# Free-radical selective functionalization of 1,4-naphthoquinones by perfluorodiacyl peroxides

Maurizio Sansotera [a,b,*], Cristian Gambarotti [a], Antonino Famulari [a,b], Alberto Baggioli [a], Raffaella Soave [b,c], Francesco Venturini [a], Stefano V. Meille [a,b], Ivan Wlassics [d], Walter Navarrini [a,b]

[a] *Dipartimento di Chimica, Materiali e Ingegneria Chimica "Giulio Natta", Politecnico di Milano, via Mancinelli 7, 20131 Milano, Italy*
[b] *Consorzio Interuniversitario Nazionale per la Scienza e Tecnologia dei Materiali, Via G. Giusti 9, 50121 Firenze, Italy*
[c] *CNR-ISTM, Istituto di Scienze e Tecnologie Molecolari, via Golgi 19, 20133 Milano, Italy*
[d] *Solvay Specialty Polymers, viale Lombardia 20, 20021 Bollate (MI), Italy*

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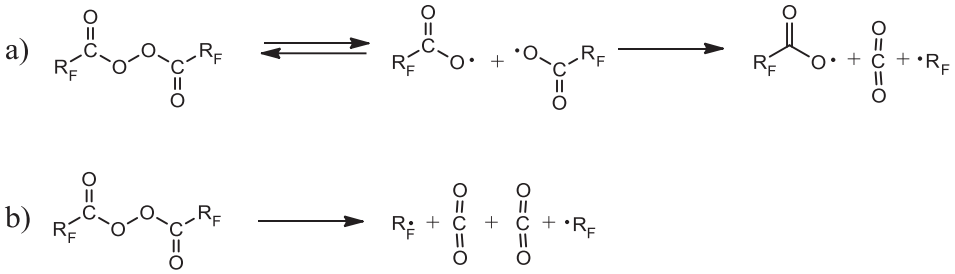
## 1. Introduction

Organic peroxides have attracted special interest due to their application in industrial and laboratory synthesis as oxidants, polymerization initiators, cross-linking agents, building blocks, intermediates in autoxidation, and substances having antimalarial and antimicrobial activities.[1–3] In particular, diacyl peroxides, RC(O)OO(O)CR, where R can be aliphatic, aromatic or other groups, have been applied to the functionalization of carbon-based nanomaterials, such as carbon nanotubes,[4–6] fullerenes,[7] carbon nanohorns,[8–10] and silicon-based materials for quantum dots.[11] The perfluorinated homologues of diacyl peroxides are perfluorodiacyl (PFDA) peroxides, $R_FC(O)OO(O)CR_F$, where $R_F$ is a perfluorinated group. Upon mild heating, PDFA peroxides decompose releasing carbon dioxide and forming free perfluoroalkyl radicals.[12] Recently, perfluoroalkyl free-radical chemistry has raised considerable interest, as demonstrated by many reviews and articles in the specialized literature.[13–21]

The comparison between electronic features and chemical behaviors of the molecules containing an oxygen–oxygen bond allowed the comprehension of some reactivity trends in this class of highly reactive molecules.[22] In addition, several quantum mechanics (QM) methods, including density functional theory (DFT) approaches, have been applied to obtain thermodynamic data of fluorinated organic peroxides with chemical accuracy.[23,24] However, the debate is still open to establish if PFDA peroxides decompose by a one-bond cleavage mechanism producing a carboxylic radical pair (Scheme 1a) or by a concerted three-bond cleavage mechanism producing an alkyl radical pair and two molecules of carbon dioxide (Scheme 1b).[25,26] The absence of products from the addition of the carboxyl radical in the reaction mixture has been frequently used to advocate the occurrence of the latter mechanism, although a few reports providing evidence of such side-products do exist in literature.[27]

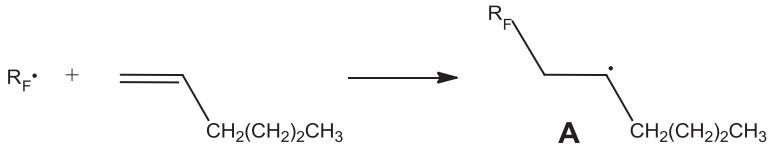
The utility of PFDA peroxides has been firstly recognized for the initiation of free-radical fluoromonomers polymerization since the early 1950s.[28] In fact, their use as initiators allowed the introduction of stable perfluoroalkyl end-groups that greatly improved the thermal stability of the synthesized fluoropolymers.[29] More recently, this class of compounds has been used in perfluoroalkylation reactions for the introduction of perfluoroalkyl groups in aromatic compounds, such as benzene, chlorobenzene, toluene, anisole, and in heteroaromatic compounds, such as furans, thiophenes, benzofurans, benzothiophenes.[14]

* Corresponding author. e-mail address: maurizio.sansotera@polimi.it (M. Sansotera).



**Scheme 1.** One-bond cleavage (a) and concerted three-bond cleavage (b) mechanisms of PFDA peroxide decomposition.

Numerous other methods have been developed for perfluoroalkyl radical production, but they have a few drawbacks.[13] Perfluoroalkyl iodides represent perhaps the most important and commonly used source of perfluoroalkyl radicals. However, iodine radicals are also generated with this synthetic methodology and iodinated derivatives are normally obtained.[19,20,30–33] Perfluoroalkyl radicals react faster with the aliphatic double bond than with the quinone ring, leading to the nucleophilic radical adduct **A** formed by the addition of perfluoroalkyl radicals to the olefin (see Scheme 2). As a result, the radical **A** reacts selectively with the naphthoquinonic molecules, also because of the relatively low reactivity of perfluoroalkyl radicals with the electron-deficient quinones.



**Scheme 2.** Addition of perfluoroalkyl radicals to olefin and formation of the nucleophilic radical adduct **A**.

fluoroalkyl sulfonyl halides are also good photochemical sources of perfluoroalkyl radicals, but problems can be encountered because the expulsion of $SO_2$ is slow and competes with the addition of $R_FSO_2$•.[34] PFDA peroxides are convenient tools for the introduction of fluoroalkyl groups in several organic substrates by carbon–carbon bond formation, because the thermal conditions to generate perfluoroalkyl radicals are mild and the perfluoroalkylation reaction is very clean.[35–38] In fact, carbon dioxide is the only byproduct besides perfluoroalkyl radicals.

The synthesis of a few of these peroxides, namely perfluorodipropionyl peroxide **1a**, perfluorodi-*iso*-butyryl peroxide **1b**, perfluorodi-*n*-butyryl peroxide **1c**, perfluorodi-2-methoxy-propionyl peroxide **1d**, and perfluorodi-2-*n*-propoxy-propionyl peroxide **1e**, is discussed, along with their characterization. In addition, these were employed in the functionalization of two naphthoquinone substrates: 1,4-naphthoquinone **2** and 2-methyl-1,4-naphthoquinone **3** (also known as menadione or vitamin $K_3$). Naphthoquinone and quinone moieties are present in many natural products and have been widely used because of their broad spectrum of biological activities.[39–42] In addition, many attempts have been spent recently in the tailoring of new naphthoquinone derivatives incorporating chemical groups.[43–48] In particular, the functionalization of naphthoquinones has been widely studied to overcome the intrinsic toxicity of quinonic compounds by synthesizing derivatives that are more stable in their reduced state and thus less likely to initiate the formation of radicals indiscriminately harmful to cells.[49] Thus, several examples of fluorinated derivatives of 1,4-naphthoquinones can be found in the literature. The inductive effect of the electronegative fluorine atoms was applied in order to reduce the tendency of these compounds to form reactive oxygen species.[50–53] Recently, Nevinsky et al. even tested the cytotoxicity of these compounds against cancer cells and their ability to protect bacterial cells from mutagenesis.[54,55]

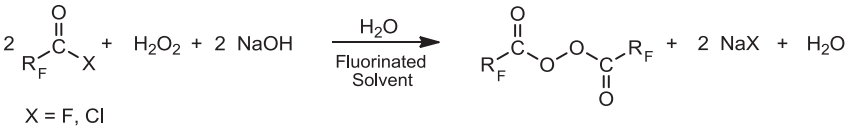
The perfluoroalkylation reaction of the naphthoquinones was performed according to two different procedures: the direct perfluoroalkylation and the perfluoroalkylation in presence of a non-conjugated alkene, such as 1-hexene. In the latter case,

In order to provide useful insight into the effect of different perfluoroalkyl substrates $R_F$ on the decomposition mechanism of PFDA peroxides and their general reactivity, a theoretical study of the five PFDA peroxides used during the synthetic procedure, along with the corresponding thermal decomposition products, was carried out. Finally, the unexpected diastereotopic behavior of the methyl hydrogen atoms of a few perfluoroalkylation products of naphthoquinone substrate **3** led to a conformational investigation and to a possible explanation of the uncommon phenomenon.

## 2. Results and discussion

### 2.1. Synthesis of PFDA peroxides

PFDA peroxides **1a**–**e** were synthesized starting from the corresponding low molecular weight perfluoroacyl halides with good-to-medium yields. The synthesis of PFDA peroxides utilized hydrogen peroxide in a biphasic system with aqueous NaOH and an inert fluorinated solvent (Scheme 3).[14,36–38] The hydrolysis of PFDA peroxides and of the starting perfluoroacyl halides was minimized by choosing proper experimental conditions. The hydrolytic decomposition is a heterogeneous reaction, and its rate is also a function of the presence of co-solvents or surfactants and of the stirring efficiency (Scheme 4). The shortness of the fluorinated chains in the molecular structures of PFDA peroxides **1a**–**e** and of the starting perfluoroacyl halides avoided the formation of annoying emulsions that often cause low preparation yields.[56] In fact, perfluorinated carboxylic side-products may act as surfactants and auto-catalyze the undesired peroxides hydrolysis. Thermolysis of PFDA peroxides **1a**–**e** is an unimolecular reaction (Scheme 1) and the thermolytic decomposition rates, $k_d$, of PFDA peroxides **1a**–**e**, were calculated at different temperatures on the basis of first-order reaction kinetic (Table 1). Hydrolysis of PFDA peroxides **1a**–**e** depends also on the concentration of water (Scheme 4), but it was possible to apply a pseudo-first-order approximation because water was supplied in great excess at the beginning of the kinetic measurement. Pseudo-first-order hydrolytic rates, $k_h$, are reported

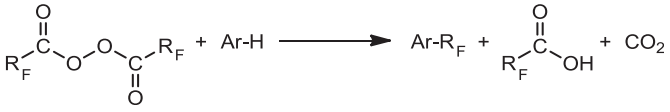


X = F, Cl

$R_F$ = **1a.** $CF_2CF_3$
**1b.** $CF(CF_3)_2$
**1c.** $CF_2CF_2CF_3$
**1d.** $CF(CF_3)OCF_3$
**1e.** $CF(CF_3)OCF_2CF_2CF_3$

**Scheme 3.** Synthesis of PFDA peroxides utilized hydrogen peroxide in a biphasic system with aqueous NaOH.

**Scheme 4.** Hydrolysis of PFDA peroxides.



**Scheme 5.** Perfluoroalkylation of aromatic substrates with PFDA peroxides.

**Table 1**
Thermolysis and pseudo-first-order hydrolysis kinetic data of synthesized PFDA peroxides

| Peroxide | $R_F$[a] | $T$ (°C) | Thermolysis $k_d$ ($\times 10^5$ $s^{-1}$) | $t_{1/2}$ (h) | Hydrolysis $k_h$ ($\times 10^5$ $s^{-1}$) |
|---|---|---|---|---|---|
| **1a** | $CF_3CF_2$ | 25 | 1.2[b] | 16.0 | 4.5 |
| | | 30 | 5.3[c] | 3.6 | — |
| **1b** | $(CF_3)_2CF$ | 60 | 4.4[b] | 4.4 | — |
| | | 70 | 17.3[b] | 1.1 | 21.1 |
| | | 80 | 56.5[b] | 0.34 | — |
| **1c** | $CF_3CF_2CF_2$ | 15 | 1.5[b] | 12.8 | 4.5 |
| | | 30 | 7.8[d] | 2.5 | — |
| **1d** | $CF_3(CF_3O)CF$ | 20 | 1.8[b] | 10.7 | 1.5 |
| | | 30 | 9.9[b] | 1.9 | — |
| | | 40 | 40.8[b] | 0.47 | — |
| **1e** | $CF_3(CF_3CF_2CF_2O)CF$ | 20 | 3.4[b] | 5.7 | — |
| | | 30 | 13.9[b] | 1.4 | — |

[a] Fluorinated residual in the structure of PFDA peroxide, accordingly to the formula $R_FC(O)OO(O)CR_F$.
[b] In $CF_2ClCFCl_2$ as solvent.
[c] In $CF_3OCFClCF_2Cl$ as solvent.
[d] In Galden® D100 as solvent.

in Table 1 and it should be pointed out that each hydrolysis kinetic constant is inclusive of the corresponding thermal decomposition. Therefore, these data should be considered as a computation of the thermal and hydrolytic decomposition. Hydrolysis is a significant side reaction in the preparation of PFDA peroxides, where highly hydrolytic conditions, like aqueous NaOH and $H_2O_2$ (Scheme 3), are utilized and can influence the yield of the synthesis.

The kinetic data reported in Table 1 reveal that hydrolysis is particularly relevant for non-branched peroxides **1a** and **1c**, whose $k_h$ are both approximately three times larger than the corresponding thermolysis kinetic constants, $k_d$. On the contrary, the thermolysis of the remaining branched peroxides is only slightly influenced by the hydrolysis, because the $k_d$ and $k_h$ are in the same range of values.

## 2.2. Naphthoquinones functionalization

It was demonstrated that PFDA peroxides are useful reagents for the introduction of the corresponding perfluoroalkyl groups into aromatic compounds such as benzene, chlorobenzene, toluene, and anisole (Scheme 5).[14] In 1983 C. Zhao et al. proposed a single electron-transfer (SET) mechanism for the perfluoroalkylation reaction with electron rich aromatic substrates.[35] More recently evidences of a free chain radical mechanism for this reaction have been observed also on electron poor substrates.[36–38]

Conversely, the thermal decomposition of perfluorodiacyl peroxides in the presence of 1,4-naphthoquinonic compounds under degassed conditions revealed that the quinonic double bond is more reactive toward radicals than the aromatic ring.[30–33] Thus, the perfluoroalkylation of the corresponding quinonic derivatives occurs selectively on the quinone ring (Scheme 6). Perfluorinated carboxylic acid and carbon dioxide are the main byproducts generated during the reaction. Traces of several other compounds originated by competitive side reactions include products from the recombination of two radicals, products from double addition on substrate **2**, and products of the addition of a perfluorocarboxyl radical.

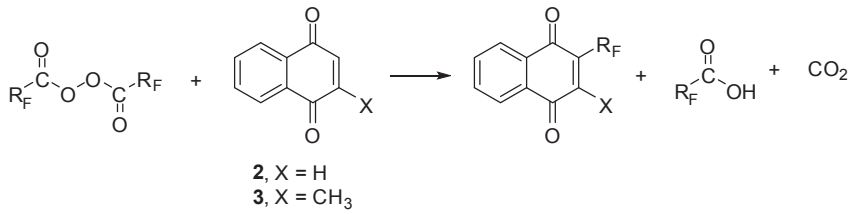
The underlying mechanism for the direct perfluoroalkylation involves the decomposition of PFDA peroxides with generation of reactive perfluoroalkyl radicals, $R_F^{\bullet}$. These radicals can selectively add to the quinone ring leading to a semiquinonic radical intermediate (Scheme 7).

The semiquinone radical has a bond-dissociation energy of the O—H bond (ca. 226 kJ $mol^{-1}$) much lower than that of phenol (369 kJ $mol^{-1}$) and it is much more acidic ($pK_a$=4.1) than phenol.[57–60] Thus, the equilibrium of the acid dissociation reaction of the semiquinone radical is not negligible, suggesting two possible mechanisms: hydrogen abstraction from the semiquinone radical or an electron-transfer in a chain process. In fact, the semiquinone radical has a proper persistency and may couple with a transient radical like $R_F^{\bullet}$.[61,62] Alternatively, a classical electron-transfer decomposition reaction of PFDA peroxides can be induced by easily-oxidizable semiquinone radical-anions.[63]

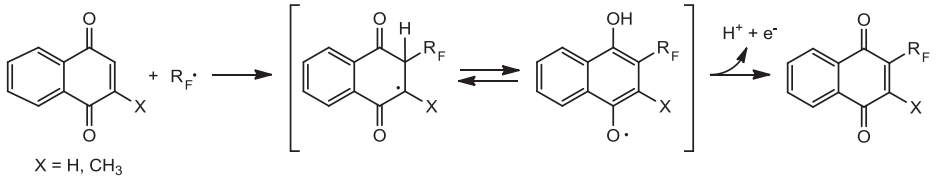
The direct perfluoroalkylation methodology was successively applied to the functionalization of naphthoquinone derivatives **2** and **3**, and high conversions and selectivities (Table 2) to the desired products **2a**—**e** and **3a**—**e** (Fig. 1) were observed in all cases.

In presence of 1-hexene, the perfluoroalkyl radicals $R_F^{\bullet}$ react faster with the olefinic double bond than with the quinone ring. In such circumstances, with reference to Scheme 2, the radical adduct **A** is formed, and then added selectively to the quinone ring, leading to the reaction product by oxidation of the semiquinone radical (Scheme 8). The overall kinetics of radicals addition make the process particularly selective for a one-step one-pot procedure. Products **2f**—**j** and **3f**—**j** were in fact obtained with rather high conversion and selectivity. The results of the olefin-driven perfluoroalkylation of naphthoquinones **2** and **3** are reported in Table 3, while the products obtained are graphically reported in Fig. 2.

Overall, no significant difference in reactivity was observed between naphthoquinone substrates **2** and **3**. The increased steric hindrance near the functionalization site of substrate **3** due to the




**Scheme 6.** Perfluoroalkylation of naphthoquinones with PFDA peroxides.




**Scheme 7.** Addition of a perfluoroalkyl radical to the quinonic double bond, tautomerism of the semiquinone radical and oxidation with hydrogen abstraction.

**Table 2**
Direct perfluoroalkylation of quinones **2** and **3**

| Peroxide | Quinone | Product | Conversion (%) | Selectivity[a] (%) | Isolated yield (%) |
|---|---|---|---|---|---|
| **1a** | **2** | **2a** | 93 | 96 | 74 |
| **1a** | **3** | **3a** | 95 | 98 | 90 |
| **1b** | **2** | **2b** | 94 | 86 | 66 |
| **1b** | **3** | **3b** | 82 | 87 | 62 |
| **1c** | **2** | **2c** | 98 | 95 | 78 |
| **1c** | **3** | **3c** | 95 | 98 | 67 |
| **1d** | **2** | **2d** | 95 | 65 | 46 |
| **1d** | **3** | **3d** | 87 | 67 | 43 |
| **1e** | **2** | **2e** | 80 | 78 | 47 |
| **1e** | **3** | **3e** | 88 | 72 | 48 |

[a] The selectivity is referred to the reported product.

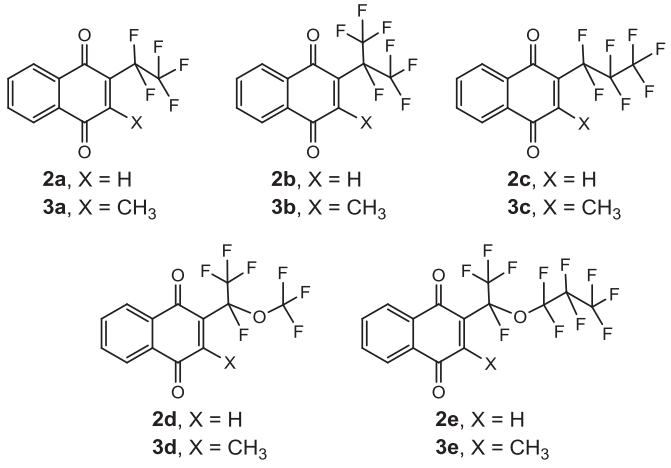



**Fig. 1.** Perfluoroalkylation of naphthoquinones **2** and **3** with PFDA peroxides **1a**–**e**.

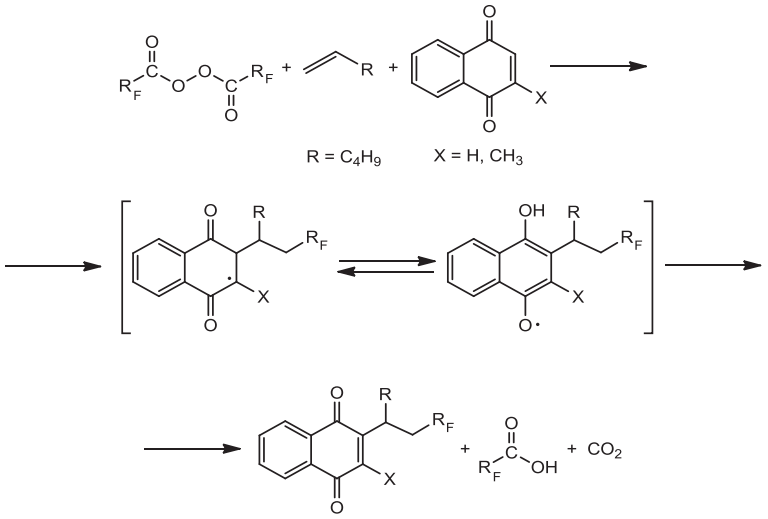
methyl group resulted negligible compared to the reactivity of the quinonic double bond toward free radicals.

Dichloromethane, $CH_2Cl_2$, was used as solvent during direct perfluoroalkylation reactions of quinones with PFDA peroxides as well as in the presence of *n*-hexene. It allowed to perform the whole experiment in a homogenous phase by dissolving the reagents and the solutions of PFDA peroxides in $CF_3OCFClCF_2Cl$. In addition, its boiling point lies within the correct temperature range for decomposition of PFDA peroxides, with thermolytic half-life times between 1 and 5 h. Hydrogen abstraction from dichloromethane was also considered but, at the experimental conditions, only traces of hydrogen abstraction side-products were observed at the end of reactions. Perfluroalkylation of quinones arose as the largely favored synthetic pathway.

## 2.3. Naphthoquinones characterization

*2.3.1. $^{1}H$ and $^{19}F$ NMR and steric hindrance of $R_F$.* Complete GC–MS, and $^{1}H$, $^{13}C$, and $^{19}F$ NMR analysis for products **2a**–**j** and **3a**–**j** are reported in the Experimental section, while NMR spectra are reported in Supplementary data. Interesting to note is the $^{1}H$ NMR spectrum for products **3b**, **3d**, and **3e**, which shows diastereotopic behavior in the methyl group hydrogen atoms. This uncommon occurrence is bound to the time-scale of two different phenomena: the characteristic time of rotation of the methyl group (actually 1/3 of that time because of the threefold symmetry) and the characteristic time of acquisition of the resonance data. In the vast majority of cases, hydrogen atoms of methyl groups are homotopic to each other, as they rotate about the C–C bond at a frequency orders of magnitude larger than typical NMR sampling rates, resulting in a single signal. This is in fact the case for the hydrogen atoms in the methyl group of products **3a**, **3c**, and **3f**–**j**, as well as for the methyl group hydrogen atoms of quinone derivative **3** itself. On the other hand, if for any reason the rotation about the C–$CH_3$ axis is significantly slower, the resonance of each hydrogen atom can be observed separately. In this case, the particular topicity of the methyl group hydrogens of products **3b**, **3d**, and **3e** might be ascribed to the combined effect of $R_F$ steric hindrance and of strong 'through space' H,F coupling.

A conformational study of products **3a** and **3d** (chosen as models for homotopic- and diastereotopic-behaving methyl hydrogens, respectively) was carried out. With reference to Fig. 3, absolute minimum energy conformations of both products (Boltzmann weight factors of 0.995 and 0.810, respectively), characterized by a $\omega$ angle of about 25°, are used as starting points for the calculation of the potential energy curves associated with the rotation about the $\omega$ torsion angle. Bold lines in Fig. 3 thus provide a quantitative insight on the extent of the potential energy well of such stable conformations along the internal coordinate $\omega$, suggesting the perfluorinated substituent of product **3a** to be substantially freely oriented compared to that of product **3d**, which shows much higher torsional barriers. Indeed, although small deviations from $\Delta\omega=0$ are allowed for product **3d**, the torsion




**Scheme 8.** Perfluoroalkylation of naphthoquinones with PFDA peroxides in presence of 1-hexene.

**Table 3**
Perfluoroalkylation of quinones **2** and **3** in presence of 1-hexene

| Peroxide | Quinone | Product | Conversion (%) | Selectivity[a] (%) | Isolated yield (%) |
|---|---|---|---|---|---|
| **1a** | **2** | **2f** | 99 | 61 | 45 |
| **1a** | **3** | **3f** | 99 | 90 | 80 |
| **1b** | **2** | **2g** | 98 | 65 | 49 |
| **1b** | **3** | **3g** | 84 | 75 | 55 |
| **1c** | **2** | **2h** | 99 | 66 | 50 |
| **1c** | **3** | **3h** | 96 | 85 | 68 |
| **1d** | **2** | **2i** | 99 | 65 | 49 |
| **1d** | **3** | **3i** | 98 | 85 | 70 |
| **1e** | **2** | **2j** | 99 | 72 | 56 |
| **1e** | **3** | **3j** | 95 | 75 | 60 |

[a] The selectivity is referred to the reported product.

potential of product **3a** shows a nearly flat low-energy segment in a range of $\Delta\omega$=30°–150° allowing for much larger deviations (it should be noted that the torsion potential of product **3a** is an even function in the reference system centered in $\Delta\omega$=90°).

Indirect dipole–dipole coupling constants $J_{HF}$ have been computed for products **3a** and **3d** at different values of $\Delta\omega$. The presence of fluorine atoms in organic compounds is known to give rise to large coupling to protons due to the high nuclear magnetic moment of $^{19}F$ nucleus. Thin lines in Fig. 3 show that $^{5}J_{HF}$ coupling constants for both products reach a maximum in the region of the minimum potential energy well (around $\Delta\omega$=0). In the $\Delta\omega$=−40° region, $^{6}J_{HF}$ coupling constants of comparable magnitude are obtained via $CF_3$ groups, but the potential energy curves of both products possess a maximum energy point in that region, making the coupling of $CF_3$ fluorine atoms irrelevant.

The strong H,F coupling around the optimal value of $\omega$, combined with the inability of $R_F$ to assume conformations characterized by large values of $|\Delta\omega|$ due to steric hindrance, result in the unwarranted diastereotopic behavior of the methyl group hydrogen atoms observed experimentally for products **3b**, **3d**, and **3e**. No particular topicity is observed instead for all other derivatives of **3** because of a much more forgiving $\omega$ torsion potential. It was demonstrated in fact that products **3a** and **3c** possess higher conformational freedom, opposing the preservation of the H,F coupling over time, while the hydrogenated fragment between menadione and $R_F$ in products **3f**–**j** disrupts the coupling in the first place.

*2.3.2. Single-crystal X-ray diffraction (XRD).* In order to further contribute to the characterization of the obtained products, several attempts were made at their crystallization. However, only product **3a** crystallized in ordered structures, suitable for diffractometric

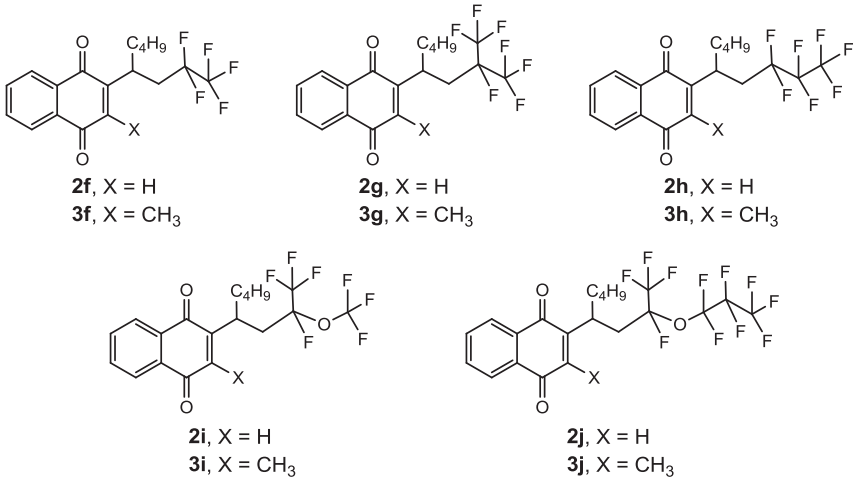



**Fig. 2.** Products obtained by perfluoroalkylation of naphthoquinones **2** and **3** with PFDA peroxides **1a**–**e** in presence of 1-hexene.

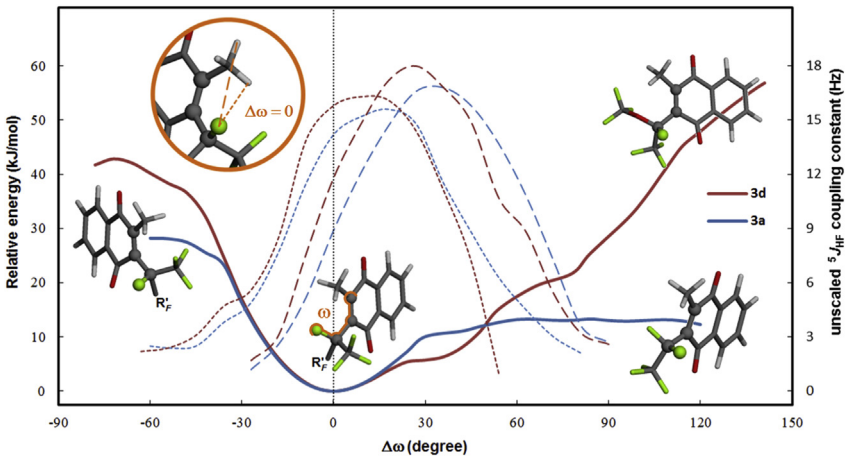



**Fig. 3.** Bold lines represent the potential energy curves associated with the rotation about $\omega$ angle (against left axis) for products **3a** and **3d**, using the optimized value of $\omega$ as reference. Thin lines represent unscaled $^5J_{HF}$ coupling constants computed for different values of $\Delta\omega$. In this case $R'_F = F$ for product **3a** and $R'_F = OCF_3$ for product **3d**.

analysis. The bulkiness of the substituents, and the conformational freedom of the perfluoroalkoxy moieties in particular (when present) are thought to be the main reasons for the inability to obtain crystalline solids suitable for single-crystal X-ray diffraction measurements from the other naphthoquinone products. Small, light orange crystalline specimens could indeed be obtained for compound **3a**. A sample of appropriate size and quality was selected for the structural analysis, which was performed at a temperature of 100 K, in order to prevent crystal degradation. Compound **3a** crystallized in the orthorhombic crystal system, with space group *Pna*21. The molecular conformation in the solid state as Oak Ridge Thermal Ellipsoid Plot (ORTEP) and the crystal packing at 100 K are, respectively, reported in Fig. 4.

other relevant geometric parameters are listed in Table 4. Reaction enthalpies and free energies were also computed assuming optimum structures for all peroxides and decomposition products. The calculation was iterated for both thermal decomposition reactions shown in Scheme 1, one-bond and concerted three-bond cleavage mechanisms, and results are listed in Table 5. Data obtained were, however, not decisive, as they did not suffice to aid in the clarification of the peroxides' chemical stability observed experimentally (see Table 1). The O—O bond lengths ($a$) computed are only slightly influenced by $R_F$ substrates as well as the other geometrical evidences listed in Table 4, and the computed reaction energies and enthalpies do not correlate well with the thermolytic half-life times measured.

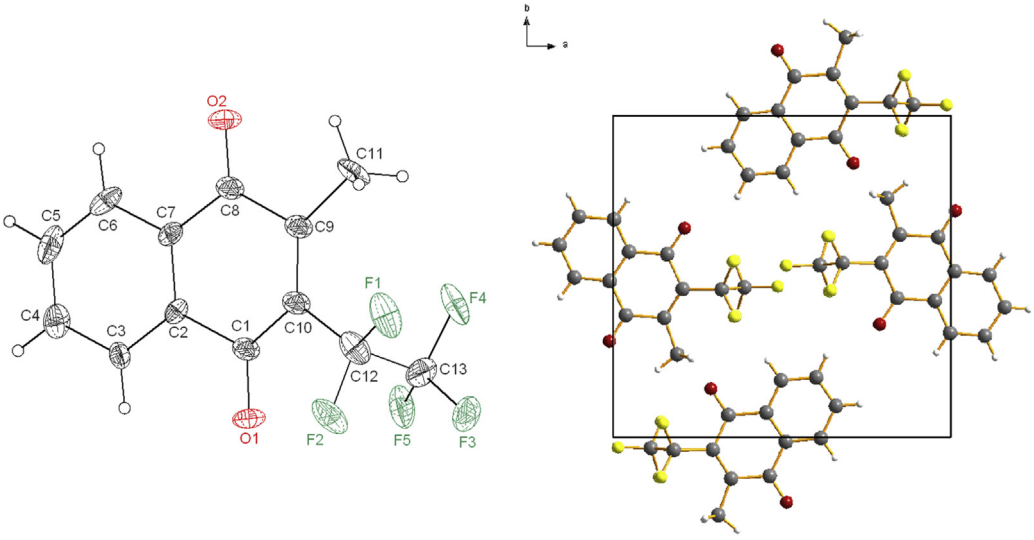



**Fig. 4.** ORTEP plot with 30% probability ellipsoids (left) and content of the crystallographic unit cell aligned along the *c* axis (right) obtained for product **3a** from single-crystal X-ray diffraction at 100 K. Color code: gray, carbon; white, hydrogen; red, oxygen; yellow, fluorine.

## 2.4. Theoretical investigation of PFDA peroxides reactivity

A conformational study of the PFDA peroxides **1a**—**e**, along with all the corresponding thermal decomposition products, was carried out in order to attempt a rationalization of their experimental reactivity. The analysis shows that the absolute minimum energy conformation for all the investigated peroxides is characterized by a dihedral angle $\theta$ (Fig. 5) with respect to the O—O bond ($a$) in the range of 84—87°, with carboxylic moieties lying on almost orthogonal planes. The computed values of these dihedral angles and

Further investigation of the topic led to the application of the quantum theory of atoms in molecules (QTAIM) proposed by Bader. This methodology analyses the electron density topology of molecular systems and reveals bonding motifs by characterizing stationary points between two or more nuclei.[64] When a stationary point is located between two atoms, it is referred to as the bond critical point (BCP), and the study of several physical quantities relative to that point can provide invaluable information about the nature of the bond itself. BCPs associated with the O—O bridging bonds in peroxides **1a**—**e** were determined from the previously

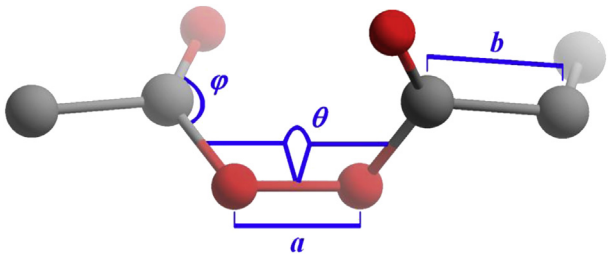



**Fig. 5.** Geometric parameters of perfluorodiacyl peroxide: O—O bond *a*, C—C bond *b*, valence angle $\varphi$ between the two oxygen atoms and dihedral angle $\theta$. Color code: gray, carbon; red, oxygen.

**Table 4**
Selected geometric parameters calculated at the U-B3LYP/6-311G(d,p) level for PFDA peroxides under investigation

| Peroxide | $R_F$ | $a$[a] | $b$[a] | $\varphi$[a] | $\theta$[a] |
|---|---|---|---|---|---|
| **1a** | $CF_3CF_2$ | 1.438 | 1.557 | 127.2 | 84.7 |
| **1b** | $(CF_3)_2CF$ | 1.439 | 1.557 | 126.9 | 86.7 |
| **1c** | $CF_3CF_2CF_2$ | 1.440 | 1.561 | 127.4 | 86.1 |
| **1d** | $CF_3(CF_3O)CF$ | 1.437 | 1.563 | 127.2 | 85.6 |
| **1e** | $CF_3(C_3F_7O)CF$ | 1.437 | 1.562 | 127.2 | 85.6 |

[a] See Fig. 4.

**Table 5**
U-B3LYP/6-311G(d,p) enthalpies and free energies of decomposition of PFDA peroxides under investigation for one-bond and concerted three-bond cleavages, as from Scheme 1. All quantities are reported in kJ $mol^{-1}$

| Peroxide | One-bond cleavage | | Three-bond leavage | |
|---|---|---|---|---|
| | $\Delta H_{d1}$ | $\Delta G_{d1}$ | $\Delta H_{d3}$ | $\Delta G_{d3}$ |
| **1a** | −10.21 | −116.50 | −121.52 | −270.54 |
| **1b** | −23.99 | −131.90 | −142.28 | −302.48 |
| **1c** | −15.86 | −120.64 | −132.36 | −283.22 |
| **1d** | −24.49 | −133.58 | −147.72 | −308.47 |
| **1e** | −23.90 | −134.41 | −146.51 | −309.64 |

optimized structures' electronic density. For each BCP, the electron density $\rho_b$, the Laplacian of the electron density $\nabla^2\rho_b$, and the Hamiltonian kinetic energy density *K*, were computed. Results are collected in Table 6. Values of electron density at BCPs ($\rho_b$) are found to be not appreciably sensitive to $R_F$, while corresponding values of the Laplacian for the electron density ($\nabla^2\rho_b$) are greater than zero, thus indicating a depletion of electron density in the region of contact of the two oxygen atoms. It is known that bond interactions for which $\nabla^2\rho_b$ is greater than zero are dominated by a local excess of kinetic energy.[65] In fact, the analysis of the energy density at BCPs shows that the values of the Hamiltonian kinetic energy density (*K*) decrease as the stability of PFDA peroxides increases, in accordance with the kinetic constants of thermolysis (see Table 1).

**Table 6**
Electron density ($\rho_b$), Laplacian ($\nabla^2\rho_b$) and relative Hamiltonian kinetic energy density ($\Delta K$) at BCPs of PFDA peroxides under investigation (atomic units)

| Peroxide | $\rho_b$ | $\nabla^2\rho_b$ | $\Delta K$ |
|---|---|---|---|
| **1a** | 0.269 | 0.332 | 1E-3 |
| **1b** | 0.269 | 0.334 | 4E-3 |
| **1c** | 0.269 | 0.336 | 4E-3 |
| **1d** | 0.270 | 0.328 | 3E-4 |
| **1e** | 0.270 | 0.327 | 0 |

## 3. Concluding remarks

A selection of five perfluorodiacyl (PFDA) peroxides were employed in the functionalization of 1,4-naphthoquinone and 2-methyl-1,4-naphthoquinone (menadione). The perfluoroalkyl groups were attached directly to the quinone, or linked to a spacer as obtained in the presence of a non-conjugated alkene such as 1-hexene. Substituted naphthoquinones were successfully obtained in good yields and with good selectivities, and full characterization was achieved by GC—MS, $^1$H and $^{19}$F NMR spectroscopic analysis. As far as $^1$H NMR spectra are concerned, a few methyl group hydrogen atoms in 2-methyl-1,4-naphthoquinone derivatives were observed to display a diastereotopic behavior. This uncommon phenomenon was attributed to the conformationally hampered structure of such products (resulting from the steric hindrance of $R_F$), allowing for the preservation over time of a strong H,F dipolar coupling.

In addition, light orange crystals of 3-(perfluoroethyl)-menadione were obtained in ordered structures suitable for diffractometric analysis. The bulkiness of the fluorinated chains and the mobility due to the presence of the oxygen atoms seemed to induce a high degree of disorder in the molecular assembly of the other quinonic derivatives.

Finally, a theoretical investigation was carried out by computational means in order to clarify the experimentally observed chemical stability of the PFDA peroxides considered. Preliminary DFT calculations revealed that the extrapolation of a direct relationship between geometrical parameters and thermolysis behavior is not straightforward. However, the QTAIM approach applied to the computed electron densities showed evidences of a subtle correlation between the local excess of kinetic energy at oxygen—oxygen bond critical points (BCPs) and kinetic constants of thermolysis.

## 4. Experimental section

### 4.1. Materials and methods

Perfluoroacyl fluorides for the syntheses of peroxides **1a** and **1b** were provided by Solvay Specialty Polymers; the perfluoroacyl chloride for peroxide **1c** and the perfluoroacyl fluoride for peroxide **1e** were supplied by Sigma—Aldrich. Heptafluoro-2-methoxy-propionyl fluoride was synthesized from carbonyl difluoride (Solvay Specialty Polymers) and trifluoro-2-(trifluoromethoxy)-ethylene (Solvay Specialty Polymers) on the basis of the procedure described in the literature.[66,67] The inert fluorinated solvent for the synthesis of PFDA peroxides was $CF_3OCFClCF_2Cl$ and it was furnished by Solvay Specialty Polymers. All other chemicals for the synthesis of PFDA peroxides were reagent grade purchased from Sigma Aldrich. *CAUTION*: Perfluoroacyl fluorides react with moisture developing HF and perfluorocarboxylic acids.

In a typical kinetic measurement, about 1.5 ml of PFDA peroxide solution was put in a glass test tube with screw neck; a whole set of these tubes was placed in a thermostat (±0.1 °C), and they were taken out at specified times and immediately frozen to dry ice temperature. In kinetic measurements in the presence of water, 2.0 ml of distilled water was also added to the glass test tube containing PFDA peroxide solution. The tubes were opened while cool, and 1.0 ml of peroxide solution was titrated by standard iodometry. First-order rate constant at different temperatures was calculated by linear regression analysis.

1,4-Naphthoquinone **2**, 2-methyl-1,4-naphthoquinone **3** (menadione), 1-hexene, and solvents (dichloromethane, ethyl acetate, and *n*-hexane) were commercial reagent grade products by Sigma—Aldrich and they were used without further purification.

The conversion was evaluated by GC analysis and calculated on the unreacted **2** or **3** referred to an internal standard.

The reaction products were isolated by flash column chromatography (silica gel, *n*-hexane/ethylacetate 9:1) and identified by GC—MS, $^1$H NMR, $^{13}$C NMR, and $^{19}$F NMR spectroscopy. Agilent 6890 Gas Chromatograph (GC) system equipped with a 30 m×0.250 mm

HP-5MS GC column and an Agilent 5973 Mass Selective Detector (MSD) detector were used to record the GC–MS spectra. Bruker AV 400 ($^1$H 400 MHz, $^{13}$C 100 MHz) equipped with a 5 mm multinuclear probe with reverse detection was used to record $^1$H NMR spectra. 32 Scans for $^1$H and 1024 scans for $^{13}$C were acquired with an acquiring time of 5 s. $^{19}$F NMR spectra were carried out with a Bruker Avance 500 spectrometer operating at 470 MHz. $^1$H and $^{19}$F NMR chemical shifts are referenced to tetramethylsilane (TMS) and $CCl_3F$, respectively. Melting points were determined with a Buchi 535 apparatus. IR spectra were collected with a Varian 640-IR IR Spectrometer equipped with an ATR-FTIR apparatus. Elemental analyses were performed on an EA 1108 CHNS-O Fison instrument.

### 4.2. Synthesis of PFDA peroxides 1a–e

The solutions of PFDA peroxides **1a**–**e** were prepared with good-to-medium yields from the perfluoroacyl halides (fluoride or chloride) with $H_2O_2$ in a biphasic alkaline system, according to methods described in the literature (Scheme 4).[36–38] Solutions having peroxide concentrations as high as 15% were prepared and stored at the appropriate temperature for days.[36–38] *CAUTION*: PFDA peroxides may decompose very quickly through auto-induced decomposition.

### 4.3. Direct perfluoroalkylation of 1,4-naphthoquinones 2 and 3

*4.3.1. 2-(Perfluoroethyl)-1,4-naphthoquinone **2a**.* Quinone **2** (0.36 mmol) was dissolved in $CH_2Cl_2$ (5 ml) and the resulting quinonic solution was added to a solution of peroxide **1a** (0.9 ml of 8.0 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 8 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **2a** (74 mg; 74%) as a yellow solid (mp 77–80 °C). GC–MS: $m/z$=276 $[M]^{+\bullet}$, 257, 248, 207, 179, 157, 129, 104, 76, 50. IR (ATR, $cm^{-1}$): $\nu_{max}$ 1672, 1591, 1454, 1359, 1326, 1298, 1224, 1197, 1157, 1117, 1089, 1005, 931, 907, 859, 831, 803, 781, 741, 719. $^1$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 7.36 (s, 1H), 7.82–7.88 (m, 2H), 8.14 (dd, $J$=2.1, 5.6 Hz, 1H), 8.19 (dd, $J$=2.1, 5.6 Hz, 1H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −115.5 (m, 2F, $F_\alpha$), −82.5 (t, 3F, $J$=1.7 Hz, $F_\beta$) ppm. $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 186.4, 185.2, 138.7, 136.0, 135.4, 134.0, 131.9, 130.9, 128.2, 127.5, 126.5, 125.6 ppm. $C_{12}H_5F_5O_2$ (276.16): calcd C 52.19, H 1.82; found C 52.3, H 1.8.

*4.3.2. 2-(Perfluoro-iso-propyl)-1,4-naphthoquinone **2b**.* Quinone **2** (0.36 mmol) was dissolved in $CH_2Cl_2$ (5 ml) and the resulting quinonic solution was added to a solution of peroxide **1b** (1.7 ml of 5.7 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 72 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **2b** (77 mg; 66%) as a yellow solid (mp 51–54 °C). GC–MS: $m/z$=326 $[M]^{+\bullet}$, 307, 298, 257, 229, 179, 157, 129, 104, 76, 50. IR (ATR, $cm^{-1}$): $\nu_{max}$ 1795, 1674, 1596, 1461, 1298, 1225, 1171, 1105, 1035, 983, 920, 825, 780, 734. $^1$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 7.42 (d, $J_{LR}$=1.4, 1 Hz), 7.82–7.88 (m, 2H), 8.14 (dd, $J$=2.6, 5.5 Hz, 1H), 8.18 (dd, $J$=2.6, 5.5 Hz, 1H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −177.2 (m, 1F, $F_\alpha$), −74.1 (d, 6F, $J$=4.8 Hz, $F_\beta$) ppm. $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 185.4, 138.7, 134.9, 134.1, 131.9, 127.1, 126.5 ppm. $C_{13}H_5F_7O_2$ (326.17): calcd C 47.87, H 1.55; found C 48.0, H 1.7.

*4.3.3. 2-(Perfluoro-n-propyl)-1,4-naphthoquinone **2c**.*[68] Quinone **2** (0.36 mmol) was dissolved in $CH_2Cl_2$ (5 ml) and the resulting quinonic solution was added to a solution of peroxide **1c** (2.3 ml of 4.2 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 8 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **2c** (92 mg; 78%) as an orange solid (mp 55–58 °C). GC–MS: $m/z$=326 $[M]^{+\bullet}$, 307, 298, 257, 229, 179, 157, 129, 104, 76, 50. IR (ATR, $cm^{-1}$): $\nu_{max}$ 1672, 1627, 1593, 1458, 1307, 1223, 1191, 1153, 1122, 1078, 1026, 949, 918, 859, 823, 780, 743, 720. $^1$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 7.34 (s, 1H), 7.82–7.88 (m, 2H), 8.14 (dd, $J$=1.5, 5.7 Hz, 1H), 8.19 (dd, $J$=1.5, 5.7 Hz, 1H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −112.7 (m, 2F, $F_\alpha$), −125.4 (m, 2F, $F_\beta$), −81.2 (t, 3F, $J$=9.8 Hz, $F_\gamma$) ppm. $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 185.3, 179.4, 138.7, 136.6, 136.0, 134.0, 131.9, 131.3, 130.9, 128.2, 127.5, 126.5, 125.6 ppm. $C_{13}H_5F_7O_2$ (326.17): calcd C 47.87, H 1.55; found C 47.9, H 1.6.

*4.3.4. 2-(1′-Trifluoromethoxy-perfluoroethyl)-1,4-naphthoquinone **2d**.* Quinone **2** (0.36 mmol) was dissolved in $CH_2Cl_2$ (5 ml) and the resulting quinonic solution was added to a solution of peroxide **1d** (2.1 ml of 4.9 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was stirred at room temperature overnight. Thereafter, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **2d** (57 mg; 46%) as a yellow solid (mp 52–54 °C). GC–MS: $m/z$=342 $[M]^{+\bullet}$, 314, 273, 245, 217, 179, 157, 129, 104, 69. IR (ATR, $cm^{-1}$): $\nu_{max}$ 1669, 1631, 1593, 1459, 1302, 1221, 1136, 1105, 1034, 921, 890, 829, 765, 741. $^1$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 7.46 (s, 1H), 7.75 (m, 2H), 8.12 (m, 2H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −127.0 (m, 1F, $F_\alpha$), −82.4 (d, 3F, $F_\beta$), −55.0 (d, 3F, $OCF_3$) ppm. $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 185.1, 138.7, 135.6, 135.3, 135.0, 134.7, 134.0, 132.0, 128.1, 127.6, 127.4, 126.5 ppm. $C_{13}H_5F_7O_3$ (342.17): calcd C 45.63, H 1.47; found C 45.5, H 1.5.

*4.3.5. 2-(1′-(Perfluoro-n-propoxy)-perfluoroethyl)-1,4-naphthoquinone **2e**.* Quinone **2** (0.36 mmol) was dissolved in $CH_2Cl_2$ (5 ml) and the resulting quinonic solution was added to a solution of peroxide **1e** (2.2 ml of 6.8 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was stirred at room temperature overnight. Thereafter, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **2e** (75 mg; 47%) as a yellowish oil. GC–MS: $m/z$=442 $[M]^{+\bullet}$, 423, 414, 386, 373, 345, 317, 257, 229, 179, 169, 157, 151, 129, 119, 104, 76, 69, 50. IR (ATR, $cm^{-1}$): $\nu_{max}$ 1676, 1595, 1459, 1335, 1302, 1229, 1198, 1143, 1080, 1035, 988, 925, 835, 805, 779, 752, 731. $^1$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 7.39 (s, 1H), 7.80–7.88 (m, 2H), 8.13 (dd, $J$=1.9, 6.4 Hz, 1H), 8.18 (dd, $J$=1.9, 6.4 Hz, 1H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −125.5 (m, 1F, $F_\alpha$), −81.7 (d, 3F, $F_\beta$), −80.5 (dm, 1F, $^2J_{F,F}$=145.7 Hz, OCF*F), −84.8 (dm, 1F, $^2J_{F,F}$=145.7 Hz, OCFF*), −129.3 to −130.5 (dm, 2F, $J_{A,B}$=283.3 Hz, $CF_2$), −81.6 (t, 3F, $CF_3$). $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 186.2, 185.5, 160.8, 160.5, 140, 139.0, 135.9, 135.5, 135.4, 134.5, 132.1, 131.9, 127.8, 127.7, 126.9 ppm. $C_{15}H_5F_{11}O_3$ (442.18): calcd C 40.74, H 1.14; found C 40.6, H 1.0.

*4.3.6. 2-Methyl-3-(perfluoroethyl)-1,4-naphthoquinone **3a**.* Quinone **3** (0.36 mmol) was dissolved in $CH_2Cl_2$ (5 ml) and the resulting quinonic solution was added to a solution of peroxide **1b** (0.9 ml of 8.0 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 8 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **3a** (94 mg; 90%) as a yellow solid (mp 75–77 °C). GC–MS: $m/z$=290 $[M]^{+\bullet}$, 270, 262, 242, 221, 193, 171, 163, 143, 115, 104, 89, 76, 69, 50. IR (ATR, $cm^{-1}$): $\nu_{max}$ 1670, 1592, 1438, 1384, 1323, 1283, 1198, 1175, 1142, 1103, 1064, 1031, 993, 951, 840, 785, 736, 706. $^1$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 2.42 (t, $J$=2.42 Hz, 3H), 7.78 (m, 2H), 8.11 (m, 2H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −108.1 (m, 2F, $F_\alpha$), −82.8 (t, 3F, $J$=2.3 Hz, $F_\beta$) ppm. $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 183.6, 180.1, 152.5, 134.6,

134.2, 132.7, 132.0, 131.0, 126.7, 13.9 ppm. $C_{13}H_7F_5O_2$ (290.19): calcd C 53.81, H 2.43; found C 53.9, H 2.3.

*4.3.7. 2-Methyl-3-(perfluoro-iso-propyl)-1,4-naphthoquinone* ***3b***. Quinone **3** (0.36 mmol) was dissolved in $CH_2Cl_2$ (5 ml) and the resulting quinonic solution was added to a solution of peroxide **1b** (1.7 ml of 5.7 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 72 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **3b** (83 mg; 62%) as a yellow solid (mp 65–68 °C). GC–MS: *m*/*z*=340 $[M]^+$•, 321, 300, 271, 243, 223, 195, 171, 146, 115, 104, 89, 76, 69, 50. IR (ATR, $cm^{-1}$): $\nu_{max}$ 1791, 1677, 1595, 1460, 1378, 1279, 1225, 1164, 993, 970, 844, 758, 734. $^1H$ NMR (500 MHz, $CDCl_3$): $\delta_H$ 2.48 (d, *J*=8.02 Hz, 2H), 2.60 (s, 1H), 7.79 (m, 2H), 8.12 (m, 2H) ppm. $^{19}F$ NMR (500 MHz, $CCl_3F$): $\delta_F$ −171.7 (m, 1F, $F_\alpha$), −72.5 (d, 6F, *J*=1.8 Hz, $F_\beta$) ppm. $^{13}C$ NMR (100 MHz, $CCl_3F$): $\delta_C$ 184.3, 180.8, 153.5, 134.5, 134.3, 134.2, 131.5, 131.1, 126.9, 126.7, 14.0–13.8 ppm. $C_{14}H_7F_7O_2$ (340.19): calcd C 49.43, H 2.07; found C 49.3, H 1.9.

*4.3.8. 2-Methyl-3-(perfluoro-n-propyl)-1,4-naphthoquinone* ***3c***.[68] Quinone **3** (0.36 mmol) was dissolved in $CH_2Cl_2$ (5 ml) and the resulting quinonic solution was added to a solution of peroxide **1c** (2.3 ml of 4.2 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 8 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **3c** (82 mg; 67%) as an orange solid (mp 69–71 °C). GC–MS: *m*/*z*=340 $[M]^+$•320, 293, 221, 193, 171, 164, 143, 115, 104, 76, 69, 50. IR (ATR, $cm^{-1}$): $\nu_{max}$ 1676, 1591, 1352, 1287, 1213, 1183, 1117, 1042, 962, 914, 837, 792, 741, 707. $^1H$ NMR (500 MHz, $CDCl_3$): $\delta_H$ 2.42 (t, 3.8 Hz, 3H), 7.78 (m, 2H), 8.11 (m, 2H) ppm. $^{19}F$ NMR (500 MHz, $CCl_3F$): $\delta_F$ −105.6 (m, 2F, $F_\alpha$), −124.8 (m, 2F, $F_\beta$), −81.3 (t, 3F, *J*=10.2 Hz, $F_\gamma$) ppm. $^{13}C$ NMR (100 MHz, $CCl_3F$): $\delta_C$ 183.6, 180.1, 152.6, 134.6, 134.1, 132.0, 131.0, 126.7, 14.0 ppm. $C_{14}H_7F_7O_2$ (340.19): calcd C 49.43, H 2.07; found C 49.5, H 2.0.

*4.3.9. 2-Methyl-3-(1′-trifluoromethoxy-perfluoroethyl)-1,4-naphthoquinone* ***3d***. Quinone **3** (0.36 mmol) was dissolved in $CH_2Cl_2$ (5 ml) and the resulting quinonic solution was added to a solution of peroxide **1d** (2.1 ml of 4.9 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was stirred at room temperature overnight. Thereafter, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **3d** (55 mg; 43%) as a yellow solid (mp 90–95 °C). GC–MS: *m*/*z*=356 $[M]^+$•, 270, 239, 201, 171, 143, 104, 69. IR (ATR, $cm^{-1}$): $\nu_{max}$ 1712, 1669, 1594, 1378, 1285, 1202, 1164, 1116, 1029, 998, 974, 919, 888, 843, 787, 750, 705. $^1H$ NMR (500 MHz, $CDCl_3$): $\delta_H$ 2.43 (d, *J*=6.2 Hz, 2H), 2.60 (s, 1H), 7.77 (m, 2H), 8.10 (m, 2H) ppm. $^{19}F$ NMR (500 MHz, $CCl_3F$): $\delta_F$ −120.1 (m, 1F, $F_\alpha$), −82.2 (s, 3F, $F_\beta$), −55.1 (d, 3F, *J*=9.1 Hz, $OCF_3$) ppm. $^{13}C$ NMR (100 MHz, $CCl_3F$): $\delta_C$ 185.2, 184.8, 148.4, 135.6, 135.2, 134.8, 134.6, 134.2, 133.6, 127.6, 127.4, 126.7, 126.1, 16.3 ppm. $C_{14}H_7F_7O_3$ (356.19): calcd C 47.21, H 1.98; found C 47.1, H 2.0.

*4.3.10. 2-Methyl-3-(1′-(perfluoro-n-propoxy)-perfluoroethyl)-1,4-naphthoquinone* ***3e***. Quinone **3** (0.36 mmol) was dissolved in $CH_2Cl_2$ (5 ml) and the resulting quinonic solution was added to a solution of peroxide **1e** (2.2 ml of 6.8 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was stirred at room temperature overnight. Thereafter, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **3e** (86 mg; 48%) as a yellow solid (mp 65–70 °C). GC–MS: *m*/*z*=456 $[M]^+$•, 387, 359, 339, 270, 243, 201, 171, 143, 104, 69. IR (ATR, $cm^{-1}$): $\nu_{max}$ 1671, 1594, 1284, 1229, 1198, 1141, 1101, 1059, 988, 787, 751, 730. $^1H$ NMR (500 MHz, $CDCl_3$): $\delta_H$ 2.45 (d, *J*=6.8 Hz, 2H), 2.60 (s, 1H), 7.77 (m, 2H), 8.11 (m, 2H) ppm. $^{19}F$ NMR (500 MHz, $CCl_3F$): $\delta_F$ −118.7 (m, 1F, $F_\alpha$), −81.8 (br s, 3F, $F_\beta$), −80.2 (dm, 1F, $^2J_{F,F}$=147.9 Hz, OCF*F), −86.5 (dm, 1F, $^2J_{F,F}$=147.9 Hz, OCFF*), −129.7 to −131.0 (dm, 2F, $J_{A,B}$=280.1 Hz, $CF_2$), −82.2 (t, 3F, $CF_3$). $^{13}C$ NMR (100 MHz, $CCl_3F$): $\delta_C$ 183.5, 180.8, 151.9, 148.5, 134.7, 134.3, 134.2, 134.1, 131.9, 131.8, 131.1, 131.0, 126.9, 126.8, 126.7, 14.0, 13.6 ppm. $C_{16}H_7F_{11}O_3$ (456.21): calcd C 42.12, H 1.55; found C 41.9, H 1.6.

## 4.4. Perfluoroalkylation of 1,4-naphthoquinones 2 and 3 in presence of 1-hexene

*4.4.1. 2-(1′-(2′2′,3′,3′,3′-Pentafluoro-propyl)-pentyl)-1,4-naphthoquinone* ***2f***. Quinone **2** (0.36 mmol) and *n*-hexene (1.08 mmol, 0.13 ml) were dissolved in $CH_2Cl_2$ (5 ml) and the resulting solution was added to a solution of peroxide **1a** (0.9 ml of 8.0 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 8 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **2f** (58 mg; 45%) as a yellowish oil. GC–MS: *m*/*z*=360 $[M]^+$•, 345, 331, 317, 227, 185, 157, 157, 104, 76, 41. IR (ATR, $cm^{-1}$): $\nu_{max}$ 2959, 2932, 2873, 1777, 1665, 1595, 1459, 1327, 1301, 1192, 1030, 994, 906, 779, 715. $^1H$ NMR (500 MHz, $CDCl_3$): $\delta_H$ 0.88 (t, *J*=7.1 Hz, 3H), 1.17–1.40 (m, 4H), 1.69–1.82 (m, 2H), 2.31–2.43 (m, 1H), 2.55–2.67 (m, 1H), 3.29 (m, 1H), 6.80 (s, 1H), 7.77–7.76 (m, 2H), 8.09 (dd, *J*=2.3, 4.5 Hz, 1H), 8.12 (dd, *J*=2.3, 4.5 Hz, 1H) ppm. $^{19}F$ NMR (500 MHz, $CCl_3F$): $\delta_F$ −117.9 to −119.5 (q, *J*=271 Hz, 2F, $F_\alpha$), −86.8 (t, 3F, *J*=1.1 Hz, $F_\beta$) ppm. $^{13}C$ NMR (100 MHz, $CCl_3F$): $\delta_C$ 185.7, 184.4, 154.0, 152.8, 135.0, 134.9, 134.1, 133.9, 132.4, 131.7, 127.0, 126.2, 37.0, 34.7, 29.4, 27.2, 22.4, 13.6 ppm. $C_{18}H_{17}F_5O_2$ (360.33): calcd C 60.00, H 4.76; found C 60.3, H 4.8.

*4.4.2. 2-(1′-(2′-Trifluoromethyl-2′,3′,3′,3′-tetrafluoro-propyl)-pentyl)-1,4-naphthoquinone* ***2g***. Quinone **2** (0.36 mmol) and *n*-hexene (1.08 mmol, 0.13 ml) were dissolved in $CH_2Cl_2$ (5 ml) and the resulting solution was added to a solution of peroxide **1b** (1.7 ml of 5.7 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 72 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **2g** (72 mg; 49%) as a yellowish oil. GC–MS: *m*/*z*=410 $[M]^+$•, 395, 381, 367, 227, 213, 185, 157, 104, 76, 41. IR (ATR, $cm^{-1}$): $\nu_{max}$ 2961, 2935, 2874, 1787, 1666, 1595, 1461, 1218, 1156, 1039, 991, 943, 904, 780, 717. $^1H$ NMR (500 MHz, $CDCl_3$): $\delta_H$ 0.87 (t, *J*=7.2 Hz, 3H), 1.16–1.36 (m, 4H), 1.64–1.76 (m, 2H), 2.34–2.43 (m, 1H), 2.69–2.77 (m, 1H), 3.29 (m, 1H), 6.77 (s, 1H), 7.75–7.77 (m, 2H), 8.09 (dd, *J*=1.7, 4.5 Hz, 1H), 8.13 (dd, *J*=1.7, 4.5 Hz, 1H) ppm. $^{19}F$ NMR (500 MHz, $CCl_3F$): $\delta_F$ −185.3 (m, 1F, $F_\alpha$), −77.1 (dm, 3F, *J*=8.2 Hz, $F_\beta$'), −78.2 (dm, 3F, *J*=8.2 Hz, $F''_\beta$) ppm. $^{13}C$ NMR (100 MHz, $CCl_3F$): $\delta_C$ 186.1, 159.6, 159.3, 135.0, 134.3, 134.1, 132.4, 131.7, 127.1, 126.3, 37.4, 35.9, 29.4, 27.2, 22.3, 13.5 ppm. $C_{19}H_{17}F_7O_2$ (410.33): calcd C 55.62, H 4.18; found C 55.8, H 4.3.

*4.4.3. 2-(1′-(2′,2′,3′,3′,4′,4′,4′-Heptafluoro-butyl)-pentyl)-1,4-naphthoquinone* ***2h***. Quinone **2** (0.36 mmol) and *n*-hexene (1.08 mmol, 0.13 ml) were dissolved in $CH_2Cl_2$ (5 ml) and the resulting solution was added to a solution of peroxide **1c** (2.3 ml of 4.2 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 8 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **2h** (74 mg; 50%) as a yellowish oil. GC–MS: *m*/*z*=410 $[M]^+$•, 395, 381, 367, 227, 185, 157, 104, 76, 41. IR (ATR, $cm^{-1}$): $\nu_{max}$ 2960, 2933, 2874, 1665, 1595, 1467, 1352, 1329, 1301, 1220, 1172, 1112, 953, 926, 779, 716. $^1H$ NMR (500 MHz, $CDCl_3$): $\delta_H$ 0.61 (t, *J*=7.2 Hz, 3H), 1.20–1.40 (m, 4H), 1.69–1.81 (m, 2H), 2.35–2.47 (m, 1H), 2.59–2.72 (m, 1H), 3.30 (m, 1H), 6.80 (s, 1H), 7.78–7.75 (m, 2H),

8.09 (dd, $J$=1.7, 4.5 Hz, 1H), 8.13 (dd, $J$=1.7, 4.5 Hz, 1H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −113.2 to −115.9 (q, $J$=271 Hz, 2F, $F_\alpha$), −128.7 (m, 2F, $F_\beta$), −81.4 (t, 3F, $J$=9.8 Hz, $F_\gamma$) ppm. $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 185.7, 184.4, 152.8, 135.5, 135.0, 134.9, 134.1, 133.9, 132.5, 131.8, 127.0, 126.9, 126.2, 37.0, 34.7, 29.5, 27.2, 22.4, 13.6 ppm. $C_{19}H_{17}F_7O_2$ (410.33): calcd C 55.62, H 4.18; found C 55.8, H 4.3.

*4.4.4. 2-(1′-(2′-Trifluoromethoxy-2′,3′,3′,3′-tetrafluoro-propyl)-pentyl)-1,4-naphthoquinone **2i**.* Quinone **2** (0.36 mmol) and *n*-hexene (1.08 mmol, 0.13 ml) were dissolved in $CH_2Cl_2$ (5 ml) and the resulting solution was added to a solution of peroxide **1d** (2.1 ml of 4.9 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was stirred at room temperature overnight. Thereafter, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **2i** (75 mg; 49%) as a yellowish oil. Mixture of diastereomeric forms. GC–MS: $m/z$=426 $[M]+\cdot$, 397, 371, 351, 281, 227, 185, 157, 128, 104, 76. IR (ATR, $cm^{-1}$): $\nu_{max}$ 2961, 2933, 2874, 1782, 1667, 1595, 1459, 1327, 1188, 1087, 1038, 898, 779, 718. $^1$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 0.87 (t, $J$=6.3 Hz, 3H), 1.21–1.36 (br m, 4H), 1.64–1.80 (br m, 2H), 2.39–2.54 (br m, 1H), 2.92–3.12 (br m, 1H), 3.18–3.28 (br m, 1H), 6.74 (s, 1H), 7.72 (m, 2H), 8.09 (m, 2H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −131.8 and −131.9 (m, 1F, $F_\alpha$), −83.7 and −83.4 (dm, 3F, $F_\beta$), −54.2 and −54.1 (m, 3F, $OCF_3$) ppm. $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 185.6, 184.4, 160.0, 159.7, 135.5, 135.4, 135.0, 134.1, 134.0, 132.5, 131.7, 127.0, 126.2, 37.3, 35.2, 34.6, 29.5, 29.4, 27.2, 27.1, 22.5, 22.3, 13.6 ppm. $C_{19}H_{17}F_7O_3$ (426.33): calcd C 53.53, H 4.02; found C 53.4, H 3.9.

*4.4.5. 2-(1′-(2′-Perfluoro-n-propoxy-2′,3′,3′,3′-tetrafluoro-propyl)-pentyl)-1,4-naphthoquinone **2j**.* Quinone **2** (0.36 mmol) and *n*-hexene (1.08 mmol, 0.13 ml) were dissolved in $CH_2Cl_2$ (5 ml) and the resulting solution was added to a solution of peroxide **1e** (2.2 ml of 6.8 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was stirred at room temperature overnight. Thereafter, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **2j** (106 mg; 56%) as a yellowish oil. Mixture of diastereomeric forms. GC–MS: $m/z$=526 $[M]^+\bullet$, 497, 471, 451, 381, 341, 285, 265, 245, 227, 215, 197, 185, 172, 157, 141, 128, 115, 104, 76, 69, 50. IR (ATR, $cm^{-1}$): $\nu_{max}$ 2961, 2933, 2864, 1783, 1557, 1596, 1459, 1330, 1302, 1231, 1194, 1146, 1060, 991, 909, 871, 808, 779, 749, 716. $^1$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 0.89 (t, $J$=6.6 Hz, 3H), 1.27 (m, 4H), 1.65–1.80 (m, 2H), 2.32–2.53 (m, 1H), 2.70–2.85 (m, 1H), 3.15–3.30 (br m, 1H), 6.75 (s, 1H), 7.75 (m, 2H), 8.08 (m, 1H), 8.11 (m, 1H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −130.1 and −131.0 (m, 1F, $F_\alpha$), −83.1 and −83.4 (d, 3F, $F_\beta$), −80.3 and −80.4 (dm, 1F, OCF*F), −82.7 and −83.0 (dm, 1F, OCFF*), −129.2 to −130.5 and −129.3 to −130.6 (dm, 2F, $CF_2$), −81.6 and −81.7 (t, 3F, $CF_3$). $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 186.9, 184.5, 160.8, 160.5, 135.5, 135.3, 135.2, 134.7, 134.6, 134.3, 134.0, 132.5, 131.7, 127.3, 126.5, 37.1, 37.0, 36.1, 35.5, 30.5, 29.8, 29.5, 27.2, 22.5, 13.4, 13.3 ppm. $C_{21}H_{17}F_{11}O_3$ (526.34): calcd C 47.92, H 3.26; found C 47.8, H 3.2.

*4.4.6. 2-Methyl-3-(1′-(2′2′,3′,3′,3′-pentafluoro-propyl)-pentyl)-1,4-naphthoquinone **3f**.* Quinone **3** (0.36 mmol) and *n*-hexene (1.08 mmol, 0.13 ml) were dissolved in $CH_2Cl_2$ (5 ml) and the resulting solution was added to a solution of peroxide **1a** (0.9 ml of 8.0 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 8 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **3f** (108 mg; 80%) as a yellowish oil. GC–MS: $m/z$=374 $[M]^+\bullet$, 359, 345, 332, 327, 319, 305, 299, 291, 271, 241, 229, 213, 198, 186, 181, 173, 157, 141, 128, 115, 105, 89, 84, 76, 69, 55, 41. IR (ATR, $cm^{-1}$): $\nu_{max}$ 2960, 2933, 2873, 1784, 1661, 1595, 1459, 1380, 1330, 1293, 1192, 1134, 1079, 1039, 906, 856, 788, 715. $^1$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 0.86 (t, $J$=6.83 Hz, 3H), 1.15–1.35 (m, 4H), 1.75–2 (m, 2H), 2.24 (s, 3H), 2.35–2.48 (m, 1H), 2.85–3.05 (m, 1H), 3.20–3.35 (br s, 1H), 7.70 (m, 2H), 8.06 (m, 2H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −116.8 to −119.2 (q, $J$=234 Hz, 2F, $F_\alpha$), −86.3 (t, 3F, $J$=1.1 Hz, $F_\beta$) ppm. $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 184.9, 184.7, 146.7, 145.1, 133.6, 133.5, 132.4, 131.8, 126.3, 34.4, 34.0, 33.8, 33.6, 22.6, 13.8, 12.5 ppm. $C_{19}H_{19}F_5O_2$ (374.34): calcd C 60.96, H 5.12; found C 60.9, H 5.1.

*4.4.7. 2-Methyl-3-(1′-(2′-trifluoromethyl-2′,3′,3′,3′-tetrafluoro-propyl)-pentyl)-1,4-naphthoquinone **3g**.* Quinone **3** (0.36 mmol) and *n*-hexene (1.08 mmol, 0.13 ml) were dissolved in $CH_2Cl_2$ (5 ml) and the resulting solution was added to a solution of peroxide **1b** (1.7 ml of 5.7 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 72 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **3g** (92 mg; 55%) as a yellowish oil. GC–MS: $m/z$ 424 $[M]^+\bullet$, 409, 395, 391, 381, 377, 369, 355, 349, 341, 321, 301, 279, 251, 241, 227, 213, 198, 186, 181, 173, 165, 157, 141, 128, 115, 105, 84, 76, 69, 55, 41. IR (ATR, $cm^{-1}$): $\nu_{max}$ 2961, 2934, 2875, 1788, 1662, 1596, 1460, 1378, 1292, 1219, 1158, 1122, 1052, 1036, 992, 952, 901, 848, 789, 717. $^1$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 0.86 (t, $J$=6.8 Hz, 3H), 1.15–1.35 (m, 4H), 1.75–1.95 (br m, 2H), 2.21 (s, 3H), 2.42–2.57 (br m, 1H), 2.90–3.10 (br m, 1H), 3.20–3.30 (br s, 1H), 7.70 (m, 2H), 8.06 (m, 2H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −186.9 (m, 1F, $F_\alpha$), −77.0 (dm, 3F, $J$=8.5 Hz, $F'_\beta$) ppm, −77.8 (dm, 3F, $J$=7.1 Hz, $F''_\beta$) ppm. $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 185.0, 184.9, 147.0, 145.0, 133.6, 133.5, 132.4, 131.8, 126.3, 35.3, 35.2, 31.6, 31.4, 29.9, 22.6, 13.8, 12.6 ppm. $C_{20}H_{19}F_7O_2$ (424.35): calcd C 56.61, H 4.51; found C 56.5, H 4.4.

*4.4.8. 2-Methyl-3-(1′-(2′,2′,3′,3′,4′,4′,4′-heptafluoro-butyl)-pentyl)-1,4-naphthoquinone **3h**.* Quinone **3** (0.36 mmol) and *n*-hexene (1.08 mmol, 0.13 ml) were dissolved in $CH_2Cl_2$ (5 ml) and the resulting solution was added to a solution of peroxide **1c** (2.3 ml of 4.2 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was heated at 40 °C (reflux). After 8 h, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **3h** (104 mg; 68%) as a yellowish oil. GC–MS: $m/z$ 424 $[M]^+\bullet$, 409, 395, 391, 382, 377, 369, 355, 341, 321, 278, 241, 229, 209, 198, 186, 173, 157, 141, 128, 115, 105, 84, 76, 55, 41. IR (ATR, $cm^{-1}$): $\nu_{max}$ 2961, 2932, 2864, 1785, 1661, 1595, 1460, 1352, 1330, 1293, 1221, 1172, 1111, 956, 901, 789, 716. $^1$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 0.86 (t, 7 Hz, 3H), 1.15–1.35 (m, 4H), 1.75–1.85 (m, 1H), 1.90–2.00 (m, 1H), 2.24 (s, 3H), 2.35–2.53 (br m, 1H), 2.90-3.10 (br m, 1H), 3.25-3.35 (br m, 1H), 7.70 (m, 2H), 8.07 (m, 2H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −113.6 to −116.1 (q, $J$=269 Hz, 2F, $F_\alpha$), −128.2 (m, 2F, $F_\beta$), −80.9 (t, 3F, $J$=9.8 Hz, $F_\gamma$) ppm. $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 184.9, 184.7, 146.7, 145.0, 133.5, 133.4, 132.4, 131.8, 126.3, 34.4, 34.1, 34.0, 33.8, 33.5, 30.0, 22.6, 13.8, 12.5 ppm. $C_{20}H_{19}F_7O_2$ (424.35): calcd C 56.61, H 4.51; found C 56.7, H 4.7.

*4.4.9. 2-methyl-3-(1′-(2′-trifluoromethoxy-2′,3′,3′,3′-tetrafluoro-propyl)-pentyl)-1,4-naphthoquinone **3i**.* Quinone **3** (0.36 mmol) and *n*-hexene (1.08 mmol, 0.13 ml) were dissolved in $CH_2Cl_2$ (5 ml) and the resulting solution was added to a solution of peroxide **1d** (2.1 ml of 4.9 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was stirred at room temperature overnight. Thereafter, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **3i** (111 mg; 70%) as a yellowish oil. Mixture of diastereomeric forms. GC–MS: $m/z$ 540 $[M]^+\bullet$, 525, 511, 493, 485, 471, 457, 355, 297, 271, 241, 229, 198, 186, 173, 141, 115, 105, 84, 76, 69. IR (ATR, $cm^{-1}$): $\nu_{max}$ 2961, 2933, 2874, 1661, 1596, 1461, 1380, 1328, 1292, 1255, 1185,

1128, 1082, 1037, 951, 896, 788, 718. $^{1}$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 0.86 (t, $J$=6.5 Hz, 3H), 1.20–1.35 (br m, 4H), 1.75–1.95 (br m, 2H), 2.22-2.23 (d, 3H, $CH_3$), 2.40–2.55 (br m, 1H), 2.90–3.10 (br m, 1H), 3.20-3.53 (br m, 1H), 7.70 (m, 2H), 8.07 (m, 2H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −131.8 and −133.2 (m, 1F, $F_\alpha$), −83.30 and −83.32 (dm, 3F, $F_\beta$), −54.4 and −54.5 (m, 3F, $OCF_3$) ppm. $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 185.1, 184.9, 159.9, 159.6, 135.6, 133.8, 133.7, 133.6, 133.5, 132.5, 131.9, 126.6, 126.3, 126.2, 36.0, 34.8, 34.7, 29.9, 22.6, 22.3, 13.7, 12.5 ppm. $C_{20}H_{19}F_7O_3$ (440.35): calcd C 54.55, H 4.35; found C 54.3, H 4.4.

*4.4.10. 2-Methyl-3-(1′-(2′-perfluoro-n-propoxy-2′,3′,3′,3′-tetrafluoro-propyl)-pentyl)-1,4-naphthoquinone* ***3j***. Quinone **3** (0.36 mmol) and *n*-hexene (1.08 mmol, 0.13 ml) were dissolved in $CH_2Cl_2$ (5 ml) and the resulting solution was added to a solution of peroxide **1e** (2.2 ml of 6.8 wt % solution in $CF_3OCFClCF_2Cl$). The reaction mixture was stirred at room temperature overnight. Thereafter, the solvent was evaporated in vacuo and purification of the crude product by flash chromatography (hexane/ethyl acetate 9:1) gave the *title compound* **3j** (128 mg, 60%) as a yellowish oil. Mixture of diastereomeric forms. GC–MS: $m/z$=540 $[M]^{+\bullet}$, 525, 511, 493, 485, 471, 457, 355, 297, 271, 241, 229, 198, 186, 173, 141, 115, 105, 84, 76, 69, 41. IR (ATR, $cm^{-1}$): $\nu_{max}$ 2962, 2934, 2875, 1786, 1662, 1596, 1460, 1381, 1330, 1293, 1232, 1195, 1147, 1060, 993, 949, 902, 859, 808, 788, 749, 719. $^{1}$H NMR (500 MHz, $CDCl_3$): $\delta_H$ 0.86 (t, $J$=7 Hz, 3H), 1.15–1.35 (m, 4H), 1.75–1.95 (m, 2H), 2.21 (d, $J$=3.4 Hz, 3H), 2.45–2.70 (m, 1H), 2.95–3.10 (br m, 1H), 3.15–3.35 (br m, 1H), 7.70 (m, 2H), 8.05 (m, 1H), 8.08 (m, 1H) ppm. $^{19}$F NMR (500 MHz, $CCl_3F$): $\delta_F$ −131.7 and −132.5 (m, 1F, $F_\alpha$), −83.6 and −83.8 (d, 3F, $F_\beta$), −80.6 and −80.9 (dm, 1F, OCF*F), −83.4 and −83.7 (dm, 1F, OCFF*), −129.8 to −131.1 and −129.9 to −131.2 (dm, 2F, $CF_2$), −82.2 and −82.4 (t, 3F, $CF_3$). $^{13}$C NMR (100 MHz, $CCl_3F$): $\delta_C$ 184.8, 146.9, 146.4, 146.3, 145.2, 145.1, 133.6, 133.5, 133.4, 132.4, 131.8, 131.7, 126.3, 126.2, 36.2, 36.1, 36.0, 35.9, 35.1, 34.8, 34.6, 34.2, 30.0, 29.9, 22.6, 22.5, 13.8, 12.5 ppm. $C_{22}H_{19}F_{11}O_3$ (540.37): calcd C 48.90, H 3.54; found C 48.7, H 3.6.

### 4.5. Single-crystal X-ray diffraction analysis of product 3a

Data collection was performed on a Bruker Smart Apex CCD diffractometer with graphite-monochromated Mo Kα radiation $\lambda$=0.71073 Å at room temperature. The structure was solved by direct methods using the program SHELXS-97.[69] CCDC 912376 contains 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/cgi-din/catreq.cgi.

### 4.6. Computational details

All calculations were performed in gas phase approximation at the Unrestricted-B3LYP/6-311G(d,p) level on the Gaussian 09 package.[70–80] QTAIM calculations were performed using the AIMPAC code.[64,81,82]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### Supplementary data

Supplementary data associated with this article can be found in the online version.

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