



Cite this: DOI: 10.1039/c8sc04437f

All publication charges for this article have been paid for by the Royal Society of Chemistry

# Nickel-catalyzed cyanation of aryl halides and triflates using acetonitrile *via* C–CN bond cleavage assisted by 1,4-bis(trimethylsilyl)-2,3,5,6-tetramethyl-1,4-dihydropyrazine†

Yohei Ueda,<sup>†</sup> Nagataka Tsujimoto,<sup>†</sup> Taiga Yurino, Hayato Tsurugi<sup>†\*</sup> and Kazushi Mashima<sup>†\*</sup>

Received 6th October 2018  
Accepted 23rd November 2018

DOI: 10.1039/c8sc04437f

rsc.li/chemical-science

We developed a non-toxic cyanation reaction of various aryl halides and triflates in acetonitrile using a catalyst system of [Ni(MeCN)<sub>6</sub>](BF<sub>4</sub>)<sub>2</sub>, 1,10-phenanthroline, and 1,4-bis(trimethylsilyl)-2,3,5,6-tetramethyl-1,4-dihydropyrazine (*Si*-Me<sub>4</sub>-DHP). *Si*-Me<sub>4</sub>-DHP was found to function as a reductant for generating nickel(0) species and a silylation reagent to achieve the catalytic cyanation *via* C–CN bond cleavage.

Nitriles are highly versatile functional compounds often used to prepare the corresponding amines, amides, and carboxylic acids.<sup>1</sup> Several useful synthetic protocols have been established as not only stoichiometric reactions, such as the Sandmeyer reaction and Rosenmund-von Braun reaction using CuCN,<sup>2</sup> but also metal-catalyzed cyanation reactions of aryl halides or aryl triflates using toxic cyanide reagents,<sup>3</sup> such as NaCN,<sup>4</sup> KCN,<sup>5</sup> CuCN,<sup>6</sup> Zn(CN)<sub>2</sub>,<sup>7</sup> and Me<sub>3</sub>SiCN.<sup>8</sup> Recent efforts have been aimed at developing non-toxic cyanation reactions using alkyl-nitriles,<sup>9</sup> despite the relatively high bond dissociation energy of the C–CN bond (*e.g.* 133 kcal mol<sup>−1</sup> for the C–CN bond of acetonitrile) compared with that of the typical C(sp<sup>3</sup>)–C(sp<sup>3</sup>) bond (*ca.* 83 kcal mol<sup>−1</sup>).<sup>10</sup> In fact, pivotal studies using acetonitrile as a cyano source were recently achieved at high temperature (120–160 °C): Cheng *et al.* used phosphine complexes of palladium and nickel for the catalytic cyanation of *ortho*-mono and *ortho*-disubstituted aryl halides with acetonitrile in the presence of zinc powder at elevated temperature (160 °C) (Fig. 1a),<sup>9d</sup> and Shen *et al.* applied a catalyst system of copper(II) nitrate with 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO) for the cyanation of aryl iodides in acetonitrile at high temperature (150 °C) (Fig. 1b).<sup>9e,f</sup> Quite recently, Morandi *et al.* demonstrated that a combination of bis(acetylacetonato) nickel(II) with Xantphos became a catalyst for the cyanation of aryl chlorides and aryl triflates with *n*-butyronitrile as a cyano

source in the presence of highly reactive Lewis acids such as tri(isobutyl)aluminum at high temperature (120 °C) (Fig. 1c).<sup>9g</sup>

In this context, we have continuously focused our efforts on finding a catalyst system active for such cyanation using acetonitrile under milder reaction conditions. Herein, we report a nickel-catalyzed cyanation of aryl halides and aryl triflates with acetonitrile at 80 °C or 100 °C in the presence of an organosilicon compound, 1,4-bis(trimethylsilyl)-2,3,5,6-tetramethyl-1,4-dihydropyrazine (*Si*-Me<sub>4</sub>-DHP), which served as both an effective reductant and a silylating reagent for nickel species (Fig. 1d).<sup>11</sup> It is noteworthy that C–CN bond cleavage of acetonitrile was achieved by  $\alpha$ -methyl elimination from an [N-(trimethylsilyl)iminoacyl]nickel intermediate, which was generated by insertion of acetonitrile into Ni–SiMe<sub>3</sub> species.

We started by searching for the best nickel catalyst system for the cyanation of 4-bromoanisole (**1a**) in acetonitrile, and the results are summarized in Table 1. The reaction mixture of **1a** and *Si*-Me<sub>4</sub>-DHP (2.5 equiv.) in the presence of catalytic amounts of [Ni(MeCN)<sub>6</sub>](BF<sub>4</sub>)<sub>2</sub> (2, 5 mol%) and 2,2'-bipyridine (**L1**, 5 mol%) in acetonitrile was heated at 80 °C for 24 h to give *p*-anisnitrile (**3a**) in 33% yield (entry 1). We further examined other nitrogen-based bidentate ligands: 4,4'-disubstituted-2,2'-bipyridine **L2–L4** afforded **3a** in low yields (entries 2–4), whereas 1,10-phenanthroline (**L5**) drastically improved the yield of **3a** up to 91% (entry 5). Other 1,10-phenanthroline-based ligands bearing substituents at 4,7-positions, such as methyl (**L6**), methoxy (**L7**), and phenyl (**L8**), were less effective than **L5**, giving **3a** in 58%, 30%, and 59% yields, respectively (entries 6–8). Accordingly, we selected **L5** as the best ligand. Furthermore, we found that the catalytic activity was quite sensitive to the amounts of **L5**: 2 equiv. of **L5** slightly decreased the yield (86%) of **3a** and 3 equiv. of **L5** significantly suppressed the activity to 54% yield (entries 9 and 10), the latter of which was consistent with the observation that an isolated dicationic tris(1,10-

Department of Chemistry, Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan. E-mail: tsurugi@chem.es.osaka-u.ac.jp; mashima@chem.es.osaka-u.ac.jp

† Electronic supplementary information (ESI) available: Experimental details for the synthesis of *Si*-Me<sub>4</sub>-DHP and **6**, screening of reaction conditions, identification of the products, and crystal data for **6**. CCDC 1852145. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c8sc04437f

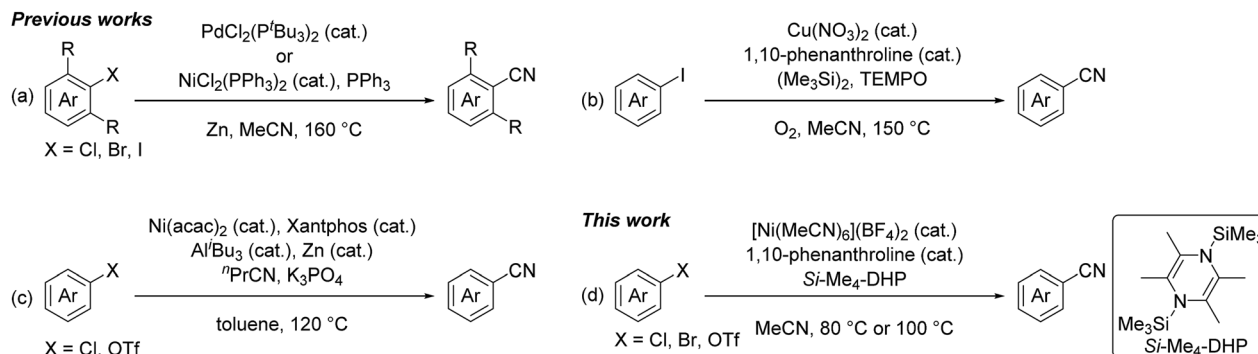
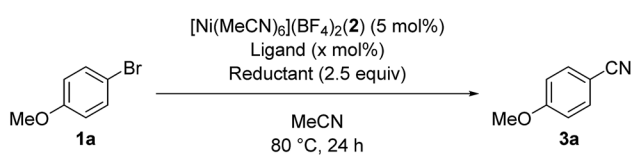


Fig. 1 Recent catalytic cyanation reactions using alkyl nitriles.

Table 1 Optimization for the cyanation of **1a** with acetonitrile<sup>a</sup>

|  |                 |                                 |                        |
|---|-----------------|---------------------------------|------------------------|
| Entry   | Ligand (x mol%) | Reductant                       | Yield <sup>b</sup> (%) |
| 1   | <b>L1</b> (5)   | <i>Si</i> -Me <sub>4</sub> -DHP | 33                     |
| 2   | <b>L2</b> (5)   | <i>Si</i> -Me <sub>4</sub> -DHP | 19                     |
| 3   | <b>L3</b> (5)   | <i>Si</i> -Me <sub>4</sub> -DHP | 17                     |
| 4   | <b>L4</b> (5)   | <i>Si</i> -Me <sub>4</sub> -DHP | 14                     |
| 5   | <b>L5</b> (5)   | <i>Si</i> -Me <sub>4</sub> -DHP | 91                     |
| 6   | <b>L6</b> (5)   | <i>Si</i> -Me <sub>4</sub> -DHP | 58                     |
| 7   | <b>L7</b> (5)   | <i>Si</i> -Me <sub>4</sub> -DHP | 30                     |
| 8   | <b>L8</b> (5)   | <i>Si</i> -Me <sub>4</sub> -DHP | 59                     |
| 9   | <b>L5</b> (10)  | <i>Si</i> -Me <sub>4</sub> -DHP | 86                     |
| 10  | <b>L5</b> (15)  | <i>Si</i> -Me <sub>4</sub> -DHP | 54                     |
| 11 <sup>c</sup>   | —               | <i>Si</i> -Me <sub>4</sub> -DHP | 61                     |
| 12 <sup>d</sup>   | <b>L5</b> (5)   | <i>Si</i> -Me <sub>4</sub> -DHP | 75                     |
| 13 <sup>e</sup>   | <b>L5</b> (5)   | <i>Si</i> -Me <sub>4</sub> -DHP | 86                     |
| 14  | —               | <i>Si</i> -Me <sub>4</sub> -DHP | 10                     |
| 15  | <b>L5</b> (5)   | Zn                              | 0                      |
| 16  | <b>L5</b> (5)   | Mn                              | 0                      |
| 17  | <b>L5</b> (5)   | TDAE                            | 0                      |
| 18  | <b>L5</b> (5)   | —                               | 0                      |

<sup>a</sup> Reaction conditions: **1a**, 0.10 mmol (0.025 M). <sup>b</sup> <sup>1</sup>H NMR yield using 1,3,5-trimethoxybenzene as an internal standard. <sup>c</sup> [Ni(**L5**)<sub>3</sub>](BF<sub>4</sub>)<sub>2</sub> was used instead of **2**. <sup>d</sup> 60 °C. <sup>e</sup> 100 °C.

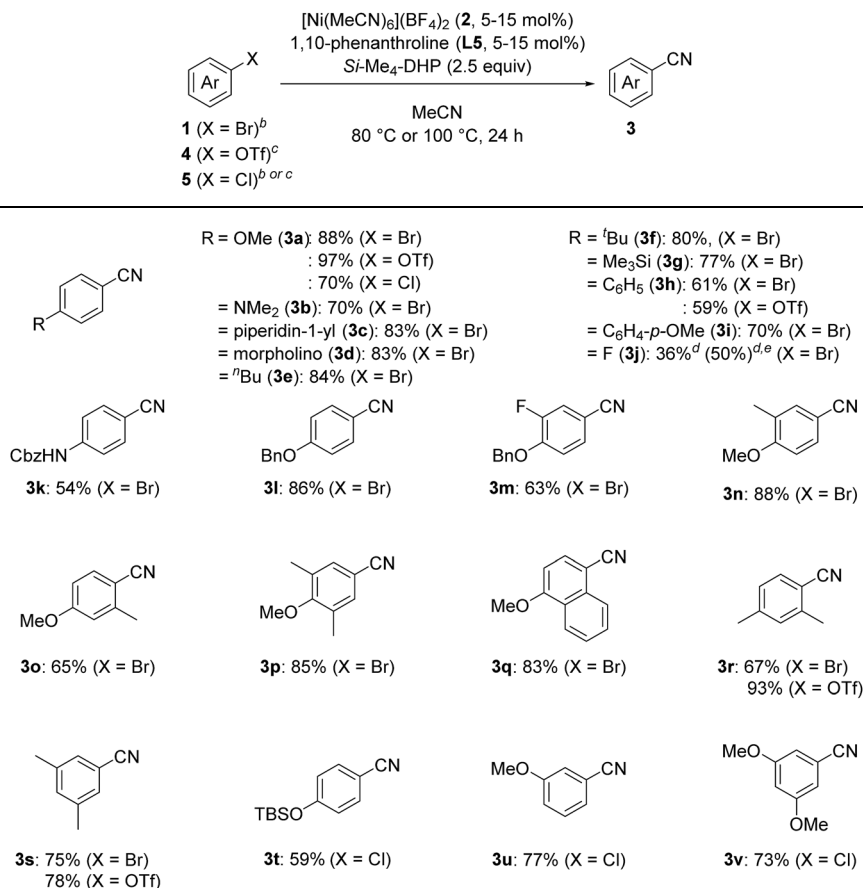
phenanthroline)nickel complex, [Ni(**L5**)<sub>3</sub>](BF<sub>4</sub>)<sub>2</sub>, afforded **3a** in 61% yield (entry 11). Upon varying the reaction temperature at 60 °C and 100 °C, we obtained **3a** in lower yields (75% and 86% yields, respectively) compared with the reaction conducted at 80 °C, giving **3a** in 91% yield (entries 12 and 13 vs. entry 5). The addition of **L5** was essential: the catalyst system without **L5** gave **3a** in a low yield (10%) (entry 14). The selection of the reducing reagents is the most significant factor for the cyanation reaction: no cyanation was observed when applying typical metal-based reducing reagents, such as zinc and manganese powder, as well as a typical organic reductant, tetrakis(dimethylamino)ethylene (TDAE) (entries 15–17), and the reaction without *Si*-Me<sub>4</sub>-DHP did not produce **3a** (entry 18), indicating that *Si*-Me<sub>4</sub>-DHP was

indispensable for the catalytic cyanation reaction (*vide infra*). As a result, we selected the mixture of catalytic amounts of **2** (5 mol%) and **L5** (5 mol%) in combination with an excess amount of *Si*-Me<sub>4</sub>-DHP (2.5 equiv.) as the best catalyst system.<sup>12</sup>



With the best catalyst system in hand, we examined the substrate scope of this nickel-catalyzed cyanation reaction (Table 2). Aryl bromides with electron-donating groups such as methoxy (**1a**), dialkylamino (**1b–1d**), and alkyl groups (**1e** and **1f**) at the *para*-position gave the corresponding aryl nitriles **3a–3f** in excellent to good yields (70–88%). Additionally, aryl bromides with electronically neutral *para*-substituents such as trimethylsilyl (**1g**), phenyl (**1h**), and *p*-methoxyphenyl (**1i**) were efficiently transformed into the corresponding aryl nitriles **3g–3i** in good yields (61–77%). On the other hand, aryl bromides with electron-withdrawing groups significantly decreased the yield of the corresponding aryl nitriles though the aryl bromides were completely consumed; 4-fluorobromobenzene (**1j**) afforded 4-fluorobenzonitrile (**3j**) in 36% yield together with unidentified byproducts, while aryl bromides with cyano, methoxycarbonyl, nitro, and trifluoromethyl groups resulted in a complex mixture. When the amount of *Si*-Me<sub>4</sub>-DHP was reduced to 1.1 equiv. for the cyanation of **1j**, **3j** was obtained in 50% yield together with 4-fluoroacetophenone (14% yield) as the main byproduct after acidic work-up. Typical protecting groups such as benzyloxycarbonyl (Cbz) and benzyl (Bn) groups were well tolerated to give the corresponding aryl nitriles in 54–86% yields (**3k–3m**). Notably, this nickel catalyst system was less sensitive to the steric hindrance around the bromide group: 4-methoxybromoarenes **1n–1p**, which respectively contained 3-Me, 2-Me, and 3,5-Me<sub>2</sub> substituents, afforded the corresponding aryl nitriles **3n–3p** in 65–88% yields. In addition, the cyanation of a polycyclic compound, 1-bromo-4-methoxynaphthalene (**1q**), gave **3q** in 83% yield. We further investigated the catalytic cyanation of several aryl triflates (**4a**, **4h**, **4r**, and **4s**), which were effectively converted to the corresponding aryl nitriles **3a**, **3h**, **3r**, and **3s** in 59–97% yields by increasing the catalytic loadings



Table 2 Substrate scope of substituted aryl halides and triflates<sup>a</sup>

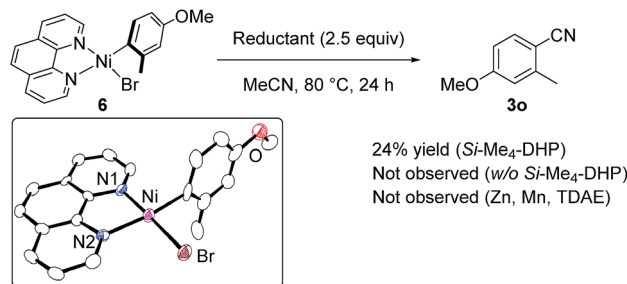
<sup>a</sup> Isolated yields. <sup>b</sup> Reaction conditions for aryl bromides 1a–1s and aryl chloride 5a: 1 or 5, 0.40 mmol (0.027 M); 2 (5 mol%); L5 (5 mol%); 80 °C. <sup>c</sup> Reaction conditions for aryl triflates 4a, 4h, 4r, and 4s and aryl chlorides 5t–5v: 4 or 5, 0.40 mmol (0.027 M); 2 (15 mol%); L5 (15 mol%); 100 °C. <sup>d</sup> <sup>1</sup>H NMR yield. <sup>e</sup> *Si*-Me<sub>4</sub>-DHP (1.1 equiv.) was used.

(15 mol%) and temperature (100 °C). Moreover, the cyanation of aryl chlorides (5a and 5t–5v) afforded 3a and 3t–3v in 59–77% yields, whereas the cyanation of 4-iodoanisole resulted in complex mixtures.

This nickel catalyst system was applicable to a wide range of heterocyclic compounds (Table 3): excellent to moderate yields were obtained for the cyanation of five- and six-membered heterocycles such as indoles (3w–3z) (53–99%), carbazole (3aa) (86%), indoline (3ab) (70%), dibenzofuran (3ac) (88%), benzothiophene (3ad) (48%), benzoxazole (3ae) (61%), pyrazole (3af) (52%), and pyrimidine (3ag) (62%). In all cases, no decomposition of the heterocycle motif was observed.

Regarding the reaction mechanism, we conducted some controlled experiments. The reaction of Ni(cod)<sub>2</sub> with 4-methoxy-2-methylbromobenzene (1o) in the presence of 1 equiv. of L5 afforded a nickel(II)  $\sigma$ -aryl complex, Ni(C<sub>6</sub>H<sub>3</sub>-4-OMe-2-Me)Br(L5) (6), in 76% yield,<sup>13</sup> which was characterized by spectral data as well as X-ray diffraction study of its single crystal. We then monitored the solution of 6 in acetonitrile with or without *Si*-Me<sub>4</sub>-DHP at 80 °C for 24 h: the reaction of 6 with acetonitrile in the presence of *Si*-Me<sub>4</sub>-DHP proceeded to give 3n in a substantial yield (24%), whereas no reaction of 6 with

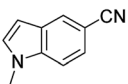
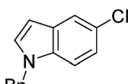
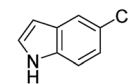
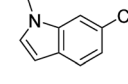
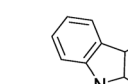
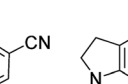
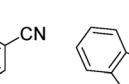
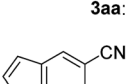
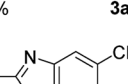
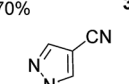
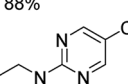
acetonitrile was observed in the absence of *Si*-Me<sub>4</sub>-DHP or in the presence of other reducing reagents (eqn (1)), clearly indicating that complex 6 was a key intermediate and *Si*-Me<sub>4</sub>-DHP played a key role for giving 3o. In fact, cyanation of 1a in the presence of 10 mol% of 6 produced 3a in 80% yield with stoichiometric amounts of 3o from 6 (eqn (2)). It is noteworthy that *Si*-Me<sub>4</sub>-DHP was consumed in the presence of Ni(cod)<sub>2</sub> (10 mol%) at room temperature to produce (Me<sub>3</sub>Si)<sub>2</sub> and 2,3,5,6-tetramethylpyrazine (Me<sub>4</sub>-pyrazine).<sup>14</sup> We thus assume that *Si*-Me<sub>4</sub>-DHP acts as a silylation reagent of nickel species.



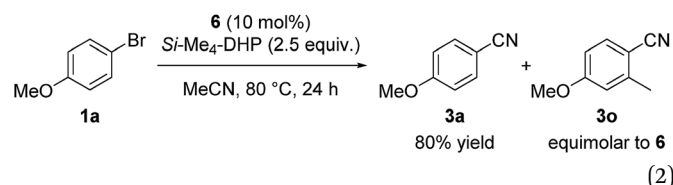
(1)



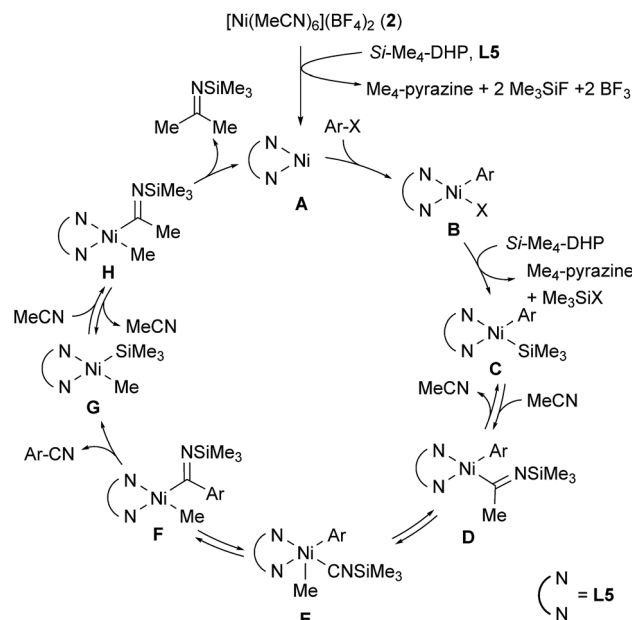
Table 3 Substrate scope of heterocyclic aryl bromides<sup>a</sup>

| $  \begin{array}{c}  \text{Ar-Br} \\  \text{1}  \end{array}  \xrightarrow[\text{MeCN, 80 } ^\circ\text{C, 24 h}]{\begin{array}{c} [\text{Ni}(\text{MeCN})_6](\text{BF}_4)_2 \text{ (2, 5 mol\%)} \\ \text{1,10-phenanthroline (L5, 5 mol\%)} \\ \text{Si-Me}_4\text{-DHP (2.5 equiv)} \end{array}}  \begin{array}{c}  \text{Ar-CN} \\  \text{3}  \end{array}  $ |   |
|---|---|
| <br>3w: 87%  | <br>3x: 98%  |
| <br>3y: 53%  | <br>3z: 99%  |
| <br>3aa: 86%   | <br>3ab: 70% |
| <br>3ac: 88%   |   |
| <br>3ad: 48%   | <br>3ae: 61% |
| <br>3af: 52%   | <br>3ag: 62% |

<sup>a</sup> Reaction conditions: **1**, 0.40 mmol (0.027 M). Isolated yield for all the products.

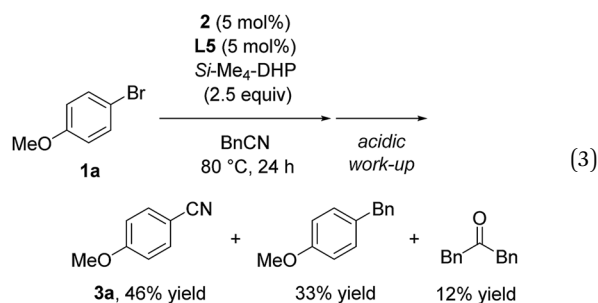


Scheme 1 shows a plausible catalytic cycle for the nickel-catalyzed cyanation reaction with acetonitrile as the sole cyano source based on the results of the controlled experiments shown in eqn (1) and (2). The initial step is the reduction of **2** by *Si-Me<sub>4</sub>-DHP* in the presence of **L5**, producing a 1,10-phenanthroline-coordinated Ni(0) species **A**.<sup>11b</sup> Subsequently, oxidative addition of aryl halides or aryl triflates (**ArX**) to **A** gives a Ni(II) species, Ni(**Ar**)X(**L5**) (**B**), **X** of which is silylated by the reaction with *Si-Me<sub>4</sub>-DHP* to afford Ni(**Ar**) (SiMe<sub>3</sub>) (**L5**) (**C**) with a release of Me<sub>3</sub>SiX and Me<sub>4</sub>-pyrazine. Insertion of acetonitrile into the Ni–Si bond of species **C** forms *N*-(trimethylsilyl)iminoacyl species **D**.<sup>15</sup>  $\alpha$ -Methyl elimination from **D** generates isonitrile species **E**, and the subsequent 1,1-insertion of CNSiMe<sub>3</sub> into the nickel-aryl moiety results in the formation of **F**.  $\beta$ -Silyl elimination of **F** spontaneously induces a liberation of aryl nitriles accompanied by the generation of Ni(Me) (SiMe<sub>3</sub>) (**L5**) (**G**).<sup>16</sup> Finally, the second insertion of acetonitrile into the Ni–Si bond of **G** followed by reductive elimination of *N*-(trimethylsilyl)propan-2-imine from **H** regenerates **A**. Notably, this is consistent with the formation of 4-fluoroacetophenone after acidic work-up when aryl bromide **1j** with an electron-withdrawing substituent is used as a substrate; reductive elimination from species **D** or **F** is competitive with the formation of **G** and **3j**.



Scheme 1 Plausible reaction mechanism.

Furthermore, we conducted the catalytic reaction in benzonitrile under the same catalytic conditions, and we obtained a mixture of **3a** (46%), 1-benzyl-4-methoxybenzene (33%), and dibenzylketone (12%) (eqn (3)).<sup>17</sup> Thus, the formation of 1-benzyl-4-methoxybenzene corresponded to reductive elimination from a similar intermediate, Ni(**Ar**) (Bn) (CNSiMe<sub>3</sub>) (**L5**) (**E'** in SI), and the formation of dibenzylketone corresponded to the formation of acetone after hydrolysis of *N*-(trimethylsilyl)propan-2-imine derived during the reaction course.



## Conclusions

We developed a toxic cyanide-free cyanation of aryl halides and aryl triflates using a nickel catalyst system of [Ni(MeCN)<sub>6</sub>](BF<sub>4</sub>)<sub>2</sub> and 1,10-phenanthroline along with a stoichiometric amount of an organosilicon reductant, *Si-Me<sub>4</sub>-DHP*, in acetonitrile. Noteworthy was that the mechanism of our catalytic system differs from the well-established direct C–CN bond cleavage involving Lewis acid-assisted oxidative addition to electron-rich low-valent group 10 metal complexes.<sup>9g,18,19</sup> In this catalytic system, *Si-Me<sub>4</sub>-DHP* had dual functions to reduce the nickel(II)





catalyst precursors but also to serve as a silylation reagent for nickel(II)  $\sigma$ -aryl species. Further application of *Si*-Me<sub>4</sub>-DHP as a silylating reagent to transition metals is ongoing in our laboratory.

## Conflicts of interest

The authors declare no conflict of interest.

## Acknowledgements

We thank Mr Shunsuke Kato for the initial experimental results. Y. U. thanks the financial support by the JSPS Research Fellowships for Young Scientists. This work was supported by JSPS KAKENHI Grant No. JP26708012 (Grant-in-Aid for Young Scientist (A)) to H. T. and JP15H05808 (Precisely Designed Catalysis with Customized Scaffolding) to K. M.

## Notes and references

- (a) Z. Rappoport, *Chemistry of the Cyano Group*, Wiley, London, 1970; (b) R. C. Larock, *Comprehensive Organic Transformations: A Guide to Functional Group Preparations*, Wiley, New York, 1989; (c) A. Kleeman, J. Engel, B. Kutschner and D. Reichert, *Pharmaceutical Substances: Syntheses, Patents, Applications*, Georg Thieme, Stuttgart, 4th edn, 2001; (d) S. I. Murahashi, *Sci. Synth.*, 2004, **19**, 345; (e) L. H. Jones, N. W. Summerhill, N. A. Swain and J. E. Mills, *MedChemComm*, 2010, **1**, 309; (f) P. Anbarasan, T. Schareina and M. Beller, *Chem. Soc. Rev.*, 2011, **40**, 5049.
- (a) T. Sandmeyer, *Ber. Dtsch. Chem. Ges.*, 1884, **17**, 2650; (b) H. H. Hodgson, *Chem. Rev.*, 1947, **40**, 251; (c) K. W. Rosenmund and E. Struck, *Ber. Dtsch. Chem. Ges.*, 1919, **52**, 1749.
- For representative reviews on stoichiometric or catalytic cyanation of aryl halides, see: (a) G. P. Ellis and T. M. Romney-Alexander, *Chem. Rev.*, 1987, **87**, 779; (b) V. V. Grushin and H. Alper, *Chem. Rev.*, 1994, **94**, 1047; (c) M. Tobisu and N. Chatani, *Chem. Soc. Rev.*, 2008, **37**, 300; (d) P. Anbarasan, H. Neumann and M. Beller, *Chem. - Eur. J.*, 2011, **17**, 4217; (e) J. Kim, H. J. Kim and S. Chang, *Angew. Chem., Int. Ed.*, 2012, **51**, 11948; (f) Q. Wen, J. Jin, L. Zhang, Y. Luo, P. Lu and Y. Wang, *Tetrahedron Lett.*, 2014, **55**, 1271; (g) Q. Wen, P. Lu and Y. Wang, *RSC Adv.*, 2014, **4**, 47806.
- Selected examples of using NaCN as cyano source: (a) L. Cassar, *J. Organomet. Chem.*, 1973, **54**, C57; (b) L. Cassar, S. Ferrara and M. Foà, *Adv. Chem. Ser.*, 1974, **132**, 252; (c) L. Cassar, M. Foà, F. Montanari and G. P. Marinelli, *J. Organomet. Chem.*, 1979, **173**, 335; (d) T. Okano, M. Iwahara and J. Kiji, *Synlett*, 1998, 243; (e) J. R. Dalton and S. L. Regen, *J. Org. Chem.*, 1979, **44**, 4443; (f) J. Zanon, A. Klarpars and S. L. Buchwald, *J. Am. Chem. Soc.*, 2003, **125**, 2890; (g) A. V. Ushkov and V. V. Grushin, *J. Am. Chem. Soc.*, 2011, **133**, 10999.
- Selected examples of using KCN as cyano source; (a) K. Takagi, T. Okamoto, Y. Sakakibara and S. Oka, *Chem. Lett.*, 1973, 471; (b) Y. Akita, M. Shimazaki and A. Ohta, *Synthesis*, 1981, **12**, 974; (c) Y. Sakakibara, F. Okuda, A. Shimobayashi, K. Kirino, M. Sakai, N. Uchino and K. Takagi, *Bull. Chem. Soc. Jpn.*, 1988, **61**, 1985; (d) B. A. Anderson, E. C. Bell, F. O. Ginah, N. K. Harn, L. M. Pagh and J. P. Wepsiec, *J. Org. Chem.*, 1998, **63**, 8224; (e) M. Sundermeier, A. Zapf, M. Beller and J. Sans, *Tetrahedron Lett.*, 2001, **42**, 6707; (f) M. Sundermeier, A. Zapf, S. Mutyala, W. Baumann, J. Sans, S. Weiss and M. Beller, *Chem.-Eur. J.*, 2003, **9**, 1828; (g) C. Yang and J. M. Williams, *Org. Lett.*, 2004, **6**, 2837; (h) H.-J. Cristau, A. Ouali, J.-F. Spindler and M. Taillefer, *Chem.-Eur. J.*, 2005, **11**, 2483.
- A Selected example of using CuCN as cyano source: T. Sakamoto and K. Ohsawa, *J. Chem. Soc., Perkin Trans. 1*, 1999, 2323.
- Selected examples of using Zn(CN)<sub>2</sub> as cyano source: (a) D. M. Tschaen, R. Desmond, A. O. King, M. C. Fortin, B. Pipik, S. King and T. R. Verhoeven, *Synth. Commun.*, 1994, **24**, 887; (b) P. E. Maligres, M. S. Waters, F. Fleitz and D. Askin, *Tetrahedron Lett.*, 1999, **40**, 8193; (c) M. Alterman and A. Hallberg, *J. Org. Chem.*, 2000, **65**, 7984; (d) F. Jin and P. N. Confalone, *Tetrahedron Lett.*, 2000, **41**, 3271; (e) J. Ramnauth, N. Bhardwaj, P. Renton, S. Rakhit and S. P. Maddaford, *Synlett*, 2003, **14**, 2237; (f) R. Chidambaram, *Tetrahedron Lett.*, 2004, **45**, 1441; (g) R. S. Jensen, A. S. Gajare, K. Toyota, M. Yoshifuji and F. Ozawa, *Tetrahedron Lett.*, 2005, **46**, 8645; (h) J. M. Veauthier, C. N. Carson, G. E. Collis, J. L. Kiplinger and K. D. John, *Synthesis*, 2005, **16**, 2683; (i) M. T. Martin, B. Liu, B. E. Cooley Jr and J. F. Eaddy, *Tetrahedron Lett.*, 2007, **48**, 2555; (j) A. Littke, M. Soumeillant, R. F. Kaltenbach, R. J. Cherney, C. M. Tarby and S. Kiau, *Org. Lett.*, 2007, **9**, 1711; (k) F. G. Buono, R. Chidambaram, R. H. Mueller and R. E. Waltermire, *Org. Lett.*, 2008, **10**, 5325; (l) D. T. Cohen and S. L. Buchwald, *Org. Lett.*, 2015, **17**, 202; (m) X. Zhang, A. Xia, H. Chen and Y. Liu, *Org. Lett.*, 2017, **19**, 2118.
- Selected examples of using Me<sub>3</sub>SiCN as cyano source: (a) N. Chatani and T. Hanafusa, *J. Org. Chem.*, 1986, **51**, 4714; (b) M. Sundermeier, S. Mutyala, A. Zapf, A. Spannenberg and M. Beller, *J. Organomet. Chem.*, 2003, **684**, 50.
- Selected examples of using harmless organic nitrile compounds as cyano source are as follows. Acetone cyanohydrin; (a) M. Sundermeier, A. Zapf and M. Beller, *Angew. Chem., Int. Ed.*, 2003, **42**, 1661; *Angew. Chem.*, 2003, **115**, 1700; (b) T. Schareina, A. Zapf, A. Cotté, M. Gotta and M. Beller, *Adv. Synth. Catal.*, 2011, **353**, 777; (c) F. Burg, J. Egger, J. Deutsch and N. Guimond, *Org. Process Res. Dev.*, 2016, **20**, 1540acetone nitrile; (d) F.-H. Luo, C.-I. Chu and C.-H. Chen, *Organometallics*, 1998, **17**, 1025; (e) M. Zhao, W. Zhang and Z. Shen, *J. Org. Chem.*, 2015, **80**, 8868; (f) Y. Zhu, M. Zhao, W. Lu, L. Li and Z. Shen, *Org. Lett.*, 2015, **17**, 2602butyronitrile; (g) P. Yu and B. Morandi, *Angew. Chem., Int. Ed.*, 2017, **56**, 15693; *Angew. Chem.*, 2017, **129**, 15899malonitrile, aminonitrile, cyanoester; (h) Z. Jiang, Q. Huang, S. Chen, L. Long and X. Zhou, *Adv. Synth. Catal.*,



- 2012, **354**, 589; (i) S. Zheng, C. Yu and Z. Shen, *Org. Lett.*, 2012, **14**, 3644; (j) S.-L. Zhang and L. Huang, *Org. Biomol. Chem.*, 2015, **13**, 9963; (k) R. Takise, K. Itami and J. Yamaguchi, *Org. Lett.*, 2016, **18**, 4428.
- 10 (a) X. Kou, M. Zhao, X. Qiao, Y. Zhu, X. Tong and Z. Shen, *Chem.-Eur. J.*, 2013, **19**, 16880; (b) A. A. Zavitsas, *J. Phys. Chem. A*, 2003, **107**, 897.
- 11 (a) T. Saito, H. Nishiyama, H. Tanahashi, K. Kawakita, H. Tsurugi and K. Mashima, *J. Am. Chem. Soc.*, 2014, **136**, 5161; (b) T. Yurino, Y. Ueda, Y. Shimizu, S. Tanaka, H. Nishiyama, H. Tsurugi, K. Sato and K. Mashima, *Angew. Chem., Int. Ed.*, 2015, **54**, 14437.
- 12 For effects of additional reaction parameters such as solvent and organosilicon reductants, see ESI†.
- 13 E. A. Standley and T. F. Jamison, *J. Am. Chem. Soc.*, 2013, **135**, 1585.
- 14 See ESI† for details.
- 15 (a) H. Nakazawa, T. Kawasaki, K. Miyoshi, C. H. Suresh and N. Koga, *Organometallics*, 2004, **23**, 117; (b) F. L. Taw, P. S. White, R. G. Bergman and M. Brookhart, *J. Am. Chem. Soc.*, 2002, **124**, 4192; (c) M. Tobisu, Y. Kita and N. Chatani, *J. Am. Chem. Soc.*, 2006, **128**, 8152; (d) M. Tobisu, Y. Kita, Y. Ano and N. Chatani, *J. Am. Chem. Soc.*, 2008, **130**, 15982; (e) S.-L. Zhang, L. Huang and W.-F. Bie, *Organometallics*, 2014, **33**, 3030.
- 16 (a) C.-Y. Ho and L. He, *Chem. Commun.*, 2012, **48**, 1481; (b) Z. Chen, M. D. Leatherman, O. Daugulis and M. Brookhart, *J. Am. Chem. Soc.*, 2017, **139**, 16013; (c) M. R. Elsby and S. A. Johnson, *J. Am. Chem. Soc.*, 2017, **139**, 9401.
- 17 For more details on the mass-balance of this reaction, see ESI†.
- 18 (a) J. J. Garcia, A. Arévalo, N. M. Brunkan and W. D. Jones, *Organometallics*, 2004, **23**, 3997; (b) Y. Nakao, A. Yada, S. Ebata and T. Hiyama, *J. Am. Chem. Soc.*, 2007, **129**, 2428.
- 19 A direct cleavage of the C–CN bond of acetonitrile by *in situ* generated Ni(0) center was excluded under our reaction condition (see ESI†).

