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Studies on ^{13}C Magnetic Resonance Spectroscopy. XVII.[1] Elucidation of Substituent-Induced Chemical Shifts of Substituted *n*-Alkane Series by Means of a Novel Substituent Entropy Constant σ_{s°

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Substituent effects on the ^{13}C and ^{1}H nuclear magnetic resonance (NMR) chemical shifts of aliphatic compounds have been studied. A good agreement was found between chemical shifts in the gas phase and those in CCl_4 solution. Regression analyses of ^{13}C and ^{1}H chemical shifts in CCl_4 solution and in the gas phase were carried out by using σ_i, σ_{s° and $\sigma_{s_{MA}}$ as descriptors for α-substituted butane and propane derivatives. Linear combinations of σ_i, $\sigma_{s^\circ}^{+}$ and/or $(\sigma_{s^\circ}^{+})^2$, where the superscript "+" indicates an electron-donating substituent, are necessary for all ^{13}C and α-^{1}H chemical shifts of propane derivatives, but those of the β- and γ-positions are correlated with σ_i. Except for the β-position signals, a term expressed as $\sigma_{s_{MA}}$ is needed to take account of the magnetic anisotropic effect of Cl, Br, I and CN groups on the ^{13}C and ^{1}H chemical shifts.

Keywords——^{13}C NMR; ^{1}H NMR; substituent entropy constant σ_{s°; gas phase NMR; substituent constant; α-substituted propane; α-substituted butane; substituent effect

Three kinds of approaches, namely, empirical, semi-empirical and non-empirical, are generally used for the elucidation of the substituent-induced chemical shifts (SCS) of aliphatic, as well as aromatic series of compounds. Since the quantum chemical treatment of nuclear magnetic resonance (NMR) chemical shifts (CS) was established by Pople,[2] several kinds of theoretical molecular orbital calculation have been applied for estimation of chemical shifts,[3,4] but these non-empirical approaches are not always effective. Although the additivity rule was found to be useful to predict the SCS of some families such as substituted alkanes[5] and benzene derivatives,[6] this empirical method has limited applicability. In our previous report[7] on a semi-empirical derivation of the SCS of substituted benzene and naphthalene series, the total charge densities obtained by the MINDO/2 method could not be successfully correlated with the observed SCS of the *ipso*-position. These results prompted us to analyze this subject by using an empirical descriptor based on the thermodynamic concept, because the quantum chemical approach does not always represent the intrinsic thermodynamic information.

Recently, we proposed the novel substituent entropy constant σ_{s°[8] defined as $\sigma_{s^\circ} = \log(S_R^\circ/S_H^\circ)$ for numerous kinds of substituent groups, and confirmed that this descriptor is very useful.[9] In this work, the regression analyses of ^{13}C SCS of substituted *n*-butanes as well as those of ^{1}H SCS of substituted *n*-propanes were carried out by using the novel descriptor σ_{s°,[8] together with the Hammett-type substituent constant σ_i,[10] including the contributions of the magnetic anisotropy and electric field effects. The σ_i scale is related to the Taft scale by $\sigma_i = 0.74\sigma_I$.[11]

Experimental

^{13}C CS of Substituted *n*-Propane (PrR) and *n*-Butane (BuR) Derivatives——^{13}C SCS of PrR were measured in the

vapor phase at 170 °C using a specially machined sample tube (Chart 1), by a substitution method. The resonance signal for $C_6H_5 \cdot Et$ as a reference was obtained and then $C_6H_5 \cdot Et$ was replaced by the sample. The resonance signal of the sample was obtained, then the reference was again placed in the probe to confirm the stability of the field. The SCS values of BuR were determined in CCl_4 (0.2 M) with Me_4Si as an internal reference. Observed values in the two series are summarized in Table I.

^{1}H CS and ^{1}H SCS of Substituted *n*-Propanes (PrR)——References used for determinations of PrR in the gas phase at 100 °C as well as in CCl_4 solution (0.1 M) were the same as described above, and the observed values are summarized in Table II.

Method of Regression Analysis——Multiple regression analyses were carried out by using an ACOS 900 system

TABLE I. ^{13}C SCS of BuR and ^{13}C CS[a] of PrR (ppm)

Substituent (R)	BuR (In CCl_4)			PrR (Gas phase)		
	α	β	γ	α	β	γ
NMe_2	40.10	5.38	−4.12	—	—	—
NH_2	27.84	10.89	−4.90	13.96	−3.30	−21.43
OEt	56.24	7.13	−5.39	—	—	—
OMe	44.28	6.93	−5.48	26.09	−7.44	−22.00
OH	48.15	10.13	−5.87	34.07	−4.11	−22.42
tert-Bu	30.23	2.04	−1.20	17.16	−12.72	−17.35
iso-Pr	24.96	4.86	−1.89	11.77	−10.07	−18.13
Et	17.76	6.74	−2.19	—	−8.30	−18.61
Me	8.51	9.29	−2.51	—	—	—
F	70.10	8.00	−6.70	—	—	—
Cl	29.87	9.80	−4.82	13.81	−4.20	−20.98
Br	18.40	9.89	−3.50	0.90	−3.81	−19.36
I	−8.66	10.64	−1.20	−28.95	−3.15	−17.26
H[b]	0	0	0	—	—	—
COPh	24.00	1.45	−2.33	—	—	—
COEt	27.90	1.09	−2.45	13.42	−13.04	−18.55
COMe	29.20	0.95	−2.54	14.74	−13.04	−18.61
CHO	29.54	−0.67	−2.55	15.52	−14.78	−18.67
$CONH_2$	22.05	3.00	−2.27	—	—	—
COOEt	19.86	2.18	−2.56	5.82	−11.98	−18.70
COOMe	19.52	2.11	−2.59	5.33	−12.04	−18.76
CN	2.89	2.68	−3.02	−10.85	−12.23	−19.33
NO_2	61.00	4.44	−5.24	—	−9.53	−21.42

a) ^{13}C chemical shift relative to CH_2 of neat $C_6H_5 \cdot Et$.
b) ^{13}C chemical shifts from internal TMS at α-, β- and γ-positions are 13.60, 24.62 and 24.62 ppm, respectively.

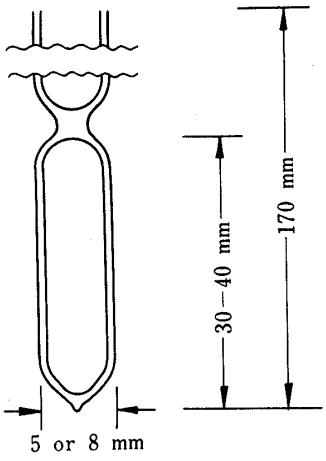

Chart 1. Specially Machined Sample Tube Used for Determination in the Gas Phase

TABLE II. ^1H CS[a] in Gas Phase and ^1H SCS in CCl_4 of PrR (ppm)

Substituent (R)	Gas phase			In CCl_4		
	α	β	γ	α	β	γ
NH_2	0.59	−0.64	−1.18	1.74	0.06	0.05
OPr	—	—	—	2.43	0.18	0.06
OEt	—	—	—	2.42	0.18	0.05
OMe	1.18	−0.51	−1.14	2.37	0.18	0.05
OH	1.46	−0.54	−1.15	2.64	0.18	0.08
tert-Bu	−0.83	−0.96	−1.20	0.35	−0.20	0.04
Et	−0.72	−0.72	−1.17	0.42	−0.09	0.03
Cl	1.21	−0.37	−1.10	2.57	0.46	0.19
Br	1.12	−0.26	−1.08	2.45	0.52	0.19
I	0.95	−0.30	−1.13	2.28	0.53	0.18
H[b]	—	—	—	0	0	0
COPh	—	—	—	2.02	0.40	0.15
COEt	0.12	−0.44	−1.17	1.49	0.22	0.05
COMe	0.17	−0.46	−1.19	1.48	0.25	0.07
CHO	0.11	−0.43	−1.13	1.49	0.31	0.12
$CONH_2$	—	—	—	1.25	0.28	0.11
COOEt	0.08	−0.43	−1.14	1.36	0.26	0.11
COOMe	0.10	−0.43	−1.14	1.37	0.28	0.11
CN	−0.05	−0.51	−1.05	1.43	0.36	0.26
NO_2	2.01	−0.13	−1.10	3.38	0.69	0.19

a) ^1H chemical shift relative to Me of neat $C_6H_5 \cdot Et$.
b) Chemical shifts from internal TMS at α-, β- and γ-positions are 0.85, 1.36 and 0.85 ppm, respectively.[12]

computer at Osaka University Computer Center utilizing a library program, NEC TSS LIBRARY TSS/LIB-6. The standard deviation (SD) is given by $SD=[S_{se}/(n-k-1)]^{1/2}$, where n and k denote the number of observations and variables, and S_{se} is the sum of squares of residuals.

Substituent Entropy Constant σ_{s°——The substituent entropy constants of PrR and BuR[13] show good linear correlations with those of methane derivatives (MeR)[8] as follows.

$$\sigma_{s^\circ PrR}=0.755\sigma_{s^\circ MeR}-0.005$$

$$r=0.996,\ SD=0.004,\ n=16$$

(R = NH_2, OMe, OH, *tert*-Bu, iso-Pr, Et, Me, F, Cl, Br, I, H, Ph, COMe, CN, NO_2)

$$\sigma_{s^\circ BuR}=0.668\sigma_{s^\circ MeR}-0.005$$

$$r=0.996,\ SD=0.004,\ n=11$$

(R = NH_2, OH, *tert*-Bu, iso-Pr, Et, Me, Cl, Br, H, Ph, NO_2)

The substituent entropy constants of MeR instead of those of PrR and BuR could be used in the regression analyses. By dividing by the factors 0.755 and 0.668, all the coefficients of the entropic terms written in the regression equations can be converted to $\sigma_{s^\circ PrR}$ and $\sigma_{s^\circ BuR}$.

Results and Discussion

Quadratic Equation of $\sigma_{s^\circ}^+$

In this work, the symbol $\sigma_{s^\circ}^+$ is used to express the substituent entropy constants of an electron–donating group (−R), and the numerical values of $\sigma_{s^\circ}^+$ are identical with the σ_{s° of that group, but for the electron-attracting group (+R) those of $\sigma_{s^\circ}^+$ are zero. When the SCS of the −R group are plotted against σ_{s°,[8] a quadratic curve (*cf.* Fig. 1) can be expected. In a regression analysis of the ^{13}C SCS of the β-position of *n*-BuR, the correlation coefficient of

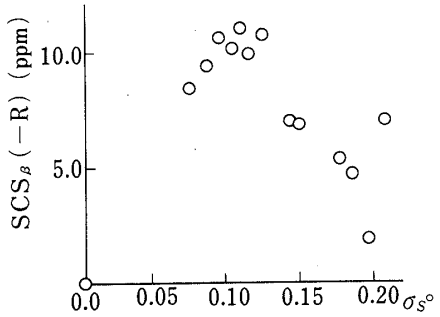

Fig. 1. Correlation between σ_{s° and ^{13}C SCS at the β-Position of BuR Bearing a −R Group

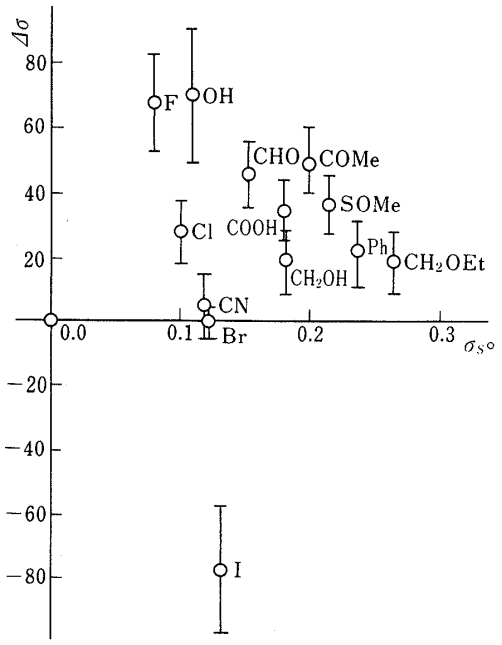

Fig. 2. Correlation between ^{13}C Shielding Anisotropies $\Delta\sigma$ and σ_{s° of MeR

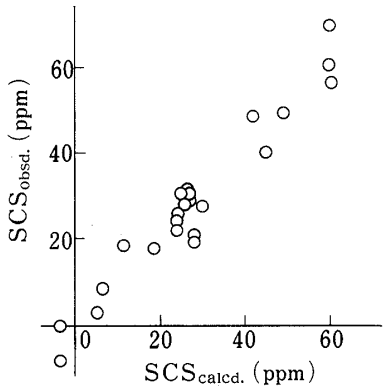

Fig. 3. Correlation between Observed and Calculated SCS of BuR(^{13}C-α)

$SCS_{calcd.} = 138.12\sigma_i + 175.53\sigma_{s^\circ}^{+} - 3510.98\sigma_{s^\circ_{MA}}\beta^{2.16}$

$r=0.674$ obtained by using two descriptors, σ_i and $\sigma_{s^\circ}^{+}$, could be improved to 0.937 on addition of the $(\sigma_{s^\circ}^{+})^2$ term as a descriptor.

The choice of a quadratic equation of σ_{s° —in other words, the presence of entropy maxima of ^{13}C SCS$_\alpha$ and SCS$_\beta$, as well as an entropy minimum of SCS$_\gamma$— suggests the existence of a most favorable or unfavorable thermodynamic state. The ΔS° data given by Brown *et al.*[14] for the thermal dissociation of amine-boron adduct and those determined in the dissociation of $R\cdot CH_2CO_2H$ in aqueous media[15] could be regarded as typical examples.

Magnetic Anisotropy Effect in Regression Analysis

To take account of the contribution of diamagnetic shielding to SCS, two parameters, namely, magnetic susceptibility χ and magnetic shielding σ, could be taken into account, where σ and χ are represented by Eqs. 1 and 2.[16]

$$\sigma^{d}_{avg} = (1/3c^2)\langle 1/r\rangle \quad (1)$$

$$\chi^{d}_{avg} = (1/4c^2)\langle r^2\rangle \quad (2)$$

where c denotes the velocity of light, and $\langle r\rangle$ means the average value of molecular radius.

In addition, the values of observed ^{13}C shielding anisotropy $\Delta\sigma$ of monosubstituted methanes determined experimentally[17] are assumed to be quadratic with respect to σ_{s° as illustrated in Fig. 2, where the data for halogens (Cl, Br, I) and CN gave another line bisecting the parabola. Consequently, an equation containing $-a(\sigma_{s^\circ})^2 + b\sigma_{s^\circ} + c$ includes the anisotropy $\Delta\sigma$, except for the 4 kinds of substituents written above. In this work, the additional contribution due to these 4 groups is expressed by the symbol $\sigma_{s^\circ_{MA}}$, corresponding to the square term $(\sigma_{s^\circ})^2$ followed by Eq. 2. Namely, the numerical values of $\sigma_{s^\circ_{MA}}$ for halogens and

CN are the same as the $(\sigma_{s^\circ})^2$ values of the 4 groups.

Electric Field Effect in Regression Analysis

The component E_z of the electric field effect is given by Eq. 3,[18] having dimensions of $(erg \cdot cm^{-3})^{1/2}$

$$E_z = 2\mu \cos\theta / r^3 \tag{3}$$

Ez could be divided into two parts, namely an enthalpic term expressed by σ_i or σ_π, and an entropic term expressed by σ_{s°.

Results of Regression Analyses

The results of comparisons of the observed ^{13}C and ^1H chemical shifts in the gas phase with those in CCl_4 solution are summarized in the following regression equations.

(−R): electron-donating group
(+R): electron-attracting group
(T): sum of electron-donating and electron-attracting group

I-1. ^{13}C SCS at α-Position of BuR (in CCl_4) (*cf.* Fig. 3)

$$(-R):\ SCS_\alpha = 143.09\sigma_i + 138.68\sigma_{s^\circ} - 3640.34\sigma_{s\hat{M}A} + 2.16$$
$$(\pm 11.19)\quad (\pm 23.58)\quad (\pm 277.94)\quad (\pm 3.87)$$
$$r = 0.979,\ SD = 5.03,\ n = 14,\ F = 77.00$$
$$(R = NMe_2,\ NH_2,\ OEt,\ OMe,\ OH,\ \textit{tert}\text{-Bu},\ \text{iso-Pr},\ Et,\ Me,\ F,\ Cl,\ Br,\ I,\ H)$$

$$(+R):\ SCS_\alpha = 131.53\sigma_i - 3534.84\sigma_{s\hat{M}A} - 2.86$$
$$(\pm 15.26)\quad (\pm 435.32)\quad (\pm 3.73)$$
$$r = 0.965,\ SD = 4.99,\ n = 10,\ F = 46.70$$
$$(R = H,\ COPh,\ COEt,\ COMe,\ CHO,\ CONH_2,\ COOEt,\ COOMe,\ CN,\ NO_2)$$

$$(\ T):\ SCS_\alpha = 138.12\sigma_i + 175.53\sigma_{s^\circ}^+ - 3510.98\sigma_{s\hat{M}A} - 3.49 \tag{4}$$
$$(\pm 9.99)\quad (\pm 16.20)\quad (\pm 238.68)\quad (\pm 2.77)$$
$$r = 0.967,\ SD = 5.23,\ n = 23,\ F = 91.46$$

I-2. ^{13}C CS at α-Position of PrR (Gas Phase)

$$(\ T):\ CS_\alpha = 128.67\sigma_i + 178.32\sigma_{s^\circ}^+ - 3564.78\sigma_{s\hat{M}A} - 16.89 \tag{5}$$
$$(\pm 32.27)\quad (\pm 41.92)\quad (\pm 522.45)\quad (\pm 8.11)$$
$$r = 0.928,\ SD = 6.52,\ n = 14,\ F = 20.68$$
$$(R = NH_2,\ OMe,\ OH,\ \textit{tert}\text{-Bu},\ \text{iso-Pr},\ Cl,\ Br,\ I,\ COEt,\ COMe,\ CHO,\ COOEt,\ COOMe,\ CN)$$

In our previous report[19] of this series, the torsion barrier V determined on the MeR series (R = electron-donating substituent) was found to be dependent on ΔS°_+. The relation expressed by Eq. 6 suggests that the torsion barrier is well defined by $\sigma_{s^\circ}^+$.

$$V = 17.18\sigma_{s^\circ}^+ + 0.42 \tag{6}$$
$$(\pm 2.28)(\pm 0.29)$$
$$r = 0.915,\ SD = 0.67,\ n = 13,\ F = 56.92$$

I-3. ^1H SCS at α-Position of PrR (in CCl_4)

$$(-R):\ SCS_\alpha = 8.30\sigma_i + 9.23\sigma_{s^\circ} - 22.98(\sigma_{s^\circ})^2 - 68.51\sigma_{s\hat{M}A} + 0.02$$
$$(\pm 0.77)\quad (\pm 3.32)\quad (\pm 11.35)\quad (\pm 16.69)\quad (\pm 0.24)$$
$$r = 0.983,\ SD = 0.24,\ n = 11,\ F = 42.21$$
$$(R = NH_2,\ OPr,\ OEt,\ OMe,\ OH,\ \textit{tert}\text{-Bu},\ Et,\ Cl,\ Br,\ I,\ H)$$

(+R): $SCS_\alpha = 7.23\sigma_i - 111.63\sigma_{s\mathring{M}A} - 0.04$
$(\pm 0.86)\quad (\pm 24.43)\quad (\pm 0.21)$

$r = 0.954$, SD $= 0.28$, $n = 10$, $F = 35.69$

(R = H, COPh, COEt, COMe, CHO, $CONH_2$, COOEt, COOMe, CN, NO_2)

(T): $SCS_\alpha = 7.73\sigma_i + 14.02\sigma_{s^\circ}^+ - 37.75(\sigma_{s^\circ}^+)^2 - 77.27\sigma_{s\mathring{M}A} - 0.20$ (7)
$(\pm 0.71)\quad (\pm 2.74)\quad (\pm 11.57)\quad (\pm 16.31)\quad (\pm 0.19)$

$r = 0.947$, SD $= 0.31$, $n = 20$, $F = 32.70$

I-4. ^{1}H CS at α-Position of PrR (Gas Phase)

(T): $CS_\alpha = 7.59\sigma_i + 21.37\sigma_{s^\circ}^+ - 75.05(\sigma_{s^\circ}^+)^2 - 87.69\sigma_{s\mathring{M}A} - 1.62$ (8)
$(\pm 0.90)\quad (\pm 3.21)\quad (\pm 19.63)\quad (\pm 15.08)\quad (\pm 0.26)$

$r = 0.964$, SD $= 0.25$, $n = 15$, $F = 32.72$

(R = NH_2, OMe, OH, *tert*-Bu, Et, Cl, Br, I, COEt, COMe, CHO, COOEt, COOMe, CN, NO_2)

II-1. ^{13}C SCS at β-Position of BuR (in CCl_4)

The previous result[19]
$SCS_\beta = 1.46\Delta S_+^\circ - 0.05\ (\Delta S_+^\circ)^2 - 0.02$
was revised to Eq. 9 in this work.

(−R): $SCS_\beta = 0.86\sigma_i + 170.31\sigma_{s^\circ} - 754.51(\sigma_{s^\circ})^2 - 0.02$
$(\pm 2.35)\quad (\pm 19.66)\quad (\pm 87.54)\quad (\pm 1.00)$

$r = 0.965$, SD $= 1.04$, $n = 13$, $F = 40.67$

(R = NMe_2, NH_2, OMe, OH, *tert*-Bu, iso-Pr, Et, Me, F, Cl, Br, I, H)

(+R): $SCS_\beta = 8.61\sigma_i - 0.25$
$(\pm 1.57)\quad (\pm 0.44)$

$r = 0.913$, SD $= 0.59$, $n = 8$, $F = 30.22$

(R = H, COPh, COEt, COMe, COOEt, COOMe, CN, NO_2)

(T): $SCS_\beta = 4.18\sigma_i + 143.25\sigma_{s^\circ}^+ - 638.20(\sigma_{s^\circ}^+)^2 + 0.82$ (9)
$(\pm 1.77)\quad (\pm 10.09)\quad (\pm 56.76)\quad (\pm 0.57)$

$r = 0.968$, SD $= 1.02$, $n = 20$, $F = 80.30$

II-2. ^{13}C CS at β-Position of PrR (Gas Phase)

(T): $CS_\beta = 5.96\sigma_i + 148.83\sigma_{s^\circ}^+ - 672.23(\sigma_{s^\circ}^+)^2 - 13.71$ (10)
$(\pm 2.93)\quad (\pm 13.00)\quad (\pm 79.68)\quad (\pm 0.98)$

$r = 0.968$, SD $= 1.12$, $n = 15$, $F = 54.26$

(R = NH_2, OMe, OH, *tert*-Bu, iso-Pr, Et, Cl, Br, I, COEt, COMe, COOEt, COOMe, CN, NO_2)

II-3. ^{1}H SCS at β-Position of PrR (in CCl_4)

(−R): $SCS_\beta = 1.62\sigma_i - 0.07$
$(\pm 0.15)\quad (\pm 0.03)$

$r = 0.964$, SD $= 0.07$, $n = 11$, $F = 118.43$

(R = the same as those included in I-3)

(+R): $SCS_\beta = 1.48\sigma_i - 1.97\sigma_{s\mathring{M}A} - 0.02$
$(\pm 0.20)\quad (\pm 0.66)\quad (\pm 0.05)$

$r = 0.943$, SD $= 0.07$, $n = 10$, $F = 27.83$

(R = the same as those included in I-3)

$$(\ T): SCS_\beta = 1.63\sigma_i - 18.20\sigma_{s\hat{M}A} - 0.07 \quad (11)$$
$$(\pm 0.12)\ \ (\pm 5.07)\ \ (\pm 0.03)$$

$r = 0.959$, SD = 0.06, $n = 20$, $F = 96.90$

II-4. ^{1}H CS at β-Position of PrR (Gas Phase)

$$(\ T): CS_\beta = 1.40\sigma_i - 23.89\sigma_{s\hat{M}A} - 0.76 \quad (12)$$
$$(\pm 0.12)\ \ (\pm 4.66)\ \ (\pm 0.03)$$

$r = 0.962$, SD = 0.06, $n = 15$, $F = 73.88$

(R = the same as those included in I-4)

III-1. ^{13}C SCS at γ-Position of BuR (in CCl_4)

$$(-R): SCS_\gamma = -13.54\sigma_i - 44.07\sigma_{s^\circ} + 154.71(\sigma_{s^\circ})^2 + 298.59\sigma_{s\hat{M}A} - 0.02$$
$$(\pm 1.15)\ \ (\pm 8.27)\ \ (\pm 33.63)\ \ (\pm 27.36)\ \ (\pm 0.48)$$

$r = 0.980$, SD = 0.49, $n = 14$, $F = 55.44$

(R = the same as those included in I-1)

$$(+R): SCS_\gamma = -11.37\sigma_i + 126.60\sigma_{s\hat{M}A} - 0.02$$
$$(\pm 0.16)\ \ (\pm 4.46)\ \ (\pm 0.04)$$

$r = 0.999$, SD = 0.05, $n = 10$, $F = 2686.77$

(R = the same as those included in I-1)

$$(\ T): SCS_\gamma = -12.82\sigma_i - 44.30\sigma_{s^\circ}^{+} + 151.84(\sigma_{s^\circ}^{+})^2 + 249.67\sigma_{s\hat{M}A} + 0.15 \quad (13)$$
$$(\pm 1.02)\ \ (\pm 5.02)\ \ (\pm 25.39)\ \ (\pm 25.20)\ \ (\pm 0.28)$$

$r = 0.960$, SD = 0.53, $n = 23$, $F = 53.09$

III-2. ^{13}C CS at γ-Position of PrR (Gas Phase)

$$(\ T): CS_\gamma = -12.43\sigma_i - 53.11\sigma_{s^\circ}^{+} + 206.83(\sigma_{s^\circ}^{+})^2 + 267.59 \quad (14)$$
$$(\pm 2.49)\ \ (\pm 8.48)\ \ (\pm 50.07)\ \ (\pm 41.80)$$

$r = 0.930$, SD = 0.70, $n = 16$, $F = 17.63$

(R = NH_2, OMe, OH, *tert*-Bu, iso-Pr, Et, Cl, Br, I, COEt, COMe, CHO, COOEt, COOMe, CN, NO_2)

III-3. ^{1}H SCS at γ-Position of PrR (in CCl_4)

$$(-R): SCS_\gamma = 0.20\sigma_i + 6.20\sigma_{s\hat{M}A} + 0.03$$
$$(\pm 0.06)\ \ (\pm 1.33)\ \ (\pm 0.01)$$

$r = 0.964$, SD = 0.02, $n = 11$, $F = 52.32$

(R = the same as those included in I-3)

$$(+R): SCS_\gamma = 0.40\sigma_i + 5.56\sigma_{s\hat{M}A} + 0.01$$
$$(\pm 0.10)\ \ (\pm 2.82)\ \ (\pm 0.02)$$

$r = 0.919$, SD = 0.03, $n = 10$, $F = 19.10$

(R = the same as those included in I-3)

$$(\ T): SCS_\gamma = 0.34\sigma_i + 4.41\sigma_{s\hat{M}A} + 0.02 \quad (15)$$
$$(\pm 0.06)\ \ (\pm 1.32)\ \ (\pm 0.01)$$

$r = 0.915$, SD = 0.03, $n = 20$, $F = 43.44$

III-4. ^{1}H CS at γ-Position of PrR (Gas Phase)

$$(\ T): SC_\gamma = 0.16\sigma_i + 3.71\sigma_{s\hat{M}A} - 1.18 \quad (16)$$
$$(\pm 0.04)\ \ (\pm 1.08)\ \ (\pm 0.01)$$

$r=0.920$, SD$=0.02$, $n=15$, $F=30.33$

(R = the same as those included in I-4)

These results suggest that the inclusion of $\sigma_{s\overset{\circ}{MA}}$ is indispensable. The correlation coefficient matrices of the 2 series in CCl_4 solution are as follows:

a. BuR ($n=23$)

	σ_i	$\sigma_{s^\circ}^+$	$(\sigma_{s^\circ}^+)^2$	$\sigma_{s\overset{\circ}{MA}}$
σ_i	1.000			
$\sigma_{s^\circ}^+$	−0.446	1.000		
$(\sigma_{s^\circ}^+)^2$	−0.482	0.955	1.000	
$\sigma_{s\overset{\circ}{MA}}$	0.479	0.053	−0.049	1.000

where substituent R = NMe_2, NH_2, OEt, OMe, OH, *tert*-Bu, iso-Pr, Et, Me, F, Cl, Br, I, H, COPh, COEt, COMe, CHO, $CONH_2$, COOEt, COOMe, CN, NO_2.

b. PrR ($n=20$)

	σ_i	$\sigma_{s^\circ}^+$	$(\sigma_{s^\circ}^+)^2$	$\sigma_{s\overset{\circ}{MA}}$
σ_i	1.000			
$\sigma_{s^\circ}^+$	−0.349	1.000		
$(\sigma_{s^\circ}^+)^2$	−0.336	0.943	1.000	
$\sigma_{s\overset{\circ}{MA}}$	0.516	0.063	−0.071	1.000

where substituent R = NH_2, OPr, OEt, OMe, OH, *tert*-Bu, Et, Cl, Br, I, H, COPh, COEt, COMe, CHO, $CONH_2$, COOEt, COOMe, CN, NO_2.

Conclusion

The results I-1—III-4 given above afford the following conclusions.

a. Both ^{13}C and ^1H SCS (or CS) can be expressed by linear combinations of the entropic and enthalpic contributions.

b. The fall-off of the coefficients of σ_i at the α-, β- and γ-positions are: 138.12, 4.18, −12.82 for ^{13}C and 7.73, 1.63, 0.34 for ^1H SCS in CCl_4 solution; 128.67, 5.96, −12.43 for ^{13}C and 7.59, 1.40, 0.16 for ^1H CS in the gas phase.

c. The participation of an entropic term for electron-attracting substituent groups could be ruled out for all ^{13}C and ^1H SCS. In contrast, the participation of the entropic term affords a parabola with a maximum among electron-donating substituent groups for β-^{13}C and α-^1H SCS, but gave a minimum for γ-^{13}C SCS. The inversion of the signs of coefficients observed between Eqs. 4 and 13, and between Eqs. 5 and 14 are consistent with the negative correlation between α-^{13}C and γ-^{13}C SCS.

d. The estimations of chemical shifts at the α, β, γ positions in both ^{13}C and ^1H NMR provided above suggest that the parameters governing chemical shifts of substituted *n*-alkanes in CCl_4 solution are the same as those in the vapor phase.

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