

New Methods of Free-Radical Perfluoroalkylation of Aromatics and Alkenes. Absolute Rate Constants and Partial Rate Factors for the Homolytic Aromatic Substitution by *n*-Perfluorobutyl Radical

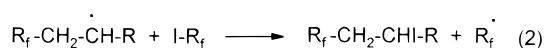
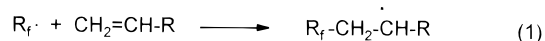
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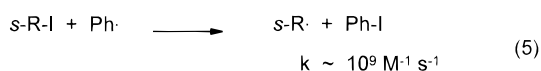
New methods of free-radical perfluoroalkylation of aromatics and alkenes are reported. *n*-C₄F₉I has been utilized as source of C₄F₉• radical through iodine abstraction by phenyl or methyl radical. The reaction with alkenes, carried out in the presence of catalytic amount of Cu(OAc)₂, leads to substitution by a mechanism substantially identical to the aromatic substitution and not to the usual chain addition of perfluoroalkyl group and iodine atom to the double bond. This has allowed to measure for the first time the absolute rate constants and the partial rate factors for the homolytic aromatic perfluoroalkylation by competition kinetics. The C₄F₉• radical shows a clear-cut electrophilic character in the aromatic substitution, as already reported for the addition to alkenes, but the low regio- and chemoselectivities suggest that the polar effect is not the main factor in determining the high reactivity of perfluoroalkyl radicals toward aromatics (10⁵–10⁶ M⁻¹ s⁻¹, 2–3 orders of magnitude more reactive than alkyl radicals). The enthalpic factor, related to the involved bond energies, appears to be the major cause of the increased reactivity. The polar effect is considered as related more to the polarizability than to the polarity of a radical (the σ -perfluoroalkyl radicals are considered less polarizable and hence less sensitive to polar effects than π -radicals).

Perfluoroalkyl iodides (R_fI) have been widely utilized as sources of perfluoroalkyl radicals (R_f•). The free-radical chain addition to alkenes¹ (eqs 1 and 2) and the homolytic aromatic substitution by thermolysis² (eq 3) are well-known processes.

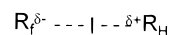


The fact that an effective free-radical chain occurs in the addition to alkenes suggests that reaction 2 must be fast enough; probably the polar effect (Scheme 1) plays a favorable role in the iodine transfer.

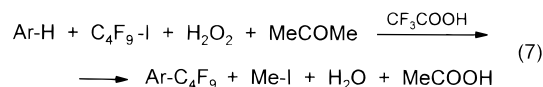
Thus we realized that iodine abstraction by phenyl radical from R_fI (eq 4) should be very fast, on the basis of the stronger Ph–I bond as compared with R–I bonds and of the very high rate constant of iodine abstraction from secondary alkyl iodides by phenyl radical³ (eq 5)



Scheme 1



We have, therefore, developed new synthetic strategies for the free-radical perfluoroalkylation of aromatics and alkenes under milder conditions, based on eq 4 (i). Moreover, eq 2 suggested that iodine abstraction from R_fI by a methyl radical (eq 6) should also be effective.



We have used the following three simple sources of methyl radical⁴ for generating *n*-perfluorobutyl radical: (ii) *t*-BuOOH and Fe(OAc)₂OH; (iii) MeCOMe and H₂O₂; (iv) DMSO/H₂O₂/Fe(II).

Aromatic perfluoroalkylation by R_fI and equimolar amounts of peroxides has been reported in a patent,⁵ which is for several aspects closely analogous to our procedures i and ii, even if, of course, the mechanism was not discussed. However, the stoichiometry was correctly given and supported by product analyses; for example, with (*t*-BuO)₂, the products CH₃I, *t*-BuOH, and MeCOMe were isolated and quantified, and it was implicitly suggested that eq 6 was involved. The main disadvantages in the use of (*t*-BuO)₂ instead of the *t*-BuOOH/Fe(III) catalytic system for the aromatic substitution are the higher temperature required for the generation of *t*-BuO• radical (>130 °C), which, for several aromatic

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(1) Yoshida, M.; Kamigata, N.; Sawada, H.; Nakayama, M. *J. Fluorine Chem.* **1990**, *49*, 1 and references therein.

(2) Tiers, G. V. D. *J. Am. Chem. Soc.* **1960**, *82*, 5513. Cowell, A. B.; Tamborski, C. *J. Fluorine Chem.* **1981**, *17*, 345.

(3) Kryger, R. G.; Lorand, J. P.; Stevens, N. R.; Herron, N. R. *J. Am. Chem. Soc.* **1977**, *99*, 7589.

(4) Fontana, F.; Minisci, F.; Vismara, E. *Free Radicals in Synthesis and Biology*; Minisci, F., Ed., Kluwer Acad. Publishers: Dordrecht, 1989; p 53.

(5) Brace, N. O. U.S. Pat. 3,271,441 (1966). We thank a referee for this suggestion.

substrates, R_fI , and solvents, do not allow working at atmospheric pressure and in general lower effectiveness in the rearomatization of the intermediate cyclohexadienyl radical adducts, as we will discuss later on.

Very recently,⁶ the absolute rate constants for the addition of perfluoroalkyl radicals to alkenes have been reported for the first time, emphasizing the great increase of reactivity of perfluoroalkyl radicals as compared to primary alkyl radicals (e.g. $n-C_3F_7\cdot$ is four orders of magnitude more reactive than primary alkyl radicals in the addition to 1-hexene). It was interesting to verify if this behavior is also reflected in the addition to aromatic rings. The reactivity of $n-C_mF_{2m+1}\cdot$ radicals appears to be the same in all cases when $m > 2$; thus, results obtained with $n-C_4F_9\cdot$ can be extrapolated to the complete series of n -perfluoroalkyl radicals, with the exception of $CF_3\cdot$ and $C_2F_5\cdot$ radicals.

Results

The n -perfluorobutylation of aromatic compounds by C_4F_9I has been carried out according to four different procedures.

(i) Benzoyl Peroxide. The reaction was simply carried out by refluxing the reagents in acetic acid solution (116 °C); other solvents, such as 1,2-dichloroethane (DCE) or cyclohexane, appear to be less effective, probably because hydrogen abstraction from the solvent by $n-C_4F_9\cdot$ competes with the aromatic addition. The reaction is quite clean; PhI and PhCOOH are the main products from $(PhCOO)_2$.

Neither significant hydrogen abstraction from the solvent nor aromatic phenylation by phenyl radical were observed, which supports our expectations about the high rate of eq 4. The presence of catalytic amounts of Cu(II) or Fe(III) salts, which generally make the rearomatization of the intermediate cyclohexadienyl radical more selective, in this case led to only little improvement, indicating that the rearomatization step by $(PhCOO)_2$ is effective. This method is particularly useful because the amount of PhI, 94–98% based on the converted C_4F_9I , reflects the amount of $C_4F_9\cdot$ radical generated and therefore provides the possibility to verify the efficiency of the aromatic perfluoroalkylation. The procedure was used with all the investigated aromatic compounds, with the exception of pyrrole, which is sensitive to benzoyl peroxide under the reaction conditions. The results are reported in Table 1.

(ii) t-BuOOH and Fe(III) Salt. The reaction was carried out by refluxing (116 °C) an acetic solution of the aromatic compound, C_4F_9I , t-BuOOH, and a catalytic amount of $Fe(OAc)_3$. The procedure is less effective than i, in that it needs more t-BuOOH, as compared to $(PhCOO)_2$, in order to obtain the same conversion of C_4F_9I , but the yields based on the converted C_4F_9I are as much high. It has been applied to benzene and anisole, and the results are reported in Table 1.

(iii) H_2O_2 and Acetone. The aromatic substitution simply occurred by refluxing (56 °C) a solution of $n-C_4F_9I$, H_2O_2 , and the aromatic substrate in acetone in the presence of CF_3COOH as catalyst. Traces of transition metal salts are harmful in this procedure because they decompose H_2O_2 without generating $C_4F_9\cdot$. We have

Table 1. Homolytic Aromatic Perfluoro- n -butylation

aromatic substrate	orientation (%)			pro-cedure	con-version ^a (%)	yields ^b (%)
benzene	—			i	88.7	94.7
benzene ^d	—			ii	58.1	96.1
benzene ^d	—			iii	46.8	93.6
benzene ^d	—			iv	41.9	95.4
anisole	o (14.7)	m (45.5)	p (39.6)	i	87.5	93.3
anisole ^d	o (15.5)	m (42.8)	p (41.7)	ii	57.7	94.8
anisole ^d	o (15.9)	m (41.1)	p (43.0)	iii	45.2	96.7
anisole ^d	o (16.1)	m (43.4)	p (40.5)	iv	42.2	97.6
diphenyl ether	o (18.1)	m (24.4)	p (57.5)	i	86.6	90.9
toluene	o (46.1)	m (30.3)	p (23.6)	i	90.1	93.5
chlorobenzene	o (41.7)	m (39.6)	p (18.7)	i	86.8	47.1
benzonitrile	o (20.5)	m (52.2)	p (27.3)	i	88.1	41.4
nitrobenzene	o (31.1)	m (36.7)	p (32.2)	i	88.8	42.3
biphenyl ^c	o (25.1)	m + p (74.9)		i	91.3	97.2
naphthalene	α (80.4)	β (19.6)		i	86.9	99.1
thiophene	α (86.5)	β (13.1)		i	89.4	97.6

^a Conversion of C_4F_9I ; by procedure i 94–98% of PhI, based on converted C_4F_9I , were obtained in all cases. ^b Yields based on converted C_4F_9I . ^c The GLC separation of the *meta* from the prevalent *para* isomer is not complete enough for a quantitative analysis. ^d The conversion of C_4F_9I increases to 70–80% by doubling the amount of H_2O_2 or t-BuOOH.

previously⁴ developed this procedure for obtaining alkyl radicals from alkyl iodides. The reaction has been applied also in this case to benzene and anisole, and the results are summarized in Table 1.

(iv) H_2O_2 , DMSO, and Fe(II) Salt. We have previously⁴ developed this procedure as a general method to obtain alkyl radicals from alkyl iodides; it also works with R_f-I under very mild conditions (a few minutes at 20–30 °C). The reaction takes place by Fenton reaction in DMSO. This procedure has been already applied for perfluoroalkylation in the pyrrole series,⁷ and the results with benzene and anisole are reported in Table 1.

All the procedures failed to induce reaction of pyridine with C_4F_9I , whereas the same reactions with alkyl iodides provided alkylation of the pyridine ring with high yields and selectivity.

n -Perfluorobutylation of Cyclohexene and 1-Octene. Procedure i, modified by the presence of a catalytic amount of $Cu(OAc)_2$, was utilized. The allylic n -perfluorobutylation of the alkene mainly took place. With cyclohexene the main reaction product (85%) was 3-(perfluorobutyl)cyclohexene (**1**). n -Perfluorobutylcyclohexane (**2**) was the only significant byproduct (15%). Compound **2** was the main reaction product (73%) obtained by procedure ii in the absence of $Cu(OAc)_2$. However, in the presence of a catalytic amount of $Cu(OAc)_2$, procedure ii also led to **1** (83%). Similarly, with 1-octene procedure i gave *trans*-1-(n -perfluorobutyl)-2-octene (**3**) as the main reaction product (83%) in the presence of $Cu(OAc)_2$. The *cis* isomer (**4**, 16%) and 1-(n -perfluorobutyl)-1-octene (**5**, 2%) were the only significant byproducts. With procedure ii 1,1,1,2,2,3,3,3,4,4-nonafluorododecane, $n-C_4F_9C_8H_{17}$ (**6**, 73%), was obtained in the absence of $Cu(OAc)_2$, whereas **3**, **4**, and **5** were the reaction products in the presence of $Cu(OAc)_2$. In all the experiments performed with benzoyl peroxide, PhI was obtained in 92–94% yield based on converted C_4F_9I and alkenes.

Competition Kinetics. (A) An excess of 1-octene and aromatic substrate (ArH), in ratios depending on their relative reactivities, were refluxed in acetic solution in

(6) (a) Avila, D. V.; Ingold, K. U.; Luszyk, J.; Dolbier, W. R., Jr.; Pan, H. Q.; Muir, M. *J. Am. Chem. Soc.* **1994**, *116*, 99. *J. Org. Chem.* **1996**, *61*, 2027. (b) Dolbier, W. R., Jr. *Chem. Rev.* **1996**, *96*, 1557.

(7) Baciocchi, E.; Muraglia, E. *Tetrahedron Lett.* **1993**, *34*, 3799.

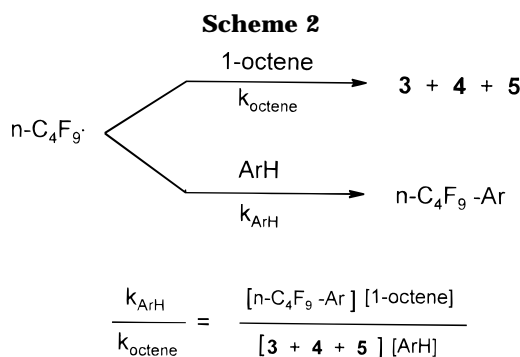


Table 2. Absolute Rate Constants and Relative Rates for the Reactions of $\text{C}_4\text{F}_9\cdot$ Radical with Aromatic Substrates

aromatic substrate	$k/10^5 \text{ M}^{-1} \text{ s}^{-1}$		relative rates		
	A ^a	B ^a	A	B	C ^a
chlorobenzene ^b					0.20
nitrobenzene ^b					0.21
benzotrile ^b					0.23
benzene	2.4	2.1	1.0	1.0	1.0
toluene	3.8	3.6	1.6	1.7	1.4
anisole	7.6	7.7	3.2	3.7	3.4
diphenyl ether	8.9	8.4	3.7	4.0	3.6
thiophene	10.1	10.6	4.2	5.0	4.8
biphenyl	12.8	13.3	5.3	6.3	5.8
naphthalene	25.7	26.6	10.7	12.7	10.8
pyrrole ^c	>100	—	—	—	—

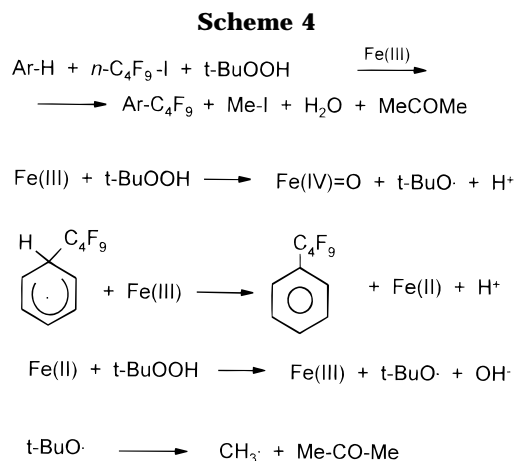
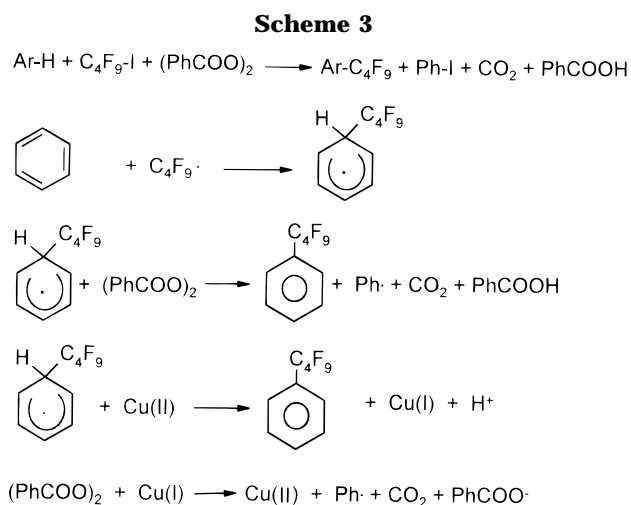
^a A: Competition with 1-octene, assuming the value of $6.2 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$ for the addition of $\text{C}_4\text{F}_9\cdot$ to 1-octene. B: Competition with cyclohexene, assuming the value of $1.2 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$ for the addition of $\text{C}_4\text{F}_9\cdot$ to cyclohexene. C: Competition between aromatic substrates. ^b The absolute rate constants, evaluated by the procedure C, are 4.4 , 4.6 , and 5.1×10^4 , respectively, for chlorobenzene, nitrobenzene, and benzonitrile. ^c Competition between pyrrole and benzene by procedure iv ($\text{H}_2\text{O}_2/\text{DMSO}/\text{Fe(III)}$).

the presence of $\text{C}_4\text{F}_9\text{I}$, $(\text{PhCOO})_2$, and $\text{Cu}(\text{OAc})_2$. The reaction was clean: **3**, **4**, **5**, and $n\text{-C}_4\text{F}_9\text{-Ar}$ were the only significant reaction products in addition to PhI and PhCOOH . The rate constants were evaluated by Scheme 2.

(B) The same procedure as in A was utilized with cyclohexene: $n\text{-C}_4\text{F}_9\text{-Ar}$, **1**, and **2** were the only reaction products. A competition between 1-octene and cyclohexene under these conditions has shown that 1-octene is 4.92 times more reactive than cyclohexene, in good agreement with the value of 5.17 evaluated from the absolute rate constants.⁶ A complete kinetic analysis by measurement of the product ratios at various concentrations of the two substrates was not carried out: thus, the error limit is not defined. Nevertheless we consider the rate constants reasonably accurate on the basis of the high yields and the consistent results found for 1-octene and cyclohexene.

(C) The relative rates, $k_{\text{ArH}}/k_{\text{ArH}}$, were determined by competition kinetics of two aromatic substrates with the same procedure, the only exception being pyrrole, which is sensitive to oxidation by procedures i–iii. In this case, the competition was carried out by procedure iv, which gave clean products. The relative rates are consistent with those obtained by procedures A and B.

All the absolute and relative rates are reported in Table 2. In first approximation we assume the temperature effect to be similar for the competing reactions characterized by similar mechanism and on the ground of consistent results by the procedures A–C.



Discussion

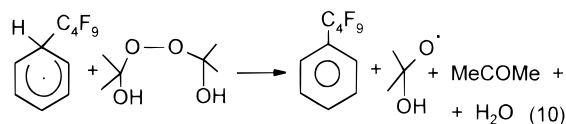
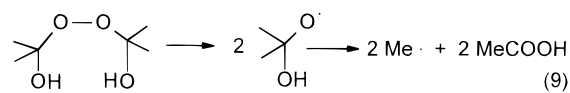
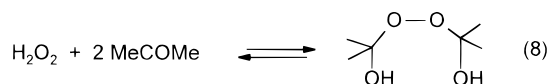
Mechanism of Aromatic Radical Perfluoroalkylation. The reaction mechanism according to procedure i clearly involves homolytic decomposition of benzoyl peroxide with the formation of phenyl radical; the reaction of this latter according to eq 4 appears to be much faster ($>10^8 \text{ M}^{-1} \text{ s}^{-1}$) than hydrogen abstraction from the solvent ($\sim 10^5 \text{ M}^{-1} \text{ s}^{-1}$)³ or than addition to the aromatic ring ($\sim 10^5 \text{ M}^{-1} \text{ s}^{-1}$),³ because no significant aromatic phenylation was observed. The radical $\text{C}_4\text{F}_9\cdot$ adds to the aromatic ring, and the radical adduct is then oxidized in a chain process. The presence of a catalytic amount of Cu(II) salt increases the reaction rate because a redox chain is superimposed to the radical chain (Scheme 3).

The reaction mechanism operating in method ii is based on the catalytic decomposition of $t\text{-BuOOH}$, initiated by the slow reaction of $t\text{-BuOOH}$ with Fe(III) , and a faster propagation chain (Scheme 4).

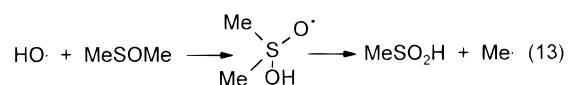
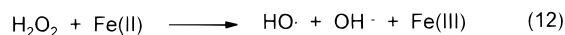
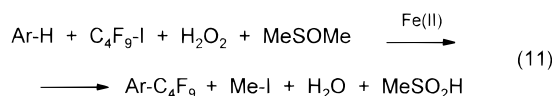
The $\text{C}_4\text{F}_9\cdot$ radical is formed, in this case, through eq 6, the methyl radical being generated by β -scission of $t\text{-BuO}\cdot$, favored by temperature and by the use of AcOH as solvent.

The stoichiometry of procedure iii is shown by eq 7: a methyl radical is generated from acetone peroxide, acid catalysis being necessary for achieving the equilibrium between H_2O_2 and acetone peroxide (eq 8). Traces of transition metal salts are, in this case, harmful because they decompose H_2O_2 , shifting equilibrium 8 at left and preventing the formation of methyl radical by thermal homolysis of acetone peroxide (eq 9). The rearomatiza-

tion of the intermediate cyclohexadienyl adduct occurs by induced homolysis of the acetone peroxide⁴ (eq 10).



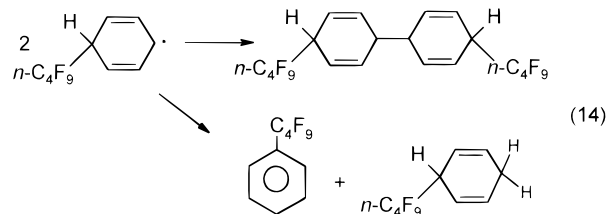
Reaction 11 represents the stoichiometry of procedure iv; it would formally appear to be quite similar to reaction 7, but the mechanism for the generation of methyl radical (eqs 12 and 13) is rather different. The substitution is explained by a redox chain similar to the one described by Scheme 2. The very fast reactions,⁸ eqs 12 and 13, allow the use of mild conditions (a few minutes at room temperature), suitable also for substrates, such as pyrrole, which are very sensitive to oxidation; methods i–iii, on the opposite, cannot be used with pyrrole.



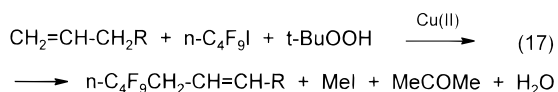
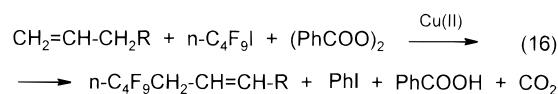
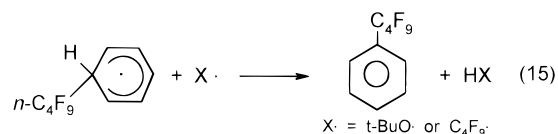
The solvent is important for the efficiency of the aromatic perfluoroalkylation, because perfluoroalkyl radicals can effectively abstract hydrogen from C–H bonds of the solvent (the rates of abstraction by $\text{R}_f \cdot$ are $>10^3$ larger than those of the analogue hydrocarbon radicals).^{6b} Thus, the rate of hydrogen abstraction by $n\text{-C}_7\text{F}_{15} \cdot$ from THF, whose α -position is particularly activated by both enthalpic and polar factors toward electrophilic radicals, has been evaluated at $6.1 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$. We expect significantly lower rate constants for hydrogen abstraction from AcOH, DMSO, and MeCOMe by $\text{R}_f \cdot$, always for enthalpic and polar reasons. We have verified⁹ these effects in hydrogen abstraction by $\text{C}_4\text{F}_9 \cdot$ from 1-chlorohexane (the rates gradually increase from the methylene group in position 1 to the one in position 5, and the methyl group is less reactive than methylene). The competition of hydrogen abstraction from the used solvents (AcOH, DMSO, and MeCOMe) appears to be negligible with activated aromatic substrates and the efficiency of aromatic n -perfluoroalkylation is high, as shown by the comparable yields of PhI and $n\text{-C}_4\text{F}_9\text{-Ar}$. However, with deactivated aromatic substrates, such as PhNO_2 or PhCN , the conversion of the aromatic com-

pound is significantly lower than the yield, always high, of PhI (Table 1); in these cases it would appear that hydrogen abstraction from the solvent by $n\text{-C}_4\text{F}_9 \cdot$ competes with the addition to the deactivated aromatic ring, even if an analysis of the volatile reaction products was not carried out.

Aromatic substitution by procedures ii–iv is generally cleaner than the previously reported substitutions by thermolysis² of R_fI or by homolysis⁵ of $(t\text{-BuO})_2$. The main reason is related, in our opinion, to the lower efficiency of the rearomatization of the intermediate cyclohexadienyl radical, which, under these conditions, can also undergo disproportionation and dimerization (i.e. eq 14), leading to high-boiling derivatives.



$(t\text{-BuO})_2$ does not undergo induced homolysis, as do $(\text{PhCOO})_2$ or acetone peroxide, and the rearomatization by hydrogen abstraction (eq 15) is generally not selective because the involved radicals are transient; therefore the Ingold–Fischer effect is not fulfilled and the self-bimolecular reactions of the radicals, such as eq 14, compete with the cross-reaction (eq 15). However, when the disproportionation prevails on the homo-coupling in eq 14, the aromatic substitution can become selective also in these cases through further oxidation of the dihydrobenzene derivatives. The oxidation of cyclohexadienyl radicals by Cu(II) or Fe(III) (Schemes 1 and 2) are, on the contrary, very fast and selective in all cases, and they are always preferable when a catalytic redox chain can be achieved.



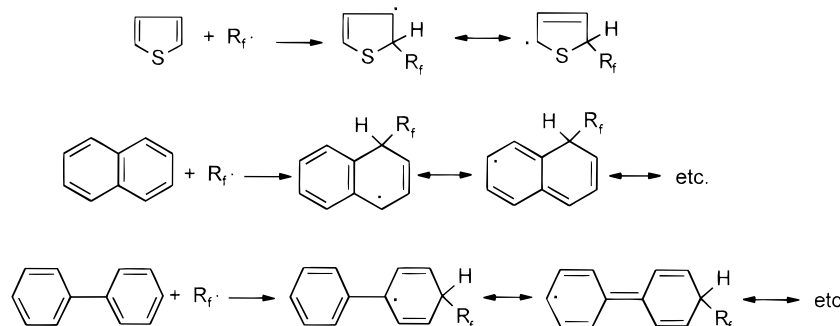
No substitution takes place with pyridine in AcOH solution, whereas nitrobenzene and benzonitrile are attacked by $\text{C}_4\text{F}_9 \cdot$ radical.

The fact that alkyl radicals, generated from alkyl iodides by the same procedures, do not react with homocyclic aromatic substrates suggested that perfluoroalkyl radicals must be much more reactive than alkyl radicals. On the other hand, protonated pyridine gives good results with alkyl radicals, but is quite unreactive toward $\text{C}_4\text{F}_9 \cdot$ under the same conditions.⁴ This would indicate that alkyl and perfluoroalkyl radicals have opposite behavior,

(8) Minisci, F. *Sulfur Centered Reactive Intermediates in Chemistry and Biology*; Chatgililoglu, C., Asmus, K. D., Eds.; Plenum Press: New York, 1990; p 303.

(9) Bravo, A.; Bjørsvik, H. R.; Fontana, F.; Liguori, L.; Minisci, F. *Chem. Commun.*, 1997, 1501.

Scheme 5



due to their opposite polar character (electrophilic and nucleophilic respectively for perfluoroalkyl and alkyl radicals).

The electrophilic character of $C_4F_9\cdot$ radical is, however, scarcely reflected on the orientation of the substitution. The *ortho*, *meta*, and *para* positions of toluene, chlorobenzene, anisole, diphenyl ether, benzonitrile, and nitrobenzene are substituted with low selectivity, without a macroscopic influence of the polar character of the substituent, the *ortho* position being, obviously, affected by steric effects (e.g. the isomer distribution in chlorobenzene² is characterized by 52% in the *ortho* position by $CF_3\cdot$, but only 14% by $n-C_{10}F_{21}\cdot$ radical). Substitution of naphthalene, biphenyl, thiophene, and pyrrole is, on the opposite, more selective. It would appear that the orientation is related more to the stabilization of the intermediate radical adducts (Scheme 5) than to the electron availability of the ring position.

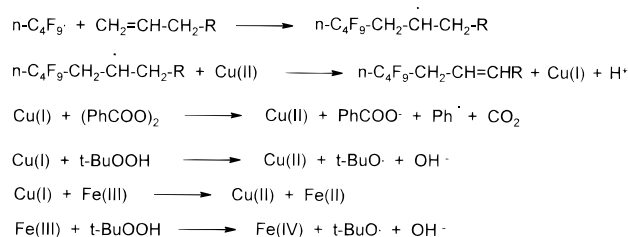
This behavior conflicts with that of electrophilic nitrogen-centered radicals, R_2NH^+ , in which a very high activation is associated to a high selectivity in the substitution of anisole and diphenyl ether (only the *ortho* and *para* positions are substituted).¹⁰ It will be discussed later on, on the basis of absolute rate constants and the partial rate factors, how the polar effect is, in our opinion, significant but it is not the major factor affecting the reactivity and selectivity of the homolytic aromatic perfluoroalkylation, the main factor being the enthalpic effect. The lack of reactivity of protonated pyridine must be ascribed to the exceptional sensitivity to polar effects of protonated heteroaromatic bases toward free radicals (small variations of polarity are reflected in large changes in reactivity).¹⁰

Mechanism of Perfluoroalkylation of Alkenes.

The free-radical chain addition of perfluoroalkyl iodides to alkenes (eqs 1 and 2) is well-known.¹ We have developed a new synthetic methodology leading to perfluoroalkyl derivatives of alkenes, based on eqs 13 and 17. The reaction takes place through addition of the perfluoroalkyl radical to the double bond and oxidation of the radical adduct by Cu(II) salt according to Scheme 6.

The Cu(I) salt catalyzes the decomposition of benzoyl peroxide, generating a redox chain. Thus, the mechanism of alkene substitution is substantially similar to aromatic substitution (Scheme 6 for alkenes and Scheme 3 for aromatics), the main difference being the higher oxidizability of the cyclohexadienyl radical as compared to the alkyl radical. The cyclohexadienyl radical is, in fact, fast and selectively oxidized by both Cu(II) and

Scheme 6



Fe(III) salts, whereas the alkyl radical adduct is oxidized by Cu(II), but it is reduced to $C_4F_9CH_2CH_2CH_2R$ (**6**) by hydrogen abstraction from the large excess of solvent in the presence of Fe(III) salt. If procedure ii is applied in the presence of Cu(II) salt, eq 17 is prevailing. On the other hand, it is well-known that alkyl radicals are rapidly and selectively oxidized to alkenes by Cu(II) salts, but that they are not oxidized by Fe(III) salts. With cyclohexene, the product of reductive alkylation **2** is a byproduct also in the presence of $Cu(OAc)_2$, probably because the C_4F_9 group in the β position diminishes to some extent the oxidizability of the cyclohexyl radical. The reaction is particularly successful because the higher oxidation potential of perfluoroalkyl radicals prevents their oxidation by Cu(II) salt. The same reaction cannot, in fact, be applied to alkyl radicals, whose oxidation by Cu(II) salts is much faster than their addition to alkenes.

Absolute Rate Constants and Partial Rate Factors in the Homolytic Aromatic Perfluoroalkylation. It was recently shown⁶ that perfluoroalkyl radicals are much more reactive than alkyl radicals toward alkenes. It was suggested that^{6b} "the dominant factor that gives rise to the observed high reactivities of perfluoroalkyl radicals, particularly in their addition to electron-rich alkenes, would appear to be the high electrophilicities of these very electron-deficient radicals". A dominant SOMO–HOMO interaction with large charge separation in the transition state has been assumed for these reactions. The prevalence of the polar effect over the other effects would not, however, be plainly justified by the relatively low value of ρ (-0.53) in the Hammett correlation of the rates of addition of the $n-C_8F_{17}\cdot$ radical to a series of *para*-substituted styrenes and by the fact that *n*-perfluoroalkyl radicals react with acrylonitrile even faster than primary alkyl radicals (2.2×10^6 and $5.3 \times 10^5 M^{-1} s^{-1}$, respectively, for $n-C_8F_{17}\cdot$ ⁶ and primary alkyl¹¹ radical at 25 °C); this means that the deactivating polar effect of the cyano group is more than balanced by the activating enthalpic effect.

(10) Minisci, F. *Substituent Effects in Free Radical Chemistry*; Viehe, H. G., Ed.; Reidel Publishing Co.: Dordrecht, 1986; p 391.

(11) Citterio, A.; Arnoldi, A.; Minisci, F. *J. Org. Chem.* **1979**, *44*, 2674.

Table 3. Partial Rate Factors for the Reactions of C₄F₉• Radical with Aromatic Substrates

aromatic substrate	relative rates ^a	partial rate factors		
		f _o	f _m	f _p
chlorobenzene	0.20	0.25	0.24	0.22
nitrobenzene	0.21	0.18	0.22	0.38
benzonitrile	0.23	0.12	0.31	0.32
toluene	1.57	2.04	1.86	1.76
anisole	3.43	1.51	4.70	8.15
diphenyl ether	3.77	2.05	4.70	11.8
thiophene	4.67	12.17 (f _o)	1.84 (f _β)	
naphthalene	11.4	11.71 (f _o)	2.85 (f _β)	

^a The relative rates are the average of the values reported in Table 2.

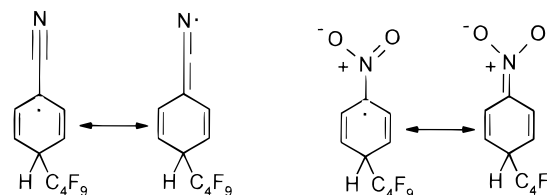
A strongly electrophilic radical, such as R₂NH⁺, is, for example, highly reactive toward 1-hexene (>10⁶ M⁻¹ s⁻¹), but completely unreactive toward acrylonitrile.¹⁰ Moreover, *n*-C₃F₇•, *n*-C₇F₁₅•, and *n*-C₈F₁₇• radicals appear to have identical reactivities, and, as such, the rates of these radicals can be considered as *generic n*-perfluoroalkyl radicals. Thus the results reported above for the *n*-C₄F₉• radical can be considered general for *n*-perfluoroalkyl radical reactions with alkenes and aromatics.

On the basis of the above considerations, the knowledge of the absolute rate constants for the addition of perfluoroalkyl radicals to aromatic substrates was of great interest for two reasons: (i) to verify if the large increase in perfluoroalkyl reactivity with alkenes is also reflected on aromatic substrates, (ii) the evaluation of the partial rate factors with aromatic compounds should give significant indications about the importance of the polar effect. As far as we know, no absolute rate constant has been reported for reactions of perfluoroalkyl radicals with aromatic compounds. The recent evaluation of the absolute rate constants for the addition of perfluoroalkyl radicals to alkenes⁶ and the above-reported substitution of alkenes with perfluoroalkyl radicals by a mechanism substantially identical to the one of homolytic aromatic substitution (Scheme 3 for the aromatic substitution and Scheme 6 for the alkene substitution) made it easy to measure the absolute rate constant for the homolytic aromatic perfluoroalkylation by competition kinetics.

We have utilized cyclohexene and 1-octene in competition with a variety of organic compounds, *n*-C₄F₉I, and benzoyl peroxide in acetic acid solution in the presence of catalytic amount of Cu(OAc)₂. It is reasonable to assume the same rate constants for 1-octene and 1-hexene; the values of 1.2 × 10⁶ and 6.2 × 10⁶ M⁻¹ s⁻¹ at 25 °C, respectively, for cyclohexene and 1-octene can be considered reliable reference rate constants for measuring the absolute rate constants for the reactions of *n*-C₄F₉• radicals with aromatic substrates by competition kinetics.

The agreement of the results with the two alkenes is satisfactory and we have obtained a further good control by competition kinetics with pairs of aromatic substrates.

The rate constants and the partial rate factors with a variety of aromatic compounds, reported in Tables 2 and 3, confirm that perfluoroalkyl radicals are generally much more reactive than alkyl radicals toward aromatic compounds (i.e. the rate constant of primary alkyl radicals reaction with benzene,^{10,12} ~10² M⁻¹ s⁻¹, is much lower than that of *n*-C₄F₉• radicals, ~10⁵ M⁻¹ s⁻¹) and that they show, as expected, a general electrophilic character; the behavior is qualitatively similar to that with alkenes.

Scheme 7

The partial rate factors, however, would suggest that the electrophilic character is a significant, but not the major factor, in determining the increased aromatic reactivity of perfluoroalkyl radicals compared to alkyl radicals. The influence of strongly polar substituents, such as MeO, CN, NO₂, is not particularly relevant and the selectivity in the *meta/para* orientation is always low with both electron-withdrawing and electron-releasing substituents, suggesting that the orientation is the result of the superimposition of polar and radical stabilizing effects of the substituents. Pyrrole represents the only macroscopic exception to this behavior: the particularly high reactivity (>10⁷ M⁻¹ s⁻¹) and selectivity in the α -position must be ascribed, in our opinion, to the low aromaticity and to the conjugated diene character, which makes this substrate as much reactive as styrenes⁶ by combination of high electron availability with radical stabilizing effects. The same effects (Scheme 5) increase the reactivity and selectivity with thiophene, biphenyl, and naphthalene to a minor extent.

Also, the similar partial rate factors for chloro-, cyano-, and nitrobenzene, in spite of the differences between the Hammett σ constants, are a further evidence that the polar effect is not dominant, but that the higher polar deactivating effect of the cyano and nitro groups compared to chlorine is balanced by the higher stabilizing effects of the intermediate cyclohexadienyl radical adducts (Scheme 7).

The fact that the C₄F₉• radical is much more reactive with nitrobenzene (~10⁴ M⁻¹ s⁻¹) than primary alkyl radicals are with benzene (~10² M⁻¹ s⁻¹) is a significant evidence that the main factor, which determines the increased reactivity in aromatic perfluoroalkylation, is not the polar factor. On the other hand, the few available data¹³ for relative rates of alkyl radical reactions with substituted benzenes would indicate that also with cyano- and nitrobenzene perfluoroalkyl radicals should be more reactive than alkyl radicals. This is also supported by the fact that alkyl radicals, generated with the same procedure and under the same conditions of *n*-C₄F₉• radical (without a large excess of aromatic substrates) react only in traces with cyano- and nitrobenzene.

If we compare the partial rate factors of aromatic perfluoroalkylation with those of homolytic amination by Me₂NH⁺ radical, in which the polar effect is certainly dominant, we observe a much higher substituent effect in this latter case: with anisole only the *ortho* and *para* isomers are formed, and the partial rate factor for the *para* position is ~10³, with naphthalene the partial rate factors for the α and β positions are, respectively, 9.3 × 10⁴ and 2.9 × 10³, whereas benzonitrile and nitrobenzene are completely unreactive toward the Me₂NH⁺ radical.^{10,14}

(12) Citterio, A.; Minisci, F.; Porta, O.; Sesana, G. *J. Am. Chem. Soc.* **1977**, *99*, 7960.

(13) Shelton, J. R.; Uzelmeier, C. W. *J. Am. Chem. Soc.* **1966**, *88*, 5222. Cowley, B. R.; Norman, R. O. C.; Waters, W. A. *J. Chem. Soc.* **1959**, 1799. Corbett, G. E.; Williams, G. H. *J. Chem. Soc.* **1964**, 3437.

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Table 4. Relative Rates for the Homolytic Alkylation of Protonated 4-X-Substituted Pyridines¹⁴

X	k_X/k_H	
	<i>n</i> -butyl ^a	<i>sec</i> -butyl ^a
CN	20.3	259.0
COCH ₃	5.6	55.6
H	1	1
CH ₃	0.3	0.2
OCH ₃	0.1	0.02

^a Only position 2 is substituted, and the substituent effect is therefore referred to the *meta* position.

Table 5. Relative Rates for the Addition of Carbon-Centered Radicals to Ph-X and Protonated 4-X-Pyridines^{13,14}

radical	X	PhX (k_X/k_H) ^a	4'-X-C ₅ H ₄ NH ⁺ (k_X/k_H) ^{a,b}
Ph	CN	3.7	1.9
Ph	Cl	1.1	1.6
Ph	CH ₃	1.2	0.6
Ph	OCH ₃	1.7	0.3
cyclopropyl	CN	3.6	14 ^c
cyclopropyl	CH ₃	1.8	1.0
cyclohexyl	CN	27	256 ^{c,d}
cyclohexyl	CH ₃	0.76	1 ^d

^a *Ortho*, *meta*, and *para* isomers are formed. ^b (k_X/k_H) is referred to the α position (both α and β isomers are formed). ^c (k_{CN}/k_{Me}) is referred to the α position. ^d Only the α isomer is formed.

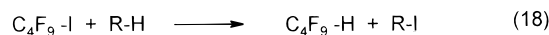
Similar features are shown by other homolytic aromatic substitutions dominated by the polar effect, such as the free radical alkylation and acylation of protonated heteroaromatic bases. Also in these cases, the selectivity is complete in the α and γ positions and the effect of the polar substituents is large (Table 4), due to the nucleophilic character of the alkyl radicals, whereas alkyl radicals bearing electron-withdrawing groups (X), X-CH₂[•], are completely unreactive. We have explained¹⁰ these behaviors by the assumption that *the Reactivity-Selectivity Principle is a generally valid criterion for radical reactions when the reactivity is mainly governed by the reaction enthalpy; when polar effects are dominating, the Principle is reversed, a high reactivity being associated to a high selectivity.*¹⁰

All these considerations suggest that the main factor determining the enhanced reactivity of perfluoroalkyl radicals toward aromatic substrates is the enthalpic effect. This is justified by the stronger (ca. 10 kcal/mol) C-C bond formed when R_f[•] versus R[•] adds to unsaturated systems (CH₃CH₃, BDE = 91 kcal/mol versus CF₃CH₃, BDE = 101 kcal/mol).¹⁵ We expect this effect to be more marked in aromatic than in alkene addition, due to the less favorable enthalpy of the aromatic addition.

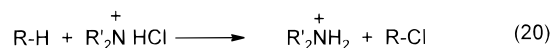
Another factor which, in our opinion, contributes to a relatively low polar effect in perfluoroalkylation is the σ -nature of perfluoroalkyl radicals (markedly pyramidal).⁶ The polar effect, being kinetic in nature, is not an intrinsic property of a free radical; it only makes sense to mention the polar effect associated to a particular reaction, which is manifested as charge separation in the transition state. In principle, and sometimes also in practice, the same radical can behave as electrophilic, nucleophilic or nonpolar species, depending on the particular reaction involved.¹⁰ Thus the polarity and the polarizability of both radical and substrate are important factors, contributing to the extent of polar effect; the

polarizability of σ -radicals is lower than that of π -radicals.

For example, the extent of polar effect for phenyl and cyclopropyl radicals (σ -radicals) is lower than that of the cyclohexyl radical (π -radical) in the addition to benzene and protonated pyridine derivatives^{10,14} (Table 5). The moderate electrophilic behavior of C₄F₉[•] is also shown by the moderate polar selectivity observed in the free-radical iodination of the C-H bond in 1-chlorohexane⁹ (eq 18), in which the selectivity is determined by hydrogen abstraction by C₄F₉[•] (eq 19).



This selectivity is much lower than that observed in the chlorination by protonated *N*-chloroamines (eq 20), in which the selectivity is determined by hydrogen abstraction by the strongly electrophilic R₂NH⁺ radical.¹⁰ (eq 21).



Conclusion

New methods of perfluoroalkylation by perfluoroalkyl iodides of aromatic compounds and alkenes have been developed, through iodine transfer by phenyl and methyl radicals. Absolute rate constants have been measured for the aromatic substitution by competition kinetics, by taking advantage of the known values of the absolute rate constants for the addition of perfluoroalkyl radicals to alkenes. Perfluoroalkyl radicals are more reactive than alkyl radicals toward aromatics. The relatively low values of the partial rate factors would indicate that this enhanced reactivity should be attributed mainly to the reaction enthalpy and only to a minor extent to the electrophilic character of the perfluoroalkyl radical.

Experimental Section

General Methods. Mass spectra were performed on a GLC-MS instrument, using a gas chromatograph equipped with SBP-1 fused silica column (30 m \times 0.2 mm i.d., 0.2 μ m film thickness) and helium as carrier gas.

GLC analyses were performed on a capillary gas chromatograph, equipped with SBP-5 fused silica column (25 m \times 0.25 mm i.d., 1 μ m film thickness) at a hydrogen flow rate of 8 cm³ min⁻¹, PTV injector, flame ionization detector.

¹H-NMR spectra were carried out on a spectrometer operating at 400 MHz. Chemical shifts are referenced to internal TMS.

¹⁹F-NMR spectra were registered on a spectrometer operating at 235 MHz. Chemical shifts are referenced to internal CFCl₃. Proton NMR spectra with ¹⁹F broadband decoupling were acquired using a supplementary frequency synthesizer.

The alkenes, the aromatic substrates, C₄F₉I, and the solvents were obtained from commercial sources and were used without further purification.

Typical Examples for Aromatic Perfluoro-*n*-butylation. (*n*-Perfluorobutyl)benzene, CF₃CF₂CF₂CF₂C₆H₅. Method i: 5 mmol of benzene, 1 mmol of C₄F₉I, 1 mmol of benzoyl peroxide, and 0.1 mmol of Cu(OAc)₂ in 10 mL of acetic acid were refluxed for 4 h (115 °C). The solution was directly analyzed by GLC, GLC-MS, and ¹⁹F-NMR (CD₃COCD₃ 10% v/v was added to the crude reaction mixture to obtain the lock

Table 6. MS (*m/z*) for Perfluoro-*n*-butyl Aromatics

aromatic	M ⁺	(ArCF ₂) ⁺
benzene	296	127
toluene	310	141
anisole	326	157
chlorobenzene	330	161
nitrobenzene	341	172
benzotrile	321	152
biphenyl	372	203
diphenyl ether	388	219
naphthalene	346	177
thiophene	302	133
pyrrole	285	116

signal). The GLC and GLC-MS analyses with *p*-iodotoluene as internal standard revealed the presence of 0.12 mmol of unreacted C₄F₉I, 0.85 mmol of C₆H₅I, and 0.81 mmol of *n*-C₄F₉-C₆H₅. The pure product, *n*-C₄F₉-C₆H₅, was isolated by dilution of the reaction mixture with water, extraction by hexane, and flash chromatography on silica gel (hexane as eluent); it was identified by comparison (GLC-MS) with an authentic sample obtained by a known procedure.¹⁶ The absolute yields of *n*-C₄F₉-Ph were determined by ¹⁹F-NMR using tetrafluoro-*p*-benzoquinone as internal standard (signal at -142.3 ppm relative to CFCl₃); known mixtures of *n*-C₄F₉-C₆H₅ or *n*-C₄F₉I (-CF₂I signal at -62.3 ppm) and tetrafluoro-*p*-benzoquinone were utilized to verify the response of the standard. The results (0.84 mmol of *n*-C₄F₉-Ph and 0.11 mmol of unreacted *n*-C₄F₉I) were in good agreement with those obtained by GLC analysis.

Method ii: 5 mmol of benzene, 1 mmol of C₄F₉I, 2 mmol of *t*-BuOOH, 0.2 mmol of Fe(OAc)₂OH in 10 mL of acetic acid were refluxed for 4 h (115 °C). The solution was analyzed by ¹⁹F-NMR as in i. 0.42 mmol of unreacted *n*-C₄F₉I and 0.56 mmol of *n*-C₄F₉-C₆H₅ were obtained. Under the same conditions, when 4 mmol of *t*-BuOOH were used, only 0.18 mmol of unreacted *n*-C₄F₉I were obtained and 0.77 mmol of *n*-C₄F₉-C₆H₅ were formed.

Method iii: 5 mmol of benzene, 1 mmol of C₄F₉I, 3 mmol of H₂O₂ (35% in water), and 6 mmol of CF₃COOH in 10 mL of acetone were refluxed for 8 h (57 °C). The solution was analyzed by ¹⁹F-NMR as in i. 0.53 mmol of unreacted *n*-C₄F₉I and 0.44 mmol of *n*-C₄F₉-Ph were obtained. Under the same conditions, when 6 mmol of *t*-BuOOH were used, only 0.25 mmol of unreacted *n*-C₄F₉I were obtained and 0.71 mmol of *n*-C₄F₉-Ph were formed.

Method iv: 3 mmol of H₂O₂ (35% in water) were dropped while stirring at room temperature into a mixture of benzene (5 mmol), *n*-C₄F₉I (1 mmol), FeSO₄·7H₂O (0.7 mmol) in 7 mL of DMSO. After 10 min the mixture was diluted in water and extracted with hexane. The hexane solution was analyzed by ¹⁹F-NMR as in i: 0.58 mmol of unreacted *n*-C₄F₉I and 0.40 mmol of *n*-C₄F₉-C₆H₅ were obtained. Under the same conditions, when 6 mmol of H₂O₂ were used, only 0.28 mmol of unreacted *n*-C₄F₉I were obtained and 0.67 mmol of *n*-C₄F₉-Ph were formed.

Procedure i was utilized for all the aromatic compounds reported in Table 1, while procedures ii-iv were utilized for benzene and anisole.

The MS of all the perfluoro-*n*-butyl aromatic derivatives are specific for the molecular ion (M⁺) and the main fragment (ArCF₂)⁺; the results are reported in Table 6.

The absolute yields were determined by ¹⁹F-NMR, using tetrafluorobenzoquinone as standard, the chemical shifts, relative to CFCl₃, being in the range -104/-109 ppm for the α-CF₂, -121 ppm for the β-CF₂, -125 ppm for the γ-CF₂, and -81 ppm for CF₃. The isomer distribution has been determined by GLC and CLG-MS by comparison with results obtained by known^{1,2,16} procedures, assuming the gas chromatographic response to be similar for the *ortho*, *meta*, and

para isomers. Thus, for example, the reaction of chlorobenzene with C₄F₉I was carried out by method i. The GC and GC/MS analyses revealed the presence of 0.13 mmol of unreacted C₄F₉I, 0.82 mmol of C₆H₅I, and 0.47 mmol of the three isomers of C₄F₉-C₆H₄Cl (all the isomers show the molecular ion 330 and the main fragment Cl-C₆H₄-CF₂⁺ 161). The chromatography on silica gel (hexane as eluent) allowed the separation of the *ortho* isomer: NMR δ (ppm): 7.35 (m, 1H), 7.48 (m, 2H), 7.68 (d, 1H), but not the isomers *meta* and *para*. Authentic samples of these isomers were prepared by the known procedure² from *m*-chloro- and *p*-chloriodobenzene, C₄F₉I, and copper bronze in DMSO; for the *meta* isomer NMR δ (ppm): 7.39 (m, 1H), 7.48 (m, 2H), 7.60 (s, 1H); for the *para* isomer NMR δ (ppm): 7.42 (d, 2H), 7.53 (d, 2H). The isomers were identified by comparison with the authentic samples and the isomer distribution was as follows: *ortho* 41.7%, *meta* 39.6%, and *para* 18.7%. The procedure of ref 2 is simple and useful for the unequivocal synthesis of the single isomers, whose structures can be simply verified by GC/MS analysis. In GC analysis the retention times of the *ortho* isomers are always shorter, while those of the *meta* and *para* isomers are very close to one another so that, in the case of biphenyl, GC separation of the *meta* and *para* isomers was not complete enough for a quantitative analysis.

n-BuI and cyclohexyl iodide provided high yields (>80%) of PhI, but only traces of alkylaromatics (<1%) under the conditions of procedure i.

Perfluoro-*n*-butylation of Cyclohexene. (A) A mixture of 5 mmol of cyclohexene, 1 mmol of C₄F₉I, 1 mmol of benzoyl peroxide, and 0.1 mmol of Cu(OAc)₂ were refluxed for 4 h in 10 mL of acetic acid. The solution was filtered on silica gel in order to eliminate Cu(OAc)₂, and then it was directly analyzed by GLC, GLC-MS, and ¹⁹F-NMR. Two fluorinated products were formed: the main product arises from the allylic substitution of cyclohexene by the C₄F₉ group, 3-(*n*-perfluorobutyl)cyclohexene, **1** (85%). The minor product (15%) is (*n*-perfluorobutyl)cyclohexane, **2**. MS (*m/z*) are characterized, for **1** and **2**, respectively, by the molecular ions (300 and 302) and the main fragments C₆H₉⁺ (81) and C₆H₁₁⁺ (83). ¹⁹F-NMR for **1** shows an AB system for the CF₂ attached to the allylic position [A from AB = -114.5 ppm, B from AB = -117.0 ppm, J(AB) = 300 Hz], the CF₂ in the β position at -123.0 ppm (m), the CF₂ in the γ position at -127.6 ppm (m), and the CF₃ at -82.2 ppm. For **2** the CF₂ attached to the cyclohexyl group at -119.5 ppm (s), the CF₂ in the β position at -123.0 ppm (s), the CF₂ in the γ position at -127.2 ppm (s), and the CF₃ at -82.4 ppm (s). The conversion of C₄F₉I is 98%; the overall yield of perfluorobutyl derivatives is 87%, based on converted C₄F₉I. PhI was obtained in 96% yield based on converted C₄F₉I.

(B) A mixture of 5 mmol of cyclohexene, 1 mmol of C₄F₉I, 2 mmol of *t*-BuOOH, and 0.2 mmol of Fe(OAc)₃ were refluxed for 4 h in 10 mL of acetic acid. The solution was filtered on silica gel and directly analyzed by GLC, GLC-MS, and ¹⁹F-NMR. Only **2** is formed in 68% yield based on C₄F₉I. MS and ¹⁹F-NMR are identical to those of the perfluoro-*n*-butyl cyclohexane obtained in A. The conversion of C₄F₉I is 86%; the overall yield of perfluorobutyl derivatives is 73%, based on converted C₄F₉I.

(C) The reaction was carried out as in B in the presence of 0.1 mmol of Cu(OAc)₂; the results are similar to those obtained in A (83% of **1** and 17% of **2**; the overall yield is 57% based on converted C₄F₉I).

Perfluoro-*n*-butylation of 1-Octene. (A) The reaction and analyses were carried out as for cyclohexene. The *trans* isomer of the allylic perfluorobutylation, C₄F₉CH₂CH=CHC₅H₁₁, **3**, was the main reaction product (82%), the *cis* isomer **4** being 16%, while only traces (<2%) of **5** were obtained. The conversion of C₄F₉I is quantitative and the yields, based on C₄F₉I, were 96%. C₆H₅I was obtained in 93% yield based on C₄F₉I. MS (*m/z*) shows the molecular ion (330), and ¹⁹F-NMR gives four signals at -114.0, -124.6, -126.5, and -81.8 ppm, respectively, for α, β, and γ CF₂ and CF₃ for **3**. The structure of the main reaction product, **3**, was elucidated on the basis of ¹H-NMR and with ¹⁹F broadband decoupling. The multiplets at 5.80 and 5.42 ppm were assigned to the vinylic hydrogens, respectively, in the β- and γ-position relative to the

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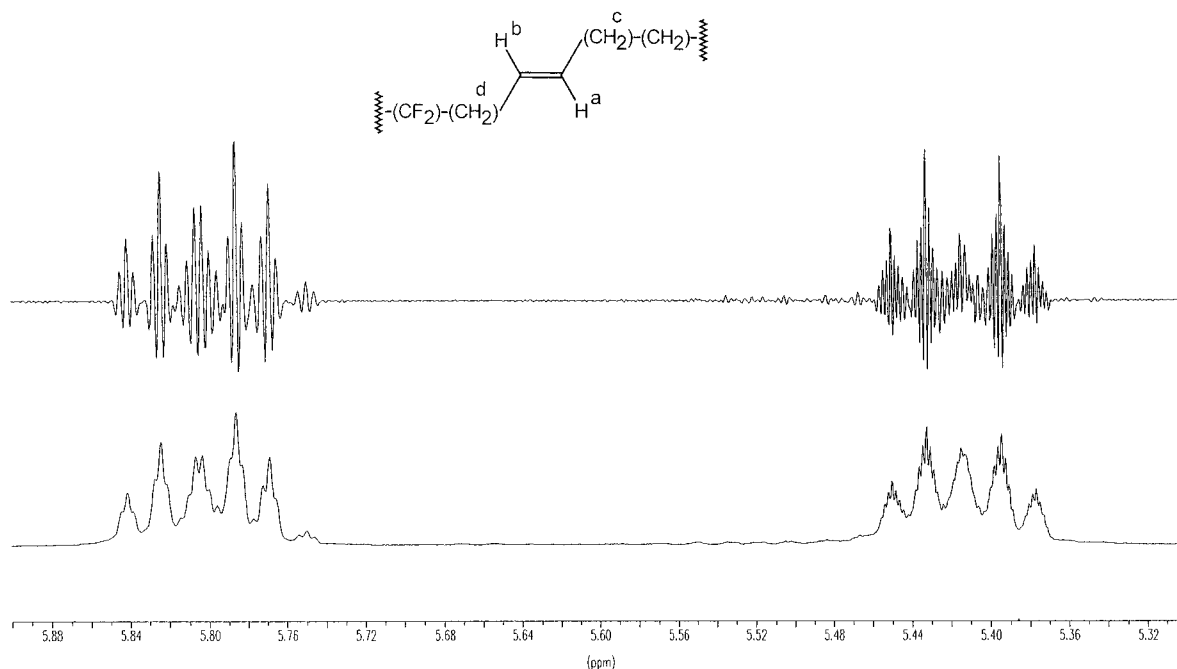


Figure 1. Expansion of the vinylic region of the ^1H -NMR spectrum of compound **3**. Lower trace: normal NMR spectrum. Upper trace: Lorentz-Gauss resolution enhancement for spectral analysis. H^a : δ (ppm) 5.80, dtt, J_{ab} 15.3 Hz, J_{ac} 6.7 Hz, J_{ad} 1.5 Hz; H^b : δ (ppm) 5.42, dttt, J_{ab} 15.3 Hz, J_{bd} 7.2 Hz, J_{bc} 1.4 Hz, J_{HF} 0.7 Hz.

R_f moiety. The multiplicity of the low field multiplet can be explained with the presence of a vicinal coupling to the other vinylic proton ($^3J = 15.3$ Hz), a second vicinal coupling to CH_2 ($^3J = 6.7$ Hz) and an allylic coupling to the CH_2 group directly attached to R_f ($^4J = 1.5$ Hz).

The multiplet at 5.42 is further complicated by long-range heteronuclear coupling to CF_2 and can be analyzed on the basis of the following coupling constants: $^3J = 15.3$ Hz; $^3J = 7.2$ Hz; $^4J = 1.4$ Hz; $^4J_{\text{H-F}} = 0.7$ Hz. These data were confirmed by acquiring ^1H spectra with ^{19}F broadband decoupling.

The (*E*) stereochemistry of the double bond can be inferred by the large value (15.3 Hz) of the vicinal J coupling between the vinylic protons, while the presence of long-range H-H allylic couplings on the proton not coupled to CF_2 allows us to rule out the formation of the addition product $\text{R}_f\text{-CH}=\text{CH}(\text{CH}_2)_5\text{CH}_3$. In Figure 1 the ^1H -NMR spectrum of **3** with a complete analysis of vinyl and allylic protons is reported, as suggested by the referee.

(B) The reaction and analyses were carried out as in B with cyclohexene; the reduced perfluoro-*n*-butyl derivative was obtained in 73% yield, based on converted $\text{C}_4\text{F}_9\text{I}$. MS (m/z) shows the molecular ion (332) and ^{19}F -NMR gives four signals at -119.2 (s, CF_2CH_2), -123.1 (s, CF_2 in the β position), -127.5 (s, CF_2 in the γ position), and -82.1 ppm (CF_3 , s).

(C) The reaction was carried out as in C with cyclohexene; the results are similar to those obtained in A.

Competition Kinetics. (A) 1-Octene and the aromatic substrate (10 mmol on the whole), $\text{C}_4\text{F}_9\text{I}$ (1 mmol), benzoyl peroxide (1 mmol), and $\text{Cu}(\text{OAc})_2$ (0.1 mmol) in 15 mL of AcOH were refluxed for 4 h (116 °C). The solution was filtered through a silica gel column for separating $\text{Cu}(\text{OAc})_2$ and analyzed by GLC and ^{19}F -NMR. The ratios between the aromatic substrate and 1-octene were 10:1 with benzene and toluene, 6:1 with anisole, diphenyl ether, thiophene, and biphenyl, and 2:1 with naphthalene.

(B) As in A using cyclohexene as alkene. The ratios between the aromatic substrates and cyclohexene were 5:1 for benzene and toluene, 2:1 for anisole and diphenyl ether, 1:1 for thiophene and biphenyl, and 1:2 for naphthalene. A typical example: 5 mmol of cyclohexene and 5 mmol of anisole, 1

mmol of $\text{C}_4\text{F}_9\text{I}$, 1 mmol of benzoyl peroxide, and 0.1 mmol of $\text{Cu}(\text{OAc})_2$ in 15 mL of AcOH were refluxed for 4 h (116 °C). The solution was filtered through silica gel and analyzed by GC by using *p*-iodotoluene as internal standard. The reaction products are as follows: **1** (0.47 mmol), **2** (0.08 mmol), *ortho*, *meta*, and *para n*-(perfluorobutyl)anisoles, respectively, 0.06, 0.15, and 0.15 mmol. **1** and **2** and the aromatic isomers were identified in the preparative experiments. MS (m/z) of the three isomers show the molecular ion 296 and the main fragment $\text{MeO-C}_6\text{H}_4\text{-CF}_2^+$ 157; almost identical are the ^{19}F NMR spectra relative to CFCl_3 , with $\alpha\text{-CF}_2$ $-104/-106$, $\beta\text{-CF}_2$ -12 , $\gamma\text{-CF}_2$ -125 , CF_3 -81 ppm. ^1H -NMR of the *meta* isomer gave δ (ppm): 3.81 (s, 3H), 7.05 (d, 1H), 7.13 (s, 1H), 7.2 (d, 1H), 7.38 (t, 1H); for the *para* isomer δ (ppm): 3.80 (s, 3H), 7.02 (d, 2H), 7.44 (d, 2H). A competition between cyclohexene and 1-octene has shown that 1-octene is 4.92 times more reactive than cyclohexene, in good agreement with the value of 5.17 derived from the absolute rate constants.

(C) Benzene and another aromatic compound (10 mmol on the whole), $\text{C}_4\text{F}_9\text{I}$ (1 mmol), benzoyl peroxide (1 mmol), and $\text{Cu}(\text{OAc})_2$ (0.1 mmol) in 15 mL of AcOH were refluxed for 4 h (115 °C). The solution was analyzed as in A. The ratios between benzene and the other aromatic substrates were 1:5 for chlorobenzene, benzonitrile, and nitrobenzene, 1:1 for toluene, 4:1 for anisole, diphenyl ether, thiophene, and biphenyl, and 10:1 for naphthalene. The results are reported in Table 2. In all the procedures A, B, and C the conversion of $\text{C}_4\text{F}_9\text{I}$ is $>85\%$, and the overall yields based on converted $\text{C}_4\text{F}_9\text{I}$ are in the range 94–97% for $n\text{-C}_4\text{F}_9\text{-Ar} + \mathbf{1} + \mathbf{2}$ (or $+ \mathbf{3} + \mathbf{4} + \mathbf{5}$) and 93–98% for $\text{C}_6\text{H}_5\text{I}$, supporting the validity of the competition kinetics and excluding the presence of significant amounts of other byproducts. With pyrrole the procedures A, B, and C were not suitable because the benzoyloxy radical adds to the pyrrole ring. In this case method iv ($\text{H}_2\text{O}_2/\text{DMSO}/\text{Fe}(\text{II})$) has been utilized in a competition between benzene and pyrrole. Even with a 10:1 benzene/pyrrole ratio, the attack to the α -position of the pyrrole ring was higher than 90%.

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