Development of Novel Synthesis Methods Using Isocyanides by Transition-Metal-Catalyzed or Photoinduced Reactions

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Tran Chi Cong

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Preface

This thesis deals with the studies conducted during October 2017 to September 2020 under the guidance of Professor Akiya Ogawa at the Department of Applied Chemistry, Graduate School of Engineering, Osaka Prefecture University.

This thesis is concerned with the development of novel transformations of isocyanides to synthesize nitrogen-containing key molecules. One important topic of this thesis is the metal-catalyzed arylation of isocyanides to selectively synthesize imines and *α*-diimines. Another topic of this thesis is the development of the photoinduced radial cyclization of *o*-diisocyanoarenes with organic diselenides and thiols to afford chalcogenated quinoxaline derivatives.

Department of Applied Chemistry

Graduate School of Engineering

Osaka Prefecture University

July 2020 ***Tran Chi Cong***

Contents

Chapter 1

General Introduction

Isocyanides are useful C1 unites in organic synthesis due to their versatility in the construction of imine derivatives and nitrogen-containing heterocyclic compounds, leading to a variety of significant applications such as ligands for metal complexes, pharmaceuticals, pesticides, dyes, organic electronic devices, and so on.[1] Indeed, insertion reaction of isocyanides has been shown as a powerful strategy to prepare various nitrogen-containing organic compounds. A number of significant progresses have been made in transition-metal-mediated or -catalyzed insertion reaction of isocyanides as well as the radical reactions involving imidoyl radical intermediates.[2] However, synthetic transformations of isocyanides sometimes require excess amounts of strong base, acid, and oxidants under harsh reaction conditions, resulting in the formation of a complex mixture involving isocyanide oligomers. Thus, the development of high atom-economic and efficient synthetic methods using isocyanides is strongly desired.

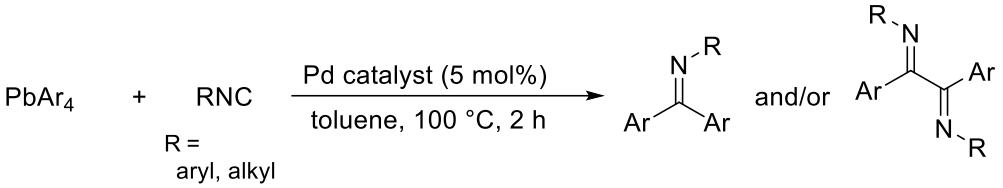
Because of the unique properties of group 16 heteroatoms (especially, S and Se), the use of chalcogen compounds including organic chalcogenides and thiols has been attracted much attention. For example, it has been proven that a lot of chalcogen compounds exhibit novel bioactivities[3] as well as superior properties in materials science.[4] Therefore, investigation of the pharmaceutical compounds such as antibacterial, antitumor, and hypotensive agents bearing sulfur and selenium has been extensively developed in recent years.[5] For example, chalcogenated quinoxalines have been reported to exhibit antioxidant activities. However, the current synthetic methods of them still suffer from the narrow substrate range. Therefore, new synthetic approaches are strongly desired to extend the substrate scope of the reaction to afford chalcogenated quinoxalines.

In this thesis, the author has developed transition-metal-catalyzed arylation reactions of isocyanides. Using tetraarylleads as arylating reagents, isocyanides could be transformed into imines and/or *α*-diimines under a catalytic amount of palladium catalysts. In addition, the diarylation of isocyanides with triarylbismuthines as aryl sources has been investigated using various catalytic transition metal systems. The synthesis of various chalcogenated, nitrogen-containing compounds has also been established under the photoirradiation conditions. In particular, the photoinduced chalcogenated cyclization of *o*-diisocyanoarenes with organic diselenides and thiols provides a useful, straightforward tool to chalcogenated quinoxalines. All the reported reactions are carried out under additive-free conditions. This thesis consists of five chapters and the outlines of each chapter are summarized as follows.

Chapter 1 describes the background, general objectives, and the contents of this thesis.

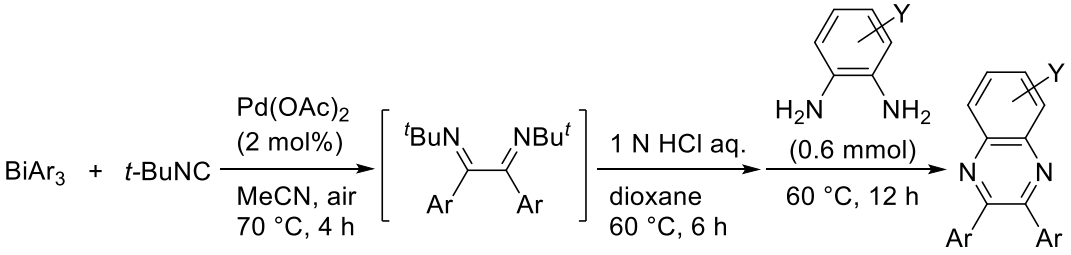
Chapter 2 describes a palladium-catalyzed arylation of isocyanides using tetraarylleads as arylating reagents to synthesize imines and/or *α*-diimines. During the investigation of arylating reagents of heavy elements, the author found that, unlike triarylbismuthines which afforded only *α*-diimines under a catalytic amount of palladium catalyst, the use of tetraarylleads provided the formation of imines as the major product in the case of some aliphatic isocyanides. On the other hand, *α*-diimines were found to be formed primarily when electron-rich aromatic isocyanides were applied to the diarylation. The mechanistic investigation indicated that the selectivity and yield of products depended on the nature structure of isocyanides used. Electron-rich aromatic isocyanides stabilized the imidoyl-metal complex; thus, secondary insertion of isocyanide happened and *α*-diimine was formed as the result. Meanwhile, unstable imidoyl-metal complexes preferred to undergo reductive elimination, affording the corresponding imines. The reaction proceeded under additive-free and base-free conditions without formation of polymers or oligomers of isocyanides. Even though the use of organoleads in organic synthesis is very limited because of the toxicity of lead compounds, this work demonstrates a very interesting organic transformation using organoleads. It is also worth noting that *α*-diimines are useful synthetic

precursors for a variety of *N*-heterocyclic carbenes (NHCs). The author believes that the present research provides an efficient synthetic tool for the preparation of NHCs.



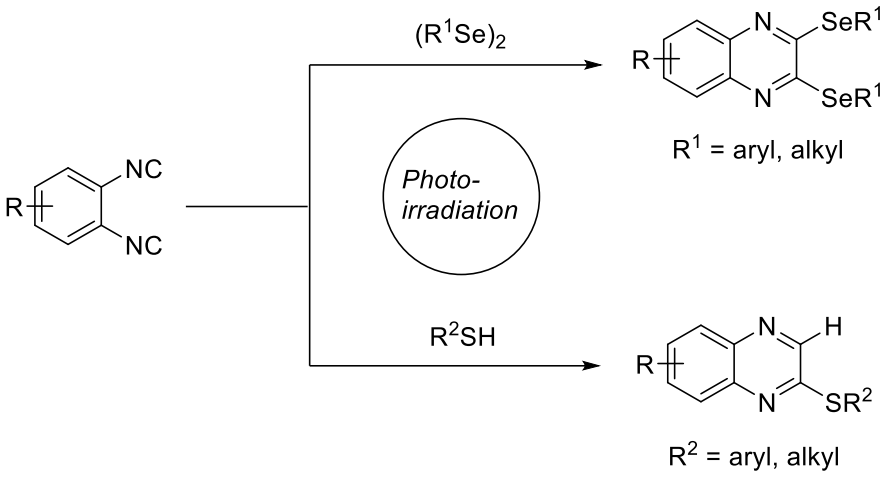
Scheme 1-1. Palladium-catalyzed arylation of isocyanides using tetraarylleads

Chapter 3 describes a transition-metal-catalyzed diarylation of isocyanides with triarylbismuthines and its synthetic application. Organobismuth compounds are well-known to be environmentally friendly reagents and have been used as unique synthetic reagents in organic chemistry. Indeed, the synthetic applications of triarylbismuthines have been investigated, and various arylation reactions have been reported using triarylbismuthines as arylating reagents. In this study, the author investigated the diarylation of isocyanides with triarylbismuthines in the presence of the palladium and rhodium catalysts; namely, condition parameters such as solvent, temperature, type of catalyst, and inert atmosphere were optimized in detail. As the results, the palladium-catalyzed diarylation afforded α-diimines as the major products, whereas the rhodium-catalyzed reaction gave imines selectively. Besides, amides as by-product was formed under some certain conditions. In addition, the present diarylation was successfully applied to the synthesis of quinoxaline derivatives in moderate to good yields. The synthesis of *N*-heterocyclic carbenes (NHCs) in one reaction bath was also carried out and the desired *N*-heterocyclic carbene precursor was obtained.



Scheme 1-2. Synthesis of quinoxalines from palladium catalyzed diarylation of isocyanides using triarylbismuthines

Chapter 4 describes a photoinduced radical cyclization of *o*-diisocyanoarenes with organic diselenides and thiols that successfully afford chalcogenated quinoxalines. The chalcogenated quinoxalines have been known to exhibit unique bioactivities, which have been proven in many reports. Conventionally, chalcogenated quinoxalines have been synthesized by the nucleophilic substitution reaction of thiols (or selenides) with the corresponding chlorinated quinoxalines. However, the method significantly suffers from the substrate scope of quinoxalines derivatives. It has been known that organic thiols, diselenides, and aromatic diisocyanides are activated under visible light irradiation. This is because their absorptions are observed in a range of 300-500 nm. The author expected that the photoinduced reaction of the above compounds must efficiently provide the corresponding quinoxaline products. Thus, the photoinduced reaction of *o*-diisocyanoarenes with thiols or diselenides provided an effective synthetic approach to the construction of chalcogenated quinoxaline derivatives. Some mechanistic investigations indicated that the reaction proceeded via a radical cyclization pathway initiated by attack of chalcogeno radicals to isocyanides. The transformation is featured by a high conversion, a broad substrate scope, and mild reaction conditions. Moreover, the cyclization reaction is scalable to gram-scale of the starting *o*-diisocyanide, which demonstrates the practicability of the present cyclization reaction.



Scheme 1-3. Photoinduced cyclization of *o*-diisocyanides with diselenides and thiols

Chapter 5 describes the conclusion of this thesis.

In conclusion, this thesis describes a series of organic transformations of isocyanides under very diverse transition-metal-catalyzed conditions. With the careful choice of catalysts (e.g., palladium or rhodium) and arylating reagent (organoleads or organobismuthines), the desired imine or α-diimine can be synthesized selectively. The reported reactions provide very powerful synthetic methods to various useful nitrogen-containing molecules including *N*-heterocyclic carbenes. The photoinduced reactions of *o*-diisocyanides with chalcogenides (e.g., thiols and diselenides) contribute very efficient and interesting synthetic methods for thio- or seleno-substituted quinoxalines with promising bioactivities. Other potential reactions of *o*-diisocyanides with radical sources are also expected to happen. For example, diphenyl ditelluride or iodine are known for very good radical trapping reagents. Thus, a new generation of quinoxalines can be created in this methodology. The author believes that these works will open up a new route to construct various bioactive and pharmaceutical compounds.

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Chapter 2

Palladium-Catalyzed Diarylation of Isocyanides with Tetraarylleads for the Selective Synthesis of Imines and *α*-Diimines

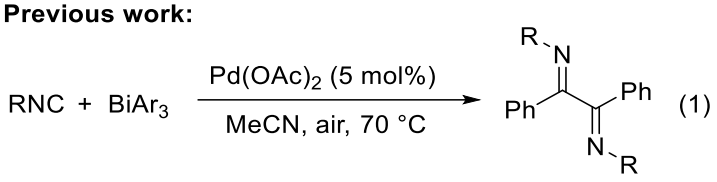
2-1 Introduction

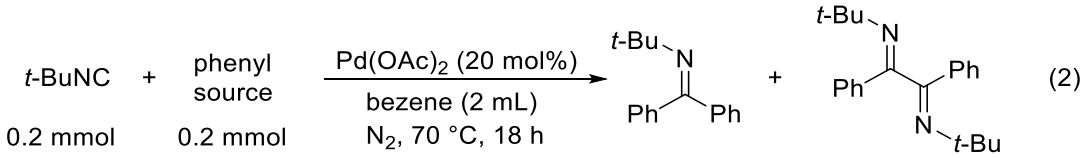
Isocyanides, which contain a moiety whose structure is isoelectronic with that of carbon monoxide, are useful C1 units in organic synthesis in addition to being excellent building blocks for nitrogen-containing heterocyclic compounds.[1] In transition-metal-catalyzed reactions, carbon monoxide inserts into carbon-metal (C-M) bonds, generating acyl-metal species as key intermediates, and usually, monocarbonylation takes place selectively. In contrast, in the case of isocyanides, not only one molecule but two or more molecules of isocyanides can insert into C-M bonds, resulting in the formation of a mixture of mono-, di-, tri-, and oligo-isocyanide containing compounds.[2-5] Thus, to develop novel synthetic reactions using isocyanides, control of this "multi-insertion" process is necessary. In this context, the authors recently developed a selective reaction between isocyanides and triarylbismuth species in the presence of a $Pd(OAc)_2$ catalyst, to selectively afford *α*-diimines, through the incorporation of two isocyanides molecules (Scheme 2-1, eq 1).[6] The same reaction failed using arylating reagents of early elements such as $PhB(OH)_2$ (eq 2). The authors therefore turned their focus to rate element arylating reagents, and examined the reaction of *t*-butyl isocyanide with PhI, Ph_3Sb, Ph_4Sn, and Ph_4Pb under similar conditions as those employed for the diarylation reaction using triarylbismuths species (eq 2). Interestingly, the use of tetraphenyllead[7,8] resulted in the novel diphenylation of one isocyanide molecule to selectively give the corresponding benzophenone imine in good yield.

In this chapter, the author describes the Pd-catalyzed diarylation of isocyanides using tetraaryllead (eq 3).

Scheme 2-1. Palladium-catalyzed arylation of isocyanides

Previous work:

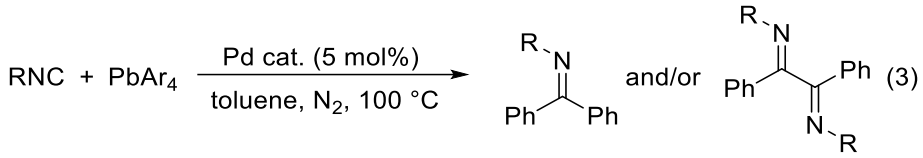




$PbAr_4$	72%	28%
$PhB(OH)_2$	trace	3%
PhI	ND	ND
$SbPh_3$	0%	18%
$SbPh_4$	ND	15%

*Determined by ^1H NMR (ND = not detected).

This work:

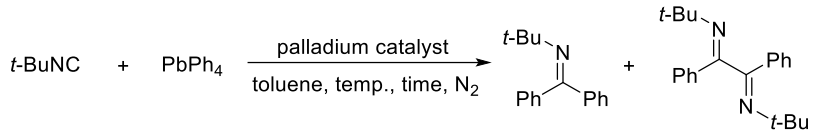


2-2 Results and discussion

Initially, the author optimized the reaction conditions for imines synthesis using *t*-butylisocyanide **1a** and tetraphenyllead **2a** (Table 2-1). When the reaction of **1a** (0.2 mmol) with **2a** (1.5 equiv) was carried out in the presence of $Pd(OAc)_2$ (2.5 mol%) in toluene under N_2 atmosphere for 4 h, imine **3aa** was obtained in a good yield (75%) along with *α*-diimine **4aa** (11%, entry 1). Increasing the quantity of palladium catalyst employed (i.e., 5 or 10 mol %) led to 85 and 72% yields of **3aa**, respectively (entries 2 and 3). The yield dramatically decreased when the reaction was conducted under air (45% yield, entry 4), while the use of acetonitrile (MeCN)

as a solvent in place of toluene also gave a low yield (42%) of **3aa** (entry 5). Increasing the quantity of **2a** to 2.0 equiv. resulted in a 77% yield of **3aa** (entry 6). Increase of the reaction temperature in shorten time resulted in the similar result as the case of entry 2 (entry 7).

Table 2-1. Optimization of the reaction conditions of the catalytic diarylation[a,b]



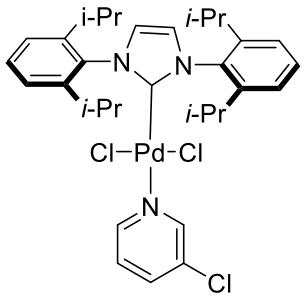
1a (0.2 mmol) **2a** (1.5 equiv.) **3aa** **4aa**

entry	Catalyst	temp., °C	time, h	yield of **3aa**, %	yield of **4aa**, %
1	$Pd(OAc)_2$ 2.5 mol%	70	4	75	11
2	$Pd(OAc)_2$ 5 mol%	70	4	85	14
3	$Pd(OAc)_2$ 10 mol%	70	4	72	12
4[c]	$Pd(OAc)_2$ 5 mol%	70	4	45	36
5[d]	$Pd(OAc)_2$ 5 mol%	70	4	43	52
6[e]	$Pd(OAc)_2$ 5 mol%	70	2	77	16
7	$Pd(OAc)_2$ 5 mol%	100	2	85	14
8[f]	**$Pd(OAc)_2$ 5 mol%**	**100**	**2**	**92 (72)**	**8**
9	$Pd(PPh_3)_4$ 5 mol%	100	2	61	26
10	$PdCl_2(PPh_3)_2$ 5 mol%	100	2	41	22
11[f,g]	$Pd(OAc)_2$ 5 mol%	100	2	75	15
12[f]	Catalyst A 5 mol%	100	2	28	53

[a]Reaction conditions: Isocyanide (**1a**, 0.2 mmol), tetraphenyllead (**2a**, 1.5 equiv.), toluene (2 mL), and the transition metal catalyst were added in this order. [b]Determined by ^{1}H NMR spectroscopy (the isolated yield is indicated in parenthesis), ND = not detected. [c]The reaction was conducted under air. [d]MeCN (2

mL) was used. [e]$PbAr_4$ (2.0 equiv.) was used. [f]Isocyanide **1a** was added last. [g]BINAP (20 mol%) was added.

Catalyst A:

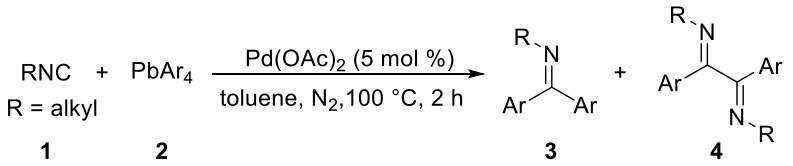


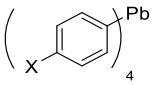
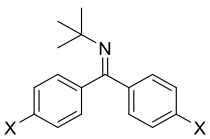
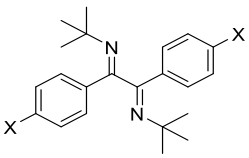
Fortunately, imine **3aa** was obtained in 92% yield (72% isolated yield, entry 8) when isocyanide **1a** was added to a mixture of $PbPh_4$ and $Pd(OAc)_2$ in toluene. The influence of the palladium catalyst to the diarylation was also investigated (entries 9 and 10), and it was found that zero- and divalent palladium complexes exhibited catalytic activity toward the diarylation of isocyanides, but the product selectivity (**3aa** vs. **4aa**) was lower compared to that obtained using $Pd(OAc)_2$. The addition of (±)-BINAP ((±)-2,2'-bis(diphenylphosphino)-1,1'-binaphthyl) ligand resulted in slight decrease of the reaction yield and imine/*α*-diimine selectivity (entry 11). Coordination mode of phosphine ligands toward palladium center might lead to minor change in the reaction yield and product selectivity. When NHC-Pd catalyst was used, interestingly, *α*-diimine **4aa** was obtained in preference to imine **3aa** (entry 12).[9]

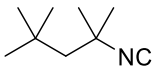
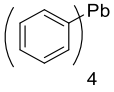
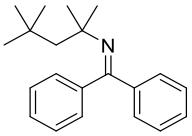
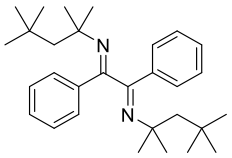
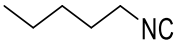
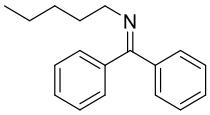
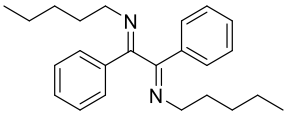
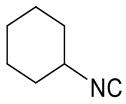
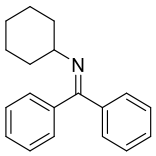
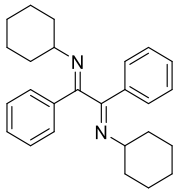
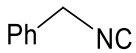
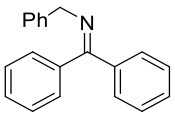
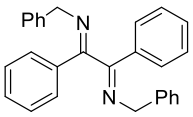
The author then investigated the scope of isocyanides and tetraaryllead compounds using the optimized conditions (Table 2-1, entry 8), and the results are presented in Table 2-2. Various *para*-substituted tetraaryllead species were investigated for the catalytic diarylation of *t*-BuNC. When electron-rich tetraaryllead compounds **2b**–**2d** (cf. Hammet σ values: -0.170 (X = Me); -0197 (^{t}Bu); -2.68 (MeO)) were employed, the corresponding imines **3ab**–**3ad** were obtained selectively in higher yields, compared with Ph_4Pb **2a** (σ = 0.00) (entries 2–4 vs. entry 1). In

contrast, *p*-Cl-substituted organolead compound **2e** (σ = +0.227) exclusively afforded imine **3ae** in lower yields (entry 5). In the case of *p*-F-substituted organolead **2f** (σ = +0.062), the yield of **3af** is similar to that of **3aa** (entry 6). These results suggest that the electronic nature of the aryl group on Pb affects the yields of imines **3**. In terms of the isocyanides, long-chain and branched aliphatic isocyanides **1b** and **1c** underwent the catalytic diarylation to give imines **3ba** and **3ca** as the major products (entries 7 and 8). However, compared to the case of *t*-BuNC, the imine/*α*-diimine selectivity was lower. Furthermore, isocyanides **1d** and **1e** bearing cyclohexyl and benzyl groups preferentially afforded imines **3da** and **3ea** in good yields along with *α*-diimines **4da** and **4ea**, respectively, as minor products (entries 9 and 10). As can be seen from the results of entries 7-10, the present diarylation was sensitive to the substituents on isocyanides. Moreover, Table 1 clearly indicates that the reaction conditions also influence the imine/*α*-diimine selectivity. Therefore, to get an excellent product selectivity, further optimization is required for each isocyanide substrate.

Table 2-2. Substrate scope for the palladium-catalyzed diarylation of alkyl isocyanides with $PbAr_4$[a]



entry	isocyanide **1**	tetraaryllead **2**	yield of **3**, %[b]	yield of **4**, %[b]
				
1	**1a**	X = H (**2a**)	**3aa**, 72	**4aa**, (8)
2	**1a**	Me (**2b**)	**3ab**, 86	**4ab**, 12
3	**1a**	*t*-C_4H_9 (**2c**)	**3ac**, 91	**4ac**, (6)

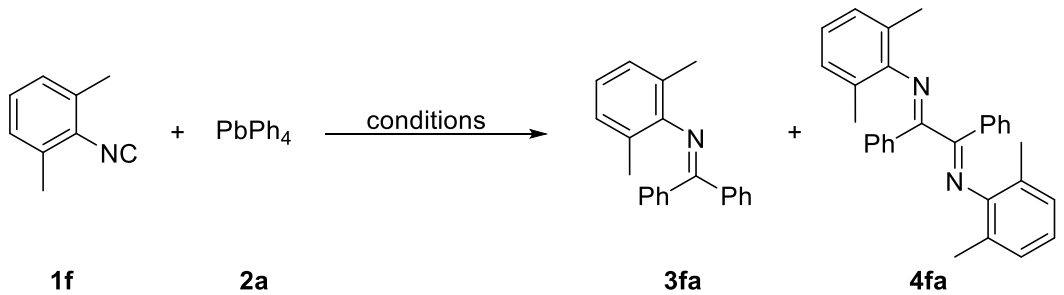
4	**1a**	OMe (**2d**)	**3ad**, 88	**4ad**, (5)
5	**1a**	Cl (**2e**)	**3ae**, 50	**4ae**, ND
6	**1a**	F (**2f**)	**3af**, 74	**4af**, ND
				
7	**1b**	**2a**	**3ba**, (52)	**4ba**, 36
				
8	**1c**	**2a**	**3ca**, (31)	**4ca**, 23
				
9	**1d**	**2a**	**3da**, 47	**4da**, 33
				
10[c]	**1e**	**2a**	**3ea**, 70	**4ea**, 20

[a]Reaction conditions: Isocyanide **1** (0.2 mmol) was added to a mixture of **2** (0.3 mmol) and $Pd(OAc)_2$ (0.01 mmol) in toluene (2 mL), 100 °C, 2 h. [b]Isolated yield (yields in parentheses were determined by ^1H NMR spectroscopy, when the product was difficult to purify from reaction mixture), ND = not detected. [c]Reaction time: 4 h.

Interestingly, when an aromatic isocyanide **1f** was employed for the $Pd(OAc)_2$-catalyzed diarylation with $PbPh_4$, the product selectivity (imine **3** vs. α-diimine **4**) was altered: α-diimines

4fa was obtained in preference to imine **3fa** (Table 2-3, entry 1). The reaction conditions were therefore investigated once again for the diarylation of aryl isocyanides with $PbPh_4$. As indicated in entry 2, the use of $Pd(PPh_3)_4$ instead of $Pd(OAc)_2$ for the diarylation of **1f** with $PbPh_4$ increased the selectivity of α-diimines **4fa**. In sharp contrast, the $Pd(PPh_3)_4$-catalyzed diarylation of *t*-BuNC **1a**, afforded imine **3aa** preferentially (see Table 2-1, entry 9). Since unreacted $PbPh_4$ was recovered after the reaction, the ratio of isocyanide **1f** to tetraphenyllead **2a** was optimized. More specifically, when a 2:1 ratio of isocyanide **1f** to **2a** was employed, α-diimine **4** were obtained in excellent yields using both palladium catalysts (entries 3 and 4). Lowering the temperature (i.e., 70 °C) or using MeCN as a solvent also resulted in the selective synthesis of α-diimine **4**, but no further improvement was observed in the yield or selectivity (entries 5 and 6). When palladium catalyst (2.5 mol%) was used, the reaction yield is lower (entry 7). The reaction using NHC-Pd catalyst proceeded quantitatively, but the α-diimine/imine selectivity was not improved anymore (entry 8). The use of PPh_3 reduced the yields of **4fa** and **3fa** with slight increase in the α-diimine/imine selectivity (entry 9). Lower amount of tetraaryllead also results in decrease of the yields (entry 10). Entry 4 was chosen as the optimized reaction conditions for further investigation.

Table 2-3. Optimization of reaction conditions for the diarylation of an aryl isocyanide **1f** using $PbPh_4$ **2a**



1f **2a** **3fa** **4fa**

entry	Conditions	yield of **3fa**, %[a]	yield of **4fa**, %[a]
1	**1f** (0.2 mmol), **2a** (0.3 mmol), $Pd(OAc)_2$ (5 mol%), toluene, 100 °C, 2 h	26	60

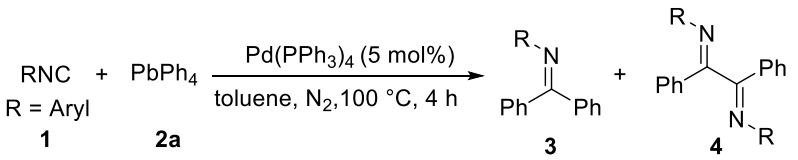
2	**1f** (0.2 mmol), **2a** (0.3 mmol), $Pd(PPh_3)_4$ (5 mol%), toluene, 100 °C, 2 h	13	87
3	**1f** (0.4 mmol), **2a** (0.2 mmol), $Pd(OAc)_2$ (5 mol%), toluene, 100 °C, 4 h	16(14)	84(85)
4	**1f (0.4 mmol), 2a (0.2 mmol), $Pd(PPh_3)_4$ (5 mol%), toluene, 100 °C, 4 h**	**13(12)**	**87(86)**
5	**1f** (0.4 mmol), **2a** (0.2 mmol), $Pd(OAc)_2$ (5 mol%), toluene, 70 °C, 4 h	8	84
6	**1f** (0.4 mmol), **2a** (0.2 mmol), $Pd(OAc)_2$ (5 mol%), MeCN, 70 °C, 4 h	13	69
7	**1f** (0.4 mmol), **2a** (0.2 mmol), $Pd(PPh_3)_4$ (2.5 mol%), toluene, 100 °C, 4 h	9	76
8	**1f** (0.4 mmol), **2a** (0.2 mmol), Catalyst A (5 mol%,) toluene, 100 °C, 4 h	23	77
9	**1f** (0.4 mmol), **2a** (0.2 mmol), $Pd(PPh_3)_4$ (5 mol%), PPh_3 (20 mol %), toluene, 100 °C, 4 h	9	66
10	**1f** (0.4 mmol), **2a** (0.05 mmol), $Pd(PPh_3)_4$ (5 mol%), toluene, 100 °C, 4 h	8	75

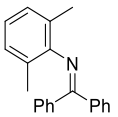
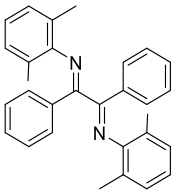
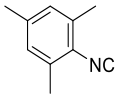
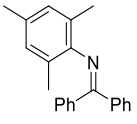
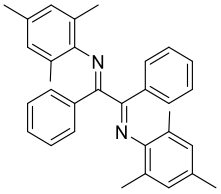
[a]Determined by ^{1}H NMR spectroscopy (isolated yield are indicated in parentheses).

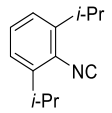
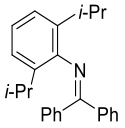
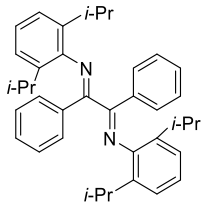
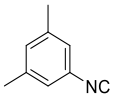
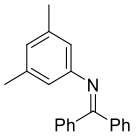
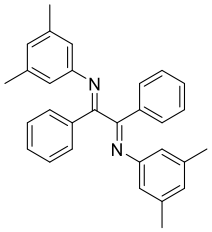
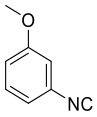
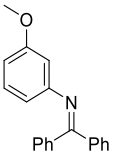
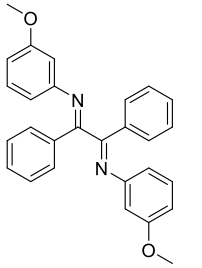
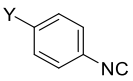
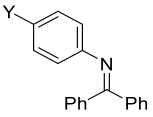
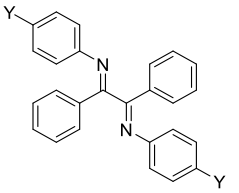
Table 2-4 shows the results obtained for the catalytic diarylation of aromatic isocyanides. Similarly, to aliphatic isocyanies, the electronic and steric properties of aromatic isocyanides strongly influenced both the yield and selectivity of products. The catalytic diarylation of *o*-substituted isocyanides **1f**, **1g**, **1h**, **1q** successfully afforded the corresponding *α*-diimines **4fa**, **4ga**, **4ha**, and **4qa** in moderate to good yields with high α-diimine/imine selectivity (Table 2-4, entries 1-3 and 10). It can be deduced that steric effect of *o*-substituents stabilized imidoyl-Pd complex resulting in high yield and formation of *α*-diimines with good product selectivity. In the cases of *m*- and *p*-substituted isocyanides, the yields and product selectivity to give of *α*-diimines depend on electronic properties of isocyanides (entries 4-9). When electron-rich isocyanides were used (**1i**-l), the *α*-diimines were obtained in moderate to good yields with good selectivity (**4ia**-**la,** entries 4-7). In sharp contrast, the electron poor isocyanides (**1m** and **1n**) afforded corresponding

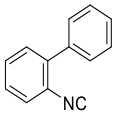
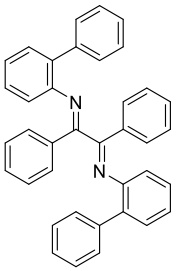
imines and α-diimines in low yields and product selectivity (entries 8 and 9). The author speculates that electronic properties of isocyanides dramatically interfere the stability of imidoyl-palladium intermediates which is crucial for the formation of imines **3** and α-dimines **4**. Moreover, *m*- and *p*-substituted isocyanides are unstable and should be used for the diarylation quickly after synthesis of them; in addition, the corresponding α-diimines, especially **4ma** and **4na**, are unstable and partially lost during separation. For example, in the case of *p*-MeO-C_6H_4NC, the product **4la** was formed in 90% yield (determined by ^{1}H NMR), but the isolated yield was 72%. When 1.0 gram of isocyanide **1g** was used, **4ga** was obtained in 50% yield (0.85 gram). *p*-Nitrophenyl isocyanide **1o** and *p*-acetylphenyl isocyanide **1p** could not be applied to the present reaction (**1o** and **1p**).

Table 2-4. Substrate scope for the palladium-catalyzed diarylation of aryl isocyanides with $PbAr_4$[a]



entry	isocyanide **1**	yield of **3**, %[b]	yield of **4**, %[b]
1	 **1f**	 **3fa**, 12	 **4fa**, 86[c] (i.r.: 5.3/1)
2	 **1g**	 **3ga**, (2)	 **4ga**, 67[c](i.r.: 5/1), 50[d]

			
3	**1h**	**3ha**, (14)	**4ha**, 52[c](i.r.: 3.5/1)
			
4	**1i**	**3ia**, 15	**4ia**, 60
			
5	**1j**	**3ja**, 19	**4ja**, 44
			
6	**1k**, Y = Me	**3ka**, 5	**4ka**, 40
7	**1l**, OMe	**3la** (8)	**4la**, 72 (90)
8	**1m**, Cl	**3ma**, 12, 31[e]	**4ma**, (46), (17)[e]
9	**1n**, F	**3na**, trace, 20[e]	**4na**, (26), (32)[e]
10	**1o**, NO_2	**3oa**, ND	**4oa**, ND
11	**1p**, $C(O)CH_3$	**3pa**, ND	**4pa**, ND

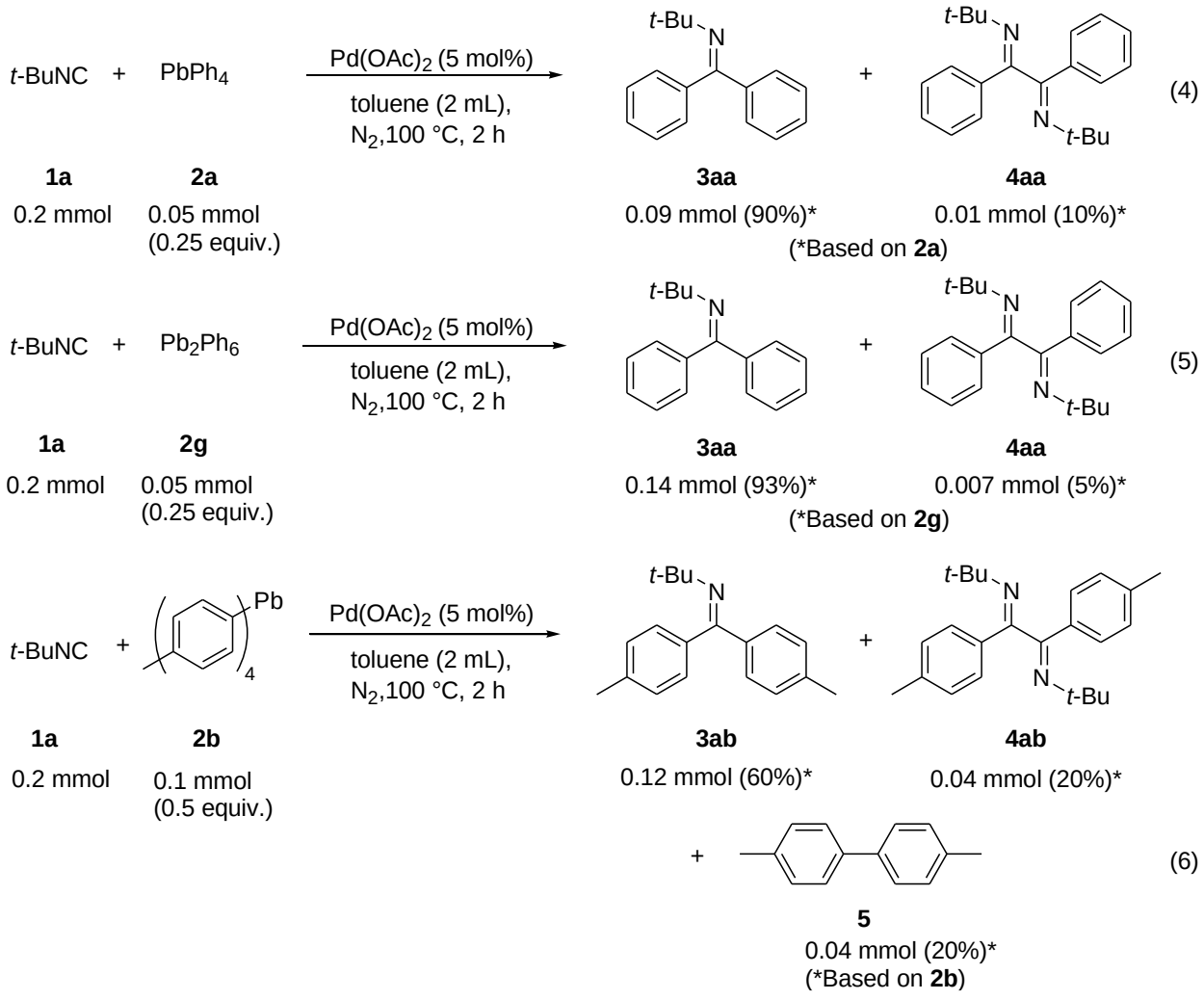
12	**1q**		**3qa**, (17)	 **4qa**, 68

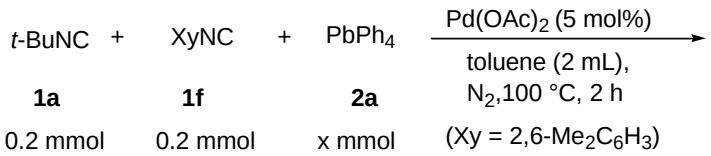
[a]Reaction conditions: Isocyanide **1** (0.4 mmol) was added to a mixture of **2a** (0.2 mmol) and $Pd(PPh_3)_4$ (0.02 mmol) in toluene (2 mL), 100 °C, 4 h. [b]Isolated yield (yields in parentheses were determined by ^1H NMR spectroscopy, when the product was difficult to purify from reaction mixture). [c]The product was obtained as a mixture of geometric isomers. [d]Isocyanide **1g** (1.0 gram, 6.9 mmol) was used. [e]$Pd(OAc)_2$ (0.02 mmol) was used instead of $Pd(PPh_3)_4$ (0.02 mmol). ND = Not detected.

To gain an insight into the reaction mechanism of this arylation process, several control experiments were carried out (Scheme 2-2). When the reaction of *t*-butyl isocyanide **1a** with 0.25 equiv. of tetraphenyllead **2a** was attempted, the corresponding imine **3aa** and α-diimine **4aa** were obtained in 90% and 10% yields, respectively, based on **2a** (eq 4). Using Pb_2Ph_6 **2g** instead of $PbPh_4$ **2a** resulted in the formation of **3aa** and **4aa** (93% and 5% yields), respectively, based on **2g** (eq 5). The reaction of **1a** with 0.5 equiv. of tetra(*p*-tolyl)lead **2b** afforded 60% yield of **3ab** and 20% yield of **4ab** along with 20% yield of biaryl **5** as a byproduct (eq 6). These results of eqs 4-6 indicate that all aryl groups of **2a**, **2g**, or **2b** could be used for the synthesis of imine **3**, α-diimine **4**, and biaryl **5**. Competition experiments using aliphatic isocyanide **1a** and aromatic isocyanide **1f** resulted in a similar tendency of the product selectivity as those of the catalytic diarylation using **1a** or **1f** independently. On the other hand, when the amounts of tetraphenyllead **2a** was reduced, imine **3aa** and α-diimine **4fa** were preferentially obtained with a similar tendency, respectively (eq 7). The result of eq 7 supports the idea that the product selectivity of imine **3**/α-diimine **4** depends on the substituents of isocyanides. Intermolecular competitive reactions of two different tetraaryllead were also carried out (eqs 8 and 9). Very interestingly, α-diimines **4aa'** and **4fa'** with both phenyl and *p*-tolyl substituents were not detected at all. The

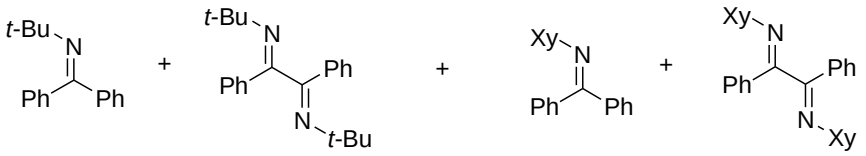
results strongly suggest that α-diimine **4** is not produced via intermolecular ligand-exchange process of intermediate **C** each other to form intermediate **E** and $Pd(PbAr_3)_2L_2$ (see, Scheme 2-3).

Scheme 2-2. Control experiments

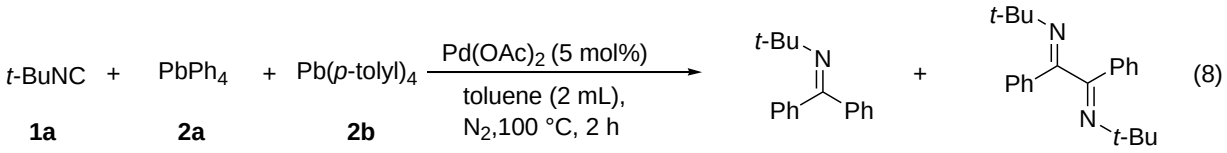




(7)

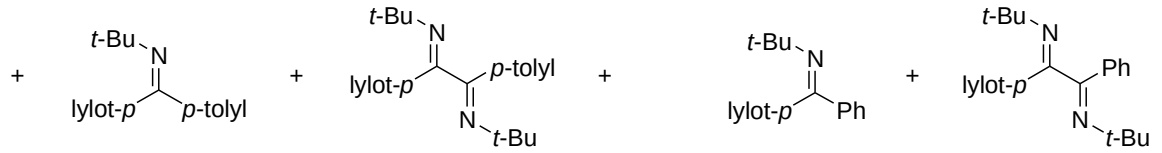


	3aa	**4aa**		**3fa**	**4fa**	
2a = 0.2 mmol	70%	7%	(Based on *t*-BuNC)	23%	50%	(Based on XyNC)
2a = 0.1 mmol	41%	5%	(Based on *t*-BuNC)	18%	57%	(Based on XyNC)

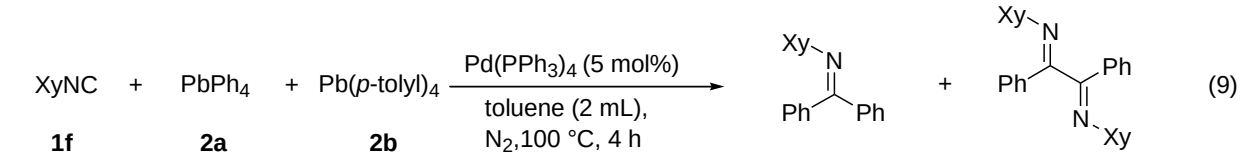


(8)

3aa 35% **4aa** 13%

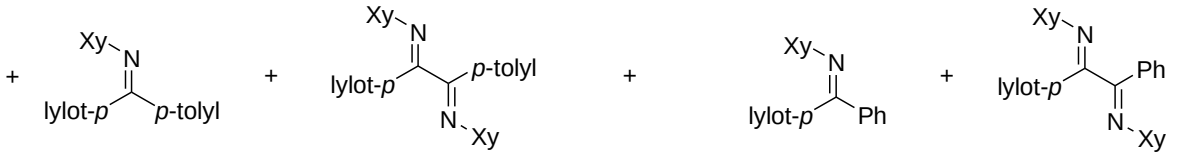


3ab 29% **4ab** 12% **3aa'** ND **4aa'** ND



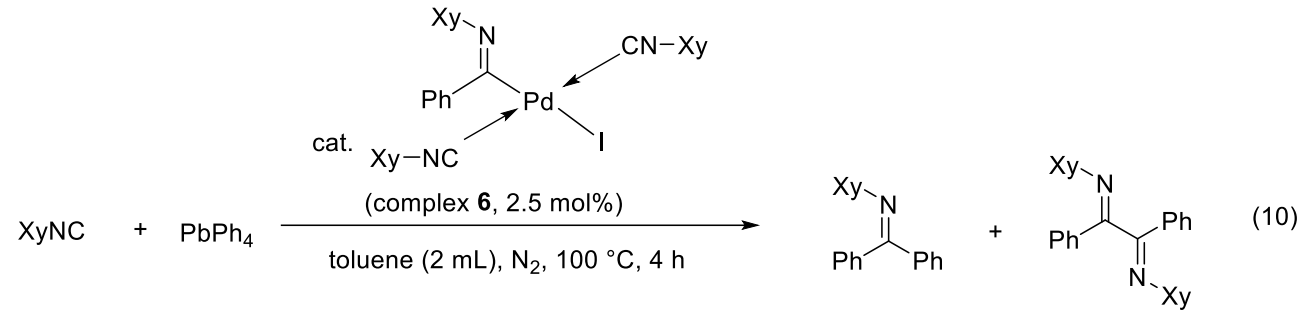
(9)

3fa 10% **4fa** 43%



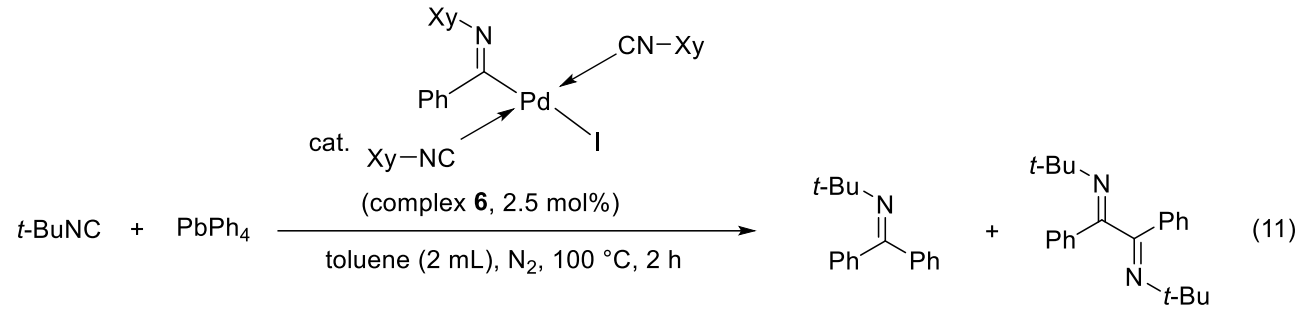
3fb 7% **4fb** 39% **3fa'** ND **4fa'** ND

Expecting that imidoylpalladium intermediate plays a crucial role in the catalytic cycle and imine/*α*-diimine selectivity, the author prepared Pd complex **6**, which was an analog of complex **C** in Scheme 2-3, according to the procedure reported by Amii[10] et al. and examined the catalytic diarylation of aromatic isocyanide **1f** with tetraphenyllead **2a**. Interestingly, the Pd complex **6** efficiently catalyzed the diarylation of **1f** with **2a** affording **4fa** selectively in good yield (eq 10). This Pd complex also catalyzed the diarylation of aliphatic isocyanide **1a** to give imine **3aa** preferentially (eq 11). These results indicate that Pd complex **6** and its analog play important roles in the catalytic diarylation of isocyanides. The key point that can explain the different imine/*α*-diimines selectivity between aliphatic and aromatic isocyanides is the stability of arylimidoylpalladium intermediate **D**. If the arylimidoyl-Pd complex **D** is stable enough, **D** can undergo another isocyanide insertion to form **E**; the following reductive elimination leads to *α*-diimines **4**. In contrast, if **D** is unstable, **D** tends to undergo reductive elimination to form imine **3**. In general, the presence or absence of resonance effect of the substituents of isocyanides contributes to the stability of arylimidoylpalladium complex **D**. In the case of aromatic isocyanides, the conjugation of C-N double bond of **D** with aryl group on N stabilizes **D** to afford *α*-diimine **4**. Aliphatic isocyanides lack such conjugation, resulting in destabilizing **D** to give imine **3**, preferentially. It is noteworthy that the model Pd complex **6** exhibits a similar product selectivity as those of other palladium catalysts (see, Table 2-1 and eq 8). In the case of equation 9, however, the imine **3aa**/*α*-diimine **4aa** selectivity was somewhat lower compared with the high imine/*α*-diimine selectivity of Table 2-1, entry 1. This is most probably because the higher stability of imidoyl-Pd complex **6** compared with **D** (R = aliphatic group) favors the double isocyanide insertion reaction, resulting in lower imine/*α*-diimine selectivity.



1f	**2a**	**3fa**	**4fa**
0.4 mmol	0.2 mmol (0.5 equiv.)	15%	68%

conversion: 83%



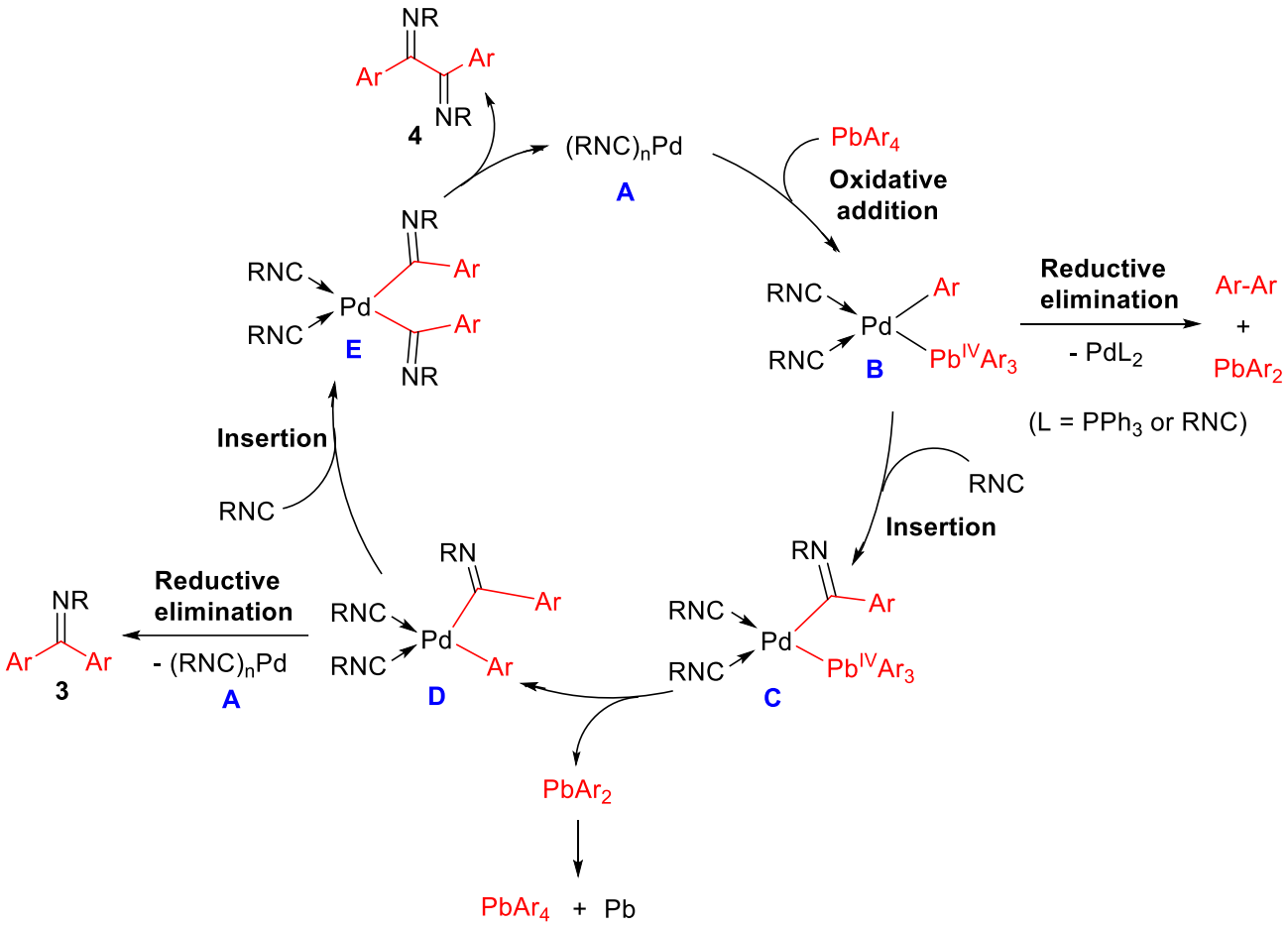
1a	**2a**	**3aa**	**4aa**
0.2 mmol	0.3 mmol	51%	35%

conversion: 86%

Based on the above results, a plausible reaction pathway is proposed in Scheme 2-3. As can be seen from the scheme, initially, palladium(0) complex **A** (generated from $Pd(PPh_3)_4$ (or $Pd(OAc)_2$) and the isocyanide) undergoes oxidative addition with $PbAr_4$ to form complex **B** bearing a Pd-Ar bond.[11] Complex **B** is then converted into imidoyl complex **C** by insertion of the isocyanide into the Pd-Ar bond. The following decomposition of complex **C** leads to arylimidoyl-Pd species **D**, the stability of which determines the reaction outcome. If complex **D** is not stable, the reductive elimination affords imine **3** preferentially. In contrast, if complex **D** is stable, **D** undergoes a second isocyanide insertion to produce complex **E**. Product **4** is then formed by reductive elimination from complex **E**. Subsequently, the formed $PbAr_2$ gives tetraphenyllead and zero-valent lead precipitated as distinct black solid.[12] When complex **B** undergoes reductive

elimination, biphenyl is formed as a byproduct with concomitant formation of $PbAr_2$ and complex **A**.

Scheme 2-3. A plausible reaction pathway



2-3 Conclusion

In summary, the author successfully developed novel, divergent transformations of isocyanides to_imines and/or *α*-diimines via a palladium-catalyzed diarylation with tetraaryllead species. It is noteworthy that, the diarylation reaction does not require any additives or bases. More specifically, this reaction afforded imines from the corresponding aliphatic isocyanides, while *α*-diimines were formed primarily from electron-rich aromatic isocyanides. Because *α*-diimines are precursor of *N*-heterocyclic carbenes (NHCs)[13], the present method is expected to

be applied for the synthesis of NHCs.

2-4 Experimental Section

General Remarks Unless otherwise stated, all starting materials and catalysts were purchased from commercial sources and used without further purification. All solvents were distilled and degassed with nitrogen before use. Isocyanides **1a-f**, tetraphenylleads **2a** and hexaphenyldileads **2g** were purchased from commercial supplies. Isocyanides **1g-1o** were prepared according to the procedure that the author previously reported.[6] Tetraarylleads **2b-f** were prepared according to the procedure.[14] ^{1}H NMR spectra were recorded on JEOL JNM-ECS400 (400 MHz) FT NMR system or JEOL JNM-ECX400 (400 MHz) FT NMR system in $CDCl_3$ and C_6D_6 with Me_4Si as an internal standard. ^{13}C NMR spectra were recorded on JEOL JNM-ECX400 (100 MHz) FT NMR or JEOL JNM-ECS400 (100 MHz) FT NMR in $CDCl_3$ and C_6D_6. ^{19}F NMR spectra were recorded on Variant NMR System 400 (376 MHz). IR spectra were reported in wave numbers (cm^{-1}). ESI and EI mass spectra were obtained by employing double focusing mass spectrometers. High resolution mass spectra (HRMS) were obtained on JEOL JMS-AX500 or MALDI TOFMS were obtained on Applied Biosystems 4800 MALDI TOF/TOF Analyzer.

Representative Procedure for the Synthesis of 1-Isocyano-4-methoxybenzene (1l). *4-Methoxyformanilide*. A solution of 4-methoxyaniline (1.85 g, 15 mmol) and formic acid (85% aq., 1.0 mL, 22.5 mmol) in toluene (15 mL) is refluxed under N_2 atmosphere. The reaction was monitored by TLC (hexane/ AcOEt = 3/1). After the reaction, volatile materials were evaporated under reduced pressure. The resulting residue containing the 4-methoxyformanilide was taken on to the next step without additional purification.

*1-Isocyano-4-methoxybenzene (**1l**).* In a 100 mL two-necked flask after heating for drying,

4-methoxyformanilide (1.51 g, 10 mmol) was dissolved in a mixture of $CHCl_3$ (15 mL) and NEt_3 (4.2 mL, 30 mml) under N_2 atmosphere and the resulting mixture was cooled to 0 ^oC in an ice bath. To the mixture, phosphoryl chloride (1.2 mL, 12 mmol, 5 mL $CHCl_3$ solution) was added dropwise slowly. After stirring for 1 h, the reaction mixture was warmed to room temperature and stirred for additional 1 h. After the reaction was complete, the resulting mixture was cooled to 0 ^oC and aqueous saturated solution of sodium carbonate (10 mL) was added dropwise to quench the reaction. After vigorous stirring for 1 h, ca. 20 mL of water was added to the mixture, and the organic layer was separated. The aqueous layer was extracted by $CHCl_3$ (20 mL) twice. The combined organic layer was dried over sodium sulfate, and solvent was removed by evaporation. The residue was purified by silica gel column chromatography (eluent hexane/ AcOEt = 9/1). 1-Isocyano-4-methoxybenzene (**1l**) was obtained in 90% yield (1.20 g) as green liquid. Only in the case of 2-biphenyl isocyanide (**1p**), CH_2Cl_2 was used as solvent instead of $CHCl_3$.

Representative Procedure for the Synthesis of Tetraaryllead Species (2b). Into a 100 mL dried round-bottom flask was added magnesium turnings (1,21 g, 0.05 mol) and dry ether (20 mL). 4-Bromotoluene (8,55 g, 0.05 mol) was then added dropwise, and the reaction mixture was stirred until the solid magnesium had disappeared. Dry benzene (20 mL) was then added to the reaction mixture, followed by the addition of lead(II) chloride (6.3 g, 0.023 mol), and the mixture was heated under reflux for 8 h in oil bath. After the reaction, the mixture was cooled to room temperature and hydrolyzed by pouring into iced hydrochloric acid. The resulting suspension was filtered through a Buchner funnel, the obtained solid was then transferred to a beaker with benzene (50 mL), and the mixture was heated until benzene was boiling. Upon cooling of the benzene solution obtained by hot filtration, crystals of the title compounds were precipitated and then isolated by filtration. The filtrate was extracted with ethyl acetate; the volatile was evaporated and the procedure was repeated twice to obtain tetra-*p*-tolylplumbane (1,86g, 26%) as white solid. In the cases of **2e** and **2f**, further purification by silica gel column (eluent: hexane), followed by

purification using recycling GPC (eluent: $CHCl_3$) is needed.

General Procedure for the Pd-Catalyzed Arylation of Alkyl Isocyanides (1a–1e) with Tetraaryllead Species. In a two-necked 10 mL flask equipped with a magnetic stirring bar under a N_2 atmosphere were placed $Pd(OAc)_2$ (2.2 mg, 0.01 mmol), tetraaryllead **4** (0.3 mmol), distilled toluene (2 mL), and isocyanide **3** (0.2 mmol), in this order. The reaction was conducted at 100 °C for 2 h in an oil bath, and then the resulting solution was filtered through Celite with ethyl acetate as an eluent. All volatiles were evaporated under reduced pressure, and the crude product was purified by recycling GPC (eluent: $CHCl_3$) to give the imine **3** and α-diimine **4**.

General Procedure for the Pd-Catalyzed Arylation of Aryl Isocyanides (1f–1o) with Tetraaryllead Species. In a two-necked 10 mL flask equipped with a magnetic stirring bar under a N_2 atmosphere were placed $Pd(PPh_3)_4$ (23.1 mg, 0.02 mmol), tetraaryllead **4** (0.2 mmol), distilled toluene (2 mL), and isocyanide **3** (0.4 mmol), in this order. The reaction was conducted at 100 °C for 4 h in oil bath, and then the resulting solution was filtered through Celite with ethyl acetate as an eluent. All volatiles were evaporated under reduced pressure, and the crude product was purified by recycling GPC (eluent: $CHCl_3$) to give imine **3** and α-diimine **4**.

Procedure for Gram-Scale Synthesis of 1-Isocyano-2,4,6-trimethylbenzene (1g) with Tetraphenyllead (2a). In a two-necked 200 mL flash equipped with a magnetic stirring bar under a N_2 atmosphere were placed $Pd(PPh_3)_4$ (392.9 mg, 0.34 mmol), tetraaryllead **2a** (1.78 gram, 3.45 mmol), distilled toluene (50 mL), and isocyanide **1g** (1.00 gram, 6.89 mmol). The reaction was conducted at 100 °C for 24 h in oil bath, and then all the volatiles were evaporated under reduced pressure. The crude product was subjected to silica-gel column chromatography (eluent: hexane/ EtOAc = 10/1) to give α-diimine **4ga** (850.2 mg, 50% yield, 90% purity).

Spectral Data for Substrates

1-Isocyano-2,4,6-trimethylbenzene (1g).[15] White solid, 1.06 g, 73%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.89 (s, 2H), 2.37 (s, *6*H), 2.29 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 166.8, 138.8, 134.7, 128.5, 124.1 (t, *J* = 11.9 Hz, C), 21.2, 18.9; MS (EI) $[M]^+$ *m*/*z* = 145.

1-Isocyano-2,6-diisopropylbenzene (1h).[15] Brown liquid, 1.5 g, 80%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31 (t, *J* = 7.7 Hz, 1H), 7.16 (d, *J* = 7.7 Hz, 2H) 3.38 (septet, *J* = 6.8 Hz, *2*H), 1.27 (d, *J* = 6.8 Hz, 12H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.8, 145.0, 129.4, 124.4 (t, *J* = 11.4 Hz), 123.4, 29.9, 22.7; MS (EI) $[M]^+$ *m*/*z* = 187.

1-Isocyano-3,5-dimethylbenzene (1i).[16] Colorless liquid, 884.4 mg, 67%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.98 (s, 1H), 6.93 (s, *2*H), 2.28 (s, 6H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 163.3, 139.4, 131.2, 126.4 (t, *J* = 12.9 Hz), 123.9, 21.0; MS (EI) $[M]^+$ *m*/*z* = 131.

1-Isocyano-3-methoxybenzene (1j).[17] Green liquid, 763.8 mg, 57%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.23 (t, *J* = 8.1 Hz, 1H), 7.00-6.86 (m, 2H), 6.81 (s, 1H), 3.75 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 164.3, 160.1, 130.3, 127.3 (t, *J* = 13.5 Hz), 118.6, 115.6, 111.9, 55.5; MS (EI) $[M]^+$ *m*/*z* = 133.

1-Isocyano-4-methylbenzene (1k).[16] Yellow liquid, 660.8 mg, 56%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.17 (d, *J* = 8.6 Hz, 2H), 7.11 (d, *J* = 8.1, 2H), 2.31 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 163.9, 139.8, 130.0, 126.1, 124.1 (t, *J* = 13.3 Hz), 21.3; MS (EI) $[M]^+$ *m*/*z* = 117.

1-Isocyano-4-methoxybenzene (1l).[16] Yellow liquid, 1.20 g, 90%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25 (d, *J* = 8.6 Hz, 2H), 6.87-6.81 (m, 2H), 3.78 (m, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 163.1, 159.9, 127.7, 119.4 (t, *J* = 13.8 Hz), 114.6, 56.6; MS (EI) $[M]^+$ *m*/*z* = 133.

1-Chloro-4-isocyanobenzene (1m).[16] Yellow solid, 938.4 mg, 68%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.41-7.36 (m, 2H), 7.33 (d, *J* = 8.6 Hz, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 165.7, 135.5, 129.8, 127.7, 125.1 (t, *J* = 13.8 Hz); MS (EI) $[M]^+$ *m*/*z* = 137.

1-Fluoro-4-isocyanobenzene (1n).[16] Green liquid, 536.8 mg, 44%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.48-7.32 (m, 2H), 7.17-7.03 (m, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 164.5, 162.4 (d, $J_{C\text{-}F}$ =

252.0 Hz), 128.5 (d, $J_{C\text{-}F}$ = 9.6 Hz), 122.9 (dt, J = 3.8 (C-F), 13.8 Hz) 116.7 (d, $J_{C\text{-}F}$ = 23.9 Hz); ^{19}F NMR (376 MHz, $CDCl_3$): δ -108.7; MS (EI) $[M]^+$ *m*/*z* = 121.

1-Isocyano-4-nitrobenzene (1o).[6] Yellow solid, 1.11 g, 75%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.32 (d, J = 9.2 Hz, 2H), 7.60 (d, J = 8.7 Hz, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 169.7, 147.6, 131.3 (t, J = 14.1 Hz), 127.7, 125.2; MS (EI) $[M]^+$ *m*/*z* = 148.

1-(4-isocyanophenyl)ethan-1-one (1p).[16] Green liquid, 1.23 g, 85%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.00 (d, J = 8.7 Hz, 2H), 7.48 (d, J = 8.7 Hz, 2H), 2.62 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 196.3, 167.4, 137.4, 130.0 (t, J = 14.4 Hz), 129.6, 126.8, 26.8; MS (EI) $[M]^+$ *m*/*z* = 145.

2-Biphenylisocyanide (1q).[6] Green liquid, 1.64 g, 91%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, J = 7.8 Hz, 2H), 7.40-7.25 (m, 6H), 7.24-7.13 (m, 1H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 167.7, 138.9, 137.2, 130.8, 129.8, 129.2, 128.8, 128.6, 128.4, 128.0, 124.7 (t, J = 10.5 Hz); MS (EI) $[M]^+$ *m*/*z* = 179.

Tetra-p-tolylplumbane (2b).[18] White solid, 1.86 g, 26%, mp 238-240 °C (decompose); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.49 (d, J = 8.1 Hz, 8H, with satellite, $J_{H\text{-}207Pb}$ = 79.3 Hz), 7.22 (d, J = 7.7 Hz, 8H, with satellite, $J_{H\text{-}207Pb}$ = 24.0 Hz), 2.38 (s, 12H, with satellite, $J_{H\text{-}207Pb}$ = 29.9 Hz); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 146.5, 138.2, 137.5, (with satellite, $J_{C\text{-}207Pb}$ = 69.6 Hz), 130.3 (with satellite, $J_{C\text{-}207Pb}$ = 87.7 Hz), 21.5; MS (FAB) m/z = 481 (M^+ -PhMe, ^{208}Pb), 480 (M^+ -PhMe, ^{207}Pb).

Tetrakis(4-(tert-butyl)phenyl)plumbane (2c). White solid, 2.47 g, 26%, mp above 300 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.53 (d, J = 8.1 Hz, 8H, with satellite, $J_{H\text{-}207Pb}$ = 72.3 Hz), 7.39-7.29 (m, 8H), 1.29 (s, 36H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 150.9, 149.8, 137.7 (with satellite, $J_{C\text{-}207Pb}$ = 71.5 Hz), 126.5, (with satellite, $J_{C\text{-}207Pb}$ = 68.7 Hz), 34.7, 31.4; HRMS (MALDI-TOF) *m*/*z*: $[M^+]$ Calcd for $C_{40}H_{52}Pb$ 740.3835; Found 740.3816.

Tetrakis(4-methoxyphenyl)plumbane (2d).[18] White solid, 2.14 g, 27%, mp 195-197 °C (decompose); ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47 (d, J = 8.6 Hz, 8H, with satellite, $J_{H\text{-}207Pb}$ = 70.0 Hz), 6.89 (d, J = 8.6 Hz, 8H, with satellite, $J_{H\text{-}207Pb}$ = 23.6 Hz), 3.78 (s, 12H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 159.7, 143.4, 138.9 (with satellite, $J_{C\text{-}207Pb}$ = 81.0 Hz), 115.4 (with satellite, $J_{C\text{-}207Pb}$

= 73.4 Hz), 55.2; MS (FAB) $[M\text{-}PhOMe]^+$ *m*/*z* = 529.

Tetrakis(4-chlorophenyl)plumbane (2e). White solid, 178 mg, 5%, mp 197-199 °C; ^1H NMR (400 MHz, $CDCl_3$): δ 7.60-7.32 (m, 16H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 146.8, 138.4 (with satellite, $J_{C\text{-}207Pb}$ = 76.3 Hz), 135.6, 130.0 (with satellite, $J_{C\text{-}207Pb}$ = 87.7 Hz); MS (FAB) $[M^+\text{-}PhCl]$ *m*/*z* = 541 (^{207}Pb). Anal. Calcd for $C_{24}H_{16}Cl_4Pb$: C, 44.12; H, 2.47. Found: C, 43.77; H, 2.66.

Tetrakis(4-fluorophenyl)plumbane (2f). White solid, 398 mg, 5%, mp 128-130 °C; ^1H NMR (400 MHz, $CDCl_3$): δ 7.68-7.37 (m, 8H), 7.23-7.05 (m, 8H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 163.6 (d, $J_{C\text{-}F}$ = 248.0 Hz), 143.8 (d, $J_{C\text{-}F}$ = 3.8 Hz), 138.8 (d, $J_{C\text{-}F}$ = 7.0 Hz, with satellite, $J_{C\text{-}207Pb}$ = 81.5 Hz), 117.0 (d, $J_{C\text{-}F}$ = 19.7 Hz, with satellite, $J_{C\text{-}207Pb}$ = 92.0 Hz); ^{19}F NMR (376 MHz, $CDCl_3$): δ -111.6; HRMS (MALDI-TOF) *m*/*z*: $[M\text{-}PhF]^+$ Calcd for $C_{18}H_{12}F_3Pb$ 493.0657; Found 493.0681.

Spectral Data for Products

N-tert-Butyl-1,1-diphenylmethanimine (3aa).[19] Colorless oil, 34.1 mg, 72%; ^1H NMR (400 MHz, $CDCl_3$): δ 7.56-7.51 (m, 2H), 7.41-.7.35 (m, 3H), 7.32-7.23 (m, 3H), 7.22-7.16 (m, 2H), 1.17 (s, 9H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 163.7, 142.1, 139.9, 129.4, 128.5, 128.2, 128.0, 127.9, 127.88, 57.1, 31.7; IR (NaCl, *v*/cm^{-1}): 694, 776, 1212, 1268, 1628, 2358, 2967; MS (EI) $[M]^+$ *m*/*z* = 237; HRMS (CI) *m*/*z*: $[M+H]^+$ Calcd for $C_{17}H_{19}N$ 238.1596; Found 238.1605.

N-tert-Butyl-1,1-di-p-tolylmethanimine (3ab).[19] White solid, 45.6 mg, 86%, mp 106-108 °C; ^1H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, *J* = 8.2 Hz, 2H), 7.17 (d, *J* = 7.8 Hz, 2H), 7.06 (dd, *J* = 8.2,8.2 Hz, 4H), 2.40 (s, 3H), 2.31 (s, 3H), 1.16 (s, 9H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 163.8, 139.8 , 139.4, 137.5, 137.1, 128.6, 128.5, 128.4, 128.1, 56.9, 31.7, 21.4, 21.3; IR (KBr, *v*/cm^{-1}): 817, 942, 957, 1210, 1605, 2264, 2627, 2961; MS (EI) $[M]^+$ *m*/*z* = 265; HRMS (EI) *m*/*z*: $[M]^+$ Calcd for $C_{19}H_{23}N$ 265.1830; Found 265.1830.

(1E,2E)-N^1,N^2-di-tert-Butyl-1,2-di-p-tolylethane-1,2-diimine (4ab).[6] White solid, 4.2mg, 12%, mp 84-86°C; ^1H NMR (400 MHz, $CDCl_3$): δ 7.65 (d, *J* = 8.2 Hz, 4H), 7.11 (d, *J* = 8.2 Hz, 4H), 2.34 (s, 6H), 1.23 (s,18H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 159.2, 139.7, 138.0, 129.0, 127.7,

57.8, 30.1, 21.4. MS (EI) $[M]^+$ *m*/*z* = 348.

N-tert-Butyl-1,1-bis(4-(tert-butyl)phenyl)methanimine (3ac). White solid, 63.6 mg, 91%, mp 77-79 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47 (d, *J* = 8.7 Hz, 2H), 7.37 (d, *J* = 8.2 Hz, 2H), 7.29 (d, *J* = 8.7 Hz, 2H), 7.10 (d, *J* = 8.7 Hz, 2H), 1.36 (s, 9H), 1.28 (s, 9H), 1.16 (s, 9H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 164.0, 152.4, 150.8, 139.7, 137.0, 128.1, 127.9, 124.9, 124.6, 56.9, 34.7, 34.7, 31.7, 31.5, 31.3; IR (KBr, *v*/cm^{-1}): 828, 843, 1216, 1270, 1361, 1625, 2963; MS (EI) $[M]^+$ *m*/*z* = 349; HRMS (EI) *m*/*z*: $[M]^+$ Calcd for $C_{25}H_{35}N$ 349.2770; Found 349.2776.

N-tert-Butyl-1,1-bis(4-methoxyphenyl)methanimine (3ad).[19] White solid, 52.3 mg, 88%, mp 78-80 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47 (d, *J* = 9.2 Hz, 2H), 7.09 (d, *J* = 8.7 Hz, 2H), 6.91 (d, *J* = 8.7 Hz, 2H), 6.79 (d, *J* = 8.7 Hz, 2H), 3.85 (s, 3H), 3.78 (s, 3H), 1.17 (s, 9H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 163.4, 160.8, 159.2, 135.3, 132.1, 129.8, 129.5, 113.23, 113.2, 56.8, 55.4, 55.3, 31.9, 31.8; IR (KBr, *v*/cm^{-1}): 758, 837. 1034, 1245, 1508, 1600, 2963; MS (EI) $[M]^+$ *m*/*z* = 297; HRMS (EI) *m*/*z*: $[M]^+$ Calcd for $C_{19}H_{23}NO_2$ 297.1729; Found 297.1723.

N-tert-Butyl-1,1-bis(4-chlorophenyl)methanimine (3ae). Pale yellow solid, 30.5 mg, 50%, mp 106-108 °C; ^{1}H NMR (400 MHz, C_6D_6): δ 7.47 (d, *J* = 8.7 Hz, 2H), 7.11 (d, *J* = 8.7 Hz, 2H), 6.95 (d, *J* = 8.2 Hz, 2H), 6.53 (d, *J* = 8.2 Hz, 2H), 1.12 (s, 9H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 161.2, 140.1, 137.8, 135.8, 134.2, 129.8, 129.4, 128.4, 128.2, 57.3, 31.6; IR (KBr, *v*/cm^{-1}): 829, 1089, 1483, 1625; MS (EI) $[M]^+$ *m*/*z* = 305; HRMS (CI) *m*/*z*: $[M+H]^+$ Calcd for $C_{17}H_{17}Cl_2N$ 306.0816; Found 306.0821.

N-tert-Butyl-1,1-bis(4-fluorophenyl)methanimine (3af). White solid, 40.4 mg, 74%, mp 117-119 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.54-7.45 (m, 2H), 7.19-7.07 (m, 4H), 7.00-6.92 (m, 2H), 1.15 (s, 9H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 164.4 (d, $J_{C\text{-}F}$ =138.9 Hz), 161.9 (d, $J_{C\text{-}F}$ = 138.0 Hz), 161.5, 138.1 (d, $J_{C\text{-}F}$ =2.9 Hz), 135.5 (d, $J_{C\text{-}F}$ =3.8 Hz), 130.1 (d, $J_{C\text{-}F}$ =8.6 Hz), 130.0 (d, $J_{C\text{-}F}$ =8.6 Hz), 115.2 (d, $J_{C\text{-}F}$ =22.0 Hz), 114.8 (d, $J_{C\text{-}F}$ =21.1 Hz), 57.1, 31.6; ^{19}F NMR (376 MHz, $CDCl_3$): δ -112.4, -113.3; IR (KBr, *v*/cm^{-1}): 841, 850, 1218, 1505; MS (EI) $[M]^+$ *m*/*z* = 273; HRMS (CI) *m*/*z*: $[M+H]^+$ Calcd for $C_{17}H_{17}F_2N$ 274.1407; Found 274.1398.

(1E,2E)-1,2-Diphenyl-N^1,N^2-bis(2,4,4-trimethylpentan-2-yl)ethane-1,2-diimine (4ba).[6] White solid, 15.5 mg, 36%, mp 107-110 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.82-7.71 (m, 4H), 7.37-7.27 (m, 6H), 1.50 (d, *J* = 1.4 Hz, 4H), 1.37 (s, 6H), 1.16 (s, 6H), 1.03 (s, 18H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 158.7, 140.8, 129.5, 128.2, 128.0, 62.1, 57.1, 30.2, 30.028, 30.035, 29.6; MS (EI) $[M]^+$ *m*/*z* = 432.

(1E,2E)-N^1,N^2-Dipentyl-1,2-diphenylethane-1,2-diimine (4ca).[6] Yellow oil, 8.0 mg, 23%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.76-7.71 (m, 4H), 7.43-7.32 (m, 6H), 3.32 (t, *J* = 7.3 Hz, 4H), 1,73-1,64 (m, 4H), 1.38-123 (m, 8H), 0.86 (t, *J* = 7.3 Hz, 6H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 165.2, 136.2, 130.6, 128.8, 127.3, 54.5, 30.7, 30.0, 22.6, 14.1 ; MS (EI) $[M]^+$ *m*/*z* = 348.

N-Cyclohexyl-1,1-diphenylmethanimine (3da). Colorless oil, 24.7 mg, 47%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.61-7.54 (m, 2H), 7.48-7.38 (m, 3H), 7.36-7.27 (m, 3H), 7.18-7.12 (m, 2H), 3.21 (tt, *J* = 7.2, 14.5 Hz, 1H), 1.79-1.67 (m, 2H), 1.65-1.53 (m, 5H), 1.32-1.06 (m, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 165.7, 140.5, 137.5, 129.64, 129.56, 128.4, 128.1, 128.0, 127.8, 61.5, 34.0, 25.8, 24.5; MS (EI) $[M]^+$ *m*/*z* = 263; HRMS (CI) *m*/*z*: $[M+H]^+$ Calcd for $C_{19}H_{21}N$ 264.1752; Found 264.1758.

(1E,2E)-N^1,N^2-Dicyclohexyl-1,2-diphenylethane-1,2-diimine (4da).[6] White solid, 12.3 mg, 33%, mp 89-93 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.81-7.74 (m,4H), 7.40-7.28 (m, 6H), 3.22 (tt, *J* = 4.1, 9.6 Hz, 2H), 1.87-1.72 (m, 2H), 1.71-1.41 (m, 10H), 1.40-1.16 (m, 6H), 1.13-0.70 (m, 2H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 162.2, 137.3, 130.4, 128.5, 127.7, 63.0, 34.0, 33.0, 25.8, 24.3, 24.2; MS (EI) $[M]^+$ *m*/*z* = 372.

N-Benzyl-1,1-diphenylmethanimine (3ea).[20] Colorless solid, 37.9 mg, 70%, mp 54-57 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.72-7.66 (m, 2H), 7.55-7.11 (m, 13H), 4.61 (s, 2H); MS (EI) $[M]^+$ *m*/*z* = 271; HRMS (CI) *m*/*z*: $[M+H]^+$ Calcd for $C_{20}H_{18}N$ 272.1439; Found 272.1440.

(1E,2E)-N^1,N^2-Bis(2,6-dimethylphenyl)-1,2-diphenylethane-1,2-diimine (4ea).[6] White solid, 7.8 mg, 20%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.88-7.83 (m, 4H), 7.44-7.13 (m, 16H), 4.6 (d, *J* = 15.9 Hz, 2H), 4.53 (d, *J* = 15.9 Hz, 2H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 166.0, 139.7, 135.8, 131.2,

129.0, 128.5, 128.0, 127.6, 126.9, 57.9; MS (EI) (M^+) m/z = 388.

N*-(2,6-Dimethylphenyl)-1,1-diphenylmethanimine** ***(3fa).[21] Yellow oil, 13.7 mg, 12%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.79 (d, *J* = 8.2 Hz, 2H), 7.50-7.40 (m, 3H), 7.28-7.19 (m, 3H), 7.10 (d, *J* = 8.2 Hz, 2H), 6.88 (d, *J* = 7.8 Hz, 2H), 6.79 (t, *J* = 7.8 Hz, 1H), 2.04 (s, 6H); MS (EI) $[M]^+$ *m*/*z* = 285; HRMS (EI) *m*/*z*: $[M]^+$ Calcd for $C_{21}H_{19}N$ 285.1517; Found 285.1510.

(1E,2E)*-N^1,N^2-Bis(2,6-dimethylphenyl)-1,2-diphenylethane-1,2-diimine** ***(4fa).[6,9] Yellow oil, 71.5 mg, 86%; ^{1}H NMR (400 MHz, $CDCl_3$) [as a mixture of two geometrical isomers, an isomer ratio of A/B = 5.3/1]: δ 8.27-8.20 (m, 4H), 7.60-6.68 (m, 12H), 2.13-1.74 (m, 12H); MS (EI) $[M]^+$ *m*/*z* = 416. It was difficult to separate the isomers of **4fa**.

Data for isomer A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 5.9 Hz, 2H), 7.61-6.70 (m, 14H), 1.98-1.74 (m, 12H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 165.6, 147.4. 134.9, 131.0, 128.7, 128.1, 127.63, 125.7, 123.3, 18.7.

Data for isomer B; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.61-6.70 (m, 16H), 2.06 (s, 12H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 165.3, 147.8, 138.0, 129.9, 128.8, 128.2, 127.58, 126.6, 123.5, 19.0.

(1E,2E)*-N^1,N^2-Dimesityl-1,2-diphenylethane-1,2-diimine** (4ga***). Yellow oil, 59.5 mg, 67%; ^{1}H NMR (400 MHz, $CDCl_3$) [as a mixture of two geometrical isomers, an isomer ratio of A/B = 5/1]: δ 8.31-6.58 (m, 14H), 2.25-2.11 (m, 6H), 2.05-1.72 (m, 12H); HRMS (ESI) *m*/*z*: $[M+Na]^+$ Calcd for $C_{32}H_{32}N_2Na$ 467.2463; Found 467.2453. It was difficult to separate the isomers of **4ga**.

Data for isomer A: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.31-8.16 (m, 2H), 7-59-6.58 (m, 12H), 2.25-2.11 (m, 6H), 1.90-1.72(m, 12H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 166.1, 145.3, 135.2, 132.4, 130.9, 128.9, 128.6, 128.2, 126.4, 20.8, 18.5.

Data for isomer B; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7-59-6.58 (m, 14H), 2.25-2.11 (m, 6H), 2.01 (s, 12H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 165.5, 144.8, 138.2, 132.6, 129.7, 128.7, 128.0, 127.6, 125.6, 20.7, 18.9.

(1E,2E)*-N^1,N^2-Bis(2,6-diisopropylphenyl)-1,2-diphenylethane-1,2-diimine** (4ha***). Yellow oil, 54.9 mg, 52%; ^{1}H NMR (400 MHz, $CDCl_3$) [as a mixture of two geometrical isomers, an isomer

ratio of A/B = 3.5/1]: δ 8.20-6.84 (m, 16H), 3.29-2.20 (m, 4H), 1.39-0.37 (m, 24H); HRMS (ESI) *m*/*z*: $[M+Na]^+$ Calcd for $C_{38}H_{44}N_2Na$ 551.3402; Found 551.3395. It was difficult to separate the isomers of **4ha**.

***N*-(3,5-Dimethylphenyl)-1,1-diphenylmethanimine *(3ia)*.** Yellow oil, 17.1 mg, 15%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.76-7.68 (m, 2H), 7.49-7.33 (m, 3H), 7.30-7.21 (m, 3H), 7.16-7.09 (m, 2H), 6.55 (s, 1H), 6.34 (s, 2H), 2.15 (s, 6H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 167.7, 151.2, 140.0, 138.0, 136.5, 130.6, 129.5, 129.3, 128.5, 128.2, 127.9, 124.9, 118.8, 21.3; IR (KBr, *v*/cm^{-1}): 503, 673, 694, 727, 780, 847, 1441, 1506, 1573; MS (EI) $[M]^+$ *m*/*z* = 285; HRMS (EI) *m*/*z*: $[M]^+$ Calcd for $C_{21}H_{19}N$ 285.1517; Found 285.1509.

***(1E,2E)*-N^1,N^2-Bis(3,5-dimethylphenyl)-1,2-diphenylethane-1,2-diimine *(4ia)*.** Yellow solid, 49.9 mg, 60%, mp 157-159 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.89-7.83 (m, 4H), 7.46-7.35 (m, 6H), 6.64 (s, 2H), 6.14 (s, 4H), 2.09 (s, 12H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 164.0, 149.6, 138.1, 137.8, 131.0, 128.7, 128.3, 126.3, 117.8, 21.3; IR (KBr, *v*/cm^{-1}): 694, 839, 1447, 1586; MS (EI) $[M]^+$ *m*/*z* = 416; HRMS (EI) *m*/*z*: $[M]^+$ Calcd for $C_{30}H_{28}N_2$ 416.2252; Found 416.2248.

***N*-(3-Methoxyphenyl)-1,1-diphenylmethanimine *(3ja)*.** Yellow oil, 21.8 mg, 19%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.77-7.72 (m, 2H), 7.50-7.44 (m, 1H),7.43-7.37 (m, 2H) 7.30-7.23 (m, 3H), 7.16-7.11(m, 2H), 7.02 (t, *J* = 7.8 Hz, 1H), 6.48 (ddd, *J* = 0.9, 2.7, 8.2, 1H), 6.33 (t, *J* = 1.8 Hz, 1H), 6.28 (ddd, *J* =0.9, 1.8, 7.8, 1H), 3.66 (s, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 168.4, 159.9, 152.6, 139.7, 136.3, 130.8, 129.5, 129.4, 129.3, 128.7, 128.3, 128.0, 113.5, 109.3, 106.6, 55.2; IR (NaCl, *v*/cm^{-1}): 693, 1128, 1262, 1575; MS (EI) $[M]^+$ *m*/*z* = 287; HRMS (EI) *m*/*z*: $[M]^+$ Calcd for $C_{20}H_{17}NO$ 287.1310; Found 287.1306.

***(1E,2E)*-N^1,N^2-Bis(3-methoxyphenyl)-1,2-diphenylethane-1,2-diimine** (**4ja**). Yellow solid, 37.0 mg, 44%, mp 95-98 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.93-7.88 (m, 4H), 7.47-7.37 (m, 6H), 6.97 (t, *J* = 8.2 Hz, 2H), 6.57 (dd, *J* = 1.8, 8.2 Hz, 2H), 6.18 (ddd, *J* = 0.9, 1.8, 7.8 Hz, 2H), 5.99 (t, *J* = 2.3 Hz, 2H), 3.49 (s, 6H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 164.2, 159.7, 150.8, 137.7, 131.3, 129.2, 128.9, 128.5, 111.8, 111.7, 105.3, 54.9; IR (KBr, *v*/cm^{-1}): 691, 783, 1149, 1278, 1588; MS

(EI) $[M]^+$ *m*/*z* = 420; HRMS (EI) *m*/*z*: $[M]^+$ Calcd for $C_{28}H_{24}N_2O_2$ 420.1838; Found 420.1840.

1,1-Diphenyl-N-(p-tolyl)methanimine (***3ka***).[22] Yellow oil, 5.4 mg, 5%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.76-7.70 (m, 2H), 7.49-7.35 (m, 3H), 7.29-7.24 (m, 3H), 7.14-7.09 (m, 2H), 6.93 (d, *J* = 8.2 Hz, 2H), 6.62 (d, *J* = 8.2 Hz, 2H), 2.22 (s, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 168.0, 148.6, 140.0, 136.6, 132.7, 130.6, 129.6, 129.3, 129.1, 128.5, 128.2, 128.0, 121.1, 20.9; MS (EI) $[M]^+$ *m*/*z* = 271.

(1E,2E)-1,2-Diphenyl-N^1,N^2-di-p-tolylethane-1,2-diimine (4ka).[23] Yellow solid, 31.0 mg, 40%, mp 161-163 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.90-7.83 (m, 4H), 7.44-7.33 (m, 6H), 6.88 (d, *J* = 8.6 Hz, 4H), 6.51 (d, *J* = 8.2 Hz, 4H), 2.23 (s, 6H) ; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 163.9, 146.8, 137.6, 134.7, 131.0, 129.1, 128.8, 128.3, 120.4, 21.0; MS (EI) $[M]^+$ *m*/*z* = 388.

(1E,2E)-N^1,N^2-Bis(4-methoxyphenyl)-1,2-diphenylethane-1,2-diimine (4la).[6] Yellow solid, 60.5 mg, 72%, mp 164-166 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.89-7.83 (m, 4H), 7.44-7.32 (m, 6H), 6.71-6.61 (m, 8H), 3.71 (s, 6H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 163.4, 157.4, 142.6, 137.5, 130.9, 128.8, 128.2, 122.2, 113.8, 55.4; MS (EI) $[M]^+$ *m*/*z* = 420.

N-(4-Chlorophenyl)-1,1-diphenylmethanimine (3ma). Yellow oil, 14.0 mg, 12%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.76 (m, 2H), 7.50-7.35 (m, 3H), 7.33-7.22 (m, 3H), 7.12-7.05 (m, 4H), 6.67-6.61 (m, 2H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 169.1, 149.8, 139.5, 136.0, 131.0, 129.5, 129.4, 128.9, 128.7, 128.5, 128.3, 128.2, 122.4; MS (EI) $[M]^+$ *m*/*z* = 291; HRMS (EI) *m*/*z*: $[M]^+$ Calcd for $C_{19}H_{14}NCl$ 291.0815; Found 291.0818.

N-(4-Fluorophenyl)-1,1-diphenylmethanimine (3na). Yellow oil, 22.0 mg, 20%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.79-7.69 (m, 2H), 7.50-7.36 (m, 3H), 7.34-7.22 (m, 3H), 7.12-7.07 (m, 2H), 6.87-6.79 (m, 2H), 6.70-6.63 (m, 2H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 169.0, 159.2 (d, $J_{C\text{-}F}$ = 241.3 Hz), 147.3 (d, $J_{C\text{-}F}$ = 2.8 Hz), 140.0, 136.2, 131.0, 129.4 (d, $J_{C\text{-}F}$ = 18.1 Hz), 128.8, 128.2 (d, $J_{C\text{-}F}$ = 18.1 Hz), 122.5, 122.4, 115.4, 115.2; ^{19}F NMR (376 MHz, $CDCl_3$) δ -120.7; IR (NaCl, ν/cm^{-1}): 694, 779, 836, 1209, 1498, 1617; MS (EI) $[M]^+$ *m*/*z* = 275; HRMS (EI) *m*/*z*: $[M]^+$ Calcd for $C_{19}H_{14}NF$ 275.1110; Found 275.1104.

(1E,2E)-N^1,N^2-Di([1,1'-biphenyl]-2-yl)-1,2-diphenylethane-1,2-diimine (4qa).[6] Yellow solid, 69.7 mg, 68%, mp 182-184 ºC; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.58 (d, *J* = 7.3 Hz, 4H); 7.41-7.33 (m, 2H), 7.28-7.21 (m, 6H), 7.20-7.10 (m, 6H), 7.11-7.01 (m, 2H), 6.91-6.80 (m, 6H), 6.46 (d, J = 7.3 Hz, 2H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 163.0, 145.9, 139.5, 137.7, 134.9, 130.7, 130.4, 129.8, 128.7, 128.4, 127.53, 127.46, 126.4, 125.9, 118.4; MS (EI) $[M]^+$ *m*/*z* = 512.

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Chapter 3

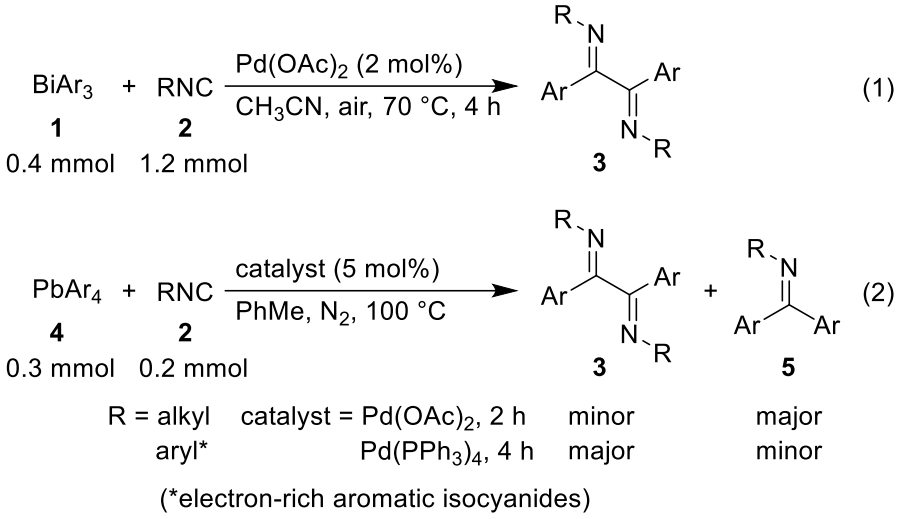
Imine/α-Diimine Selectivity in the Transition-Metal-Catalyzed Diarylation of Isocyanides with Triarylbismuthines

3-1 Introduction

As the chemistry of heteroatom-containing compounds has significantly grown in recent decades, the properties and reactivities of high-period elements have been gradually focused on.[1] Bismuth is the heaviest element in group 15, and its organic and inorganic compounds are regarded to be non-toxic.[2] However, organobismuth compounds are generally unstable due to the weakness of the carbon-bismuth bond. An exception to this is triarylbismuthines (Ar_3Bi, **1**), which are stable and some of which are commercially available. The synthetic applications of triarylbismuthines[3] have therefore been investigated by many organic chemists including Barton,[4] Finet,[5] Uemura,[6] Dodonov,[7] Shimada,[8] Kurita[9] and Rao,[10] and *N*-, *O*-, *S*- and *C*-arylation reactions have been developed using triarylbismuthines as arylating reagents.

Recently, the authors developed novel palladium-catalyzed diarylation reactions of isocyanides **2**[11, 12] using triarylbismuthines **1** and tetraarylleads **4** (Scheme 3-1). The use of $BiAr_3$ **1** result in α-diimines **3** being selectively obtained (Scheme 3-1-(1))[13]. Using $PbAr_4$ **4** instead of **1** led to the formation of α -diimines **3** and/or imines **5** (Scheme 3-1-(2))[14]. With aliphatic isocyanides **2** (R = alkyl), imines **5** were preferentially obtained, whereas α-diimines **3** were formed when electron-rich aromatic isocyanides **2** (R = electron-rich Ar) were used.

Scheme 3-1. Palladium-catalyzed diarylation of isocyanides

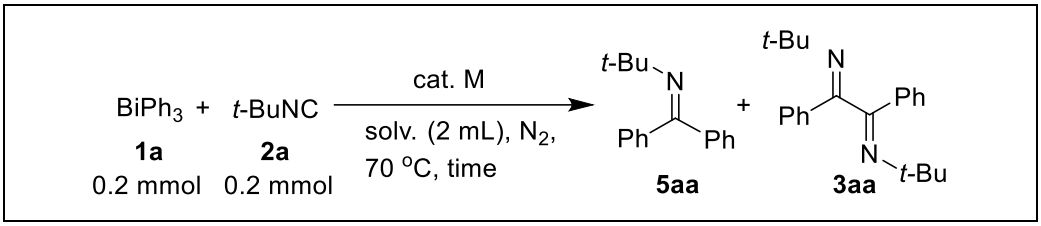


It is important to clarify whether the **3**/**5** product selectivity can be influenced when using a specific high-period element (Bi or Pb). Hence, the authors have investigated the product selectivity of **3**/**5** in the transition-metal-catalyzed diarylation of isocyanides with $BiAr_3$ **1** under several reaction conditions, and in addition, some synthetic applications of the products, especially α-diimines **3**, have been examined.

3-2 Results and discussion

In the previous paper[13], the authors reported that $Pd(OAc)_2$-catalyzed diarylation of isocyanides **2** with $BiAr_3$ **1** selectively afforded α-diimines **3** (a representative result is shown in Table 3-1, entry 1). Changing the catalyst to $Pd(PPh_3)_4$ as a representative zero-valent palladium complex resulted in the yield of **3aa** significantly decreasing (entry 2). On the other hand, other divalent palladium complexes such as $PdCl_2$ and $Pd(PPh_3)_2Cl_2$ selectively afforded **3aa** in good yields (entries 3 and 4). The addition of PPh_3 to $Pd(OAc)_2$ decreased the yield of **3aa** (entry 5). The zero-valent Pd complex, $Pd_2(dba)_3$, gave **3aa** in moderate yield (entry 6).

Table 3-1. Influence of reaction conditions on **5aa**/**3aa** selectivity



entry	cat. M (mol%)	solv.	time	yields[a] (%)	
		2 mL	h	**5aa**	**3aa**
1	$Pd(OAc)_2$ (20)	C_6H_6	18	9	90
2	$Pd(PPh_3)_4$ (20)	C_6H_6	18	trace	23
3	$PdCl_2$ (20)	C_6H_6	18	5	71
4	$Pd(PPh_3)_2Cl_2$ (20)	C_6H_6	18	11	62
5[b]	$Pd(OAc)_2$ (20)	C_6H_6	18	5	66
6	$Pd_2(dba)_3 \cdot CHCl_3$ (10)	C_6H_6	18	trace	56
7	$RhCl(PPh_3)_3$ (20)	C_6H_6	18	63	0
8	$RhCl(PPh_3)_3$ (10)	C_6H_6	18	52	0
9	$RhCl(PPh_3)_3$ (5)	C_6H_6	18	42	0
10[c]	$RhCl(PPh_3)_3$ (20)	C_6H_6	18	55	0
11	$RhH(CO)(PPh_3)_3$ (20)	C_6H_6	18	20	4
12	$[RhCl(nbd)]_2$ (10)	C_6H_6	18	50	0
13	$[RhCl(nbd)]_2$ (5)	C_6H_6	18	32	0
14[c]	$[RhCl(nbd)]_2$ (10)	C_6H_6	18	75	0
15	none	C_6H_6	18	0	2
16[d]	$Pd(OAc)_2$ (20)	C_6H_6	18	trace	58
17[e]	$Pd(OAc)_2$ (20)	C_6H_6	18	10	82
18[f]	$Pd(OAc)_2$ (20)	C_6H_6	18	8	59
19	$Pd(OAc)_2$ (10)	C_6H_6	18	4	65

20	$Pd(OAc)_2$ (5)	C_6H_6	18	4	51
21	$Pd(OAc)_2$ (20)	THF	18	21	63
22	$Pd(OAc)_2$ (20)	EtOH	18	trace	49
23	$Pd(OAc)_2$ (20)	MeCN	18	0	84
24	$Pd(OAc)_2$ (20)	PhMe	18	9	73
25	$Pd(OAc)_2$ (20)	C_6H_6	4	1	81
26[g]	$Pd(OAc)_2$ (20)	C_6H_6	18	6	77

[a]Determined by ^{1}H NMR. Calculated based on the amount of **2a**. [b]Triphenylphosphine (40 mol%) was used as a ligand. [c]Loading of **1a** was 0.4 mmol. [d]Loading of **1a** was 0.1 mmol. [e]Air. [f]Room temp. [g]The reaction was conducted in a globe box under Ar.

Surprisingly, changing the catalyst to rhodium complexes selectively afforded imine **5aa** without formation of **3aa** (entries 7–14). For example, the diarylation using Wilkinson's catalyst, $RhCl(PPh_3)_3$, exclusively afforded imine **5aa** in 63% yield (entry 7). Decreasing the loading of this catalyst gradually reduced the yield of **5aa** (entries 8-9). Use of excess **1a** reduced the yield of **5aa** (entry 10). $RhH(CO)(PPh_3)_3$, which is an active catalyst for hydroformylation, was ineffective when used for the present diarylation of isocyanide **2a** (entry 11). $[RhCl(nbd)]_2$ also predominantly afforded **5aa** (entries 12 and 13), with the use of excess amounts of **1a** dramatically improving the yield of **5aa** with this catalyst (entry 14). In the absence of a catalyst, barely any diarylation occurred (entry 15).

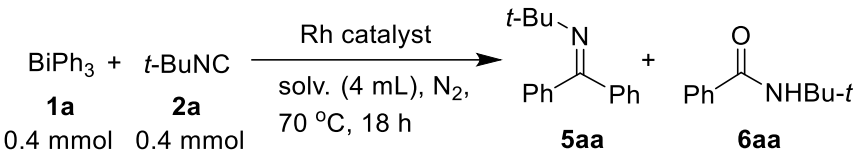
The reaction conditions for the $Pd(OAc)_2$-catalyzed diarylation of **2a** with **1a** were also investigated in further detail (entries 16–26). In all cases, α-diimine **3aa** was obtained as the major product, mostly along with very small amounts of imine **5aa**. Decreasing the loading of **1a** resulted in a decrease in the yield of **3aa** (entry 16). The presence of air did not inhibit the formation of **3aa** (entry 17). When the reaction was conducted at room temperature, the yield of

3aa was decreased (entry 18). Decreasing the amount of $Pd(OAc)_2$ used resulted in a gradual decrease in the yield of **3aa** (entries 19 and 20). Among the solvents examined (entries 21-24), acetonitrile provided the best result for the diarylation giving **3aa** in an 84% yield (entry 23). The present diarylation also proceeded even with a shorter time (4 h), affording **3aa** in an 81% yield (entry 25). A similar result was obtained when using an Ar atmosphere as was seen using air (entry 26 vs. 17).

As some rhodium complexes exhibited good imine selectivity, the authors next examined the rhodium-catalyzed diarylation of *t*-butyl isocyanide **2a** with triphenylbismuthine **1a** (Table 3-2). The Rh-catalyzed diarylation was performed on a 0.4 mmol scale (**1a** and **2a)**, and the desired imine **5aa** was obtained in 59% yield when using Wilkinson's catalyst (entry 1). As a small amount of amide **6aa** was also formed as the major byproduct, the diarylation was examined under an atmosphere of air (entry 2) and with the addition of water (entry 3). In both cases, the diarylation was significantly retarded. Reducing the catalyst loading to 10 mol% did not influence the yield of **5aa** (entry 4). Use of 0.6 mmol of **2a** also did not influence the reaction (entry 5), whereas using 1.0 mmol of **1a** resulted in a slight decrease of the yield of **5aa** (entry 6). Some other rhodium catalysts such as $RhH(PPh_3)_3$, $RhBr(PPh_3)_3$, $[Rh(dppp)(cod)]^+BF^{4-}$, $RhCl_3$, and $[Rh(OAc)_2]_2$, were ineffective for the desired diarylation (entries 7, 8, and 10–12). In addition, the diarylation failed when using other transition metal catalysts such as $[Ru(NH_3)_5Cl]Cl_2$, $RuCl_3{\bullet}nH_2O$, $[Ir(cod)Cl]_2$, $Ir(CO)Cl[n\text{-}C_{10}F_{21}]PPh_2]_2$, $Ir(CO)Cl(PPh_3)_2$, CuI, $CuCl_2$, and $CoCl(PPh_3)_3$, with no reaction taking place in most cases (this data is not shown in Table 2). Among the catalysts examined, *trans*-$RhCl(CO)(PPh_3)_3$ exhibited a similar catalytic activity to Wilkinson's catalyst for the diarylation to give **5aa** (entry 10 vs. entry 4). The authors next examined the $RhCl(PPh_3)_3$-catalyzed arylation using solvents such as acetonitrile, toluene, DMSO, and methanol (entries 13-16) and acetonitrile and toluene were found to be suitable solvents for the diarylation. Moreover, combinations of Wilkinson's catalyst and various

phosphines were tested as catalysts (entries 17–24). Phosphines with smaller cone angles such as dppm (θ = 121°)[15] and $^{n}Bu_3P$ (129°)[15] resulted in lower yields of **5aa** (entries 17-19), while phosphines with larger cone angles such as PPh_3 (145°)[15] and $^{t}Bu_3P$ (129°)[15] afforded **5aa** in relatively high yields (entries 20 and 21). The highest yield of **5aa** was obtained, when an electron-rich triarylphosphine such as (*p*-MeO-$C_6H_4)_3P$ was used as a ligand (entry 24).

Table 3-2. Rh-catalyzed diarylation of *t*-BuNC with $BiPh_3$

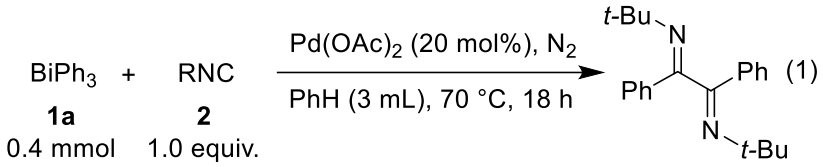


entry	Rh catalyst (mol%)	solvent	yields[a] (%)	
			5aa	**6aa**
1	$RhCl(PPh_3)_3$ (20)	C_6H_6	59	5
2[b]	$RhCl(PPh_3)_3$ (20)	C_6H_6	18	12
3[c]	$RhCl(PPh_3)_3$ (10)	C_6H_6	0	5
4	$RhCl(PPh_3)_3$ (10)	C_6H_6	59	4
5[d]	$RhCl(PPh_3)_3$ (10)	C_6H_6	61	trace
6[e]	$RhCl(PPh_3)_3$ (10)	C_6H_6	51	8
7	$RhH(PPh_3)_3$ (10)	C_6H_6	12	10
8	$RhBr(PPh_3)_3$ (10)	C_6H_6	17	11
9	*trans*-$RhCl(CO)(PPh_3)_3$ (10)	C_6H_6	55	7
10	$[Rh(dppp)(cod)]^{+}BF^{4-}$ (10)	C_6H_6	0	trace

11	$RhCl_3$ (10)	C_6H_6	2	2
12	$[Rh(OAc)_2]_2$ (10)	C_6H_6	6	2
13	$RhCl(PPh_3)_3$ (10)	MeCN	43	4
14	$RhCl(PPh_3)_3$ (10)	PhMe	53	4
15	$RhCl(PPh_3)_3$ (10)	DMSO	19	6
16	$RhCl(PPh_3)_3$ (10)	MeOH	trace	2
17	$RhCl(PPh_3)_3$/dppm (10/20)	C_6H_6	7	10
18	$RhCl(PPh_3)_3$/^{n}Oct_3P (10/20)	C_6H_6	27	10
19	$RhCl(PPh_3)_3$/nBu_3P (10/20)	C_6H_6	26	15
20	$RhCl(PPh_3)_3$/$t$$Bu_3P$ (10/20)	C_6H_6	49	22
21	$RhCl(PPh_3)_3$/Ph_3P (10/20)	C_6H_6	46	5
22[f]	$RhCl(PPh_3)_3$/Ar_3P (10/20)	C_6H_6	35	5
23[g]	$RhCl(PPh_3)_3$/Ar_3P (10/20)	C_6H_6	41	2
24[h]	$RhCl(PPh_3)_3$/Ar_3P (10/20)	C_6H_6	62	13

[a]Determined by ^1H NMR. 1,3,5-Trioxane was used as an internal standard. [b]Air. [c]Water (2 mL) was added and MeCN was used as a solvent. [d]Loading of **2a** was 0.6 mmol. [e]Loading of **1a** was 1.0 mmol. [f]Ar = *o*-MeO-C_6H_4. [g]Ar = *p*-F_3C-C_6H_4. [h]Ar = *p*-MeO-C_6H_4.

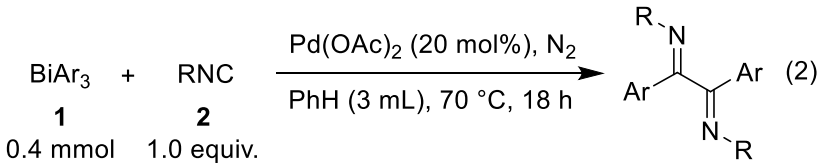
As mentioned above, Pd and Rh catalysts were found to afford α-diimines **3** and imines **5**, respectively, with excellent product selectivity. Conceivably, α-diimines **3** might be more important as synthetic intermediates than imines **5**. Hence, the authors examined the scope and limitations of this catalytic diarylation using the reaction conditions found in entry 1 of Table 3-1 (eq 1).



R =	*t*-Bu	**3aa**, 88%[a]
	t-$BuCH_2C(Me_2)$-	**3ab**, 78%[a]
	[c]Hex	**3ac**, 73%[a]
	[n]Pen	**3ad**, 85%[a]
	p-$(MeO)C_6H_4$-	**3ae**, 80%[a,b]
	2,6-Xy	**3af**, 84%[a,b]

[a]Isolated yield. [b]$BiPh_3$ **1a** (0.2 mmol), PhH (2 mL).

In the cases of aliphatic isocyanides **2a–2d**, the corresponding α-diimines **3aa–3ad** were successfully obtained in good yields. The diarylations of electron-rich aromatic isocyanides **2e–2f** also afforded the corresponding α-diimines **3ae–3af** in good yields, whereas aromatic isocyanides with electron-withdrawing groups such as *p*-nitro and *p*-cyano groups resulted in the formation of a complex mixture. In addition, the scope and limitations of the triarylbismuthines were investigated (eq 2). The diarylation of *t*-BuNC **2a**, with $BiAr_3$ **1b–1d** were conducted, and the corresponding α-diimines **3ba–3da** were formed in moderate yields. When the *p*-methoxyphenyl isocyanides **2e** was used for the arylation, similar results were observed. The combination of **2e** and p-fluorophenyl isocyanide **2d** led to the successful isolation of **3de**.

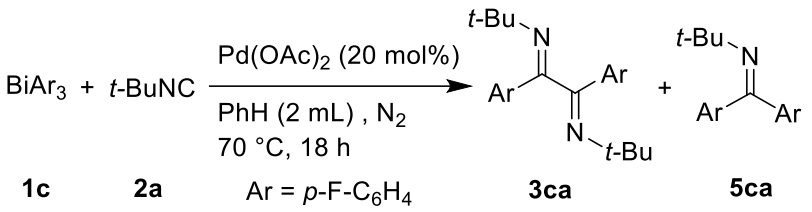


Ar =	*p*-Tol	R =	*t*-Bu	**3ba**, 58% (81%)[a]
	p-F-C_6H_4-		*t*-Bu	**3ca**, 27% (49%)[a,c]
	p-F_3C-C_6H_4-		*t*-Bu	**3da**, (62%)[a,c]
	p-Tol		*p*-$(MeO)C_6H_4$-	**3be**, 47%[a,b]
	p-$(MeO)C_6H_4$-		*p*-$(MeO)C_6H_4$-	**3ce**, 54%[a,b]
	p-F-C_6H_4-		*p*-$(MeO)C_6H_4$-	**3de** 81%[a,b]

[a]Isolated (NMR) yield. [b]$BiPh_3$ **1a** (0.2 mmol), PhH (3 mL).
[c]Isocyanide **2** (0.6 mmol) was used.

The $Pd(OAc)_2$-catalyzed diarylation of *t*-BuNC **2a** with $Bi(C_6H_4\text{-}F\text{-}p)_3$ **1c** was carried out under several different conditions to provide insights into the reason for the lower yield of **3ca** (Table 3-3). An equimolar reaction of **2a** with **1c** was found to afford imine **5c** in parallel to α-diimine **3ca** (entry 1), while decreasing the amount of **1c** resulted in the selective formation of **3ca** (entry 3). Therefore, the molar ratio of **1c** to **2a** was an important factor for the selective synthesis of α-diimine **3ca**.

Table 3-3. Pd-catalyzed of *t*-BuNC with $Bi(C_6H_4\text{-}F\text{-}p)_3$



1c **2a** **3ca** **5ca**

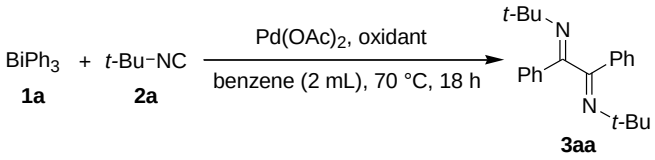
entry	**2a**		**1c**	yields[a] (%)	
	mmol		equiv.	**3ca**	**5ca**
1	0.2		1.0	37	48
2	0.2		0.75	45	43
3	0.2		0.5	74	2

[a]Determined by ^{1}H NMR; calculated based on the amount of **2a**.

The impact of reducing the catalyst loading was then examined to allow for the easy isolation of α-diimines **3** (Table 3-4). The catalytic diarylation of isocyanide **2a** was conducted using 5 mol% of $Pd(OAc)_2$ and one equivalent of triphenylbismuthine **1a** to **2a** under an atmosphere of N_2, and α-diimine **3aa** was obtained in low yield (entry 1). Interestingly, the yield of **3aa** was dramatically improved under an atmosphere of air (entry 2). Using molecular oxygen instead of air was also effective (entry 3). However, use of a combination of divalent copper salts was ineffective as an oxidant for the diarylation (entries 4 and 5). Moreover, the effect of

reducing the amount of $BiPh_3$ **1a** was examined (entries 6–8). Even when using 1/3 equiv. of **1a**, α-diimine **3aa** was obtained in satisfactory yield (entry 6). This clearly indicates that all three phenyl groups on **1a** could be used for the formation of **3aa**. When the loading of $Pd(OAc)_2$ was reduced to 1 mol%, the yield of **3aa** slightly decreased (entry 7). However, the use of 2 mol% of $Pd(OAc)_2$ led to the formation of **3aa** in a satisfactory yield (81%). As can be seen from the data in Table 3-3, the use of a combination of $Pd(OAc)_2$ and air made it possible to reduce the loading of both the catalyst and the triarylbismuthine.

Table 3-4. Influence of oxidants on Pd-catalyzed diarylation of *t*-BuNC with $BiPh_3$

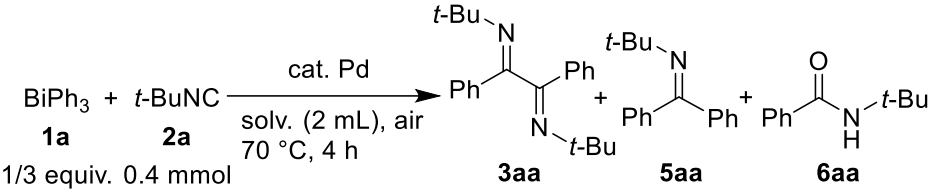


entry	oxidant (equiv.)	cat. (mol%)	**2a** (mmol)	**1a** (equiv.)	yield[a] (%)
1	none (N_2 atm.)	5	0.4	1	27
2	Air	5	0.4	1	85
3	O_2	5	0.4	1	77
4	$Cu(OAc)_2·H_2O$ (1/2)	5	0.4	1	0
5	$CuCO_3·Cu(OH)_2·H_2O$ (1/4)	5	0.4	1	19
6	Air	5	0.4	1/3	85[b]
7	Air	1	1.5	1/3	69[b]
8	Air	2	1.5	1/3	81[b]

[a]Determined by ^1H NMR. Calculated based on the amount of **2a**. [b]Calculated based on the amount of the phenyl moieties on bismuth atom.

The diarylation of isocyanide **2a** was conducted under several conditions using 5.0 or 2.5 mol% of Pd catalyst and 1/3 equiv. of $BiPh_3$ **1a**, and the results are shown in Table 3-5.

Table 3-5. Influence of reaction conditions on Pd-catalyzed diarylation of *t*-BuNC with $BiPh_3$



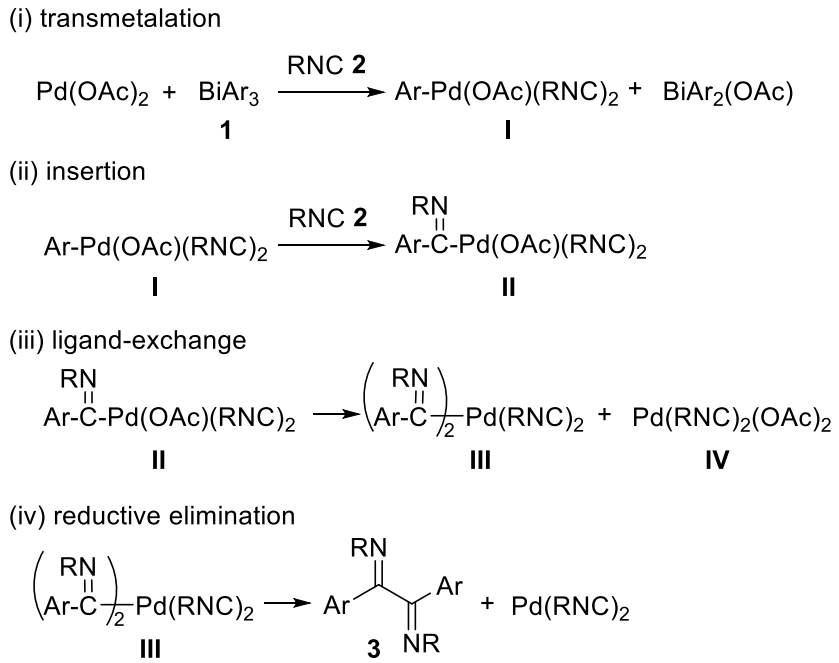
entry	cat. Pd (mol%)	solv.	yields, %[a]		
			3aa	**5aa**	**6aa**
1	$Pd(OAc)_2$ (5)	PhH	93	2	7
2	$PdCl_2$ (5)	PhH	67	9	9
3	$PdCl_2(PPh_3)_2$ (5)	PhH	60	7	6
4	$Pd(PPh_3)_4$ (5)	PhH	69	3	7
5	$Pd_2(dba)_3{\cdot}CHCl_3$ (2.5)	PhH	78	5	8
6	$PdCl_2(PhCN)_2$ (5)	PhH	69	5	13
7	$PdCl_2$(cod) (5)	PhH	63	6	11
8	$Pd(OAc)_2$ (5)	PhMe	94	4	12
9	$Pd(OAc)_2$ (5)	MeCN	97	2	4
10	$Pd(OAc)_2$ (5)	acetone	31	1	1
11	$Pd(OAc)_2$ (5)	MeOH	18	0	0
12	$Pd(OAc)_2$ (5)	THF	96	6	2
13[b]	**$Pd(OAc)_2$ (2)**	**MeCN**	**99**	**0**	**trace**
14[b]	$Pd(OAc)_2$ (1)	MeCN	29	2	trace

[a]Determined by ^{1}H NMR. Yields were calculated based on the amount of the phenyl moieties on bismuth atom. [b]Reaction conditions: **1a** (0.4 mmol) and **2a** (1.2 mmol) was used.

When the reaction time was 4 h, the yield of **3aa** was slightly increased compared with a reaction time of 18 h (entry 1, Table 3-5 vs. entry 6, Table 3-4). Diarylation using other palladium catalysts such as $PdCl_2$, $PdCl_2(PPh_3)_2$, $Pd(PPh_3)_4$, $Pd_2(dba)_3{\cdot}CHCl_3$, $PdCl_2(PhCN)_2$, and $PdCl_2(cod)$ provided **3aa** in 63–78% yields, along with imine **5aa** and amide **6aa** (entries 2–7). Among the solvents examined (entries 8–12), acetonitrile was found to be the best for this diarylation (entry 9). The loading of $Pd(OAc)_2$ could be reduced to 2 mol% at a 1.2 mmol scale of **2a**, with **3aa** being obtained quantitatively (entry 13).

In the previous paper, authors proposed a possible pathway for the $Pd(OAc)_2$-catalyzed diarylation of isocyanide **2** with triarylbismuthine **1** to afford α-diimine **3**, and its essence is shown in **Scheme 3-2**.

Scheme 3-2. A possible pathway for Pd-catalyzed diarylation



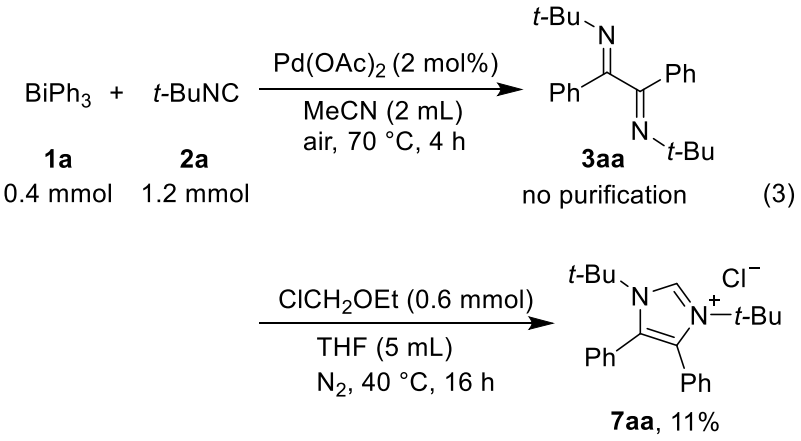
Transmetalation between $Pd(OAc)_2$ and $BiAr_3$ **1** might generate an arylpalladium species **I**, which undergoes insertion of isocyanide **2** to form the imidoylpalladium species **II**. The subsequent ligand-exchange reaction of **II** with itself then leads to the palladium complexes **III**

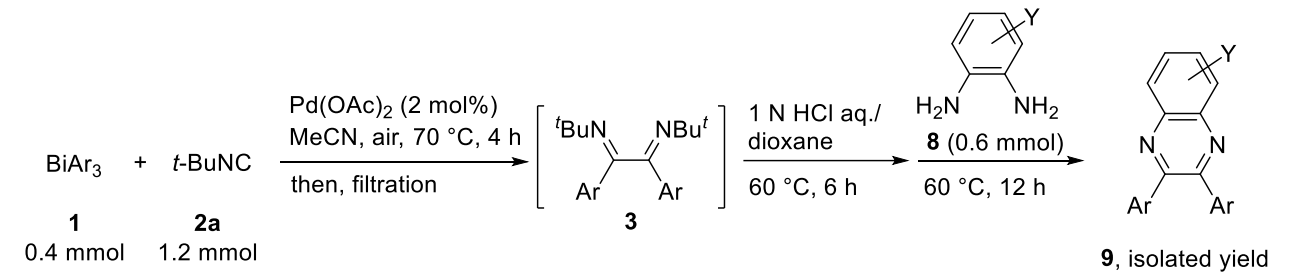
and **IV**. Reductive elimination from **III** affords the α-diimine **3** along with the Pd(0) species. Since the $Pd(OAc)_2$-catalyzed diarylation proceeds smoothly in the presence of oxidizing agents such as air, the Pd(0) species might be oxidized to the Pd(II) species by air, or by the bismuth compounds present in the reaction system.

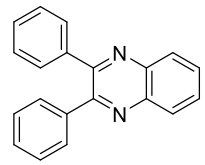
In the case of rhodium catalysts such as $RhCl(PPh_3)_3$, oxidative addition of $BiAr_3$ **1** generates $Ar\text{-}RhCl(BiAr_2)(PPh_3)_3$, which undergoes insertion of **2** to form an imidoylrhodium species. Presumably, the ligand-exchange reaction is less important for the imidoylrhodium species compared with the $Pd(OAc)_2$-based system. Accordingly, transmetalation of imidoylrhodium species with $BiAr_3$ **1** might generate aryl imidoylrhodium species of the type "$ArC(=NR)\text{-}RhL_n\text{-}Ar$," and the subsequent reductive elimination might selectively afford imine **5**.

Since α-diimines **3** are expected to be important precursors for the synthesis of nitrogen-containing heterocyclic compounds (NHCs), some attempts to synthesize nitrogen-containing heterocycles without purification of α-diimines **3** prepared by the $Pd(OAc)_2$-catalyzed diarylation of isocyanides with triarylbismuthines were made. The α-diimine **3aa** was synthesized and reacted with methoxymethyl chloride, affording the NHC precursor **7aa** directly (eq 3). Although the yield of **7aa** was not satisfactory, the result strongly indicated that a facile method of preparing nitrogen-containing heterocycles might be possible using this reaction. Hence, the authors next examined the synthesis of quinoxaline derivatives (Table 3-6).

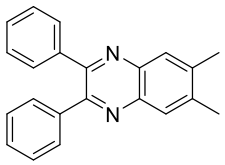
Table 3-6. Application to cascade synthesis of 2,3-diarylquinoxalines



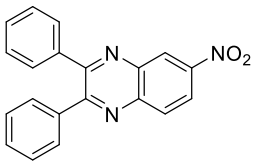




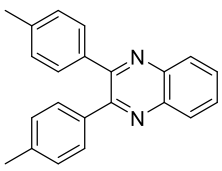
9a, 84%



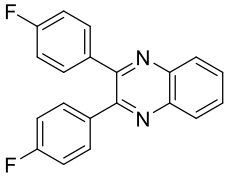
9b, 82%



9c, 55%



9d, 76%



9e, 63%

After the catalytic diarylation of *t*-BuNC **2a** with $BiAr_3$ **1a** was complete, the reaction mixture was filtered through a Celite pad. The filtrate was then treated with 1 N HCl aq., followed by the addition of *o*-phenylenediamine **8a**. The mixture was heated at 60 °C for 12 h to successfully afford the corresponding quinoxaline derivative **9a** in high yield. 4,5-Dimethyl-substituted *o*-phenylenediamine **8b** also reacted with the in situ formed α-diimine **3aa** to give the quinoxaline **9b** in high yield. In the case of *o*-phenylenediamine **8c**, which has an electron-withdrawing nitro

group, the corresponding quinoxaline **9c** was formed in moderate yield. Moreover, when $BiAr_3$ compounds with *p*-methyl- or *p*-fluoro-groups were employed for this cascade synthesis, the corresponding quinoxalines **9d** and **9e** were obtained in good yields. The present method of quinoxaline synthesis is very convenient, because the in situ formed α-diimines **3** can be used directly without any purification.

3-3 Conclusion

Herein, the authors have described the details of the transition metal-catalyzed diarylation of isocyanides with triarylbismuthines. The palladium-catalyzed diarylation afforded α-diimines as the major products, whereas the rhodium-catalyzed reaction gave imines selectively. The reaction conditions were then optimized, including the selection of catalysts and solvents, and the byproducts were determined. Furthermore, the diarylation was successfully applied to the cascade synthesis of quinoxalines.

3-4 Experimental Section

General Comment Triphenylbismuthine (**1a**) was obtained from commercial supply. The other bismuthines were synthesized according to the literature. All aliphatic isocyanides and 2,6-xylylisocyanide (2g) were obtained from commercial supplies. The other isocyanides were synthesized according to the literatures. All solvents were distilled before use. 1H NMR spectra were recorded on JEOL JNM-ECX400 (400 MHz) FT NMR or JEOL JNMECS400 (400 MHz) FT NMR in $CDCl_3$ with Me_4Si as an internal standard. ^{13}C NMR spectra were recorded on JEOL JNM-ECX400 (100 MHz) FT NMR or JEOL JNM-ECS400 (100 MHz) FT NMR in $CDCl_3$. ^{19}F NMR spectra were recorded on JEOL JNM-ECX400 (376 MHz) FT NMR or JEOL JNM-ECS400 (376 MHz) FT NMR in $CDCl_3$ with $CFCl_3$ as an external standard. High resolution mass spectra were obtained on JEOL JMS700. GC-MS spectra were obtained on SHIMADZU

GCMS-QP5000. HPLC (recycle GPC) method for isolation was performed on JAPAN ANALYTICAL INDUSTRY LC-908 with JAIGEL-2HH (polystyrenebased column).

Typical Reaction Procedure for α-Diimine Synthesis (Table 1–5)

Triphenylbismuthine (**1a**; 0.4 mmol) and *tert*-butyl isocyanide (**2a**; 0.4 mmol) were dissolved in benzene (2 mL) in a dried two-necked test tube under a N_2 atmosphere. Palladium diacetate (0.08 mmol) was added to the mixture. The resulting mixture was stirred for 18 h at 70 °C. After the reaction, the crude product was filtered through a Celite pad. All volatiles were evaporated under reduced pressure, and the NMR spectrum was measured (solv.: $CDCl_3$). Dioxane was used as an internal standard.

N,N'-Bis(1,1-dimethylethyl)-1,2-diphenylethane-1,2-diimine (**3aa**).[13] 88% yield (56.3 mg); white solid; m.p. 107.5–109.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.83–7.74 (m, 4H), 7.37–7.27 (m, 6H), 1.24 (s, 18H); ^{13}C NMR (100 MHz, CDCl3) δ 159.1, 140.4, 129.6, 128.2, 127.7, 57.9, 30.0; HRMS (FAB) Calcd for $C_{22}H_{29}N_2$ [M+H]+: 321.2331, Found: 321.2320.

N,N'-Bis(1,1,3,3-tetramethylpropyl)-1,2-diphenylethane-1,2-diimine (**3ab**).[13] 78% yield (67.4 mg); white solid; m.p. 108.0–109.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.81–7.74 (m, 4H), 7.34–7.28 (m, 6H), 1.50 (s, 4H), 1.38 (s, 6H), 1.16 (s, 6H), 1.04 (s, 18H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.6, 140.7, 129.5, 128.1, 127.9, 62.0, 57.1, 32.1, 32.0, 30.0, 29.5; HRMS (FAB) Calcd for $C_{30}H_{45}N_2$ [M+H]+: 433.3583, Found: 433.3580.

N,N'-Dicyclohexyl-1,2-diphenylethane-1,2-diimine (**3ac**).[13] 73% yield (54.3 mg); white solid; m.p. 89.5–91.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.84–7.74 (m, 4H), 7.40–7.29 (m, 6H), 3.25 (tt, *J* = 4.1, 9.6 Hz, 2H), 1.89–1.84 (m, 2H), 1.73–1.18 (m, 16H), 1.14–0.99 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.1, 137.1, 130.2, 128.4, 127.6, 62.8, 33.9, 32.9, 25.6, 24.1, 24.0; HRMS (FAB) Calcd for $C_{26}H_{33}N_2$ [M+H]+: 373.2644, Found: 373.2644.

N,N'-Dipentyl-1,2-diphenylethane-1,2-diimine (**3ad**).[13] 85% yield (59.2 mg); pale yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77–7.72 (m, 4H), 7.39–7.31 (m, 6H), 3.33 (t, *J* = 7.3 Hz, 4H),1.74–1.65 (m, 4H), 1.37–1.23 (m, 8H), 0.86 (t, *J* = 7.3 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 136.1, 130.5, 128.6, 127.1, 54.5, 30.5, 29.8, 22.5, 14.0.

N,N'-Bis(4-methoxyphenyl)-1,2-diphenylethane-1,2-diimine (**3ae**).[13] 80% yield (33.6 mg); yellow solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.88–7.83 (m, 4H), 7.43–7.33 (m, 6H), 6.70–6.61 (m, 8H), 3.72 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.2, 157.3, 142.4, 137.4 130.8, 128.7, 128.0, 122.1, 113.7, 55.3; GC- MS (EI) m/z = 420 (M+).

N,N'-Bis(2,6-dimethylphenyl)-1,2-diphenylethane-1,2-diimine (**3af**).[13] 84% yield (34.9 mg); viscous yellow oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.27–8.20 (m, 4H), 7.60–6.68 (m, 12H), 2.13–1.75 (m, 12H); GC-MS (EI) m/z = 416 (M+).

N,N'-Bis(1,1-dimethylethyl)-1,2-bis(4-methylphenyl)ethane-1,2-diimine (**3ba**).[13] 58% yield (40.4 mg); white solid; m.p. 83.5–85.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.69–7.62 (m, 4H), 7.13–7.08 (m, 4H), 2.32 (s, 6H), 1.23 (s, 18H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.1, 139.6, 137.9, 128.9, 127.6, 57.7, 30.0, 21.3.

N,N'-Bis(1,1-dimethylethyl)-1,2-bis(4-fluorophenyl)ethane-1,2-diimine (**3ca**).[13] 27% yield (19.2 mg); white solid; m.p. 99.5–102.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.78–7.71 (m, 4H), 7.03–6.97 (m, 4H), 1.23 (s, 18H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.8 (d, J_{C-F} = 250.8 Hz), 157.5, 136.3 (d, J_{C-F} = 2.9 Hz), 129.5 (d, J_{C-F} = 8.6 Hz), 115.2 (d, J_{C-F} = 21.9 Hz), 58.0, 29.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ -111.3.

N,N'-Bis(4-methoxyphenyl)-1,2-di-p-tolylethane-1,2-diimine (**3be**).[16, 17] 47% yield (21.1 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 (d, *J* = 8.4 Hz, 4H), 7.16 (d, *J* = 8.0 Hz, 4H), 6.55-6.65 (m, 8H), 3.71 (s, 6H), 2.36 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.3, 157.1, 142.6, 141.1, 134.9, 129.4, 128.1, 122.1, 113.6, 55.3, 21.5.

N,N'-1,2-tetrakis(4-methoxyphenyl)ethane-1,2-diimine (**3ce**).[17] 54% yield (25.9 mg); ^{1}H NMR

(400 MHz, $CDCl_3$) δ 7.90–7.70 (m, 4H), 6.95–6.80 (m, 4H), 6.60-6.72 (m, 8H), 3.82 (s, 6H), 3.72 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.8, 161.6, 142.7, 130.4, 129.8, 122.1, 114.0, 113.6, 55.3.

1,2-Bis(4-fluorophenyl)-N,N'-bis(4-methoxyphenyl)ethane-1,2-diimine (**3de**). 81% yield (36.9 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 7.90–7.71 (m, 4H), 7.15–7.0 (m, 4H),6.60-6.80 (m, 8H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.3. (d, *J* = 251.7 Hz), 161.6, 157.5, 142.0, 133.29 (d, *J* = 2.9 Hz), 130.0 (d, *J* = 8.6 Hz), 122.3, 115.8 (d, *J* = 21 Hz), 113.8, 55.3. ^{19}F NMR (376 MHz, $CDCl_3$) δ -108.7.

Typical Reaction Procedure for cascade synthesis of 2,3 diarylquinoxalines (Table 6)

Triphenylbismuthine (**1a**; 0.4 mmol) and *tert*-butyl isocyanide (**2a**; 1.2 mmol) were dissolved in MeCN (2 mL) in a dried two-necked test tube under air. Palladium diacetate (0.024 mmol) was added to the mixture. The resulting mixture was stirred for 4 h at 70 °C. After the reaction, the crude product was filtered through a Celite pad. All volatiles were evaporated under reduced pressure, after which dioxane (5 mL) and 1 N HCl (5 mL) were added. The mixture was stirred at 60 °C for 6 h, then α-diamine (0.6 mmol) was added and the reaction was stirred at 60 °C for 12 h. The mixture was extracted three time with EtOAc (10 mL), dried over $MgSO_4$, and the desired product was purified by silica gel chromatography (eluent: hexane/EtOAc).

2,3-Diphenylquinoxaline (**9a**).[18] 84% yield (142.1 mg); white solid; m.p. 124–125 °C. ^{1}HNMR ($CDCl_3$, 300MHz) δ 8.16–8.19 (m, 2 H), 7.74–7.77 (m, 2H), 7.32–7.35 (m, 6H), 7.50–7.53 (m, 4H).

6,7-Dimethyl-2,3-diphenylquinoxaline (**9b**).[18] 82% yield (152.5 mg); white solid; m.p. 174–175 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, *J* = 8.8 Hz, 1 H), 7.51–7.58 (m, 5H), 7.30–7.32 (m, 6H), 2.78 (s, 3H), 2.51 (s, 3H).

6-Nitro-2,3-diphenylquinoxaline (**9c**).[18] 55% yield (107.9 mg); yellow solid; m.p. 188–189 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.10 (s, 1H), 8.53–8.56 (m, 1H), 8.32 (d, *J* = 9.2 Hz, 1H), 7.57–7.60 (m, 4H), 7.38–7.47 (m, 6H).

2,3-Di-p-tolylquinoxaline (**9d**).[19] 76% yield (141.4 mg); m.p. 142-144 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.11–8.03 (m, 2H), 7.71–7.63 (m, 2H), 7.36 (d, 4H), 7.10 (d, 4H), 2.35 (s, 6H).

2,3-Bis(4-flouro-phenyl)quinoxaline (**9e**).[20] 63% yield (120.2 mg); m.p. 134–136 °C; ^{1}H NMR ($CDC1_3$, 400 MHz) δ 7.97 (dd, *J* = 6.4, 3.6 Hz, 2H), 7.6 (dd, *J* = 6.4, 3.2 Hz, 2H), 7.40-7.28 (m, 4H), 6.86 (t, *J* = 8.8 Hz, 4H).

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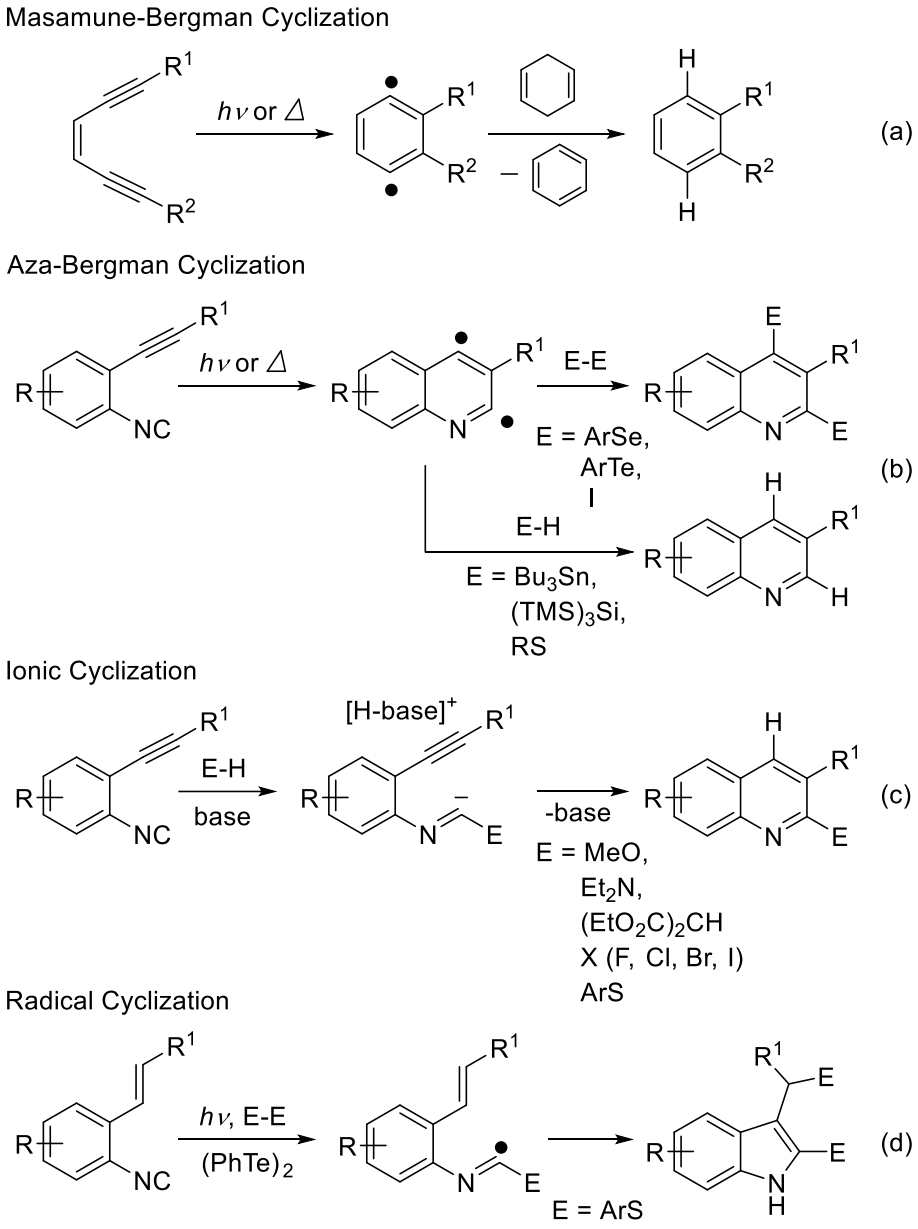
Chapter 4

Photoinduced Cyclizations of *o*-Diisocyanoarenes with Organic Diselenides and Thiols that Afford Chalcogenated Quinoxalines

4-1 Introduction

The Masamune–Bergman cyclization, i.e., the thermal or photochemical cycloaromatization of an endiyne in the presence of a hydrogen donor such as 1,4-cyclohexadiene (Scheme 4-1(a)) to afford a substituted arene,[1] involves the formation of an arene biradical as the key intermediate and is widely used in natural products synthesis[2] and in the cleavage of DNA.[3] The quinoline 2,4-biradical intermediate formed during the photoinduced/thermal aza-Bergman cyclization of an *o*-alkynylarylisocyanide can be trapped with I_2,[4] $(PhSe)_2$,[5] or $(PhTe)_2$[6] to furnish heteroatom-substituted quinoline derivatives (Scheme 4-1(b)), or, alternatively, it can be trapped with a hydrogen donor such as a tin hydride, PhSeH, or an alkanethiol, to afford a quinoline derivative.[5] However, arenethiols, which are more acidic than alkanethiols, prefer to undergo an ionic cyclization reaction over aza-Bergman cyclization, especially in the presence of a base such as triethylamine (Scheme 4-1(c)).[5,7] Notably, while *o*-alkynylarylisocyanides undergo ionic cyclization in the presence of alcohols, amines, active methylene compounds,[8] and hydrogen halides,[9] *o*-alkenylarylisocyanides predominantly undergo radical cyclization, as exemplified by their photoinduced 5-*exo*-cyclizations with $(PhS)_2$ in the presence of $(PhTe)_2$ (Scheme 4-1(d)).[10]

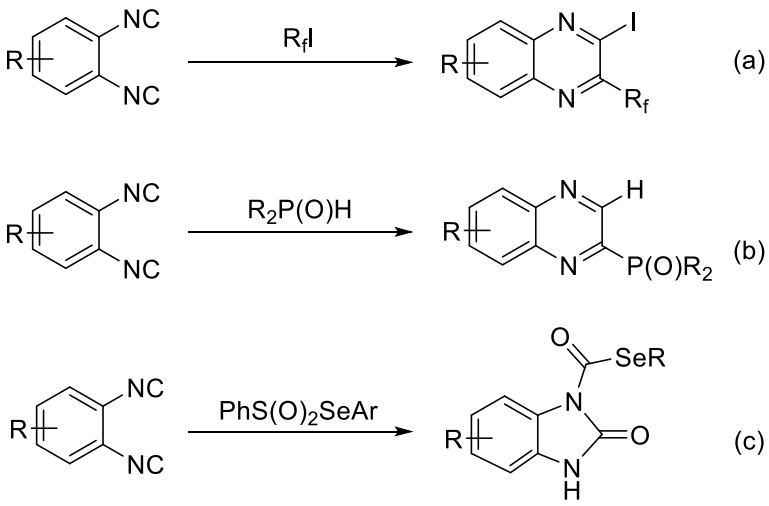
Scheme 4-1. Cycloaromatizations Reactions of Endiynes and Their Analogues



Recently, several examples of quinoxaline syntheses from *o*-diisocyanoarenes via radical-mediated perfluoroalkyliodination[11,12] and hydrophosphorylation[13] processes have been reported (Schemes 4-2(a) and 4-2(b)), and the efficient syntheses of *N*-(carboselenoate)benzimidazolones via the cascade cyclization reactions of *o*-diisocyanides

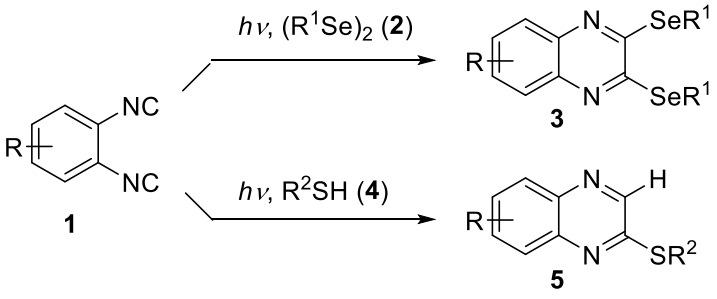
have also been reported[14] (Scheme 4-2(c)). These reactions utilize the good radical acceptor properties of isocyanides.[15]

Scheme 4-2. Radical Cyclization Reactions of *o*-Diisocyanoarenes



This manuscript describes the photoinduced cyclization reactions of *o*-diisocyanoarenes **1** with diorganyl diselenides **2** that afford 2,3-bis(selanyl)quinoxalines **3** and the cyclization reactions of *o*-diisocyanoarenes **1** with thiols **4** that afford 2-thiylquinoxalines **5**, respectively. These cyclization reactions can be carried out under mild metal- and additive-free conditions (Scheme 4-3).

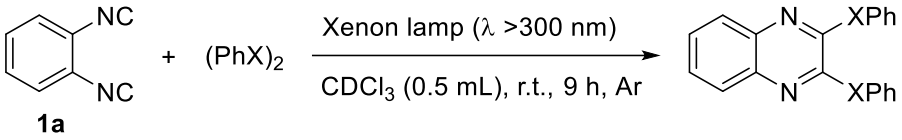
Scheme 4-3. Photoinduced Cycloaromatization Reactions of *o*-Diisocyanoarenes



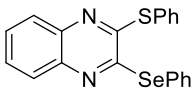
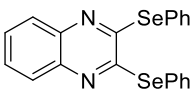
4-2 Results and discussion

Initially, the author investigated the photoinduced reactions of *o*-diisocyanobenzene (**1a**) with diphenyl dichalcogenides (Table 4-1). In the case of diphenyl disulfide (X = S), the desired thiolated quinoxaline was not formed (entry 1). When equimolar amounts of diphenyl disulfide and diphenyl diselenide (**2a**, X = Se) were used, a 1:1 mixture of thioselenated and diselenated quinoxaline derivatives was obtained (entry 2) while 2,3-bis(phenylselanyl)quinoxaline (**3a**) was produced in high yield in the presence of two equivalents of **2a** alone (entry 3). In sharp contrast, no reaction was observed when diphenyl ditelluride was used instead of **2a** (entry 4). Hence, **2a** was chosen for further investigations into the photoinduced cyclization reactions of *o*-diisocyanobenzenes **1** (entry 3, Table 4-1).

Table 4-1. Photoinduced Reactions of *o*-Diisocyanobenzene (1a) with Chalcogenides[a]



Entry	$(PhX)_2$	Yield[b], %
1	$(PhS)_2$ 2.0 equiv.	N.D
2	$(PhS)_2$ 2.0 equiv., and $(PhSe)_2$ 2.0 equiv.	80 (40/40)[b]
3	$(PhSe)_2$ 2.0 equiv.	90
4	$(PhTe)_2$ 2.0 equiv.	N.D[c]

[a]Reaction conditions: **1a** (0.1 mmol), diphenyl dichalcogenide, $CDCl_3$ (0.5 mL) under Ar, Pyrex tube, room temperature, 9 h. N.D.: not detected. [b]A mixture of cyclic thioselenide and diselenide, *i.e.*,  and  was formed (1:1 ratio, as determined by ^{77}Se NMR spectroscopy). [c]A filter (λ > 400 nm) was used.

In the next step, the author optimized the reaction of **1a** with **2a** (Table 4-2). The yield of **3a** significantly decreased when a high-pressure Hg lamp was employed as the light source (entry 1), whereas a tungsten lamp proved to be more suitable for the reaction (entry 2). When acetonitrile (MeCN) or dichloromethane (CH_2Cl_2) was used as the solvent, the desired quinoxaline **3a** was obtained in good yield (71 or 67% respectively, entries 3 and 4). Irradiation with a Xe lamp gave **3a** in a yield of 81% (entry 5), which increased to 90% (entry 6) when the loading of **2a** was raised to 2.0 equiv. and decreased as this loading was increased further (entry 7). Heating at 80 °C in toluene in the dark led to a low yield of **3a** (entry 8)[16], whereas no reaction was observed at room temperature in the dark (entry 9). Hence, the conditions of entry 6 were chosen to investigate the substrate scope of the transformation.

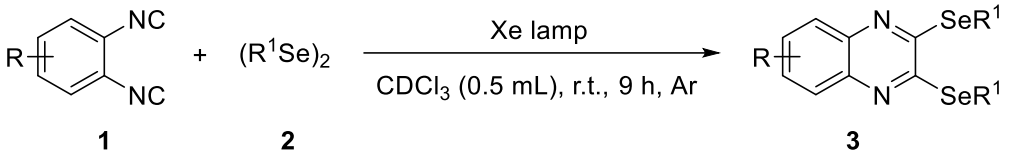
Table 4-2. Optimization of the Photoinduced Cyclization of *o*-Diisocyanobenzene with Diphenyl Diselenide

Entry	Reaction conditions	Yield (%)
1	Mercury lamp, $(PhSe)_2$ 1.0 equiv., 0.5 mL $CDCl_3$	48
2	Tungsten lamp, $(PhSe)_2$ 1.0 equiv., 0.5 mL $CDCl_3$	59
3	Xenon lamp, $(PhSe)_2$ 1.0 equiv., 0.5 mL MeCN	71
4	Xenon lamp, $(PhSe)_2$ 1.0 equiv., 0.5 mL CH_2Cl_2	67
5	Xenon lamp, $(PhSe)_2$ 1.0 equiv., 0.5 mL $CDCl_3$	81
6	**Xenon lamp, $(PhSe)_2$ 2.0 equiv., 0.5 mL $CDCl_3$**	**90**
7	Xenon lamp, $(PhSe)_2$ 3.0 equiv., 0.5 mL $CDCl_3$	72
8[a]	In dark, $(PhSe)_2$ 2.0 equiv., 0.5 mL toluene	33
9	In dark, $(PhSe)_2$ 2.0 equiv., 0.5 mL $CDCl_3$	0
[a]80 °C.		

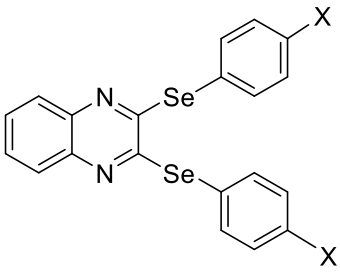
Table 4-3 demonstrates the substrate scope of the reaction of *o*-diisocyanoarenes with diselenides. A variety of substituted diaryl diselenides was generally tolerated. *p*-Substituted diaryl diselenides gave the desired bisselenated quinoxalines **3b**–**3e** in moderate-to-good yields, while products from *m*-substituted diaryl diselenides **3f**–3**i** were obtained in 57–85% isolated yields. Notably, selenides bearing electron-donating or electron-withdrawing groups were supported. When a *m*,*p*-difluorinated diaryl diselenide was employed, quinoxaline **3j** was isolated in good yield (78%). Owing to the steric effect, bis(*o*-chlorophenyl) diselenide gave the corresponding quinoxaline **3k** in a low yield. Interestingly, the reaction of **1a** with aliphatic diselenides (diethyl diselenide and dibutyl diselenide) afforded the desired quinoxalines (**3l** and **3m**, respectively) in good yields. Furthermore, the author examined the *o*-diisocyanobenzene scope. The cyclization of methyl-substituted *o*-diisocyanobenzenes with **2a** successfully afforded the corresponding products (**3n** and **3o**) in yields of 90 and 77%, respectively. In the case of *o*-diisocyanobenzene bearing an electron-withdrawing group, the desired quinoxaline **3p** was obtained in satisfactory yield (83%). The reaction was also scalable in good yield (Table 4-3, footnote c).

Sulfur-containing molecules are widely used in materials chemistry, bioscience, and organic chemistry, which makes the development of corresponding synthetic methods a task of high importance.[17] Unfortunately, because of their lower carbon-radical capturing abilities, organic disulfides proved to be ineffective for the cycloaromatization of *o*-diisocyanoarenes (Table 4-1, entry 1). Consequently, the author next examined the cycloaromatization of *o*-diisocyanobenzene using thiols **4** as sulfur sources under various irradiation conditions (Table 4-4). Upon irradiation with a high-pressure Hg lamp through Pyrex glass, cyclization with hydrothiolation afforded 2-(cyclohexylsulfanyl)quinoxaline (**5a**) in moderate yield (entry 1), and this yield was found to increase when the light source was changed to a xenon lamp (entry 2).

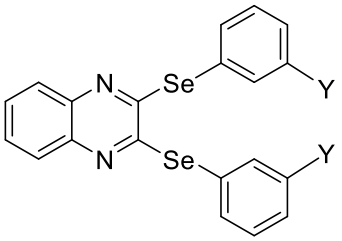
Table 4-3. Cyclization Reaction of *o*-Diisocyanoarenes with Diselenides:[a,b] Reaction Scope



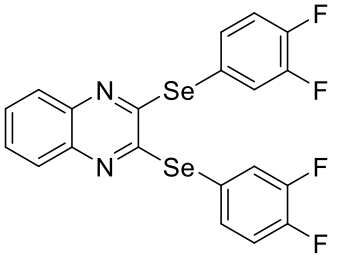
1 **2** **3**



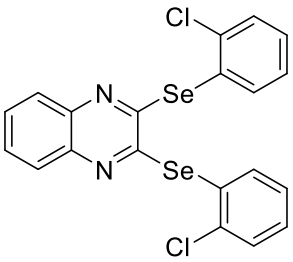
3a, X = H, 90%, 83%[c]
3b, X = OCH_3, 63%
3c, X = F, 61%
3d, X = Cl, 79 %
3e, X = CF_3, 87%



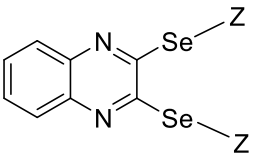
3f, Y = CH_3, 57%
3g, Y = F, 85%
3h, Y = Cl, 65%
3i, Y = CF_3,77%



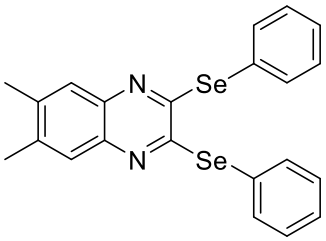
3j, 78%



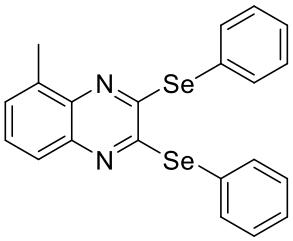
3k, 21%



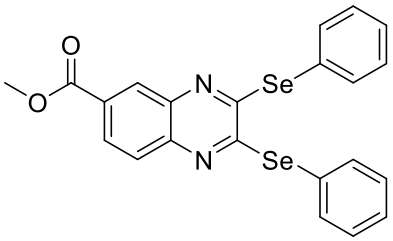
3l, Z = C_2H_5, 88%
3m, Z = C_4H_9, 99%



3n, 90%



3o, 77%



3p, 83%

[a]Reaction conditions: *o*-diisocyanoarene (0.1 mmol), diselenide (0.2 mmol), $CDCl_3$ (0.5 mL), Xe lamp, Pyrex tube, Ar, room temperature, 9 h. [b]Isolated yield. [c]Gram-scale reaction: *o*-diisocyanobenzene (**1a**, 1.00 g, 7.8 mmol), diphenyl diselenide (**2a**, 4.9 g, 15.6 mmol) in $CHCl_3$ (10 mL).

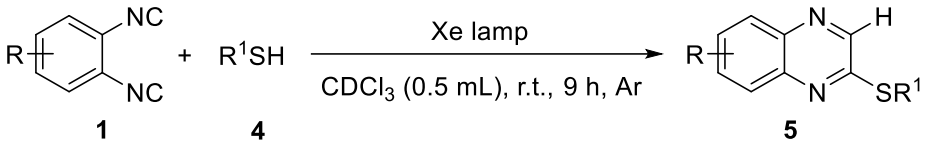
Similarly, high yields of **5a** were obtained at elevated thiol loadings (entries 3 and 4). Upon heating at 80 °C in the dark, **5a** was obtained in a moderate yield (entry 5), while no reaction was observed in the dark at room temperature (entry 6). Addition of a base, Et_3N, was not effective for the desire cyclization reaction (entry 7).

Table 4-4. Optimization of the Photoinduced Thiolative Cyclization of **1a** with Cyclohexanethiol (**4a**)

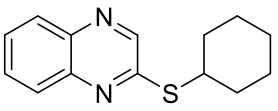
Entry	Reaction conditions	Yield (%)
1	Hg lamp, ^{c}HexSH 1.0 equiv.	45%
2	Xenon lamp, ^{c}HexSH 1.0 equiv.	81%
3	**Xenon lamp, ^{c}HexSH 2.0 equiv.**	**89%**
4	Xenon lamp, ^{c}HexSH 3.0 equiv.	72%
5[a]	In dark, ^{c}HexSH 2.0 equiv.	63%
6	In dark, ^{c}HexSH 2.0 equiv.	0 %
7	In dark, ^{c}HexSH 2.0 equiv., Et_3N 4.0 equiv.	9%
(^{c}Hex = cyclohexyl). [a]In toluene (0.5 mL), 80 °C.		

With the above results in mind, the author selected the conditions of entry 3 in Table 4-4 to study the substrate scope of the thiolative *o*-diisocyanoarene cyclization reaction (Table 4-5). When aliphatic thiols were used to cyclize **1a**, the desired cycloaromatization products **5a**–**5f** were obtained in moderate to high yields (62–89%). Despite steric hindrance, *tert*-butanethiol successfully afforded the corresponding quinoxaline **5f** in a 71% yield. Furthermore, a variety of aromatic thiols was tolerated, affording quinoxaline derivatives **5g**–**5k** in good yields (64–71%).

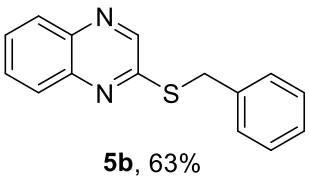
Table 4-5. Cyclization Reactions of *o*-Diisocyanoarenes with Thiols:[a,b] Substrate Scope



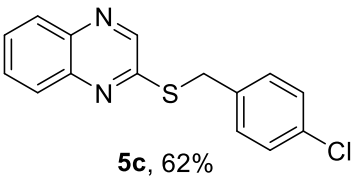
1 **4** **5**



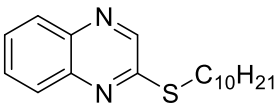
5a, 89%



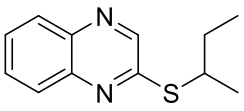
5b, 63%



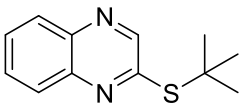
5c, 62%



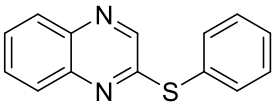
5d, 87%



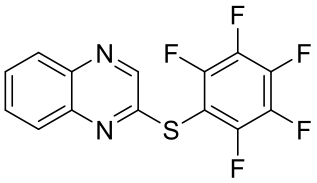
5e, 89%



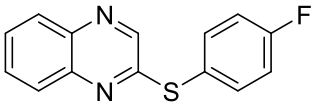
5f, 71%



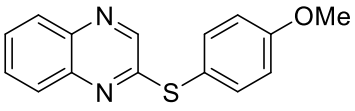
5g, 68%



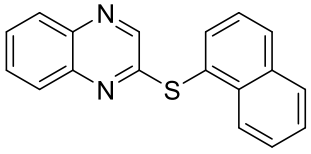
5h, 63%



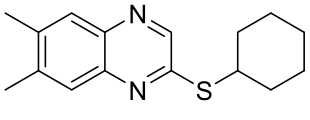
5i, 69%



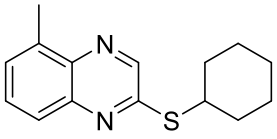
5j, 64%



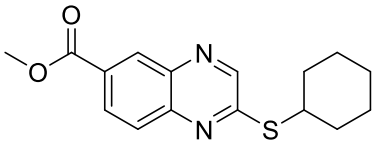
5k, 71%



5l, 81%

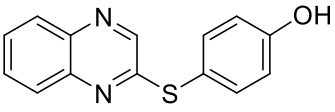


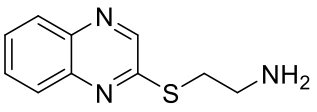
5m + **5m'**,74% (44%/30%)

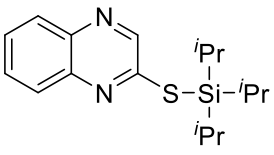


5n + **5n'**,65% (31%/34%)[b]

Unsuccessful examples





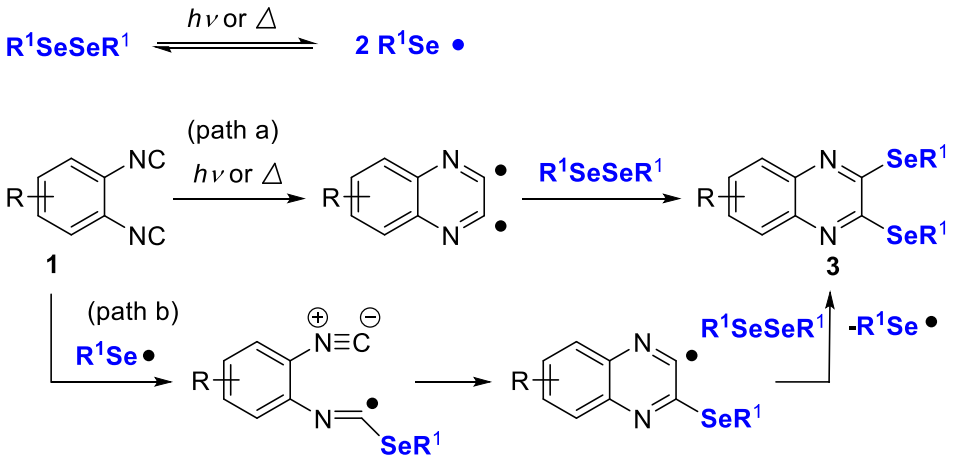


[a]Reaction conditions: *o*-diisocyanoarene (0.2 mmol), thiol (0.4 mmol), $CDCl_3$ (0.5 mL), xenon lamp, Pyrex tube, argon, room temperature, 9 h. [b]Isomer ratio was determined by ^1H NMR spectroscopy. （表修正）

The substituent on the aromatic thiol had no significant effect on the yields of the cyclization products. Moreover, the reaction of ^{c}HexSH with *o*-diisocyanoarenes provided good yields of quinoxalines **5l**–**5n**. In the cases of **5m** and **5n**, a regioisomeric mixture (**5m'** and **5n'**, respectively) was obtained. Unfortunately, the developed cyclization protocol was not applicable to thiols bearing unprotected alcohol groups (a complex mixture was formed), amines (no product), and $(^{i}Pr)_3SiSH$ (no product). In summary, thiols were tolerated to provide the corresponding thiolated quinoxalines **5** in moderate to good yields.

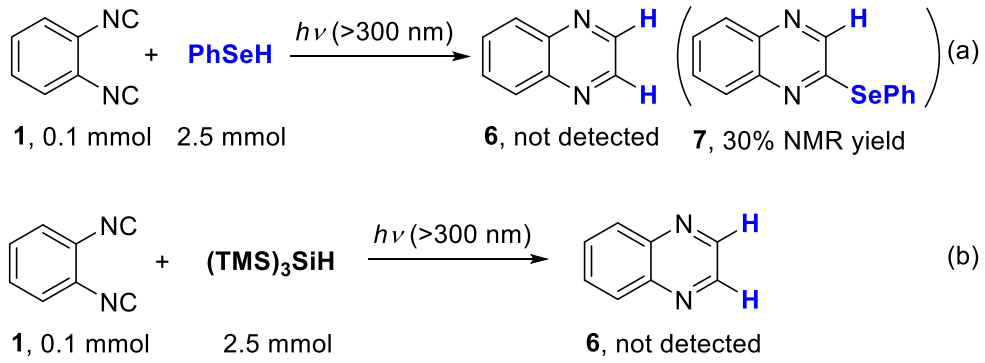
The author considered the following two pathways for the mechanism of the photoinduced bisselenative cyclization of an *o*-diisocyanoarene with an organic diselenide (Scheme 4-4). *o*-Diisocyanobenzene absorbs in the near-UV region and therefore can undergo an aza-Bergman-type cyclization upon irradiation with near-UV light to generate biradical species that are subsequently captured by organic selenides (path a). Alternatively, selenyl radicals generated by irradiation with near-UV or visible light[18] may attack an isocyanide group in **1** to form an imidoyl radical intermediate that can then intramolecularly add to the other isocyano group to afford a cyclized imidoyl radical that is finally captured by the diselenide to afford **3** (path b).

Scheme 4-4. Possible Pathways for the Bisselenative Cyclization of an *o*-Diisocyanoarene



To clarify which pathway contributes to the bisselenated cyclization of **1**, the author examined the photoinduced reactions of **1a** with benzeneselenol and $(TMS)_3SiH$ (Scheme 4-5). If path a in Scheme 3-4 is dominant, formation of quinoxaline (**6**) is excepted. However, no quinoxaline (**6**) was obtained, probably because radical cyclization follows path b in which **6** cannot be formed. This result strongly suggests that *o*-diisocyanobenzene does not undergo the aza-Bergman-type cyclization when irradiated at room temperature. In Scheme 4-5(a), selenoquinoxaline adduct **7** is confirmed as a byproduct. This result might support that pathway b is preferred.

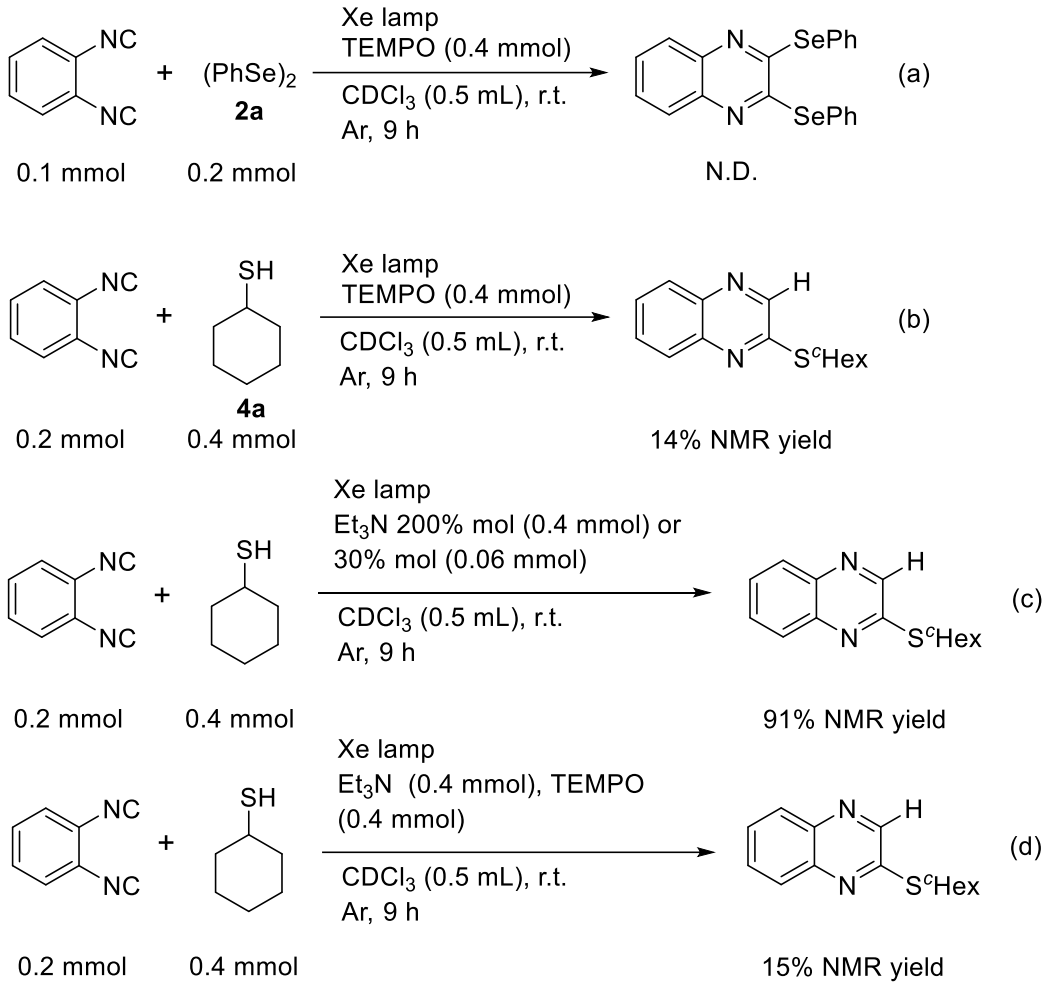
Scheme 4-5. Mechanistic Insight into the Bisselenative Cyclization Reactions of *o*-Diisocyanobenzene



The author subsequently examined the cyclization of *o*-diisocyanobenzene with **2a** or benzenethiol in the presence of 2,2,6,6-tetramethylpiperidine 1-oxyl (TEMPO) as a radical-trapping reagent (Scheme 4-6). In the case of **2a**, no reaction was observed (Scheme 4-6(a)), which strongly suggests that the bisselenative cyclization involves a radical process. Similarly, thiolative cyclization reaction in the presence of benzenethiol (**4a**) barely proceeded in the presence of TEMPO (Scheme 4-6(b) and 4-6(d)). The base selected was found to have no significant effect on the product yield (Scheme 4-6(c) and 4-6(d)). The author therefore considers

that radical pathway is dominant in the case of aliphatic thiol although an ionic pathway is not still excluded[19,20].

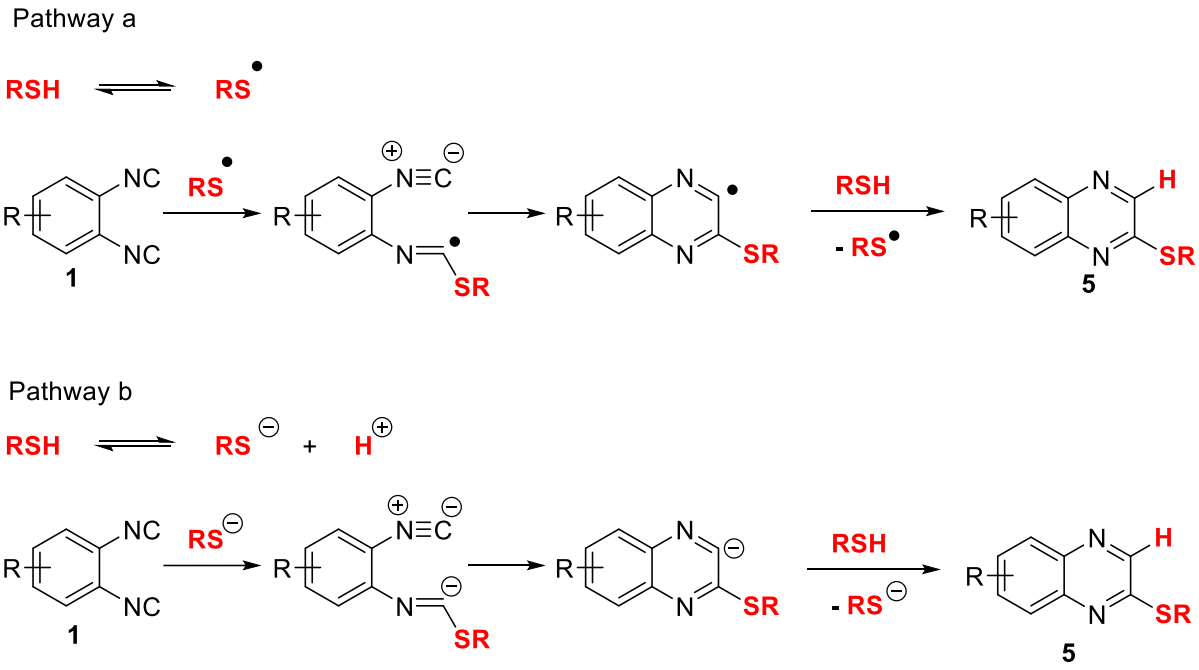
Scheme 4-6. Mechanistic Insight into the Bisselenative Cyclization of *o*-Diisocyanobenzene



A possible pathway for the thiolative cyclization of an *o*-diisocyanoarene is shown in Scheme 4-7. Thiyl radicals generated by irradiation with near-UV or visible light may attack an isocyano group in **1** to form an imidoyl radical intermediate that can then intramolecularly add to the other isocyano group to afford a cyclized imidoyl radical that is finally captured by the thiol to afford **5** (Pathway a). Alternatively, thiolate anion generated from the corresponding thiol attacks an isocyano group in **1** to form an imidoyl anion intermediate that can then

intramolecularly add to the other isocyano group to afford the quinoxaline anion that is finally protonated by the thiol to afford **5** (Pathway b).

Scheme 4-7. A Possible Pathway for the Thiolative Cyclization of an *o*-Diisocyanoarene



4-4 Conclusion

In summary, the author developed mild and efficient photoinduced cyclization reactions of *o*-diisocyanoarenes with organic diselenides and thiols that afford chalcogenated quinoxalines. In the case of a diselenide, cyclization is believed to involve a radical process, while both a radical pathway and an ionic pathway are considered in the case of thiols. The developed protocol can be used to establish a library of chalcogen-substituted quinoxalines which are known to be potential oxidants with promising bioactivities.

4-5 Experimental Section

General Remarks Unless otherwise stated, all starting materials and catalysts were purchased from commercial sources and used without further purification. All solvents were distilled and degassed with N_2 before use. Thiol, diphenyl dichalchogenide, and diethyl diselenide **2l** were purchased from Tokyo Chemical Industry. Other diselenides **2b–k**, **2m**, and *o*-diisocyanoarenes **1b–d** were prepared according to previously reported procedures.[11,18,19] ^{1}H NMR spectra were recorded on JEOL JNM-ECS400 (400 MHz) and JEOL JNM-ECX400 (400 MHz) FT spectrometers in $CDCl_3$ with Me_4Si as the internal standard. ^{13}C NMR spectra were recorded on JEOL JNM-ECX400 (100 MHz) FT NMR or JEOL JNM-ECS400 (100 MHz) FT NMR spectrometers in $CDCl_3$. ^{19}F and ^{77}Se NMR spectra were recorded on a JEOL JNM-ECX400 (373 MHz and 75 MHz, respectively) instrument in $CDCl_3$ with $CFCl_3$ and Me_2Se as external standards, respectively. IR spectra are reported in wave numbers (cm^{-1}). ESI and EI mass spectra were recorded using double-focusing mass spectrometers. High-resolution mass spectra (HRMS) were recorded on a Bruker micrOTOF II ESI(+)/TOF instrument.

General Procedure for the Synthesis of *o*-Diisocyanides.[10] An equimolar mixture of formic acid and acetic anhydride (slight excess of formic acid) was stirred for 2 h at 55–60 °C in an oil bath to form formic acetic anhydride *in situ* (5.3 mL, 40.0 mmol, 4.0 equiv.). The prepared mixture was added to a solution of aryl diamine (10 mmol, 1.0 equiv.) in DCM (15 mL) at 0 °C. After stirring for 2–3 h at room temperature, saturated aqueous $NaHCO_3$ was added and the aqueous phase was extracted multiple times with DCM and ethyl acetate (EtOAc). The combined organic phases were dried over anhydrous $MgSO_4$, filtered and concentrated *in vacuo*. The residue was dissolved in a mixture of DCM (15 mL) and trimethylamine (17 mL, 0.12 mol, 12 equiv.), and the solution was slowly charged with $POCl_3$ (2.7 mL, 30 mmol, 3.0 equiv.) at 0 °C. The resulting mixture was then stirred for 2 h at this temperature, after which saturated aqueous

$NaHCO_3$ was added slowly. After stirring for at least 1 h at room temperature, the aqueous phase was extracted three times with DCM. The combined organic phases were dried over anhydrous $MgSO_4$, filtered, and concentrated *in vacuo*. The desired *o*-diisocyanides **1** were isolated by silica gel column chromatography (hexane/ Et_2O = 100/10 - 100/30).

General Procedure for the Synthesis of Diselenides.[21] Mg powder (0.48 g, 20 mmol), a stirring bar, and a small piece of I_2 were added to a 100-mL three-necked flask. The flask was then equipped with a condenser and charged with N_2. Under a N_2 atmosphere, anhydrous diethyl ether (10 mL) was injected using a syringe, after which 20 mmol of the aryl bromide was added slowly followed by anhydrous ether (5 mL). After the preparation of this Grignard reagent, dried selenium powder (20 mmol, 1.6 g) was added slowly. After stirring for 1 h, the mixture was dumped into 100 mL of 3 M HCl solution cooled in ice to acidolyze the mixture. The mixture was then extracted with diethyl ether (3 x 20 mL) and the combined organic layers were dried over anhydrous Na_2SO_4. The solution was charged with O_2 for 48 h during which time it turned a red-orange color. Distillation of the solvent afforded the crude diselenide, which was purified by column chromatography (eluent: hexane) *(the products may contain a small amount of unisolable* Ar_2Se_3 *and starting material).*[22] Dibutyl diselenide **2m** was prepared according to a literature report[23] using 20 mmol of butyl bromide.

General Procedure for the Photoinduced Cyclization of *o*-Diisocyanoarene with Organic Diselenide. *o*-Diisocyanoarene **1** (0.1 mmol), diselenide **2** (0.2 mmol), and $CDCl_3$ (0.5 mL) were placed sequentially into in a Pyrex tube under an inert atmosphere. The reaction mixture was irradiated with a xenon lamp at room temperature for 9 h, after which the resulting solution was subjected to preparative TLC (hexane/AcOEt = 9/1) to afford the desired quinoxaline **3**.

General Procedure for the Photoinduced Cyclization of *o*-Diisocyanoarene with Thiols. *o*-Diisocyanoarene **1** (0.2 mmol), thiol **4** (0.4 mmol), and $CDCl_3$ (0.5 mL) were placed sequentially into a Pyrex tube under an inert atmosphere. The reaction was irradiated with a xenon lamp at room temperature for 9 h, after which the resulting solution was subjected to preparative TLC (hexane/AcOEt = 9/1) to afford the desired quinoxaline **5**.

Procedure for the Gram-Scale Reaction of 1a with 2a. *o*-Diisocyanobenzene **1a** (1.00 g, 7.8 mmol), diphenyl diselenide **2a** (4.9 g, 15.6 mmol), and $CHCl_3$ (10 mL) were placed in a Pyrex tube under an argon atmosphere. The reaction was irradiated with a xenon lamp at room temperature for 48 h and after this time, the solvent was evaporated and the product was purified by silica-gel column chromatography (hexane/AcOEt = 100/1) to afford quinoxaline **3a** (83%, 3.45 g).

Spectral Data for the Products

2,3-Bis(phenylselanyl)quinoxaline (3a).[24] The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 39.8 mg, 90%, mp 90–92 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.85–7.63 (m, 6H), 7.55–7.47 (m, 2H), 7.45–7.33 (m, 6H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 155.4, 142.0, 135.8, 129.4, 129.0, 128.5. 127.9; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 466.6; IR (KBr, ν/cm^{-1}): 585, 688, 737, 1020, 1068, 1122, 1152, 1237.

2,3-Bis((4-methoxyphenyl)selanyl)quinoxaline (3b). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 31.6 mg, 63%, mp 142–144 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30–7.67 (m, 2H), 7.64 (d, J = 8.7 Hz, 4H), 7.53–7.46 (m, 2H), 6.95 (d, J = 8.7 Hz, 4H), 3.86 (s, 6H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 160.4, 155.8, 142.0, 137.8, 128.7, 128.4, 117.9, 115.1, 55.4; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 452.8; IR (KBr, ν/cm^{-1}): 761, 816, 975, 1025, 1092, 1174, 1247, 1492, 2357; HRMS (ESI+/TOF) m/z: $[M+Na]^+$ Calcd. for $C_{22}H_{18}N_2NaO_2Se_2$ 524.9596; Found 524.9595.

2,3-Bis((4-fluorophenyl)selanyl)quinoxaline (3c). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 29.1 mg, 61%, mp 137–139 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.82–7.6 (m, 6H), 7.60–7.44 (m, 2H), 7.18–7.01 (m, 4H); $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ 163.5 (d, $J_{C–F}$ = 249.2 Hz), 154.9, 142.0, 138.1 (d, $J_{C–F}$ = 7.7 Hz), 129.2, 128.4, 122.2 (d, $J_{C–F}$ = 2.9 Hz), 116.7 (d, $J_{C–F}$ = 22.0 Hz); ^{19}F (373 MHz, $CDCl_3$): δ −116.8; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 458.0; IR (KBr, ν/cm^{-1}): 508, 757, 808, 976, 1065, 1095, 1126, 1156, 1227, 1485; HRMS (EI) *m*/*z*: $[M]^+$ Calcd. for $C_{20}H_{12}F_2N_2Se_2$ 477.9303; Found 477.9307.

2,3-Bis((4-chlorophenyl)selanyl)quinoxaline (3d). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 40.3 mg, 79%, mp 165–167 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.77–7.69 (m, 2H), 7.63 (d, *J* = 8.2 Hz, 4H), 7.58–7.52 (m, 2H), 7.37 (d, *J* = 8.2 Hz, 4H); $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ 154.6, 142.0, 137.1, 135.4, 129.6, 129.4, 128.5, 125.8; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 461.1; IR (KBr, ν/cm^{-1}): 758, 807, 979, 1012, 1090, 1472; HRMS (EI) *m*/*z*: $[M]^+$ Calcd. for $C_{20}H_{12}Cl_2N_2Se_2$ 509.8704; Found 509.8707.

2,3-Bis((4-(trifluoromethyl)phenyl)selanyl)quinoxaline (3e). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 50.3 mg, 87%, mp 171–173 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.82 (d, *J* = 8.2 Hz, 4H), 7.79–7.73 (m, 2H), 7.64 (d, *J* = 8.2 Hz, 4H), 7.61–7.56 (m, 2H); $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ 154.1, 142.1, 135.5, 132.5, 130.9 (q, $J_{C–F}$ = 32.6 Hz), 129.4 (d, $J_{C–F}$ = 123.6 Hz), 126.1 (q, $J_{C–F}$ = 3.8 Hz), 125.4, 122.7; ^{19}F (373 MHz, $CDCl_3$): δ −62.6; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 468.5; IR (KBr, ν/cm^{-1}): 762, 828, 973, 1013, 1060, 1077, 1328, 1601; HRMS (EI) *m*/*z*: $[M]^+$ Calcd. for $C_{22}H_{12}F_6N_2Se_2$ 577.9239; Found 577.9232.

2,3-Bis(m-tolylselanyl)quinoxaline (3f). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow liquid, 26.8 mg, 57%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.79–7.66 (m, 2H), 7.55 (s, 2H), 7.53–7.47 (m, 4H), 7.32–7.17 (m, 4H), 2.37 (s, 6H); $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ 155.6, 142.0, 139.1, 136.1, 132.7, 129.6, 129.1, 128.9, 128.5, 127.7, 21.4; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 466.5; IR (KBr, ν/cm^{-1}): 685, 759, 974, 1091, 1161, 1246, 1472,

1512, 1642, 3462; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{22}H_{18}N_2NaSe_2$ 492.9698; Found 492.9688.

2,3-Bis((3-fluorophenyl)selanyl)quinoxaline (3g). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 40.6 mg, 85%, mp 118−120 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.90−7.71 (m, 2H), 7.64−7.53 (m, 2H), 7.52−7.43 (m, 4H), 7.42−7.30 (m, 2H), 7.19−7.04 (m, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 162.7 (d, J_{C-F} = 250.2 Hz), 154.5, 142.1, 131.0 (d, J_{C-F} = 2.9 Hz), 130.5 (d, J_{C-F} = 7.7 Hz), 129.5, 129.2 (d, J_{C-F} = 7.7 Hz), 128.5, 122.4 (d, J_{C-F} = 22.0 Hz), 116.1 (d, J_{C-F} = 21.1 Hz); ^{19}F (373 MHz, $CDCl_3$): δ −111.4; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 471.5; IR (KBr, *v*/cm^{-1}): 674, 755, 752, 856, 978, 1093, 1125, 1160, 1210, 1424, 1470; HRMS (EI) *m*/*z*: $[M]^+$ Calcd. for $C_{20}H_{12}F_2N_2Se_2$ 477.9303; Found 477.9293.

2,3-Bis((3-chlorophenyl)selanyl)quinoxaline (3h). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 33.1 mg, 65%, mp 157−159 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.88−7.70 (m, 4H), 7.65−7.51 (m, 4H), 7.45−7.28 (m, 4H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 154.4, 142.1, 135.2, 134.8, 133.6, 130.3, 129.5, 129.2, 129.1, 128.6; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 472.2; IR (KBr, *v*/cm^{-1}):755, 773, 976, 1094, 1457, 1506; HRMS (EI) *m*/*z*: $[M]^+$ Calcd. for $C_{20}H_{12}Cl_2N_2Se_2$ 509.8704; Found 509.8706.

2,3-Bis((3-(trifluoromethyl)phenyl)selanyl)quinoxaline (3i). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 44.5 mg, 77%, mp 100−102 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.09 (s, 2H), 7.89 (d, *J* = 7.8 Hz, 2H), 7.80−7.65 (m, 4H), 7.63−7.47 (m, 4H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 153.9, 142.1, 138.8, 130.5 (q, J_{C-F} = 3.8 Hz), 131.6 (q, J_{C-F} = 32.6 Hz), 129.6, 128.5, 128.4, 125.8 (q, J_{C-F} = 2.9 Hz,), 125.2, 122.4; ^{19}F (373 MHz, $CDCl_3$): δ −62.5; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 467.9; IR (KBr, *v*/cm^{-1}): 5503, 690, 756, 789, 975, 1066, 1081, 1093, 1110, 1171, 1276, 1304, 1324, 1423; HRMS (EI) *m*/*z*: $[M]^+$ Calcd. for $C_{22}H_{12}F_6N_2Se_2$ 577.9239; Found 577.9233.

2,3-Bis((3,4-difluorophenyl)selanyl)quinoxaline (3j). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 40.1 mg, 78%, mp 162−164 °C; ^{1}H NMR (400 MHz,

$CDCl_3$): δ 7.82−7.71 (m, 2H), 7.63−7.53 (m, 4H), 7.50−7.40 (m, 2H), 7.29−7.15 (m, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 154.1, 151.2 (dd, J_{C-F} = 24.0, 262.6 Hz), 150.4 (dd, J_{C-F} = 16.3, 255.9 Hz), 142.1, 132.4 (dd, J_{C-F} = 2.9, 3.8 Hz), 129.6, 128.5, 125.1 (d, J_{C-F} = 18.2 Hz), 122.5 (t, J_{C-F} = 4.8 Hz), 118.2 (d, J_{C-F} = 17.2 Hz); ^{19}F (373 MHz, $CDCl_3$): δ −135.8 (t, J_{F-F} = 11.6, 2F), −136.1 (t, J_{F-F} = 11.6, 2F); ^{77}Se NMR (75 MHz, $CDCl_3$): δ 469.0; IR (KBr, ν/cm^{-1}): 755, 772, 1095, 1273, 1498; HRMS (EI) *m*/*z*: $[M]^+$ Calcd. for $C_{20}H_{10}F_4N_2Se_2$ 513.9114; Found 513.9119.

2,3-Bis((2-chlorophenyl)selanyl)quinoxaline (3k). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow liquid, 10.7 mg, 21%; ^1H NMR (400 MHz, $CDCl_3$): δ 7.84−7.40 (m, 2H), 7.67−7.55 (m, 4H), 7.54−7.48 (m, 2H), 7.37−7.29 (m, 2H), 7.28−7.19 (m, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 154.4, 142.2, 138.0, 136.2, 130.1, 130.0, 129.6, 129.3, 128.7, 127.4; HRMS (EI) *m*/*z:* $[M]^+$ Calcd. for $C_{20}H_{12}Cl_2N_2Se_2$ 509.8704; Found 509.8711.

2,3-Bis(ethylselanyl)quinoxaline (3l). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow oil, 30.4 mg, 88%; ^1H NMR (400 MHz, $CDCl_3$): δ 7.94−7.82 (m, 2H), 7.63−7.53 (m, 2H), 3.36 (q, *J* = 7.9 Hz, 4H), 1.58 (t, *J* = 7.3 Hz, 6H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 155.7, 141.4, 128.3, 127.9, 21.6, 15.3; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 373.6; IR (NaCl, ν/cm^{-1}): 758, 961, 984, 1100, 1125, 1162, 123, 1371, 1511, 2863, 2921; HRMS (EI) *m*/*z*: $[M]^+$ Calcd. for $C_{12}H_{14}N_2Se_2$ 345.9490; Found 345.9494.

2,3-Bis(butylselanyl)quinoxaline (3m). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow oil, 39.8 mg, 99%; ^1H NMR (400 MHz, $CDCl_3$): δ 7.95−7.82 (m, 2H); 7.83−7.51 (m, 2H), 3.39 (t, *J* = 7.3 Hz, 4H), 1.84 (quintet, *J* = 7.3 Hz, 4H), 1.51 (septet, *J* = 7.3 Hz, 4H), 0.97 (t, *J* = 7.3 Hz, 6H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 155.7, 144.3, 128.1, 127.8, 30.0, 27.4, 23.2, 12.7; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 343.5; IR (KBr, ν/cm^{-1}): 587, 758, 983, 1101, 1162, 1253, 1512, 2870, 2928, 2956; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{16}H_{22}N_2NaSe_2$ 425.0011; Found 425.0021.

6,7-Dimethyl-2,3-bis(phenylselanyl)quinoxaline (3n). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 42.3 mg, 90%, 160-162 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.80−7.62 (m, 4H), 7.47 (s, 2H), 7.43−7.31 (m, 6H), 2.33 (s, 6H); $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ 153.9, 141.0, 139.5, 135.5, 129.3, 128.6, 128.5, 127.7, 20.1; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 463.2; IR (KBr, ν/cm^{-1}): 971, 1099, 1194, 1237, 1437, 1474, 1506, 2358; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{22}H_{18}N_2NaSe_2$ 492.9698; Found 492.9690.

5-Methyl-2,3-bis(phenylselanyl)quinoxaline (3o). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 35.1 mg, 77%, 63−65 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.83−7.66 (m, 4H), 7.47 (d, *J* = 7.3 Hz, 1H), 7.45−7.30 (m, 8H), 2.31 (s, 3H); $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ 155.0, 153.7, 142.0, 141.1, 136.7, 136.5, 135.4, 129.34, 129.30, 129.2, 128.9, 128.7, 128.6, 127.98, 127.96, 126.2, 16.5; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 476.4, 457.7; IR (KBr, ν/cm^{-1}): 687, 736, 765, 926, 1058, 1118, 1164, 1246, 1438, 1475, 1510; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{21}H_{16}N_2NaSe_2$ 478.9542; Found 478.9544.

Methyl 2,3-bis(phenylselanyl)quinoxaline-6-carboxylate (3p). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow solid, 41.5 mg, 83%, 120−122 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.38 (s, 1H), 8.09 (d, *J* = 8.7 Hz, 1H), 7.82−7.63 (m, 5H), 7.52−7.35 (m, 6H), 3.91 (s, 3H); $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ 166.4, 158.5, 156.7, 143.9, 141.1, 136.2, 136.1, 131.0, 130.9, 129.9, 129.5, 129.5, 129.3, 129.2, 128.6, 128.5, 127.0, 52.5; ^{77}Se NMR (75 MHz, $CDCl_3$): δ 476.4, 469.2; IR (KBr, ν/cm^{-1}): 688, 738, 978, 1103, 1134, 1253, 1294, 1438, 1475, 1509, 1721, 2365; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{22}H_{16}N_2NaO_2S_2$ 522.9440; Found 522.9442.

2-(Cyclohexylthio)quinoxaline (5a). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Pale yellow liquid, 43.4 mg, 89%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.52 (s, 1H), 7.97 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.90 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.70−7.63 (m, 1H), 7.62−7.55 (m, 1H), 4.19−4.01 (m, 1H), 2.25−1.13 (m, 10H); $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ 156.5,

145.2, 142.9, 139.8, 130.1, 129.3, 127.95, 129.94, 42.8, 33.0, 26.0, 25.8; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{14}H_{16}N_2NaS$ 267.0932; Found 267.0935.

2-(Benzylthio)quinoxaline (5b). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow liquid, 31.5 mg, 63%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.57 (s, 1H), 8.00 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.97 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.74−7.67 (m, 1H), 7.66−7.58 (m, 1H), 7.48 (d, *J* = 7.3 Hz, 2H), 7.34−7.25 (m, 3H), 4.56 (s, 2H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 155.7, 144.6, 142.7, 140.1, 137.4, 130.3, 129.35, 129.29, 128.7, 128.2, 127.9, 127.5, 33,8; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{15}H_{12}N_2NaS$ 275.0619; Found 275.0612.

2-((4-Chlorobenzyl)thio)quinoxaline (5c). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Yellow liquid, 35.5 mg, 62%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.57 (s, 1H), 8.01 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.95 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.42 (d, *J* = 8.6 Hz, 2H), 7.26 (d, *J* = 8.6 Hz, 2H), 4.54 (s, 2H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 155.2, 144.6, 142.6, 140.1, 136.1, 133.3, 130.6, 130.4, 129.4, 128.8, 128.3, 127.8, 33,0; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{15}H_{11}ClN_2NaS$ 309.0229; Found 309.0225.

2-(Decylthio)quinoxaline (5d). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Colorless liquid, 52.6 mg, 87%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.57 (s, 1H), 7.99 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.91 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.71−7.64 (m, 1H), 7.63−7.56 (m, 1H), 3.32 (t, *J* = 7.3 Hz, 2H), 1.90−0.80 (m, 19H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 156.6, 145.0, 142.9, 139.8, 130.1, 129.3, 127.9 (overlap), 32.0, 29.65, 29.60 (overlap), 29.4, 29.2, 29.1, 29.0, 22.8, 14.2; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{18}H_{26}N_2NaS$ 325.1714; Found 325.1717.

2-(sec-Butylthio)quinoxaline (5e). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Colorless liquid, 38.8 mg, 89%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.55 (s, 1H), 7.99 (dd, *J* = 1.6, 8.0 Hz, 1H), 7.90 (dd, *J* = 0.9, 8.2 Hz, 1H), 7.71−7.64 (m, 1H), 7.63−7.56 (m, 1H), 4.12 (quintet, *J* = 6.9 Hz, 1H), 1.91−1.70 (m, 2H), 1.48 (d, *J* = 6.9 Hz, 3H), 1.07 (t, *J* = 7.6 Hz, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 156.8, 145.2, 142.9, 139.7, 130.1, 129.3, 127.9 (overlap),

41.4, 29.5, 20.6, 11.5; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{12}H_{14}N_2NaS$ 241.0775; Found 241.0771.

2-(tert-Butylthio)quinoxaline (5f). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Colorless liquid, 31.0 mg, 71%; ^1H NMR (400 MHz, $CDCl_3$): δ 8.54 (s, 1H), 7.99 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.95 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.72−7.65 (m, 1H), 7.65−7.59 (m, 1H), 1.69 (s, 9H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 157.3, 146.1, 142.6, 139.6, 130.0, 129.3, 128.2 (overlap), 49.1, 30.4; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{12}H_{14}N_2NaS$ 241.0775; Found 241.0778.

2-(Phenylthio)quinoxaline (5g).[25] The product was purified by preparative TLC (hexane/AcOEt = 9/1). Colorless liquid, 32.4 mg, 68%; ^1H NMR (400 MHz, $CDCl_3$): δ 8.43 (s, 1H), 7.98 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.89 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.72−7.60 (m, 4H), 7.49−7.44 (m, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 157.3, 143.5, 142.2, 139.9, 135.1, 130.5, 129.9, 129.7, 129.2, 129.0, 128.8, 128.4.

2-((Perfluorophenyl)thio)quinoxaline (5h). The product was purified by preparative TLC (hexane/AcOEt = 9/1). White solid, 41.3 mg, 63%, mp 70-72 °C; ^1H NMR (400 MHz, $CDCl_3$): δ 8.73 (s, 1H), 8.12−8.01 (m, 1H), 7.82−7.64 (m, 3H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 151.5, 142.7, 142.6, 140.6, 130.8, 129.4, 129.3, 128.4; ^{19}F (373 MHz, $CDCl_3$): δ −129.3-−129.9 (m, 2F), −148.8-−149.2 (m, 1F), −159.7-−160.5 (m, 2F); HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{14}H_5F_5N_2NaS$ 350.9991; Found 350.9994.

2-((4-Fluorophenyl)thio)quinoxaline (5i). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Colorless liquid, 35.3 mg, 69%; ^1H NMR (400 MHz, $CDCl_3$): δ 8.45 (s, 1H), 7.99 (dd, *J* = 1.6, 8.0 Hz, 1H), 7.85 (dd, *J* = 1.8, 7.8 Hz, 1H), 7.74−7.57 (m, 4H), 7.22-7.13 (m, 2H); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 163.8 (d, J_{C-F} = 250.2 Hz), 156.8, 143.2, 142.3, 140.0, 137,4 (d, J_{C-F} = 8.6 Hz), 130.6, 129.3, 128.9, 128.3, 123.9 (d, J_{C-F} = 2.9 Hz), 117.1 (d, J_{C-F} = 22.0 Hz); ^{19}F (373 MHz, $CDCl_3$): δ −110.3; HRMS (ESI) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{14}H_9FN_2NaS$ 279.0368; Found 279.0365.

2-((4-Methoxyphenyl)thio)quinoxaline (5j). The product was purified by preparative TLC (hexane/AcOEt = 9/1). White solid, 34.3 mg, 64%, mp 53−55 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.38 (s, 1H), 7.97 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.89 (dd, *J* = 1.4, 8.2 Hz, 1H), 7.72−7.55 (m, 4H), 7.04−6.97 (m, 2H), 3.87 (s, 3H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 161.1, 158.2, 143.0, 142.2, 139.8, 137.2, 130.5, 129.2, 128.6, 128.3, 119.0, 115.5, 55.5; HRMS (ESI/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{15}H_{12}N_2NaOS$ 291.0568; Found 291.0550.

2-(Naphthalen-1-ylthio)quinoxaline (5k). The product was purified by preparative TLC (hexane/AcOEt = 9/1). Colorless liquid, 40.9 mg, 71%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.37 (d, *J* = 8.2 Hz, 1H), 8.15 (s, 1H), 8.02 (t, *J* = 6.6 Hz, 2H), 7.93 (d, *J* = 8.2 Hz, 2H), 7.87 (dd, *J* = 1.1, 8.4 Hz, 1H), 7.72−7.46 (m, 5H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 157.6, 142.9, 142.2, 139.8, 135.9, 134.7, 134.6, 131.5, 130.5, 129.2, 128.9, 128.7, 128.3, 127.8, 126.9, 126.1, 125.8, 125.7; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{18}H_{12}N_2NaS$ 311.0619; Found 311.0616.

2-(Cyclohexylthio)-6,7-dimethylquinoxaline (5l). The product was purified by preparative TLC (hexane/AcOEt = 9/1). White solid, 40.9 mg, 81%, mp 55−57 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.45 (s, 1H), 7.72 (s, 1H), 7.67 (s, 1H), 4.15-4.00 (m, 1H), 2.45 (s, 3H), 2.44 (s, 3H), 2.25−1.25 (m, 10H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 155.1, 144.3, 141.8, 140.4, 138.7, 138.1, 128.4, 127.3, 42.8, 33.1, 26.1, 25.9, 20.3, 20.2; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{16}H_{20}N_2NaS$ 295.1245; Found 295.1246.

2-(Cyclohexylthio)-8-methylquinoxaline (5m). The product was purified by preparative TLC (hexane/AcOEt = 9/1). White solid, 22.7 mg, 44%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.54 (s, 1H), 7.84 (dd, *J* = 1.6, 8.0 Hz, 1H), 7.58−7.45 (m, 2H), 4.20−4.00 (m, 1H), 2.74 (s, 3H), 2.40−1.30 (m, 10H); ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 155.1, 144.7, 141.8, 139.7, 136.1, 130.2, 127.6, 127.0, 43.4, 32.8, 26.3, 25.9, 16.9; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{15}H_{18}N_2NaS$ 281.1088; Found 281.1086.

2-(Cyclohexylthio)-5-methylquinoxaline (5m'). The product was purified by preparative TLC (hexane/AcOEt = 9/1). White solid, 15.5 mg, 30%; ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.54 (s, 1H),

7.75 (d, *J* = 8.2 Hz, 1H), 7.56 (t, *J* = 7.8 Hz, 1H), 7.43 (d, *J* = 6.9 Hz, 1H), 4.20−4.00 (m, 1H), 2.74 (s, 3H), 2.30−1.11 (m, 10H); $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ 155.9, 143.9, 143.0, 138.9, 137.5, 129.8, 128.3, 125.9, 42.8, 33.0, 26.1, 25.9, 17.4; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{15}H_{18}N_2NaS$ 281.1088; Found 281.1086.

Methyl 3-(cyclohexylthio)quinoxaline-6-carboxylate and ***methyl 2-(cyclohexylthio)quinoxaline-6-carboxylate (5n + 5n')***. The product was purified by preparative TLC (hexane/AcOEt = 9/1). Pale yellow oil, 39.3 mg, 65%; obtained as a mixture of **5n**/**5n'** (48/52); the two isomers were difficult to separate.

Isomer **5n**. Pale yellow oil, 31% ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.61 (d, *J* = 1.8 Hz, 1H), 8.57 (s, 1H), 8.19 (dd, *J* = 1.8, 8.4 Hz, 1H), 8.02 (d, *J* = 8.7 Hz, 1H), 4.18−4.04 (m, 1H), 4.01 (s, 3H), 2.30−1.12 (m, 10H); $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ 166.5, 157.9, 147.0, 145.0, 142.2, 131.3, 130.4, 129.2, 127.5, 52.7, 43.06, 29.8, 26.1, 25.83; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{16}H_{18}N_2NaO_2S$ 325.0987; Found 325.0985.

Isomer **5n'**. Pale yellow oil, 34% ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.69 (d, *J* = 1.8 Hz, 1H), 8.57 (s, 1H), 8.28 (dd, *J* = 1.8, 8.4 Hz, 1H), 7.93 (d, *J* = 8.7 Hz, 1H), 4.18−4.04 (m, 1H), 3.99 (s, 3H), 2.30−1.12 (m, 10H); $^{13}C\{^{1}H\}$ NMR (100 MHz, $CDCl_3$): δ 166.5, 159.2, 146.2, 141.9, 138.9, 131.9, 129.9, 129.5, 128.1, 52.6, 43.00, 32.9, 26.0, 25.81; HRMS (ESI+/TOF) *m*/*z*: $[M+Na]^+$ Calcd. for $C_{16}H_{18}N_2NaO_2S$ 325.0987; Found 325.0985.

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19) In entry 5 in Table 4, the thiolative cyclization of *o*-diisocyanobenzene (**1a**) occurred in the dark upon heating at 80 ^{o}C to afford **5a** in 63% yield. Therefore, an ionic pathway might contribute to the thiolative cyclization reaction.

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Chapter 5

Conclusion

In this research work, novel transformations of isocyanides to synthesize nitrogen-containing key organic molecules has been developed.

Chapter 2 described a novel, divergent transformations of isocyanides to yield imines and *α*-diimines via a palladium-catalyzed diarylation with tetraaryllead species. It is noteworthy that, the diarylation reaction proceeded without the requirement of any additives or bases. More specifically, this catalytic diarylation reaction afforded imines from the corresponding aliphatic isocyanides, while *α*-diimines were formed primarily in the case of electron-rich aromatic isocyanides. Because *α*-diimines are key precursors of *N*-heterocyclic carbenes (NHCs), it is expected that the present method will be used for the synthesis of NHCs.

Chapter 3 described a highly selective diarylation of isocyanides with triarylbismuthines using palladium and rhodium catalysts. The palladium catalysts such as $Pd(OAc)_2$ preferentially afforded *α*-diimines, whereas the rhodium catalysts such as $RhCl(PPh_3)_3$ selectively gave rise to imines. The arylation reaction to give *α*-diimines could successfully be applied to the preparation of quinoxaline derivatives with simple and effective operations.

Chapter 4 described a mild and efficient photoinduced cyclization reactions of *o*-diisocyanoarenes with organic diselenides and thiols that afford chalcogenated quinoxalines. In the case of organic diselenides, cyclization is believed to involve a radical process, while both a radical pathway and/or an ionic pathway can be considered in the case of thiols. The developed protocol can be used to establish a library of chalcogen-substituted quinoxalines which are known to be potential oxidants with promising bioactivities.

In summary, a series of transformations of isocyanides under various reaction conditions

have been developed. The author believes that these unprecedented research works will make a great contribution for the development of organic synthetic chemistry.

List of Publications

1. Palladium-Catalyzed Diarylation of Isocyanides with Tetraarylleads for the Selective Synthesis of Imines and α-Diimines

   Tran, C. C.; Kawaguchi, S-i.; Kobiki, Y.; Matsubara, H.; Tran, D. P.; Kodama, S.; Nomoto, A.; Ogawa, A.

   J. Org. Chem. **2019**, *84*(*18*), 11741-11751.

   (Chapter 2)

2. Imine/α-Diimine Selectivity in the Transition-Metal-Catalyzed Diarylation of Isocyanides with Triarylbismuthines

   Tran, C. C.; Kobiki, Y.; Kawaguchi, S-i.; Kodama, S.; Matsubara, H.; Nomoto, A.; Ogawa, A.

   Tetrahedron **2020**, submitted.

   (Chapter 3)

3. Photoinduced Cyclizations of *o*-Diisocyanoarenes with Organic Diselenides and Thiols that Afford Chalcogenated Quinoxalines

   Tran, C. C.; Kawaguchi, S-i.; Sato, F.; Nomoto, A.; Ogawa, A.

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   (Chapter 4)

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