

Cite this: *Chem. Sci.*, 2021, **12**, 10092

All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 14th May 2021
Accepted 24th June 2021

DOI: 10.1039/d1sc02682h
rsc.li/chemical-science

Introduction

The development of new approaches for the construction of CF_3 - or CF_2H -containing target molecules is becoming increasingly important owing to the growing applications of organo-fluorinated compounds in *inter alia* pharmaceutical and agrochemical industries.^{1–3} Thus, the incorporation of fluoroalkyl groups into organic molecules can significantly improve their physical, chemical, and biological properties, such as permeability, bioavailability, and metabolic stability.^{4–6} Although a multitude of methods have been developed for the preparation of trifluoromethylated or difluoromethylated compounds by radical addition to unsaturated bonds,⁷ a protocol for directly introducing CF_3 or CF_2H onto spiro[5.5]trienone has thus far proven elusive, despite these motifs being prevalent in a number of natural products and bioactive molecules (Fig. 1).

Electrochemistry has surfaced as an attractive technique for the discovery of new modes of reactivity and transformations that are not readily accessible with chemical reagents.⁸ As radical spirocyclization by dearomatization of biaryls is an attractive strategy for the rapid construction of spiro[5.5] molecules,^{9,11b} we questioned whether the efficiency and mildness noted in the CF_3 -radical formation could be translated into an electrooxidative biaryl dearomatization strategy. However, significant challenges would need to be overcome (Fig. 1). (1)

Electrooxidative dearomatization of biaryls: synthesis of tri- and difluoromethylated spiro[5.5]trienones[†]

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Radical spirocyclization *via* dearomatization has emerged as an attractive strategy for the rapid synthesis of structurally diverse spiro molecules. We report the use of electrochemistry to perform an oxidative dearomatization of biaryls leading to tri- and difluoromethylated spiro[5.5]trienones in a user friendly undivided cell set-up and a constant current mode. The catalyst- and chemical oxidant-free dearomatization procedure features ample scope, and employs electricity as the green and sole oxidant.

Regioselectivity between 5-*exo*-trig, 6-*exo*-trig and 7-*endo*-trig cyclization needs to be controlled. (2) The low reactivity of alkynes towards fluoroalkyl radicals needs to be addressed. Compared to the radical addition onto alkenes,¹⁰ alkyne functionalization by radical addition is more challenging.¹¹ Herein, we report an unprecedented dearomatization of biarylynes under green and operationally-simple electrochemical conditions. The salient features of our strategy comprise the following: (a) the first efficient dearomatization of biaryls to CF_3 -containing spiro[5.5]trienones, (b) a most user-friendly undivided cell set-up, (c) simple reaction conditions devoid of a redox mediator, (d) the absence of catalysts and chemical oxidants, and (e) high regioselectivity.

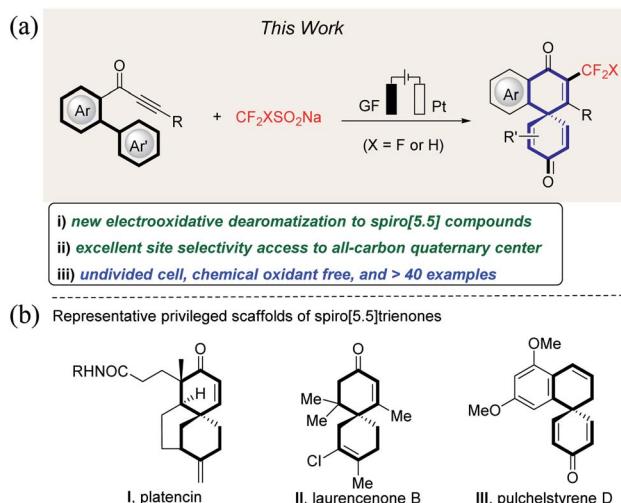


Fig. 1 Electrooxidative biaryl dearomatization: (a) reaction design and (b) selected examples of bioactive spiro compounds.

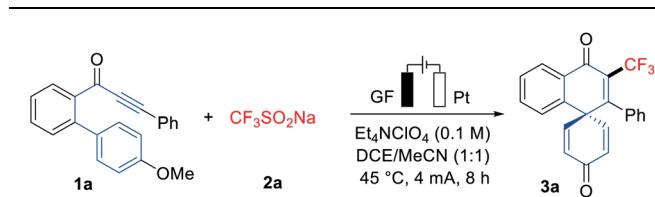
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† Electronic supplementary information (ESI) available: Experimental details and characterization of all new compounds and details of DFT calculations. CCDC 2056406 and 2075572. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d1sc02682h



Table 1 Optimization of the electrooxidative dearomatization^a



Entry	Variation from standard conditions	Yield ^b /%
1	No change	60
2	MeCN	40
3	MeCN/H ₂ O (2 : 1)	15
4	In the absence of Et ₄ NClO ₄	46
5	<i>n</i> -Bu ₄ NBF ₄ instead of Et ₄ NClO ₄	20
6	Et ₄ NPF ₆ instead of Et ₄ NClO ₄	18
7	Na ₂ CO ₃ and H ₂ O instead of Et ₄ NClO ₄	55 ^c
8	At room temperature (25 °C)	40
9	Addition of [Mes-Acr]ClO ₄ (10 mol%)	50 ^d
10	Addition of Cp ₂ Fe (10 mol%)	45
11	1 mmol scale (4 mL solvent)	50
12	No electricity	0

^a Standard conditions: undivided cell, GF anode, Pt cathode, constant current (CCE) = 4 mA, **1a** (0.3 mmol), **2a** (0.6 mmol), Et₄NClO₄ (0.1 M, 0.4 mmol), DCE/MeCN (4 mL), under air, 8 h. ^b Yield of isolated products. ^c H₂O (1 mL) was added. ^d 30 W blue LED, GF = graphite felt.

products. H_2O (1 mL) was added. 30 W, blue LED. GR = graphite felt.

Results and discussion

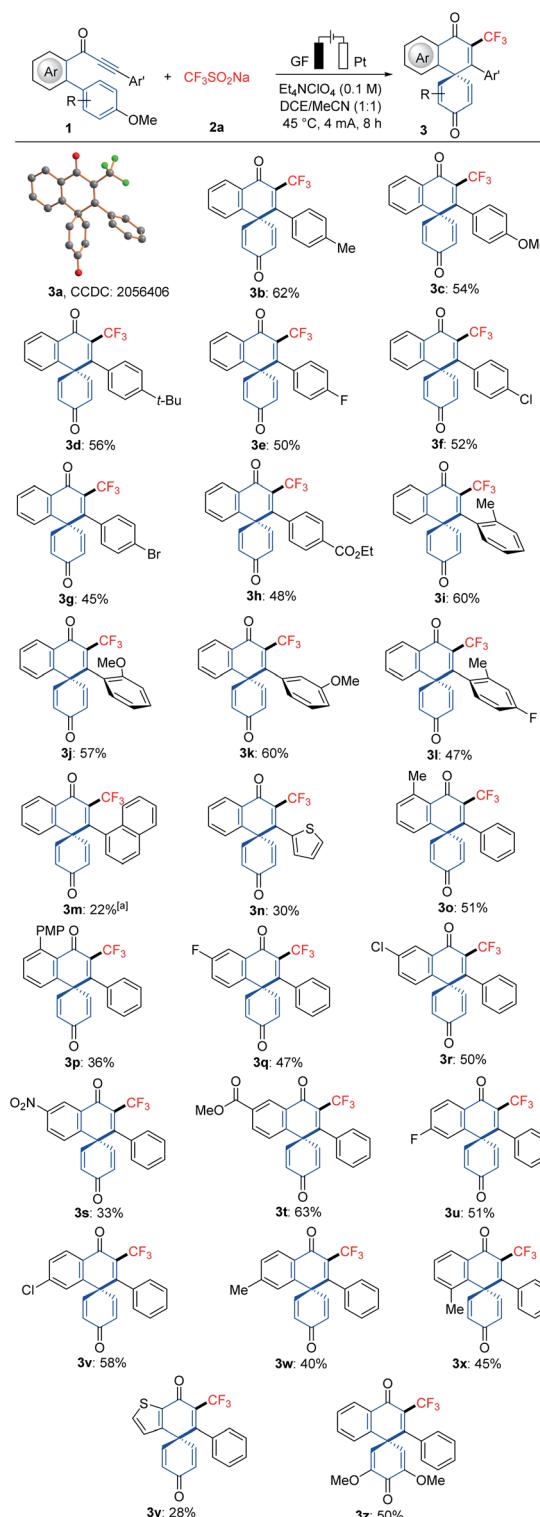
Optimization of reaction conditions

We initiated our studies by probing various reaction conditions for the envisioned electrochemical dearomatization reaction of biaryllynone **1a** in a most user-friendly undivided cell set-up (Tables 1 and S2 in the ESI†), using the bench-stable and inexpensive Langlois' reagent ($\text{CF}_3\text{SO}_2\text{Na}$, **2a**) as the CF_3 source. After considerable preliminary experimentation, we observed that the desired trifluoromethylation/dearomatization was accomplished with a mixed solvent system consisting of DCE/MeCN (1 : 1) and Et_4NClO_4 as the electrolyte (entry 1). Different solvents and a series of supporting electrolytes were tested but found not to be beneficial (entries 2–7). Neither decreasing nor increasing the reaction temperature improved the yield of product **3a** (entry 8). In contrast to previous literature reports,^{12–14} a catalytic redox mediator was not required for this transformation (entries 9 and 10). When the dearomatative reaction was performed on a 1 mmol scale, the product **3a** was isolated in 50% yield (entry 11). Control experiments confirmed the essential role of electricity for the electrooxidative dearomatization (entry 12). The structure of **3a** was unambiguously confirmed by single-crystal X-ray analysis (Scheme 1).^{15a}

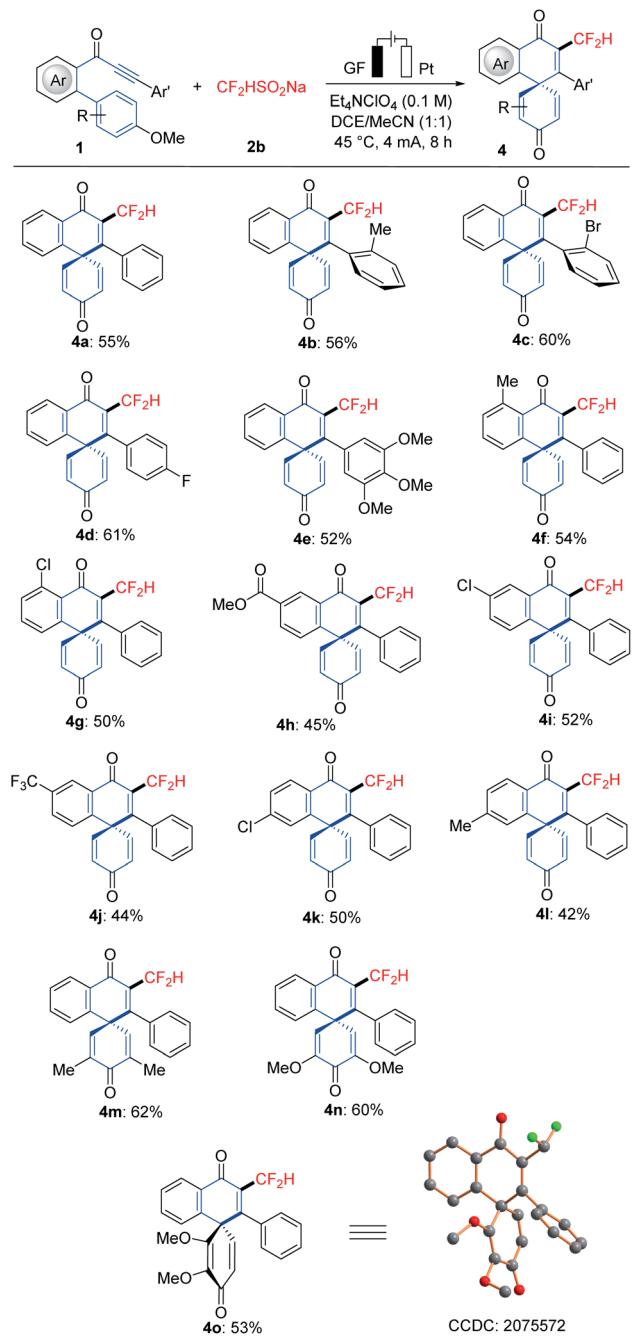
Robustness

With the optimized reaction conditions in hand, we explored the viable scope of the electrochemical transformation. Various biarylynones **1** were investigated and the results are shown in Scheme 1. Generally, the electronic effect of substituents on the arene Ar' did not influence the reaction efficiency and

synthetically useful yields of spiro[5.5]trienones were obtained (3a-3h). We were pleased to find that *ortho*- and *meta*-substituted arene Ar' underwent this transformation efficiently despite a possible steric repulsion (3i-3l), even for

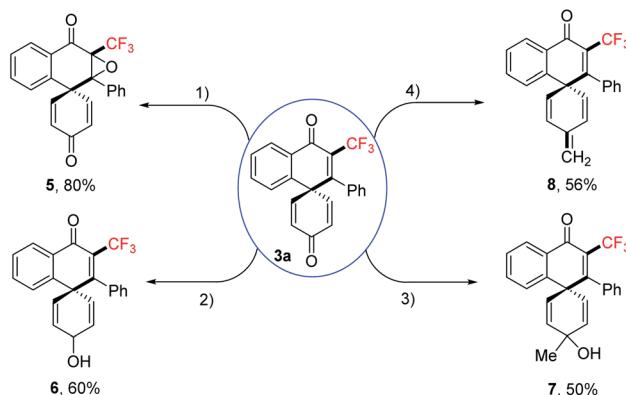


Scheme 1 Scope of trifluoromethylated spiro[5.5]trienones 3. [a] NMR yield.



Scheme 2 Scope of difluoromethylated spiro[5.5]trienones 4.

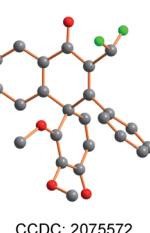
polysubstituted substrates. A naphthyl substituent was also compatible (**3m**). Substitutions on the phenome scaffold were next examined. Substrates bearing either electron-withdrawing or electron-donating groups did not significantly alter the reaction outcome and the spiro compounds **3** were efficiently obtained (**3o–3x**). As depicted, the dearomatization approach was compatible with several functional groups, such as chloro, bromo, ether, nitro and ester. A heterocyclic substrate was also applicable in this electrooxidative transformation to afford the corresponding product **3y** in a moderate yield. It is noteworthy that a substrate with a substituent at the *ortho*-position of OMe (**1z**) also formed the desired compound **3z**.¹⁶

Scheme 3 Reaction conditions: (1) H_2O_2 (1.5 equiv.), Na_2CO_3 (1.5 equiv.), EtOH , 45°C , 2 h. (2) DIBAL (1.0 equiv.), THF , -78°C , 3 h. (3) CH_3MgCl (2.0 equiv.), THF , room temperature, 3 h. (4) Methyl-triphenylphosphonium bromide (2.0 equiv.), $t\text{-BuOK}$ (2.0 equiv.), THF , room temperature, 6 h.

As the difluoromethyl group (CF_2H) can serve as a hydrogen bond donor, it has been employed as a lipophilic isostere in drug design for functionalities such as amides, alcohols, thiols and hydroxamic acids.¹⁷ Thus, we turned our attention to electrochemical difluoromethylation/dearomatization with differently substituted biaryllynes **1** and $\text{CF}_2\text{HSO}_2\text{Na}$ (**2b**). Similarly, the electronic properties of arenes Ar and Ar' in substrate **1** did not have distinct influence on the efficiency of the dearomatization, and moderate to good yields of the spiro[5.5]trienones **4** were obtained (Scheme 2). The structure of product **4o** was unambiguously verified by X-ray crystallographic analysis.^{15b}

We further demonstrated the synthetic utility and showed that the trifluoromethylated spiro[5.5]trienones are a versatile framework that can be readily transformed into more value-added scaffolds in single step reactions (Scheme 3). The biologically relevant epoxyquinone **5** could be obtained in excellent yield *via* oxidation, while reduction of the ketone selectively furnished alcohol **6**. Alcohol **7** was synthesized by selective addition of Grignard reagent, while alkene **8** could be prepared by a Wittig reaction.

To gain mechanistic insight into this electrochemical dearomatization reaction, the radical clock reaction using (1-cyclopropylvinyl)benzene (**1'**) as the radical-trapping reagent provided the known product **9** in 25% yield (Fig. 2a). Based on these results, a radical mechanism is proposed in Fig. 2c for this electrooxidative dearomatization reaction. First, radical $\text{CF}_3\cdot$ is generated from **2a** through anodic oxidation. Radical addition of $\text{CF}_3\cdot$ to C–C triple bonds of **1a** affords a vinyl radical **A**, which undergoes 6-*exo*-trig cyclization to the radical species **B**. Intermediate **B** is reoxidized to oxocarbenium ion **C** at the anode. Finally, the corresponding product **3a** is formed after demethylation. The incorporation of the difluoro moiety proceeds *via* the same mechanism, but the oxidation peak of $\text{CF}_2\text{HSO}_2\text{Na}$ was found much lower than that of $\text{CF}_3\text{SO}_2\text{Na}$ by a cyclic voltammetry (CV) experiment.¹⁸ In addition, inspired by the pioneering work of Jiao for 1,2-dichloroethane (DCE) dehydrochlorination,¹⁹ we also found that when the model



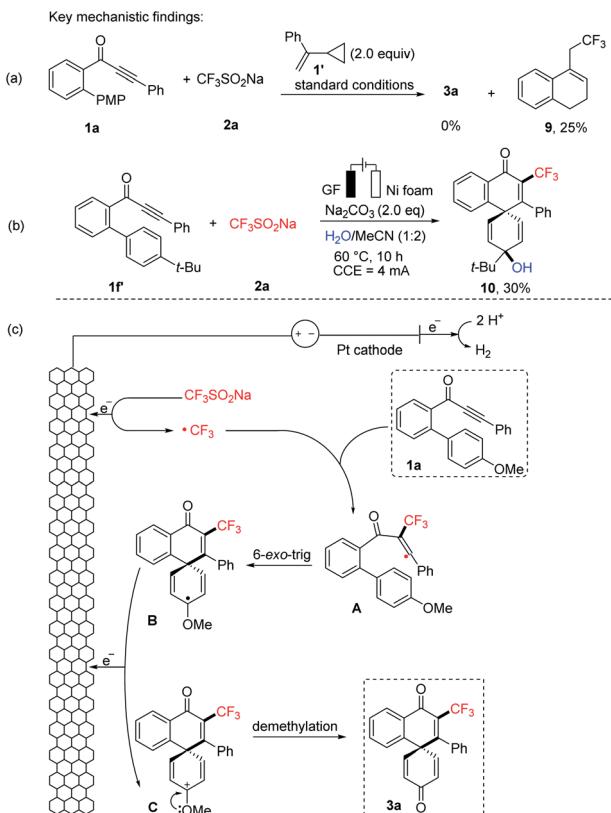


Fig. 2 Mechanistic investigation of the electrooxidative biaryl dearomatization: (a) radical clock experiment, (b) trapping experiment for the key intermediate, and (c) proposed mechanism.

reaction between **1a** and **2a** was performed under the standard conditions, the reaction mixture clearly became acidic as shown by pH measurement (in ESI†). Hence, we propose that HCl was generated from the dehydrochlorination of DCE. Notably, the analogue of ion **C** could be trapped by water while changing the reaction solvent system with 1-(4-(*tert*-butyl)-[1,1'-biphenyl]-2-yl)-3-phenylprop-2-yn-1-one **1f**. The trapping product **10** was here isolated in 30% yield (Fig. 2b).

Conclusions

In summary, we have developed an efficient approach for the electrochemical dearomatization of biaryls under metal catalyst- and chemical oxidant-free conditions. This green and environmentally friendly strategy showed a broad scope and great compatibility with sensitive functional groups, affording a series of CF_3 - and CF_2H -substituted spiro[5.5]trienones in moderate to good yields. It represents the first electrooxidative 6-*exo*-trig radical dearomatic spirocyclization process, and a plausible mechanism was proposed.

Data availability

All experimental data, procedures for data analysis and pertinent data sets are provided in the ESI.

Author contributions

Y. Z. and L. A. conceived the project. Y. Z. and C. M. performed the experiments, Y. Z., J. F. and J. S. analyzed and interpreted the experimental data. Y. Z. and J. S. drafted the paper. G. Z., Y. Z. and L. A. supervised the project. All of the authors discussed the results and contributed to the preparation of the final manuscript.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

Generous support by the National Natural Science Foundation of China (No. 21702188) and by the DFG (Gottfried-Wilhelm-Leibniz award to LA) is gratefully acknowledged.

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