



Short communication

Gold-catalyzed cyclotrimerization of arynes for the synthesis of triphenylenes

Lili Chen ^{a,1}, Changyuan Zhang ^{b,1}, Chunxiao Wen ^b, Kun Zhang ^{a,b,*}, Wenfeng Liu ^b, Qian Chen ^{b,**}^a School of Chemical & Environmental Engineering, Wuyi University, Jiangmen, Guangdong 529020, China^b School of Chemical Engineering and Light Industry, Guangdong University of Technology, Guangzhou, Guangdong 510006, China

ARTICLE INFO

Article history:

Received 5 January 2015

Received in revised form 25 February 2015

Accepted 26 February 2015

Available online 28 February 2015

Keywords:

Aryne

Cyclotrimerization

Gold catalyst

Triphenylene

ABSTRACT

A novel and efficient Au(I)-catalyzed cyclotrimerization of arynes, generated by fluoride-induced elimination of Kobayashi's silylaryl triflates, is described. The reactions led to the formation of triphenylenes in 45–88% yields under mild conditions. © 2015 Elsevier B.V. All rights reserved.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Aryne chemistry has been of particular interest due to its high reactivity and broad applications in organic synthesis [1–4]. Recently, transition metal-catalyzed reactions involving arynes, which are generated by fluoride-induced elimination of Kobayashi's silylaryl triflate under mild conditions [5], have been well documented [6–17]. Since Guitián and co-workers [6] first reported Pd(0)-catalyzed cyclotrimerization of arynes to generate triphenylenes in 1998 (Scheme 1), a variety of important triphenylene derivatives, which demonstrated potent applications in organic materials, have been prepared under similar reaction conditions [18–25]. To our knowledge, there are many methods for triphenylene formation via arynes. For examples, the cyclotrimerization of benzyne catalyzed by Cu(I) (20 mol%) afforded triphenylene in refluxing CH₃CN (Scheme 1) [26], and triphenylenes were also isolated during attempts at obtaining a metal complex of arynes [27–30]. The efficient preparation of triphenylenes with a catalytic amount of promoters is still a demand to fulfill the modern synthesis.

Most recently, our group developed a novel Au(III)-catalyzed tetramerization of terminal electron-deficient alkynes to afford 1,2,5,6-tetrasubstituted-cyclooctatetraene (1,2,5,6-COT) [31]. We have been interested in studying gold-catalyzed cyclotrimerization of arynes (active π -components), which have seldom served as the substrate for

gold catalysis [9, 26]. Herein, we report that the use of PPh₃AuCl as the catalyst for the cyclotrimerization of arynes provides a convenient and general approach to triphenylenes under mild conditions (Scheme 1).

2. Experimental

2.1. General

All reactions were carried out under an atmosphere of argon/nitrogen using oven-dried glassware and standard syringe/septa techniques. Tetrahydrofuran (THF) was distilled from sodium. Acetonitrile (CH₃CN) and toluene were distilled from calcium hydride. 1,2-Dichloroethane (DCE) was dried over 4 Å molecular sieve. Hexanes refer to the petroleum fraction bp 40–60 °C. Commercial reagents were used without purification unless otherwise noted. Kobayashi's aryne precursors were prepared according to the literature [5]. Flash chromatography was performed using the indicated solvent system on silica gel standard grade 60 (230–400 mesh). ¹H NMR spectra were recorded on a 400 MHz spectrometer. ¹³C NMR spectra were recorded on a 100 MHz spectrometer. ¹⁹F NMR spectra were recorded on a 376 MHz spectrometer. Chemical shifts are reported relative to CDCl₃ (δ 7.26 ppm) for ¹H NMR and CDCl₃ (δ 77.00 ppm) for ¹³C NMR.

2.2. General procedure for gold-catalyzed cyclotrimerization of arynes

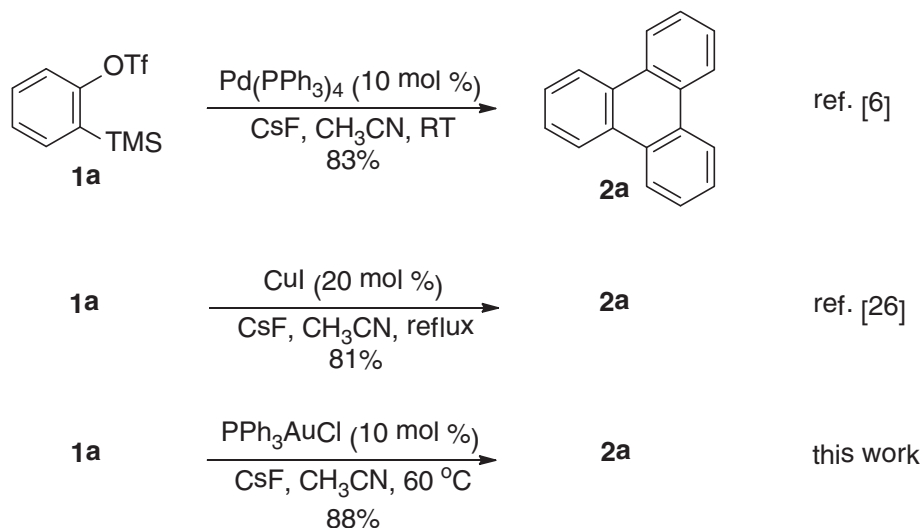
To a solution of Kobayashi's silylaryl triflate **1** (0.60 mmol) in anhydrous acetonitrile (3.0 mL), catalytic PPh₃AuCl (32 mg, 0.060 mmol) and CsF (182 mg, 1.2 mmol) were added. The mixture was stirred at 60 °C or room temperature for 6 h or 12 h. After removal of the solvent, the

* Correspondence to: K. Zhang, School of Chemical & Environmental Engineering, Wuyi University, Jiangmen, Guangdong 529020, China.

** Corresponding author.

E-mail addresses: kzhang@gdut.edu.cn (K. Zhang), qianchen@gdut.edu.cn (Q. Chen).

¹ The first two authors contributed equally to this work and are listed alphabetically.



Scheme 1. Overview of cyclotrimerization of benzyne using Kobayashi's precursor.

residue was then purified by flash column chromatography on silica gel (eluent = hexanes/ethyl acetate 40:1 v/v) to give the desired triphenylene **2**.

3. Results and discussion

The catalytic activity of AuCl_3 (10 mol%) was first tested for the reaction of benzyne precursor **1a** in the presence of CsF in DCE at room temperature (Table 1, entry 1) [31], and the desired triphenylene **2a** was not detected even when the reaction temperature was set to 60 °C (entry 2). To our delight, switching the solvent from DCE to CH_3CN led to the formation of cyclotrimerization product **2a** in 76% yield (entry 3) [32]. We then turned to screen other Au/Ag/Pt catalysts, and PPh_3AuCl was proved to be the optimum catalyst (92% yield, entry 8). When the catalytic amount of PPh_3AuCl was decreased to 5 mol%, the yield of **2a** was significantly decreased to 66% (entry 11). When the reaction was carried out at RT or 40 °C, the yield of **2a** was also decreased (entries 12, 13). Switching solvent from CH_3CN to THF did not increase the yield of triphenylene (entry 14). Thus, we concluded that the optimized combination for the cyclotrimerization of benzyne was to use 10 mol% of PPh_3AuCl as the catalyst, 2 equiv. of CsF as the fluoride ion, CH_3CN as the solvent, and the reaction was set at 60 °C (entry 8).

To investigate the scope of the cyclotrimerization protocol, we applied the optimum reaction conditions to a variety of Kobayashi's aryne precursors **1** and the results are illustrated in Table 2. Benzyne precursor **1a**, 4-methoxy-, 4-methyl-, 4-*tert*-butyl-, 4-trifluoromethoxy-, and 3,6-dimethyl-substituted aryne precursors **1b–1f** and naphthalene precursor **1g** were all well tolerated for the cyclotrimerization to give the corresponding triphenylenes in 45–88% yields. For unsymmetrical aryne precursors **1b–1e** and **1g**, the consistent 1:3 ratio of triphenylene regioisomers, which was in good agreement with the experimental results of Pd(0)-catalyzed cyclotrimerization of arynes [33], strongly demonstrated that these reactions involved an aryne pathway. It is noteworthy that the cyclotrimerization of **2c**, **2e** and **3g** also was achieved smoothly at room temperature, and the yields were even higher than those at 60 °C. We also tried the cyclotrimerization of **1** under optimum conditions with addition of a small amount of water (~5 equiv., 0.05 mL), and the reaction gave the desired product in 80% yield. We then tried $\text{Pd(PPh}_3)_4$ -catalyzed cyclotrimerization [6] of **1** with addition of the same amount of water, however, no desired product was detected. In comparison with Pd(0)-catalyzed reaction conditions, the

Au(I)-catalyzed cyclotrimerization of arynes was neither air nor moisture sensitive, which only decreased the yields slightly.

Based on the experimental results, a plausible mechanism [34] for the formation of triphenylenes, which is similar to that of Pd(0)-catalyzed cyclotrimerization [35], is proposed as shown in Scheme 2. Benzyne **3**, which is generated by fluoride-induced elimination of benzyne precursor **1a**, interacts with a cationic gold(I) complex ($[\text{PPh}_3\text{Au}^+]$) was probably formed in the presence of an excess of CsF) to form complex **4**. Subsequent cyclometallation of two molecules of **4** gives the organogold intermediate **5**, followed by one more benzyne insertion to produce complex **6**, which liberates the cyclotrimerization product triphenylene **2a** and the cationic gold(I) complex by demetallation.

Table 1
Gold-, silver- and platinum-catalyzed cyclotrimerization of benzyne.^a

Entry	Catalyst	Solvent	Temperature	Yield (%) ^b
1	AuCl_3	DCE	RT	–
2	AuCl_3	DCE	60 °C	–
3	AuCl_3	CH_3CN	60 °C	76
4	AuCl	CH_3CN	60 °C	14
5	$\text{PPh}_3\text{AuSbF}_6$	CH_3CN	60 °C	50
6	AgSbF_6	CH_3CN	60 °C	–
7 ^c	AgSbF_6	CH_3CN	60 °C	Trace
8	PPh_3AuCl	CH_3CN	60 °C	92 (88)^d
9	PtCl_2	CH_3CN	60 °C	–
10	PtCl_4	CH_3CN	60 °C	12
11 ^e	PPh_3AuCl	CH_3CN	60 °C	66
12	PPh_3AuCl	CH_3CN	40 °C	78
13	PPh_3AuCl	CH_3CN	RT	46
14	PPh_3AuCl	THF	60 °C	40

The significance of bold entries in table 1 shows the optimum conditions.

^a The reaction of **1a** (0.20 mmol) was carried out in the presence of 10 mol% of catalysts and CsF (0.40 mmol) in the corresponding solvent (1.0 mL) for 6 h.

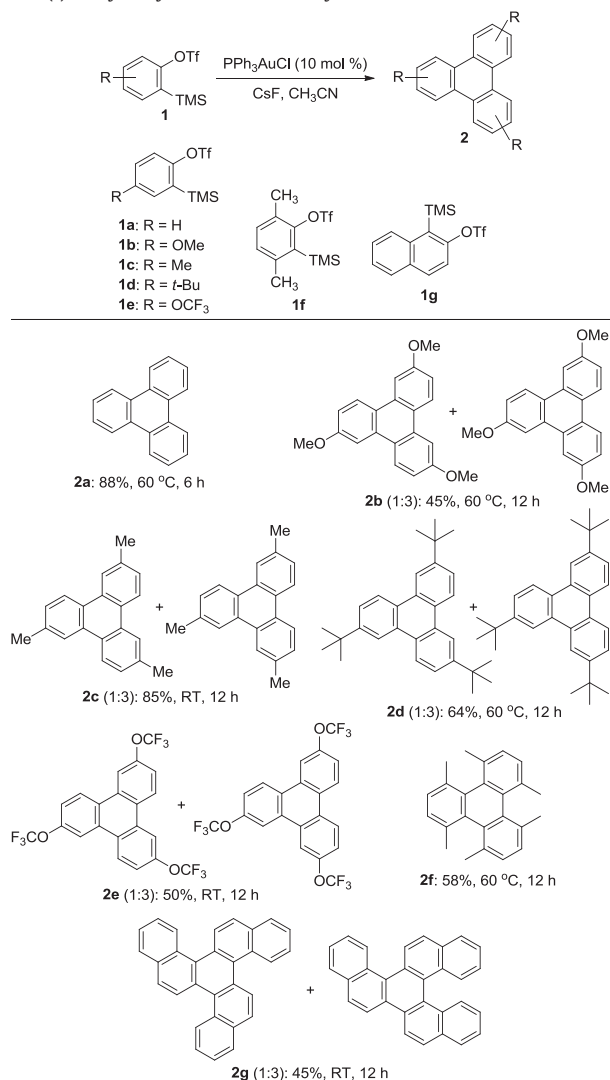
^b Yield was determined by ^1H NMR analysis of crude products using an internal standard.

^c PPh_3 (10 mol%) was added.

^d Isolated yield on 0.6 mmol scale in parentheses.

^e 5 mol% of PPh_3AuCl was used.

Table 2
Gold(I)-catalyzed cyclotrimerization of arynes.^{a,b,c}



^a The reaction of **1** (0.60 mmol) was carried out in the presence of PPh_3AuCl (0.060 mmol) and CsF (1.2 mmol) in CH_3CN (3.0 mL).

^b Isolated yield.

^c Ratio was determined by ^1H NMR analysis.

4. Conclusion

These results provide a facile entry to the synthesis of triphenylene derivatives which demonstrates that PPh_3AuCl is an efficient catalyst for the cyclotrimerization of arynes under mild conditions to give the desired products in up to 88% yield. To the best of our knowledge, this is the first study describing the efficient Au(I)-catalyzed cyclotrimerization of arynes. This interesting property of gold complexes should lead to new and useful applications in catalysis, organic synthesis and organic materials. Further investigations on the oligomerization of alkynes are ongoing and will be reported in due course.

Acknowledgments

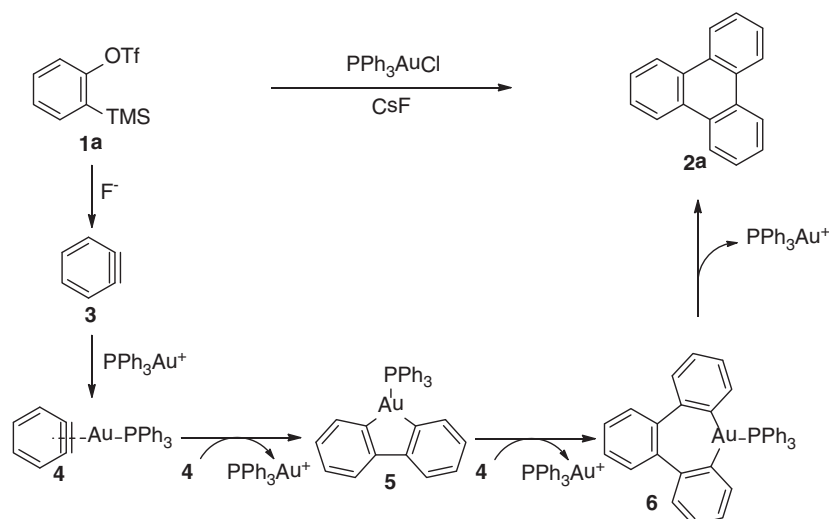
This work was supported by the National Natural Science Foundation of China (Project No. 21242002), 100 Young Talents Programme of Guangdong University of Technology, Guangdong Undergraduate Innovation Training Program (Project No. 1184513178), and the Open Funding of Hubei Novel Reactor & Green Chemical Technology Key Laboratory (Project No. RGCT201302).

Appendix A. Supplementary data

Supplementary data to this article (^1H and ^{13}C NMR spectra of **2**, and the ^{19}F NMR spectrum associated with **2e**) can be found online at <http://dx.doi.org/10.1016/j.catcom.2015.02.029>.

References

- [1] C.M. Gampe, E.M. Carreira, *Angew. Chem.* 124 (2012) 3829–3842; *Angew. Chem. Int. Ed.* 51 (2012) 3766–3778.
- [2] P.M. Tadross, B.M. Stoltz, *Chem. Rev.* 112 (2012) 3550–3577.
- [3] A.V. Dubrovskiy, N.A. Markina, R.C. Larock, *Org. Biomol. Chem.* 11 (2013) 191–218.
- [4] D. Pérez, D. Peña, E. Guitián, *Eur. J. Org. Chem.* 27 (2013) 5981–6013.
- [5] Y. Himeshima, T. Sonoda, H. Kobayashi, *Chem. Lett.* 12 (1983) 1211–1214.
- [6] D. Peña, S. Escudero, D. Pérez, E. Guitián, L. Castedo, *Angew. Chem. Int. Ed.* 37 (1998) 2659–2660.
- [7] N. Chatani, A. Kamitani, M. Oshita, Y. Fukumoto, S. Murai, *J. Am. Chem. Soc.* 123 (2001) 12686–12687.
- [8] J.C. Hsieh, D.K. Rayabarapu, C.H. Cheng, *Chem. Commun.* (2004) 532–533.
- [9] N. Asao, K. Sato, *Org. Lett.* 8 (2006) 5361–5363.
- [10] J.L. Henderson, A.S. Edwards, M.F. Greaney, *J. Am. Chem. Soc.* 128 (2006) 7426–7427.
- [11] Z. Liu, R.C. Larock, *Angew. Chem.* 119 (2007) 2587–2590; *Angew. Chem. Int. Ed.* 46 (2007) 2535–2538.
- [12] C.D. Gilmore, K.M. Allan, B.M. Stoltz, *J. Am. Chem. Soc.* 130 (2008) 1558–1559.
- [13] C. Xie, Y. Zhang, Y. Yang, *Chem. Commun.* (2008) 4810–4812.
- [14] F. Sha, X. Huang, *Angew. Chem.* 121 (2009) 3510–3513; *Angew. Chem. Int. Ed.* 48 (2009) 3458–3461.



Scheme 2. Plausible mechanism of Au(I)-catalyzed cyclotrimerization of benzyne.

- [15] A.T. Biju, F. Glorius, *Angew. Chem.* 122 (2010) 9955–9958; *Angew. Chem. Int. Ed.* 49 (2010) 9761–9764.
- [16] S.Y. Yun, K.P. Wang, N.K. Lee, P. Mamidipalli, D. Lee, *J. Am. Chem. Soc.* 135 (2013) 4668–4671.
- [17] H. Yoshida, R. Yoshida, K. Takaki, *Angew. Chem.* 125 (2013) 8791–8794; *Angew. Chem. Int. Ed.* 52 (2013) 8629–8632.
- [18] D. Peña, D. Pérez, E. Guitián, L. Castedo, *Org. Lett.* 1 (1999) 1555–1557.
- [19] D. Peña, A. Cobas, D. Pérez, E. Guitián, L. Castedo, *Org. Lett.* 2 (2000) 1629–1632.
- [20] D. Peña, A. Cobas, D. Pérez, E. Guitián, L. Castedo, *Org. Lett.* 5 (2003) 1863–1866.
- [21] B. Iglesias, A. Cobas, D. Pérez, E. Guitián, *Org. Lett.* 6 (2004) 3557–3560.
- [22] A. Sygula, R. Sygula, L. Kobryn, *Org. Lett.* 10 (2008) 3927–3929.
- [23] J. Yin, H. Qu, K. Zhang, J. Luo, X. Zhang, C. Chi, J. Wu, *Org. Lett.* 11 (2009) 3028–3031.
- [24] P.T. Lynett, K.E. Maly, *Org. Lett.* 11 (2009) 3726–3729.
- [25] J.M. Alonso, A.E. Díaz-Álvarez, A. Criado, D. Pérez, D. Peña, E. Guitián, *Angew. Chem.* 124 (2012) 177–181; *Angew. Chem. Int. Ed.* 51 (2012) 173–177.
- [26] C. Xie, L. Liu, Y. Zhang, P. Xu, *Org. Lett.* 10 (2008) 2393–2396.
- [27] M.A. Bennett, M.R. Kopp, E. Wenger, A.C. Willis, *J. Organomet. Chem.* 667 (2003) 8–15.
- [28] T.L. Gilchrist, F.J. Graveling, C.W. Rees, *J. Chem. Soc.* (1971) 977–980.
- [29] C.M. Buess, D.D. Lawson, *Chem. Rev.* 60 (1960) 313–330.
- [30] K.D. Bartle, H. Heaney, D.W. Jones, P. Lees, *Tetrahedron* 21 (1965) 3289–3296.
- [31] Q. Chen, C. Zhang, C. Wen, J. Fang, Z. Du, D. Wu, *Catal. Commun.* 56 (2014) 101–105.
- [32] For the first use of AuCl₃/MeCN, see: A.S.K. Hashmi, L. Schwarz, J.H. Choi, T.M. Frost, *Angew. Chem. Int. Ed.* 39 (2000) 2285–2288.
- [33] J.A. García-López, M.F. Greaney, *Org. Lett.* 16 (2014) 2338–2341.
- [34] A.S.K. Hashmi, *Angew. Chem. Int. Ed.* 49 (2010) 5232–5241.
- [35] E. Guitián, D. Pérez, D. Peña, in: J. Tsuji (Ed.), *Topics in Organometallic Chemistry*, Springer-Verlag, Weinheim, 2005, pp. 109–146.