RSC Advances

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/advances

Journal Name

ARTICLE

Ruthenium/Base-Catalyzed Ortho-Selective C-H Arylation of Acylarenes with Halogenated Arylboronates

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

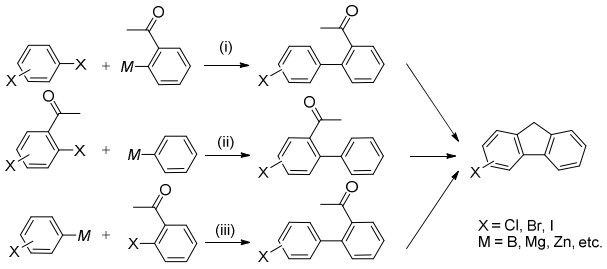
www.rsc.org/

Tetsuya Yamamoto[a,b] and Tetsu Yamakawa[a]*

Ruthenium-catalyzed ortho-selective C-H arylation of acylarenes with halogenated arylboronates was promoted by the catalytic amount of bases and provided desired halogenated biaryls in excellent yields under 0.2–1 mol% ruthenium catalyst loading.

Introduction

As halogenated 2-acyl-1,1'-biaryls are readily transformed to halogenated fluorene derivatives, they are key intermediates of organic electronic materials such as liquid crystals, organic light-emitting diodes, organic semiconductors, dye sensitized solar cells and conductive polymers.[1] Halogenated 2-acyl-1,1'-biaryls are simply synthesized by direct halogenation of corresponding 2-acyl-1,1'-biaryls.[2] However, this method has two disadvantages. The one is the limitation of halogenated position and the other is the formation of oligo-halogenated products as by-products. Transition metal-catalyzed cross-coupling such as Suzuki-Miyaura coupling has attracted as a candidate for the practical syntheses of halogenated 2-acyl-1,1'-biaryls.[3,4] There are three kinds of the possible combination of substrates in this coupling reaction as depicted in Scheme 1: dihaloarenes and (2-acyl)arylmetallic reagents (i), 2-acyl(halo)haloarenes and arylmetallic reagents (ii), and (haloaryl)metallic reagents and (2-acyl)haloarenes (iii). In (i) and (ii) where dihaloarenes or 2-acyl(halo)haloarenes are used, the over-reaction inevitably occurs at the second halo group by the use of the general-purpose coupling catalysts. Indeed, most of the reported examples afforded from low to moderate yields of the desired product.[4a—c] The high yield and selectivity even using 2-acyl-4-bromoiodobenzene was achieved by the Pd-catalyzed Suzuki-Miyaura coupling for (2-acyl-4-bromophenyl)arene synthesis.[4d] However, the partner is limited to anthrathen-9-ylboronic acid, suggesting that the bulky anthrathen-9-yl group retarded over-reaction. The use of bromochloro or iodochloroarenes is promising to overcome this advantage, because C-Cl bond cannot be activated by the general-purpose coupling catalysts.[3] Nevertheless, the product of chloro-substituted biaryls are ones of PCBs derivatives and their syntheses and uses are restricted due to toxicity and carcinogenesis in many countries.[5] As well as C-Cl bond, C-S bond also cannot be activated by the general-purpose coupling catalysts. Shi and co-workers reported the Rh-catalyzed cross-coupling of halogenated arylboroxines and 2-acyl(alkylthio)arenes to halogenated 2-acyl-1,1'-biaryls through C-S bond activation.[6] However, this reaction afforded low yield of the desired product though it requires the excess amount of arylboroxine.



Scheme 1. Syntheses of halogenated fluorene derivatives via transition metal-catalyzed cross-coupling

Thus far, the cross-coupling including C-H bond activation has been also investigated as one of the candidates for halogenated 2-acyl-1,1'-biaryls syntheses. Glorius and co-workers reported the Rh-catalyzed coupling of *N*,*N*-diisopropylbenzamides or 2,2-dimethyl-1-phenyl-1-propanone and bromobenzenes to brominated 2-acyl-1,1'-biaryls; diisopropylamide and pivaloyl groups are readily converted to an acyl group by the hydrolysis. In these reactions, both of selective C-H bond activation of *N*,*N*-diisopropylbenzamides or 2,2-dimethyl-1-phenyl-1-propanones at the ortho position of diisopropylamide or pivaloyl group and non-selective C-H activation of bromobenzenes are included, resulting in the mixture of 3'- and 4'-bromo-1,1'-biphenyls.[7] Nakamura and co-workers reported Fe-catalyzed arylation of 3-bromo(alkylimino)benzenes with aryl Grignard reagents. In this

[a] *Catalysis Group, Sagami Chemical Research Institute, Hayakawa 2743-1, Ayase, Kanagawa 252-1193, Japan. E-mail: t_yamakawa@sagami.or.jp*
[b] Present address: *Department of green and sustainable chemistry, Tokyo Denki University, Senju-Asahi-cho 5, Adachi-ku, Tokyo 120-8551, Japan. E-mail: t-yamamoto@mail.dendai.ac.jp*
† Footnotes Electronic Supplementary Information (ESI) available: Copies of ^{1}H NMR, ^{13}C NMR and ^{19}F NMR spectra. See DOI: 10.1039/x0xx00000x

reaction, only the selective C-H activation occurred at the ortho position of the alkylimino group, providing inevitably 4-bromo-2-alkylimino-1,1'-biphenyl as a sole product.[8] Although this reaction is promising for 2-acyl-1,1'-biaryls syntheses through the acid hydrolysis of 2-alkylimino-1,1'-biphenyl, an excess amount of aryl Grignard reagent is necessary.

From the beginning of the 21th century, Ru-catalyzed ortho-selective arylation of arylketones or arylketimines have been developed as one of the most useful synthetic tools for fine chemicals synthesis.[9–11] In particular, Kakiuchi C-H arylation has a great potential for bromo- or iodo-substituted 2-acyl-1,1'-biaryls synthesis. This arylation does not include the oxidative addition of aryl halides to ruthenium complex in the catalytic cycle.[11] Therefore, the succeeding coupling with aryl boronates or acylketones which would afford multi-arylated products does not occur.

Herein, we examined the Ru-catalyzed ortho-selective C-H arylation of acylarenes using haloarylboronates on the standpoint of the practical use and founds that the addition of catalytic amount of a base and the use of excess amount of acylarenes are the important key to obtain the satisfactory yields of the desired product.

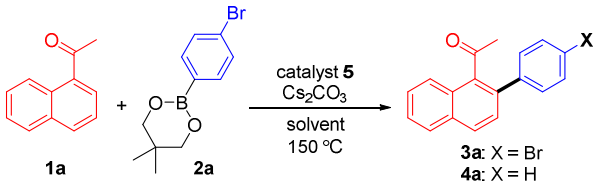
Results and discussion

At first, we examined ruthenium-catalyzed cross-coupling of 1-(naphthalen-1-yl)ethanone **1a** and 2-(4-bromophenyl)-5,5-dimethyl-1,3,2-dioxaborinane **2a** (Table 1). In the previous reports of Kakiuchi and co-workers,[11] the $RuH_2(CO)(PPh_3)_3$-catalyzed cross-coupling afforded the corresponding product **3a** in low yields with concomitant formation of debrominated product **4a** (entries 1 and 2). The yield of **3a** and the selectivity of **3a**/**4a** were improved to 29% and 29/1, respectively, by increasing the used amount of **1a** under solvent-free condition (entry 3). Generally, the use of an excess amount of base has activated arylboron compounds and promoted a transmetalation of arylboron compounds to transition metals.[12] Indeed, the cross-coupling also proceeded smoothly in the presence of a stoichiometric amount of Cs_2CO_3 in this case despite the slight increase in the yield of debrominated product **4a** to 6% (entry 4). Intriguingly, a catalytic amount of Cs_2CO_3 further promoted the reaction and the yield of debrominated product was restrained to 2% (entries 5 and 6). Additionally, the **5a**/Cs_2CO_3 catalyzed reaction proceeded smoothly under moderate temperature, 100 °C, in an excellent yield, though the longer reaction time was required (entry 7). The combination of the other ruthenium-triphenylphosphine complexes **5b–d** and a catalytic amount of Cs_2CO_3 similarly showed the satisfactory yield and excellent selectivity of **3a** (entries 8–10).

Next, we examined the dependence of the yield of **3a** on the used amount of **1a** in 0.2 mol% **5b**/Cs_2CO_3 catalyzed cross-coupling of **1a** and **2a** (**Fig. 1**). The linear correlation between the yield of **3a** and the used amount of **1a** was observed in the region of 2–4 equivalent of **1a**. The yield was retained by the use of **1a** more than 4 equivalent.

Table 2 lists the survey of a base in the cross-coupling of **1a** and **2a** using 0.2mol% **5b**. Of the bases tested, 20 mol% of Rb_2CO_3 exhibited the highest turnover number of 435 (entry 2). Virtually the same selectivity of **3a**, 95 – 97% was obtained with any other bases.

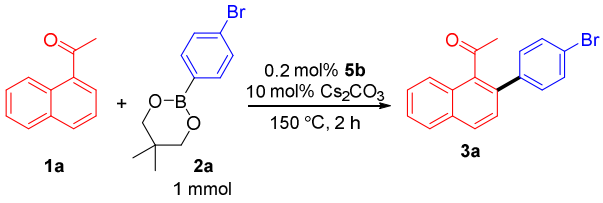
Table 1 Ru-catalyzed cross-coupling of 1-(naphthalen-1-yl)ethanone **1a** and 2-(4-bromophenyl)-5,5-dimethyl-1,3,2-dioxaborinane **2a**[a]



5a: $RuH_2(CO)(PPh_3)_3$
5b: $RuHCl(CO)(PPh_3)_3$
5c: $RuCl_2(PPh_3)_3$
5d: $RuH_2(PPh_3)_4$

entry	Catalyst (mol%)	**1a** (eq.)	Cs_2CO_3 (mol%)	Reaction time (h)	Yield (%) **3a**[e]/**4a**[f]
1[b]	**5a** (5)	2.0	0	2	5/1
2[c]	**5a** (2)	1.0	0	2	8/2
3	**5a** (2)	6.6	0	2	29/1
4	**5a** (2)	6.6	100	1	75/6
5	**5a** (2)	6.6	10	1	80/2
6	**5a** (1)	6.6	10	1	81/2
7[d]	**5a** (1)	6.6	10	12	83/3
8	**5b** (1)	6.6	10	1	81/3
9	**5c** (1)	6.6	10	12	79/4
10	**5f** (1)	6.6	10	12	77/2

[a] Conditions: 1 mmol of **2a** was used. [b] Toluene solvent 1 mL. [c] Pinacolone solvent 1 mL. [d] Reaction temperature was 100 °C. [e] Isolated yield. [f] GC yield.



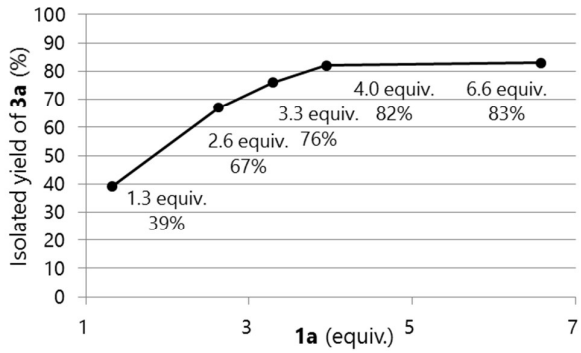
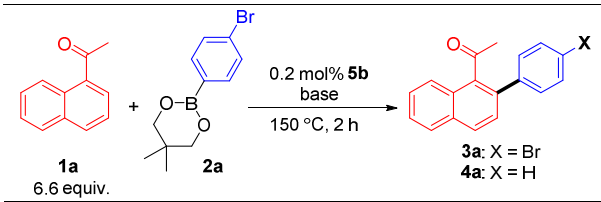


Fig. 1 The dependence of the yield of **3a** on the used amount of **1a**

Table 2 Survey of base catalyst in Ru complex **5b**-catalyzed cross-coupling[a]



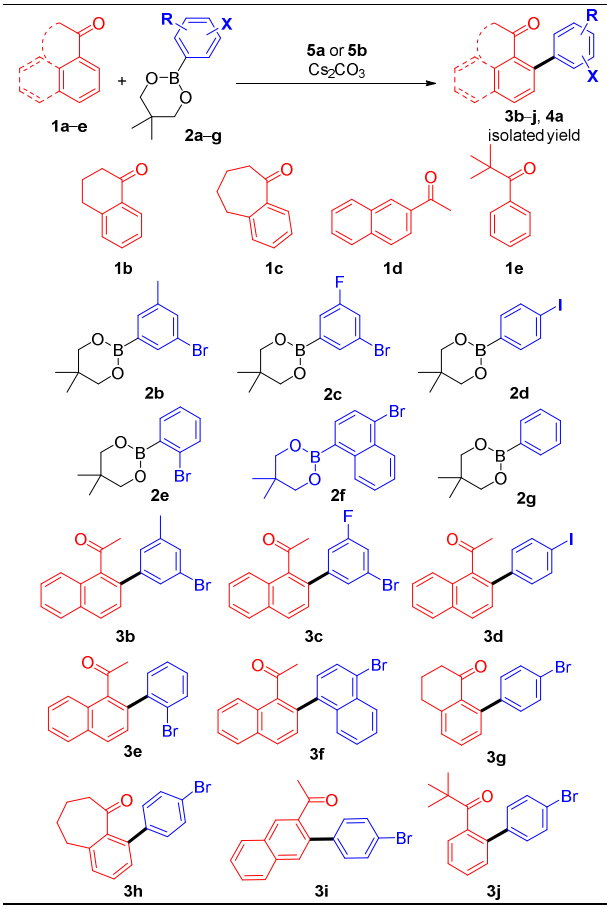
entry	base (mol%)	Yield (%) **3a**[b]/**4a**[c]	TON
1	Cs_2CO_3 (10)	83/3	415
2	Rb_2CO_3 (10)	77/2	385
3	Rb_2CO_3 (20)	87/4	435
4	CsF (10)	82/4	410
5	*tert*-BuOK (20)	83/4	415
6	K_3PO_4 (20)	78/3	390
7	KOH (10)	75/2	375

[a] Conditions: 1 mmol of **2a** was used. [b] Isolated yield. [c] GC yield.

On the basis of these results, we synthesized various bromo- or iodo-substituted 2-acyl-1,1'-biaryls using the ruthenium-PPh_3 complex **5a** or **5b**/Cs_2CO_3 catalyzed reaction (Table 3). 3-Bromo-substituted phenylboronates **2b** and **2c** reacted smoothly with 1-(naphthalen-1-yl)ethanone **1a** as with 4-bromophenyl-boronate **2a** to provide corresponding products **3b** and **3c** in good yields (entries 1 and 2). The reaction of **1a** and 2-(4-iodophenyl)-5,5-dimethyl-1,3,2-dioxaborinane **2d** required lower reaction temperature and longer reaction time than 4-bromophenylboronate **2a** for a good yield (entry 3). This catalysis system was not applied to the ortho-substituted phenylboronate such as 2-(2-bromophenyl)-5,5-dimethyl-1,3,2-dioxaborinane **2e** and 2-(4-bromonaphtha-len-1-yl)-5,5-dimethyl-1,3,2-dioxaborinane **2f** (entries 4 and 5). With regard to the cyclic alkylarylketones, although **2a** and α-tetralone **1b** afforded **3g** in 42% yield, 1-benzosuberone **1c** yielded product **3h** in a good yield (entries 6 and 7). On the other hand, acyclic acylbenzenes such as 1-(naphthalen-2-yl)ethan-1-one **1d** and 2,2-dimethyl-1-phenylpropan-1-one **1e** that have no substituents on ortho-positions were lower reactivity than **1a** under this reaction condition (entries 8 and 9). In addition, this catalyst gave 81% yield in the coupling of **1a** and 2-phenyl-5,5-dimethyl-1,3,2-dioxaborinane **2g** that has no substituent under 0.2 mol% ruthenium catalyst **5b** loading (entry 10). In the absence of Cs_2CO_3, the reaction afforded the coupling product **4a** in remarkably low 4% yield (entry 11).

Generally, arylboronic acids are suited for industrial uses, because they are more readily available than arylboronates. However, the use of arylboronic acid afforded little desired product in the present coupling. Therefore, the one-pot synthesis of **3a** from 4-bromophenylboronic acid and **1a** in the presence of 2,2-dimethylpropane-1,3-diol was examined in a Dean-Stark apparatus. $RuHCl(CO)(PPh_3)_3/Cs_2CO_3$ catalyst provided **3a** in 78% yield in a gram-scale (**Scheme 2**).

Table 3 Synthesis of 2-acyl-1,1'-biaryl derivatives [a]



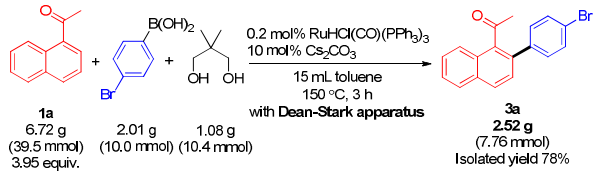
entry	Catalyst (mol%)	**1** (eq.)	**2**	Cs_2CO_3 (mol%)	Reaction temp./time (°C/h)	**3** Yield (%)[b]
1	**5b** (0.5)	**1a** (6.6)	**2b**	5	150/3	**3b** 80
2	**5b** (0.5)	**1a** (6.6)	**2c**	10	150/3	**3c** 75
3	**5b** (0.5)	**1a** (6.6)	**2d**	30	135/12	**3d** 70
4	**5a** (2)	**1a** (6.6)	**2e**	20	150/3	**3e** trace[c]
5	**5a** (2)	**1a** (6.6)	**2f**	20	150/3	**3f** trace[c]
6	**5a** (1)	**1b** (7.5)	**2a**	20	150/2	**3g** 42
7	**5a** (1)	**1c** (6.7)	**2a**	20	150/3	**3h** 74
8	**5b**(2)	**1d** (6.6)	**2a**	10	150/3	**3i** 22
9	**5a** (2)	**1e** (6.0)	**2a**	20	150/3	**3j** trace[c]
10	**5b** (0.2)	**1a** (6.6)	**2g**	10	150/3	**4a** 81
11	**5b** (0.2)	**1a** (6.6)	**2g**	0	150/3	**4a** 4

[a] Conditions: 1 mmol of **2** was used. [b] Isolated yield. [c] Detected by GC.

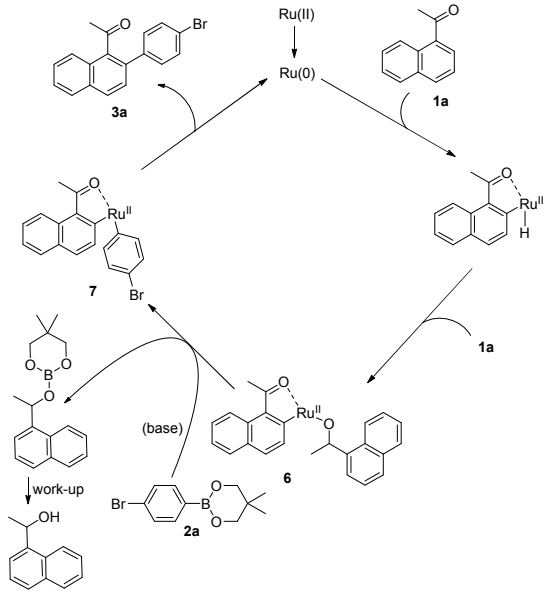
A possible catalytic cycle of the C-H arylation with 4-bromophenylboronate **2a** and 1-acylnaphthalene **1a** is illustrated in **Scheme 3**. The mechanism depicted has already proposed by Kakiuchi and co-workers.[11e,f] Thus, catalytically active Ru(0) complex oxidatively inserts in C-H bond at the ortho position of the acyl group. The formed Ru(II) species and **1a** provides 1-naphthalenemethoxy Ru(II) complex **6**, followed by the transmetalation with **2a** to **7**. Although the byproduct from **6** and **2a** to **7**, 5,5-dimethyl-2-[1-(1-naphtyl)ethoxy]-1,3,2-dioxaborinane, could not be isolated presumably because of its unstability, 2-(1-naphtyl)ethanol that should be originated from this trialkoxyborane was detected by GC. Reductive elimination of the desired product **3a** reproduces the catalytically active Ru(0) complex. In this mechanism, a base is not necessary. On the other hand, our C-H arylation with acylarenes and bromo- or iodo-substituted aryl boronates required a base (Table 1). Because an oxidative addition of bromo- or iodo-substituted aryl boronates to Ru(0) complex should occur as a side reaction, catalytically active Ru(0) complex would convert into catalytically inactive bromo- or iodo Ru(II) complexes. As depicted in **Scheme 4**, Anderson and co-workers previously reported that Ru(0) complex **8** was generated from **5a** and readily reacted with 4-bromo- or 4-iodotoluene to (tolyl)ruthenium(II) complex **9** via oxidative addition in moderate yields. Furthermore, thus obtained complex **9** and α-tetralone quickly provided ruthenacycle **10** and toluene selectively via transmetalation through C-H bond cleavage in 99% yield.[13]

In our case, similar reactions as **Scheme 4** will occur. As depicted in **Scheme 5**, the reaction of Ru(0) complex and boronate **2a** to **11** and further transmetalation of **11** and **1a** to ruthenacycle **12** will proceeds as a side reaction. Because the transmetalation of ruthenium halide complexes such as **12** between aryl boronate hardly occurs without a base, this side reaction would cause the reduction of the catalytically active Ru(0) complex, resulting in low yield. Since the transmetalation of arylboronic acids to Ru(II) complexes is promoted by a base as reported,[12] the transmetalation between ruthenacycles **12** and bromophenyl boronate **2a** to aryl substituted ruthenacycle **7** would be also accelerated by a base. Thereby, catalytically active Ru(0) complex for Kakiuchi C-H arylation is recovered from **12** in the presence of a base. Likewise, the transmetalation of **6** with **2a** in **Scheme 3** would be accelerated by a base. Thus, the yield of **3a** does not exceed 50% theoretically, if **3a** is formed only with the mechanism in **Scheme 5**. Therefore, the enhancement of the yield from 4% (entry 11) to 81% (entry 10) in **Table 3** cannot be explained only by a regeneration of **7** from **12** with a base in **Scheme 5**.

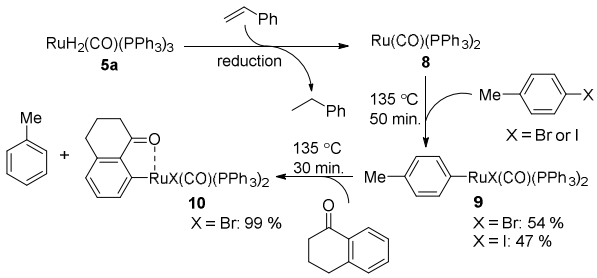
Moreover, the base could have another contribution in this arylation. As Pignolet and co-workers reported an orthometalation between acetophenone and halogen coordinated Ru(II) complex that has a basic ligand such as acetate ion,[14] the orthometalation of acylarenes to halogen coordinated Ru(II) complex such as **5b** or **5c** would be similarly promoted by a base. Therefore, this orthometalation would generate a ruthenacycle which has the similar structure as ruthenacycle **12** and trigger this catalytic C-H arylation.



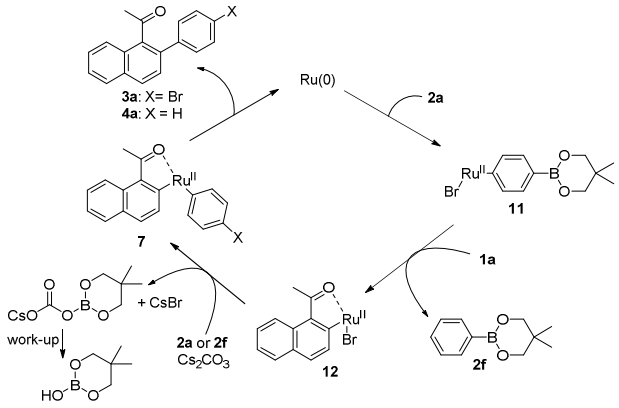
Scheme 2. One-pot synthesis of **3a** from 4-bromophenylboronic acid



Scheme 3. Catalytic cycle of Ru-catalyzed arylation with **1a** and **2a**



Scheme 4. Stoichiometric reaction of Ru(0) complex with 4-bromo- or 4-iodotoluene and α-tetralone[13]



Scheme 5. Assumed side reaction of Ru(0) with **2a** and recovery process of Ru(0)

Conclusions

In conclusion, we developed the ruthenium/base catalyzed arylation of 2-acylarenes with halogenated arylboron compounds to give corresponding halogenated 2-acyl-1,1'-biaryls. The catalytic amount of a base drastically improved the yield and selectivity of the desired product. For example, the turnover number reached more than 435 from 15 in 1-(2-(4-bromophenyl)naphthalen-1-yl)ethanone **3a** synthesis by the addition of various bases. The catalytic amount of bases would serve two effects; one is a promotion of the orthometalation of acylarenes by halogen coordinated Ru(II) complexes such as **5b** or **5c**, the other is an accelerattion the transmetalation between ruthenacycles and arylboronate.

Experimental section

General Information

All reactions were carried out under an argon atmosphere. ^{1}H, ^{13}C, and ^{19}F NMR spectra were recorded on a Brucker AVANCE III 400 spectrometer (400.13 MHz) at ambient temperature. The chemical shifts of ^{1}H were reported in delta (δ) units, parts per million (ppm) downfield from tetramethylsilane (0.0 ppm). Chemical shifts of ^{13}C were reported in delta (δ) units, ppm relative to the center of the triplet at 77.0 ppm for $CDCl_3$. The chemical shifts of ^{19}F were referenced to the resonance frequency (0.0 ppm) and ^{19}F 376.27 MHz with a negative sign indicating an upfield shift. High-resolution mass spectra were taken with a JEOL MStaion JMS-700. Low-resolution mass spectra was measured on a Shimadzu GCMS-QP2010. IR spectra were recorded on a HORIBA FT-720. Melting points were recorded on a METTLER TOLEDO MP-70. Commercially available inorganic compounds including ruthenium complexes were used without purification. Freshly-distilled ketones were used in these reactions. Arylboroates were prepared from commercially available arylboronic acids with 2,2-dimethyl-1,3-propanediol according to the reported procedure.[15]

Typical procedure for Ru-catalyzed Kakiuchi arylation using halgene-substituted arylboronates: Ruthenium complex **5** (0.02–0.05 mmol), an arylboronate **2** (1.00 mmol) and an inorganic base (0.05–1.00 mmol) were charged in a 10 mL test tube sealed with a rubber septum. The test tube was evacuated and backfilled with argon. This sequence was repeated five times. Then acylarenes **1** (0.2–1.0 mL) was added via the rubber septum with syringe. In an argon flow, the rubber septum was replaced with a Teflon liner screw cap. The test tube was placed into an oil bath preheated at 100–150 °C. After the reaction mixture was stirred for 2–12 h and cooled to room temperature. The obtained crude was purified by passing it through a silica gel column with a hexane / ethyl acetate eluent to give the title compound.

1-(2-(4-bromophenyl)naphthalen-1-yl)ethan-1-one [**3a**: Table 2, entry 1]

Using 2-(4-bromophenyl)-5,5-dimethyl-1,3,2-dioxaborinane **2a** (269 mg, 1.00 mmol), cesium carbonate (32.6 mg, 100 µmol), 1-(naphthalen-1-yl)ethan-1-one **1a** (1.12 g, 6.6 mmol) and **5b** (1.9 mg, 2.0 µmol), the product was obtained in 83% yield (269 mg, 0.827 mmol) as a white solid after column chromatography (hexane/ethyl acetate: 10/0 to 9/1). mp 103─104 °C; IR (neat, cm^{-1}) 1687, 1591, 1489, 1350, 1209, 1130, 1080, 1011, 864, 839, 818, 791, 756; ^{1}H NMR (400 MHz, $CDCl_3$, ppm): δ 7.83–7.81 (m, 3H), 7.61–7.52 (m, 4H), 7.46 (d, J = 8.4 Hz, 1H), 7.36–7.33 (m, 2H), 2.14 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, ppm) δ 207.3, 139.2, 138.5, 134.5, 132.7, 131.9, 131.0, 129.6, 128.8, 128.3, 127.6, 127.0, 126.6, 124.8, 122.5, 32.9; HRMS (FAB) m/z: [M]+ calcd. for $C_{18}H_{13}BrO$: 324.0150. Found: 324.0157.

1-(2-(3-bromo-5-methylphenyl)naphthalen-1-yl)ethan-1-one [**3b**: Table 3, entry 1]

Using 2-(3-bromo-5-methylphenyl)-5,5-dimethyl-1,3,2-dioxaborinane **2b** (283 mg, 1.00 mmol), cesium carbonate (12.3 mg, 50.0 µmol), 1-(naphthalen-1-yl)ethan-1-one **1a** (1.12 g, 6.6 mmol) and **5b** (4.8 mg, 10 µmol), the product was obtained in 80% yield (272 mg, 0.802 mmol) as a white solid after column chromatography (hexane/ethyl acetate: 10/0 to 9/1). mp 105─106 °C; IR (neat, cm^{-1}) 1689, 1597, 1568, 1556, 1350, 1217, 1130, 866, 843, 822, 744, 706, 677; ^{1}H NMR (400 MHz, $CDCl_3$, ppm): δ 7.86–7.83 (m, 3H), 7.58–7.52 (m, 2H) , 7.46–7.43 (m, 2H), 7.39 (s, 1H), 7.18 (d, J = 0.6 Hz, 1H), 2.38 (s, 3H), 2.15 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, ppm) δ 206.9, 142.2, 140.5, 138.4, 134.5, 132.7, 131.7, 129.5, 129.2, 129.0, 128.8, 128.3, 127.6, 127.1, 126.6, 124.9, 122.6, 32.8, 21.2; HRMS (FAB) m/z: [M]+ calcd. for $C_{19}H_{15}BrO$: 338.0306. Found: 338.0295.

1-(2-(3-bromo-5-fluorophenyl)naphthalen-1-yl)ethan-1-one [**3c**: Table 3, entry 2]

Using 2-(3-bromo-5-fluorophenyl)-5,5-dimethyl-1,3,2-dioxaborinane **2c** (287 mg, 1.00 mmol), cesium carbonate (32.6 mg, 100 µmol), 1-(naphthalen-1-yl)ethan-1-one **1a** (1.12 g, 6.6 mmol) and **5b** (4.8 mg, 10 µmol), the product was obtained in 75% yield (257 mg, 0.749 mmol) as a white solid after column chromatography (hexane/ethyl acetate: 10/0 to 9/1). mp 85─87 °C; IR (neat, cm^{-1}) 1682, 1601, 1574, 1427, 1414, 1350, 1217, 1188, 847, 818, 756, 746, 700, 675; ^{1}H NMR

(400 MHz, $CDCl_3$, ppm): δ 7.95 (d, J = 8.4 Hz, 1H), 7.93–7.82 (m, 2H), 7.60–7.54 (m, 2H), 7.45–7.42 (m, 2H), 7.31 (ddd, J = 1.9, 2.2, 8.0 Hz, 1H), 7.13 (ddd, J = 1.5, 2.3, 9.0 Hz, 1H), 2.21 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, ppm) δ 206.5, 162.4 (d, J = 250.8 Hz), 143.8 (d, J = 8.1 Hz), 138.8, 133.0, 132.9 (d, J = 2.1 Hz), 129.7, 128.7, 128.4, 128.3 (d, J = 2.8 Hz), 127.8, 126.9, 126.7, 124.9, 123.0 (d, J = 9.7 Hz), 118.7 (d, J = 24.3 Hz), 115.6 (d, J = 23.6 Hz), 32.9; ^{19}F NMR (376 MHz, $CDCl_3$, ppm) δ -109.7 (s, 1F); HRMS (FAB) m/z: [M]+ calcd. for $C_{18}H_{12}BrFO$: 342.0056. Found: 342.0049.

1-(2-(4-Iodophenyl)naphthalen-1-yl)ethan-1-one [**3d**: Table 3, entry 3]

Using 2-(4-bromophenyl)-5,5-dimethyl-1,3,2-dioxaborinane **2a** (316 mg, 1.00 mmol), cesium carbonate (97.8 mg, 300 µmol), 1-(naphthalen-1-yl)ethan-1-one **1a** (1.12 g, 6.6 mmol) and **5b** (4.8 mg, 5.0 µmol), the product was obtained in 70% yield (259 mg, 0.696 mmol) as a white solid after column chromatography (hexane/ethyl acetate: 10/0 to 9/1). mp 115—117 °C; IR (neat, cm^{-1}) 1738, 1689, 1485, 1371, 1350, 1211, 1130, 1080, 1005, 970, 953, 862, 837, 816, 789, 754; ^{1}H NMR (400 MHz, $CDCl_3$, ppm): δ 7.93 (d, J = 8.5 Hz, 1H), 7.92–7.82 (m, 4H), 7.58–7.51 (m, 2H), 7.46 (d, J = 8.5 Hz, 1H), 7.23–7.19 (m, 2H), 2.14 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, ppm) δ 207.2, 139.8, 138.4, 137.9, 134.6, 132.7, 131.2, 129.6, 128.8, 128.3, 127.6, 127.0, 126.6, 124.8, 94.2, 32.9; HRMS (FAB) m/z: [M]+ calcd. for $C_{18}H_{13}IO$: 372.0011. Found: 372.0019.

8-(4-bromophenyl)-3,4-dihydronaphthalen-1(2*H*)-one [**3g**: Table 3, entry 6]

Using 2-(4-bromophenyl)-5,5-dimethyl-1,3,2-dioxaborinane **2a** (269 mg, 1.00 mmol), cesium carbonate (65.2 mg, 200 µmol), 3,4-dihydronaphthalen-1(2*H*)-one **1b** (1.10 g, 7.5 mmol) and **5a** (9.2 mg, 10 µmol), the product was obtained in 42% yield (125 mg, 0.415 mmol) as a pale yellow solid after column chromatography (hexane/ethyl acetate: 10/0 to 8/1). mp 109—111 °C; IR (neat, cm^{-1}) 2935, 2858, 1680, 1583, 1489, 1458, 1269, 1250, 1207, 1178, 1068, 1022, 1009, 930, 822, 796, 766, 684; ^{1}H NMR (400 MHz, $CDCl_3$, ppm): δ 7.50–7.46 (m, 2H), 7.42 (dd, J = 7.6, 7.6 Hz, 1H), 7.26 (d, J = 7.6 Hz, 1H), 7.09–7.06 (m, 3H), 3.01 (t, J = 6.1 Hz, 2H), 2.61 (t, J = 6.6 Hz, 2H), 2.19–2.09 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$, ppm) δ 198.4, 145.8, 142.7, 141.9, 132.0, 131.0, 130.9, 130.1, 129.9, 128.6, 120.8, 40.5, 30.7, 23.0; HRMS (FAB) m/z: [M]+ calcd. for $C_{16}H_{13}BrO$: 300.0150. Found: 300.0155.

4-(4-bromophenyl)-6,7,8,9-tetrahydro-5*H*-benzo[7]annulen-5-one [**3h**: Table 3, entry 7]

Using 2-(4-bromophenyl)-5,5-dimethyl-1,3,2-dioxaborinane **2a** (269 mg, 1.00 mmol), cesium carbonate (65.2 mg, 200 µmol) , 6,7,8,9-tetrahydro-5*H*-benzo[7]annulen-5-one **1c** (1.07 g, 6.7 mmol) and **5a** (9.2 mg, 20 µmol), the product was obtained in 74% yield (233 mg, 0.740 mmol) as a white solid after column chromatography (hexane/ethyl acetate: 10/0 to 8/1). mp 151—152 °C; IR (neat, cm^{-1}) 2927, 2860, 1684, 1587, 1454, 1242, 1178, 1103, 1078, 1005, 876, 837, 823, 796, 775, 758, 688; ^{1}H NMR (400 MHz, $CDCl_3$, ppm): δ 7.49–7.46 (m, 2H), 7.36 (dd, J = 7.6, 7.6 Hz, 1H), 7.20 (dd, J = 1.1, 7.6 Hz, 1H), 7.15 (d, J = 7.6 Hz, 1H), 7.12–7.08 (m, 2H), 2.81 (t, J = 6.3 Hz, 2H), 2.66–2.63 (m, 2H), 1.95–1.84 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$, ppm) δ 209.9, 140.3, 139.9, 139.0, 137.9, 131.4, 130.3, 130.0, 128.7, 128.2, 121.4, 42.8, 32.5, 25.6, 22.8; HRMS (FAB) m/z: [M]+ calcd. for $C_{17}H_{15}BrO$: 314.0306. Found: 314.0312.

1-(2-(4-bromophenyl)naphthalen-1-yl)ethan-1-one [3i: Table 3, entry 8]

Using 2-(4-bromophenyl)-5,5-dimethyl-1,3,2-dioxaborinane **2a** (269 mg, 1.00 mmol), cesium carbonate (32.6 mg, 100 µmol) , 1-(naphthalen-2-yl)ethan-1-one **1d** (1.13 g, 6.6 mmol) and **5b** (19.2 mg, 20.0 µmol), the product was obtained in 22% yield (70 mg, 0.215 mmol) as a white solid after column chromatography (hexane/ethyl acetate: 10/0 to 10/1). mp 83–85 °C; IR (neat, cm^{-1}) 1689, 1489, 1458, 1440, 1419, 1392, 1360, 1279, 1269, 1244, 1209, 1191, 1130, 1072, 1009, 982, 964, 951, 914, 899, 823, 761, 667; ^{1}H NMR (400 MHz, $CDCl_3$, ppm): δ 8.11 (s, 1H), 7.94 (d, J = 7.8 Hz, 1H) , 7.88 (d, J = 7.9 Hz, 1H), 7.80 (s, 1H), 7.62–7.55 (m, 4H), 7.30 (d, J = 8.3 Hz, 2H), 2.23 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, ppm) δ 203.3, 140.0, 138.6, 136.2, 134.0, 131.8, 130.5, 129.6, 128.9, 128.7, 128.3, 127.8, 127.1, 122.0, 30.4 HRMS (ESI orbitrap) m/z: $[M + Na]^+$ calcd. for $C_{18}H_{13}BrONa$: 347.0042. Found: 347.0036.

1-(2-phenylnaphthalen-1-yl)ethan-1-one [**4a**: Table 3, entry 10][11f]

Using 2-phenyl-5,5-dimethyl-1,3,2-dioxaborinane **2f** (190 mg, 1.00 mmol), cesium carbonate (32.6 mg, 100 µmol) and **5b** (1.9 mg, 2.0 µmol), the product was obtained in 81% yield (199 mg, 0.809 mmol) as a pale yellow liquid after column chromatography (hexane/ethyl acetate: 10/0 to 9/1). ^{1}H NMR (400 MHz, $CDCl_3$, ppm): δ7.94 (d, J = 8.4 Hz, 1H), 7.92–7.85 (m, 2H), 7.58–7.39 (m, 8H), 2.09 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, ppm) δ 207.4, 140.3, 138.3, 136.0, 132.6, 129.4, 129.4, 128.8, 128.7, 128.2, 128.0, 127.4, 126.3, 124.8, 32.7; GCMS(EI): 246.

Gram-scale synthesis of Ru-catalyzed Kakiuchi arylation with 4-bromophenylboronic acid and 1-(naphthalen-1-yl)ethan-1-one: Under an argon atmosphere, 4-bromophenylboronic acid (2.080 g, 10.36 mmol), 2,2-Dimethyl-1,3-propanediol (1.08 g, 10.4 mmol), cesium carbonate (326 mg, 1.00 mmol), 1-(naphthalen-1-yl)ethan-1-one **1a** (6.81 g, 40.0 mmol), **5b** (19.0 mg, 20.0 µmol) and toluene (15 mL) were charged in a 50 mL round-bottom flask with the Dean-Stark apparatus. The flask was placed into an oil bath preheated at 150 °C. After the reaction mixture was stirred for 3 h and cooled to room temperature. The obtained crude was purified by passing it through a silica gel column with a hexane / ethyl acetate eluent to give 1-(2-(4-bromophenyl)naphthalen-1-yl)ethan-1-one **3a** in 78% yield (2.61 g, 8.03 mmol) as a white solid.

Acknowledgements

We thank the Instrumental Analysis Laboratory, University of Toyama, and Prof. Mino, Chiba University, for the HRMS measurements. Technical assistance for the additional experiment by Mr. Ryo Akiyama (undergraduate student of Tokyo Denki University) is gratefully acknowledged.

Notes and references

1 T. P. I. Saragi, T. Spehr, A. Siebert, T. Fuhrmann-Lieker and J. Salbeck, *Chem. Rev.*, 2007, **107**, 1011.
2 Selected examples of a bromination of biaryls: (*a*) B. M. Schmidt, B. Topolinsky, M. Yamada, S. Higashibayashi, M. Shionoya, H. Sakurai and D. Lentz, *Chem.— Eur. J.,* 2013, **19**, 13872; (*b*) S. Song, S. Park, S. Kwon, B. H. Lee, J. Y. Shim, J. Lee, S. H. Park, Y. Jin, I. Kim, K. Lee and H. Suh, *Sol. Energ. Mat. Sol. C.*, 2012, **105**, 229; (*c*) M.-S. Gong, H.-S. Lee and Y.-M. Jeon, *J. Mater. Chem.*, 2010, **20**, 10735.
3 For selected recent reviews: (*a*) R. Rossi, F. Bellina and M. Lessia, *Adv. Synth. Catal.*, 2012, **354**, 1181; (*b*) R. Rossi, F. Bellina and M. Lessi, *Tetrahedron*, 2011, **67**, 6969.
4 Brominated 2-acyl-1,1'-biaryls synthesis via Suzuki-Miyaura coupling: (*a*) M. Nawaz, I. Ullah, O.-U.-R. Abid, A. Villinger and P. Langer, *Eur. J. Org. Chem.*, 2011, 6670; (*b*) Y. Wu, X. Hao, J. Wu, J. Jin and X. Ba, *Macromolecules*, 2010, **43**, 731; (*c*) L. Lunazzi, A. Mazzanti and M. Minzoni, *J. Org. Chem.*, 2007, **72**, 2501; (*d*) C. Yang, J. Jacob and K. Müllen, *Macromolecules*, 2006, **39**, 5696.
5 For selected examples: (*a*) Q. Zhang, M. Lu, C. Wang, J. Du, P. Zhou and M. Zhao, *Environ. Pollut.*, 2014, **189**, 169; (*b*) M. V. Berghe, L. Weijs, S. Habran, Krishna Das, Céline Bugli, , Stéphane Pillet, J.-F. Rees, P. Pomeroy, A. Covaci and C. Debier, *Environ. Res.*, 2013, **120**, 18; (*c*) M. P. Ward, C. Jablonski, B. Semel and D. Soucek, *Ecotoxicology*, 2010, *19*, 1513; (*d*) S. Akzinnay, F. Bisaro and C. S. Cazin, *Chem. Commun.* 2009, 5752; (*e*) D. G. Patterson Jr., W. E. Turner, S. P. Caudill and L. L. Needham, *Chemosphere*, 2008, **73**, 261; (*f*) S. H. Safe, *Crit. Rev. Toxicol.*, 1994, **24**, 87.
6 F. Pan, H. Wang, P.-X. Shen, J. Zhaob and Z.-J. Shi, *Chem. Sci.*, 2013, **4**, 1573.
7 J. Wencel-Delord, C. Nimphius, F. W. Patureau and F. Glorius, *Angew. Chem., Int. Ed.*, 2012, **51**, 2247.
8 (*a*) L. Ilies, M. Kobayashi, A. Matsumoto, N. Yoshikai and E. Nakamura, *Adv. Synth. Catal.*, 2012, **354**, 593; (*b*) N. Yoshikai, S. Asako, T. Yamakawa, L. Ilies and E. Nakamura, *Chem. Asian J.* 2011, **6**, 3059; (*c*) N. Yoshikai, A. Matsumoto, J. Norinder and E. Nakamura, *Angew. Chem., Int. Ed.*, 2009, **48**, 2925.
9 For selected recent reviews: (*a*) L. Ackermann, *Org. Process Res. Dev.*, 2015, **18**, 260; (*b*) P. B. Arockiam, C. Bruneau and P. H. Dixneuf, *Chem. Rev.* 2012, **112**, 5879; (*c*) L. Ackermann, *Chem. Rev.* 2011, **111**, 1315; (*d*) L. Ackermann and R. Vicente, *Top. Curr. Chem.*, 2010, **292**, 211.
10 (*a*) E. Diers, N. Y. P. Kumar, T. Mejuch, I. Marek and L. Ackermann, *Tetrahedron*, 2013, **69**, 4445; (*b*)B. Li, K. Devaraj, C. Darcel and P. H. Dixneuf, *Tetrahedron*, 2012, **68**, 5179; (*c*) B. Li, C. B. Bheeter, C. Darcel and P. H. Dixneuf, *ACS Catal.*, 2011, **1**, 1221.
11 (*a*) K. Kitazawa, T. Kochi, M. Nitani, Y. Ie, Y. Aso and F. Kakiuchi, *Chem. Lett.*, 2011, **40**, 300; (*b*) S. Hiroshima, D. Matsumura, T. Kochi and F. Kakiuchi, *Org. Lett.*, 2010, **12**, 5318; (*c*) K. Kitazawa, M. Kotani, T. Kochi, M. Langeloth and F. Kakiuchi, *J. Organomet. Chem.*, 2010, **695**, 1163; (*d*) K. Kitazawa, T. Kochi, M. Sato and F. Kakiuchi, *Org. Lett.*, 2009, **11**, 1951; (*e*) F. Kakiuchi, Y. Matsuura, S. Kan and N. Chatani, *J. Am. Chem. Soc.*, 2005, **127**, 5936; (*f*) F. Kakiuchi, S. Kan, K. Igi, N. Chatani and S. Murai, *J. Am. Chem. Soc.*, 2003, **125**, 1698.
12 (*a*) K. Li, N. Hu, R. Luo, W. Yuan and W. Tang, *J. Org. Chem.*, 2013, **78**, 6350; (*b*) Y. Yamamoto, K. Kurihara, Y. Takahashi and N. Miyaura, *Molecules*, 2013, **18**, 14; (*c*) Y. Yamamoto, T. Shirai and N. Miyaura, *Chem. Commun.*, 2012, **48**, 2803; (*d*) M. Kawatsura, K. Kamesaki, M. Yamamoto, S. Hayase and T. Itoh, *Chem. Lett.*, 2010, **39**, 1050; (*e*) Y. Yamamoto, K. Kurihara and N. Miyaura, *Angew. Chem., Int. Ed.* 2009, **48**, 4414; (*f*) Y. Na, S. Park, S. B. Han, H. Han, S. Ko, S. Chang, *J. Am. Chem. Soc.*, 2004, **126**, 250; (g) H. Kondo, N. Akiba, T. Kochi and F. Kakiuchi, *Angew. Chem., Int. Ed.*, 2015, **54**, 9293.
13 H. Grounds, J. C. Anderson, B. Hayter and A. J. Blake, *Organometallics*, 2009, **28**, 5289.
14 M. F. McGuiggan and L. H. Pignolet, *Inorg. Chem.*, 1982, **21**, 2523.
15 (*a*) J. Takaya, S. Tadami, K. Ukai and N. Iwasawa, *Org. Lett.*, 2008, **10**, 2697; (b) S. L. Zheng, S. Reid, N. Lin and B. H. Wang, *Tetrahedron Lett.*, 2006, **47**, 2331.