Copper(I)-Catalyzed Tandem Carboarylation/Cyclization of Alkynyl Phosphonates with Diaryliodonium Salts

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ABSTRACT: A copper-catalyzed tandem carboarylation/cyclization of alkynyl phosphonates with diaryliodonium salts is reported. The reaction gives straightforward access to valuable cyclic enol phosphonates in good yields under mild conditions. This transformation entails an initial chemoselective arylation of the alkyne followed by an intramolecular trapping of an intermediate vinyl cation by the phosphoryl group. Observation of β-aryl rearrangements across the double bond in intermediates generated from 1,2-diaryl alkynes support the intermediacy of a vinyl cation.

KEYWORDS. Copper, diaryliodonium salts, phosphonates, alkynes, carbocations

Introduction

Phosphorus heterocycles represent an important class of compounds which exhibit a wide range of biological activities.[1] In particular, cyclic enol phosphonates bearing a tetrasubstituted double bond have found application as potent enzyme inhibitors (Figure 1).[2]

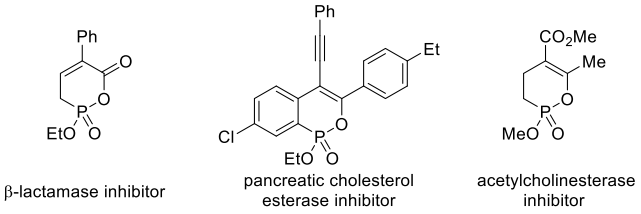
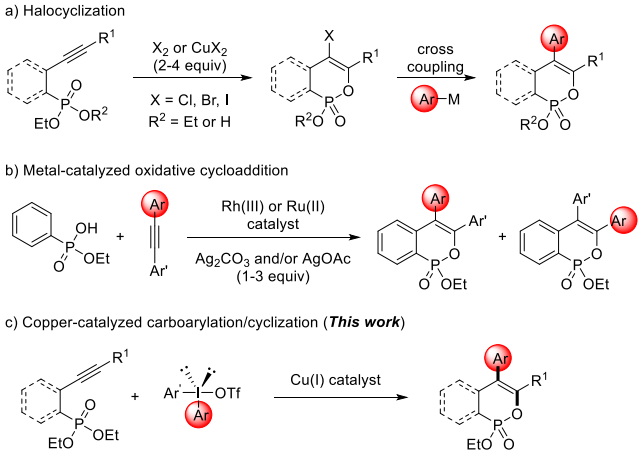


Figure 1. Examples of biologically active cyclic phosphonates

As a result, the development of new catalytic methodologies to prepare these important cyclic phosphonate derivatives is highly desirable. Synthetic methods for the preparation of these molecules mainly rely on multistep procedures based on halocyclization of alkynyl dialkyl phosphonates or phosphonic acid monoesters which are prepared from the former adding an extra step to the synthesis.[3] These transformations typically involve intramolecular nucleophilic attack by the oxygen of the phosphoryl group to the alkyne which is activated by coordination with a superstoichiometric amount of halide or metal halide (Scheme 1a). Resulting alkenyl halides can then be functionalized by cross-coupling procedures. Cyclic enol phosphonates have also been obtained by Rh- or Ru-catalyzed oxidative coupling of phosphonic acid monoesters and alkynes (Scheme 1b).[4] These reactions entail a more atom-efficient formation of cyclic phosphonates. However, they require the stoichiometric use of Ag salts as oxidants and are mainly limited to aromatic substrates which provide regioisomeric mixtures when unsymmetrical alkynes are used.

Scheme 1. Synthetic Methods for the Preparation of Cyclic Enol Phosphonates



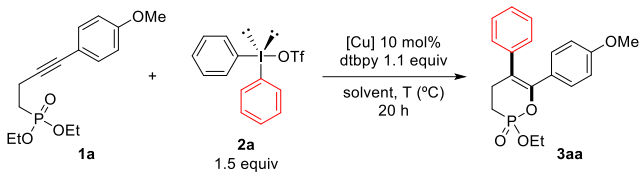
Diaryliodonium salts, which are air- and moisture-stable, non-toxic and easy to prepare compounds, have recently gained considerable attention as mild and selective arylating reagents in organic synthesis.[5] In particular, copper-catalyzed arylation with diaryliodonium salts has become a powerful tool for the development of a wide range of synthetic transformations.[6] These reactions typically involve the formation of a highly electrophilic aryl-Cu(III) intermediate by activation of the diaryliodonium salt with a Cu(I) catalyst.[7] This type of aryl-Cu(III) species has been described to activate alkynes forming a reactive intermediate which can then be trapped by a pendant nucleophile leading to aryl/cyclization processes.[8-11,12]

We envisioned that an alkynyl phosphonate could react with a diaryliodonium salt under Cu catalysis to afford an arylated cyclic enol phosphonate in a simple and efficient manner (Scheme 1c). This transformation would feature the concomitant formation of a C-C and a C-O bond and the use of a cheap and readily available catalyst thus representing a step and costly effective alternative for the synthesis of these important phosphorous compounds. Success of our proposed transformation would require a high level of chemoselectivity in the arylation step as competitive copper-catalyzed oxygen-arylation of the phosphonate group,[13] which has been described to occur under similar conditions than alkyne arylation,[8] has to be suppressed. We report here the development of a copper-catalyzed synthesis of cyclic enol phosphonates bearing tetrasubstituted double bonds from readily available alkynyl phosphonates. The new catalytic process is operationally simple, occurs under mild conditions and proceeds both with aliphatic and aromatic alkynyl phosphonates and a variety of diaryliodonium salts.

Results and discussion

Optimization studies. We started our studies by investigating the reaction between alkynyl phosphonate **1a** and diphenyliodonium triflate **2a** (Table 1).

Table 1. Screening of Reaction Conditions



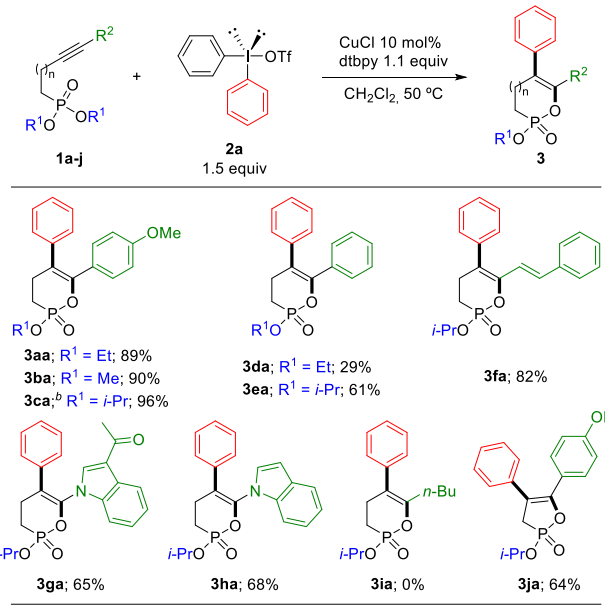
entry[a]	[Cu]	solvent	T (°C)	**3aa** yield(%)[b]
1[c]	CuCl	CH_2Cl_2	40	84
2[c]	CuTC	CH_2Cl_2	40	76
3[c]	$Cu(OTf)_2$	CH_2Cl_2	40	6
4[c]	CuCl	DCE	40	58
5[c]	CuCl	1,4-dioxane	40	60
6	CuCl	CH_2Cl_2	50	97 (89)[d]
7	CuCl	CH_2Cl_2	60	89[e]
8[f]	CuCl	CH_2Cl_2	50	64
9	-	CH_2Cl_2	60	0

[a]Reactions performed on a 0.1 mmol scale (0.1 M) in a sealed tube. [b]Determined by ^{1}H-NMR using Ph_3CH as internal standard. [c]Full conversion not achieved. [d]Yield of isolated product shown in brackets. [e]10% of O-arylation of **3aa** was observed. [f]In the absence of dtbpy. DCE = 1,2-dichloroethane.

To test the feasibility of our proposed carboarylation/cyclization process, we first run the reaction under the conditions reported for the copper-catalyzed O-arylation of phosphonates (CuCl as catalyst, 2,6-di-tert-butyl pyridine (dtbpy) as additive in dichloromethane at 40 °C).[13] To our delight cyclic enol phosphonate **3aa**, arising from a formal 6-endo-*dig* cyclization, was the only product of the reaction and no traces of O-arylation products were observed (entry 1). A screening of copper complexes (entries 1-3) and solvents (entries 4-5) revealed that CuCl/dichloromethane is the most efficient catalyst-solvent combination for this transformation. By carrying out the reaction at 50 °C, full conversion was achieved and cyclic phosphonate **3aa** was obtained in almost quantitative yield (entry 6). At higher temperature a decrease in yield was observed due to formation of a small amount of O-arylation of **3aa** (entry 7). Although reaction proceeded in the absence of dtbpy, product **3aa** was obtained in lower yield (entry 8). Importantly, no reaction took place in the absence of copper catalyst (entry 9). Moreover, in the absence of diaryliodonium salt no conversion of **1a** was observed thus ruling out a possible mechanism involving copper(I)-catalyzed cyclization[14] followed by oxidation of resulting vinylcopper species with the diaryliodonium salt.

Scope of the reaction. Having established optimized conditions for the carboarylation/cyclization of alkynyl phosphonates (Table 1, entry 6), we set out to investigate the scope of the reaction. We first explored the reaction of several alkynyl phosphonates **1** with diphenyliodonium triflate **2a** (Table 2).

Table 2. Scope of Dialkyl γ-Alkynyl Phosphonates 1[a]



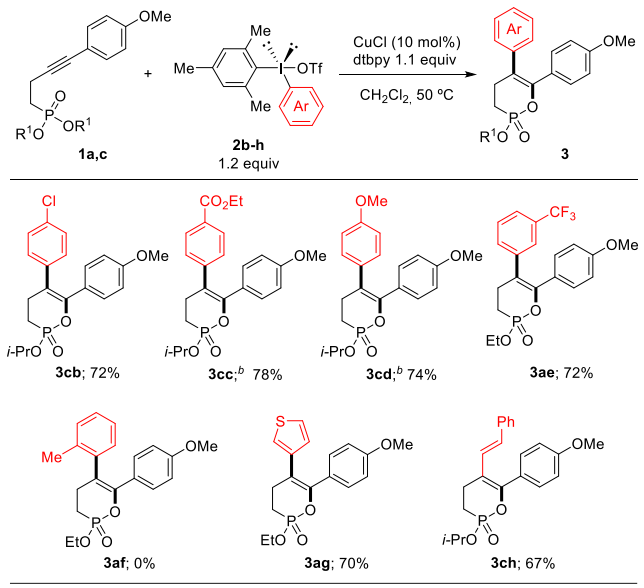
[a] Reactions performed on a 0.2 mmol scale. Yields refer to isolated pure products. [b] 1.1 equiv of **2a**.

This catalytic transformation proved to be very efficient for several dialkylphosphonates bearing methyl, ethyl or isopropyl groups providing products **3aa-ca** in very good yields. Diisopropyl phosphonate **1c** showed higher reactivity and it was necessary to decrease the amount of **2a** (1.1 equiv) to avoid further product O-arylation. We observed that the nature of the substituent on the triple bond played an important role in the outcome of the reaction. Besides the *p*-anisyl group, a phenyl group was suitable

enough to perform the reaction although in this case diethylphosphonate **1d** led to product **3da** in a diminished yield.[15] However, the use of diisopropylphosphonate **1e** allowed to obtain the corresponding product **3ea** in restored yield. Substrate **1f** bearing a styrenyl group also worked well and led to product **3fa** in good yield. This new methodology is also applicable to alkynyl phosphonates bearing heteroaryl groups as illustrated by the synthesis of indole-substituted cyclic enol phosphonates **3ga** and **3ha**. Importantly, no arylation on the C2 or C3 position on the indole group[6b] was observed further highlighting the high level of chemoselectivity of this catalytic reaction. On the other hand, substrate **1i** bearing an alkyl group on the alkyne did not give any conversion. Interestingly, a formal arylation/5-endo-*dig* cyclization was also possible as shown for the synthesis of five-membered phosphonate **3ja**.

Different arylmesityliodonium salts were used for this carboarylation/cyclization of alkynyl phosphonates (Table 3). These unsymmetrical diaryliodonium salts bearing a bulky mesityl ligand allow the selective transfer of the other aryl group under copper-catalysis.[6] This approach is attractive from a practical point of view as only one equivalent of the desired transferring aryl group is required. Furthermore, these diaryliodonium salts are easily prepared from commercially available reagents in one-pot operations.[16]

Table 3. Scope of Diaryliodonium Salts[a]

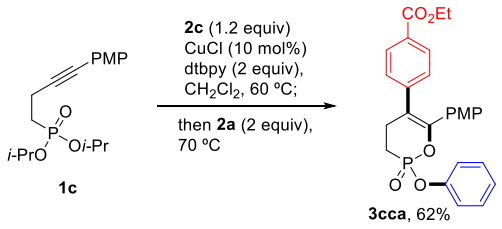


[a] Reactions performed on a 0.2 mmol scale. Yields refer to isolated pure products. [b] Reaction run at 60 °C.

Diaryliodonium salts **2b-e** bearing *meta*- and *para*-substituents all worked well in combination with both diethyl and diisopropyl alkynyl phosphonates independently of the electronic nature of the aryl group. The corresponding cyclic phosphonates **3** were exclusively obtained in good yields (Table 3). In sharp contrast, no conversion was observed when diaryliodonium salt **2f** displaying an *ortho*-methyl substituted aryl group was used, probably due to its steric hindrance which imposes lower reactivity to this salt.[8] Importantly, this tandem C-C/C-O bond forming reaction was also suitable for the transfer of heteroaryl and vinyl groups as shown by the synthesis of cyclic phosphonates **3ag** and **3ch**.

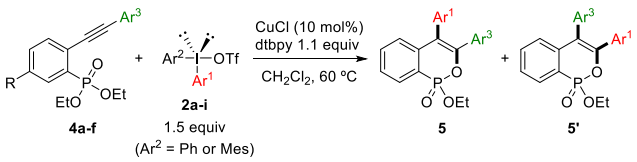
Interestingly, the present methodology could be combined with the copper-catalyzed O-arylation of phosphonates[13] to perform a selective one-pot diarylation with two different diaryliodonium salts in which CuCl acts as the same catalyst for both arylation reactions.[17] Thus, treatment of phosphonate **1c** with diaryliodonium salt **2c** under optimized conditions and subsequent addition of **2a** afforded the diarylated product **3cca** in good yield (Scheme 2).

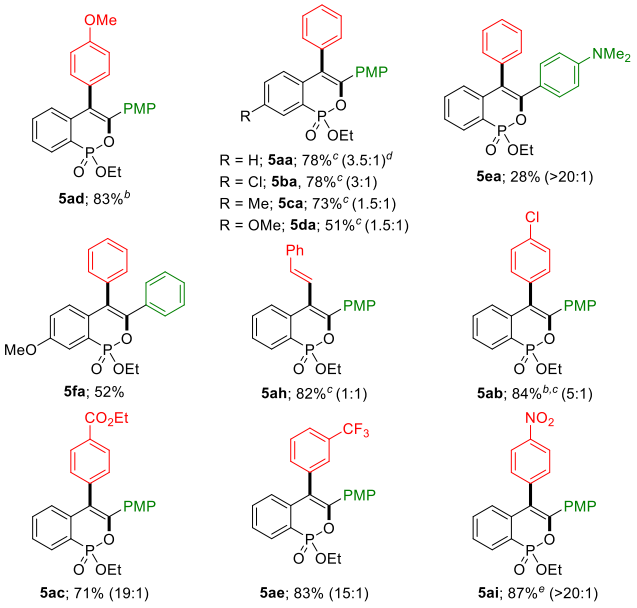
Scheme 2. Copper-catalyzed one-pot diarylation with two different diaryliodonium salts



Once having studied the behavior of alkynyl phosphonates **1** bearing an aliphatic linking unit we turned our attention to aromatic substrates **4** (Table 4).

Table 4. Copper-catalyzed carboarylation/cyclization of aromatic alkynyl phosphonates[a]



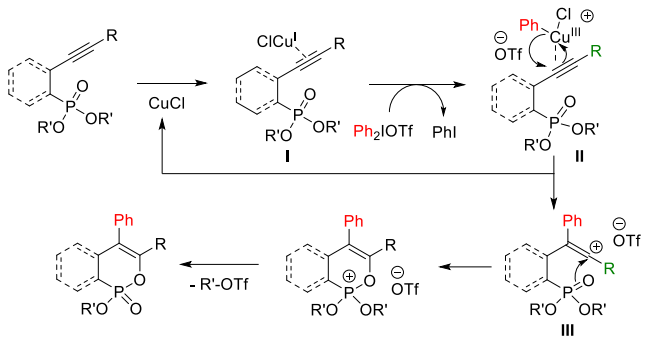


[a] Reactions performed on a 0.2 mmol scale. Yields refer to isolated pure products. PMP = 4-OMe-C_6H_4. [b] 2 equiv of **2** were used. [c] Combined yield of both isomers. [d] Regioisomeric ratio (**5**:**5'**) shown in brackets. [e] Reaction run at 70 °C.

The carboarylation/cyclization of alkynyl phosphonates **4** would give straightforward access to tetrasubstituted phosphaisocoumarins which resemble the structure of potent inhibitors for pancreatic cholesterol esterase (Figure 1).[2c] We were pleased to find that treatment of phosphonate **4a** with mesityl *para*-methoxyphenyliodonium triflate **2d** under the optimized conditions gave rise to the formation of phosphaisocoumarin **5ad** in very good yield. Interestingly, when diaryliodonium triflates bearing a transferable group different than *p*-anisyl were used the corresponding products **5** were obtained in good yields as variable mixtures of two regioisomers in which one of them displayed a shifted *p*-anisyl group.[18] Reaction of phosphonate **4a** with diphenyliodonium triflate **2a** gave rise to a 3.5:1 mixture of **5aa** and **5'aa**. Similar result was obtained with chloro-substituted phosphonate **4b** (**5ba**:**5'ba** = 3:1) while the use of substrates **4c** and **4d** bearing a more electron rich substituent on the arylphosphonate ring gave rise to an almost equimolar isomeric ratio. Substrate **4e** bearing a more electron rich *para*-dimethylamino phenyl group on the alkyne afforded product **5ea** with total regioselectivity albeit in a diminished yield. A phenyl group was also tolerated as alkyne substituent although in this case it was necessary to run the reaction with the more electron rich substrate **4f** to obtain the corresponding phosphoisocoumarin **5fa**.[19] The electronic nature of the transferring aryl group of the diaryliodonium salt plays a crucial role on the outcome of the reaction. While the use of a electron rich mesitylstyrenyliodonium triflate **2h** gave rise to a 1:1 mixture of **5ah** and **5'ah**, the use of diaryliodonium salt **2b** bearing a *p*-chloro susbtituted aryl group led to an increase of the regioisomeric ratio (**5ab**:**5'ab** = 5:1). Importantly, this selectivity trend could be further exploited to control the regioselectivity of the reaction. Thus, by using more electron deficient diaryliodoniums salts **2c**, **2e** and **2i** the corresponding products **5** were obtained almost exclusively.

Mechanistic considerations. An important mechanistic feature of the copper-catalyzed carboarylation/cyclization of alkynes with diaryliodoinum salts is the nature of the reactive intermediate which is formed during the arylation step. Different intermediates have been proposed depending on the nature of the pendant nucleophile. While Gaunt[8,9a] and Chen[9b,11] described the formation of vinyl carbocation type intermediates in cyclizations involving Friedel-Crafts processes,[8] hydride migration[9] or etherification,[11] Novák proposed a mechanism for the arylation/cyclization of alkynyl amides which entails the attack of the amide group to an aryl-Cu(III)-acetylene complex and subsequent reductive elimination of the formed vinylcopper species.[10] On the basis of our experimental observations, in which the strong effect of the alkyne substituent resembles the requirements for vinyl cation stabilization,[20] we propose the following mechanism for the copper-catalyzed carboarylation/cyclization of alkynyl phosphonates with diaryliodonium salts (Scheme 3). Initially, the Cu(I) catalyst would coordinate the alkyne forming intermediate **I**.[21] Subsequent oxidation with diaryliodonium salt would give rise to a coordinated Cu(III) intermediate **II** which would undergo intramolecular nucleophilic attack of the alkyne with concomitant formation of vinyl cation intermediate **III** and regeneration of the Cu(I) catalyst after reductive elimination. Subsequent intramolecular nucleophilic attack of the oxygen of the phosphoryl group followed by Arbuzov-type alkyltriflate elimination[13] would afford the cyclic enol phosphonate.

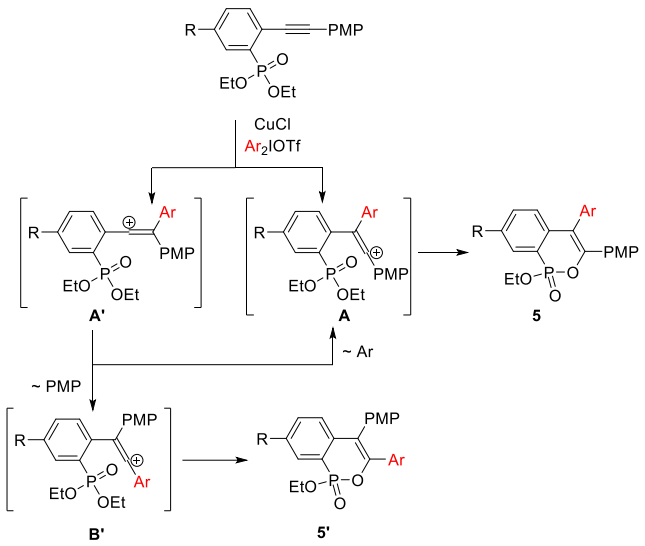
Scheme 3. Proposed mechanism for the Cu-catalyzed carboarylation/cyclization of alkynyl phosphonates



An interesting observation made in the copper-catalyzed carboarylation/cyclization of aromatic alkynylphosphonates **4** was the formation of variable regioisomeric mixtures of products **5** and **5'**. As aromatic substituents are known to stabilize vinyl cations,[20] the arylation of 1,2-diarylalkynes **4** could occur on both sites of the alkyne (Scheme 4). Intermediate **A** would evolve, as explained above, by intramolecular trapping affording compound **5**. On the other hand, intramolecular trapping to afford a five-membered heterocycle might be slower (or no competitive) in intermediate **A'** and β-aryl rearrangement across the double bond would occur faster.[20b,22] Depending on both the stabilization ability of the rearrangement transition state (**A'**-->**A** or **A'**-->**B'**) and of the different vinyl cations by each aryl group, intermediate **A'** would undergo migration of the aryl unit transferred by the diaryliodonium salt giving intermediate **A** or would evolve through β-anisyl rearrangement leading to intermediate **B'** which would afford product **5'** by nucleophilic attack of the phosphoryl group. Given the higher migratory aptitude of the anisyl vs. the phenyl group,[22] formation of **B'** from **A'** would be more favorable and the formation of **5** as the major isomer could account for a more efficient stabilization of vinyl cation **A**. Decrease in the regioisomeric ratio in **5ca** and **5da** could be attributed to a higher stabilization of the corresponding vinyl intermediate **A'** due to the presence of a electron-donating group in the aryl phosphonate group. On the other hand, the presence on the alkyne of a more electron rich substituent such as the *p*-dimethylaminophenyl group leads to the formation of a single product probably due to a better stabilization of the vinyl cation intermediate **A**. The high regioselectivity observed for the use of diaryliodonium salts bearing an electron-deficient aryl group may arise from the poor ability of this type of aryl groups as α-vinyl

cation stabilizers which would preclude the migration of the anisyl group across the double bond of intermediate **A'**.

Scheme 4. Rationale for the formation of regioisomers 5 and 5'



Conclusions

In summary, we have developed an efficient copper-catalyzed tandem carboarylation/cyclization of alkynyl phosphonates with diaryliodonium salts. The reaction occurs with excellent level of chemoselectivity, as no traces of O-arylation are observed, and affords cyclic enol phosphonates in high yields under relatively mild conditions. Moreover, copper catalysis can also be applied to one-pot diarylation processes with two distinct diaryliodonium salts. We believe this transformation proceeds through the formation of an intermediate vinyl cation which is intramolecularly trapped by nucleophilic attack of the phosphoryl group. Observed β-aryl rearrangements across the double bond in 1,2-diaryl systems further suggest the intermediacy of a vinyl cation.

ASSOCIATED CONTENT

Supporting Information. Experimental procedures and characterization data. This material is available free of charge via the Internet at http://pubs.acs.org.

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REFERENCES

(1) (a) Quin, L. D. *A Guide to Organophosphorus Chemistry*; ; Wiley-Interscience: New York, 2000. (b) McGrath, J. W.; Chin, J. P.; Quinn, J. P. *Nat. Rev. Microbiol.* **2013**, *11*, 412-419.

(2) (a) Kaur, K.; Lan, M. J. K.; Pratt, R. F. *J. Am. Chem. Soc.* **2001**, *123*, 10436-10443. (b) Kaur, K.; Adediran, S. A.; Lan, M. J. K.; Pratt, R. F. *Biochemistry*, **2003,** *42*, 1529-1536. (c) Li, B.; Zhou, B.; Lu, H.; Ma, L.; Peng, A. Y. *Eur. J. Med. Chem.* **2010**, *45*, 1955-1963. (d) Dutta, S.; Malla, R. K.; Bandyopadhyay, S.; Spilling, C. D.; Dupureur, C. M. *Bioorg. Med. Chem.* **2010**, *18*, 2265-2274.

(3) (a) Peng, A.-Y.; Ding, Y.-X. *Org. Lett.* **2004**, *6*, 1119-1121. (b) Peng, A.-Y.; Ding, Y.-X. *Tetrahedron* **2005**, *61*, 10303-10308. (c) Peng, A.-Y.; Hao, F.; Li, B.; Wang, Z.; Du, Y. *J. Org. Chem.* **2008**, *73*, 9012-9015. (d) André, V.; Robin, S.; Rousseau, G. *Tetrahedron Lett.* **2008**, *49*, 5059-5062. (e) Huang, J.; Wang, H.; Peng, A.-Y. *Eur. J. Org. Chem.* **2014**, *2014*, 8126-8132.

(4) (a) Unoh, Y.; Hashimoto, Y.; Takeda, D.; Hirano, K.; Satoh, T.; Miura, M. *Org. Lett.* **2013**, *15*, 3258-3261. (b) Seo, J.; Park, Y.; Jeon, I.; Ryu, T.; Park, S.; Lee, P. H. *Org. Lett.* **2013**, *15*, 3358-3361. (c) Park, Y.; Seo, J.; Park, S.; Yoo, E. J.; Lee, P. H. *Chem. - Eur. J.* **2013**, *19*, 16461-16468. (d) Park, Y.; Jeon, I.; Shin, S.; Min, J.; Lee, P. H. *J. Org. Chem.* **2013**, *78*, 10209-10220.

(5) (a) Zhdankin, V. V.; Stang, P. J. *Chem. Rev.* **2008,** *108*, 5299-5358. (b) Merritt, E. A.; Olofsson, B. *Angew. Chem., Int. Ed.* **2009**, *48*, 9052-9070. (c) Aradi, K.; Tóth, B. L.; Tolnai, G. L.; Novák, Z. *Synlett* **2016,** *27*, 1456-1485.

(6) For a review, see: (a) Fañanás-Mastral, M. *Synthesis* **2017**, *49*, 1905-1930. For selected examples, see: (b) Phipps, R. J.; Grimster, N. P.; Gaunt, M. J. *J. Am. Chem. Soc.* **2008**, *130*, 8172-8174. (c) Phipps, R. J.; Gaunt, M. J. *Science* **2009**, *323*, 1593-1597. (d) Zhu, S.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2012**, *134*, 10815-10818. (e) Suero, M. G.; Bayle, E. D.; Collins, B. S. L.; Gaunt, M. J. *J. Am. Chem. Soc.* **2013**, *135*, 5332-5335. (f) Collins, B. S. L.; Suero, M. G.; Gaunt, M. J. *Angew. Chem., Int. Ed.* **2013**, *52*, 5799-5802. (g) Xu, Z.-F.; Cai, C.-X.; Liu, J.-T. *Org. Lett.* **2013**, *15*, 2096-2099. (h) Wang, Y.; Chen, C.; Peng, J.; Li, M. *Angew. Chem., Int. Ed.* **2013**, *52*, 5323-5357. (i) Cahard, E.; Male, H. P. J.; Tissot, M.; Gaunt, M. J. *J. Am. Chem. Soc.* **2015**, *137*, 7986-7989. (j) Beaud, R.; Phipps, R. J.; Gaunt, M. J. *J. Am. Chem. Soc.* **2016**, *138*, 13183–13186. (k) Teskey, C. J.; Sohel, S. M. A.; Bunting, D. L.; Modha, S. G.; Greaney, M. J. *Angew. Chem., Int. Ed.* **2017**, *56*,5263-5266.

(7) (a) Beringer, F. M.; Bodlaender, P.; *J. Org. Chem.* **1969**, *34*, 1981-1985. (b) Lockhart, T. P. *J. Am. Chem. Soc.* **1983**, *105*, 1940-1946. For reviews on high-valent organometallic copper complexes, see: (c) Hickman, A. J.; Sanford, M. S. *Nature*, **2012**, *484*, 177-185. (d) Casitas, A.; Ribas, X. *Chem. Sci.*, **2013**, *4*, 2301-2318.

(8) Walkinshaw, A. J.; Xu, W.; Suero, M. G.; Gaunt, M. J. *J. Am. Chem. Soc.* **2013**, *135*, 12532-12535.

(9) (a) Zhang, F.; Das, S.; Walkinshaw, A. J.; Casitas, A.; Taylor, M.; Suero, M. G.; Gaunt, M. J. *J. Am. Chem. Soc.* **2014**, *136*, 8851-8854. (b) Peng, J.; Chen, C.; Chen, J.; Su, X.; Xi, C.; Chen, H. *Org. Lett.* **2014**, *16*, 3776-3779.

(10) (a) Sinai, Á.; Mészáros, Á.; Gáti, T.; Kudar, V.; Palló, A.; Novák, Z. *Org. Lett.* **2013**, *15*, 5654-5657. (b) Sinai, Á.; Vangel, D.; Gáti, T.; Bonbicz, P.; Novák, Z. *Org. Lett.* **2015**, *17*, 4136-4139.

(11) Chen, J.; Chen, C.; Chen, J.; Wang, G.; Qu, H. *Chem. Commun.* **2015**, *51*, 1356-1359.

(12) For examples on Pd(II)-catalyzed tandem reactions of alkynes and diaryliodonium salts, see: (a) Tang, S.; Peng, P.; Zhong, P.; Li, J.-H. *J. Org. Chem.* **2008**, *73*, 5476-5480. (b) Lopez Suarez, L.; Greaney, M. F. *Chem. Commun.* **2011**, *47*, 7992–7994.

(13) Fañanás-Mastral, M; Feringa, B. L. *J. Am. Chem. Soc.* **2014**, *136*, 9894-9897.

(14) Peng, A.-Y.; Ding, Y.-X. *J. Am. Chem. Soc.* **2003**, *125*, 15006-15007.

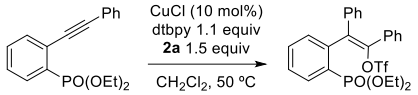
(15) When reaction was run with an alkynyl phosphonate bearing an electron poor aromatic substituent such as *p*-trifluoromethylphenyl group, a complex mixture of products was obtained.

(16) Bielawski, M.; Zhu, M.; Olofsson, B. *Adv. Synth. Catal.* **2007**, *349*, 2610-2618.

(17) Arylation of **3cc** did not occur in the absence of CuCl.

(18) Structure of regioisomers was determined by 2D-NMR spectroscopy of separated pure isomers (See Supporting Information for further details).

(19) When reaction was run with substrate **4g**, vinyl triflate **6** was obtained as single reaction product. For this type of reactivity see ref. 6e.

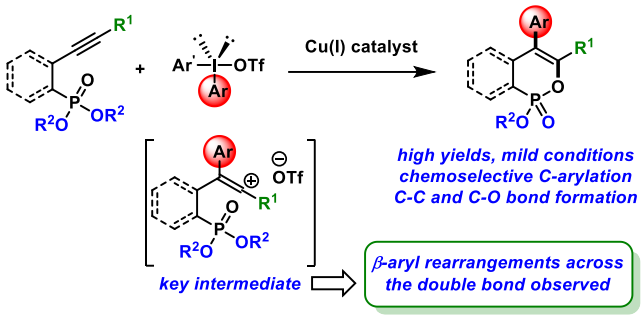


4g **6**, 32%

(20) (a) Hanack, M. *Acc. Chem. Res.* **1976**, *9*, 364-371. (b) *Vinyl cations*; Stang, P. J.; Rappoport, Z.; Hanack, M.; Subramanian, L. R. Eds.; Academic Press: New York, 1979. (c) Okuyama, T. *Acc. Chem. Res.* **2002**, *35*, 12-18.

(21) This initial coordination might explain the high chemoselectivity of this transformation. Formation of a non-coordinated aryl-Cu(III) intermediate could lead to competing O-arylation of the phosphonate group (ref. 13) given the high oxophilicity of this type of Cu complexes: Xu, Z.-F.; Cai, C.-X.; Jiang, M.; Liu, J.-T. *Org. Lett.* **2014**, *16*, 3436-3439.

(22) For studies on β-aryl rearrangements across the double of *p*-anisyl and phenyl groups on related triarylvinyl cations, see: (a) Rappoport, Z.; Houminer, Y. *J. Chem. Soc., Perkin Trans. 2,* **1973**, 1506-1518. (b) Rappoport, Z.; Noy, E.; Houminer, Y. *J. Am. Chem. Soc.* **1976**, *98*, 2238-2244.


Cu(I) catalyst
high yields, mild conditions
chemoselective C-arylation
C-C and C-O bond formation
key intermediate
β-aryl rearrangements across
the double bond observed