

# Separation of polar and enthalpy effects in radical addition reactions using polar ( $\sigma$ ) and radical ( $\sigma^\cdot$ ) sigma scales†

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**ABSTRACT:** Rate constants ( $k$ ) of radical addition reactions between 15 carbon- and sulfur-centered radicals and 15 vinyl-type alkenes were collected from the literature. Three descriptor variables {a polar (Hammett) sigma scale [ $\sigma(\text{H})$ ] and two radical sigma scales as defined by Creary and co-workers [ $\sigma^\cdot(\text{C})$ ] and Dust, Arnold and Wayner [ $\sigma^\cdot(\text{DAW})$ ]} were chosen to express polar and enthalpy effects.

The reactivity data ( $\log k$  values) of radicals were correlated with the three descriptor variables using stepwise linear regression analysis. The Hammett  $\sigma$  can describe the polar effects, whereas the radical  $\sigma^\cdot(\text{C})$  and, to a somewhat lesser extent,  $\sigma^\cdot(\text{DAW})$  can describe the enthalpy effects in radical addition reactions. The regression equations support the symmetry pattern of correlations proposed in Part IV. Radical reactivity ( $\log k$ ) correlates (i) with Hammett  $\sigma$  alone for strongly nucleophilic radicals where polar effects dominate, (ii) with Hammett  $\sigma$  and one of the radical  $\sigma^\cdot$  scales for moderately nucleophilic (or electrophilic) radicals and (iii) with one of the radical  $\sigma^\cdot$  scales alone for weakly nucleophilic radicals where enthalpy effects dominate. Copyright © 2000 John Wiley & Sons, Ltd.

**KEYWORDS:** radical addition reactions; polar effects; enthalpy effects; sigma scales

## INTRODUCTION

Considerable efforts have been made<sup>1–6</sup> to define special substituent scales which are free from polar effects and can be applied for radical reactions. However, little is known about the usefulness, comparison and application of such scales<sup>7,8</sup>. Most scales are not appropriate for a detailed statistical analysis because they are not available for a sufficient number of substituents.

Our earlier investigations<sup>7</sup> were limited to hydrogen abstraction reactions by polar radicals. The results suggest that (i) there is no universal radical sigma ( $\sigma^\cdot$ ) scale for radical reactions; (ii) only two radical sigma scales { $\sigma^\cdot(\text{Creary})$ ,<sup>5</sup>  $\sigma^\cdot(\text{Dust–Arnold–Wayner})$ <sup>6</sup>} are appropriate, showing a small, yet significant, role of radical stabilization. Therefore, in this work, our aim was to extend the investigations (i) to radical addition reactions and (ii) to non-polar (enthalpy-controlled) radicals.

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In addition we sought to answer the following questions:

- are the radical sigma scales suitable to express enthalpy effects in radical reactions?;
- is the polar Hammett sigma scale suitable to express polar effects in radical reactions?;
- is it possible to separate polar and enthalpy effects using only polar and radical sigma scales in themselves?

**Table 1.** Vinyl-type alkenes ( $\text{CH}_2=\text{CR}_1\text{R}_2$ ) involved in the study

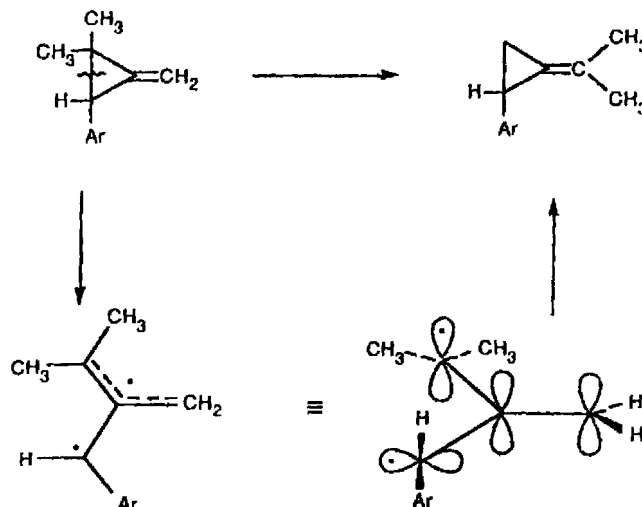
No.	R <sub>1</sub>	R <sub>2</sub>	Alkene name
1	H	CN	Acrylonitrile
2	Me	Ph	Methylstyrene
3	H	Ph	Styrene
4	H	COOMe	Methyl acrylate
5	Cl	Cl	1,1-Dichloroethylene
6	H	Si(OEt) <sub>3</sub>	Triethoxy(vinyl)silane
7	H	Si(Me) <sub>3</sub>	Trimethyl(vinyl)silane
8	H	OCOMe	Vinyl acetate
9	H	CH <sub>2</sub> CN	Allyl cyanide
10	Me	Cl	2-Chloropropene
11	Me	OCOMe	Prop-2-enyl acetate
12	H	CH <sub>2</sub> Si(Me) <sub>3</sub>	Allyl(trimethyl)silane
13	H	tBu	tert-Butylethylene
14	H	OEt	Vinyl ethyl ether
15	Me	OMe	Prop-2-enyl methyl ether

**Table 2.** Radical reactivities (log*k* values) for various radicals<sup>9</sup> (for notations, see text)

R <sub>1</sub> , R <sub>2</sub>	TBU	HP	MEOBZ	FBZ	B	MEBZ	CNP	BCM	CNBZ	HM	CM	ME	MAL	TOS	PHSO <sub>2</sub>
H, CN	6.000	8.000	3.255	3.512	3.342	3.322	3.305	5.732	3.146	6.041	5.041	5.785	5.173	-0.721	-2.22
Me, Ph	4.832	8.602			2.929		3.364	6.591		4.447	5.820	5.477	6.124		0.507
H, Ph	5.121	6.342	3.362	3.380	3.041	3.362	3.382	6.279	3.531	4.362	5.580	5.415	6.061	1.170	0.000
H, COOMe	6.017	7.000	3.389	3.079	2.633	3.477	2.565	5.690	2.833	5.851	5.041	5.531	5.049	-0.456	-1.92
Cl, Cl	5.544	5.332	3.021	2.908	2.663	2.690	2.780	5.431	2.949	4.724	4.519	5.362	5.589		
H, Si(OEt) <sub>3</sub>	4.439	4.917			1.643		2.509	4.826							
H, SiMe <sub>3</sub>	3.982	4.396			1.519		1.875	4.949		3.314	4.114	4.380	5.348		
H, OCOMe	3.623	3.875	1.556	1.431	1.176	1.398	1.613	4.813	1.301	2.771	4.114	4.000	5.597	-0.523	-2.10
H, CH <sub>2</sub> CN	4.049	4.367	1.447	0.903	0.477	1.000	1.944	4.643	1.000					-1.17	
Me, Cl	4.057	4.346			1.633		2.079	5.204		3.324	4.204	4.544	5.964		
Me, OCOMe	3.230	3.686			1.663		1.898	4.944		2.833	4.716	4.079	5.766		
H,	3.049	3.114			1.748		1.672	4.978							
CH <sub>2</sub> SiMe <sub>3</sub>															
H, tBu	2.176	3.029	1.176	1.398	1.255	1.690	1.940	4.544	1.756	2.477	4.041	3.881	5.283	-0.237	-1.70
H, OEt	2.591	2.505	1.079	1.255	1.146	1.505	2.033	5.176	2.415	2.255	4.633	4.146	5.480		
Me, OMe	2.342	3.033			1.322		1.914	5.146		2.362	4.544	4.079	5.602		

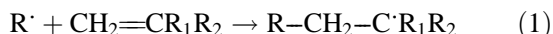
**Table 3.** Values of sigma scales (descriptor variables) used<sup>5d,6a,10</sup>

R <sub>1</sub> , R <sub>2</sub>	Hammett $\sigma(H)$	$\sigma^{\cdot}(Creary)$	$\sigma^{\cdot}(DAW)$
H, CN	0.660	0.460	0.040
Me, Ph	-0.180	0.570	
H, Ph	-0.010	0.460	
H, COOMe	0.450	0.350	0.043
Cl, Cl	0.460	0.240	0.022
H, Si(OEt) <sub>3</sub>	0.190		
H, SiMe <sub>3</sub>	-0.070	0.180	0.017
H, OCOMe	0.310		-0.005
H, CH <sub>2</sub> CN	0.010		
Me, Cl	0.060	0.230	0.026
Me, OCOMe	0.140		0.010
H, CH <sub>2</sub> SiMe <sub>3</sub>	-0.210	0.270	
H, tBu	-0.200	0.130	0.008
H, OEt	-0.240	0.240	0.018
Me, OMe	-0.440	0.350	0.033

**Scheme 1**

## METHODS

The calculations were performed on radical addition reactions of various carbon- and sulfur-centered radicals and vinyl-type alkenes:



We analyzed the reactivities (logarithms of rate constants) of the radicals towards the alkenes.

The radicals studied were as follows (in decreasing order of nucleophilicity; abbreviations in parentheses); 2-hydroxyprop-2-yl (HP), *tert*-butyl (tBu), hydroxymethyl (HM), *p*-methoxybenzyl (MeOBz), *p*-fluorobenzy (FBz), *p*-methylbenzyl (MeBz), methyl (Me),

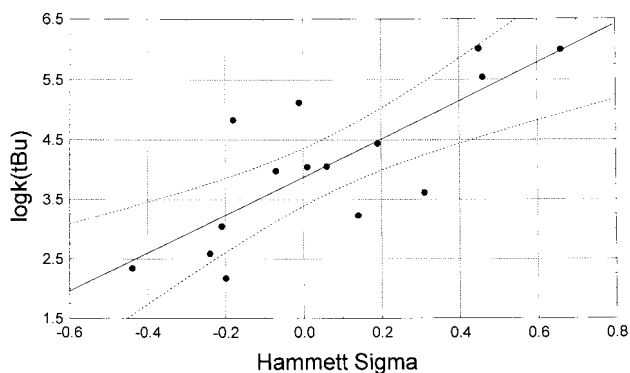
benzyl (Bz), *p*-cyanobenzyl (CNBz), 2-cyanoprop-2-yl (CNP), *tert*-butoxycarbonylmethyl (BCM), cyanomethyl (CM), 2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-yl (malonyl; MAL), phenylsulfonyl (PhSO<sub>2</sub>) and tosyl (TOS).

The names and notations of alkenes investigated are listed in Table 1 and rate constants were collected from the literature<sup>9</sup> and are given in Table 2. However, some of the rate constants were not available and they are missing from Table 2. In each case the largest possible data set was analyzed.

On the basis of the earlier investigations,<sup>7</sup> two radical sigma scales as defined by Creary and co-workers<sup>5</sup> [ $\sigma^{\cdot}(C)$ ] and Dust, Arnold and Wayner<sup>6</sup> [ $\sigma^{\cdot}(DAW)$ ] were chosen to express the enthalpy effects, whereas the polar

**Table 4.** Regression equations obtained for experimental radical reactivities<sup>9</sup> as a function of  $\sigma(H)$ ,  $\sigma^{\cdot}(C)$ , and  $\sigma^{\cdot}(DAW)$  [the significance of involving the  $\sigma(H)$ ,  $\sigma^{\cdot}(C)$ , and  $\sigma^{\cdot}(DAW)$  descriptors into the equations are given as percentages]:  $\log k = a + b\sigma(H) + c\sigma^{\cdot}(C) + d\sigma^{\cdot}(DAW)$ 

Radical	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>n</i>	<i>r</i>	<i>F</i>	<i>s</i>
HP	4.638	3.201 (4.48%)			15	0.5243	4.93	1.657
tBu	3.872	3.187 (0.07%)			15	0.7768	19.8	0.823
HM	3.500	2.933 (0.63%)			12	0.7363	11.8	0.943
MeOBz	1.886	2.219 (5.10%)			8	0.7047	5.92	0.808
FBz	1.852	2.120 (7.71%)			8	0.6563	4.54	0.881
	1.272	1.605 (2.18%)		28.88 (2.99%)	6	0.9800	36.5	0.259
MeBz	1.350	0.9928 (6.16%)		36.14 (1.35%)	6	0.9798	36.1	0.242
Me	3.851	1.311 (0.01%)		27.35 (0.03%)	10	0.9741	65.0	0.182
Bz	0.8174	1.357 (0.06%)	3.983 (0.03%)		11	0.9543	40.8	0.272
CNBz	1.645			35.97 (1.23%)	6	0.9080	18.8	0.342
CNP	1.282	0.7509 (3.46%)	3.620 (0.15%)		11	0.9003	17.1	0.321
	1.193		3.960 (0.25%)		11	0.8109	17.3	0.407
BCM	4.713	0.4597 (0.92%)		18.78 (0.05%)	10	0.9497	32.2	0.134
	4.130		4.108 (0.01%)		11	0.9191	49.0	0.251
CM	3.457		4.041 (0.00%)		10	0.9414	62.3	0.217
	4.116			17.96 (1.89%)	10	0.7200	8.61	0.274
MAL	5.185	-0.4977 (15.9%)	1.266 (15.7%)		10	0.6181	2.16	0.335
PHSO <sub>2</sub>	-2.782	-2.550 (2.66%)	5.286 (3.35%)		5	0.9823	27.6	0.326
TOS	-1.405	-2.576 (11.0%)	5.496 (13.1%)		4	0.9861	17.6	0.243



**Figure 1.** Logarithm of rate constants for *tert*-butyl radical vs Hammett sigma plot. In each figure the dotted lines show the 95% confidence interval for the regression line

effects were expressed by the Hammett sigma scale<sup>10</sup> [ $\sigma(\text{H})$ ]. The values of these scales are given in Table 3.

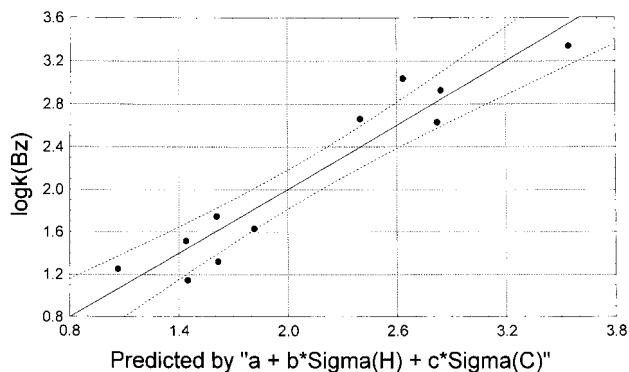
The Hammett scale is based on the dissociation of *para*-substituted benzoic acids, whereas the Creary scale is based on the rearrangement of the cyclopropane ring<sup>5d</sup> shown in Scheme 1, where Ar represents a substituted phenyl ring. This rearrangement is a radical process without any (significant) polar character in the transition state.

The  $\sigma^{\cdot}(\text{DAW})$  scale is defined from the benzylic  $\alpha$ -hydrogen hyperfine coupling constants:<sup>6</sup>

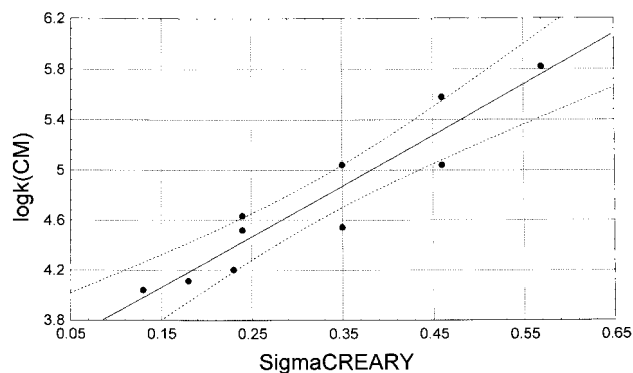
$$\sigma^{\cdot}(\text{DAW}) = 1 - \text{hfc}_X/\text{hfc}_0$$

This scale represents the component of energy that may be attributed to spin delocalization in the X-substituted benzyl radical relative to the unsubstituted radical.

The reactivity data of radicals were investigated as a function of  $\sigma^{\cdot}(\text{C})$ ,  $\sigma^{\cdot}(\text{DAW})$  and  $\sigma(\text{H})$  using stepwise linear regression analysis.<sup>11</sup> For all three sigma scales the sum of the sigma values of the R<sub>1</sub> and R<sub>2</sub> substituents in reaction (1) were considered.



**Figure 2.** Logarithm of rate constants for benzyl radical vs Hammett sigma and one of the radical scales (defined by Creary and co-workers<sup>5</sup>)



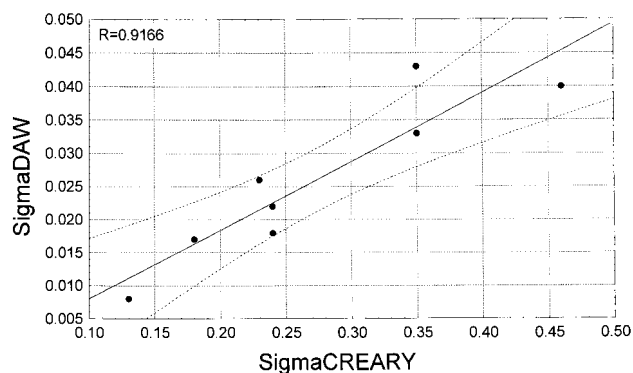
**Figure 3.** Logarithm of rate constants for cyanomethyl radical vs the radical scale defined by Creary and co-workers<sup>5</sup>

## RESULTS AND DISCUSSION

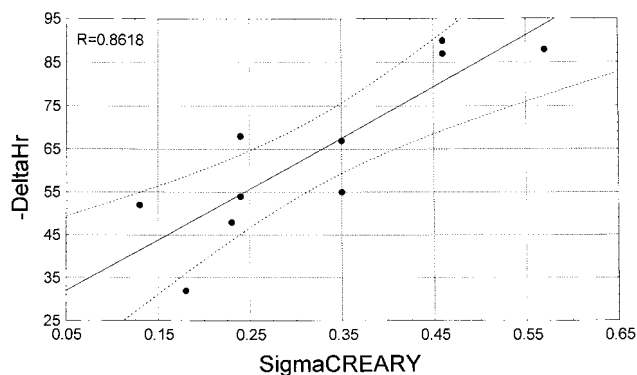
The results are summarized in Table 4, and a clear trend can be observed where the radicals are listed in decreasing nucleophilic/increasing electrophilic character. As the polar effects decrease (from the top and bottom to the middle of the table), the Hammett sigma becomes less important in the equations. Similarly, as the enthalpy effects decrease (from the middle to the top and bottom of the table), the radical sigma scales become less important in the equations.

Some prototype radicals were chosen to show the goodness of description and the errors associated with the approach. Only the Hammett sigma scale is significant with the *tert*-butyl radical where polar effects dominate. Figure 1 shows the respective  $\log k$  vs Hammett sigma plot.

Figure 2 shows the description for the benzyl radical controlled by both the polar and the enthalpy effects. Consequently, both the polar and one of the radical scales (defined by Creary and co-workers) are significant in the respective equation. Figure 3 presents the result for the non-polar, enthalpy-controlled cyanomethyl radical, where only one of the radical scales is significant. The



**Figure 4.** Correlation of the two radical scales:  $\sigma^{\cdot}(\text{C})$  and  $\sigma^{\cdot}(\text{DAW})$



**Figure 5.** Correlation of the reaction enthalpy and one of the radical scales (defined by Creary and co-workers<sup>5</sup>)

scatter inherent in the approach can be seen in the figures.

The last column of Table 4 contains the standard error of the estimate. This column shows the limits for the reliability of predictions obtained by the equations.

The negative regression coefficients of  $\sigma(H)$  for the malonyl, phenylsulfonyl and tosyl radicals are in accordance with their electrophilic character. Similarly, the positive regression coefficients of  $\sigma(H)$  for all remaining radicals are in accordance with their nucleophilicity. Although some of the regression coefficients in Table 4 are not significant at the 5% level, even the respective equations are justified by the above-mentioned trend (i.e. which sigma scale enters in which equation) observed in Table 4.

There would be good reasons to leave out the two styrene derivatives from the equations as the Hammett scale cannot express the resonance stabilization of the phenyl ring properly. We still kept the styrenes in the equations, mainly because the observed trend and the conclusions would not change much with their exclusion. Moreover, we wanted to use as many data as possible to avoid any chance correlation.

It is well known that correlated descriptor variables can lead to unstable models. Therefore, we investigated the intercorrelations among the three sigma scales. We found that  $\sigma(H)$  is not correlated with either  $\sigma'(C)$  ( $n = 10$ ,  $r = 0.1752$ ) or  $\sigma'(DAW)$  ( $n = 10$ ,  $r = 0.2448$ ). On the other hand,  $\sigma'(C)$  and  $\sigma'(DAW)$  are highly correlated with each other ( $n = 8$ ,  $r = 0.9166$ ), as shown in Fig. 4. However, this does not cause any problem since we did not obtain any equations including both radical sigma scales together.

In addition, we investigated the correlation of the two radical sigma scales with the exothermicity ( $-\Delta H_r$ , negative enthalpy) of reactions between the alkenes and the methyl radical chosen as a model. As the reaction enthalpy was estimated<sup>9e-k</sup> using the method of increments, any radical may be suitable to model the others. The  $-\Delta H_r$  values used in the correlations are taken from Part IV.<sup>12</sup>

There is a significant correlation between  $-\Delta H_r$  and  $\sigma'(C)$  ( $n = 10$ ,  $r = 0.8618$ ). The respective plot is shown in Fig. 5.

On the other hand, the correlation between  $-\Delta H_r$  and  $\sigma'(DAW)$  is not significant at the 5% level ( $n = 10$ ,  $r = 0.5558$ ). Hence our conclusion is that the sigma scale defined by Creary and co-workers<sup>5</sup> expresses the effect of radical stabilization better than the other scale.

It is well known that radical reactivities depend on certain polar variables (such as ionization potential and electron affinity) in a non-linear way.<sup>13</sup> However, our approach is linear, since it is based on linear free energy relationships (LFER) and uses LFER descriptors.

## CONCLUSIONS

We found that the Hammett  $\sigma$  can describe the polar effects, whereas the radical  $\sigma'(C)$  and, to a somewhat lesser extent,  $\sigma'(DAW)$  can describe the enthalpy effects in radical addition reactions.

The regression equations support the symmetry pattern of correlations proposed earlier,<sup>12</sup> namely that radical reactivity ( $\log k$ ) correlates with Hammett  $\sigma$  alone for strongly nucleophilic radicals where polar effects dominate, with Hammett  $\sigma$  and one of the radical  $\sigma'$  scales for moderately nucleophilic (or electrophilic) radicals and with one of the radical  $\sigma'$  scales alone for weakly nucleophilic radicals where enthalpy effects dominate.

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