ChemPubSoc Europe

DOI: 10.1002/chem.201504852

CHEMISTRY A European Journal Full Paper

Synthetic Methods

Generation of Aryl Radicals through Reduction of Hypervalent Iodine(III) Compounds with TEMPONa: Radical Alkene Oxyarylation

Marcel Hartmann,[a] Yi Li,[a] Christian Mück-Lichtenfeld,[a, b] and Armido Studer*[a]

Abstract: A novel method for selective generation of aryl radicals from diaryliodonium salts and iodanylidene malonates with sodium 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPONa) as a single-electron transfer (SET) reducing reagent is described. In the presence of various alkenes, aryl radicals formed after SET-reduction of hypervalent iodine compounds undergo alkene addition and the adduct radicals that are thus generated are efficiently trapped by the concomitantly generated TEMPO radical to eventually afford oxyarylated products in moderate to very good yields. The efficiency of aryl radical generation of various iodine(III) reagents is studied and the generation of an iodanylidene malonate aryl radical is also investigated by computational methods.

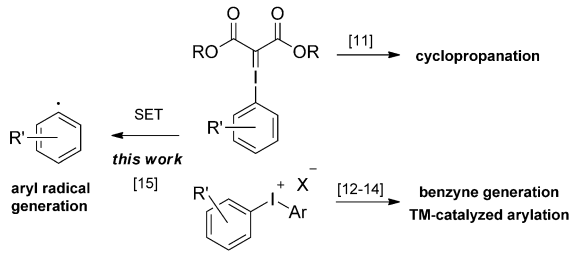
Introduction

For decades, carbon-centred radicals have played an important role as reactive intermediates in the field of synthetic organic chemistry. Along these lines, aryl radicals show great potential for C–C bond-forming reactions.[1] They can be used in aryl couplings without the need for expensive transition-metal catalyst. Aryl radicals have been generated by reduction of aryl halides with reducing reagents such as tin hydride[1] or samarium iodide,[2] by reduction of (in situ generated) diazonium salts,[3,4,5a–e] or by oxidation of aryl hydrazines.[5f–h] However, despite these achievements, the development of novel complementary methods that allow for selective and clean generation of aryl radicals is still of importance, because novel processes will offer new options for the design of radical cascades with alternative radical precursors. A general problem in aryl radical chemistry lies in the high reactivity of these intermediates, which renders their clean and selective generation and, in particular, their application in intermolecular C–C bond-forming reactions challenging.

Hypervalent iodine(III) compounds derived from *ortho*-iodobenzoic acid have found widespread application in transition-metal catalyzed cyanations or alkynylations proceeding through nonradical mechanisms.[6,7] Recently, we have successfully used these types of iodine compounds for the clean generation of trifluoromethyl-, perfluoroalkyl- or azidyl radicals.[8–10] Importantly, given that azidyl radicals are reactive, high-energy species,[10] we deduce from these results that iodine(III) compounds should be valuable and perhaps even general precursors for nonstabilised radicals through single-electron transfer (SET) reduction.

Iodanylidene malonates have mainly been used for cyclopropanation,[11] and, to our knowledge, their application for aryl radical generation has not been reported. There are well-established protocols that use diaryliodonium salts for metal-catalysed cross-coupling reactions, α-arylations of carbonyl compounds, heteroatom arylations or for benzyne generation.[12–14] However, their application as aryl radical precursors is not well explored. Diaryliodonium salts have been used in photoredox catalysed radical arylations,[15a–d] and transition-metal-free heteroarene arylation with such iodonium salts have been reported.[15e]

Motivated by these results, we wondered whether hypervalent iodine compounds such as iodanylidene malonates and diaryliodonium salts can be used for the selective generation of aryl radicals in the absence of any transition metal upon SET-reduction with an organic electron donor (Scheme 1). We



Scheme 1. Use of iodanylidene malonates and diaryliodonium salts as precursors for reactive intermediates.

[a] *M. Hartmann, Dr. Y. Li, Dr. C. Mück-Lichtenfeld, Prof. Dr. A. Studer*
Organisch-Chemisches Institut
Westfälische Wilhelms-Universität
Corrensstraße 40, 48149 Münster (Germany)
E-mail: studer@uni-muenster.de

[b] *Dr. C. Mück-Lichtenfeld*
Center for Multiscale Theory and Computation
Westfälische Wilhelms-Universität
Corrensstraße 40, 48149 Münster (Germany)

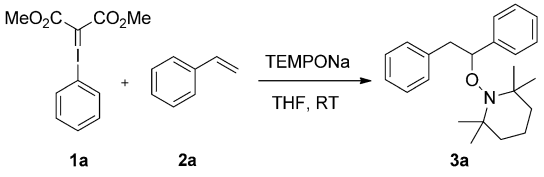
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/chem.201504852.

report herein two new protocols for aryl radical generation from iodanylidene malonates and diaryliodonium salts with the sodium 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPONa) salt[4,8,10,16,17] as an organic SET reducing reagent. Moreover, we will show that this approach for aryl radical generation can be implemented in cascade reactions comprising alkene arylation followed by TEMPO trapping to afford 1,2-oxyarylated products. In addition, we will discuss the mechanism of aryl radical generation from iodanylidene malonates upon SET reduction based on DFT calculations.

Results and Discussion

Iodanylidene malonates were investigated first. The I^{III} reagents are readily prepared by first oxidising the iodoarene with Selectfluor in acetic acid to give the corresponding bisacetoxy I^{III} reagents. Treatment of these I^{III} reagents with the K-enolate of the dialkylmalonate afforded the iodanylidene malonates (for details, see the Supporting Information). As a test reaction, oxyarylation of styrene with dimethyl 2-(phenyl-λ^3-iodanylidene)malonate (**1a**) as a radical precursor and TEMPONa as a stoichiometric SET reducing reagent to afford alkoxyamine **3a** was chosen (Table 1). Reactions were conducted under an argon atmosphere in tetrahydrofuran (THF) at room temperature and the TEMPONa solution was added over 2 min. We noted slow decomposition of **1a** in solution under the applied conditions (see the Supporting Information), thus it was clear that the reaction time had to be kept short.

Table 1. Oxyarylation of styrene with **1a** and TEMPONa.



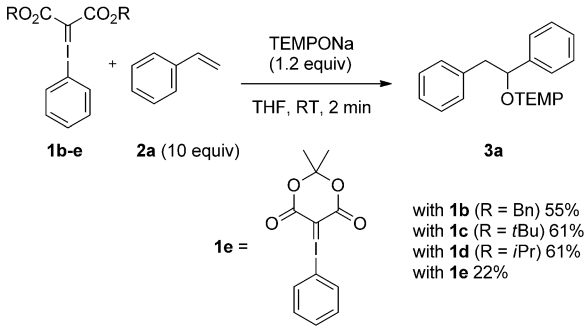
1a **2a** **3a**

Entry	**2a** [equiv]	Time [min][a]	Yield [%]
1	1.5	2	49
2	2.0	2	51
3	5.0	2	64
4	10.0	2	77
5	10.0	30	71
6	10.0	120	61
7	10.0	120	70[b]

[a] Time period used for TEMPONa addition (for the 0.5 h and 2.0 h experiments, TEMPONa was added by using a syringe pump). [b] With 2,6-diethyl-2,3,6-trimethylpiperidin-*N*-oxy-Na instead of TEMPONa.

The initial experiment was performed with 1.5 equivalent of styrene, and we were delighted to see that the target oxyarylation product **3a** was formed in 49% yield (Table 1, entry 1). This initial result clearly revealed that the 2-(phenyl-λ^3-iodanylidene)malonate serves as a phenyl radical precursor. Surprisingly, products derived from fragmentation towards the malonyl radical anion were not identified, indicating that SET-reduction leads to selective fragmentation of the phenyl radical (see also computational studies below). As a side product in this and the following experiments, TEMPO-C_6H_5 derived from direct trapping of the phenyl radical with TEMPO is formed.[18] A similar yield was achieved by using 2.0 equivalents of styrene under otherwise identical conditions (entry 2). Further increasing the amount of radical acceptor to 5.0 equivalents led to an increase in the isolated yield (64%; entry 3) and the best result (77%) was obtained with a tenfold excess of styrene (entry 4). Extending the reaction time by adding TEMPONa over a longer period provided worse results, likely due to decomposition of starting **1a** (entries 5 and 6). To suppress initial trapping of the phenyl radical by TEMPO, we also tested a bulkier TEMPO analogue. However, compared with TEMPONa, oxyarylation with the 2,6-diethyl-2,3,6-trimethylpiperidin-*N*-oxy Na salt provided the corresponding alkoxyamine in slightly lower yield (70%; entry 7). Therefore, the following experiments were conducted with the readily generated TEMPONa salt.

We next tested whether the ester substituent in the iodanylidene has an effect on aryl radical generation. To this end, phenyl radical precursors dibenzyl-, di-*tert*-butyl- diisopropyl- and 2,2-dimethyl-5-(phenyl-λ^3-iodanylidene)-1,3-dioxane-4,6-dione (**1b–e**) were reacted under the optimised conditions (see Table 1, entry 4) with styrene and TEMPONa to yield **3a** in 22–61% yield (Scheme 2). Compared with the methyl

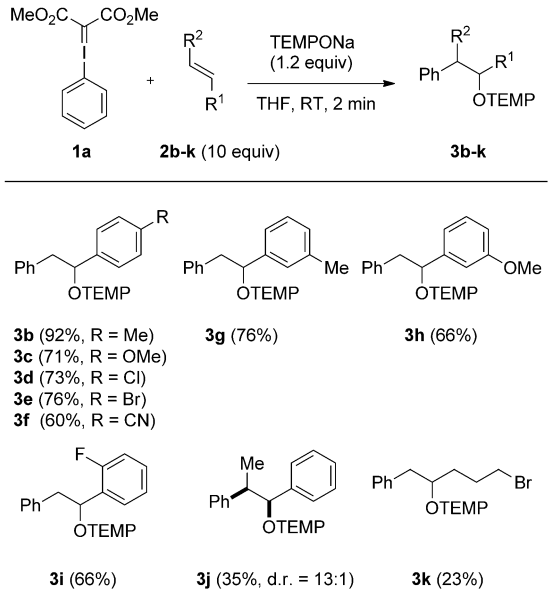


Scheme 2. Variation of the iodanylidene malonates.

congener **1a**, use of bulkier malonates **1b–d** led to slightly lower yields, and the cyclic derivative **1e** led to significantly lower yield. These results reveal that methyl derivative **1a** was the most efficient phenyl radical precursor in this series.

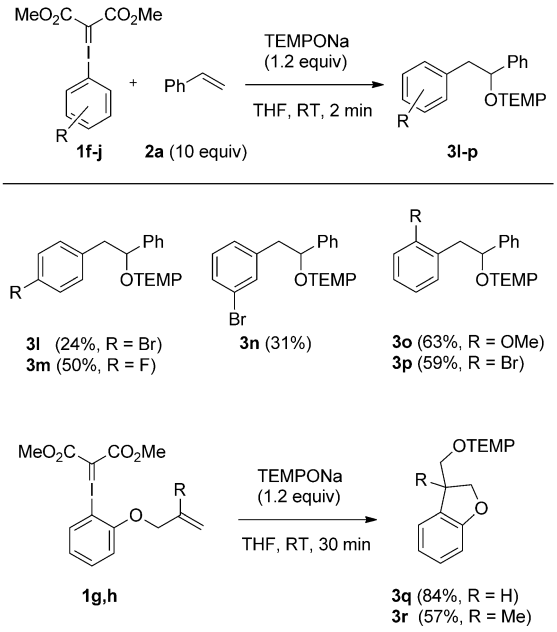
We therefore kept **1a** as radical precursor and then varied the radical acceptor. Various styrenes **2b–i** bearing either electron-donating or electron-withdrawing substituents were successfully reacted under the optimised conditions to give the oxyphenylated products **3b–i** in high isolated yields (60–92%; Scheme 3). Radical addition to internal alkenes was also possible, albeit with decreased yield. Hence, reaction with *trans*-β-methyl styrene afforded **3j** with complete regioselectivity and high diastereoselectivity.[19] *Cis*-β-methyl styrene provided **3j** with slightly lower yield (30%) and, as expected, with the same selectivity ($dr = 13:1$). A low yield was also obtained for oxyarylation of an unactivated alkene (see **3k**; 23%).

We also tested aryl radical precursors bearing a range of substituted aryl groups. Iodanylidene malonates **1f–j** were suc-



Scheme 3. Variation of the aryl radical acceptor.

cessfully prepared and reacted with styrene under the optimised conditions to give oxyarylated products **3l**–**p** (Scheme 4). Whereas *ortho*-substituted iodanylidene malonates **1o** and **1p** provided good results, use of the *meta*- and *para*-congeners (in particular the Br-derivatives) led to significantly lower yields. Given that the reactivity of the corresponding aryl radicals did not differ significantly (steric effects in the *para*- and *meta*-derivatives should be even smaller than in the two *ortho*-systems), we assume that the lower yields are caused by the lower stability of the *meta*- and *para*-substituted aryl radical precursors under the applied conditions. Good results were also achieved for intramolecular oxyarylations, as documented

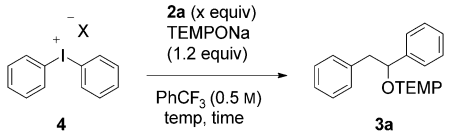


Scheme 4. Variation of the aryl radical precursor and cyclisation.

by the transformations of **1g** and **1h**. We found that oxyarylation of **1g** was more efficient when TEMPONa was added slowly over 0.5 h by using a syringe pump, to provide **3q** in 84% yield. In analogy, **1h** was converted in good yield into **3r**, bearing a quaternary carbon-centre. Considering also the good results obtained with **1i** to give **3o** and **1j** to afford **3p**, it seems that the *ortho*-substituent in the starting iodanylidene malonates stabilises the radical precursor (slower decomposition), which is reflected in the higher yields observed for these substrates.

Given that the stability of some iodanylidene malonates was not satisfactorily, we tested diaryliodonium salts as alternative aryl radical precursors[15] in the reaction with TEMPONa. Diaryliodonium salts were readily prepared according to a reported procedure by oxidation of the corresponding aryl iodide and subsequent coupling with an aryl boronic acid.[20] Reaction conditions were optimised by using diphenyliodonium salts **4** and styrene as a radical acceptor to yield oxyarylation product **3a** (Table 2). The first experiment was conducted with

Table 2. Optimisation reactions for the oxyarylation with diaryliodonium salts.



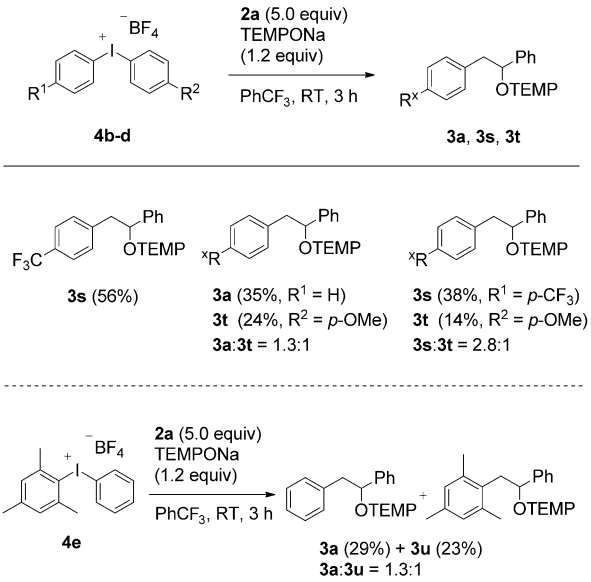
Entry	X^-	**2a** [equiv]	Temp. [°C]	Time [h][a]	Yield [%]
1	Br^-	5.0	20	3.0	41
2	PF_6^-	1.5	20	3.0	36
3	PF_6^-	5.0	20	3.0	54
4	BF_4^-	5.0	20	3.0	56
5	BF_4^-	10.0	20	3.0	57
6	BF_4^-	5.0	0	3.0	52
7	BF_4^-	5.0	50	3.0	51
8	BF_4^-	5.0	20	5.0	51
9[b]	BF_4^-	5.0	20	3.0	50
10	BF_4^-	5.0	20	1.0	43
11[c]	BF_4^-	5.0	20	3.0	49

[a] Time period used for TEMPONa syringe pump addition. [b] Run at 0.25 molar concentration. [c] In THF.

diphenyliodonium bromide, 5.0 equivalents of styrene and TEMPONa (1.2 equiv) was added over 3 h by using a syringe pump. The target **3a** was isolated in 41% yield (entry 1). By using diphenyliodonium hexafluorophosphate as a radical precursor, **3a** was isolated in 54% yield (entry 3). Reducing the amount of **2a** to 1.5 equivalents provided a lower yield (36%; entry 2). Compared with the hexafluorophosphate salt, use of the corresponding diphenyliodonium tetrafluoroborate salt afforded a similar yield (56%; entry 4). Neither increasing the amount of radical acceptor nor varying temperature affected the outcome of the reaction significantly (entries 5–7). Extending the reaction time to 5 h or decreasing concentration did also not lead to significant effect on the isolated yield (entries 8 and 9). Furthermore, shorter reaction times or switching

to THF as solvent did not affect the yield to a significant extent (entries 10 and 11).

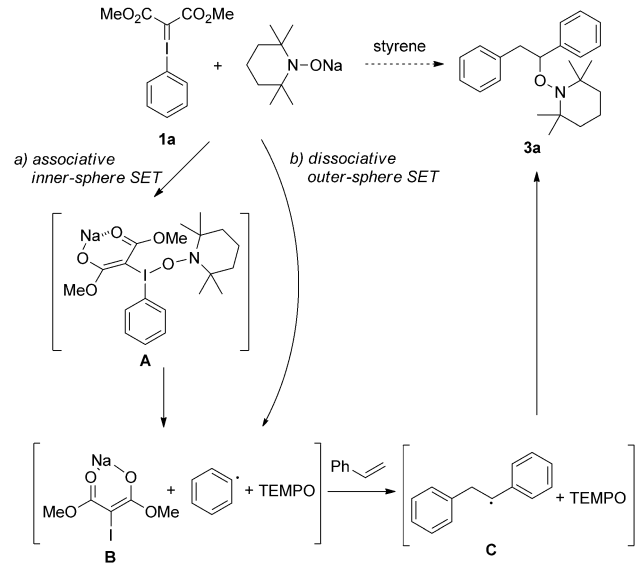
To study the electronic effects on the fragmentation reaction of the iodonium salt, we prepared symmetric and asymmetric diaryliodonium tetrafluoroborate salts bearing electron-withdrawing and electron-donating substituents at the arene moiety (Scheme 5). In the reaction with styrene, the symmetric



Scheme 5. Oxyarylation of styrene using diaryliodonium tetrafluoroborates.

para-CF_3 salt **4b** provided oxyarylation product **3s** in 56% yield. The iodonium salt **4c**, bearing a phenyl and a *p*-$MeOC_6H_4$ substituent, provided the oxyarylation products **3a** and **3t** in 59% combined yield as a 1.3:1 mixture of separable compounds (**3a**/**3t**, 1.3:1). Even for the electronically more differentiated aryl radicals derived from **4d** (*p*-$MeOC_6H_4^{\cdot}$ versus *p*-$CF_3C_6H_4^{\cdot}$), selectivity was moderate and products **3s** and **3t** were isolated in 38 and 14% yield, respectively (**3s**/**3t**, 2.8:1). Low selectivities for aryl radical fragmentation of photoredox-generated aryl radicals were observed before.[15] Notably, nucleophilic aromatic substitutions on asymmetric diaryliodonium salts occur with high selectivity.[21] Steric effects seem to be negligible on aryl radical generation because reaction with salt **4e** (phenyl versus mesityl radical generation) afforded oxyarylation products **3a** and **3u** in 52% combined yield with a low 1.3:1 selectivity favouring the phenylated derivative **3a**.

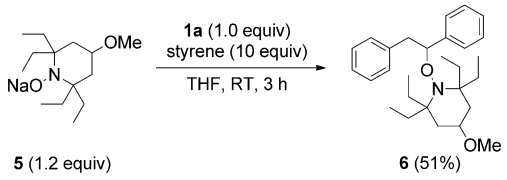
Two slightly different reaction mechanisms, which vary in the aryl radical generation step, are considered for the oxyarylation of styrene with 2-(phenyl-λ^3-iodanylidene)malonate (**1a**) and TEMPONa (Scheme 6). TEMPONa can react with **1a** in an associative process to generate the adduct **A**, which then fragments to enolate **B**, phenyl radical and TEMPO (inner-sphere SET, pathway a). Alternatively, **1a** becomes reduced with TEMPONa through single-electron transfer (outer-sphere SET) to directly generate a phenyl radical, iodoenolate **B** and the persistent TEMPO radical (dissociative, pathway b).[22] Phenyl



Scheme 6. Two possible mechanisms for reaction of **1a** with styrene and TEMPONa.

radical addition to styrene gives adduct radical **C**, which is then trapped by TEMPO to eventually provide the oxyarylation product **3a**. Selective cross coupling of benzylic radical **C** with TEMPO is controlled by the persistent radical effect.[23]

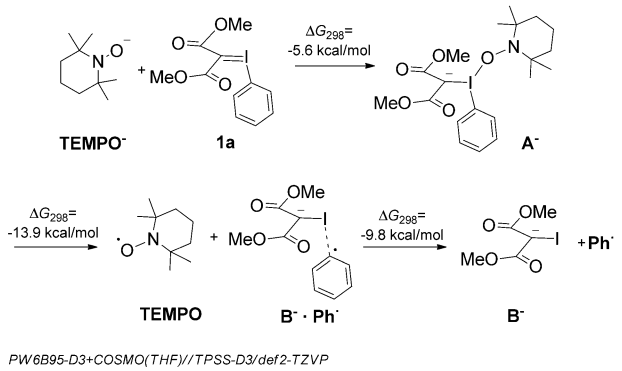
To challenge the possible "associative mechanism", we tested the very bulky Na-salt **5**[24] in the reaction with **1a** and styrene under the optimised conditions (Scheme 7; see the



Scheme 7. Oxyphenylation of styrene with the Na-salt **5** and **1a**.

Supporting Information for the preparation of **5**). The oxyphenylated product **6** was formed, albeit in lower yield (50%) compared with that with TEMPONa. It is clear that adduct formation of **5** and **1a** to give an intermediate of type **A** must be more difficult than for the analogous reaction with the smaller TEMPONa. However, the successful transformation of **5** into **6** cannot be taken as a proof for the occurrence of the SET-pathway (against the associative route).

To gain a clearer picture of whether an associative process is viable, we performed DFT calculations on the reaction of TEMPO anion and TEMPONa with 2-(phenyl-λ^3-iodanylidene)-malonate (**1a**).[25] Irrespective of the presence or absence of the Na cation, the trivalent iodine(III) intermediate **A** is formed in an exergonic reaction (Scheme 8, for the results of the reaction with TEMPONa and more details, see the Supporting Information). We were not able to identify a transition structure for homolytic cleavage of the I–O bond in **A**. The radical anion of



Scheme 8. Associated pathway for reductive cleavage of **1 a** based on DFT calculations.

1 a is not a stable intermediate, but immediately fragments into a loose complex of phenyl radical and iodoenolate B. The dissociation of the complex $\mathbf{B}^{-}\cdot Ph^{\cdot}$ is entropically favoured and contributes to the total reaction free energy of almost 30 kcal mol^{-1}. The reaction of 2,2,6,6-tetraethylpiperidin-1-yloxyl (as a model for **5**) instead of $TEMPO^{-}$ gives comparable free reaction energies, which indicates that an associative mechanism would also be possible with **5** (see the Supporting Information).

The higher intrinsic propensity of $(\mathbf{1a})^{\cdot-}$ to cleave the I–phenyl bond can be demonstrated by partial optimisations along the dissociating bonds (Figure 1). Assuming that this path is not qualitatively changed by the sodium cation, we have ignored the presence of Na^{+} in that step. The release of the phenyl radical proceeds without any barrier and leads directly to the van der Waals (vdW) complex $B^{-}\cdot Ph^{\cdot}$ (Figure 1 (a)). In contrast, for the elongation of the malonyl–iodine bond (Figure 1 (b)), almost 30 kcal mol^{-1} must be overcome before the malonyl radical anion and phenyl iodide are formed.

The results of the DFT calculations provide further evidence that an associative electron-transfer mechanism is likely and explains the selective formation of phenyl radicals from **1 a**.

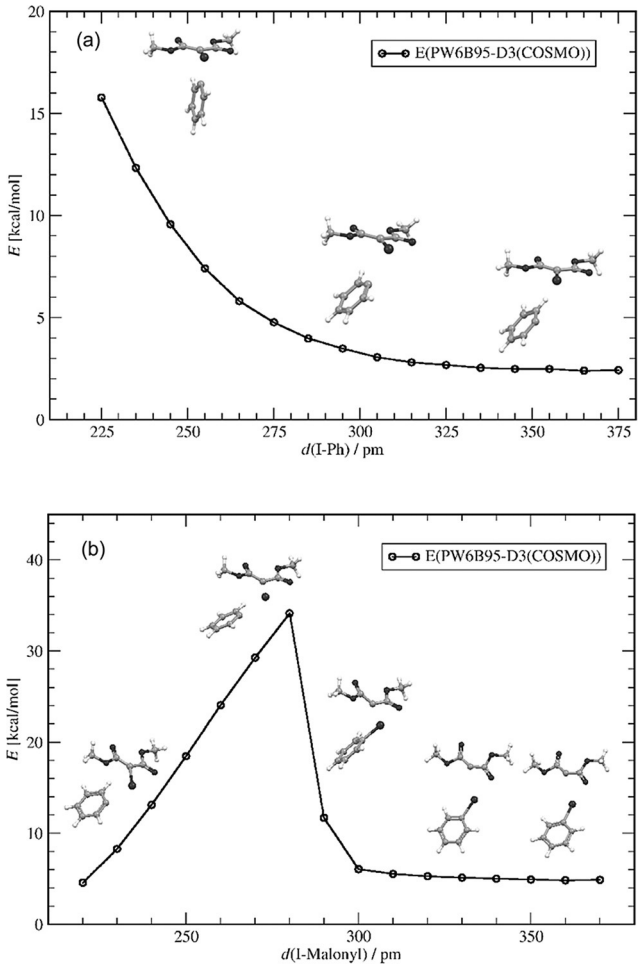


Figure 1. Partial optimisation (TPSS-D3/def2-TZVP) of **1 a** (radical anion) as a function of the I–C(phenyl) and I–C(malonyl) distance. Energies (PW6B95-D3/def2-TZVP) include solvation implicitly (THF) and are given relative to $TEMPO^{-}$ adduct $\mathbf{A}^{-}$ (excluding enthalpic and entropic contributions).

Summary and Conclusion

We have shown that iodanylidene malonates are efficiently reduced with TEMPONa to give aryl radicals. Computational studies reveal that aryl radical generation occurs through an associative electron transfer for which reaction of the iodanylidene malonate with TEMPONa provides an intermediate, which then further fragments in a second step to the aryl radical, TEMPO and Na-iodomalonate. In the presence of alkenes, these aryl radicals undergo addition and the adduct radicals thus generated are selectively trapped by the concomitantly formed TEMPO radical. Selective cross coupling with TEMPO is steered by the persistent radical effect. The overall process represents an alkene oxyarylation that is high yielding if the initial iodanylidene malonate shows sufficiently high stability in solution. The concept can also be applied to intramolecular oxyarylation. In addition, we have shown that readily prepared diaryliodonium salts react with TEMPONa to give the corresponding aryl radicals along with TEMPO. For nonsymmetrical diaryliodonium salts, selectivity in aryl radical generation is low. Aryl radical generation from diaryliodonium salts with TEMPO-Na has also been implemented in a novel method for alkene oxyarylation. Notably, such oxyarylation products are useful compounds with which to conduct follow-up chemistry, as previously shown.[4f]

Acknowledgements

We thank the Westfälische Wilhelms-University Münster and the Deutsche Forschungsgemeinschaft (DFG) for supporting our work.

Keywords: density functional calculations · hypervalent compounds · radical reactions · radicals · synthetic methods

[1] a) S. E. Vaillard, A. Studer, *In Modern Arylation Methods: Radical-Based Arylation Methods*, (Ed.: L. Ackermann), Wiley-VCH, Weinheim, **2009**, pp. 475 – 511; b) S. E. Vaillard, A. Studer, *In Encyclopedia of Radicals in*

Chemistry, Biology, and Materials, Vol. 2, (Eds.: C. Chatgilialoglu, A. Studer), Wiley, Chichester, **2012**, pp. 1059 – 1093.

[2] H. B. Kagan, *Tetrahedron* **2003**, *59*, 10351 – 10372.

[3] For reviews on radical reactions using aryl diazonium salts, see: a) C. Galli, *Chem. Rev.* **1988**, *88*, 765 – 792; b) S. K. Fehler, M. R. Heinrich, *Synlett* **2015**, *26*, 580 – 603.

[4] a) J. A. Murphy, *Pure. Appl. Chem.* **2000**, *72*, 1327 – 1334; b) N. Bashir, J. A. Murphy, *Chem. Commun.* **2000**, 627 – 628; c) O. Blank, S. Wölfel, M. R. Heinrich, *Org. Lett.* **2006**, *8*, 3323 – 3325; d) O. Blank, D. Ullrich, M. Kirchstein, M. R. Heinrich, *J. Org. Chem.* **2007**, *72*, 9609 – 9616; e) O. Blank, A. Wetzel, M. R. Heinrich, *J. Org. Chem.* **2007**, *72*, 476 – 484; f) M. Hartmann, Y. Li, A. Studer, *J. Am. Chem. Soc.* **2012**, *134*, 16516 – 16519.

[5] For generation of aryl radicals in situ from the corresponding anilines„ see: a) M. R. Heinrich, *Chem. Eur. J.* **2009**, *15*, 820 – 833; b) F. Mo, G. Dong, Y. Zhang, J. Wang, *Org. Biomol. Chem.* **2013**, *11*, 1582 – 1593; c) D. P. Hari, B. König, *Angew. Chem. Int. Ed.* **2013**, *52*, 4734 – 4743; *Angew. Chem.* **2013**, *125*, 4832 – 4842; d) M. Hartmann, A. Studer, *Angew. Chem. Int. Ed.* **2014**, *53*, 8180 – 8183; *Angew. Chem.* **2014**, *126*, 8319 – 8322; e) M. Hartmann, C. G. Daniliuc, A. Studer, *Chem. Commun.* **2015**, *51*, 3121 – 3123. For the use of aryl hydrazines as radical precursors, see: f) T. Taniguchi, H. Zaimoku, H. Ishibashi, *Chem. Eur. J.* **2011**, *17*, 4307 – 4312; g) J. Hofmann, H. Jasch, M. R. Heinrich, *J. Org. Chem.* **2014**, *79*, 2314 – 2320; h) S. Kindt, H. Jasch, M. R. Heinrich, *Chem. Eur. J.* **2014**, *20*, 6215 – 6255.

[6] Cyanation: a) V. V. Zhdankin, C. J. Kuehl, A. P. Krasutsky, J. T. Bolz, B. Mismash, J. K. Woodward, A. J. Simonsen, *Tetrahedron Lett.* **1995**, *36*, 7975 – 7978; b) R. Chowdhury, J. Schörgenhumer, J. Novacek, M. Waser, *Tetrahedron Lett.* **2015**, *56*, 1911 – 1914; c) Y.-F. Wang, J. Qiu, D. Kong, Y. Gao, F. Lu, P. G. Karmaker, F.-X. Chen, *Org. Biomol. Chem.* **2015**, *13*, 365 – 368.

[7] Alkynylation: a) S. Nicolai, S. Erard, D. F. Gonzáles, J. Waser, *Org. Lett.* **2010**, *12*, 384 – 387; b) R. Frei, J. Waser, *J. Am. Chem. Soc.* **2013**, *135*, 9620 – 9623; c) F. Xie, Z. Qi, S. Yu, X. Li, *J. Am. Chem. Soc.* **2014**, *136*, 4780 – 4787; d) R. Frei, M. D. Wodrich, D. P. Hari, P.-A. Borin, C. Chauvier, J. Waser, *J. Am. Chem. Soc.* **2014**, *136*, 16563 – 16573; e) P. Finkbeiner, N. M. Weckenmann, B. J. Nachtsheim, *Org. Lett.* **2014**, *16*, 1326 – 1329; f) C. C. Chen, J. Waser, *Org. Lett.* **2015**, *17*, 736 – 739; g) Y. Wu, Y. Yang, B. Zhou, Y. Li, *J. Org. Chem.* **2015**, *80*, 1946 – 1951; h) M. Kamlar, I. Císařová, J. Veselý, *Org. Biomol. Chem.* **2015**, *13*, 2884 – 2889.

[8] a) Y. Li, A. Studer, *Angew. Chem. Int. Ed.* **2012**, *51*, 8221 – 8224; *Angew. Chem.* **2012**, *124*, 8345 – 8348; Review on the use of the Togni reagent in synthesis, see: J. Charpentier, N. Früh, A. Togni, *Chem. Rev.* **2015**, *115*, 650 – 682.

[9] B. Zhang, A. Studer, *Org. Lett.* **2014**, *16*, 3990 – 3993.

[10] B. Zhang, A. Studer, *Org. Lett.* **2013**, *15*, 4548 – 4551.

[11] a) C. Perreault, S. R. Goudreau, L. E. Zimmer, A. B. Charette, *Org. Lett.* **2008**, *10*, 689 – 692; b) S. R. Goudreau, D. Marcoux, A. B. Charette, *J. Org. Chem.* **2009**, *74*, 470 – 473; c) H. Huang, Y. Yang, X. Zhang, W. Zeng, Y. Liang, *Tetrahedron Lett.* **2013**, *54*, 6049 – 6052; d) D. R. Wenz, J. R. deAlaniz, *Org. Lett.* **2013**, *15*, 3250 – 3253; e) S. Breitler, E. M. Carreira, *Angew. Chem. Int. Ed.* **2013**, *52*, 11168 – 11171; *Angew. Chem.* **2013**, *125*, 11375 – 11379; for a discussion on the I=X double bond see: A. S. Ivanov, I. A. Popov, A. I. Boldyrev, V. V. Zhdankin, *Angew. Chem. Int. Ed.* **2014**, *53*, 9617 – 9621; *Angew. Chem.* **2014**, *126*, 9771 – 9775.

[12] For alpha-arylation see: a) F. Marshall Beringer, P. S. Forgione, M. D. Yudis, *Tetrahedron* **1960**, *8*, 49 – 63; b) J. H. Ryan, P. J. Stang, *Tetrahedron Lett.* **1997**, *38*, 5061 – 5064; c) K. Chen, G. F. Koser, *J. Org. Chem.* **1991**, *56*, 5764 – 5767; d) C. H. Oh, J. S. Kim, H. H. Jung, *J. Org. Chem.* **1999**, *64*, 1338 – 1340; e) Z. Jia, E. Gálvez, R. M. Sebastián, R. Pleixats, Á. Álvarez-Larena, E. Martin, A. Vallribera, A. Shafir, *Angew. Chem. Int. Ed.* **2014**, *53*, 11298 – 11301; *Angew. Chem.* **2014**, *126*, 11480 – 11483.

[13] For arylation of alkenes see: a) A. Kina, H. Miki, Y.-H. Cho, T. Hayashi, *Adv. Synth. Catal.* **2004**, *346*, 1728 – 1732; b) M. Zhu, Y. Song, Y. Cao, *Synthesis* **2007**, 853 – 856; c) J. Aydin, J. M. Larsson, N. Selander, K. J. Szabó, *Org. Lett.* **2009**, *11*, 2852 – 2854; d) F. Zhang, S. Das, A. J. Walkinshaw, A. Casitas, M. Taylor, M. G. Suero, M. J. Gaunt, *J. Am. Chem. Soc.* **2014**, *136*, 8851 – 8854; alkynes: e) S.-K. Kang, K. H. Lim, P. S. Ho, W. Y. Kim, *Synthesis* **1997**, 874 – 876; f) S.-K. Kang, S.-K. Yoon, Y.-M. Kim, *Org. Lett.* **2001**, *3*, 2697 – 2699; g) U. Radhakrishnan, P. J. Stang, *Org. Lett.* **2001**, *3*, 859 – 860; h) Z. Xue, D. Yang, C. Wang, *J. Organomet. Chem.* **2006**, *691*, 247 – 250; i) M. Zhu, Z. Zhou, R. Chen, *Synthesis* **2008**, 2680 – 2682; j) J. Chen, C. Chen, J. Chen, G. Wang, H. Qu, *Chem. Commun.* **2015**, *51*, 1356 – 1359.

[14] For benzyne formation, see: a) T. Kitamura, Z. Meng, Y. Fujimara, *Tetrahedron Lett.* **2000**, *41*, 6611 – 6614; b) T. Kitamura, M. Todaka, Y. Fujiwara, *Org. Synth.* **2002**, *78*, 104 – 112; c) T. Kitamura, Y. Aoki, S. Isshiki, K. Wasai, Y. Fujiwara, *Tetrahedron Lett.* **2006**, *47*, 1709 – 1712; d) J. Xue, X. Huang, *Synth. Commun.* **2007**, *37*, 2179 – 2185.

[15] a) S. R. Neufeldt, M. S. Sanford, *Adv. Synth. Catal.* **2012**, *354*, 3517 – 3522; b) Y.-X. Liu, D. Xue, J.-D. Wang, C.-J. Zhao, Q.-Z. Zou, C. Wang, J. Xiao, *Synlett* **2013**, 507 – 513; c) A. Baralle, L. Fensterbank, J.-P- Goddard, C. Ollivier, *Chem. Eur. J.* **2013**, *19*, 10809 – 10813; d) R. Wang, H. Jiang, Y. Cheng, A. A. Kadi, H.-K. Fun, Y. Zhang, S. Yu, *Synthesis* **2014**, *46*, 2711 – 2726; e) J. Wen, R.-Y. Zhang, S.-Y. Chen, J. Zhang, X.-Q. Yu, *J. Org. Chem.* **2012**, *77*, 766 – 771.

[16] Y. Li, M. Hartmann, C. G. Daniliuc, A. Studer, *Chem. Commun.* **2015**, *51*, 5706 – 5709.

[17] L. Tebben, A. Studer, *Angew. Chem. Int. Ed.* **2011**, *50*, 5034 – 5068; *Angew. Chem.* **2011**, *123*, 5138 – 5174.

[18] Direct trapping of the phenyl radical with TEMPO can basically be used to determine rate constants for aryl radical additions to alkenes. For such an application in the field of CF_3-radical addition, see: M. Hartmann, Y. Li, A. Studer, *Org. Biomol. Chem.* **2016**, *14*, 206 – 210.

[19] The relative configuration of the major isomer was assigned by using the $A_{1,3}$-strain model. See: G. J. Thoma, D. P. Curran, *J. Am. Chem. Soc.* **1992**, *114*, 4436 – 4437.

[20] M. Bielawski, D. Aili, B. Olofsson, *J. Org. Chem.* **2008**, *73*, 4602 – 4607.

[21] a) M. Iyanaga, Y. Aihara, N. Chatani, *J. Org. Chem.* **2014**, *79*, 11933 – 11939; b) Á. Sinai, D. Vangel, T. Gáti, P. Bombicz, Z. Novák, *Org. Lett.* **2015**, *17*, 4136 – 4139; c) E. Cahard, H. P. J. Male, M. Tissot, M. J. Gaunt, *J. Am. Chem. Soc.* **2015**, *137*, 7986 – 7989.

[22] In case of the diaryliodonium salts, an associative mechanism is also likely. The remaining part of the cascade proceeds in analogy to the reactions with **1a**.

[23] a) H. Fischer, *Chem. Rev.* **2001**, *101*, 3581 – 3610; b) A. Studer, *Chem. Eur. J.* **2001**, *7*, 1159 – 1164; c) A. Studer, *Chem. Soc. Rev.* **2004**, *33*, 267 – 273; d) A. Studer, T. Schulte, *Chem. Rec.* **2005**, *5*, 27 – 35.

[24] C. Wetter, J. Gierlich, C. A. Knoop, C. Müller, T. Schulte, A. Studer, *Chem. Eur. J.* **2004**, *10*, 1156 – 1166.

[25] PW6B95 functional: a) Y. Zhao, D. G. Truhlar, *J. Phys. Chem. A* **2005**, *109*, 5656 – 5667. TPSS functional: b) J. Tao, J. P. Perdew, V. N. Staroverov, G. E. Scuseria, *Phys. Rev. Lett.* **2003**, *91*, 146401. def2-TZVP basis set: c) F. Weigend, R. Ahlrichs, *Phys. Chem. Chem. Phys.* **2005**, *7*, 3297 – 3305. Dispersion correction: d) S. Grimme, J. Antony, S. Ehrlich, H. Krieg, *J. Chem. Phys.* **2010**, *132*, 154104; e) S. Grimme, S. Ehrlich, L. Goerigk, *J. Comput. Chem.* **2011**, *32*, 1456 – 1465. COSMO solvation model: f) A. Klamt, G. Schüürmann, *J. Chem. Soc. Perkin Trans. 2* **1993**, 799 – 805.

Received: December 3, 2015
Published online on February 2, 2016