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Substituent effects in addition of iodine thiocyanate to alkenes

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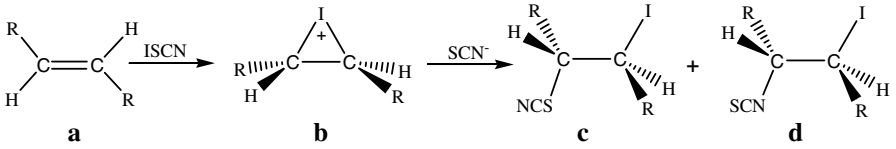
Abstract—The plots of logarithms of relative rates of ISCN addition to alkenes versus alkene IPs and versus alkene HOMO energies reveal that the alkene relative reactivity depends upon both electronic and steric effects of the substituents. Steric effects are related not only to the degree of substitution on the C=C bond but also to the relative position, size, and branching of alkyl substituents.

Organoiodine compounds play a significant role in many areas, such as, organic synthesis,[1] biochemistry,[2] biogeochemical reactions,[3] and environmental studies.[4] Adding I_2 to alkenes might initially seem to be a simple way to introduce iodine into an organic compound, but this reaction actually can only be carried out photochemically under very low temperatures (below −40 °C) to give diiodo products that are decomposed quickly at room temperature.[5,6] However, iodine incorporation is achievable via alkene addition of an iodine-containing compound, such as ICl,[7] IF,[8a] IN_3,[8b] INO_3,[8c] IOAc,[8d] INCO,[8e] ISeCN,[8f] and ISCN;[9] these are reported to undergo complete reaction under mild reaction conditions. One iodine-containing compound, which is often used in alkene addition, is ISCN.[9–13] Its reaction (Scheme 1) yields *vic*-iodothiocyanates **c** and *vic*-iodoisothiocyanates **d**, which are used as intermediates in synthesizing useful compounds, such as episulfides,[10,11] thiazolidin-2-ones,[12] 2-amino-2-thiazolines,[12] and 2-alkoxy-2-thiazolines.[13a]

The first step of ISCN addition to alkenes is proposed[13] to be the formation of a bridged iodonium ion intermediate **b**, which is generally believed[14] to be the rate-determining step of the reaction (Scheme 1). It is reported that intermediate **b** does not undergo complete ring-opening prior to anti attack by nucleophiles in the second step.[13] There seems to be general agreement regarding initial attack on C=C by electrophilic ISCN,[13] although controversy still exists about the exact species of nucleophile that attacks iodonium ion **b** in the second step and about the final anti addition product distribution.[13] Similarly to ISCN addition, additions of other iodine-containing compounds[7,8] to alkenes normally also yield vicinal anti addition products. Therefore, the reaction mechanisms of additions of these iodine-containing compounds might have some aspects in common and so further comparison may reveal additional similarities. Of the iodine-containing compounds listed above, there seem to be few kinetic studies on additions to a wide range of alkenes, but those of ISCN[15] and ICl[7] have been reported. We present here, the analysis of substituent effects upon alkene reactivity toward ISCN addition to alkenes and a comparison with ICl addition; this might provide useful information about the reaction mechanism, since detailed



Scheme 1. ISCN addition to alkenes.

Keywords: Iodine thiocyanate; Additions to alkenes; Correlations; Substituent effects.
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mechanistic studies about the title reaction are still somewhat scarce.

Alkene IPs, HOMO energy levels, and relative rates of ISCN and ICl additions to alkenes are listed in Table 1. Alkene HOMO energies were calculated,[17] because experimental IPs for some alkenes in Table 1 were not available in the literature. We report ab initio (HF level, 6-31G* basis set) values here because they correlated best versus alkene IPs, in our calculations by a variety of computational methods.[18c] Cyclic and aryl alkenes are excluded in order to avoid complications due to ring strain or conjugation with aryl groups. Figure 1a shows the plot of $\log k_{rel}$ values of ISCN addition to alkenes versus alkene IPs. The plot of $\log k_{rel}$ values versus alkene HOMO energies in Figure 1b is essentially analogous to that in Figure 1a. The overall trend of relative reactivity of alkenes shown in Figures 1a and b support the suggestion[14] that the rate-determining step of ISCN addition to alkenes is the first step, **a**→**b** in

Table 1. Alkene IPs, HOMO energies, and relative rates of ISCN and ICl additions to alkenes

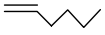
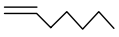
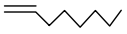
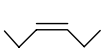
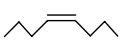
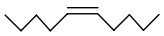
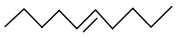
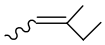
No.	Alkene	IP[a] (eV)	HOMO (eV)	$k_{rel,ISCN}$[b]	$k_{rel,ICl}$[c]
1		10.52	−10.19		2.28
2		9.74	−9.72		40.5
3		9.63	−9.70	121	100
4		9.51[d]	−9.65	105	
5		9.53	−9.70	40.0	190
6		9.48	−9.66	100	
7		9.46[e]	−9.67	36.0	
8		9.45	−9.66	47.0	
9		9.45	−9.65	24.0	34.2
10		9.44	−9.61	137	
11		9.43[f]	−9.61	137	
12		9.40	−9.59	21.0	
13		9.24	−9.39	1.53×10^3	1.12×10^3
14		9.15	−9.37	1.84×10^3	2.14×10^3
15		9.12	−9.26	790	2.91×10^3
16		9.12	−9.25	411	934
17		9.08	−9.36	1.32×10^3	
18		9.07	−9.34	1.21×10^3	1.55×10^3
19		9.04	−9.27		4.15×10^3
20		9.04	−9.21		1.80×10^3
21		9.02	−9.17	521	1.36×10^3
22		8.98	−9.28		2.27×10^3
23		8.97	−9.28		1.10×10^3
24		8.97	−9.27	495	
25		8.95	−9.27	895	
26		8.92	−9.27		4.61×10^3
27		8.91	−9.25		50.6
28		8.84	−9.22	684	

Table 1 (*continued*)

No.	Alkene	IP[a] (eV)	HOMO (eV)	$k_{rel,ISCN}$[b]	$k_{rel,ICl}$[c]
29		8.83	−9.23	305	
30		8.77	−9.20	790	
31		8.76	−9.21	390	
32		8.68	−8.86	3.21×10^3	1.88×10^4
33		8.60[g]	−8.99	3.68×10^3	
34		8.59[h]	−8.78	2.53×10^3	
35		8.27	−8.70		3.74×10^4

[a] Ref. 16a, unless otherwise noted.
[b] Ref. 15.
[c] Ref. 7a.
[d] IP for 1-decene used as an approximation. Ref. 16a.
[e] Estimated by applying to the IP for 1-pentene a correction factor, which is the difference between the IPs of *trans*-4-methyl-2-hexene and *trans*-2-hexene: 9.52 eV − (8.97 eV − 8.91 eV) = 9.46 eV. Ref. 16a.
[f] Ref. 16b.
[g] Estimated by applying to the IP for 2-methyl-2-butene a correction factor, which is the difference between the IPs of 2-butene and 2-pentene: 8.68 eV − (9.12 eV − 9.04 eV) = 8.60 eV. Ref. 16a.
[h] Estimated by applying to the IP for 2-methyl-2-butene a correction factor, which is the difference between IPs of 2-methyl-1-propene and 2-methyl-1-butene: 8.68 eV − (9.24 eV − 9.15 eV) = 8.59 eV. Ref. 16a.

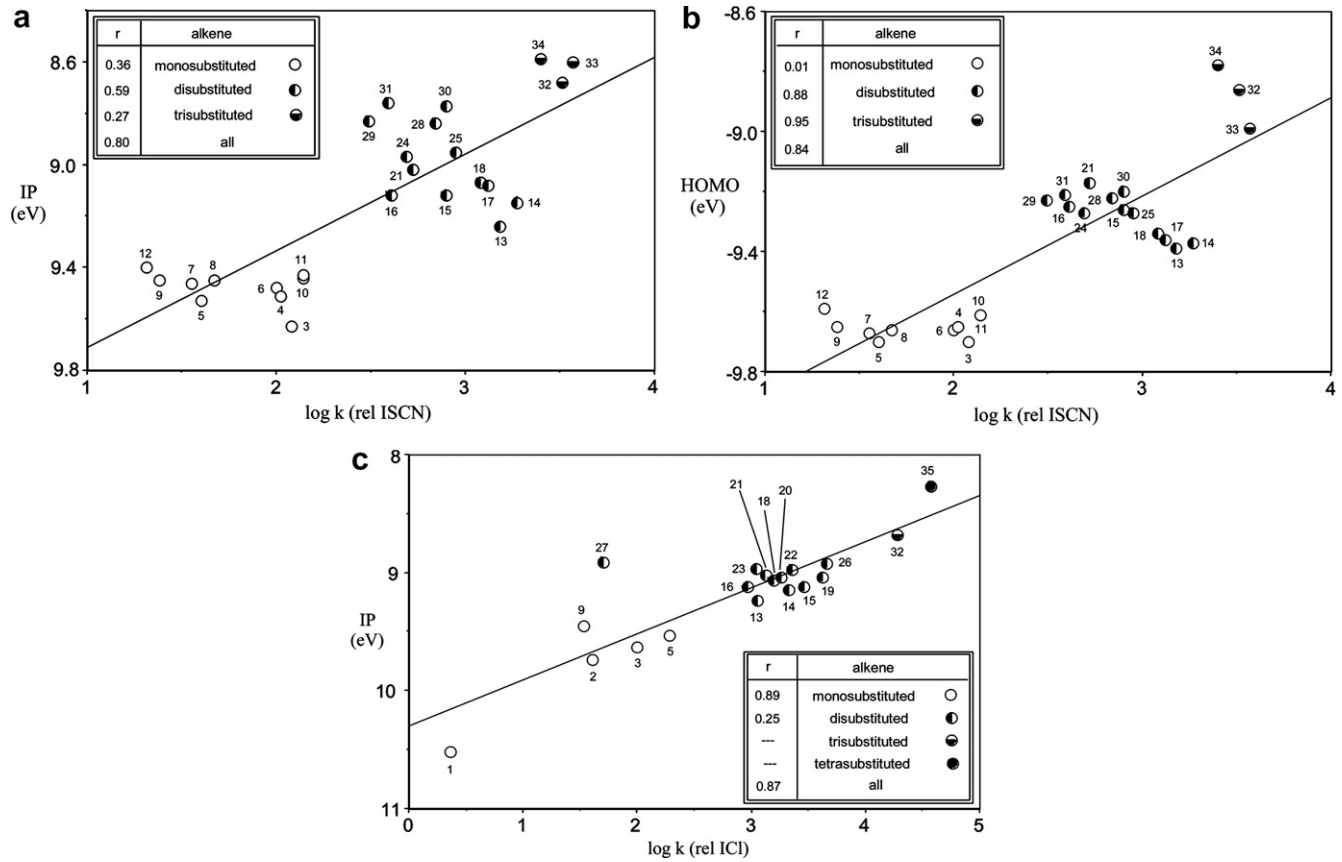


Figure 1. Plots of logarithms of relative rates of (a) ISCN addition to alkenes versus alkene IPs, (b) ISCN addition to alkenes versus alkene HOMO energies, and (c) ICl addition to alkenes versus alkene IPs. *Y*-Axis IP data are plotted in inverse order to facilitate comparison with the plot of HOMO energies. The data points in the plots are coded according to the steric similarities given by the number of alkyl groups attached to the double bond: mono-, di-, tri-, and tetrasubstituted.

Scheme 1, in which the alkene π bond is attacked by the electrophile ISCN to form a three-membered cyclic iodonium ion intermediate **b**. Increasing alkyl substitution on the alkenyl double bond increases the reaction rate, presumably due to the electron-donating electronic effects of the alkyl groups, rather than to steric effects, which should retard the reaction rate. This would be expected because enriching electron density on the alkenyl carbons makes their π electrons more loosely held and facilitates processes which remove or reduce π electron density. This manifests itself experimentally as a lower IP, as well as an increased rate of reaction with an electrophile.

The general pattern of relative reactivity of alkenes observed in ISCN addition has some similarities to our previous studies of electrophilic additions,[18a,b] which depended mainly upon electronic effects: (1) the relative rates of trisubstituted alkenes are greatest because they have the lowest IP values, (2) disubstituted alkenes react slower because they have higher IP values, and (3) the monosubstituted alkenes react slowest because they have the highest IP values. However, unlike those previous studies, the data points in the plots in Figures 1a and b do not fall on a correlation line neatly, but clearly cluster into three groups according to number of alkyl substituents on the C=C bond. Within each group, relative rates depend greatly upon position, size, and branching of alkyl substituents, as well as the alkene IP or HOMO energy values. For example, in ISCN addition to disubstituted alkenes, the ordering according to reaction rates produces further subgroups: geminal alkenes (**13**, **14**, **17**, and **18**) > vicinal *cis*-alkenes (**15**, **25**, **28**, and **30**) > vicinal *trans*-alkenes (**16**, **24**, **29**, and **31**). 2,3,3-Trimethyl-1-butene (**21**) reacts much slower than do other geminal alkenes probably due to the bulky *t*-butyl group, which may retard the reaction significantly. Similarly, the ordering of reaction rates of monosubstituted alkenes produces two subgroups: faster-reacting alkenes, each with a straight chain alkyl substituent (**3**, **4**, **6**, **10**, and **11**), and slower-reacting alkenes, each with a branched alkyl substituent (**5**, **7**, **8**, **9**, and **12**). The relationship between alkene reactivity and the position, size, and branching of its alkyl substituents in ISCN addition is quite different from what we observed in our previous studies.[18a,b] In those either (1) a single line of correlation among all alkenes regardless of the degree of substitution and of the positions and sizes of the substituents, or (2) multiple lines of correlation among similarly-substituted alkenes regardless of the positions and sizes of the substituents was obtained. Therefore, this study demonstrates that, in addition to the degree of substitution of the alkene C=C bonds, the position, size, and branching of substituents can be a major part of the total steric effects upon the reactivity in some alkene additions.

The plot of alkene IPs versus $\log k_{rel}$ values of ICl addition is given in Figure 1c. The overall trend here is similar to that shown in Figures 1a and b for ISCN additions, that is, the reaction rate increases as more alkyl substituents are introduced onto the C=C bond. However, the clustering and subgrouping of the data points observed in ISCN addition are less apparent here and $\log k_{rel}$ values correlate alkene IPs better in ICl addition than in ISCN addition. Additions of ICl,[7] Br_2,[19] and Cl_2,[19] are more complicated than ISCN addition; the proposed mechanism for each involves several steps. Therefore, one might expect a lower correlation in these reactions than in ISCN addition. Surprisingly, ISCN addition appears to have the worst correlation.[18b] Reasons which might account for the unexpected result include (1) the substituent effects are spread across multiple reaction steps in the addition of ICl, Br_2, and Cl_2 and (2) ISCN is lower in electrophilicity, but larger in size than those halogens, which enhances the relative importance of steric effects.

Acknowledgments

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