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Light-induced iodoperfluoroalkylation reactions of carbon–carbon multiple bonds in water

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ABSTRACT

In this work we have undertaken the radical-induced addition of 1-iodo-*n*-perfluorobutane onto electron-rich alkenes, alkenes with electron withdrawing groups, and alkynes in water, initiated photochemically. The lack of hydrogen donor (*i.e.*: $(Me_3Si)_3SiH$) in our reaction medium facilitates a Halogen Atom-transfer reaction (HAT), affording the respective perfluorobutylated alkyl and alkenyl halides (*iodides*) in good yields in water. We have also found that water exerts a relevant solvent effect on the rates of perfluoroalkyl radical additions onto double and triple bonds. The stereoselectivity of the radical addition reaction of alkynes is studied. The novelty of this work relies on the photochemical generation of fluorinated radicals in water, and the Halogen Atom-transfer addition reactions of iodoperfluoroalkanes onto carbon–carbon unsaturated bonds in water induced by light.

1. Introduction

Halogen Atom-transfer (HAT) reactions have been extensively studied and widely used in organic synthesis. The addition of a carbon–halogen bond across a double bond was pioneered by Kharasch [1a] (Scheme 1) and provides new carbon–carbon and carbon–halogen bonds in a single operation. The choice of the halogen that transfers in the reaction determines the success of atom-transfer additions. More recently, HAT reactions have been studied and reviewed in water [1b].

On the other hand, perfluoroalkyl-substituted compounds are regarded as important components of fluorophors and for the introduction of fluorous tags into organic substrates [2]. In medicine, fluorocarbons and perfluoroalkyl-substituted alkanes serve as vascular implants [3], inhalation anesthetics [4] aerosol propellants [5], breathing liquids for immature or damaged lungs, and components in blood substitutes [6]. Biotechnology employs fluorocarbon liquids to transport respiratory gases in cell culture systems [7]. Their syntheses in organic solvents are achieved through different methods, among which, the addition of perfluoroalkyl radicals to unsaturated bonds represents a convenient choice [8,9]. Another route to the synthesis of compounds with perfluoroalkyl moieties is through the $S_{RN}1$ mechanism, which involves radicals and radical ions as intermediates [10,11].

Perfluoroalkyl iodides and bromides are convenient perfluoroalkyl radical precursors in the presence of radical initiators [12]. Because perfluoroalkyl iodides exhibit their absorption in UV and near-UV regions, the photoinitiation based on the homolytic dissociation of the R_f–I bond is also applicable for the radical iodoperfluoroalkylation of unsaturated compounds with R_fI [13].

Ogawa et al. undertook a photochemically induced radical iodoperfluoroalkylation reaction of unsaturated carbon–carbon double and triple bonds in benzotrifluoride as solvent [13]. These authors also utilized non-conjugated dienes, conjugated dienes, allenes, vinylcyclopropanes, and *iso*cyanides as radical-acceptor substrates for the radical iodoperfluoroalkylation reactions in benzotrifluoride, affording good yields of the corresponding iodoperfluoroalkylated derivatives. In the past, these reactions have been attempted as neat liquids [14a].

The work of Huang and collaborators on sulfinatodehalogenation reactions has contributed significantly to the development of perfluoroalkylation reactions of unsaturated systems [15–19]. For example, radical reactions of alkenes, alkynes, isocyanides, etc. with R_fI initiated by sodium dithionate in aqueous systems lead to addition perfluoroalkylated products in high yields. Their work triggered intensive research on this area [20–22].

The need to resort to more environmentally friendly solvents opened the scope of radical carbon–carbon bond formation reactions in water, and other aqueous mixtures. Atom transfer intermolecular carbon–carbon bond formation reactions in water have been investigated in detail by many authors [23]. Oshima

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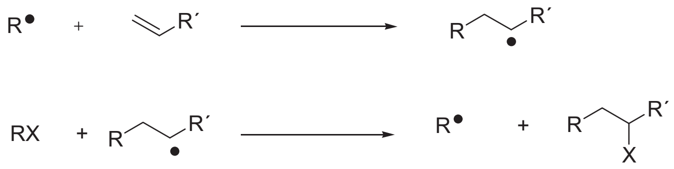
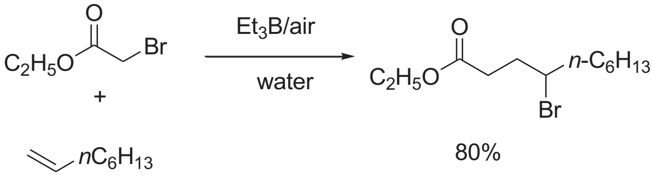


Scheme 1. Mechanism for carbon–carbon bond formation with Halogen Atom-transfer.

et al. [24] reported the intermolecular carbon–carbon bond formation reaction in water from ethyl bromoacetate and 1-octene affording ethyl 4-bromodecanoate in 80% yield when the reaction is initiated by triethylborane (Et_3B)/air.



(1)

Other types of intermolecular radical carbon–carbon bond formation reactions in water have been lately reported, describing radical additions to radical acceptors such as imines and their derivatives [25–27]. These latter consecutive radical reactions are also initiated by Et_3B/air.

Dolbier et al. [28] have found that perfluorinated radicals were much more reactive than their hydrocarbon counterparts in addition to normal, electron rich alkenes such as 1-hexene (40,000 times more reactive) in organic solvents. Thus the authors determined that k_{add} has a value of $7.9 \times 10^6\,M^{-1}\,s^{-1}$ in benzene-d_6 at 298 K, and the rate value of H-transfer from the silicon hydride $(Me_3Si)_3SiH$ (k_H) is *ca.* $50 \times 10^6\,M^{-1}\,s^{-1}$ in benzene-d_6 at 303 K.

Barata-Vallejo and Postigo [29] have undertaken the consecutive radical perfluoroalkylation addition reaction of alkenes in water, mediated by $(Me_3Si)_3SiH$ as hydrogen donor, initiated either through the decomposition of azo compounds or dioxygen initiation. Thus, the authors obtained perfluoroalkylated alkanes in fairly good yields in water, either from electron-rich and electron-deficient alkenes. The mechanism of the $(Me_3Si)_3SiH$-mediated intermolecular perfluoroalkylation of alkenes in water has been investigated in detail [29], with reasonable evidence for the presence of silyl and perfluoroalkyl radical intermediates. The same authors found that the rates of perfluoroalkylation reactions of olefins seemed to be increased in water with respect to organic solvents.

Given the known rate acceleration effects of radical reactions in water, it becomes challenging at this time to attempt to explore the iodoperfluoroalkylation reactions of multiple-bonded substrates in this medium (HAT), through photochemical initiation, as a potential entry route for the generation of fluorinated radicals in water.

2. Materials and methods

2.1. Method of radical initiation in water

The photoinduced homolysis (254 nm, 2 × 40 W UV lamps, 25 °C, quartz vessel) of the C–I bond from C_4F_9I was used at room temperature in water as a means of radical initiation. The reactions (2 h) proceeded in quartz cells provided with stir bars, and rubber septa. The vessels contain 3 mL of Ar-deoxygenated (15 min) milli-Q water, 10–12 mM of substrate, and *ca.* 12 mM C_4F_9I, introduced as neat liquids with microsyringe through the septa. The solutions were vigorously stirred throughout the irradiation.

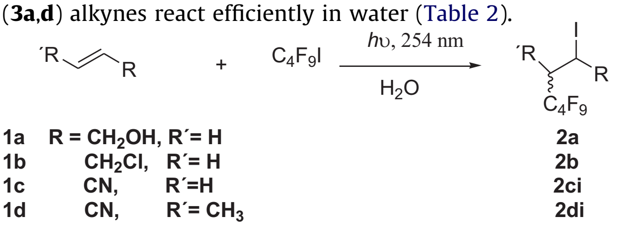
3. Results

When we subject alkenes **1a–d** (10 mM) to reaction with 1-iodo-perfluorobutane (11 mM) in water (3 mL) under irradiation (254 nm, 2 h, quartz, vigorous stirring), we obtain iodo-perfluorobutyl alkanes **2a–d** in yields ranging from 58 to 84% (Eq. (2) and Table 1). Both electron-rich (entries 1 and 2, Table 1) and electron-deficient (entries 3 and 4, Table 1) alkenes react efficiently in water (entries 1–4, Table 1). Organic solvent-soluble alkenes **1b–d** (entries 2–4, Table 1) as well as water-soluble (allyl alcohol **1a**, entry 1, Table 1) alkenes react with 1-iodoperfluorobutane in water (Eq. (2)).

Acrylonitrile **1c** affords two HAT products, *i.e.*: **2ci** and **2cii** (Table 1, entry 3) in a 88:12 ratio (isolated combined yield 66%). Product **2ci** prevails in the mixture, as arising from a cyano-substituted, resonance stabilized secondary alkyl radical adduct (see Section 4).

Interestingly, crotononitrile**1d** (entry 4, Table 1) also affords two iodoperfluoroalkylated products, 3,3,4,4,5,5,6,6,6-nonafluoro-2-(1-iodoethyl)hexanenitrile **2di** and 4,4,5,5,6,6,7,7,7-nonafluoro-2-iodo-3-methylheptanenitrile **2dii** in 3 and 97% relative yields, respectively (isolated 58%). Clearly, product **2dii** is favored over product **2di**, as the cyano-substituted radical adduct is resonance-stabilized as opposed to the inductively stabilized alkyl-substituted radical adduct intermediate (*vide infra*, Section 4).

When we subject alkynes **3a–d** (12 mM) to reaction with 1-iodo-perfluorobutane (10 mM) in water (3 mL) under irradiation (254 nm, 2 h, quartz) and vigorous stirring, we obtain iodo-perfluorobutyl-substituted alkenes **4a–d** (Eq. (3)) in yields ranging from 67 to 98% (Table 2). The stereoselectivity of the iodo-perfluorobutyl-substituted alkenes obtained is shown in column 4, Table 2. Both organic-solvent soluble (**3b**,**c**) and water-soluble (**3a**,**d**) alkynes react efficiently in water (Table 2).



(2)

Table 1
Photochemical-induced (254 nm, 60 W, 2 h) radical perfluoro-*n*-butylation of alkenes **1a–d** (10 mM) with C_4F_9I (11 mM) in Ar-deoxygenated water (3 mL) under vigorous stirring at 25 °C.

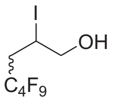
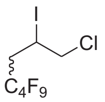
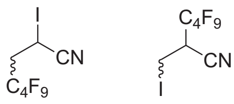
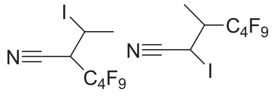
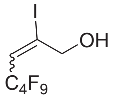
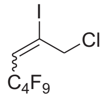
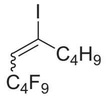
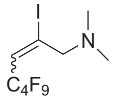
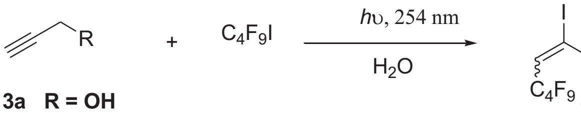
Entry	Substrate	Product, %
1	Allylic alcohol, **1a**	 ***2a*, 84**
2	Allylic chloride, **1b**	 ***2b*, 75**
3	Acrylonitrile, **1c**	 ***2ci* + *2cii*, 66**
4	Crotononitrile, **1d**	 ***2di* + *2dii*, 58**

Table 2
Photochemical-induced (254 nm, 2 h) radical perfluoro-*n*-butylation of alkynes (12 mM) with C_4F_9I (10 mM) in Ar-deoxygenated water (3 mL) under vigorous stirring at 25 °C.

Entry	Alkyne	Product, yield%	*E*:*Z* ratio
1	Propargyl alcohol [14a], *3a*	 ***4a*, 84**	70:30[a]
2	Propargyl chloride [14a], *3b*	 ***4b*, 94**	45:55[a]
3	1-hexyne [32], *3c*	 ***4c*, 98**	93:7[a]
4	*N*,*N*-dimethylpropargyl amine, *3d*	 ***4d*, 67**	67:33[a]

[a] Non-optimized isomer ratio obtained after 2 h-irradiation.



3a R = OH **4a** (3)
3b R = Cl **4b**
3c R = C_3H_9 **4c**
3d R = $N(CH_3)_2$ **4d**

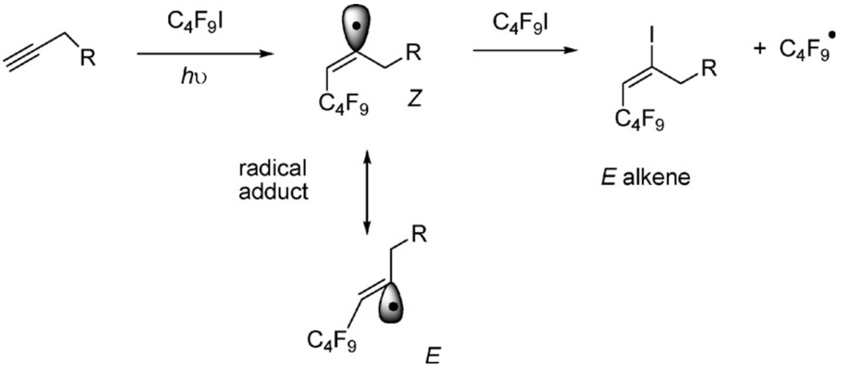
4. Discussion

The electrophilicity of $R_f^{\bullet}$ radicals are the dominant factor giving rise to their high reactivity. The stronger carbon–carbon bond which forms when $R_f^{\bullet}$ versus $R^{\bullet}$ radicals add to an alkene is a driving force for the radical addition (the greater exothermicity of the $R_f^{\bullet}$ radical addition is expected to lower the activation energy) [30,31]. It has been observed, in organic solvents, that the rates of addition of $R_f^{\bullet}$ radicals onto alkenes correlate with the alkene IP (which reflects the *HOMO* energies) [32]. Indeed, the major transition state orbital interaction for the addition of the highly electrophilic $R_f^{\bullet}$ radical to an alkene is that between the *SOMO* of the radical and the *HOMO* of the alkene. Thus, the rates of $R_f^{\bullet}$ radical addition to electron deficient alkenes are slower than those to electron rich alkenes (as observed in organic solvents) [33]. From our results, however, it becomes apparent, that in water the reactivity for both electron rich and electron deficient alkenes towards $R_f^{\bullet}$ radical addition could be comparable. This trend has also been found in the consecutive radical perfluoroalkylation addition reaction of alkenes in water mediated by $(Me_3Si)_3SiH$ [29]. We suspect that kinetic solvent effects (KSE) are somewhat responsible for this leveling of reactivity (*vide infra*). Perhaps, some amphiphilic character of R_f radicals can be invoked to account for these indirect kinetic solvent effects.

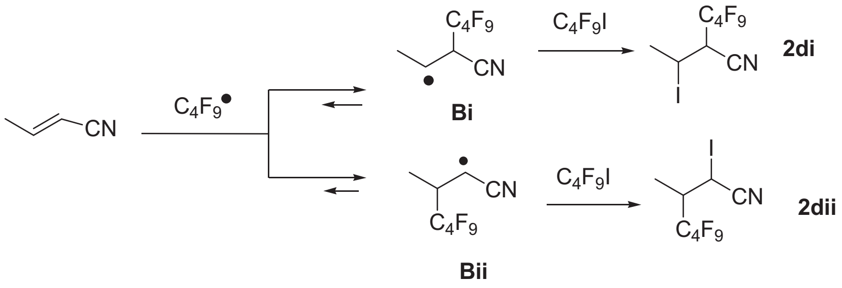
In previous reports, we have observed that the radical hydrosilylation reactions in water of water-soluble substrates took place efficiently with the aid of amphiphilic 2-mercaptoethanol, as chain carrier [34]. This is because silyl radicals being hydrophobic need the assistance of amphiphilic thiyl radicals (*i.e.*: $^{\bullet}SCH_2CH_2OH$) to carry on the chain reaction into the aqueous environment, where the water-soluble substrate is dissolved. Interestingly, both organic solvent-soluble substrates and water-soluble substrates undergo radical pefluoroalkylation reactions in water without the assistance of a chain carrier. This observation could be better interpreted in light of the distinct reactivity of R_f radicals in water rather than to a difference in hydrophobicity of R_f radicals in comparison to silyl radicals. Perhaps, some distinct amphiphilic character of R_f radicals can be invoked in this case.

Ogawa and collaborators have shown that the perfluoroalkylated radical adduct formed upon addition of R_f radicals to alkenes or alkynes is followed by addition of an iodine atom to afford the iodo-perfluoroalkylated compound. For a chain reaction to take place, it is likely that a mechanism such as that illustrated in Scheme 2 takes place. The radical adduct (in this case an alkenyl-substituted adduct) abstracts iodine atom from C_4F_9I, rendering the end addition product (*i.e.* **4a**–**e**) and C_4F_9 radical, which carries on the chain reaction. The *E* end-alkene is favored over the *Z* isomer, as accounted in Scheme 2, and Table 2. The radical adduct formed upon addition of R_f radical onto the alkyne, which can equilibrate between the *E* and *Z* stereoisomers, will abstract iodine atom from the less hindered/congested radical adduct in the *Z* configuration than the *E* configuration, rendering the *E* alkene end-product (Scheme 2).

The prevalence of the Z stereoisomer from propargyl chloride **3b** radical addition reaction, *i.e.*: products **4b**, is due to a post-isomerization process of the initially formed **4b** (*E*) isomer, as confirmed by analyzing aliquots at shorter photolysis times, where the mixture is enriched in the *E*-isomer. Data in Table 2 are given at



Scheme 2. Proposed mechanism for the formation of perfluoroalkyl-substituted *E*-alkenes in water.



Scheme 3. Formation of products **2di** and **2dii** from crotononitrile.

2 h-irradiation time. The same applies to *N*,*N*-dimethylpropargyl amine **3d**. In the original work reported by Keese and collaborators [14b], alkyne substrates (**3c** among them) render a mixture of the *Z* and *E* diastereomers (see Scheme 2).

The observation of the two iodo-perfluoroalkylated products **2di** and **2dii** (entry 4, Table 1) obtained from the radical iodoperfluoroalkylation of crotononitrile **1d** in water is notorious. It is well known that internal alkenes are far less reactive than terminal alkenes in radical alkylation and hydrosilylation reactions, both in organic solvents and in water [20].

Intermediates **Bi** and **Bii** (Scheme 3) are able to abstract iodine atom from C_4F_9I to render products **2di** and **2dii**, respectively. This difference could be due to a combination of factors, such as the enhanced reactivity of R_f radicals in water; the smaller size of fluorinated radicals in comparison to $(Me_3Si)_3Si$ radicals or other radicals; the enthalpy effect involved, which precludes reversibility of the radical-adduct formation, the effect of water in radical reactivity as opposed to organic solvents, and the distinct stabilization of the radical intermediates formed [34]. The ratio of products **2di** and **2dii** (29:71) should also reflect on the ratio of radical intermediates **Bi** and **Bii**, being the methyl-substituted secondary alkyl radical intermediate **Bi** two-and-a-half fold less stable than the cyano-substituted resonance-stabilized secondary alkyl radical intermediate **Bii**. This behavior has been reported neither in organic solvents nor in neat liquid [13,14a].

Inthe case for substrate **1c**, an analogous resonance stabilization of the cyano group could be invoked as well in accounting for the prevalence of product **2ci**.

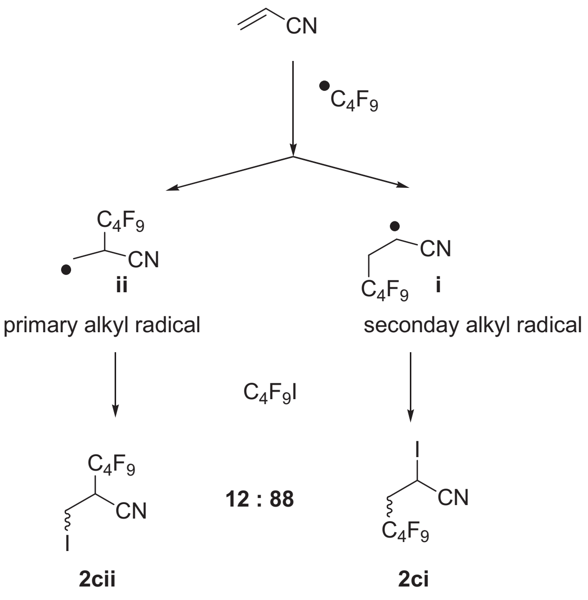


Fig. 1. Primary and secondary alkyl radicals from **1c**.

The finding of products **2ci** and **2cii** from the radical iodoperfluorobutylation reaction of **1c** in water (entry 3, Table 1 and Fig. 1) is significant in terms of the reaction pathways accounting for both products, as depicted in Fig. 1.

The ratio of products **2ci** and**2cii** (Table 1, entry 3) obtained (88:12) is in agreement with both the stability of the radicals involved (secondary alkyl radicals **i** being better-stabilized than primary alkyl radical **ii**, Fig. 1) and in accordance with the terminal sp^2 carbon of acrylonitrile being less impeded for attack from the R_f radical than the central sp^2 carbon (*vide infra*). However, at this point it is not yet clear why neither substrates **1a** or **1b** undergo attack of the R_f radical at the central sp^2 carbon atom, unless some effect of resonance stabilization of the cyano group at the β position of the radical intermediate **ii** (Fig. 1) could be invoked (intermediate **i** is resonance-stabilized by the α-CN group). Hence, if this is the case, a resonance stabilization of the cyano group at the β position of radical intermediate **ii** should outweigh or compensate steric effects in the approximation of the R_f radical.

The enhanced reactivity of R_f radicals in addition reactions (*vide supra*) as opposed to alkyl radicals, has been explained in terms of the substantial bending (14–15° from planarity) apparently required in the transition state for alkyl radical addition to alkenes, *i.e.*: non-planar perfluoroalkyl radicals might therefore be expected to have an inherent energetic advantage over a (planar) alkyl radicals in addition reactions. It is also presumed that the polar effect is playing a role in the iodine transfer, being the incipient electrophilic C_4F_9-substituted radical adduct and the I atom involved in a polar state, as in Fig. 2.

Since the rate constant (*k*c) for cyclization of 5-hexenyl radical is $2.0 \times 10^5\ s^{-1}$ [35,36], it was estimated that the rate constant for the iodine abstraction by radical intermediates from $nC_{10}F_{21}I$ is roughly $2.6 \times 10^5\ M^{-1}\ s^{-1}$ [13]. This radical capturing ability is lower compared with those of nBu_3SnH or $(PhSe)_2$ and similar than those of $(Me_3Si)_3SiH$ or nBu_3GeH [29,37].

The fact that *n*-perfluoroalkyl radicals react with acrylonitrile even faster than primary alkyl radicals [9] (2.2×10^6 and $5.3 \times 10^5\ M^{-1}\ s^{-1}$for $n\text{-}C_8F_{17}^\bullet$ and primary alkyl radical,

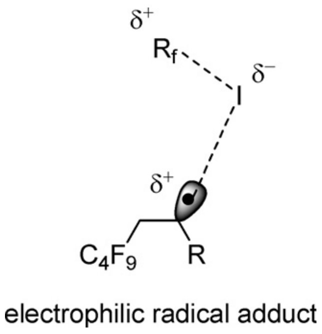


Fig. 2. Transition state for the HAT to the perfluoroalkyl-substituted radical adduct.

respectively, at 25 °C and in organic solvents [38]) means that the deactivating polar effect of the cyano group is more than balanced by the activating enthalpic effect, and the same would apply to **1d**. It is also interesting to point out that the photoinduced-iodoperfluoroalkylation reaction of acrylonitrile in benzotrifluoride as solvent only led to oligomerization product [13]. It is likely that the rate of the reaction of perfluoroalkyl radicals in water is enhanced with respect to organic solvent, as it has been suggested recently [29]. It has also to be pointed out, that the photoinduced-iodoperfluorobutylation in neat liquid (absence of solvent) is less efficient than the methodology presented in this paper in water as sole solvent [14a].

Quite remarkable is the finding of products **2a**,**b** and **4a**, derived from allylic alcohol, allyl chloride, and propargyl alcohol, respectively. In the case of alcohols, R–OH, the carbon radicals (R_f) can abstract H atoms from either the O–H functionality or one of the hydrogen atoms of the R group. The former abstraction is few kcal/mol more endothermic than the latter because of the relative bond strengths of the O–H and C–H bonds. We could expect that R_f radicals would abstract hydrogen from the allylic position of substrates **1a** and **1b** to render allyl radical intermediates that react with C_4F_9I. However, no substitution products were observed in the reaction mixtures. No β-elimination–substitution product (chlorine atom elimination) derived from allyl chloride **1b** were neither observed (*i.e.*: *4,4,5,5,6,6,7,7,7-nonafluorohept-1-ene*). This is quite interesting, since the same substrate, **1b**, upon reaction with $(Me_3Si)_3Si$ radicals in water affords a β-elimination (chlorine atom)–substitution product as well as the radical addition product [22].

This subtle point among the peculiar distinct behavior of $(Me_3Si)_3Si$ and R_f radicals in water towards the same substrate (**1b**) is a telltale sign of the enhanced reactivity of R_f radicals in water. Presumably, the rate constant for formation of the substitution product that would derive from substrate **1b** (β-elimination of the Cl atom and substitution product *i.e.*: *4,4,5,5,6,6,7,7,7-nonafluorohept-1-ene*) is much lower, and is not competing with the rate constant for R_f radical addition onto the double bond of substrate **1b** to form product **2b**.

H-abstraction from the OH functionality of alcohols **1a** and **3a** is neither observed. The apparent relative rate constant for H abstraction of carbon-centered (R_f) radicals from H-donors ($(Me_3Si)_3SiH$) in organic solvents is higher than the rate constant for addition onto carbon–carbon multiple bonds when both H-donors and alkenes are present [28b]. However Ingold and co-workers, found that rate constants for hydrogen atom abstractions from phenols were reduced in solvents where the phenol was stabilized by hydrogen bonding [39]. In this case, it was the reactivity of the substrate (*i.e.*: **3a**), not the radical, that was diminished as a result of a solute/solvent interaction. In the last few years, solvent effects have been extensively investigated by Ingold and co-workers [40]. This work can be summarized briefly as follows:

(i) There are generally no solvent effects on the rates of hydrogen atom abstraction from a C-H bond.
(ii) There may be solvent effects on the rates of unimolecular radical scission reactions (*i.e.;* R_f–I) but these are generally fairly small.
(iii) There are large solvent effects on the rates of hydrogen atom abstraction from O–H bonds (and to a lesser extend from N–H bonds) [41–44].

Point (i) means that radical reactivities, insofar as hydrogen abstraction (and addition) reactions are concerned, are not influenced by the solvent. Point (iii) means that O–H containing substrates *(e.g.*, phenols, hydroperoxides, etc.) have their reactivities towards radicals influenced by the solvent. Therefore, it was predicted that the KSE should be dependent on the ability of XOH to participate as a hydrogen bond donor to HBA solvents but should be independent of the reactivity or nature of the radical which does the hydrogen atom abstraction. This prediction, which is the first new and unifying principle for organic free radical chemistry to have been proposed in the last forty years, has been confirmed for hydrogen abstraction from phenol by the highly reactive cumyloxyl radical, $PhCMe_2O\cdot$ [43,44], and by the very unreactive diphenylpicryl hydrazyl radical, DPPH, Ph, $N\cdot NC_6H(NO)$ [45].

5. Conclusions

Radical atom transfers reactions (such as those studied here) are classical examples of atom efficiency in Organic synthesis devoted to waste minimization. The lack of hydrogen donor (*i.e.*: $(Me_3Si)_3SiH$) in our reaction medium facilitates a Halogen Atom-transfer reaction (HAT), affording the respective perfluoroalkylated alkyl and alkenyl *iodides* in good yields.

Interestingly is the fact that both organic solvent-soluble and water-soluble substrates react well with C_4F_9I in water, not necessitating the aid of a chain carrier such as 2-mercaptoethanol. We have shown that the iodoperfluorobutylation of alkynes in water render the thermodynamically favored *E* isomers in higher yields than the previously reported *Z* isomers.

Our account provides a versatile and convenient method to achieve perfluoroalkylation reactions of alkenes and alkynes in water to render perfluoroalkylated haloalkanes and alkenes as key intermediates in the synthesis of fluorophors and other fluorinated materials. This is the first report where iodoperfluoroalkyl-substituted alkanes and alkenes are synthesized through intermolecular radical carbon–carbon bond formation reactions in water alone, induced by light. We also found that water exerts a relevant solvent effect on the rates of perfluoroalkyl radical additions onto double bonds.

6. Experimental part

6.1. General

The internal standard method was employed for quantitative GC analysis with use of authentic samples when available, and one of the following capillary columns was employed: HP-5 (30 m × 0.28 mm i.d.) or HP-1 (30 m × 0.32 mm i.d.). Oven program: starting at 50 °C for 5 min, followed by an increase of 5 °/min up to 250 °C. NMR spectra were recorded at 500 MHz (for ^1H) or 125.77 MHz (for ^{13}C) or at 400 MHz (for ^1H) or 100.6 MHz (for ^{13}C) and 376.17 MHz (for ^{19}F) in $CDCl_3$ as deuterated solvent and referenced with the residual solvent peak at 7.26 ppm in the ^1H NMR spectra and 77.0 ppm ($CDCl_3$) in the ^{13}C NMR spectra, and the internal spectrometer reference for ^{19}F NMR. Materials. Alkene and alkyne substrates were also commercially available and used as received from the supplier, except for acrylonitrile, crotononitrile, 1-hexyne, *N*,*N*-dimethylpropargylamine, which were previously distilled at atmospheric pressure and stored over molecular sieves (4 Å) prior to use.

6.2. Isolation, purification and characterization of compounds

The reactions were monitored by TLC analysis, at regular photolysis intervals. Compounds were isolated by extraction into pentane or ethyl ether (3×), the organic layers gathered, dried over sodium sulfate, evaporated, checked by TLC for purity, and when necessary, column-chromatographed on silica gel with hexane: ethyl acetate (9:1 or 8:2).

Sometimes the mixtures were sufficiently pure to conduct compound characterization. Characterization of compounds was achieved by regular spectroscopic techniques, such as NMR, MS, and HRMS analyses. *E* and *Z* isomers were identified in the mixture, by high resolution NMR and HSQC experiments.

Unequivocal assignment of ^{1}H and ^{13}C resonances was obtained from HSQC experiments for compounds **2c**, and **2d**. Some NMR spectral connectivity data were confirmed by ^{1}H–^{13}C HSQC for the other compounds. Products from Eqs. (2), (3) and Tables 1 and 2 were characterized by standard spectroscopic techniques and compared with spectral data from the literature when available.

Spectral characterization of compounds **4a**–**c**, have been previously reported [14], but some spectroscopic data informed do not match with those found in this work, which were re-confirmed by high field NMR experiments, especially for the *E* and *Z* isomers (for **4b**,**c**) and are presented below:

4,4,5,5,6,6,7,7,7-Nonafluoro-2-iodoheptan-1-ol **2a**: (oil) ^{1}H NMR (400 MHz, CHLOROFORM-D) δ ppm 2.81 (td, *J* = 6.3 Hz, 1.5 Hz, 1H, H5), 3.01 (td, *J* = 6.3 Hz, 1.5 Hz, 1H, H5′), 3.78 (broad s, 2H, H2, H2′), 4.4 (m, 9 lines, 1H, H3). ^{19}F NMR (376.17 MHz, CHLOROFORM-D) δ ppm −81.48, −114.49, −124.90, −126.34. MS, EI, 70 eV, m/z (%): 404 (M$^+$, 1), 278 (10), 277 (100), 189 (76), 127 (51), 69 (79). EI-HRMS anal. calc. for $C_7H_6F_9I$: 403.9319. Found: 403.9325.

7-Chloro-1,1,1,2,2,3,3,4,4-nonafluoro-6-iodoheptane **2b**: (oil) ^{1}H NMR (400 MHz, CHLOROFORM-D) δ ppm 2.71 (m, 1H, H5), 3.15 (m, 1H, H5′), 3.82 (dd, *J* = 12 Hz, 8.5 Hz, 1H, H3), 4.01 (dd, *J* = 11.7 Hz, 4.4 Hz, 1H, H3′), 4.43 (ddd, *J* = 12.6 Hz, 8.2 Hz, 4.5 Hz, 1H, H2). ^{19}F NMR (376.17 MHz, CHLOROFORM-D) δ ppm −81.42, −114.30, −124.96, −126.30. ^{13}CNMR (100.54 MHz CHLOROFORM-D) δ ppm 29.7 (**C**H$_2$R$_f$), 37.9 (**C**HI), 50.3 (**C**H$_2$Cl). MS, EI, 70 eV, m/z (%): 422 (M$^+$, 1), 297 (26), 295 (72), 259 (100), 189 (45), 127 (51), 69 (87). EI-HRMS anal. calc. for $C_7H_5ClF_9I$: 421.8981. Found: 421.8975.

4,4,5,5,6,6,7,7,7-Nonafluoro-2-iodoheptanenitrile **2ci**: (oil) ^{1}H NMR (500 MHz, CHLOROFORM-D) δ ppm 2.87 (complex m, 1H, H5), 3.09 (complex m, 1H, H5′), 4.49 (dd, 1H, H3). MS, EI, 70 eV, m/z (%): 399 (M$^+$, 50), 231 (45), 203 (100), 175 (21), 119 (22), 69 (60). EI-HRMS anal. calc. for $C_7H_3F_9IN$: 398.9166. Found: 398.9145.

3,3,4,4,5,5,6,6,6-Nonafluoro-2-(iodomethyl)hexanenitrile **2cii**: (oil) ^{1}H NMR (500 MHz, CHLOROFORM-D) δ ppm 3.26 (complex m, 2H, H2, H2′), 4.46 (m, 1H, H3). MS, EI, 70 eV, m/z (%): 399 (M$^+$, 45), 231 (35), 203 (100), 175 (26), 119 (21), 69 (60). EI-HRMS anal. calc. for $C_7H_3F_9IN$: 398.9166. Found: 398.9125.

3,3,4,4,5,5,6,6,6-Nonafluoro-2-(1-iodoethyl)hexanenitrile **2di**: (oil) ^{1}H NMR (500 MHz, CHLOROFORM-D) δ ppm 1.60 (d, *J* = 6.9 Hz, 3H, CH$_3$), 4.22 (m, 1H, C**H**(I)Me), 4.66 (d, *J* = 2.3 Hz, 1H, C**H**R$_f$CN). MS, EI, 70 eV, m/z (%): 413 (M$^+$, 15), 286 (45), 266 (12), 195 (3), 68 (100). EI-HRMS anal. calc. for $C_8H_5F_9IN$: 412.9323. Found: 412.9321.

4,4,5,5,6,6,7,7,7-Nonafluoro-2-iodo-3-methylheptanenitrile **2dii**: (oil) ^{1}H NMR (500 MHz, CHLOROFORM-D) δ ppm 1.46 (d, *J* = 6.9 Hz, 3H), 2.75 (m, 1H, C**H**R$_f$Me), 4.81 (d, *J* = 3.2 Hz, 1H, C**H**(I)CN). MS, EI, 70 eV, m/z (%): 413 (M$^+$, 18), 286 (43), 266 (16), 68 (100). EI-HRMS anal. calc. for $C_8H_5F_9IN$: 412.9323. Found: 412.9315.

(2*E*)-4,4,5,5,6,6,7,7,7-nonafluoro-2-iodohept-2-en-1-ol **4a**(**E**) [14a]: (oil) MS, EI, 70 eV, m/z (%): 402 (M$^+$, 42), 231 (73), 203 (73), 127 (18), 69 (100).

(2*Z*)-4,4,5,5,6,6,7,7,7-nonafluoro-2-iodohept-2-en-1-ol **4a** (**Z**) [14a]: (oil) MS, EI, 70 eV, m/z (%): 402 (M$^+$, 5), 274 (1), 231 (40), 203 (100), 127 (20), 69 (54).

(2*E*)-1-chloro-4,4,5,5,6,6,7,7,7-nonafluoro-2-iodohept-2-ene **4b** (**E**) [14a]: (oil) ^{1}H NMR (400 MHz, CHLOROFORM-D) δ ppm 4.44 (s, 2H, H6, H6′), 6.79 (t, *J* = 14.5 Hz, 1H, =C**H**R$_f$, H3). ^{19}F NMR (376.17 MHz, CHLOROFORM-D) δ ppm −81.39, −106.93, −124.20, −126.20. MS, EI, 70 eV, m/z (%): 420 (60), 422 (10), 274 (21), 253 (30), 251 (90), 124 (94), 89 (100).

(2*Z*)-1-chloro-4,4,5,5,6,6,7,7,7-nonafluoro-2-iodohept-2-ene **4b** (**Z**) [14a]: (oil) ^{1}H NMR (400 MHz, CHLOROFORM-D) δ ppm 6.45 (t, *J* = 14.5 Hz, 1H, =C**H**R$_f$). MS, EI, 70 eV, m/z (%): 422 (27), 420 (75), 274 (26), 253 (33), 251 (100), 124 (80), 89 (76).

(5*E*)-1,1,1,2,2,3,3,4,4-nonafluoro-6-iododec-5-ene **4c** (**E**) [14a,b]: (oil) ^{1}H NMR (400 MHz, CHLOROFORM-D) δ ppm 0.94 (t, *J* = 8 Hz, 3H, CH$_3$), 1.35 (m, 2H, H8, H8′), 1.57 (m, 2H, H7, H7′), 2.63 (m, 2H, H6, H6′), 6.31 (t, *J* = 14.5 Hz, 1H, = C**H**R$_f$, H3). ^{19}F NMR (376.17 MHz, CHLOROFORM-D) δ ppm −81.55, −106.01, −124.66, −126.28. ^{13}C NMR (125.77 MHz CHLOROFORM-D) δ ppm 13.8 (**C**H$_3$), 21.6 (**C**H$_2$CH$_3$), 32.1 (CH$_2$**C**H$_2$CH$_2$), 40.9 (**C**H$_2$–C(I)=), 126.3 (**C**(I)=C), 126.5 (HR$_f$**C**=C). MS, EI, 70 eV, m/z (%): 428 (6), 386 (100), 301 (64), 259 (90), 213 (33), 195 (29), 139 (20), 127 (10), 103 (50).

(5*Z*)-1,1,1,2,2,3,3,4,4-nonafluoro-6-iododec-5-ene **4c** (**Z**) [14a,b]: (oil) ^{1}H NMR (400 MHz, CHLOROFORM-D) δ ppm 6.31 (t, *J* = 14.5 Hz, 1H, =C**H**R$_f$). ^{13}C NMR (125.77 MHz CHLOROFORM-D) δ ppm 14.1 (**C**H$_3$), 21.2 (**C**H$_2$CH$_3$), 29.7 (CH$_2$**C**H$_2$CH$_2$), 48.1 (**C**H$_2$–C(I)=), 123.1 (**C**(I)=C), 123.0 (HR$_f$**C**=C). MS, EI, 70 eV, m/z (%):428 (5), 386 (100), 301 (33), 259 (41), 127 (10).

(2*E*)-4,4,5,5,6,6,7,7,7-nonafluoro-2-iodo-*N*,*N*-dimethylhept-2-en-1-amine **4d** (**E**): (oil) ^{1}H NMR (400 MHz, CHLOROFORM-D) δ ppm 2.28 (s, 6H), 3.12 (broad s, 2H), 6.54 (t, *J* = 14.5 Hz, 1H). ^{19}F NMR (376.17 nMHz, CHLOROFORM-D) δ ppm −81.42, −114.30, −124.67, −126,11. MS, EI, 70 eV, m/z (%): 429 (34), 302 (20), 164 (22), 69 (43), 58 (100). EI-HRMS anal. calc. for $C_9H_9F_9IN$: 428.9636. Found: 428.9639.

(2*Z*)-4,4,5,5,6,6,7,7,7-nonafluoro-2-iodo-*N*,*N*-dimethylhept-2-en-1-amine **4d** (**Z**): (oil) ^{1}H NMR (400 MHz, CHLOROFORM-D) δ ppm 2.30 (s, 6H), 3.31 (br s, 2H), 6.79 (t, *J* = 14.5 Hz, 1H). MS, EI, 70 eV, m/z (%): 429 (5), 302 (5), 164 (12), 127 (10), 69 (28), 58 (100). EI-HRMS anal. calc. for $C_9H_9F_9IN$: 428.9636. Found: 428.9630.

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References

[1] (a) M.S. Kharasch, F.R. Mayo, J. Am. Chem. Soc. 55 (1933) 2468–2496;
(b) A. Postigo, Royal SocietyChemistry Advances, RSC Adv. 1 (2011) 14–32. doi:10.1039/C1RA00372K.
[2] J.A. Gladysz, D.P. Curran, I.T. Horváth (Eds.), Handbook of Fluorous Chemistry, Wiley-VCH, Weinheim, 2004.
[3] See, for example G.J. Murphy, S.A. White, M.L. Nicholson, Brit. J. Surg. 87 (2000) 1300–1315;
C.M. Townsend, Jr. (Ed.), Sabiston Textbook of Surgery, 16th ed., W.B. Saunders, Philadelphia, 2001.
[4] D.F. Halpern, J. Fluorine Chem. 118 (2002) 47–53.
[5] T. Noakes, J. Fluorine Chem. 118 (2002) 35–45.
[6] R.E. Banks, B.E. Smart, J.C. Tatlow (Eds.), Organofluorine Chemistry, Principles and Commercial Applications, Plenum, New York, 1994, p. 555;
M.A. Hamza, G. Serratrice, M.-J. Stebe, J.-J. Delpeuch, J. Am. Chem. Soc. 103 (1981) 3733–3738.
[7] K.C. Lowe, J. Fluorine Chem. 118 (2002) 19–26.
[8] A. Bravo, H.-R. Bjorsvik, F. Fontana, L. Liguori, A. Mele, F. Minisci, J. Org. Chem. 62 (1997) 7128–7136.
[9] M. Yoshida, N. Kamigata, H. Sawada, M. Nakayama, J. Fluorine Chem. 49 (1990) 1.
[10] (a) R.A. Rossi, A. Postigo, Curr. Org. Chem. 7 (2003) 747–769;
(b) S. Vaillard, A. Postigo, R.A. Rossi, Organometallics 23 (2004) 3003–3007.
[11] R.A. Rossi, A.B. Pierini, A.B. Peñeñory, Chem. Rev. 103 (2003) 71–168.
[12] B. Baasner, H. Hagemann, J.C. Tatlow, Houben-WeylOrgano-Fluorine Compounds, Thieme, Stuttgart, New York, 2000, pp. 1–56.
[13] K. Tsuchii, M. Imura, N. Kamada, T. Hirao, A. Ogawa, J. Org. Chem. 69 (2004) 6658–6665.
[14] (a) M.H. Habibi, T.E. Mallouk, J. Fluorine Chem. 53 (1991) 53–60;
(b) G. Rong, R. Keese, Tetrahedron Lett. 31 (1990) 5615–5616.
[15] W.-Y. Huang, B.-N. Hung, C.-M. Hu, J. Fluorine Chem. 23 (1983) 193–204.
[16] W.-Y. Huang, W. Wang, B.-N. Huang, Acta Chim. Sin. 43 (1985) 409–410.
[17] W.-Y. Huang, L. Lii, Y.-F. Shang, Chinese J. Chem. 4 (1990) 350–354.
[18] W.-Y. Huang, L. Lii, Chinese J. Chem. 9 (1991) 174–180.

[19] (a) W.-Y. Huang, W.-P. Ma, W. Wang, Chinese J. Chem. 2 (1990) 175–181;
(b) W.-Y. Huang, H.-B. Yu, Chinese Chem. Left 7 (1996) 425–426;
(c) H.-B. Yu, W.-Y. Huang, Tetrahedron Lett. 37 (1996) 7999–8000;
(d) F.-H. Wu, W-Y- Huang, J. Fluorine Chem. 110 (2001) 59–61.
[20] M. Shi, J.-W. Huang, J. Fluorine Chem. 126 (2005) 809–817.
[21] (a) H.-P. Cao, J.-C. Xiao, Q.-Y. Chen, J. Fluorine Chem. 127 (2006) 1079–1086;
(b) Chao Liu, D.-M. Shen, Zhuo Zeng, C.-C. Guo, Q.-Y. Chen, J. Org. Chem. 71 (2006) 9772–9783.
[22] J. Calandra, A. Postigo, D. Russo, N.S. Nudelman, J.J. Tereñas, J. Phys. Org. Chem. 23 (2010) 944–949.
[23] (a) H. Yorimitsu, H. Shinokubo, S. Matsubara, K. Oshima, J. Org. Chem. 66 (2001) 7776–7785;
(b) H. Miyabe, K. Fujii, T. Goto, T. Naito, Org. Lett. 2 (2000) 4071–4074.
[24] J. Kondo, H. Shinokubo, K. Oshima, Angew. Chem. Int. Ed. 42 (2003) 825–827.
[25] H. Miyabe, M. Ueda, T. Naito, J. Org. Chem. 65 (2000) 5043–5047.
[26] S.B. McNabb, M. Ueda, T. Naito, Org. Lett. 6 (2004) 1911–1914.
[27] H. Miyabe, Y. Yamaoka, Y. Takemoto, J. Org. Chem. 70 (2005) 3324–3327.
[28] (a) X.X. Rong, H.-Q. Pan, W.R. Dolbier Jr., J. Am. Chem. Soc. 116 (1994) 4521–4522;
(b) D.V. Avila, K.U. Ingold, J. Lusztyk, W.R. Dolbier Jr., H.Q. Pan, M. Muir, J. Am. Chem. Soc. 116 (1994) 99–104;
(c) D.V. Avila, K.U. Ingold, J. Lusztyk, W.R. Dolbier Jr., H.Q. Pan, M. Muir, J. Org. Chem. 61 (1996) 2027–2030.
[29] S. Barata-Vallejo, A. Postigo, J. Org. Chem. 75 (2010) 6141–6148.
[30] (a) J.C. Scaiano, L.C. Stewart, J. Am. Chem. Soc. 105 (1983) 3609–3614;
(b) L.J. Johnston, J.C. Scaiano, K.U. Ingold, J. Am. Chem. Soc. 106 (1984) 4877–4881.
[31] D.M. Lemal, J. Org. Chem. 69 (2004) 1–11.
[32] Y. Ueda, M. Kanai, K. Uneyama, Bull. Chem. Soc. Jpn. 67 (1994) 2273–2277.
[33] W.R. Dolbier Jr., Chem. Rev. 96 (1996) 1557–1584.
[34] (a) A. Postigo, S. Kopsov, C. Ferreri, C. Chatgilialoglu, Org. Lett. 9 (2007) 5159–5162;
(b) A. Postigo, C. Ferreri, M.L. Navacchia, C. Chatgilialoglu, Org. Lett. 18 (2005) 2854–2856;
(c) S. Barata-Vallejo, N. Sbarbati Nudelman, A. Postigo, Curr. Org. Chem. 15 (2011) 1826–1842.
[35] (a) A.L.J. Beckwith, K.U. Ingold, In Rearrangements in Ground and Excited States, de Mayo, P. (Ed.), Academic Press, New York, vol. 1, (Chapter 2).
(b) D. Griller, K.U. Ingold, Acc. Chem. Res. 13 (1980) 317–323;
(c) A. Postigo, N. Sbarbati Nudelman, Coord.Chem.Rev. 255 (2011) 2991–3030.
[36] C. Chatgilialoglu, K.U. Ingold, J.C. Scaiano, J. Am. Chem. Soc. 103 (1981) 7739–7742.
[37] Some representative rate constants for the hydrogen atom transfer reactions in organic solvents are as follows: nBu3SnH, 2.4 × 106 M−1 s−1; (Me3Si)3SiH, 3.8 × 105 M−1 s−1; nBu3GeH, 1.0 × 105 M−1 s−1.
See J. Fossey, D. Lefort, J. Sorba, Free Radicals in Organic Chemistry, Wiley, New York, 1995.
[38] A. Citterio, A. Arnoldi, F. Minisci, J. Org. Chem. 44 (1979) 2674–2682.
[39] G. Litwinienko, K.U. Ingold, Acc. Chem. Res. 40 (2007) 222–230.
[40] K.U. Ingold, Pure Appl Chem. 69 (1997) 241–243.
[41] G. Litwinienko, G.A. DiLabio, P. Mulder, H.-G. Korth, K.U. Ingold, J. Phys. Chem. A 113 (2009) 6275–6288.
[42] M.F. Nielsen, K.U. Ingold, J. Am. Chem. Soc. 128 (2006) 1172–1182.
[43] D.W. Snelgrove, J. Lusztyk, J.T. Banks, P. Mulder, K.U. Ingold, J. Am. Chem. Soc. 123 (2001) 469–477.
[44] D.V. Avila, K.U. Ingold, J. Am. Chem. Soc. 117 (1995) 2929–2930.
[45] G. Litwinienko, A.L.J. Beckwith, K.U. Ingold, Chem. Rev. 40 (2011) 2157–2163.