Pergamon

Tetrahedron Letters 43 (2002) 1333–1335

TETRAHEDRON
LETTERS

First examples of superelectrophile initiated iodination of alkanes and cycloalkanes

Irena Akhrem,* Alexander Orlinkov, Sergei Vitt and Anatolii Chistyakov

A.N. Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences, 119991 Moscow, GSP-1, 28 Vavilova st., Russia

Received 29 October 2001; revised 7 December 2001; accepted 13 December 2001

Abstract—Direct iodination of alkanes and cycloalkanes in the presence of superelectrophiles has been accomplished for the first time. The reactions of saturated hydrocarbons with I_2 in the presence of $CCl_4 \cdot 2AlI_3$ at −20°C afforded monoiodides in good yields and selectivities. © 2002 Elsevier Science Ltd. All rights reserved.

Elaboration of one-pot selective transformations of alkanes and cycloalkanes into their functionalized derivatives is a topic of current interest.[1] In recent years, topics for study have become not only thermodynamically favorable reactions of alkanes but also those occurring with consumption of energy.[2–5] Iodination of saturated hydrocarbons is an example of this type of reaction.

The enthalpies of halogenation of propane, E_t and E_t^0 (zero-point energy) in kcal/mol, which we have calculated by a DFT-PBE method,[6] are as follows:

$$C_3H_8+X_2 \longrightarrow {}^iC_3H_7X+HX \qquad (1)$$

$E_t = -105.3$ ($E_t^0 = -106.5$), X = F; −28.5 (−31.0), X = Cl; −8.9 (−12.3), X = Br; 10.2 (3.3), X = I.

These calculations show that fluorination, chlorination and bromination are exothermic with enthalpies decreasing by 3- and 10-fold on passing from the reaction with F_2 to those with Cl_2 and Br_2, respectively. In contrast, iodination is endothermic. Nevertheless, the free-radical iodination of alkanes and cycloalkanes has been performed in photo-induced reactions using either the ^{t}BuCOI/$HgCl_2$ system as a source of *tert*-butylhypoiodide[3], or a mixture of I_2/Cl_2 serving as a donor of the ICl species.[4] Recently, a promising method has been reported for the preparation of monoiodides from saturated hydrocarbons by the reaction with CH_2I_2/solid NaOH.[5]

The substitution of a hydrocarbon hydrogen by iodine in electrophilic reactions has been feasible only for aromatics.[7–13] Most typically, iodinating systems were based on I_2 combined with oxidizing agents[7–12] (Ag^+ salts,[7] $(NH_4)_2S_2O_8$,[8] $NO^+\,BF_4^-$,[9] Ce^{10}) and iodosuccinimide in CF_3SO_3H.[13] The latter system will even iodinate deactivated aromatics effectively. The $CF_3SO_2OI^+\,[CF_3SO_3]^-$ complex is assumed to be responsible for the high activity of this system.[13] Electrophile-initiated iodination of alkanes and cycloalkanes has not been previously described.

This work reports the first one-pot transformations of alkanes and cycloalkanes into the corresponding monoiodides in the presence of superelectrophilic systems, $CX_4 \cdot 2AlI_3$ (X = Cl, Br). At −20°C propane, mono-, bi- and tricycloalkanes react with I_2 in the presence of equimolar amounts of the $CX_4 \cdot 2AlI_3$ complexes in CH_2Br_2 to give the corresponding monoiodides in 50–80% yields after 1.5–2 h (Table 1).

$$RH+I_2 \xrightarrow[-20°C]{CCl_4 \cdot 2AlI_3} RI$$

RH = propane, cyclopentane, cyclohexane, norbornane, adamantane.

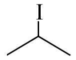
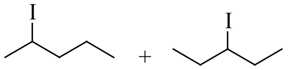
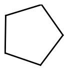
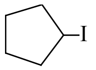
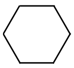
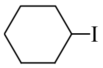
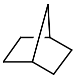
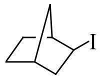
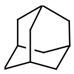
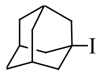
All reactions (except for the case of *n*-pentane) give rise to a single isomer, while diiodides and bromides are absent or produced in trace amounts only. The iodination of *n*-pentane is less effective, since it affords a 2:1 mixture of two isomers in a total yield of 19%. At −40°C, the yields of monoiodides decreases to 10% and at 0°C these reactions become unselective. At the stoichiometric I_2/CX_4 ratio, CX_4 is quantitatively reduced into CHX_3.

---

* Corresponding author. Fax: 7 (095) 1355085; e-mail: cmoc@ineos.ac.ru

0040-4039/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0040-4039(01)02371-1

Table 1. Ionic iodination of alkanes and cycloalkanes (RH) with I_2 in the presence of the $CCl_4{\cdot}2AlI_3$ system in CH_2Br_2; molar ratio of $I_2/CCl_4=1$, −20°C, 1.5–2 h

ALKANE (RH)	PRODUCT	YIELD, mol %
Propane		50
n-Pentane		19[a]
		66 39[b] 64[c] 4[d] 0[e]
		75
		78
		79

[a]Two isomers in a 2:1 ratio are formed; [b]In the absence of I_2; [c]Reaction with the $CBr_4{\cdot}2AlI_3$ system; [d]Reaction with the I_2-CCl_4-AlI_3 (1:1:1) system; [e]In the absence of CCl_4

The systems $CX_4{\cdot}2AlI_3$ (X = Cl, Br) turned out to be unique since aluminum iodide alone (in the absence of CX_4) does not initiate iodination of alkanes and cycloalkanes with I_2. At the same time, the $CCl_4{\cdot}2AlI_3$ complex itself (without I_2) causes iodination of cyclopentane, although the yield of cyclopentyl iodide is two times lower as compared with that for the run with I_2+$CCl_4{\cdot}2AlI_3$. The use of the $CCl_4{\cdot}2AlBr_3$ complex instead of $CCl_4{\cdot}2AlI_3$ completely suppresses the iodination by I_2 with the corresponding bromides becoming the products of the reactions.

The following scheme can be suggested for the iodination of alkanes and cycloalkanes.

(i) Generation of a carbocation:

$$CCl_4 \xrightarrow{AlI_3} CCl_3{}^+\,AlI_3Cl^- \xrightarrow{AlI_3} CCl_3{}^+\,Al_2I_6Cl^-$$

$$RH + CCl_3{}^+\,Al_2I_6Cl^- \longrightarrow R^+\,Al_2I_6Cl^- + CCl_3H$$

(ii) Iodination in the absence of I_2:

$$R^+\,Al_2I_6Cl^- \longrightarrow RI + Al_2I_5Cl$$

(iii) Iodination in the presence of I_2:

$$\begin{array}{ccccc} R^+\,Al_2I_6Cl^- + I_2 & \longrightarrow & RI & + & I^+\,Al_2I_6Cl^- \\ & & & & \upharpoonleft\downharpoonright \\ & & & & I_2 + Al_2I_5C \end{array}$$

According to the above scheme, the $CX_3{}^+\,Al_2I_6Cl^-$ cationic complex[14] abstracts hydride to afford a carbocation. The latter immediately captures an iodide anion either from the $Al_2I_6Cl^-$ anion or the I_2 molecule. Therefore, this reaction can be considered as a superelectrophile-initiated nucleophilic substitution of an alkane (cycloalkane) hydrogen by iodide. In this respect, it is noteworthy that the above calculations seem to exclude the alternative mechanism of the direct electrophilic iodination, and in fact, the formation of alkyl iodides was not observed in the reaction of alkanes with the I_2/Al_2I_6 system.

Earlier we have found that $I_2{\cdot}2AlBr_3$ can promote an effective cracking of *n*-octane at 20°C.[15] Aluminum iodide is known to be the most powerful Lewis acid among the aluminum halides.[16] Therefore, the $I_2{\cdot}2AlI_3$ complex obviously belongs to the category of superelectrophilic systems. However, the results of the present work indicate that the two types of superelectrophilic systems, i.e. $CCl_4{\cdot}2AlI_3$ and $Hal_2{\cdot}2AlI_3$, differ considerably in activities at −20°C. The lower activity of $CCl_4{\cdot}2AlI_3$ compared with that of $I_2/CCl_4{\cdot}2AlI_3$ is probably due to the rapid I/Cl exchange between Al_2I_6 and CCl_4 (or its reduced forms). As a result, more favorable chlorination occurs rather than iodination due to the increased chlorine content in the mixed $Al_2I_nCl_{6-n}$ species. Similarly, the $I_2/CCl_4{\cdot}2AlBr_3$ system acts as a brominating agent only.

The DFT-PBE quantum-chemical calculations[6] revealed that, in contrast to the endothermic nature of reaction (1), the iodination of propane by the $I_2/CCl_4 \cdot 2AlI_3$ system, reaction (2), becomes exothermic by −16.5 kcal/mol:

$$C_3H_8 + CCl_4 + Al_2I_6 \longrightarrow {}^{i}C_3H_7I + CHCl_3 + Al_2I_5Cl \qquad (2)$$

$E_t = -16.5$ kcal/mol ($E_t^0 = -17.1$).

In conclusion, the one-pot selective transformations of propane and cycloalkanes into monoiodides by superelectrophiles has been performed for the first time.

1. Experimental

CCl_4 (0.13 g; 0.85 mmol) was added to a pre-cooled (−30°C) stirred solution of 0.7 g (1.7 mmol) of anhydrous AlI_3 in 2.5 mL of CH_2Cl_2. Then 0.22 g (0.85 mmol) of powdered iodine was introduced and the mixture was allowed to warm to −20°C. After 10 min the reaction flask was connected to a source of gaseous propane (or alternatively, 6.0 mmol of the corresponding liquid hydrocarbon was added to the reaction mixture). The reaction mixture was stirred at −20°C for 1.5 h and was then treated with a cooled aqueous solution of Na_2SO_3. The products were carefully extracted with ether, the ether extracts were washed with diluted $NaHCO_3$ solution, dried with $CaCl_2$ and analyzed by gas chromatography (GC) and GC-mass spectrometry (MS) using *n*-amyl iodide (or *n*-heptyl iodide) as internal standards. For nuclear magnetic resonance (NMR) studies, ether and other light products were distilled from the ether extracts.

1.1. Selected spectral data

Mass spectra; m/z (I, %): 2-iodopropane; 170 (M^+, 24), 127 (4), 43 (100), 41 (28), 27 (26); iodocyclopentane; 196 (M^+, 8), 127 (20), 69 (100), 67 (57), 68 (17); iodocyclohexane; 210 (M^+, 7), 127 (9), 83 (100), 55 (87), 67 (50), 54 (34); 2-iodonorbornane: 254 (M^+, 1), 127 (41), 95 (99), 94 (26), 79 (64), 78 (26), 67 (48), 66 (100); 1-iodoadamantane: 135 (100), 127 (12), 93 (24), 79 (34), 77 (16), 67 (18), 55 (12). ^{13}C NMR; δ, ppm: 2-iodonorbornane, 15.16 (CHI), 28.37, 28.61, 36.21, 37.86 (CH_2), 45.06, 47.84 (CH).

Acknowledgements

This work was supported by the Russian Foundation of Basic Research (Grant Nos. 99-03-33006 and 01-03-32105).

References

1. (a) Hill, C. L. *Activation and Functionalization of Alkanes*; Wiley-Interscience: New York, 1989; (b) Olah, G. A.; Prakash, G. K. S. In *The Chemistry of Alkanes and Cycloalkanes*; Patai, S.; Rappoport, Z., Eds.; Wiley-Interscience: New York, 1992; pp. 609–651; (c) Bromberg, S. E.; Yang, W.; Asplund, M. C.; Lian, T.; McNamara, B. K.; Kotz, K. T.; Jeston, J. S.; Wilkens, M.; Frei, H.; Bergman, R. G.; Harris, C. B. *Science* **1997**, *278*, 260–263; (d) Crabtree, R. H. *Chem. Rev.* **1995**, *95*, 987–1007; (e) Sommer, J.; Bukala, J. *Acc. Chem. Res.* **1993**, *26*, 370–376; (f) Akhrem, I. S.; Orlinkov, A. V. *Russ. Chem. Bull.* **1998**, *47*, 771–795.
2. Akhrem, I. S.; Vitt, S. V.; Churilova, I. M.; Orlinkov, A. V. *Russ. Chem. Bull.* **1999**, *48*, 2279–2285.
3. Liquori, L.; Bjorsvik, H.-R.; Bravo, A.; Fontana, R.; Miniski, F. *J. Chem. Soc., Chem. Commun.* **1997**, 1501–1502.
4. (a) Tanner, D. D.; Gidley, G. C. *J. Am. Chem. Soc.* **1968**, *90*, 808–809; (b) Tanner, D. D.; Rowe, J. E.; Potter, A. *J. Org. Chem.* **1986**, *51*, 457–460.
5. Schreiner, P. R.; Lauenstein, O.; Butova, E. D.; Fokin, A. A. *Angew. Chem., Int. Ed.* **1999**, *38*, 2786–2788.
6. The calculations were performed using the program 'PRIRODA' (version 1-10) reported in (a) Perdew, J. P.; Burke, K.; Ernzerhof, M. *Phys. Rev. Lett.* **1996**, *11*, 3865–3868; (b) Laikov, D. DFT2000—*Satellite Symp. 10th International Congress Quantum Chemistry*, Menton, 11–14 June 2000; (c) Laikov, D. N. *Chem. Phys. Lett.* **1997**, *281*, 151–156. Calculated total energies of molecules (E_t a.u.) participating in the reactions (1) and (2) are as follows: C_3H_8 (119.0595); CCl_4 (1884.0924); $CHCl_3$ (1423.1972); ${}^{i}C_3H_7F$ (218.3801); ${}^{i}C_3H_7Cl$ (579.9753); ${}^{i}C_3H_7Br$ (2724.9965); ${}^{i}C_3H_7I$ (7235.9160); F_2 (199.6069); Cl_2 (922.9777); Br_2 (5213.0482); I_2 (14234.9154); HF (100.4843); HCI (462.1074); HBr (2607.1254); HI (7118.04320); Al_2I_6 (43130.6255); $I_2Al(ICl)AlI_2$ (36534.6905); I_2AlI_2AlClI (36534.6904).
7. (a) Merkushev, E. B. *Russ. Chem. Rev.* **1984**, *53*, 343; (b) Merkushev, E. B. *Synthesis* **1988**, 923.
8. Wirth, H. O.; Konigstein, O.; Kern, W. *Liebigs Ann. Chem.* **1960**, *634*, 84–104.
9. Radner, F. *J. Org. Chem.* **1988**, *53*, 3548–3553 and references cited therein.
10. Sugiyama, T. *Bull. Chem. Soc. Jpn.* **1981**, *54*, 2847–2850.
11. Galli, G. *J. Org. Chem.* **1991**, *56*, 3238–3245.
12. Seevers, R. H.; Counsell, R. E. *Chem. Rev.* **1982**, *82*, 575–590.
13. Olah, G. A.; Wang, Q.; Sandford, G.; Prakash, G. K. S. *J. Org. Chem.* **1993**, *58*, 3194–3195.
14. The experimental data on $CX_4 \cdot nSbF_5$ systems: (a) Olah, G. A.; Heiliger, L.; Prakash, G. K. S. *J. Am. Chem. Soc.* **1989**, *111*, 8020–8021; (b) Vancik, H.; Perkas, C.; Sunko, D. E. *J. Am. Chem. Soc.* **1990**, *112*, 7418–7419.
   The calculations of polyhalomethyl cations and related systems: (a) Chistyakov, A. L.; Stankevich, I. V.; Akhrem, I. S.; Gambaryan, N. P.; Vol'pin, M. E. *Russ. Chem. Bull.* **1996**, *45*, 514–521; (b) Olah, G. A.; Rasul, G.; Yudin, A.; Burrichter, A.; Prakash, G. K. S.; Chistyakov, A. L.; Stankevich, I. V.; Akhrem, I. S.; Gambaryan, N. P.; Vol'pin, M. E. *J. Am. Chem. Soc.* **1996**, *118*, 1446–1451; (c) Akhrem, I. S.; Chistyakov, A. L.; Gambaryan, N. P.; Stankevich, I. V.; Vol'pin, M. E. *J. Organomet. Chem.* **1997**, *536*, 489–494; (d) Olah, G. A.; Rasul, G.; Heiliger, L.; Prakash, G. K. S. *J. Am. Chem. Soc.* **1996**, *118*, 3580–3583; (e) Franking, G.; Fau, S.; Marchandm, C. M.; Grutzmacher, H. *J. Am. Chem. Soc.* **1997**, *119*, 6648–6655.
15. Akhrem, I. S.; Afanas'eva, L. V.; Orlinkov, A. V.; Vol'pin, M. E. *Mendeleev Commun.* **1994**, *1*, 131–134.
16. Olah, G. A. *Friedel–Crafts and Related Reactions*; John Wiley & Sons: New York, 1963; Vol. 1, pp. 252–253.