Green Chemistry

PAPER

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Cite this: *Green Chem.*, 2021, **23**, 8131

Product selective reaction controlled by the combination of palladium nanoparticles, continuous microwave irradiation, and a co-existing solid; ligand-free Buchwald–Hartwig amination *vs.* aryne amination†

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Received 19th May 2021,
Accepted 26th August 2021

DOI: 10.1039/d1gc01782a

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We have developed a continuous microwave irradiation-assisted Buchwald–Hartwig amination using our original Pd nanoparticle catalyst with a copper plate as a co-existing metal solid. In this methodology, a microwave-controlled product selectivity was achieved between Buchwald–Hartwig amination and aryne amination performed under strongly basic conditions and at a high reaction temperature, because a polar chemical species such as Ar–Pd–halogen might be activated selectively by microwave radiation. Moreover, our catalyst could be used repeatedly over 10 times, and the amount of Pd leaching could be suppressed to a low level.

Introduction

Arylamines are widely utilized as functional organic materials in fields such as pharmaceuticals, agrochemicals, dyes, and polymers. Among methodologies for convenient synthesis of arylamines, carbon–nitrogen bond forming reactions are very important.[1]

The Pd-catalyzed cross-coupling of tin amides and aryl halides to generate arylamines in homogeneous systems was first studied by Migita and colleagues in 1983.[2] Followed by this report, the Buchwald and Hartwig groups developed a Pd-catalyzed amination under relatively mild reaction conditions independently.[3,4] However, sophisticated dialkylaryl phosphine ligands are often used to promote these reactions.[1]

To develop a ligand-free and environmentally benign metal-catalyzed coupling reaction, metal nanoparticle (NP) catalysts have been widely used to catalyze the coupling reaction.[5] We have also developed Pd NP catalysts immobilized on gold or glass and applied them to organic reactions.[6]

Although many examples of Suzuki–Miyaura coupling, Heck reaction, and Sonogashira coupling have been reported,[7] Buchwald–Hartwig amination catalyzed by a metal NP catalyst was reported in only 13 examples (Scheme 1a).[8] Moreover, the catalysts used in 13 examples have four drawbacks: (1) ligand addition, (2) inconvenient removal of NPs, (3) insufficient recyclability of NP catalysts (up to six times), and (4) a few reports about leaching analysis of NPs.

On the other hand, external energy-assisted (visible light, microwave) organic synthesis has been enthusiastically researched to perform reactions that are difficult or impossible and to access eco-friendly methodologies.[9] Among them, microwave radiation has been applied for the metal NP-catalyzed coupling reaction (Suzuki–Miyaura coupling, Ullmann coupling, and Heck reaction).[10] A conventional microwave machine which was used in a previous report turns off within a very short period when the temperature limit was reached and cannot use microwave efficiently. Therefore, we developed a continuous irradiation type microwave machine, and then we have reported continuous microwave irradiation-assisted ligand-free Suzuki–Miyaura coupling of inert aryl chlorides using a Ru NP catalyst on sulfur-modified gold (henceforth referred to as SARu) or a Pd NP catalyst on sulfur-modified glass (henceforth referred to as SGlPd).[11] In the latter case, it

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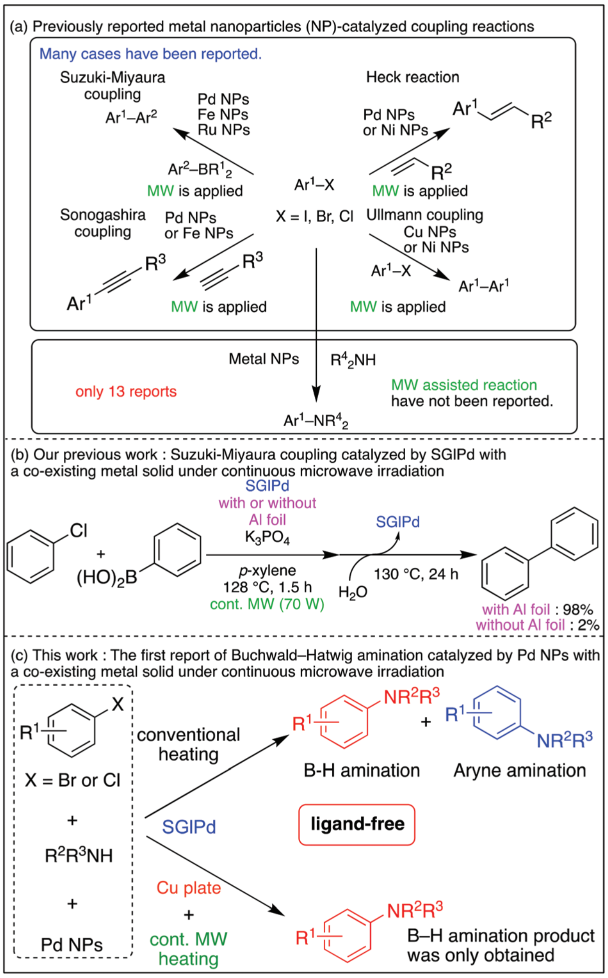
† Electronic supplementary information (ESI) available. See DOI: 10.1039/d1gc01782a



Scheme 1 Microwave-assisted coupling reaction catalyzed by metal nanoparticles.

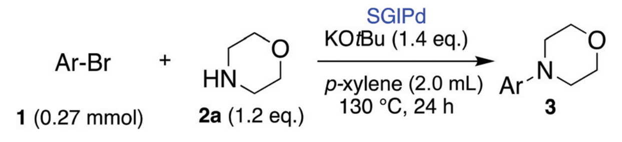
is unique that the addition of a solid metal promotes the reaction due to increased microwave absorption of the reaction system (Scheme 1b).[12] We wondered whether this methodology could be applicable to Buchwald–Hartwig amination.

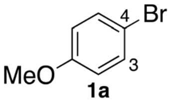
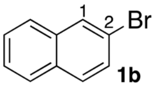
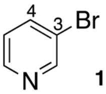
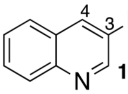
Herein, we report the first example of continuous microwave irradiation-assisted ligand-free Buchwald–Hartwig amination using a Pd NP catalyst and a co-existing solid metal (copper plate, Scheme 1c), and we also found that this combination can work together to control the product selectivity to give only a Buchwald–Hartwig amination product.

Results and discussion

In the beginning, we attempted the ligand-free Buchwald–Hartwig amination between aryl bromides and morpholine (**2a**) using SGIPd,[13] without microwave irradiation under the conditions quoted (Table 1). Regioisomers were obtained from **1a**, **1b**, **1c**, and **1d** respectively because an aryne was generated by strongly basic conditions and high temperatures[14] (entries 1–4).

Table 1 Buchwald–Hartwig amination of some aryl bromides catalyzed by SGIPd under conventional heating

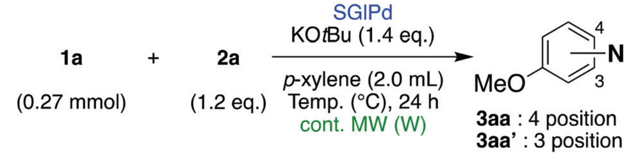


Entry	Ar–Br	Yield (%)
1[a]	 **1a**	3 position: 41 4 position: 48
2	 **1b**	1 position: 22 2 position: 76
3	 **1c**	3 position: 59 4 position: 39
4	 **1d**	3 position: 30 4 position: 19 (recovered 48% of SM)

[a] The reaction was performed for 7 h.

Therefore, we investigated the optimization of reaction conditions to prevent the generation of regioisomers (Table 2). When the reaction was carried out at lower temperatures such as 80 or 90 °C, the corresponding coupling product was barely formed (entries 1 and 2). Moreover, the regioisomer was formed by heating at 100 °C (entry 3); hence the reaction using continuous microwave irradiation was carried out at temperatures lower than 90 °C. The substrates were heated to 80 or 90 °C under microwave irradiation for 24 h (entries 4 and 5). Even though the yield was improved, it hit the ceiling of 36%. We considered that this might be because a large amount of Pd was leached and aggregated, so it lost its catalytic activity. Then, we conducted the reaction in two steps and removed the SGIPd between the first step and second step, as shown in the

Table 2 Optimization of reaction conditions for the reaction of aryl bromide (single step)

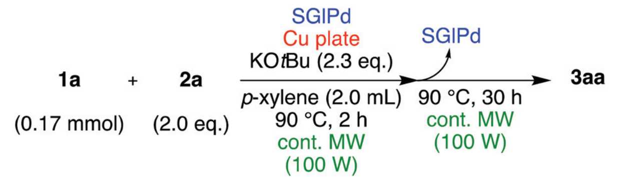


Entry	Temp. (°C)	Cont. MW (W)	Yield (%)	
			3aa	**3aa′**
1	80	—	ND	ND
2	90	—	5	Trace
3	100	—	9	5
4	80	50	12	ND
5	90	50	36	Trace

ND = not detected. **N** = 4-morpholinyl.

equation in Table 3. The reaction mixture was heated for a short time to elute the Pd NPs into the reaction system (1st step) and then heated for a long time to effect the reaction. The yield was slightly increased with longer reaction time, and higher microwave power and temperature (entries 1–4). When the reaction was carried out with an aluminum foil which is effective for Suzuki–Miyaura coupling of aryl chlorides based on our previous work,[11b] the corresponding coupling product was obtained in just only 11% yield (entry 5). It is because aluminum foil decayed under the strongly basic conditions, and the microwave absorption in the reaction system was not increased. Therefore, we used copper plates instead of aluminum foil as the co-existing metal, and we found that the yield of the product improved to 64% (entry 6). Encouraged by these results, we continued our experiments to optimize the equivalence of reagents and the reaction time of the first and second steps (entries 7 and 8); and finally, we found that the coupling product was obtained in 90% yield under the conditions indicated in entry 9.[15] When the reaction was performed under the conditions of entry 9 without microwave irradiation, the product was not obtained (entry 10). In addition, the reaction did not proceed with only a Cu plate as the metal source (entry 11). According to this result, Pd is the active species for the reaction, but Cu is not (example of Cu-catalyzed C–N coupling, see ref. 4). Subsequently, we investigated the reusability of SGlPd for the Buchwald–Hartwig amination. When the SGlPd was used repeatedly 10 times in the reaction under the optimal conditions, the coupling product in each case was obtained in high yield (Table 4). In addition, the amount of Pd leaching into each reaction solution was measured by inductively coupled plasma mass spectrometry (ICP-MS; Table 4). As a result, it was found that up to 0.33 μg (1.84 mmol%) of Pd leached into the reaction solution. Under the optimized reaction conditions (entry 9, Table 4), a tiny quantity of Pd NPs on SGlPd is leached into the reaction solution because it is firmly immobilized on glass. Therefore, we considered that SGlPd could be used repeatedly for the reaction and low leaching of Pd NPs succeeded in giving the product in good yield in each reaction.

Table 4 Repeated use of the catalyst and Pd leaching into the reaction mixture

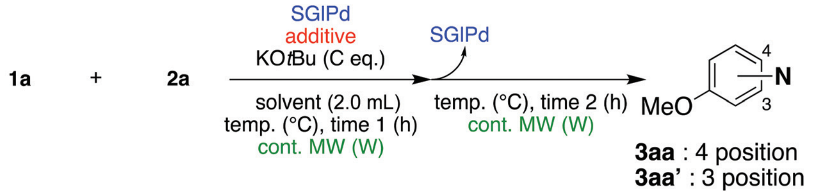


Run	Yield (%)	Leached Pd[a] (μg)	Leached Pd[a] (mmol%)
1	92	0.26	1.44
2	90	0.15	0.84
3	91	0.23	1.29
4	89	0.23	1.28
5	89	0.31	1.69
6	88	0.25	1.40
7	86	0.28	1.57
8	86	0.33	1.84
9	86	0.15	0.83
10	84	0.27	1.52

[a] The average of three samples.

Next, SGlPd was used repeatedly for the Buchwald–Hartwig amination between several aryl bromides **1** and morpholine

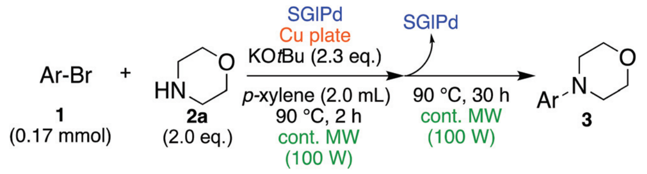
Table 3 Optimization of reaction conditions for the reaction of aryl bromide (double step)

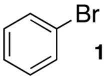
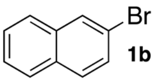
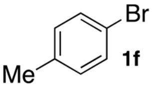
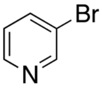
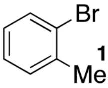
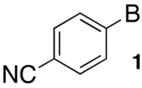
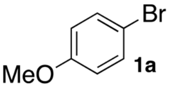
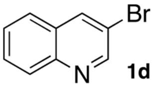


Entry	**1a** (mmol)	**2a** (eq.)	Additive	KOtBu (eq.)	Temp. (°C)	Cont. MW (W)	1st step time 1 (h)	2nd step time 2 (h)	Yield (%) **3aa**	Yield (%) **3aa′**
1	0.27	1.2	—	1.4	80	50	1.5	12	4	ND
2	0.27	1.2	—	1.4	90	50	2	12	5	ND
3	0.27	1.2	—	1.4	90	100	2	12	7	ND
4	0.27	1.2	—	1.4	90	100	2	24	9	ND
5	0.27	1.2	Al foil	1.4	90	100	2	24	11	Trace
6	0.27	1.2	Cu plate	1.4	90	100	2	24	64	Trace
7	0.17	2.0	Cu plate	2.3	90	100	2	24	84	Trace
8	0.17	2.0	Cu plate	2.3	90	100	1	24	45	Trace
9	0.17	2.0	Cu plate	2.3	90	100	2	30	90	Trace
10	0.17	2.0	Cu plate	2.3	90	—	2	30	8	ND
11[a]	0.17	2.0	Cu plate	2.3	90	100	2	30	Trace	ND

[a] SGlPd was not used for the reaction, ND = not detected. **N** = 4-morpholinyl.

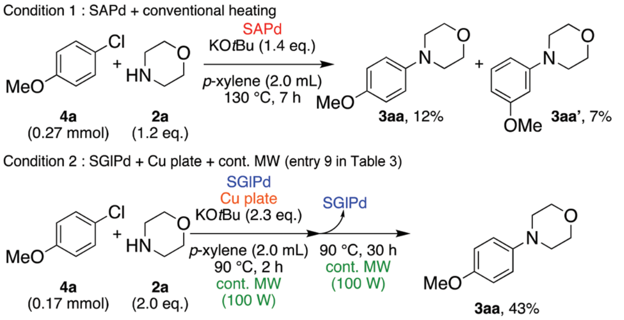
Table 5 Sequential re-use of SGIPd (scope of aryl bromides)



Run	Ar–Br	Yield (%)	Run	Ar–Br	Yield (%)
1	 **1e**	**3ea**, 98	5	 **1b**	**3ba**, 93
2		**3fa**, 97	6	 **1c**	**3ca**, 87
3	 **1g**	**3ga**, 90	7	 **1h**	**3ha**, 85
4		**3aa**, 90	8		**3da**, 81

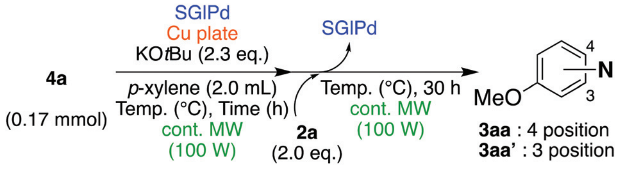
(**2a**) to give eight different types of products (sequential re-use of SGlPd; Table 5).[16] The reaction proceeded, with bromobenzene (**1e**) and aryl bromides **1f**, and **1h** bearing electron-donating and electron-withdrawing groups (runs 1, 2 and 7). Also, *ortho*-substituted aryl bromide **1g** was converted to the corresponding compound **3ga** in 90% yield (run 3). Also, the desired coupled products **3ba**, **3ca**, and **3da** were obtained in good yields from 2-bromonaphthalene (**1b**), 3-bromopyridine (**1c**) and 3-bromoquinoline (**1d**), respectively (runs 5, 6 and 8).

This was also the case when the amines were changed. SGlPd was also repeatedly used for the Buchwald–Hartwig amination of 4-bromoanisole (**1a**) with several amines **2** (Table 6). Every corresponding coupled product was obtained in around 90% yield.



Scheme 2 Buchwald–Hartwig amination between 4-chloroanisole (**4a**) and morpholine (**2a**).

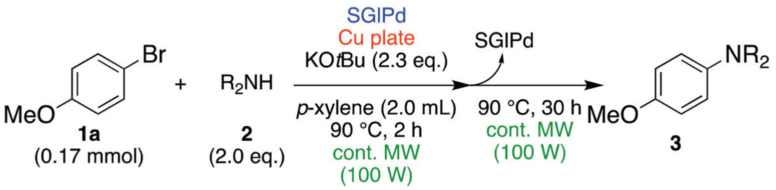
Table 7 Optimization of reaction conditions for the reaction of aryl chloride

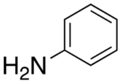
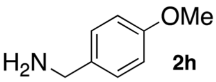


Entry	1st step Time (h)	Temp. (°C)	Yield (%) 3aa	Yield (%) 3aa′
1	2	100	59	ND
2	2	120	75	Trace
3	2	130	78	5
4	3	120	61	10
5	1.5	120	81	Trace
6	70 min	120	75	ND
7	80 min	120	78	ND
8	1	120	73	ND

ND = not detected. **N** = 4-morphorinyl.

Table 6 Sequential re-use of SGlPd (scope of amines)



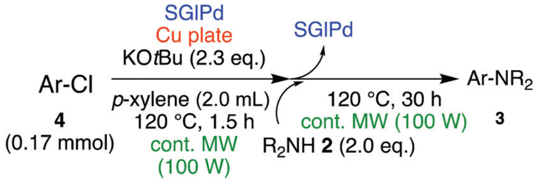
Run	Amines	Yield (%)	Run	Amines	Yield (%)
1	Et_2NH, **2b**	**3ab**, 98	5	*c*Hex_2NH, **2f**	**3af**, 93
2	*i*Pr_2NH, **2c**	**3ac**, 97	6	 **2g**	**3ag**, 87
3	Pyrrolidine, **2d**	**3ad**, 95	7	 **2h**	**3ah**, 85
4	Piperidine, **2e**	**3ae**, 96			

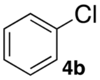
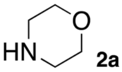
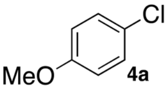
Ligand-free Buchwald–Hartwig amination between aryl chlorides and amines using SGlPd

Next, we investigated the Buchwald–Hartwig amination of aryl chloride as a more inert compound than aryl bromides. At first, the SGlPd was utilized for the reaction under the conditions as described in Table 1. In addition to the desired product, regioisomers were also obtained in low yield (Scheme 2, Condition 1). Next, the optimal reaction conditions for aryl bromides (entry 9, Table 3) were utilized for the Buchwald–Hartwig amination of 4-chloroanisole (**4a**) and morpholine (**2a**; Scheme 2). However, the desired coupled product **3aa** was obtained in only 43% yield and the 4-chloroanisole remained (Scheme 2, Condition 2).

Therefore, we continued our experiments to determine appropriate reaction conditions for the Buchwald–Hartwig amination of aryl chlorides and amines. We changed each condition in both step 1 and step 2; finally, we found the experimental conditions as outlined in the equation in Table 7, in which amine **2a** was added in the second step. When the reaction temperature was higher, the yield of **3aa** was higher (100 °C: 59% 120 °C: 75%, 130 °C: 78%, entries 1–3). However, when the reaction was carried out at 130 °C, the regioisomer **3aa′** *via* the aryne intermediate was obtained in 5% yield (entry 3). Next, we investigated the reaction time for the first step (entries 4–8). When the reaction was performed for 3 h, the yield of the desired product was decreased to 61% (entry 4). It was considered that a large number of Pd NPs leached into the reaction solution were agglomerated and deactivated. Moreover, a shorter reaction time, such as 60–80 min, also decreased the yield of the product between 73 and 78% respectively, because the amount of Pd NPs leached into the

Table 8 Substrate scope of aryl chlorides and amines



Entry	Ar–Cl	Amines	Yield (%)	Entry	Ar–Cl	Amines	Yield (%)
1	 **4b**	 **2a**	**3ea**, 86	5	 **4a**	*n*Bu$_2$NH, **2i**	**3ai**, 82
2	**4b**	*n*Bu$_2$NH, **2i**	**3ei**, 83	6	**4a**	BnNH$_2$, **2j**	**3aj**, 83
3	**4b**	BnNH$_2$, **2j**	**3ej**, 85	7	**4a**	*c*Hex$_2$NH, **2f**	**3af**, 80
4	**4b**	*c*Hex$_2$NH, **2f**	**3ef**, 81				

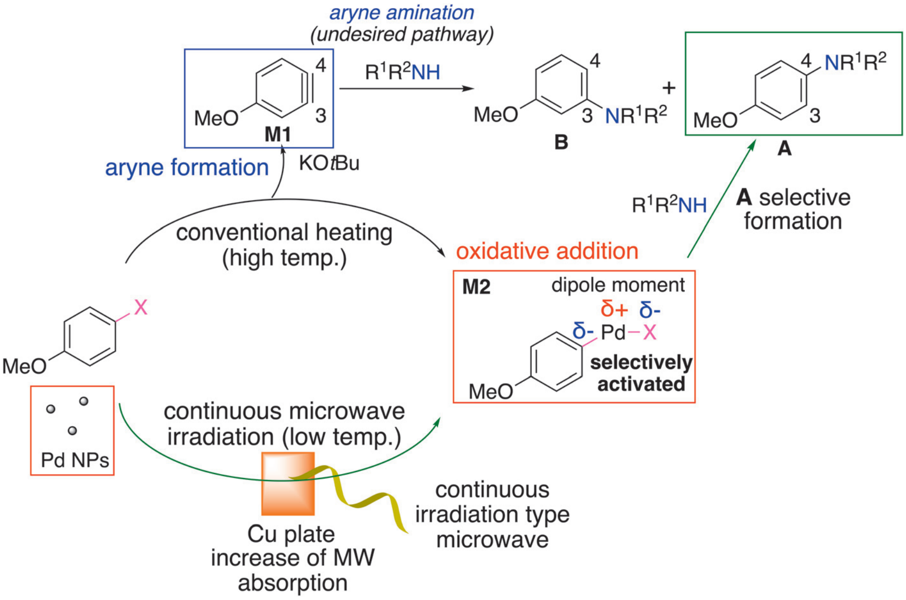


Fig. 1 Plausible mechanism and effect of microwave irradiation.

reaction system was not enough for this reaction to proceed (entries 6–8). When the reaction was performed for 1.5 hours in the 1st step, the product was obtained in 81% yield (entry 5).

From the above results, we investigated the substrate scope of aryl chlorides and amines under the optimum conditions (entry 8, Table 7). When chlorobenzene (**4b**) or 4-chloroanisole (**4a**) was subjected to the reaction with amines such as morpholine (**2a**), *N*,*N*-dibutylamine (**2i**), benzylamine (**2j**) or *N*,*N*-dicyclohexylamine (**2f**), the corresponding coupled products were obtained in good yields, respectively (entries 1–7, Table 8).

Based on the generally known effect of microwave irradiation on compounds with a dipole moment and the experimental results of the product selective formation of the desired coupled product under continuous microwave irradiation, we proposed the plausible reaction mechanism (Fig. 1). In conventional heating at high temperature, not only the typical Buchwald–Hartwig amination but also the carbon–nitrogen bond forming reaction *via* an aryne intermediate (**M1**) proceeded.

That is to say, the aryne was formed under the strongly basic conditions at a high temperature, and the amines then attacked the aryne intermediate. In contrast, under continuous microwave irradiation conditions at a lower temperature, Buchwald–Hartwig amination might have been selectively activated due to the specific activation of Pd NPs and/or the polar chemical species, Ar–Pd–Br (**M2**).

Conclusion

In summary, we have developed a product selective Buchwald–Hartwig amination controlled by the combination of palladium nanoparticles, continuous microwave irradiation, and a co-existing metal solid. In conventional heating, the aryne formation occurred and generated the undesired regioisomer due to the high temperature and strongly basic conditions. On the other hand, the Buchwald–Hartwig amination could proceed selectively to obtain the corresponding coupled product by this methodology because the microwave-assisted heating system suppressed the reaction temperature and might have selectively activated the species with a dipole moment. The Buchwald–Hartwig amination of aryl chlorides, which are inert compounds, was also promoted by the microwave-assisted system. Moreover, we found that the SGlPd can be used repeatedly over 10 times for the reaction, and the amount of Pd leached into the reaction mixture was detected at a quite low level (ppb level) by ICP-MS.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgements

The XAFS measurements were performed at beamlines BL14B2 of SPring-8, with the approval of the Japan Synchrotron Radiation Research Institute (JASRI) (Proposal No. 2019B1907). This work was partially supported by a Grant-in-Aid from the JSPS KAKENHI for Precisely Designed Catalysts with Customized Scaffolding (Grant No. JP 15KT0063), by the Platform Project for Supporting Drug Discovery and Life Science Research (Basis for Supporting Innovative Drug Discovery and Life Science Research (BINDS)) from the AMED under Grant Number JP21am0101084, by Yazaki Memorial Foundation for Science and Technology and Sasagawa Science Research Foundation of The Japan Science Society.

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13 We performed XPS, Powder XRD and HR TEM experiments for SGlPd, see ESI.† We also analysed the SGlPd by XAFS and it showed that Pd NPs on SGlPd is 0 valences. See ref. 6*b*.

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15 When the reaction was performed under optimized reaction conditions (entry 9) without continuous microwave irradiation, the desired coupled product was obtained in only 8% yield (entry 10), and we confirmed that the continuous microwave irradiating is necessary for the reaction.

16 SGlPd was removed from the reaction solution with a pair of tweezers after completing of the first step of the reaction. Then, the surface was washed with ethanol, dried under reduced pressure, and used repeatedly.