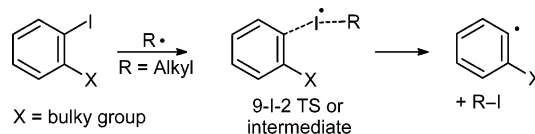# JOC Article

Abstraction of Iodine from Aromatic Iodides by Alkyl Radicals: Steric and Electronic Effects[†,‡]

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Relief of steric strain lowers the activation energy

Abstraction of the iodine atom from aryl iodides by alkyl radicals takes place in some cases very efficiently despite the unfavorable difference in bond dissociation energies of C−I bonds in alkyl and aryl iodides. The abstraction is most efficient in iodobenzenes, ortho-substituted with bulky groups. The ease of abstraction can be explained by the release of steric strain during the elimination of the iodine atom. The rate of abstraction correlates fairly well with the strain energy, calculated by density functional theory (DFT) and Hartree−Fock (HF) methods as a difference in the total energy of ortho and para isomers. However, besides the steric bulk, the presence of some other functional groups in an ortho substituent also influences the rate. The stabilization of the transition state, resembling a 9-I-2 iodanyl radical, by electron-withdrawing groups seems to explain a positive sign of the Hammett ρ value in the radical abstraction of halogen atoms.

Introduction

Abstraction of halogen atoms from organic halides by aryl and alkyl radicals has been extensively studied from a mechanistic point of view as well as being a synthetically interesting process.[2−4] The abstraction is generally more facile in alkyl halides as the C−halogen bonds are weaker than in aryl analogues. In aromatic substrates, only the abstraction of iodine is documented and it takes place with aryl but not with alkyl radicals.[5] The proposed mechanism involves the direct attack of the abstracting radical on the iodine atom and subsequent scission of one of the C−I bonds. The process either can be a one-step reaction or it can involve the formation of an 9-I-2 intermediate in a two-step process.[5]

Substituent effects on the abstraction by phenyl radicals were studied by Danen and Saunders,[5c] who found that the reaction is facilitated by the presence of electron-withdrawing groups in the aryl iodide (Hammett $\rho = +0.57$). Tanner et al.[6] rationalized the sign of the substituent effect and scattering of the data by the formation and subsequent decomposition of the 9-I-2 iodanyl radical as the intermediate.

In the course of our research, we have observed a very facile abstraction of the iodine atom from some ortho-substituted iodobenzenes, namely, 2-(2-iodophenyl)propan-2-ol and par-

[†] Presented in part at the 15th IUPAC Conference on Physical Organic Chemistry, Göteborg, Sweden, July 2000; book of abstracts, p P26.

[‡] Dedicated to Professor Miha Tišler on the occasion of his 80th birthday.

(1) Deleted in press.

(2) Dolenc, D.; Plesničar, B. *J. Am. Chem. Soc.* **1997**, *119*, 2628−2632.

(3) See, for example, (a) Fossey, J.; Lefort, D.; Sorba, J. *Free Radicals in Organic Chemistry*; Wiley & Sons: New York, 1995. (b) *Radicals in Organic Synthesis*; Renaud, P., Sibi, M. P., Eds.; Wiley−VCH: Weinheim, Germany, 2001. (c) Zard, S. Z. *Radical Reactions in Organic Synthesis*; Oxford University Press: Oxford, U.K., 2003.

(4) See, for example, (a) Evans, F. W.; Fox, R. J.; Szwarc, M. *J. Am. Chem. Soc.* **1960**, *82*, 6414−6415. (b) Zavitsas, A. A.; Ehrenson, S. *J. Am. Chem. Soc.* **1965**, *87*, 2841−2846. (c) Danen, W. C.; Winter, R. L. *J. Am. Chem. Soc.* **1971**, *93*, 716−720. (d) Giese, B. *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 173−176. (e) Dinçtürk, S.; Jackson, R. A. *J. Chem. Soc., Perkin Trans. 2* **1981**, 1127−1131. (f) Curran, D. P.; Bosch, E.; Kaplan, J.; Newcomb, M. *J. Org. Chem.* **1989**, *54*, 1826−1831. (g) Quiclet-Sire, B.; Zard, S. Z. *J. Am. Chem. Soc.* **1996**, *118*, 9190−9191. (h) Laarhoven, L. J. J.; Born, J. G. P.; Arends, I. W. C. E.; Mulder, P. *J. Chem. Soc., Perkin Trans. 2* **1997**, 2307−2312 and references therein.

(5) (a) Bunnett, J. F.; Wamser, C. C. *J. Am. Chem. Soc.* **1966**, *88*, 5534−5537. (b) Brydon, D. L.; Cadogan, J. I. G. *J. Chem. Soc. C* **1968**, 819−824. (c) Danen, W. C.; Saunders, D. G. *J. Am. Chem. Soc.* **1969**, *91*, 5924−5925. (d) Danen, W. C.; Saunders, D. G.; Rose, K. A. *J. Am. Chem. Soc.* **1973**, *95*, 1612−1615. (e) Davis, W. H.; Gleaton, J. H.; Pryor, W. A. *J. Org. Chem.* **1977**, *42*, 7−12.

(6) Tanner, D. D.; Reed, D. W.; Setiloane, B. P. *J. Am. Chem. Soc.* **1982**, *104*, 3917−3923.

ticularly 2-(5-methyl-2-iodophenyl)-1,1,1,3,3,3-hexafluoropro-pan-2-ol, by cyclohexyl radicals.[2]
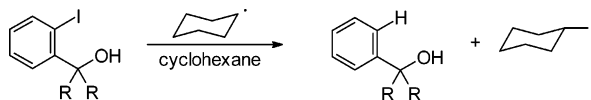
R = Me or CF$_3$

Further investigations of this reaction revealed that the abstraction is most efficient in iodides, ortho-substituted with a bulky group, usually containing electronegative atom(s), such as CMe$_2$OH, C(CF$_3$)$_2$OH or CF$_3$; somewhat less efficient groups were COOH and CH$_2$OH.[2] Measurements of the rate of abstraction of iodine from substituted 2-iodocumyl alcohols by cyclohexyl radicals exhibits a fair Hammett correlation with ρ = +1.10 (r = 0.97).[2] A rather high positive value of ρ could be explained by a higher nucleophilicity of the secondary alkyl radicals, compared with aryl radicals used in the previous studies.

Two factors, that is, steric and electronic, appear to govern the energetics of this process. In our previous paper[2] we attributed the electronic effect to a possible weak hydrogen bonding of the OH group to the iodine atom in the transition state. Such interaction could effectively reduce the electron density on the iodine atom during the abstraction (positive Hammett ρ). In this paper, we present the results of a systematic study of the effect of ortho substituents in iodobenzenes on the rate of the abstraction of iodine by cyclohexyl radicals.

Results and Discussion

Our finding that alkyl radicals are capable of the abstraction of iodine from aryl iodides is rather astonishing, since the C−I bonds in aryl iodides are considerably stronger than in alkyl analogues, and such a reaction should be endothermic. The difference in BDE between various alkyl and phenyl iodides is, according to literature data, on the order of 8−10 kcal mol^{-1}.[7] The computed reaction energy for the abstraction of iodine from iodobenzene by the cyclohexyl radical is 9.97 kcal mol^{-1} at the B3LYP/6-31G(d,p) level of theory.[8] To obtain the activation energy for the abstraction, an additional activation threshold should be added, which can be estimated at 2−3 kcal mol^{-1}.[9] The activation energy for the abstraction of iodine from

(7) (a) Luo, Y.-R. *Handbook of Bond Dissociation Energies in Organic Compounds*; CRC Press: Boca Raton, FL, 2003. (b) *CRC Handbook of Chemistry and Physics*, 76th ed.; Lide, D. R., Ed.; CRC Press: Boca Raton, FL, 1995. (c) Wentrup, C. *Reactive Molecules*; Wiley: New York, 1984. (d) Denisov, E. T. *Zh. Fiz. Khim.* **1995**, *69*, 436−440.

(8) The energy was calculated as the energy of the reaction of iodobenzene and the cyclohexyl radical yielding the phenyl radical and iodocyclohexane. The energies of reactants and products are total energies computed at the B3LYP/6-31G(d,p) level including the zero-point energy correction. The corresponding value for the abstraction by the methyl radical is 10.38 kcal mol^{-1} with B3LYP/6-31G(d,p) and 13.00 kcal mol^{-1} with MPW1K/LACV3P**.

(9) The activation energy for the exothermic abstraction of chlorine from tetrachloromethane by various alkyl radicals is around 5 kcal mol^{-1}.[10] For the phenyl radical this is approximately 3 kcal mol^{-1}.[11] A similar value can be estimated from the measured reaction rate of phenyl radicals with tetrachloromethane[12] by assuming that log A for the reaction is 8.5. The activation energy for the abstraction of iodine is expected to be somewhat lower.

(10) Hawari, J. A.; Davis, S.; Engel, P. S.; Gilbert, B. C.; Griller, D. *J. Am. Chem. Soc.* **1985**, *107*, 4721−4724.

(11) Yu, T.; Lin, M. C. *J. Phys. Chem.* **1995**, *99*, 8599−8603.

(12) Scaiano, J. C.; Stewart, L. C. *J. Am. Chem. Soc.* **1983**, *105*, 3609−3614.

TABLE 1. Activation Parameters for the Abstraction of Iodine from Ortho-Substituted Iodobenzenes with Cyclohexyl Radicals[a]

Substrate		log A_{rel}	log A^b	$E_{a\,rel}$ (kcal mol^{-1})	E_a^b (kcal mol^{-1})
	3	−0.44 ± 0.28	8.1	0.92 ± 0.44	6.9
	9	−0.22 ± 0.02	8.3	1.56 ± 0.10	7.6
	10	0.21 ± 0.29	8.7	2.11 ± 0.45	8.1
	11	−0.69 ± 0.08	7.8	0.19 ± 0.09	6.2
	15	−0.57 ± 0.01	7.9	−1.30 ± 0.04	5.2

^{a} Measured in cyclohexane, temperature range 35−70 °C. ^{b} Calculated from measured relative and adopted values for tetrachloromethane, log A = 8.5 and E_a = 6.0 kcal mol^{-1}.

TABLE 2. Relative Rates for the Abstraction of Iodine from Ortho-Substituted Iodobenzenes with Cyclohexyl Radicals[a] and the Calculated Strain Energies

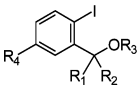| iodide	log $k(I)/k(Cl)^b$	E_s^c (kcal mol^{-1})	iodide	log $k(I)/k(Cl)^b$	E_s^c (kcal mol^{-1})
2	−2.93	1.47	**10**	−1.21	7.07
3	−1.06	7.12	**11**	−0.59	8.53
4	−1.81^d	7.20	**12**	−0.31	7.94
5	−1.68	7.24	**13**	0.17	10.39^e
6	−1.48	6.28	**14**	0.56	10.69
7	−1.76	4.90	**14a**	−0.38	10.00
8	−2.72	0.51	**15**	0.32	10.69
9	−1.21	6.64	**15a**	−0.41	10.00
9a	−1.30	7.04^e			

^{a} Measured at 50 °C in cyclohexane, unless otherwise stated. ^{b} Rate of abstraction of iodine from aryl iodide, $k(I)$, relative to rate of abstraction of chlorine from CCl$_4$, $k(Cl)$. ^{c} $E(ortho) - E(para)$, B3LYP/6-31G(d,p); see text and Supporting Information. ^{d} Rate measured in a cyclohexane/benzene mixture, 1:1(v/v). ^{e} Zero-point vibrational energy correction not included.

iodobenzene by alkyl radicals should thus be 8−13 kcal mol^{-1}. This value indicates a rather slow reaction (at 50 °C, k = 1−100 L mol^{-1} s^{-1}, assuming log A = 8.5 as a typical value; see below), which could not compete with other radical processes, for example, combination, and thus the abstraction would not be effective.

To elucidate the factors influencing the rate of the abstraction, we measured the reaction rates and determined activation parameters for the abstraction of iodine from several substituted iodobenzenes by cyclohexyl radicals (Tables 1 and 2). A series of ortho-substituted iodobenzenes with increasing size of the ortho group of various composition was prepared (see Chart 1), and reactivities of these compounds were measured.

Activation parameters for the abstraction of iodine from selected iodobenzenes were determined relative to the abstraction of chlorine from tetrachloromethane. Absolute values can

CHART 1

	R
1	H
2	*i*-Pr
3	*t*-Bu
4	COOH
5	COOMe
6	SO$_3$Me
7	CF$_3$

	R$_1$	R$_2$	R$_3$	R$_4$
8	H	H	H	H
9	Me	Me	H	H
9a	Me	Me	Me	H
10	Et	Et	H	H
11	*i*-Pr	*i*-Pr	H	H
12	Me	CF$_3$	H	H
13	*t*-Bu	CF$_3$	H	H
14	CF$_3$	CF$_3$	H	H
14a	CF$_3$	CF$_3$	Me	H
15	CF$_3$	CF$_3$	H	Me
15a	CF$_3$	CF$_3$	Me	Me

FIGURE 1. Plot of log k (relative rates) of the abstraction of iodine from ortho-substituted iodobenzenes versus computed strain energy.

measurements of the reaction rates at single temperatures reflect the differences in E_a for a series of compounds as presented in Table 2.

To evaluate the importance of steric strain on the rate of the abstraction of iodine, we tried to correlate log k values with the steric bulk of an ortho substituent. Numerous approaches for evaluating steric bulk of substituents and tabulated data on van der Waals radii or other parameters can be found in the literature.[19] Most of the work was done on more or less branched alkyl groups, which are not part of our interest or, even worse, we did not succeed in introducing an iodine atom ortho to such a group in the benzene ring by direct or indirect synthetic procedures. For this reason we decided to evaluate steric bulk and the strain energy by computational methods at the HF 6-31G(d,p) and B3LYP/6-31G(d,p) levels of theory. The strain energy is expressed as the difference between the computed total energies of the ortho and para isomers of a substituted iodobenzene (Table 2, Figure 1):

$$E_s = E(\text{o}) - E(\text{p}) \qquad (1)$$

where E_s is the strain energy and $E(\text{o})$ and $E(\text{p})$ are total energies including the zero-point vibrational energy correction of the ortho and para isomers, respectively. Since the Hartree−Fock (HF) and density functional theory (DFT) methods yielded very similar strain energies, only the results of DFT calculations were taken into account. Steric strain in an ortho-substituted iodobenzene should be reflected also in a deformation of a bond angle I−C1−C2. Two of our compounds, namely, **6** and **15**, were subjected to X-ray diffraction structural analysis. Crystallographic data are in good agreement with the calculated bond angles and bond lengths (see Supporting Information).

then be calculated from the absolute parameters for the standard; however, it is difficult to find reliable data. Namely, the reported activation parameters for the abstraction of chlorine from tetrachloromethane by various alkyl radicals differ substantially, but we can assume log A = 8.5 (L mol^{-1} s^{-1}) and E_a = 6.0 kcal mol^{-1} as reasonable values for the abstraction of chlorine atoms from CCl$_4$ by cyclohexyl radicals.[13] Nevertheless, even if these figures are far from real, the preexponential factors for the abstraction of iodine from iodobenzenes (**3**, **9**−**11**, and **15**) are similar to those for the abstraction of chlorine from CCl$_4$.[17]

Activation parameters for the abstraction of iodine from compounds in Table 1 exhibit a fairly constant preexponential factor A and differ mainly in the activation energy.[18] Therefore,

(13) Reported values for log A are 7.3−9.5, but most of them are centered around 8.5, which is also a mean value. Activation energies vary from 4.7 to 7.3 kcal mol^{-1}, but again, most values do not differ much from a mean, that is, 6.0 kcal mol^{-1}.[10,14−16]

(14) Jewel, D. R.; Mathew, L.; Warkentin, J. *Can. J. Chem.* **1987**, *65*, 311−315.

(15) Lindsay, D. A.; Lusztyk, J.; Ingold, K. U. *J. Am. Chem. Soc.* **1984**, *106*, 7087−7093.

(16) Katz, M. G.; Horowitz, A.; Rajbenbach, L. A. *Int. J. Chem. Kinet.* **1975**, *7*, 183−194.

(17) A slightly lower value of a log A for iodobenzenes is to be expected, since the accessibility of iodine in iodobenzenes is lower than that of chlorine in a nearly spherical molecule of CCl$_4$.
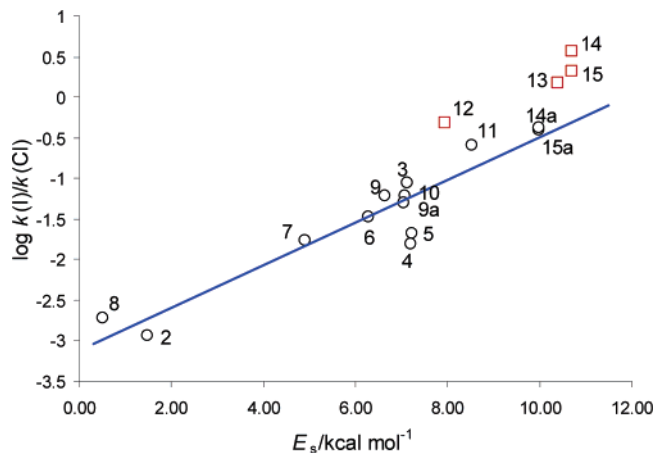
(18) The values of log A for a series of structurally similar compounds presented in Table 1 differ from one another to the extent of 0.6 (except for the compound **10**, for which a higher value is most probably a consequence of an experimental uncertainty). Such a change in log A amounts to a factor of 4 in the rate constant, which is much smaller than differences in the measured rate constants. However, slightly lower values of log A can be found for sterically more hindered compounds, which is in agreement with the expectations.

(19) (a) Charton, M. *J. Am. Chem. Soc.* **1975**, *97*, 1552−1556. (b) Tidwell, T. T. *Tetrahedron* **1978**, *34*, 1855−1868. (c) Zefirov, Y. V.; Zorkii, P. M. *Russ. Chem. Rev.* **1989**, *58*, 421−440. (d) Isizawa, J.; Sakakibara, K.; Hirota, M. *Bull. Chem. Soc. Jpn.* **1996**, *69*, 1003−1015. (e) White, D. P.; Anthony, J. C.; Oyefeso, A. O. *J. Org. Chem.* **1999**, *64*, 7707−7716. (f) Timperley, C. M.; White, W. E. *J. Fluorine Chem.* **2003**, *123*, 65−70.

The results presented in Table 2 and Figure 1 reveal that the rate of abstraction of iodine in most compounds correlates well with the computed strain energy. The exceptions are *o*-iodobenzoic acid (**4**) and its methyl ester (**5**), which are less reactive than expected from the calculations. The possible reason for too high a calculated strain energy could be a computational overestimation of the tendency of the COOH group to be coplanar with the aromatic ring. In the computed structures the torsional angle between the ring and COOR is around 25° for both compounds. Further exceptions are benzyl alcohols, containing one or two α-trifluoromethyl groups (**12**−**15**). These compounds exhibit markedly higher reactivity than expected.

The principal factor governing the energetics of the abstraction is obviously the steric bulk of a substituent. A relatively large effect exhibited by $C(CF_3)_2OH$ (**14**, **15**) and $C(CF_3)_2OMe$ (**14a**, **15a**) groups, compared with, for example, *tert*-Bu (**3**) or $C(t\text{-Bu})(CF_3)OH$ (**13**) could be, at least to some degree, accounted for by the electronic repulsion between iodine and fluorine atoms.[20]

Besides the steric effect, there are also purely electronic (through-bond) factors that influence the activation energy of the abstraction of iodine.[2,4−6,21−23] As already mentioned, electron-withdrawing substituents accelerate the radical abstraction of halogen atoms; this is in contrast with the abstraction of hydrogen, where the substituent effect is just the opposite.[24,25] One would expect, on the basis of electronic effects only, the greatest acceleration of the rate with COOR, SO_3Me, and CF_3, which is not the case. Moreover, groups, such as $C(CF_3)_2OH$ and $C(CF_3)_2OMe$ should have approximately the same effect on the rate of abstraction; however, they do not. The highest rate of abstraction is observed with alcohols of the benzylic type, containing one or two CF_3 groups at the α-carbon (**12**−**15**), but not with structurally similar alcohols containing no CF_3 groups. Methoxy derivatives of trifluoromethyl alcohols (**14a**, **15a**) do not exhibit enhanced reactivity (for example, the reactivity of a hexafluorocumyl alcohol **14** is 9 times higher than that of the methyl ether **14a**). The possible explanation of this phenomenon might be the higher acidity of trifluoromethyl alcohols compared with the "normal" alcohols.[26] In our previous paper, we attributed this effect to a possible hydrogen bonding between the OH group and the iodine atom in the transition state.[2] This explanation could still hold, but unfortunately, we have no evidence for the formation of such a bonding yet. Also, it is not clear why 2-iodobenzoic acid does not exhibit enhanced reactivity; just the opposite, its reactivity is below that expected from the computed steric strain energy. Measurements with a stronger acid, 2-iodobenzenesulfonic acid, also did not give results consistent with this hypothesis. The measured reactivity of 2-iodobenzenesulfonic acid was comparable to its methyl ester (**6**); however, the sulfonic acid is a strong acid, and with traces of water it forms a salt, oxonium sulfonate, that has different electronic and acid properties. Because it is difficult

to say what species is actually present in the reaction mixture, the results of this measurement were not included into Table 2 and Figure 1.

The difference in the reactivity of compounds **14** and **15**, which differ only in the methyl group at the para position relative to the iodine atom, could be attributed to the electronic effect of the methyl group. A reactivity ratio **14**:**15**, calculated from the Hammett correlation, is 1.54 (ρ = 1.10 with σ_{4-Me} = −0.17),[2] which is in reasonable agreement with the measured value of 1.73.

Abstraction of the iodine atom from iodobenzene with an alkyl radical is in all cases an endothermic process.[27] This indicates a late transition state with the Ar−I bond being broken to a great extent. Therefore, destabilization of a C−I bond, caused by steric or stereoelectronic strain, has a profound effect on the energy of the transition state and, consequently, on the reaction rate. The question of the involvement of an intermediate, that is, a 9-I-2 iodanyl radical, during the course of the radical abstraction of iodine is not yet resolved. Quantum chemical calculations of Schiesser et al.[28] on the abstraction of halogens by various radicals predict a one-step reaction without the involvement of an intermediate. An interesting feature of the computed transition states is that their geometries depend on the halogen atom as well as on the two ligands connected to halogen. In the case of chlorine, the transition-state geometry is always linear, while going toward heavier halogens it becomes more and more bent. The angle X−I−Y (X, Y = H, Me) is the smallest when X = Y = hydrogen (strongest bond I−X). The computed angle and the energy of transition states also depend on the level of theory applied; that is, the higher the level, the smaller the angle and the lower the energy. A (hypothetical) 9-I-2 radical is a hypervalent species and is expected to be nonlinear. The reported theoretical results would thus seem to suggest that the transition states are most likely very close in structure to the hypothetical 9-I-2 iodanyl radical.

Our calculations of the transition states of the type H−I−H, Me-I−H, Ph-I−H, and Ph-I-Me exhibit a similar pattern. The bond angle on the iodine atom in the above series is becoming more and more open as the I−ligand bond strength decreases. Unfortunately, we did not succeed in modeling the transition states for the abstraction of iodine from the more hindered iodobenzenes, for example, **3** or **14**. The computed activation energy for the abstraction of iodine from iodobenzene by methyl radicals is 13.9 kcal mol^{-1} (MPW1K/LACV3P**, see Supporting Information). On the other hand, the activation energy for the abstraction of iodine from iodobenzene by cyclohexyl radicals, calculated from experimental data, amounts to 8.0 kcal mol^{-1}.[29] Although the abstracting radicals are not the same, the difference should not exceed 1 kcal mol^{-1}. Such a discrepancy between the experimental and calculated activation energy might indicate that, despite the relatively high level of theory employed, the calculations are still rather crude.[30] Further improvements in calculations could lead to a closer structural

(20) In the calculated structure of **13** (HF or DFT), the *tert*-butyl group is positioned closer to iodine than CF_3.

(21) Dannen, W. C.; Saunders, D. G.; Rose, K. A. *J. Am. Chem. Soc.* **1974**, *96*, 4558−4562.

(22) Migita, T.; Nagai, T.; Abe, Y. *Chem. Lett.* **1975**, 543−546.

(23) Heidbrink, J. L.; Thoen, K. K.; Kenttämaa, H. I. *J. Org. Chem.* **2000**, *65*, 645−651.

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(25) Zavitsas, A. A.; Pinto, J. A. *J. Am. Chem. Soc.* **1972**, *94*, 7390−7396.

(26) Dyatkin, B. L.; Mochalina, E. P.; Knunyants, I. L. *Tetrahedron* **1965**, *21*, 2991−2995.

(27) The computed reaction energies for the abstraction of iodine from various iodobenzenes by cyclohexyl radicals exhibit a general trend which is in reverse proportionality with computed steric energies.

(28) Schiesser, C. H.; Smart, B. A.; Tran, T. *Tetrahedron* **1995**, *51*, 3327−3338.

(29) The activation energy for the abstraction of an iodine atom from iodobenzene was calculated from the extrapolated log $k(I)/k(Cl)$ = −3.0 for E_s = 0 (Figure 1), and log A = 8.5 (Table 1).

(30) See, for example, Lynch, B. J.; Fast, P. L.; Harris, M.; Truhlar, D. G. *J Phys. Chem. A* **2000**, *104*, 4811−4815.
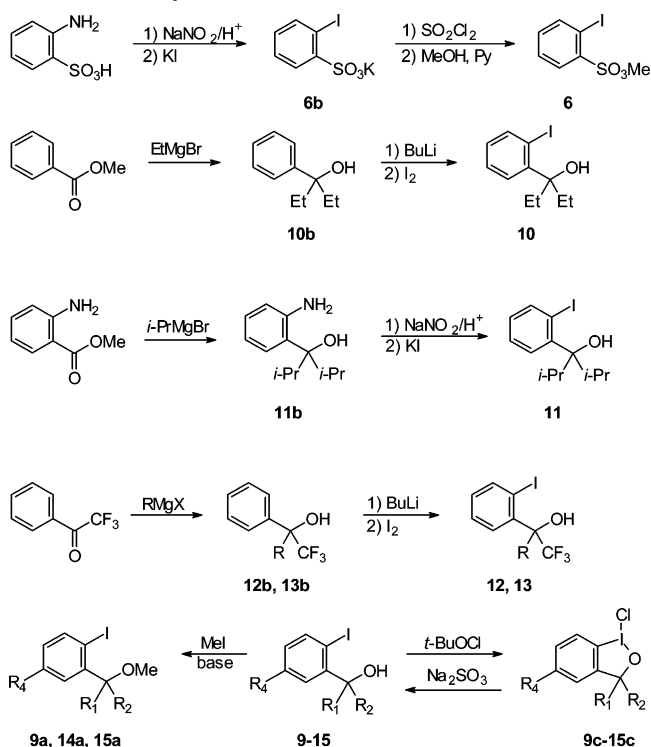
resemblance of the transition state to a hypothetical 9-I-2 iodanyl radical intermediate.

The existence of 9-I-2 iodanyl radicals as short-lived intermediates with two benzylic groups bound to the iodine atom, as well as a related radical with one aryl and one alkoxy ligand, was already reported.[31,32] The stability of a 9-I-2 iodanyl radical (i.e., the bond strength of the C—I bond) is expected to be inversely proportional to the stability of alkyl (or aryl) radicals attached to the iodine atom. The stability of iodanyl radicals, containing groups that form less stable radicals than benzyl (e.g., methyl or phenyl) could thus be even greater, and one could expect such a radical to be a real species.

Substituent Effects. Studies of the abstraction of iodine and other halogens by aryl or alkyl radicals have demonstrated positive Hammett ρ values for this reaction. Many studies concerning the origin of this effect were made; the question whether it is a consequence of the influence of substituents on the C—I bond strength or on the energy of the transition state is still open. Recent studies and our calculations favor the latter possibility.[23] Regardless of whether the reaction course involves the transition state or intermediate, the transition state resembles a (hypothetical) 9-I-2 radical. A radical of such type is hypervalent, which implies that it is nonlinear with the electron density concentrated on ligands rather than distributed evenly. The stability of hypervalent species is enhanced by the electronegativity of the ligands attached to the central atom.[33] Because of the hypervalent nature of the transition state, a positive charge is localized on the iodine atom. Electron-withdrawing ligands thus stabilize 9-I-2 hypervalent radicals or related transition states. The atomic charge distribution calculations by NBO analysis at the B3LYP/6-31G(d,p) or HF/6-31G(d,p) levels indicate a positive charge buildup in the range of 0.2−0.6 au on the iodine atom in the transition states of the type H—I—H, Me-I—H, Ph-I—H, or Ph-I-Me, as compared with the charge on the iodine atom in the starting molecule (MeI or PhI, respectively). The "positive" substituent effect can thus be attributed to pushing off the electrons from the iodine atom in the transition state, which is thus stabilized by the ligands able to absorb the electron density.
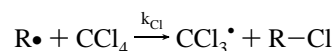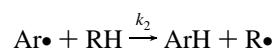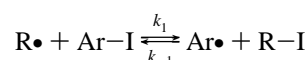
Synthesis. 2-(2-Iodophenyl)propan-2-ol (**9**) was prepared from methyl 2-iodobenzoate by Grignard addition of methylmagnesium iodide, but this method failed with other alkyl substituents. 3-(2-Iodophenyl)pentan-3-ol (**10**) was synthesized in low yield from 3-phenylpentan-3-ol by ortho-directed lithiation followed by the addition of iodine.[34] The only efficient procedure for preparing **11** was starting from 2-(2-aminophenyl)-2,4-dimethylpentan-3-ol via diazotization and nucleophilic iodination of the diazonium salt. All α,α-dialkylbenzyl alcohols (**9**−**15**) were purified by oxidation to the corresponding crystal

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SCHEME 1. Synthesis of Iodoarenes

line 1-chloro-3,3-dialkyl-1*H*-1,2-benziodoxoles and subsequent reduction back to alcohol.[35] These procedures are outlined in Scheme 1.

Kinetic Measurements. Measurements of the rate of abstraction of iodine by cyclohexyl radicals were made by competition kinetics with tetrachloromethane as the internal standard:

$$R\bullet + Ar{-}I \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} Ar\bullet + R{-}I$$

$$Ar\bullet + RH \xrightarrow{k_2} ArH + R\bullet$$

$$R\bullet + CCl_4 \xrightarrow{k_{Cl}} CCl_3^{\bullet} + R{-}Cl$$

$$k_{obs}[R][ArI] = \frac{d[RI]}{dt} = k_1[R][ArI]\left\{1 - \frac{k_{-1}[RI]}{k_2[RH] + k_{-1}[RI]}\right\}$$

$$(2)$$

The value of k_1 can be evaluated from the measured k_{obs} by use of eq 1, which takes into account the possible reaction of aryl radicals with the already formed alkyl iodide. The term in the parentheses equals 1, when the concentration of the product (RI) is zero, as it is at the beginning of the reaction. But even when the concentration of RI is considerable, it can be estimated from the values of activation parameters for the reactions of phenyl radicals with alkanes,[11] as well as from those for the reactions of alkyl radicals with iodoalkanes,[4f] that the values for k_2 and k_{-1} are not far apart. When cyclohexane is the solvent, the concentration of RH is at least 10^3 times higher than that of RI (even at the highest conversion) and the term $k_{-1}[RI]$ becomes negligible. Moreover, the measured ratio k_I/k_{Cl} appeared not to

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be dependent on the conversion. Therefore, it appears safe to assume that the value of k_1 is very close to k_{obs}.

Cyclohexyl radicals were chosen because of their relatively high reactivity and ease of formation. When cyclohexane was the solvent, they were formed by thermal decomposition of a suitable radical initiator, for example, di-*tert*-butyl peroxyoxalate (DBPO).[36] The radical clock 5-hexenyl/cyclopentylmethyl[37] proved unsatisfactory, since the reaction products of the clock are not stable under the reaction conditions. The reaction of cyclohexyl radicals with iodoarenes and tetrachloromethane produces only iodocyclohexane, chlorocyclohexane, and deiodinated arenes. Other products in traces are cyclohexanol and cyclohexanone and variable but small amounts of bicyclohexyl.

Conclusions

The ease of abstraction of the iodine atom from ortho-substituted iodobenzenes seems to have arisen mainly from steric strain, which is a consequence of steric and/or stereoelectronic repulsion between two closely positioned groups. In *o*-iodobenzyl alcohols, bearing trifluoromethyl group(s) on an α-C atom, such groups exhibit a large steric effect, bigger than that of the *tert*-butyl group. The abstraction is generally an endothermic process with a late transition state in which the Ar—I bond is substantially broken and steric strain is relieved to a high degree. Some ortho groups, particularly of the $C(CF_3)_2$-OH type, exhibit a particularly high accelerating effect, which cannot be explained solely on the basis of the relief of steric strain or "through-bond" substituent effect.

The quantum chemical calculation of the activation energy for the abstraction of iodine from iodobenzene by methyl radical is 5—6 kcal mol^{-1} higher as compared with the experimentally determined one. The hypervalency of the iodine atom lowers the energy of either the transition state or the shallow barrier for decomposition of the 9-I-2 intermediate. Such intermediates were already experimentally established, however, computational methods do not find them as real species.

Electron-withdrawing groups accelerate the reactions (positive Hammett ρ), which can be explained by the hypervalent nature of the transition state or a 9-I-2 intermediate.

Experimental Section

Synthesis. 1-Isopropyl-2-iodobenzene (**2**),[38] 1-*tert*-butyl-2-iodobenzene (**3**),[39] methyl 2-iodobenzoate (**5**),[40] 2-(2-iodophenyl)propan-2-ol (**9**),[35,41] 1,1,1,3,3,3-hexafluoro-2-(2-iodophenyl)propan-2-ol (**14**),[42] 1,1,1,3,3,3-hexafluoro-2-(2-iodo-5-methylphenyl)propan-2-ol (**15**),[35] 2-(2-iodophenyl)-2-methoxypropane (**9a**),[2] and di-*tert*-butylperoxyoxalate[36] were synthesized by literature procedures. NMR spectra were measured on a 300 MHz instrument, and chemical shifts are reported relative to a $SiMe_4$ reference.

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Potassium 2-Iodobenzenesulfonate (6b). The compound was prepared according to the procedure of Chau and Kice[43] for the synthesis of 2-iodobenzenesulfonic acid. The product obtained was in fact a potassium salt hydrate rather than the acid (mp >300 °C, lit. 344−345 °C[43]); the compound is pH neutral. Anal. Calcd for $C_6H_4IKO_3S \cdot H_2O$: C, 21.18; H, 1.78. Found: C, 21.10; H, 1.74. ^{1}H NMR (D_2O) δ/ppm 7.21 (dt, *J* = 1.4, 7.7 Hz, 1H), 7.51 (dt, *J* = 1.0, 7.8 Hz, 1H), 8.00 (dd, *J* = 1.4, 7.8 Hz, 1H), 8.11 (dd, *J* = 1.0, 7.7 Hz, 1H). ^{13}C NMR (D_2O) δ/ppm 91.5 (C), 128.9 (CH), 129.1 (CH), 133.0 (CH), 142.7 (CH), 145.4 (C).

Methyl 2-Iodobenzenesulfonate (6). A dispersion of 7.69 g (22.6 mmol) of potassium 2-iodobenzenesulfonate hydrate (**6b**) in 15 mL of dichloromethane and 0.3 mL of *N*,*N*-dimethylformamide (DMF) was stirred at room temperature, and 5.95 g (50 mmol, 3.6 mL) of $SOCl_2$ was added in a few portions. After 2 h of reflux, 20 mL of cyclohexane was added, and the solvents and unreacted $SOCl_2$ were distilled off. The resulting mixture was filtered by suction and the filtrate was evaporated under reduced pressure. The yield of crude, oily 2-iodobenzenesulfonyl chloride was 7.17 g, of which 3.02 g (10 mmol) was dissolved in a mixture of 5 mL of MeOH and 0.80 g (10 mmol) of pyridine. After 0.5 h of stirring at room temperature, the mixture was diluted with diethyl ether, washed with aqueous citric acid and water, and dried with anhydrous sodium sulfate, and the solvent was evaporated under reduced pressure. Product **7b** (2.58 g, 87%) was obtained as an oil, which crystallized after a few weeks in the refrigerator. The crystalline product was then recrystallized from hexane/dichloromethane, and colorless crystals with mp 37−38.5 °C were isolated. ^{1}H NMR (CDCl$_3$) δ/ppm 3.82 (s, 3H), 7.28 (dt, *J* = 1.6, 7.6 Hz, 1H), 7.54 (dt, *J* = 1.1, 7.7 Hz, 1H), 8.13 (m, 2H). ^{13}C NMR (CDCl$_3$) δ/ppm 56.4 (CH$_3$), 92.2 (C), 128.3 (CH), 131.8 (CH), 134.4 (CH), 138.5 (C), 142.9 (CH). EI, *m/z* (%) 298 (M$^+$, 100), 267 (13), 203 (74), 127 (10), 92 (24), 77 (39), 76 (67), 50 (49). Anal. Calcd for $C_7H_7IO_3S$: C, 28.20; H, 2.37. Found: C, 28.18; H, 2.35.

1-Chloro-3,3-diethyl-1*H*-benzoiodoxole (10c). 3-Phenylpentan-3-ol[44] (0.98 g, 5.0 mmol) and TMEDA (1.4 g, 12 mmol) were dissolved in 15 mL of dry pentane in a three-necked flask under argon. The flask was cooled in an ice bath, and 10 mL of butyllithium solution (1.6 M) was slowly added under stirring. The reaction mixture was refluxed for 17 h and then cooled to −50 °C, and a solution of 2.9 g (11.4 mmol) of iodine in 20 mL of dry diethyl ether was added.[34] After it was warmed to room temperature, the mixture was acidified with aqueous citric acid, the organic layer (there was some dark oil, insoluble in ether/pentane, which was discarded) was washed with sodium hydrogen carbonate and water and dried with sodium sulfate, and the solvent was evaporated under reduced pressure. Impure 3-(2-iodophenyl)pentan-3-ol (1.50 g) was dissolved in 10 mL of hexane, cooled in an ice bath, and oxidized with 0.65 g (6.0 mmol) of *tert*-butyl hypochlorite. The resulting yellow precipitate (0.90 g, 55%) was filtered off and recrystallized from chloroform/hexane, yielding 0.65 g of 1-chloro-3,3-diethyl-*1H*-benzoiodoxole as pale yellow crystals, mp 109−111 °C. ^{1}H NMR (CDCl$_3$) δ/ppm 0.82 (t, *J* = 7.4 Hz, 6H), 1.86 (m, 4H), 7.03 (dd, *J* = 1.7, 7.3 Hz, 1H), 7.6 (m, 2H), 8.02 (dd, *J* = 1.3, 8.0 Hz, 1H). ^{13}C NMR (CDCl$_3$) δ/ppm 7.8 (CH$_3$), 34.4 (CH$_2$), 90.5 (C), 115.4 (C), 127.1 (CH), 128.3 (CH), 130.5 (CH), 130.6 (CH), 146.9 (C). Anal. Calcd for $C_{11}H_{14}ClIO$: C, 40.70; H, 4.35. Found: C, 40.59; H, 4.57.

3-(2-Iodophenyl)pentan-3-ol (10). Chloroiodoxole **10c** (0.65 g) was dissolved in 10 mL of methanol, and a solution of 0.32 g (2.5 mmol) of Na_2SO_3 in 5 mL of water was added under stirring. After 15 min the reaction mixture was diluted with diethyl ether and water. The organic layer was washed with water and dried with anhydrous sodium sulfate, and the solvent was evaporated under

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reduced pressure, yielding 0.55 g (95%, or 38% overall) of 3-(2-iodophenyl)pentan-3-ol as a colorless oil. ^{1}H NMR (CDCl$_3$) δ/ppm: 0.74 (t, J = 7.5 Hz, 6H), 1.83 (dq, J = 14, 7.5 Hz, 2H), 2.49 (dq, J = 14, 7.5 Hz, 2H), 6.87 (dt, J = 1.7, 7.6 Hz, 1H), 7.32 (dt, J = 1.3, 7.6 Hz, 1H), 7.67 (dd, J = 1.7, 7.9 Hz), 7.96 (dd, J = 1.3, 7.8 Hz, 1H). ^{13}C NMR (CDCl$_3$) δ/ppm 7.8 (CH$_3$), 32.1 (CH$_2$), 78.5 (C), 92.9 (C), 127.7 (CH), 128.3 (CH), 129.1 (CH), 142.7 (CH), 146.1 (C). MS, EI, m/z (%) 290 (M$^+$, 1), 261 (100), 133 (12), 116 (18), 105 (26), 91 (32), 77 (36), 57 (78). Anal. Calcd for C$_{11}$H$_{15}$IO: C, 45.55; H, 5.21. Found: C, 45.57; H, 5.45.

3-(2-Aminophenyl)-2,4-dimethylpentan-3-ol (11b). Magnesium (1.22 g, 50 mmol) was dissolved in a solution of 6.77 g (55 mmol) of 2-bromopropane in 20 mL of dry diethyl ether. The resulting solution was diluted with 20 mL of benzene and 3.02 g (20 mmol) of methyl 2-aminobenzoate in 10 mL of benzene was added. The reaction mixture was stirred at room temperature for 1 h and neutralized with 25 mL of 1 M aqueous citric acid. The organic layer was washed with sodium hydrogen carbonate and water and dried with anhydrous sodium sulfate, and the solvent was evaporated under reduced pressure. The resulting oil was crystallized from methyl *tert*-butyl ether/hexane, and 1.96 g (47%) of slightly impure 3-(2-aminophenyl)-2,4-dimethylpentan-3-ol (6) was obtained. An analytical sample was recrystallized from petroleum ether/dichloromethane and white crystals with mp 82−83 °C were obtained. ^{1}H NMR (CDCl$_3$) δ/ppm 0.83 (d, J = 6.8 Hz, 6H), 0.96 (d, J = 6.7 Hz, 6H), 2.32 (septet, J = 6.8 Hz, 2H), 6.60 (m, 1H), 6.66 (m, 1H), 6.91 (m, 1H), 6.98 (m, 1H). ^{13}C NMR, CDCl$_3$, δ/ppm 16.5 (CH$_3$), 17.7 (CH$_3$), 35.6 (CH), 85.5 (C), 117.2 (CH), 118.8 (CH), 124.8 (C), 127.1 (CH), 128.6 (CH), 147.4 (C). MS, EI, m/z (%) 207 (M$^+$, 8), 164 (55), 146 (100), 131 (43), 120 (18). Anal. Calcd for C$_{13}$H$_{21}$NO: C, 75.32; H, 10.21; N, 6.76. Found: C, 75.32; H, 10.52; N, 7.07.

1-Chloro-3,3-diisopropyl-1H-benzoiodoxole (11c). Amino alcohol **11b** (1.12 g, 5.4 mmol) was dissolved in 1.2 mL of 8 M HBF$_4$ and 5 mL of water, and the solution was cooled to −5 °C in a salt/ice bath and diazotized with 0.40 g (5.7 mmol) of NaNO$_2$. After standing for 15 min at −5 °C, the diazotized mixture was poured into a suspension of CuI (made from 5 mmol of CuSO$_4$·5H$_2$O) in 5 g of KI and 10 mL of water. The mixture was warmed to approximately 80 °C, cooled, and extracted with diethyl ether. the organic layer was washed with aqueous Na$_2$SO$_3$ and water and dried with anhydrous sodium sulfate. After the evaporation of solvent, the resulting brown oil (1.30 g) was chromatographed over silica (hexane/ethyl acetate 3:1). An oily product (0.66 g) was dissolved in 5 mL of dichloromethane and oxidized with 0.30 g (2.8 mmol) of *tert*-butyl hypochlorite (room temperature, 1 h). After dilution with hexane and cooling, 0.42 g (24%) of 1-chloro-3,3-diisopropyl-1H-benzoiodoxole was filtered off as yellow crystals, melting range 137−156 °C.[45] ^{1}H NMR (CDCl$_3$) δ/ppm 0.84 (d, J = 6.7 Hz, 6H), 0.92 (d, J = 6.9 Hz, 6H), 2.31 (septet, J = 6.8 Hz, 2H), 7.12 (dd, J = 1.5, 7.5 Hz, 1H), 7.48−7.62 (m, 2H), 8.04 (dd, J = 0.9, 8.2 Hz, 1H). ^{13}C NMR (CDCl$_3$) δ/ppm 16.6 (CH$_3$), 17.7 (CH$_3$), 37.4 (CH), 94.6 (C), 115.6 (C), 127.6 (CH), 128.3 (CH), 130.2 (CH), 130.6 (CH), 145.5 (C). Anal Calcd for C$_{13}$H$_{18}$ClIO: C, 44.28; H, 5.14. Found: C, 44.00; H, 5.27.

3-(2-Iodophenyl)-2,4-dimethylpentan-3-ol (11). Chloroiodoxole **11c** (0.35 g) was suspended in 5 mL of methanol, and a solution of 0.15 g (1.2 mmol) of Na$_2$SO$_3$ and 0.10 g (1.2 mmol) of sodium hydrogen carbonate in 5 mL of water was added under stirring at room temperature. After 10 min, 20 mL of diethyl ether was added, the organic layer was washed three times with water and dried with anhydrous sodium sulfate, and the solvent was evaporated under reduced pressure. The yield of oily 3-(2-iodophenyl)-2,4-dimethylpentan-3-ol was 0.30 g (94%). ^{1}H NMR (CDCl$_3$) δ/ ppm 0.78 (d, J = 6.8 Hz, 6H), 0.97 (d, J = 7.4 Hz, 6H), 1.9 (br s, 1H), 2.5 (br s, 2H), 6.84 (t, J = 8.4 Hz, 1H), 7.29 (t, J = 7.0 Hz, 1H), 7.3

(br s, 1H), 8.00 (d, 7.9 Hz, 1H). ^{13}C NMR (CDCl$_3$) (at −40 °C, the compound exhibits two sets of peaks due to two rotamers; the major one is cited) δ/ppm 16.7 (CH$_3$), 17.5 (CH$_3$), 35.0 (CH), 81.1 (C), 92.7 (C), 126.8 (CH), 127.9 (CH), 128.8 (CH), 141.3 (C), 143.6 (CH). MS, EI, m/z (%) 318 (M$^+$, 0.1), 275 (80), 231 (7), 105 (100), 77 (17), 43 (23). Anal. Calcd for C$_{13}$H$_{19}$IO: C, 49.12; H, 6.01. Found: C, 49.07; H, 6.39.

1,1,1-Trifluoro-2-phenylpropan-2-ol (12b). Methylmagnesium bromide in diethyl ether (4 mL of 3 M solution, 12 mmol) was diluted with 4 mL of dry diethyl ether in a three-necked flask under argon. The solution was cooled in an ice bath and a solution of 1.74 g (10 mmol) of trifluoroacetophenone in 5 mL of ether was slowly added. The reaction mixture was stirred for 30 min and quenched with aqueous citric acid. The organic layer was washed twice with water and dried with anhydrous sodium sulfate, and the solvent was evaporated under reduced pressure. A colorless oil (1.73 g, 91%) remained, which was revealed by GC and ^{1}H NMR to be pure **12b**.[46]

1-Chloro-3-methyl-3-trifluoromethyl-1H-benzoiodoxole (12c). Butyllithium (13.0 mL of 1.6 M solution in hexane, 21 mmol) was placed in a three-necked flask, 0.58 g (5.0 mmol) of TMEDA was added, ant the mixture was stirred under argon at room temperature. After 30 min, a solution of 1.71 g (9,0 mmol) of **12b** in 1.5 mL of THF was slowly added, and the resulting mixture was stirred for 20 h at room temperature. Solid iodine (2.54 g, 10.0 mmol) was then added, and after 20 min the reaction mixture was diluted with diethyl ether, washed with aqueous citric acid, sodium thiosulfate, and water, and dried with anhydrous sodium sulfate. GC showed 36% of the desired iodo alcohol in the reaction mixture, which was chromatographed (silica, CH$_2$Cl$_2$) and 455 mg of crude iodo alcohol (**12**) was isolated. The crude **12** was dissolved in 1 mL of chloroform, and 200 mg (1.9 mmol) of *tert*-butyl hypochlorite was added. The mixture was allowed to stand at room temperature for 30 min, diluted with 2 mL of hexane, and cooled in the freezer, and 307 mg (10%) of yellow crystals were filtered off, mp 117−119 °C. ^{1}H NMR (CDCl$_3$) δ/ppm 1.73 (q, J = 1.0 Hz, 3H), 7.39 (m, 1H), 7.64 (dt, J = 1.0, 7.4 Hz, 1H), 7.71 (ddd, J = 1.6, 7.4, 8.4 Hz, 1H), 8.05 (dd, J = 1.0, 8.4 Hz, 1H). ^{13}C NMR (CDCl$_3$) δ/ppm 23.3 (CH$_3$), 84.1 (q, $^2J_{F-C}$ = 29.6 Hz, C), 114.3 (C), 125.9 (q, $^1J_{F-C}$ = 288.3 Hz, CF$_3$), 128.3 (CH), 128.8 (m, CH), 131.2 (CH), 132.3 (CH), 140.2 (C). Anal. Calcd for C$_9$H$_7$ClF$_3$IO: C, 30.84; H, 2.01. Found: C, 30.85; H, 2.08.

1,1,1-Trifluoro-2-(2-iodophenyl)propan-2-ol (12). Chloroiodoxole **12c** (344 mg, 0.98 mmol) was dispersed in 3 mL of methanol, and a solution of 140 mg (1.1 mmol) of Na$_2$SO$_3$ and 85 mg (1 mmol) of NaHCO$_3$ in 3 mL of water was added under stirring. After 10 min the reaction mixture was diluted with diethyl ether, washed with water, and dried, and the solvent was evaporated under reduced pressure. The resulting oil was purified by column chromatography (silica, CH$_2$Cl$_2$) and 246 mg (79%) of **12** was obtained as a colorless oil. ^{1}H NMR (CDCl$_3$) δ/ppm 1.92 (q, J = 1.2 Hz, 3H), 3.36 (s, 1H), 6.99 (ddd, J = 1.7, 7.3, 7.9 Hz, 1H), 7.37 (ddd, J = 1.4, 7.3, 8.1 Hz, 1H), 7.53 (dm, J = 8.1 Hz, 1H), 8.04 (dd, J = 1.3, 7.9 Hz, 1H). ^{13}C NMR (CDCl$_3$) δ/ppm 23.6 (CH$_3$), 76.6 (q, $^2J_{F-C}$ = 29.1 Hz, C), 92.1 (C), 125.7 (q, $^1J_{F-C}$ = 286.8 Hz, CF$_3$), 128.0 (CH), 129.3 (q, $^3J_{F-C}$ = 2.4 Hz, CH), 130.1 (CH), 138.8 (C), 143.7 (CH). MS, EI, m/z (%) 316 (M$^+$, 52), 247 (100), 231 (14), 127 (10), 105 (22), 77 (19), 43 (62). Anal. Calcd for C$_9$H$_8$F$_3$IO: C, 34.20; H, 2.55 Found: C, 34.47; H, 2.63.

1,1,1-Trifluoro-3,3-dimethyl-2-phenylbutan-2-ol (13b). *tert*-Butylmagnesium chloride in diethyl ether (15 mL of a 2 M solution) was put in a three-necked flask under argon and cooled in an ice bath, and a solution of 3.48 g (20 mmol) of trifluoroacetophenone in 10 mL of diethyl ether was slowly added under stirring. The mixture was stirred for 1 h at room temperature, diluted with ether and aqueous citric acid, and washed with water. The organic layer

(45) Spectroscopically pure compound (NMR, elemental analysis) exhibits an unusually broad melting range, measured on various instruments.

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was transferred to a distillation apparatus together with 100 mL of water and distilled. The distillate was extracted with petroleum ether, the organic layer was dried with anhydrous sodium sulfate, the solvent was evaporated under reduced pressure, and 2.37 g of the yellow oil was obtained. A part (1.10 g) of the above oil was chromatographed (silica, CH_2Cl_2/petroleum ether 1:1) and 633 mg (29%) of pure **13b** was isolated as a colorless oil. ^{1}H NMR (CDCl$_3$) δ/ppm 1.04 (q, $^5J_{F-H}$ = 1.2 Hz, 9H), 2.5 (br s, 1H), 7.36 (m, 3H), 7.58 (m, 2H). ^{13}C NMR (CDCl$_3$) δ/ppm 26.3 (q, $^4J_{F-C}$ = 2.2 Hz, CH$_3$), 37.9 (C), 81.8 (q, $^2J_{F-C}$ = 25.8 Hz, C), 126,92 (q, $^1J_{F-C}$ = 289.1 Hz, CF$_3$), 126,93 (CH), 127.5 (CH), 128.0 (CH), 137.1 (C). ^{19}F NMR (CDCl$_3$) δ/ppm −68.6 (s). MS, EI, m/z (%) 232 (M$^+$, 1), 175 (6), 105 (21), 77 (12), 57 (100). Anal. Calcd for $C_{12}H_{15}F_3O$: C, 62.06; H, 6.51 Found: C, 61.76; H, 6.41.

1-Chloro-3-(1,1-dimethylethyl)-3-trifluoromethyl-*1H*-benzo-iodoxole (13c). TMEDA (0.31 g, 2.5 mmol) and 5 mL of 1.6 M butyllithium solution in hexane were placed in a three-necked flask under argon, and the mixture was stirred for 30 min. To this was added 620 mg of **13b** in 1 mL of pentane, and the resulting mixture was stirred for 20 h at room temperature, then cooled in an ice bath, and 2.0 g (8 mmol) of solid iodine was added. After 10 min, the mixture was diluted with diethyl ether, washed with aqueous sodium sulfite, citric acid, and water, and dried with anhydrous sodium sulfate, and after evaporation of solvent, 607 mg of a brown oil was obtained. The crude product was chromatographed on silica (CH$_2$Cl$_2$/petroleum ether 1:1.5), and 155 mg of impure iodo alcohol was isolated. This product was dissolved in 0.5 mL of hexane and treated with 110 mg (1 mmol) of *tert*-butyl hypochlorite at room temperature. Upon cooling, 95 mg (9%) of **13c** as a yellow precipitate was filtered off: mp 94−122 °C.[45] ^{1}H NMR (CDCl$_3$) δ/ppm 1.11 (q, $^5J_{F-H}$ = 1.1 Hz, 9H), 7.61 (m, 2H), 7.71 (m, 1H), 8.07 (d, J = 8.4 Hz, 1H). ^{13}C NMR (CDCl$_3$) δ/ppm 26.5 (q, $^4J_{F-C}$ = 1.8 Hz, CH$_3$), 41.6 (q, $^3J_{F-C}$ = 1.0 Hz, C), 91.0 (q, $^2J_{F-C}$ = 26.8 Hz, C), 114.4 (C), 126,4 (q, $^1J_{F-C}$ = 289.9 Hz, CF$_3$), 128.3 (CH), 129.7 (q, J = 2.5 Hz, CH), 130.3 (CH), 132.0 (CH), 139.1 (C). ^{19}F NMR (CDCl$_3$) δ/ppm −70.63 (s). MS, EI, m/z (%) 395 (M$^+$ + 3, 0.1), 393 (M$^+$ + 1, 0.3), 357 (2), 335 (34), 300 (65), 231 (100), 203 (45), 127 (6), 123 (20), 76 (46), 69 (10), 57 (97). Anal. Calcd for $C_{12}H_{13}ClF_3IO$: C, 36.71; H, 3.34 Found: C, 36.80; H, 3.58.

1,1,1-Trifluoro-3,3-dimethyl-2-(2-iodophenyl)butan-2-ol (13). Compound **13c** (80 mg, 0.20 mmol) was dissolved in 1 mL of methanol, and a solution of 25 mg (11 mmol) of K$_2$S$_2$O$_5$ in 0.5 mL of water was added under stirring at room temperature. After 20 min, the mixture was diluted with diethyl ether and water, the organic layer was washed with water and dried, and after evaporation of the solvent, 63 mg (86%, 2.2% overall) of **13** as a colorless oil was obtained. ^{1}H NMR (CDCl$_3$) δ/ppm 1.13 (q, $^5J_{F-H}$ = 1.1 Hz, 9H), 2.8 (br s, 1H), 6.95 (ddd, J = 1.5, 7.2, 7.9 Hz, 1H), 7.33 (ddd, J = 1.5, 7.2, 8.5 Hz, 1H), 7.50 (m, 1H), 8.10 (dd, J = 1.5, 8.0 Hz, 1H). ^{13}C NMR (CDCl$_3$) δ/ppm 26.8 (q, $^4J_{F-C}$ = 2.3 Hz, CH$_3$), 40.2 (C), 83.2 (q, $^2J_{F-C}$ = 25.3 Hz, C), 91.5 (C), 126.6 (q, $^1J_{F-C}$ = 290.6 Hz, CF$_3$), 126.6 (CH), 129.5 (CH), 130.2 (q, J = 4.4 Hz, CH) 136.0 (C), 144.7 (CH). ^{19}F NMR (CDCl$_3$) δ/ppm −67.07 (s). MS, EI, m/z (%) 358 (M$^+$, 0.5), 302 (6), 231 (15), 203 (4), 127 (2), 105 (8), 77 (10), 57 (100). Anal. Calcd for $C_{12}H_{14}F_3IO$: C, 40.24; H, 3.94 Found: C, 40.37; H, 4.07.

1,1,1,3,3,3-Hexafluoro-2-(2-iodophenyl)-2-methoxypropane (14a). Sodium hydride (0,11 g, 3.9 mmol, 85% dispersion in mineral oil) was placed in a V vial and washed with pentane and anhydrous diethyl ether. Hydride was diluted with 1 mL of dry THF, and 810 mg (2.2 mmol) of **14** was slowly added under stirring. After evolution of gas ceased, 1.0 mL of methyl iodide was added, and the vial was capped and placed into a sand bath with a temperature of approximately 50 °C. After 2 days (when GC showed complete conversion of the starting alcohol), the reaction mixture was diluted with diethyl ether and washed with aqueous citric acid and water, and the organic layer was dried with anhydrous sodium sulfate. After evaporation of the solvent under reduced pressure, 318 mg (38%) of colorless oil remained, which crystallized in a refrigerator.

Recrystallization from hexane yielded 246 mg (29%) of colorless crystals, mp 32−33.5 °C. ^{1}H NMR (CDCl$_3$) δ/ppm 3.54 (septet, J = 1.1 Hz, 3H), 7.08 (ddd, J = 1.6, 7.3, 8.0 Hz, 1H), 7.43 (ddd, J = 1.4, 7.3, 8.1 Hz, 1H), 7.55 (br d, J = 8.1 Hz, 1H), 8.19 (dd, J = 1.4, 8.0 Hz, 1H). ^{13}C NMR (CDCl$_3$) δ/ppm 54.9 (CH$_3$), 84.1 (septet, $^2J_{F-C}$ = 28.1 Hz, C), 92.4 (C), 122.5 (q, $^1J_{F-C}$ = 292.6 Hz, CF$_3$), 128.0 (CH), 129.1 (C), 131.3 (CH), 131.5 (CH), 145.2 (CH). MS, EI, m/z (%) 384 (M$^+$, 80), 315 (100), 231 (34), 207 (16), 157 (17), 145 (17), 127 (39), 123 (85), 107 (11), 91 (16), 69 (22). Anal. Calcd for $C_{10}H_7F_6IO$: C, 31.27; H, 1.81. Found: C, 31.14; H, 1.85.

1,1,1,3,3,3-Hexafluoro-2-(2-iodo-5-methylphenyl)-2-methoxypropane (15a). Sodium hydride (80% suspension in mineral oil, 67 mg, 2.2 mmol) was washed with pentane and dry diethyl ether in a V vial and diluted with 1 mL of dry ether. After cooling in an ice bath, 384 mg of alcohol **5a** was added, followed by 0.7 mL (11 mmol) of iodomethane. The vial was capped and stirred for 5 days at approximately 35 °C. The reaction mixture was diluted with ether, washed twice with water, and dried with anhydrous sodium sulfate, and the solvent was evaporated under reduced pressure. The white, crystalline product (360 mg, 90%) was recrystallized from methanol and 223 mg (56%) of white needles (mp 72.5−73.5 °C) were isolated. ^{1}H NMR (CDCl$_3$) δ/ppm 2.34 (s, 3H), 3.53 (m, 3H), 6.91 (dd, J = 1.7, 8.1 Hz, 1H), 7.32 (br s, 1H), 8.04 (d, 8.1 Hz, 1H). ^{13}C NMR (CDCl$_3$) δ/ppm 21.1 (CH$_3$), 54.9 (CH$_3$), 84.1 (septet, $^2J_{F-C}$ = 28.1 Hz, C), 88.3 (C), 122.5 (q, $^1J_{F-C}$ = 292.1 Hz, CF$_3$), 128.8 (C), 132.2 (m, CH), 132.3 (CH), 138.2 (C), 144.8 (CH). ^{19}F NMR (CDCl$_3$) δ/ppm −68.6 (s). MS, EI, m/z (%) 398 (M$^+$, 90), 329 (100), 245 (45), 151 (31), 137 (93), 127 (11), 90 (22), 69 (16), 63 (17). Anal. Calcd for $C_{11}H_9F_6IO$: C, 33.19; H, 2.28. Found: C, 33.01; H, 2.24.

Computations. All HF and DFT calculations were carried out on Gaussian 03[47] except for the transition state Ph-I-Me, which were carried out on Jaguar 6.5, Schrodinger, LLC, New York, 2005. Initial optimizations on semiempirical level were made by Hyper-Chem (Hypercube Inc., release 6.0) package. Energies of formation and zero-point vibrational energies were calculated on fully optimized structures by use of B3LYP/6-31G(d,p) and Lanl2mb basis sets for iodine. Transition states were optimized by standard methods at the B3LYP/6-31G(d,p) (Gaussian) or MPW1K/ LACV3P** (Jaguar) level of theory.

Kinetic Measurements. In a typical experiment, a reaction mixture made up of substituted iodobenzene (15 mM), tetrachloromethane (50 mM), bromobenzene (internal standard, 20 mM), and DBPO (1 mM) in argon-purged cyclohexane was filled under argon atmosphere into glass ampules (three for each point) and sealed (the amounts of tetrachloromethane and the initiator were varied, depending on the reactivity of substrate). Ampules were heated in a water bath thermostat at various temperatures (35−71 °C) for at least 10 half-lives of the initiator at that temperature. The amounts of iodocyclohexane and chlorocyclohexane formed were then measured by GC. Relative rates $k(1)/k(Cl)$ were calculated by using the integrated rate equation $k(1)/k(Cl) = \ln [(A − X)/A]/$

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ln $[(B - Y)/B]$, where A is the amount of the substituted iodobenzene, B is the amount of tetrachloromethane at the beginning of the reaction, and X and Y are the amounts of the corresponding halocyclohexanes at the end of the reaction. Each set of measurements was repeated 2−3 times with independently prepared reaction mixtures of different composition.

Supporting Information Available: Geometries and energies of compounds referenced, geometries and atomic charges for model transition states, and crystal structure data for compounds **6** and **15**. This material is available free of charge via the Internet at http://pubs.acs.org.

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