



## Communication

## Electrocatalytic fluoroalkylation of olefins

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## ABSTRACT

An efficient nickel-catalyzed method devoted to the direct addition of perfluoroalkyl halides (I, Br) to  $\alpha$ -methylstyrene is described. This procedure allows for synthesis of compounds resulting from addition-dimerization in good yields.

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## 1. Introduction

The conjugate addition of organometallic reagents to electron-deficient olefins is a powerful method for formation of new carbon–carbon bonds, yielding Michael adducts which represent useful synthons to further organic transformations [1]. Moreover, such methodology can be expanded to include the addition of radical substrates to  $\alpha,\beta$ -unsaturated compounds, and in many cases these radical additions proceed enantioselectively [2]. The most commonly used methods to generate radicals for olefin addition chemistry involve the oxidation of trialkylboranes [2], oxidation of organozinc reagents [3], and the reduction of alkyl halides by low valent metal complexes [4]. The last of these methods can be made catalytic in metal complex upon the introduction of a chemical reducing agent [4] or by electrochemical means [5,6]. Some of the metals capable of generating organic radicals for olefin addition chemistry via electrocatalytic reduction are [Ni(tet a)]<sup>2+</sup> [5], CoBr<sub>2</sub>(py)<sub>x</sub> [7,8], NiBr<sub>2</sub>(py)<sub>x</sub> [9] (tet a = 5,5,7,12,12,14-hexamethyl-1,4,-8, 11-tetra-azacyclotetradecan; py = pyridine).

With a few exceptions [4,7], most of the substrates used in radical olefin addition chemistry are unfunctionalized, thereby limiting the scope of the methodology. In efforts to further expand the scope we set out to explore the possibility of using electrochemical methods to add perfluoroalkyl radicals across double bonds to generate new functionalized fluorocarbons. This class of substrates was chosen because fluoroalkyl moieties are becoming

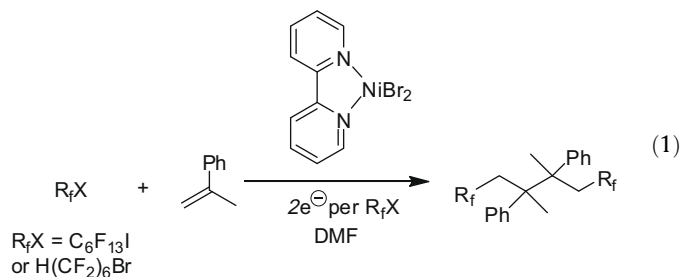
increasingly important in the medicinal, materials, and agricultural fields [10–12], yet their chemical syntheses remain problematic. In fact, while there has been many advances in incorporating the simplest fluoroalkyl group (trifluoromethyl) stoichiometrically into organic electrophiles [13–22], only two catalytic processes have ever been reported [23,24]. Moreover, most of the catalytic and stoichiometric processes employ expensive sources of the fluoroalkyl group, limiting their use in a large-scale process. The goal of the work presented was to demonstrate the proof-in-principle that selective additions of inexpensive perfluoroalkyl synthons to olefins can occur electrocatalytically under mild conditions.

## 2. Results and discussion

The electrochemical reduction of Ni(II) to Ni(0) complexes is a key stage in many electrocatalytic reactions involving  $\alpha$ -organo-nickel complexes [25–28], so NiBr<sub>2</sub>bpy (bpy = bipyridine) was targeted for use in coupling fluoroalkyl halides and olefins. We have discovered that the joint electrolysis of NiBr<sub>2</sub>bpy and fluoroalkyl halides (R<sub>x</sub>X, X = I, Br) in dimethylformamide in the presence of  $\alpha$ -methylstyrene in cathode compartment of electrolyzer (potential kept at –1.2 V vs. SCE to regenerate Ni(0)) yields new organic products in which the perfluoroalkyl group has added to the olefin substrate (Eq. (1)). The course of the reaction was followed by combined gas chromatography mass-spectrometry. The reactions can be run at 10 mol% nickel catalyst to afford product in moderate yields. Interestingly, the end-product is a dimer, bearing two perfluoroalkyl and two olefin synthons, unlike all previously described cases of electrocatalytic additions to olefins [1,5,7–9,25].

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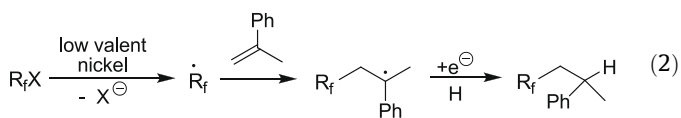
E-mail address: [yulia@iopc.knc.ru](mailto:yulia@iopc.knc.ru) (Y.H. Budnikova).



The structure of 2,3-dimethyl-2,3-diphenyl-1,4-bis(perfluorohexyl)butane (**1**) and 2,3-dimethyl-2,3-diphenyl-1,4-bis(6-H-perfluorohexyl)butane (**2**) were confirmed by X-ray analysis (Fig. 1). Both molecules are located on a special position at the center of symmetry in the asymmetric unit cell, affording two fragments bearing chiral centers. Due to coincidence of molecular centers with the centers of inversion, each molecule is the *meso* form.

Several possible reaction mechanisms must be considered, including traditional organometallic mechanisms involving oxidative addition and reductive elimination as well as traditional radical chain mechanisms. We can, however, note several important features of the addition reactions. First, no reaction occurs in the absence of a nickel catalyst. Second, the use of  $NH_4ClO_4$  as a proton source does not result in monomer formation, inconsistent with a mechanism like that shown in Eq. (2), which has literature precedence [5,29–31]. Finally, a control experiment demonstrates that reduction of  $R_fX$  at the electrode in the absence of nickel and the presence of olefin does not result in olefin addition products or  $R_f$  dimerization according to gas chromatography. Further studies

are underway to unravel more mechanistic features of these unusual addition reactions.



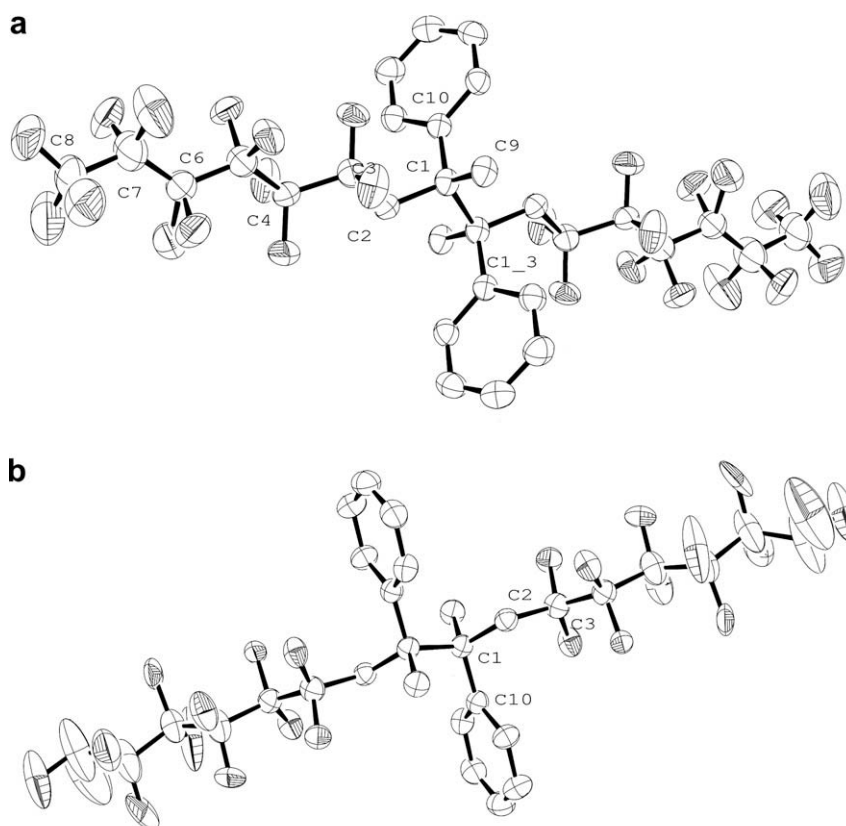
### 3. Conclusion

The new method reported herein allows for the introduction of inexpensive perfluoroalkyl synthons with long  $R_f$  chains to olefins. This work is the first time that dimer formation occurs under electrocatalytic conditions. Further investigations in this area will hopefully afford ways to control monomer/dimer formation as well as stereochemistry of the resulting addition products.

### 4. Experimental

#### 4.1. X-ray analysis

Data were collected on a Bruker Smart Apex II CCD diffractometer using graphite monochromated  $Mo K\alpha$  (0.71073 Å) radiation. Details concerning data collection and refinement are given in Table 1. Data were corrected for absorption using *SADABS* [32] program. All non-hydrogen atoms were refined anisotropically. The hydrogen atoms were calculated and refined as riding atoms. Data collection images were indexed, integrates, and scaled using the *APX2* data reduction package [33]. Structure solution and refinement *SIR* [34], *SHELXL97* [35], *WINGX* [36] program. Pictures were generated with *ORTEP3* for Windows [37]. In molecules **1** and **2**



**Fig. 1.** Molecular structure of 2,3-dimethyl-2,3-diphenyl-1,4-bis(perfluorohexyl)butane (**1**) and 2,3-dimethyl-2,3-diphenyl-1,4-bis(6-H-perfluorohexyl)butane (**2**). Disordered atoms were omitted for clarity, thermal ellipsoids drawn at 30% probability.

**Table 1**  
Crystallographic data for **1** and **2**.

Compound	<b>1</b>	<b>2</b>
Empirical formula	C <sub>30</sub> H <sub>20</sub> F <sub>26</sub>	C <sub>30</sub> H <sub>22</sub> F <sub>24</sub>
Formula weight	874.46	838.48
Crystal color/habit	Colorless/prism	Colorless/prism
<i>Unit cell dimensions</i>		
<i>a</i> (Å)	14.9307(16)	14.984(7)
<i>b</i> (Å)	11.1647(12)	11.052(6)
<i>c</i> (Å)	10.3937(11)	10.416(5)
$\beta$ (°)	103.548(1)	103.958(7)
<i>V</i> (nm <sup>3</sup> )	1684.4(3)	1674(1)
Density (calcd) (Mg m <sup>-3</sup> )	1.724	1.663
Absorption coefficient (mm <sup>-1</sup> )	0.201	0.191
<i>F</i> (0 0 0)	868	836
$\theta$ Range for data collection (°)	2.30–26.0	2.32–26.0
Index ranges	−18 ≤ <i>h</i> ≤ 17, −13 ≤ <i>k</i> ≤ 13, −12 ≤ <i>l</i> ≤ 12	−18 ≤ <i>h</i> ≤ 18, −13 ≤ <i>k</i> ≤ 13, −12 ≤ <i>l</i> ≤ 12
Reflections collected	12 447	12 397
Independent reflections	3302 [ <i>R</i> <sub>int</sub> = 0.0217]	3277 [ <i>R</i> <sub>int</sub> = 0.0356]
Restraints/parameters	109/373	68/349
Goodness of fit (GOF) on <i>F</i> <sup>2</sup>	1.241	1.028
Final <i>R</i> indices [ <i>I</i> > 2σ( <i>I</i> )]	<i>R</i> <sub>1</sub> = 0.0775, <i>wR</i> <sub>2</sub> = 0.2128	<i>R</i> <sub>1</sub> = 0.0724, <i>wR</i> <sub>2</sub> = 0.1991
<i>R</i> indices (all data)	<i>R</i> <sub>1</sub> = 0.1033, <i>wR</i> <sub>2</sub> = 0.2353	<i>R</i> <sub>1</sub> = 0.1335, <i>wR</i> <sub>2</sub> = 0.2485
Largest difference in peak/hole (e Å <sup>-3</sup> )	0.588/−0.386	0.400/−0.296

Temperature 293 K, wavelength  $\lambda$  0.71073 pm, crystal system monoclinic, space group *P*<sub>2</sub><sub>1</sub>/*c*; crystal size (mm). Compound **1**, 0.30 × 0.20 × 0.20. Compound **2**, 0.10 × 0.10 × 0.10; Z 2 (molecule in special position).

fluorine atoms of fluoroalkyl substituents are disordered in crystals and were refined with occupancy 0.598(0.402) for **1** and 0.537(0.463) for **2**, respectively.

#### 4.2. General procedures

All reactions were carried out under dry argon atmosphere. All solvents employed were purified and dried prior to use. *N,N*-Dimethylformamide was purified by double fractionation distillation over melting potash. Perfluoroiodohexane and 6-*H*-perfluorobromohexane were purchased from P&M Invest and used without further purification.  $\alpha$ -Methylstyrene was procured from Acros Organics. Tetrabutylammonium tetrafluoroborate was purchased from Aldrich and recrystallized from diethylether. NiBr<sub>2</sub>bpy were prepared according reported procedure [26]. Preparative electrolyses were performed by means of the direct current source B5-49 in thermostatically controlled cylindrical divided 40 ml electrolyser (a three-electrode cell). Platinum with surface areas of 20 cm<sup>2</sup> was used as a cathode. The working electrode potential was determined using reference electrode SCE. During electrolysis, the electrolyte was stirred with a magnetic stirrer. The saturated solution of Et<sub>4</sub>NBF<sub>4</sub> in DMA was used as anolyte, and the anode compartment was separated by ceramic membrane. The <sup>1</sup>H NMR spectra were recorded on a Bruker MSL-400 (400 MHz). IR spectra of the compounds were recorded on a FTIR spectrometer "Vector 22" (Bruker) in the 400–4000 cm<sup>-1</sup> range. Solid samples were prepared as KBr pellets. Mass spectra were recorded in EI mode using ThermoQuest TRACE MS.

#### 4.3. Preparative electrolyses

##### 4.3.1. Electrosynthesis of 2,3-dimethyl-2,3-diphenyl-1,4-bis(perfluorohexyl)butane

A solution for electrolysis was prepared by mixing 0.317 g (0.85 mmol) NiBr<sub>2</sub>bpy, 7.54 g (16 mmol) perfluoroiodohexane and 1 g (8.5 mmol)  $\alpha$ -methylstyrene in DMF (70 ml). Electrolysis was carried out in an electrochemical cell with separation of anode and cathode compartments at ambient temperature under argon atmosphere at the potential of a working electrode −1.2 V. The amounts of electricity passed through the electrolyte were 2*F* per

one mole of perfluoroiodohexane (454 mA h). After completing the electrolysis, the solution was washed with distilled water (100 ml) and extracted with benzene (3 × 100 ml). The organic layer was dried over magnesium sulfate and filtered. The residual solution was concentrated under reduced pressure and left overnight, then the white solid precipitated from the mixture, filtered and dried *in vacuo* to give 2,3-dimethyl-2,3-diphenyl-1,4-bis(perfluorohexyl)butane. Yield 2.6 g (70%). m.p.: 160–162 °C. <sup>1</sup>H NMR (400 Hz, C<sub>6</sub>D<sub>6</sub>):  $\delta$  = 1.45 and 1.46 (two s, 6H, CH<sub>3</sub>), 2.25 and 3.23 (m, 4H, CH<sub>2</sub>), 7.07–7.19 (m, 10H, C<sub>6</sub>H<sub>5</sub>). IR (KBr,  $\nu$ , cm<sup>-1</sup>): 1144, 1208, 1237 (C–F), 1602 (C=C aromatic), 3069 (HC=). EIMS, *m/z* (rel. intensity): 437.0 (1/2M<sup>+</sup>). Anal. Calc.: C, 41.19; H, 2.29; F, 56.52. Found: C, 41.28; H, 2.45%.

##### 4.3.2. Electrosynthesis of 2,3-dimethyl-2,3-diphenyl-1,4-bis(6-*H*-perfluorohexyl)butane

A solution for electrolysis was prepared by mixing 0.576 g (1.5 mmol) NiBr<sub>2</sub>bpy, 5.86 g (15 mmol) 6-*H*-perfluorobromohexane and 1.81 g (15 mmol)  $\alpha$ -methylstyrene in DMF (100 ml). Electrolysis was carried out in an electrochemical cell with separation of anode and cathode compartments at ambient temperature under argon atmosphere at the potential of a working electrode −1.2 V. The amounts of electricity passed through the electrolyte were 2*F* per one mole of 6-*H*-perfluorobromohexane (824 mA h). After completing the electrolysis, the solution was washed with distilled water (150 ml) and extracted with benzene (3 × 100 ml). The organic layer was dried over magnesium sulfate and filtered. The residual solution was concentrated under reduced pressure and left overnight, then the white solid precipitated from the mixture, filtered and dried *in vacuo* to give 2,3-dimethyl-2,3-diphenyl-1,4-bis(6-*H*-perfluorohexyl)butane. Yield 3.2 g (49.6%). <sup>1</sup>H NMR (400 Hz, C<sub>6</sub>D<sub>6</sub>):  $\delta$  = 1.34 and 1.35 (two s, 6H, CH<sub>3</sub>), 2.17 and 3.13 (m, 4H, CH<sub>2</sub>), 4.94 (tt, 2H, <sup>2</sup>J<sub>HF</sub> 51.62 Hz, <sup>3</sup>J<sub>HF</sub> 5.12 Hz), 6.96–7.07 (m, 10H, C<sub>6</sub>H<sub>5</sub>). IR (KBr,  $\nu$ , cm<sup>-1</sup>): 1145, 1208, 1238 (C–F), 1600 (C=C), 3071 (HC=). EIMS, *m/z*: 419.0 (1/2M<sup>+</sup>). Anal. Calc.: C, 42.96; H, 2.62; F, 54.41. Found: C, 42.58; H, 2.51%.

#### Acknowledgement

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## Appendix A. Supplementary material

CCDC 720933 and 720934 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via [www.ccdc.cam.ac.uk/data\\_request/cif](http://www.ccdc.cam.ac.uk/data_request/cif). Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jorganchem.2009.08.015.

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