DIFFERENTIATION OF ELECTROPHILIC AND AMBIPHILIC CARBENES

Robert A. Moss[*] and Ramesh C. Munjal

Department of Chemistry, Rutgers, The State University of New Jersey,
New Brunswick, New Jersey, 08903

Summary: Comparative selectivities toward alkenes of CH_3CCl, CCl_2, and CH_3OCCl establish the former two carbenes as electrophiles; the latter is an ambiphile.

Methoxychlorocarbene is an ambiphile; it displays electrophilic selectivity toward electron-rich alkenes and nucleophilic selectivity toward electron-poor alkenes.[1] This unusual reactivity pattern serves as an operational definition of ambiphilicity,[2] but it is essential to demonstrate that the commonly encountered "electrophilic" carbenes do indeed exhibit characteristically different selectivities. In this Letter, appropriate demonstrations are made for dichlorocarbene and methylchlorocarbene.

We first require a convenient overview of carbenic selectivity or "philicity". We know that the selectivity of CXY toward a standard[3] alkene set follows eq. (1),[3] in which m_{CXY} is the least-squares slope of $\log(k_i/k_{isobutene})_{CXY}$ vs. $\log(k_i/k_{isobutene})_{CCl_2}$, and $\Sigma_{X,Y}$ represents the sum of the appropriate substituent constants[4] for X and Y.

$$m_{CXY} = -1.10\Sigma_{X,Y}\sigma_R^+ + 0.53\Sigma_{X,Y}\sigma_I - 0.31 \qquad (1)$$

Experimental[3] or calculated [from eq. (1)] values of m_{CXY} form a "carbene selectivity spectrum", Figure 1. (Carbenes positioned according to calculated m_{CXY}'s are shown in brackets.) Here, such apparently nucleophilic carbenes as $(CH_3O)_2C$[5] and $CH_3OCN(CH_3)_2$[6] have $m_{CXY} > 2.2$, whereas typically encountered "electrophiles" such as CCl_2[7] or CF_2[7] have $m_{CXY} < 1.5$. Ambiphilic[1] CH_3OCCl, $m^{calc} = 1.59$, resides in a transitional region. For comparisons with CH_3OCCl, we have chosen CCl_2 ($m = 1.00$), the reference carbene of eq. (1),[3] and CH_3CCl ($m = 0.50$). Figure 1 indicates these species to be electrophiles of moderate and low selectivity, respectively. Oddly enough, the literature[7] gives no account of their selectivities toward common electron-deficient alkenes,[8] a situation which must be remedied if their electrophilicity is truly to be tested.

CCl_2 was thermally generated ($80°$) from $PhHgCCl_2Br$,[9] a method which appears to involve direct carbene extrusion.[10] CH_3CCl was generated by photolysis ($\lambda > 300$ nm, $25°$) of 3-chloro-3-methyldiazirine.[11] The carbenes were added to $Me_2C=CMe_2$, $Me_2C=CH_2$, t-MeCH=CHMe, $CH_2=CHCOOMe$, and $CH_2=CHCN$; cyclopropane adducts were isolated by gc. The CCl_2 adducts were previously known[7,9] and their identities were confirmed by nmr spectroscopy. Adducts of CH_3CCl to the alkylethylenes were also known;[11] the new acrylonitrile and methyl acrylate adducts were characterized by their elemental analyses and nmr spectra.

CCl_2 and CH_3CCl were generated in large excesses of selected binary alkene mixtures. Quantitative gc analysis (calibrated tc detector) of the product cyclopropanes, coupled with competition reaction analysis,[7] gave the primary relative reactivities summarized in Table I. These

Table I. Measured Relative Reactivities of CCl_2 ($80°$) and CH_3CCl ($25°$)

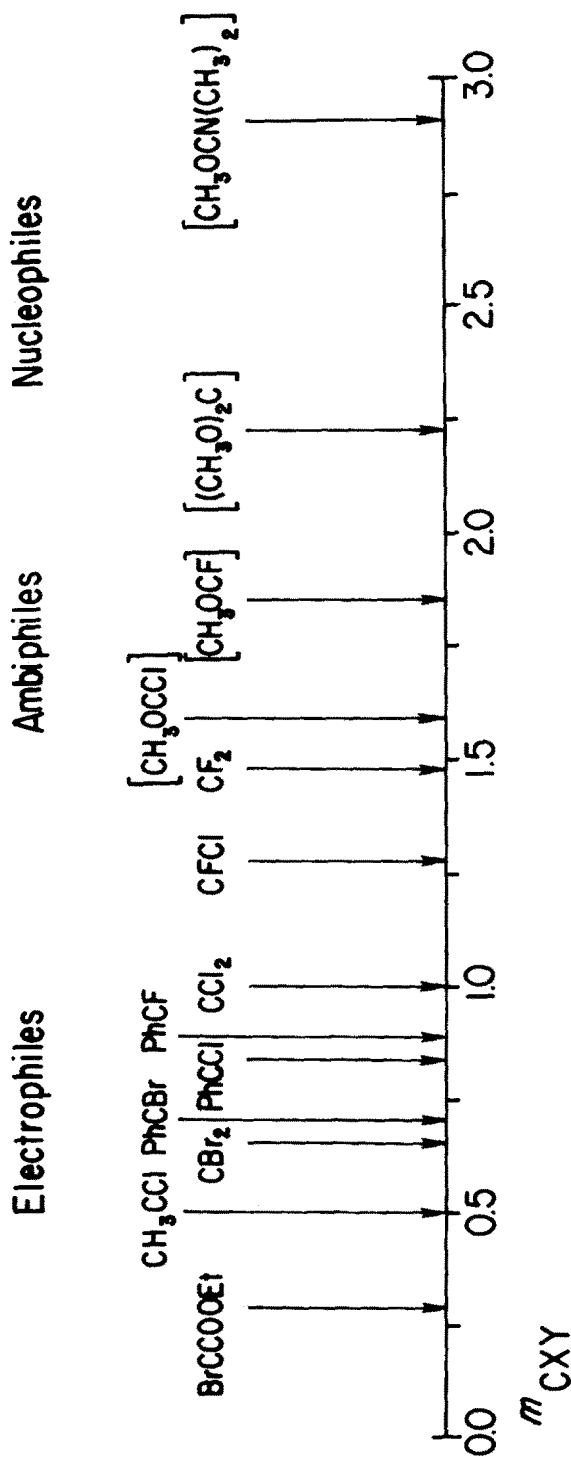| Olefin$_A$/Olefin$_B$	GC Conditions[a]		k_{rel}	$\pm$ av dev$_n$[b]
	Column	Temp ($°C$)		
(CCl_2)				
Me$_2$C=CH$_2$/CH$_2$=CHCOOMe	A	120	79.7	4.4$_3$
t-MeC=CHMe/CH$_2$=CHCOOMe	B	98-140 ($8°$/min)	16.6	1.3$_5$
CH$_2$=CHCN/CH$_2$=CHCOOMe	A	122	0.78	0.04$_4$
Me$_2$C=CMe$_2$/Me$_2$C=CH$_2$	B	98-140 ($8°$/min)	13.1	0.7$_4$
Me$_2$C=CMe$_2$/t-MeCH=CHMe	C	90-135 ($8°$/min)	76.6	1.9$_5$
Me$_2$C=CH$_2$/t-MeCH=CHMe	B	98	4.89	0.40$_5$
(CH_3CCl)				
Me$_2$C=CMe$_2$/CH$_2$=CHCOOMe	D	87	95.1	3.5$_4$
Me$_2$C=CMe$_2$/CH$_2$=CHCN	C'	100	100.	2.3$_3$
CH$_2$=CHCN/CH$_2$=CHCOOMe	C'	100	0.919	0.006$_2$

[a]Columns: A, 18 ft. x 3/16 in. Al column packed with 16% QF-1 + 4% FFAP on 60/80 Chromosorb W; B, 22 ft. x 1/8 in. Al column packed with 20% SF-96 on 80/100 Chromosorb W; C, 20 ft. (C'=11 ft.) x 1/4 in. Al column packed with 15% SF-96 on 80/100 Chromosorb W; D, 18 ft. x 1/4 in. Al column packed with 15% Carbowax 20M on 60/80 Chromosorb W. General operating conditions: injector, $160°$; detector, $200°$; He flow rate 20-50 ml/min. [b]Average deviation of n experiments.

Table II. Standardized Relative Reactivities of Carbenes

Olefin	k_{rel} for CXY		
	CH_3CCl ($25°$)	CCl_2 ($80°$)	CH_3OCCl ($25°$)[a]
Me$_2$C=CMe$_2$	7.44[b]	78.4	12.6
Me$_2$C=CH$_2$	1.92[b]	4.89	5.43
t-MeCH=CHMe[c]	1.00	1.00	1.00
CH$_2$=CHCOOMe	0.078	0.060	29.7
CH$_2$=CHCN	0.074	0.047	54.6

[a]From ref. 1. [b]From ref. 11. [c]Standard olefin.

CARBENE SELECTIVITY SPECTRUM

Electrophiles   Ambiphiles   Nucleophiles

BrCCOOEt

CH$_3$CCl PhCBr PhCF

CBr$_2$ PhCCl CCl$_2$

CFCl

[CH$_3$OCCl]

CF$_2$

[CH$_3$OCF]

[(CH$_3$O)$_2$C]

[CH$_3$OCN(CH$_3$)$_2$]

0.0   0.5   1.0   1.5   2.0   2.5   3.0

m_{CXY}

data, together with results for CH_3OCCl,[1] are normalized to a _trans_-butene standard in Table II. Satisfactory cross-check experiments (<5% deviation) linked the relative reactivities of the triads $Me_2C=CH_2$, _t_-$MeCH=CHMe$, and $CH_2=CHCOOMe$ (CCl_2), and $Me_2C=CMe_2$, $CH_2=CHCOOMe$, and $CH_2=CHCN$ (CH_3CCl). The value of $k_{Me_2C=CH_2}/k_{t\text{-}MeCH=CHMe}$ observed with CCl_2 (4.89 ± 0.40) was ~19% lower than that calculated (5.84 ± 0.34) from $k_{Me_2C=CH_2}/k_{Me_2C=CMe_2}$ and $k_{Me_2C=CMe_2}/k_{t\text{-}MeCH=CHMe}$, but the difference is nearly within the combined experimental error. Additionally, values of $k_{Me_2C=CMe_2}/k_{Me_2C=CH_2}$ (11.2) and $k_{Me_2C=CH_2}/k_{t\text{-}MeCH=CHMe}$ (4.48), calculated from differential activation parameters,[12] agree reasonably well with the corresponding $80°$ data in Table I.

Strikingly different selectivity patterns emerge from Table II for ambiphilic CH_3OCCl and electrophilic CCl_2 or CH_3CCl. The electrophiles exhibit steadily decreasing reactivity as the substrate changes from electron-rich to electron poor.* Indeed, logarithms of the CCl_2 and CH_3CCl relative reactivities are inversely related to the ionization potentials of the substrate alkenes, indicative of control by LUMO-carbene/HOMO-alkene orbital interactions. Ambiphilic CH_3OCCl, in contrast, exhibits a selectivity inversion at _trans_-butene; electron-rich alkenes react more rapidly, but then so do electron-deficient alkenes. Reactions of the latter are controlled by LUMO-alkene/HOMO-carbene orbital interactions.[1,2]

Clearly, there are dramatic, experimentally accessible selectivity differences which distinguish electrophilic from ambiphilic carbenes. These differences are expected (_cf._, Figure 1), and can be rationalized theoretically.[1,2] Note, however, that all singlet carbenes are _inherently_ both electrophiles and nucleophiles;[13] their expressed selectivity depends on the substrate set. The LUMO and HOMO energies of conceivable carbenes and commonly available alkenes, as well as the geometries of their reaction transition states, however, appear to restrict additional experimental demonstrations of ambiphilicity to a few candidates (_e.g._, $FCOCH_3$). Most divalent carbon species will react as electrophiles in accessible intermolecular situations; rather a lesser number should behave as nucleophiles.

References and Notes

(1) R.A. Moss, M. Fedorynski, and W-C. Shieh, _J. Am. Chem. Soc._, _101_, 4736 (1979).
(2) Carbenic electrophilicity, ambiphilicity, and nucleophilicity can be understood in terms of frontier molecular orbital theory; _cf._, ref. 1 and N. G. Rondan, K.N. Houk, and R.A. Moss, submitted for publication.
(3) R.A. Moss, C.B. Mallon, and C-T. Ho, _J. Am. Chem. Soc._, _99_, 4105 (1977).
(4) S. Ehrenson, R.T.C. Brownlee, and R.W. Taft, _Prog. Phys. Org. Chem._, _10_, 1 (1973).
(5) R.W. Hoffmann, W. Lilienblum, and B. Dittrich, _Chem. Ber._, _107_, 3395 (1974).
(6) M. Reiffen and R.W. Hoffmann, _Chem. Ber._, _110_, 37 (1977).
(7) R.A. Moss in "Carbenes," Vol. I, M. Jones, Jr., and R.A. Moss, Ed., Wiley , New York, 1973, pp. 153 _ff._; R.A. Moss and C.B. Mallon, _J. Am. Chem. Soc._, _97_, 344 (1975).
(8) CCl_2 does, however, display decreasing reactivity toward 1-$\overline{R}$-cyclohexene in the order R= CH_3>Cl>CH_3CO: O.M. Nefedov and R.N. Shafran, _Izv. Akad. Nauk SSSR, Ser. Khim._, 538 (1965).
(9) D. Seyferth, J.M. Burlitch, R.J. Minasz, J. Y-P. Mui, H.D. Simmons, Jr., A.J.H. Treiber, and S. R. Dowd, _J. Am. Chem. Soc._, _87_, 4259 (1965).
(10) D. Seyferth, M.E. Gordon, J. Y-P. Mui, and J.M. Burlitch, _J. Am. Chem. Soc._, _89_, 959 (1967).
(11) R.A. Moss and A. Mamantov, _J. Am. Chem. Soc._, _92_, 6951 (1970).
(12) See reference 7, p. 221.
(13) W. M. Jones and U. H. Brinker in "Pericyclic Reactions," Vol. 1, A.P. Marchand and R.E. Lehr, Ed., Academic Press, New York, 1977, pp. 110 _ff._
*More reactive, less selective CH_3CCl discriminates less effectively than CCl_2 toward _both_ electron-rich and electron-poor alkenes.