (entry 10).

To gain insight into the reaction mechanism, the interactions between 8a and 9a were investigated by <sup>1</sup>H NMR titration with varying amounts of carboxytethered alkyne 9a (9a/Ag: 0-4 equiv) in CD<sub>3</sub>CN at 25 °C. Only a trace of cyclization was observed at this temperature. Upon addition of the alkyne (9a), signals for a new species appeared and their intensities

increased gradually as the **9a**/Ag ratio increased (see Supporting Information for details of the titration). Figure 2 shows aromatic regions of the spectra of **8a** in CD<sub>3</sub>CN and the mixture of **8a** and **9a** at **9a**/Ag = 4, where the ratio between the new species and **8a** is 19:81. <sup>[19]</sup> The most significant spectral change upon addition of **9a** is the downfield shift of the signals arising from the imidazole pendant. This is likely due to protonation of the imidazole at the N(4) atom by the

carboxyl group of **9a**, resulting in dissociation of the intermolecular N–Ag interactions and monomerization of the silver complex. Since no significant chemical shift change was observed at the propargylic methylene protons of **9a**, its alkyne moiety should be virtually uncoordinated with the silver atom. Instead, coordination of CD<sub>3</sub>CN to the vacant site of the silver atom is reasoned (see Supporting Information for <sup>1</sup>H NMR titrations). <sup>[20]</sup>





Reaction conditions: **9** (0.1 mmol) and **8a** (0.001 mmol, 2 mol% on Ag atom) in CH<sub>3</sub>CN (0.5 mL) at 80 °C for 15 h. <sup>[a]</sup>Determined by <sup>1</sup>H NMR analysis using phenanthrene as an internal standard due to the volatility of the product. <sup>[b]</sup>Including 1% of 3-phenyl-1*H*-isochromen-1-one.



Figure 2. <sup>1</sup>H NMR spectra of 8a (bottom) and 8a+9a (9a/Ag: 4 equiv) (top). \*: 8a; •: 9a; ▲: new species.

Density functional theory (DFT) calculations were conducted to investigate the mechanism of the Agcatalyzed cyclization. The geometry optimizations as well as frequency calculations were performed at the M06/lanl2dz (for silver) and 6-31+G(d,p) (for other elements) levels of theory<sup>[21,22]</sup> using Gaussian 16, <sup>[23]</sup> and the solvation effect of acetonitrile was introduced using the CPCM model.<sup>[24]</sup> The relative energies were corrected for the Gibbs free energies and given in kcal mol<sup>-1</sup> (Figure 3).

A mononuclear silver-alkyne  $\pi$  complex (Int-A) with an interaction between imidazole and the carboxylic acid is proposed as a plausible precursor for the cyclization. Nucleophilic *anti*-attack of the carboxy group to the alkyne moiety in the 6-exo-dig mode occurs through TS-A to form a six-membered lactone (Int-B) hydrogen-bonded with the protonated imidazole moiety. This step has an energy barrier of 21.4 kcal/mol and is 15.7 kcal mol<sup>-1</sup> endothermic. After dissociation of the hydrogen bond leading to the more stable intermediate Int-C, protonation of the Ag–C bond through **TS-B** gives the lactone (**Int-D**)  $\pi$ coordinated to the Ag atom at the exo alkene moiety. These results support our expectation that the Brønsted base moiety of the NHC ligand would participate cooperatively in the silver-catalyzed cyclization of the alkyne-tethered carboxylic acid.



**Figure 3**. Energy diagram for cyclization of **9a** catalyzed by silver complex **8a**. Calculations were performed at M06/ lanl2dz (for silver) and 6-31+G(d,p) (for other elements) levels of theory. The counter anion (PF<sub>6</sub><sup>-</sup>) of 3D model of **TS-A** is omitted for clarity.

In conclusion, we synthesized neutral and cationic silver(I) complexes with 5-(4-(*tert*-butyl)-1*H*-imidazol-1-yl)-imidazo[1,5-*a*]pyridin-3-ylidene ligands. Single-crystal XRD analysis showed that the neutral and cationic complexes existed as monomers or dimers. The cationic silver complexes showed catalytic activity for the cyclization of alkyne-tethered carboxylic acids. NMR experiments and DFT calculations indicated that an *in situ* generated monomeric cationic silver complex with an imidazole pendant acts as a cooperative Lewis acid-base catalyst. Exploration toward the development of other cooperative NHC-metal catalysis is underway.

#### **Experimental Section**

## General Procedure for Silver-Catalyzed Cyclization of 9

In a nitrogen-filled glove box, alkynoic acid (9, 0.1 mmol) was placed in a vial containing a magnetic stirring bar. A solution of cationic silver complex **8a** (1.2 mg, 0.001 mmol, 2 mol% on Ag) in dry CH<sub>3</sub>CN (0.5 mL) was added to the vial, and the vial was sealed with a screw-cap and removed from the glove box. After stirring at 80 °C for 15 hours, the mixture was cotton-filtered, and the resulting solution was concentrated under reduced pressure. The residue was purified by silica-gel column chromatography to afford alkylidenelactone **10**.

#### **Crystal Structures**

CCDC-2045683-2045686 for **7a**, **7b**, **8a**, and **8b** contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data\_request/cif.

#### Acknowledgements

This work was supported by JSPS KAKENHI Grant No. JP20K15268 in Grant-in-Aid for Early-Career

Scientists to K.H. and No. JP18H03906 in Grant-in-Aid for Scientific Research (A) to M.S.

#### References

- [1] a) W. A. Herrmann, C. Köcher, Angew. Chem., Int. Ed. Engl. 1997, 36, 2162–2187; b) W. A. Herrmann, Angew. Chem., Int. Ed. 2002, 41, 1290–1309; c) C. M. Crudden, D. P. Allen, Coord. Chem. Rev. 2004, 248, 2247–2273; d) O, Kühl, Chem. Soc. Rev. 2007, 36, 592–607; e) F. E. Hahn, M. C. Jahnke, Angew. Chem., Int. Ed. 2008, 47, 3122–3172; f) M. H. Hopkinson, C. Richter, M. Schedler, F. Glorius, Nature 2014, 510, 485-496.
- [2] M. Alcarazo, S. J. Roseblade, A. R. Cowley, R. Fernández, J. M. Brown, J. M. Lassaletta, *J. Am. Chem. Soc.* 2005, *127*, 3290–3291.
- [3] C. Burstein, C. W. Lehmann, F. Glorius, *Tetrahedron* 2005, 61, 6207–6217.
- [4] a) M. Espina, I. Rivilla, A. Conde, M. M. Díaz-Requejo, P. J. Pérez, E. Álvarez, R. Fernández, J. M. Lassaletta, *Organometallics* 2015, 34, 1328–1338; b) Y. Kim, Y. Kim, M. Y. Hur, E. Lee, J. Organomet. Chem. 2016, 820, 1–7; c) D.-A. Park, J. Y. Ryu, J. Lee, S. Hong, *RSC Adv.* 2017, 7, 52496–52502; d) M. Kashihara, R.-L. Zhong, K. Semba, S. Sakaki, Y. Nakao, *Chem. Commun.* 2019, 55, 9291–9294; e) X. Yi, K. Chen, J. Guo, W. Chen, W. Chen, *Adv. Synth. Catal.* 2020, 362, 4373–4377.
- [5] a) C. Grohmann, T. Hashimoto, R. Fröhlich, Y. Ohki, K. Tatsumi, F. Glorius, Organometallics 2012, 31, 8047–8050; b) E. Y. Tsui, T. Agapie, Polyhedron 2014, 84, 103–110; c) R. Nakao, K. Nozaki, J. Am. Chem. Soc. 2015, 137, 10934–10937; d) W. Tao, R. Nakano, S. Ito, K. Nozaki, Angew. Chem., Int. Ed. 2016, 55, 2835–2839; e) W. Tao, S. Akita, S. Ito, Y. Hoshimoto, S. Ogoshi, K. Nozaki, Chem. Commun. 2017, 53, 2630–2633; f) G. Liu, C. Liu, F. Han, Z. Wang, J. Wang, Tetrahedron Lett. 2017, 58, 726–731; g) K. Azouzi, C. Duhayon, I. Benaissa, N. Lugan, Y. Canac, S. Bastin, V. César, Organometallics 2018, 37, 4726–4735.
- [6] a) F. Grande-Carmona, J. Iglesias-Sigüenza, E. Álvarez, E. Díez, R. Fernández, J. M. Lassaletta, Organometallics 2015, 34, 5073–5080; b) C. T. Check, K. P. Jang, C. B. Schwamb, A. S. Wang, M. H. Wang,

K. A. Scheidt, *Angew. Chem., Int. Ed.* **2015**, *54*, 4264–4268; c) J. Iglesias-Sigüenza, C. Izquierdo, E. Díez, R. Fernández, J. M. Lassaletta, *Dalton. Trans.* **2016**, *45*, 10113-10117; d) J.-Q. Zhang, Y. Liu, X.-W. Wang, L. Zhang, *Organometallics* **2019**, *38*, 3931–3938; e) C. A. Swamy P, A. Varenikov, G. de Ruiter, *Chem. Eur. J.* **2020**, *26*, 2333–2337.

- [7] a) A. Fürstner, M. Alcarazo, H. Krause, C. W. Lehmann, J. Am. Chem. Soc. 2007, 129, 12676–12677; b) S. J. Roseblade, A. Ros, D. Monge, M. Alcarazo, E. Álvarez, J. M. Lassaletta, R. Fernández, Organometallics 2007, 26, 2570–2578; c) M. Alcarazo, T. Stoke, A. Anoop, W. Thiel, A. Fürstner, Angew. Chem., Int. Ed. 2010, 49, 2542–2546; d) Y. Tang, I. Benaissa, M. Huynh, L. Vendier, N. Lugan, S. Bastin, P. Belmont, V. César, V. Michelet, Angew. Chem., Int. Ed. 2019, 58, 7977–7981; S. Byun, H. Seo, J.-H. Choi, J. Y. Ryu, J. Lee, W. Chung, S. Hong, Organometallics 2019, 38, 4121–4132.
- [8] a) H. Nogami, M. Kanai, M. Shibasaki, *Chem. Pharm. Bull.* 2003, *51*, 702–709; b) D. H. Paull, C. J. Abraham, M. T. Scerba, E. Alden-Danforth, T. Lectka, *Acc. Chem. Res.* 2008, *41*, 655–663; c) E. L. Margelefsky, R. K. Zeidan, M. E. Davis, *Chem. Soc. Rev.* 2008, *37*, 1118– 1126; d) D. W. Stephan, *Acc. Chem. Res.* 2015, *48*, 306– 316; e) S. Afewerki, A. Córdova, *Chem. Rev.* 2016, *116*, 13512–13570; f) G. J. Knox, L. S. Hutchings-Goetz, C. M. Pearson, T. N. Snaddon, *Top. Curr. Chem.* 2020, *378*, 16.
- [9] Silver-catalyzed cyclization of alkynoic acids, see: a) K. Schötz, T. Clark, H. Schaller, P. von R. Schleyer, J. Org. Chem. 1984, 49, 735–736; b) P. Pale, J. Chuche, Tetrahedron Lett. 1987, 28, 6447–6448; c) V. Dalla, P. Pale, Tetrahedron Lett. 1994, 35, 3525–3528; d) J. A. Marshall, M. A. Wolf, E. M. Wallace, J. Org. Chem. 1997, 62, 367–371; e) R. Rossi, F. Bellina, C. Bechini, L. Mannina, P. Vergamini, Tetrahedron 1998, 54, 135–156; f) V. Dalla, P. Pale, New. J. Chem. 1999, 23, 803–805; g) F. Bellina, D. Ciucci, P. Vergamini, R. Rossi, Tetrahedron 2000, 56, 2533–2545; h) T. Yoshikawa, M. Shindo, Org. Lett. 2009, 11, 5378–5381; i) R. Nolla-Saltiel, E. Robles-Marín, S. Porcel, Tetrahedron Lett. 2014, 55, 4484–4488; j) I. J. Barve, T. U. Thikekar, C.-M. Sun, Org. Lett. 2017, 19, 2370–2373.
- [10] For cyclization of alkynoic acids catalyzed by acid-base cooperative catalysts, see: a) N. Á. Espinosa-Jalapa, D. Ke; N. Nebra, L. L. Goanvic, S. Mallet-Ladeira, J. Monot, B. Martin-Vaca, D. Bourissou, *ACS Catal.* 2014, *4*, 3605–3611; b) J. Monot, P. Brunel, C. E. Kefalidis, N. Á. Espinosa-Jalapa, L. Maron, B. Martin-Vaca, D. Bourissou, *Chem. Sci.* 2016, *7*, 2179–2187.
- [11] A. K. Verma, J. Singh, V. K. Sankar, R. Chaudhary, R. Chandra, *Tetrahedron Lett.* 2007, 48, 4207–4210.
- [12] A. Fürstner, M. Alcarazo, V. César, C. W. Lehmann, *Chem. Commun.* 2006, 2176–2178.
- [13] J. C. Garrison, W. J. Youngs, Chem. Rev. 2005, 105, 3978–4008.
- [14] a) P. de Frémont, N. M. Scott, E. D. Stevens, T. Ramnial, O. C. Lightbody, C. L. B. Macdonald, J. A. C.

Clyburne, C. D. Abernethy, S. P. Nolan, *Organometallics* **2005**, *24*, 6301–6309; b) H.-L. Su, L. M. Pérez, S.-J. Lee, J. H. Reibenspies, H. S. Bazzi, D. E. Bergbreiter, *Organometallics* **2012**, *31*, 4063–4071.

- [15] In the <sup>13</sup>C{<sup>1</sup>H} NMR spectra of the neutral AgCl complexes 7a and 7b in CD<sub>2</sub>Cl<sub>2</sub>, resonances for the carbene carbon were not observed. This is likely due to line-broadening of the signals, reflecting labile nature of the coordination of the carbene carbon atom to the Cl-bound silver atom. See: M. E. Garner, W. Niu, X. Chen, I. Ghiviriga, K. A. Abboud, W. Tan, A. S. Veige, *Dalton. Trans.* 2015, *44*, 1914–1923.
- [16] 1,3-Dimesitylimidazol-2-ylidene (IMes) was purchased from Sigma-Aldrich Co. LLC: A. J. Arduengo III, H. V. R. Dias, R. L. Harlow, M. Kline, J. Am. Chem. Soc. 1992, 114, 5530–5534.
- [17] 1,3-Bis(2,6-diisopropylphenyl)imidazol-2-ylidene (IPr) was purchased from Tokyo Chemical Industry Co.:
  A. J. Arduengo III, R. Krafczyk, R. Schmutzler, *Tetrahedron* 1999, 55, 14523–14534.
- [18] a) H. Harkat, J.-M. Weibel, P. Pale, *Tetrahedron Lett.* **2006**, 47, 6273-6276; b) H. Harkat, A. Y. Dembelé, J.-M. Weibel, A. Blanc, P. Pale, *Tetrahedron* **2009**, 65, 1871-1879.
- [19] The apparent chemical shift change was observed for H<sub>a</sub>\* upon the addition of **9a**. It may be due to weak interaction between H<sub>a</sub>\* and **9a**.
- [20] <sup>1</sup>H NMR titration of **8a** with benzoic acid in CD<sub>3</sub>CN produced new signals similar to those detected in the titration of **8a** with **9a** in CD<sub>3</sub>CN. In contrast, no new species appeared in the titration of **8a** with benzoic acid in CD<sub>2</sub>Cl<sub>2</sub>. This suggests that acetonitrile coordinates to the cationic silver complex, facilitating the monomerization of the complex with simultaneous protonation of the imidazole moiety. This behavior is consistent with the low catalytic activity of **8a** in toluene, 1,4-dioxane, and 1,2-dichloroethane.
- [21] Y. Zhao, D. G. Truhlar, Theor. Chem. Acc. 2008, 120, 215–241.
- [22] a) P. J. Hay, W. R. Wadt, J. Chem. Phys. 1985, 82, 299–310; b) R. Ditchfield, W. J. Hehre, J. A. Pople, J. Chem. Phys. 1971, 54, 724–728; c) W. J. Hehre, R. Ditchfield, J. A. Pople, J. Chem. Phys. 1972, 56, 2257-2261; d) P. C. Hariharan, J. A. Pople, Theoret. Chim. Acta. 1973, 28, 213–222.
- [23] Gaussian 16, Revision C.01: M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, G. A. Petersson, H. Nakatsuji, X. Li, M. Caricato, A. V. Marenich, J. Bloino, B. G. Janesko, R. Gomperts, B. Mennucci, H. P. Hratchian, J. V. Ortiz, A. F. Izmaylov, J. L. Sonnenberg, D. Williams-Young, F. Ding, F. Lipparini, F. Egidi, J. Goings, B. Peng, A. Petrone, T. Henderson, D. Ranasinghe, V. G. Zakrzewski, J. Gao, N. Rega, G. Zheng, W. Liang, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, K. Throssell, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. J.

Bearpark, J. J. Heyd, E. N. Brothers, K. N. Kudin, V. N. Staroverov, T. A. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. P. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, J. M. Millam, M. Klene, C. Adamo, R. Cammi, J. W. Ochterski, R. L. Martin, K. Morokuma,

O. Farkas, J. B. Foresman, and D. J. Fox, Gaussian, Inc., Wallingford CT, 2019.

[24] V. Barone, M. Cossi, J. Phys. Chem. A 1998, 102, 1995–2001.

### COMMUNICATION

Use of Imidazo[1,5-*a*]pyridin-3-ylidene as a Platform for Metal-Imidazole Cooperative Catalysis: Silver-Catalyzed Cyclization of Alkyne-Tethered Carboxylic Acids

Adv. Synth. Catal. Year, Volume, Page – Page

Vishal Kumar Rawat, Kosuke Higashida,\* Masaya Sawamura\*



