Tetrahedron Letters No. 35, pp 3293 - 3296.
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0040-4039/78/0822-3293$02.00/0

OPERATIONAL DEFINITION OF THE TAFT STERIC PARAMETER. AN HOMOGENEOUS SCALE FOR ALKYL GROUPS - EXPERIMENTAL EXTENSION TO HIGHLY HINDERED GROUPS.

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For some time we have been interested in the synthesis and properties of highly hindered molecules and in ketones in particular.[1] In this area, work on structure-reactivity relationships pointed out *a dearth of reliable steric parameters* for hindered groups as well as the absence of a precise operational definition of the steric effect.[2] This latter problem is essentially due to the fact that Taft, in his original papers, made use of average reactivity data for four closely related reactions (acid catalysed hydrolysis of carboxylic esters in various media) in a manner that is difficult to follow up experimentally.[3]

A precise operational definition of the steric effect is necessary from two standpoints: firstly, measurements of new Taft steric constants requires this if the complete scale is to be self-consistent and, secondly, a more thorough analysis of the "mechanism" by which steric effects operate makes this desirable since minor effects may be masked by averaging procedures. We therefore propose the acid catalysed esterification of carboxylic acids in methanol at 40° as reference reaction and define the "revised" Taft steric parameter as

$$E'_S = \log (k/k_o) \qquad (1)$$

where k_o refers to the rate of esterification of acetic acid. The choice of this particular reaction as reference is occasioned by the abundance of reliable literature data available, especially where alkyl groups are concerned. In this note our goal is to set up a reliable set of steric constants for alkyl groups which may subsequently be extended.

The use of the acid catalysed esterification reaction as probe for the steric effect has been treated in some detail by Taft and others[3-5] and may be considered as proved. Reactions which follow the steric effect, but which correspond to conditions differing from the reference conditions, are correctly considered by Eq. 2

$$\log (k/k_o) = \delta E'_S \qquad (2)$$

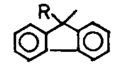
which allows one to take into consideration differing sensitivities to changes in the steric effect (variation of δ). This is the conventional way of avoiding the use of average values of $\log (k/k_o)$. The ensemble of E'_S values calculated by Eqs. 1 and 2 thereby correspond to the same reference. The selection of E'_S as symbol representing the "revised" Taft steric constants serves both to avoid confusion with E_S and to emphasize how well the fundamental Taft-Ingold hypothesis has withstood the test of time.

Scale of E_S' Values for Alkyl Groups

Using the rationale discussed above we have undertaken the calculation of a reliable basic set of E_S' values for open-chain alkyl groups. These values are given in Table I along with the corresponding E_S values. In addition we have measured quite a variety of steric effects by direct esterification procedures as well as by competition experiments in order to extend and complete the scale. Our measurements were all carried out in methanol with p-toluenesulfonic acid as catalyst. The set of E_S' values reported in Table I covers a range of more than eight powers of ten.

A glance at Table I shows that differences between E_S and E_S' (except for the groups t-$BuMe_2C$- and Et_3C-) are in some cases negligible while in others small and of the same sign. This is of course the result of taking average values in establishing the E_S scale. The E_S' values for the groups t-$BuMe_2C$- and Et_3C- are, however, very much different from the accepted E_S values[3] by ca. 1.5 units. An analysis of the available E_S values for alkyl groups based on the DARC topological system has previously led us to suspect the validity of the reported steric constants for these two groups.[6] Our preliminary competition experiments between t-$BuMeCHCO_2H$ and t-$BuMe_2CCO_2H$ indicated a reactivity difference much greater than may be calculated from the differences in their E_S values (a factor of 3.7). Direct kinetic experiments for these two compounds gave the values recorded in Table I indicating a reactivity ratio of 117. The remaining E'_S values for highly hindered groups were determined from competition experiments. The rate data used by Taft for the groups t-$BuMe_2C$- and Et_3C- correspond to esterification at 40° in methanol with HCl as catalyst.[7] It is probable that, in the case of very slow esterifications, the reaction of HCl with solvent interferes seriously with the rate determination. In the present case we use p-toluenesulfonic acid which does not react with solvent[8] and find much slower rates.

Internal Consistency of E_S' Values

It is worth noting that the E_S' value accorded to the group t-$BuMe_2C$- is not unusual when one considers the parallel in the effect of the introduction of the groups H, Me, Et, i-Pr, and t-Bu on the E_S' values of the 1-substituted fluorenyl groups () and the groups RMe_2C-. Molecular models indicate that these two sets of groups attached to a carboxyl group represent equivalent steric environments. The following equation is obtained:

$$E_S'(1\text{-R-Fl}) = 0.667\ (RMe_2C\text{-}) - 0.810 \qquad (3)$$

$$r = 0.99,\ \psi = 0.200,\ R = H,\ Me,\ Et,\ i\text{-}Pr,\ tBu$$

The quality of the correlation demonstrates the internal consistency of the five pairs of values used.

The E_S' value obtained for the group Et_3C- is likewise seen to be consistent when one considers the analogy between the effect of the replacement of the hydrogens of the methyl group by methyl and ethyl sub-groups, expressed as the following equation:

TABLE I: Set of E'_S values for open-chain alkyl groups

R	$-E_S$ (Taft)	$-E'_S$	Δ	Source	R	$-E_S$ (Taft)	$-E'_S$	Δ	Source
H	− 1.24	− 1.12	− 0.12	a	t-BuCH$_2$Me$_2$C-	2.57	2.48	0.09	d
Me	0.0	0.0	-	-	(t-BuCH$_2$)$_2$CH-	3.18	3.06	0.12	d
Et	0.07	0.08	− 0.01	a	[‡]FlCH	-	1.15	-	e
Pr	0.36	0.31	0.05	a	[‡]FlCMe	-	1.81	-	e
n-Bu	0.39	0.31	0.08	a	[‡]FlCEt	-	2.07	-	e
i-Pr	0.47	0.48	− 0.01	c	[‡]FlCPr^i	-	3.46	-	e
s-Bu	1.13	1.00	0.13	d	[‡]FlCBu^t	-	4.32	-	e
i-Bu	0.93	0.93	0.00	d	i-PrMe$_2$C-	-	3.54	-	f
t-Bu	1.54	1.43	0.11	b,f	i-Pr$_2$CH-	-	5.01	-	f
Et$_2$CH-	1.98	2.00	− 0.02	b,f	Et$_3$C-	3.8	5.29	-1.49	f
EtMe$_2$C-	-	2.28	-	g,f	t-BuMe$_2$C-	3.9	5.40	-1.50	f
i-PrEtCH-	-	3.23	-	d,f	i-PrEt$_2$C-	-	6.20	-	f
t-BuCH$_2$-	1.74	1.63	0.11	d,f	i-Pr$_2$MeC-	-	7.38	-	f
t-BuMeCH-	3.33	3.21	0.12	d,f	i-Pr$_2$EtC-	-	7.38	-	f
n-Pr$_2$CH-	2.11	2.03	0.08	b	i-Pr$_3$C-	-	6.73	-	f
n-Bu$_2$CH-	-	2.08	-	b	t-BuPr^{i}CH-	-	6.53	-	f
i-Bu$_2$CH-	2.47	2.38	0.09	b	t-Bu$_2$CH-	-	6.97	-	f
i-PrCH$_2$CH$_2$-	0.35	0.32	0.03	d	t-BuPr^{i}MeC-	-	7.56	-	f
t-BuCH$_2$CH$_2$-	0.34	0.33	0.01	d	t-BuEt$_2$C-	-	7.21	-	f
t-BuCH$_2$MeCH-	1.85	1.81	0.04	d	t-BuPr^{i}EtC-	-	6.62	-	f

[‡] Fl = fluorenyl

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b H. A. Smith, J.Am.Chem.Soc., 62, 1136 (1940).

c H. A. Smith, J.Am.Chem.Soc., 61, 1176 (1939).

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f This work.

g N. B. Chapman, J. R. Lee and J. Shorter, J.Chem.Soc., B, 788 (1969).

$$E'_S(CEt_nH_{3-n}) = aE'_S(CMe_nH_{3-n}) + b \quad n = 0, 1, 2, 3$$

The correlation obtained is excellent ($r = 0.999$, $\psi = 0.064$).

Special Effects in Congested Groups

Beginning with the E'_S values in the region of ca. -6 or less there appears to be a definite *levelling* effect, i.e. the trends noted for groups less hindered than this become attenuated at this point. For example, the E'_S difference between the groups t-BuPrCH- and t-Bu_2CH· is slight (0.44) and for the groups i-Pr_2MeC- and i-Pr_2EtC- it is zero. As the steric effect increases towards very hindered groups a rather surprising *inversion* effect is noted in two distinct cases:

for t-$BuPr^i$MeC-, $E'_S = -7.56$ and t-$BuPr^i$EtC-, $E'_S = -6.62$
and for i-Pr_2EtC-, $E'_S = -7.38$ and i-Pr_3C-, $E'_S = -6.73$.

We have checked our data carefully and are convinced that this effect is real. An anaysis of the behaviour of steric effects of alkyl groups with substitution making use of the complete E'_S scale developed here is in progress.

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(Received in UK 15 June 1978; accepted for publication 3 July 1978)