Polyaromatic Products of Three-Component Coupling of Aryl Halide with Two Molecules of Arylacetylene and Arylboronic Acid under Ligand-Free Catalysis Conditions

E. V. Yarosh^a, E. V. Larina^a, N. A. Lagoda^a, A. A. Kurokhtina^a, and A. F. Schmidt^{a,*}

^a Irkutsk State University, ul. K. Marksa 1, Irkutsk, 664003 Russia *e-mail: aschmidt@chem.isu.ru

Received December 13, 2018; revised February 10, 2019; accepted February 21, 2019

Abstract—The aryl halide–arylacetylene–arylboronic acid three-component coupling in the presence of a Pd catalyst containing no organic ligands is described. The reaction routes that take place in the reaction system are shown to include the consecutive carbopalladation of two arylacetylene molecules, leading to unsaturated polyaromatic compounds. The possibility of controlling the alternative reaction routes is demonstrated.

Keywords: three-component coupling, polyaromatic compounds, catalysis, palladium, carbopalladation

DOI: 10.1134/S1070428019050154

The natural result of many years of research into traditional two-component coupling reactions of aryl halides with various nucleophiles [1] was that the regularities established for these processes were extended to more intricate related processes. Thus, in 2003, Zhou et al. demonstrated for the first time a three-component aryl halide–alkyne–arylboronic acid coupling reaction leading to tetrasubstituted alkenes [2, 3].

Previously we found that two-component aryl halide-arylacetylene coupling under ligand-free catalysis conditions [4] and in the absence of Cu(I) compounds (copper-free variant of the Sonogashira reaction [1]) involves carbopalladation of the acetylene molecule by the σ -aryl palladium complexes formed from aryl halide and zero-valent palladium, which occurs in preference to the traditional Sonogashira reaction. Therewith, two or even three consecutive carbopalladations may take place: carbopalladation of arylacetylene with an σ -aryl palladium complex to form the corresponding σ -alkenyl palladium complex which can further effect carbopalladation of two more arylacetylene molecules. This reaction sequence was completed by intramolecular cyclization to form tetraarylbenzenes and tetraarylfulvenes.

The obtained evidence for carbopalladation involving more than one arylacetylene molecule allowed us to suggest that this process occurs via one or several consecutive acetylene carbopalladation stages and in the presence of an additional nucleophile, i.e. under three-component coupling conditions. The additional nucleophile (organometallic reagent [2], arylboronic acid [2, 5], alkene [6, 7], or terminal alkyne [8, 9]) can intercept intermediates that build-up their structure in consecutive carbopalladation stages, which makes it possible to obtain linear acyclic products by interrupting the sequence of carbopalladation stages with regeneration of the initial form of the catalyst [Pd(0) compound].

We found that using the simplest ligand-free catalytic system based on palladium acetate and sodium acetate as a base (without phosphorus and nitrogen-containing ligands, Scheme 1) with iodobenzene, tolane, and phenylboronic acid the reaction, along with the products of two-component coupling of aryl halide and alkyne [triphenylethylene (1)], gave the products of three-molecular assembly of two components [tetraphenylnaphthalene (3), pentaphenylbutadiene (4)] and three components [tetraphenylethylene (2)], as well as of four-molecular assembly of all the three components [hexaphenylbutadiene (5)].

Analysis of the mass spectra of the products obtained by varying the para-substituents in the benzene ring of aryl halide and arylboronic acid provides clear evidence for the incorporation of one



aryl fragment of the aryl halide molecule in all products 1–5, as well as the incorporation of one aryl fragment of the arylboronic acid in products 2 and 5. These results rule out the oxidative variant of the reaction involving only arylboronic acid and acetylene and give unambiguous evidence showing that compounds 2 and 5 are formed by three-component coupling. The composition of the products suggests the following routes of their formation in the studied three-component coupling reaction (Scheme 2).

Triarylethylene 1 is formed by the reduction of σ alkenyl palladium complex **B**, a product of the carbopaladation of tolane with palladium–aryl halide adduct ArPdX **A**. Tetraarylethylene 2 is formed by the reaction of the same complex **B** with arylboronic acid (transmetalation similar to the Suzuki–Miyaura reaction). Products **3–5** arise from transformations of σ -alkenyl palladium complex **C** formed by consecutive carbopalladation of two tolane molecules. The formation of tetraphenylnaphthalene **3** occurs as a result of the completion of the catalytic cycle via intramolecular C–H activation in complex **C** with closure of a new six-membered ring (similar to so-called direct arylation of aromatic compounds [10]).

Pentaarylbutadiene **4** is formed by an alternative route of completion of the catalytic cycle, involving reduction of σ -alkenyl palladium complex **C**, which is accompanied by regeneration of the starting Pd(0) compound too, whereas hexaarylbutadiene **5** arises from reduction of complex **C** with the third component, viz. arylboronic acid *via* the Suzuki– Miyaura reduction.



RUSSIAN JOURNAL OF ORGANIC CHEMISTRY Vol. 55 No. 5 2019

Despite the fact that polyaromatic unsaturated products of coupling with two alkyne molecules, like 3-5, are of great interest for the production of modern optoelectronic and emission materials [11], a limited number of works have been published, where their formation in two- and three-component coupling reactions was detected. The first detection of compound 3 among Pd-catalyzed reaction products was reported by Wu et al. [12] more than 20 years ago, but the authors used a phosphine-containing catalytic system.

Under the conditions of the most practically attractive ligand-free catalysis, tetraphenylnaphthalene **3** was obtained only as a by-product in an aryl halide–alkyne–alkene three-component system in the presence of silver acetate as a base [13]. Wu et al. [14] reported the formation of tetraarylnaphthalenes via consecutive carbopalladation of two arylacetylene molecules during two-component oxidative coupling of alkyne with arenes, but the reaction required the use of stoichiometric oxidant amounts and was quite time-consuming (up to 36 h).

As only known precedent of the targeted synthesis of tetraarylnaphthalenes **3** by the ligand-free route described in this paper we can mention the work of Bej et al. [15], but the authors used such a specific solvent as polyethylene glycol. The formation of type **5** products in ligand-free conditions by carbopalation of two arylacetylene molecules was observed in two-component aryl acetylene—arylboronic acid oxidative coupling [16], but here equimolar oxidant amounts (silver salts) were required too to regenerate Pd(II) complexes that reacted with arylboronic acid at the stage of formation of σ -aryl palladium complexes. As far as we know, the formation of type **4** products under catalytic conditions has never been reported.

A series of preliminary experiments showed that the yields of the transformation products of two acetylene molecules in three-component coupling reactions (compounds 3-5) can be controlled within wide limits (Scheme 1). For example, raising the temperature from 80 to 140 ° C allowed fairly selective synthesis of product 3 in yields of up to 70%. The use of a reducing agent (sodium formate) expectedly significantly increased the yield of reduction product 4, while the use of aqueous DMF as a solvent increased the selectivity in product 5 (up to 20%).

Thus, our present results provide evidence showing that three-component coupling catalyzed by simple ligand-free catalytic systems in an available organic solvent holds promise as a synthetic approach to different types of unsaturated polyaromatic products via consecutive carbopalladation of two arylacetylene molecules. Preliminary results indicate the possibility of controlling the selectivity of the process in order to optimize the yield of one or another product.

EXPERIMENTAL

Gas chromatography–mass spectrometry was performed on a Shimadzu QP 2010 Ultra instrument (column 30 m × 0.25 mm × 0.25 μ m GsBP-5MS), carrier gas He, programmed temperature from 100 to 250°C, *m*/*z* range 15–900, scan rate 5000 amu/s. The measured mass spectra were compared with those retrieved from libraries (Wiley, NIST, NIST05) and obtained for authentic samples (Aldrich).

Three-component coupling in the aryl halide– tolane–arylboronic acid system. The reaction was accomplished in a thermostated reactor $(80-140^{\circ}C)$ equipped with a rubber membrane and a magnetic stirrer (stirring speed 477.5 rpm), mixing in DMF or a 4 : 1 DMF–water mixture (5 mL) aryl iodide, tolane, and arylboronic acid (5 mmol each), PdCl₂ (0.0016– 0.08 mmol), NaOAc (6.5 mmol) as a base, and naphthalene (1 mmol) as an internal standard. In the cases, when sodium formate or oxygen was used, their amounts were 0.975 and 0.8 mmol, respectively. The samples periodically withdrawn from the reaction mixture were analyzed by GC–MS; the product yields were determined by the internal standard method using authentic sample calibration.

1,1,2-Triphenylethene (1a). Mass spectrum, m/z (I_{rel} , %): 256 (100.0) $[M]^+$, 255 (24.2), 179 (30.4), 178 (38.4), 77 (7.8).

1-(4-Methoxyphenyl)-1,2-diphenylethene (1b). Mass spectrum, m/z (I_{rel} , %): 286 (100.0) [M]⁺, 285 (10.2), 255 (10.3), 178 (10.88), 165 (16.8), 77 (4.1).

1,1,2,2-Tetraphenylethene (2a). Mass spectrum, m/z (I_{rel} , %): 332 (100.0) [M]⁺, 255 (15.4), 254 (14.5), 253 (23.9), 252 (14.5).

2-(4-Methoxyphenyl)-1,1,2-triphenylethene (2b). Mass spectrum, m/z (I_{rel} , %): 362 (100.0) [M]⁺, 253 (12.9), 241 (10.4), 239 (8.9).

2-(4-Metylphenyl)-1,1,2-triphenylethene (2c). Mass spectrum, m/z (I_{rel} , %): 346 (100.0) [M]⁺, 269 (8.8), 255 (11.1), 254 (16.1), 253 (29.6), 252 (20.0). **1,2,3,4-Tetraphenylnaphthalene** (3a). Mass spectrum, m/z (I_{rel} , %): 432 (100.0) $[M]^+$, 355 (14.6), 354 (8.7), 339 (10.4), 177 (10.0).

6-Methoxy-1,2,3,4-tetraphenylnaphthalene (3b). Mass spectrum, m/z (I_{rel} , %): 462 (100.0) [M]⁺, 352 (5.4), 339 (7.3), 194 (7.4), 352 (8.5), 168 (5.8).

1,1,2,3,4-Pentaphenylbuta-1,3-diene (4a). Mass spectrum, m/z (I_{rel} , %): 434 (45.2) $[M]^+$, 279 (16.0), 267 (54.3), 265 (17.8), 167 (100.0), 77 (5.8).

1-(4-Methoxyphenyl)-1,2,3,4-tetraphenylbuta-1,3-diene (4b). Mass spectrum, m/z (I_{rel} , %): 464 (3.5) $[M]^+$, 462 (33.0), 375 (17.6), 197 (20.7), 105 (100.0), 77 (26.7).

1,1,2,3,4,4-Hexaphenylbuta-1,3-diene (5a). Mass spectrum, m/z (I_{rel} , %): 510 (100.0) [M]⁺, 433 (11.5), 355 (22.4), 343 (54.3), 265 (29.6), 177 (32.4), 167 (56.4), 165 (30.1), 77 (3.4).

4-(4-Methoxyphenyl)-1,1,2,3,4-pentaphenylbuta-1,3-diene (5b). Mass spectrum, m/z (I_{rel} , %): 540 (100.0) $[M]^+$, 463 (22.2), 373 (22.7), 231 (18.2), 197 (58.1), 165 (19.4).

4-(4-Metylphenyl)-1,1,2,3,4-pentaphenylbuta-1,3-diene (5c). Mass spectrum, m/z (I_{rel} , %): 524 (100.0) $[M]^+$, 357 (27.8), 355(20.0), 265 (16.3), 181 (48.6), 167 (15.2), 165 (20.3).

FUNDING

The work was funded by the Ministry of Education and Science of the Russian Federation in the framework of the basic part of the State order for scientific research (project no. 4.9489.2017/8.9) and Russian Foundation for Basic Research (project no. 18-33-00362 mol_a).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- Gildner, P.G. and Colacot, T.J., *Organometallics*, 2015, vol. 34, p. 5497. doi 10.1021/acs.organomet.5b00567
- Zhou, C., Emrich, D.E. and Larock, R.C., Org. Lett., 2003, vol. 5, p. 1579. doi 10.1021/ol034435d
- Zhou, C. and Larock, R.C., J. Org. Chem., 2005, vol. 70, p. 3765. doi 10.1021/j0048265+
- Larina, E.V., Kurokhtina, A.A., Yarosh, E.V., Lagoda, N.A., and Schmidt, A.F., *Russ. J. Org. Chem.*, 2016, vol. 52, p. 1356. doi 10.1134/S1070428016090190
- Horiguchi. H., Tsurugi, H., Satoh, T., and Miura, M., Adv. Synth. Catal., 2008, vol. 350, p. 509. doi 10.1002/ adsc.200700533
- Wen, Y., Huang, L., and Jiang, H., J. Org. Chem., 2012, vol. 77, p. 5418. doi 10.1021/jo300662x
- Shibata, K., Satoh, T., and Miura, M., Org. Lett., 2005, vol. 7, p. 1781. doi 10.1021/ol0503743
- Pal, M., Parasuraman, K., Subramanian, V., Dakarapu, R., and Yeleswarapu, K.R., *Tetrahedron Lett.*, 2004, vol. 45, p. 2305. doi 10.1016/j.tetlet.2004.01.113
- Shi, M., Liu, L.-P., and Tang, J., Org. Lett., 2005, vol. 7, p. 3085. doi 10.1021/ol051101a
- Campeau, L.-C., Parisien, M., Jean, A., and Fagnou, K., J. Am. Chem. Soc., 2006, vol. 128, p. 581. doi 10.1021/ ja055819x
- Turker, L., Tapan, A., and Gumus, S., *Polycycl. Aromat. Compd.*, 2009, vol. 29, p. 123. doi 10.1080/10406630902956260
- Wu, G., Rheingold, A.L., Geib, S.J., and Heck, R.F., Organometallics, 1987, vol. 6, p. 1941. doi 10.1021/ om00152a019
- Horiguchi, H., Hirano, K., Satoh, T., and Miura, M., Adv. Synth. Catal., 2009, vol. 351, p. 1431. doi 10.1002/ adsc.200900096
- Wu, Y.-T., Huang, K.-H., Shin, C.-C., and Wu, T.-C., *Chem. Eur. J.*, 2008, vol. 14, p. 6697. doi 10.1002/ chem.200800538
- Bej, A., Chakraborty, A., and Sarkar, A., *RSC Adv.*, 2013, vol. 3, p. 15812. doi 10.1039/C3RA41924J
- Satoh, T., Ogino, S., Miura, M., and Nomura, M., Angew. Chem. Int. Ed., 2004, vol. 43, p. 5063. doi 10.1002/anie.200460409