

# CHEMOMETRICAL ANALYSIS OF SUBSTITUENT EFFECTS. XIII. COMPARISON OF SUBSTITUENT EFFECTS ON DISSOCIATION AND CHEMICAL SHIFT IN $^{13}\text{C}$ NMR SPECTRA OF MONO- AND DISUBSTITUTED BENZOIC ACIDS

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The  $^{13}\text{C}$  chemical shifts have been measured of the carboxyl carbon atoms for all the 2-, 3-, and 4-substituted benzoic acids with H, CH<sub>3</sub>, CH<sub>3</sub>O, F, Cl, Br, I, and NO<sub>2</sub> substituents, as well as for all 3,4-, 3,5-, and 2,6-disubstituted benzoic acids with combinations of CH<sub>3</sub>, CH<sub>3</sub>O, Cl (or Br), NO<sub>2</sub> substituents and for symmetrically 2,6-disubstituted derivatives with Et, EtO, PrO, *i*-PrO, and BuO substituents. The chemical shifts of carboxylic group carbon atoms of the 3- and 4-substituted derivatives show correlation only with the substituent constants  $\sigma_1$ . For the 2-substituted derivatives was found the dependence only on  $\sigma_1$  and on the  $\nu$  constant describing steric effects ( $s = 0.122$ ,  $R = 0.996$ , without the CH<sub>3</sub> derivative which has a distinct anisotropic effect). The substituent effects on the carboxylic carbon chemical shift show additivity with 3,4-, 3,5-, and 2,6-substituents, and the 2,6-disubstituted derivatives show a linear synergic effect of substituents due obviously to the steric hindrance to resonance. Application of the principal component analysis to the data matrix involving all the combinations of mono- and disubstitution involving the above-mentioned substituents has proved an identical substituent effect from all the positions on the chemical shift described by one latent variable, steric effects and anisotropic behaviour of methyl at the 2 and 2,6 positions being predominantly described by the second latent variable (with the total explained variability of 99.5%). Comparison of substituent effects on the chemical shift of carboxylic carbon with that on the dissociation constant measured in the same solvent has confirmed the anisotropy due to *ortho* methyl group, the *ortho* halogen substituents in monosubstituted derivatives also having a different effect. The dependence of chemical shift on  $\text{p}K_a$  was not very close for the derivatives studied ( $s = 1.005$ ,  $R = 0.690$ ). The inclusion of anisotropy of *ortho* alkyl group by means of an indicator variable improved the correlation ( $s = 0.533$ ,  $R = 0.925$ ), and omitting of 2-F, 2-Cl, 2-Br, and 2-I substituents gave a regression without deviating points ( $s = 0.352$ ,  $R = 0.968$ ).

**Key words:**  $^{13}\text{C}$  substituent-induced chemical shifts; Disubstitution; *ortho* Effect; Dissociation of benzoic acids.

Studies of substituent effects on chemical shifts of other nuclei than proton (substituent-induced chemical shifts, SCS) have been made possible by development of apparatus, *i.e.* by the possibility of routine measurements of the NMR spectra of compounds with those nuclei<sup>1</sup>. The substituent effect on chemical shifts of atomic nuclei is more complex than that on equilibrium or rate constants. This is a consequence of manifestation of additional non-bonding interactions through space, which need not be associated with the properties described by standard substituent constants. Hence the quantitative evaluation of SCS adopts a variety of correlation equations; however, it seems most suitable to use either the classic Hammett constants ( $\sigma_m$ ,  $\sigma_p$ ) or the more general substituent constants separately describing the inductive ( $\sigma_I$ ), mesomeric ( $\sigma_R$ ,  $\sigma_R^0$ ,  $\sigma_R^-$ ,  $\sigma_R^+$ ), and steric ( $\nu$ ) effects<sup>1</sup>. For a survey of this problem, see Exner *et al.*<sup>2-6</sup>.

Papers dealing with SCS frequently concern the atoms in benzene ring<sup>7-9</sup> but also those in side chains<sup>10-29</sup>. Although there are papers dealing with the carboxyl carbon atom of benzoic acid<sup>10-13</sup>, more frequent are structural studies of related compounds such as methyl<sup>3,4,13</sup> or ethyl benzoates<sup>10</sup>, benzamides<sup>10,14-16</sup> and thiobenzamides<sup>14</sup>, benzonitriles<sup>2,17</sup>, benzaldehydes<sup>10,18</sup>, acetophenones<sup>10,18-21</sup>, benzophenones<sup>10,24</sup>, and chalcones<sup>22</sup>. Another frequently studied type of compounds with carbon atoms in side chains is styrenes<sup>23-27</sup>. The substituent effect on the chemical shifts of nuclei in side chains was studied almost exclusively from the *meta* and *para* positions, whereas papers dealing with the *ortho* substituent effect on NMR chemical shifts are substantially rarer<sup>28,29</sup>. If a correlation is available, its fit (in the case of the <sup>13</sup>C NMR chemical shift) can be, in the best case, expressed by the value of residual standard deviation  $s \approx 0.1$  ppm, whereas the usual value is about 0.3 ppm or even more<sup>2,3,8,22</sup>.

From the survey given it follows that benzoic acid – the basic molecule of classical studies of the substituent effect – has been investigated relatively little from the point of view of SCS: neither the *ortho* effect has been examined nor the additivity of disubstitution has been proved; the corresponding data about dissociation constants in the same substituted series are known. The aim of the present paper is to measure the <sup>13</sup>C NMR chemical shifts of carboxylic carbon in the series of 2-, 3-, 4-substituted and 3,4-, 3,5- and 2,6-disubstituted benzoic acids, to verify the validity of correlation relationships for these models and the additivity of substituent effects for disubstitution, and to evaluate the relationship between the chemical shifts and dissociation constants of the same substituted benzoic acids.

## EXPERIMENTAL

The syntheses of the mono- and disubstituted benzoic acids used, the methods of potentiometric measurements of  $pK_a$  of the compounds in dimethyl sulfoxide are described elsewhere<sup>30-34</sup>. Additional measurements were carried out in the same way for 3-methylbenzoic acid ( $pK_a = 11.21 \pm 0.05$ ), 3-methoxybenzoic acid ( $pK_a = 10.91 \pm 0.03$ ), 3-fluorobenzoic acid ( $pK_a = 10.07 \pm 0.04$ ), 3-chlorobenzoic acid ( $pK_a = 10.00 \pm 0.02$ ), 3-iodobenzoic acid ( $pK_a = 10.02 \pm 0.06$ ), 3-nitrobenzoic acid ( $pK_a = 9.26 \pm 0.01$ ), 4-fluorobenzoic acid ( $pK_a = 10.61 \pm 0.01$ ), 4-iodobenzoic acid ( $pK_a = 10.35 \pm 0.03$ ), and 2,6-diethylbenzoic acid ( $pK_a = 10.69 \pm 0.01$ ). The  $^{13}\text{C}$  NMR spectra of the compounds studied were measured on a Bruker AMX 360 apparatus at 90.56 MHz in standard way at 25 °C. The samples were dissolved in hexadeuteriodimethyl sulfoxide, the solvent signal serving as a standard ( $\delta$  39.60 ppm).

## RESULTS AND DISCUSSION

*Substituent Effect on Chemical Shift of Carboxylic Carbon in Mono-substituted Benzoic Acids*

The chemical shifts of carbon atom of carboxylic group of 2-, 3-, and 4-substituted benzoic acids in hexadeuteriodimethyl sulfoxide are presented in Table I. The method of linear regression was adopted to evaluate the dependence of these quantities on substituent constants<sup>35</sup>  $\sigma_I$ ,  $\sigma_R$  and – for the 2 position – also the  $\nu$  parameter describing the steric requirements of substituent<sup>36</sup>; the results are given in Eqs (1) through (4).

TABLE I  
 $^{13}\text{C}$  NMR chemical shifts ( $\delta$ , DMSO- $d_6$ ) of the carboxylic carbons in 2-, 3-, and 4-substituted benzoic acids

| Substituent       | 2-     | 3-     | 4-     |
|-------------------|--------|--------|--------|
| H                 | 167.48 | 167.48 | 167.48 |
| CH <sub>3</sub>   | 168.88 | 167.66 | 167.63 |
| CH <sub>3</sub> O | 167.56 | 167.38 | 167.24 |
| F                 | 165.36 | 166.40 | 166.51 |
| Cl                | 166.95 | 166.32 | 166.74 |
| Br                | 167.62 | 166.22 | 166.87 |
| I                 | 168.45 | 166.04 | 167.06 |
| NO <sub>2</sub>   | 166.27 | 165.74 | 165.99 |

$$\delta_4 = (167.7 \pm 0.1) - (2.09 \pm 0.31)\sigma_1, \quad (1)$$

$$n = 8, s = 0.195, R = 0.942$$

$$\delta_3 = (167.6 \pm 0.2) - (2.80 \pm 0.50)\sigma_1, \quad (2)$$

$$n = 8, s = 0.320, R = 0.916$$

$$\delta_2 = (167.3 \pm 0.3) - (5.08 \pm 0.76)\sigma_1 + (381 \pm 0.63)\nu, \quad (3)$$

$$n = 8, s = 0.379, R = 0.962$$

After elimination of the deviating point of 2-CH<sub>3</sub> substituent:

$$\delta_2 = (167.5 \pm 0.1) - (6.81 \pm 0.40)\sigma_1 + (466 \pm 0.26)\nu, \quad (4)$$

$$n = 7, s = 0.122, R = 0.996.$$

The correlation of chemical shift of carbon in non-dissociated carboxylic acid depending on 4-substituents (Eq. (1)) is relatively close, which is probably caused by statistical nonsignificance (at the significance level  $\alpha = 0.05$ ) of the parameter describing the mesomeric effect. This parameter is significant at the significance level  $\alpha = 0.027$ . The signs of both reaction constants indicate that electron-acceptor substituents cause a decrease in electron density at the centre measured. 3-Substituents exert inductive effect depending on the used relationship (Eq. (2)). A statistically different effect on the chemical shift of carboxylic carbon, as compared with the other substituents, is observed in the case of methoxy group, the experimental value being higher than the predicted one. We have no logical explanation for this finding yet. At position 2, the mesomeric effect does not make itself felt but steric effects are manifested (Eqs (3) and (4)). Methyl group, the experimental value here being lower than the predicted one, exerts an exceptional influence on the carboxyl chemical shift. We explain this phenomenon by increased shielding of carboxylic carbon by hydrogen atoms in methyl group. The chemical shift of the carboxylic carbon increases with increasing steric requirements of the *ortho* substituent. From that we deduce that the deviation of carboxylic group out of the benzene ring plane

lowers the extent of conjugation between both systems, and – on the other hand – the mesomeric stabilisation within the carboxylic group itself is increased, which is associated with an increase in the electron density at the carbon atom measured. The same reason, obviously, eliminates the mesomeric effect.

Comparison of values of reaction constants affected from positions 2, 3, and 4 indicates a systematic decrease in the inductive effect with decreasing distance of the substituent from the reaction centre, which is in accordance with the generally accepted views.

In order to compare our results with the earlier published ones<sup>10</sup> we have carried out analysis of data by means of the Principal Component Analysis (PCA). For various model compounds with reaction centres CONH<sub>2</sub>, COOCH<sub>2</sub>CH<sub>3</sub>, COOH, COCH<sub>3</sub>, CHO, OCOCH<sub>3</sub> (columns of the source matrix) chemical shifts of carboxyl carbon atom have been compared analogous values obtained from our measurements for the substituents H, CH<sub>3</sub>, OCH<sub>3</sub>, F, Cl, Br, NO<sub>2</sub> (rows of the source matrix). The comparison only concerned the 3- and 4-substituted derivatives, because the earlier works did not include the *ortho* derivatives.

Only one latent variable has been found for the 3-substituents (98.90% of explained variability). The measure of common explained variability is high and indicates an identical mechanism of influence of chemical environment on the chemical shift of carbon atom of the centre measured. The latent variable shows a close fit with the  $\sigma_I$  scale ( $r = 0.949$ ), hence the change in chemical shift with a change of substituent is due to inductive effects of substituents. The comparison of communalities corresponding to the individual columns representing the corresponding functional groups showed that the results of our measurements ( $h^2 = 0.992$ ) exhibit a high measure of accordance with the others.

The calculation for 4-substituted model compounds gave two latent variables (the first latent variable 88.48%, the second latent variable 10.82%, and total 99.30%). These two latent variables fully explain the variability of data. We carried out orthogonal rotation of the score matrix maximising the approach to the scale of  $\sigma_I$  and  $\sigma_R$  substituent constants (rotation by 5.923°). After this operation, the first latent variable correlated closely with the  $\sigma_I$  substituent constant ( $r = 0.986$ ) while the second latent variable correlated with  $\sigma_R$  ( $r = 0.968$ ), hence it can be stated that the latent variables express these variables. The comparison of communalities for the first latent variable indicates the measure of accordance of results of our measurement ( $h^2 = 0.955$ ) with the columns representing carboxyl ( $h^2 = 0.976$ ), amide ( $h^2 = 0.968$ ), and ester ( $h^2 = 0.927$ ). A lower measure of common vari-

ability can be observed for the columns with the following reaction centres: acetyl ( $h^2 = 0.901$ ), aldehyde ( $h^2 = 0.876$ ), and phenyl acetate ( $h^2 = 0.529$ ). This is probably caused in these cases by the presence of another type of reaction centre as compared with the carboxyl carbon atom in the functional derivatives of substituted benzoic acid. On the whole it can be concluded that the values of chemical shift of carboxyl carbon atom from our measurements are comparable with the data published earlier<sup>10</sup>.

*Additivity of Substituent Effect on  $^{13}\text{C}$  NMR Chemical Shift of Carboxylic Carbon in Disubstituted Benzoic Acids*

The most suitable way of evaluation of additivity of substituent effects in disubstituted derivatives is a correlation using the explaining variable obtained by summation of the values valid for the individual derivatives and subtraction of the value of the parent compound. In this way, we obtained the following relationships for the respective combinations of substituents  $\text{CH}_3$ ,  $\text{CH}_3\text{O}$ ,  $\text{Cl}$  ( $\text{Br}$ ), and  $\text{NO}_2$  given in Tables I and II.

$$\delta_{3,4} = (9.72 \pm 6.81) + (0.94 \pm 0.04)(\delta_3 + \delta_4 - \delta_{\text{H}}), \quad (5)$$

$$n = 16, s = 0.163, R = 0.987$$

$$\delta_{3,5} = (7.58 \pm 3.51) + (0.95 \pm 0.02)(\delta_3 + \delta_5 - \delta_{\text{H}}), \quad (6)$$

$$n = 10, s = 0.082, R = 0.998$$

$$\delta_{2,6} = -(6.38 \pm 5.56) + (1.38 \pm 0.03)(\delta_2 + \delta_6 - \delta_{\text{H}}), \quad (7)$$

$$n = 10, s = 0.156, R = 0.998$$

If the effects were additive, the relationships given should have slope unity and cross the origin. This hypothesis can be statistically tested. At the significance level  $\alpha = 0.05$ , the hypothesis mentioned applies to the 3,4- and 3,5-disubstituted derivatives (Eqs (5) and (6)). Hence, the substituent effects from these positions on the chemical shift of carboxylic carbon in  $^{13}\text{C}$  NMR spectra of benzoic acids are additive. The same result was also obtained for the dissociation constants of the corresponding acids<sup>30,31</sup>. However, no sim-

ple interpretation can be given in the case of the dependence for the 2,6-disubstituted derivatives (Eq. (7)) although it is linear and well-fitting. The slope of dependence is higher than unity, which indicates some synergic effect, most probably steric hindrance to resonance between the benzene ring and carboxylic group in the sense of interpretation of Eqs (3) and (4), respectively.

TABLE II  
 $^{13}\text{C}$  NMR chemical shifts ( $\delta$ , DMSO- $d_6$ ) of the carboxylic carbons in 3,4-, 3,5-, and 2,6-disubstituted benzoic acids

| Substituent       |                   | 3-X,4-Y | 3-X,5-Y | 2-X,6-Y |
|-------------------|-------------------|---------|---------|---------|
| X                 | Y                 |         |         |         |
| CH <sub>3</sub>   | CH <sub>3</sub>   | 167.55  | 167.67  | 170.86  |
| CH <sub>3</sub>   | CH <sub>3</sub> O | 167.38  | 167.34  | 168.99  |
| CH <sub>3</sub>   | Cl                | 166.73  | 166.28  | 168.14  |
| CH <sub>3</sub>   | NO <sub>2</sub>   | 165.92  | 165.71  | 167.29  |
| CH <sub>3</sub>   | CH <sub>3</sub>   | 167.41  | -       | -       |
| CH <sub>3</sub> O | CH <sub>3</sub> O | 167.19  | 167.13  | 166.89  |
| CH <sub>3</sub> O | Cl                | 166.61  | -       | 166.14  |
| CH <sub>3</sub> O | NO <sub>2</sub>   | 166.04  | 165.38  | 165.22  |
| Br                | CH <sub>3</sub>   | 166.11  | -       | -       |
| Br                | CH <sub>3</sub> O | 165.97  | 166.08  | -       |
| Cl                | Cl                | 165.91  | -       | 165.47  |
| Cl                | NO <sub>2</sub>   | 164.84  | 164.54  | 164.78  |
| NO <sub>2</sub>   | CH <sub>3</sub>   | 165.61  | -       | -       |
| NO <sub>2</sub>   | CH <sub>3</sub> O | 165.58  | -       | -       |
| NO <sub>2</sub>   | Cl                | 164.99  | -       | -       |
| NO <sub>2</sub>   | NO <sub>2</sub>   | 164.21  | 164.04  | 163.61  |
| Br                | Br                | -       | 164.84  | -       |
| Et                | Et                | -       | -       | 171.06  |
| EtO               | EtO               | -       | -       | 166.90  |
| PrO               | PrO               | -       | -       | 166.90  |
| i-PrO             | i-PrO             | -       | -       | 167.05  |
| BuO               | BuO               | -       | -       | 166.89  |

*Effect of the Disubstitution Type on Chemical Shift of the Carboxylic Carbon in Disubstituted Benzoic Acids*

For comparison of individual types of substitution, we compiled a set of values of chemical shifts for the carboxylic group carbon in Tables I and II for all combinations including H, CH<sub>3</sub>, CH<sub>3</sub>O, Cl (Br), and NO<sub>2</sub> substituents at positions 3,4, 3,5, and 2,6 using the principal component analysis (PCA). The source matrix contained 25 rows (substituents) and 3 columns (type of substitution). The first latent variable could explain 93.9% of total variability of data (96.5, 96.6, and 88.5 for 3,4-, 3,5-, and 2,6-disubstitution, respectively), whereas the second latent variable explained even 99.5% of total variability of data (99.4, 99.2, and 99.97 for 3,4-, 3,5-, and 2,6-disubstitution, respectively). If the column of 2,6-disubstitution is excluded, the first latent variable explains 99.4% of variability. The results show that the 2,6-disubstituted derivatives are different from 3,4- and 3,5-disubstituted derivatives, and the difference is mostly described by the second latent variable.

The regression of  $\delta_{2,6}$  vs  $\delta_{3,5}$  values (the same symmetry of disubstitution) and subsequent analysis of residues clearly show that the differences between the two types of substitution are caused by the values of methyl group at *ortho* position. The addition of an indicator variable into the regression expressing the number of methyl groups at position 2 leads to Eq. (8).

$$\delta_{2,6} = (2.27 \pm 16.11) + (0.99 \pm 0.01)\delta_{3,5} + (1.74 \pm 0.17)n_{\text{Me}} , \quad (8)$$

$$n = 8, s = 0.256, R = 0.996$$

From the results it is clear that the straight line crosses the origin and has slope unity, the differences being caused by the additive anisotropic effect of methyl group at position 2 as already stated. It is of interest that in comparison with the analysis of residues for the data described by Eq. (3), where the experimental value is lower than the predicted one, the opposite is true for Eq. (8). From that it follows that methyl group at *ortho* position shows a different behaviour in monosubstituted derivatives from that in the disubstituted ones.



*Substituent Effect on Chemical Shift of the Carboxylic Carbon and on Dissociation Constants of Benzoic Acids*

While the chemical shift of non-dissociated carboxylic group in the  $^{13}\text{C}$  NMR spectra is a measure of electron density at this centre, the dissociation constant is a measure of substituent effect on the energy difference between the non-dissociated and dissociated forms of the respective acid. The two forms need not be affected by the substituent in the same way; clearly, it can be expected that the substituent will affect the ionized form more strongly. Also the interaction between carboxylic/carboxylate group and an *ortho* substituent varies and its consequences for the quantities measured can vary, too. These presumptions start from known facts<sup>32-34</sup> and they made themselves felt also in the set investigated. Figure 1 presents the dependence of chemical shift vs  $\text{p}K_{\text{a}}$  (refs<sup>30-34</sup>) for all the derivatives from Tables I and II. From the figure as well as from the analysis of residues of the respective linear regression ( $s = 1.005$ ,  $R = 0.690$ ), it follows that the presence of alkyl group at *ortho* position is statistically indicated as a deviating point. The introduction of indicator variable indicating the number of alkyl groups at *ortho* position improves the quality of regression ( $s = 0.533$ ,  $R = 0.925$ ); nevertheless, the derivatives with 2-F, 2-Cl, 2-Br, and 2-I substituents continue to be indicated as deviating points. When these are eliminated, the linear regression gives Eq. (9).

$$\delta = (158.3 \pm 0.4) - (0.79 \pm 0.04) \log K_{\text{a}} + (2.07 \pm 0.11)n_{\text{Me}}, \quad (9)$$

$$n = 59, s = 0.352, R = 0.968$$

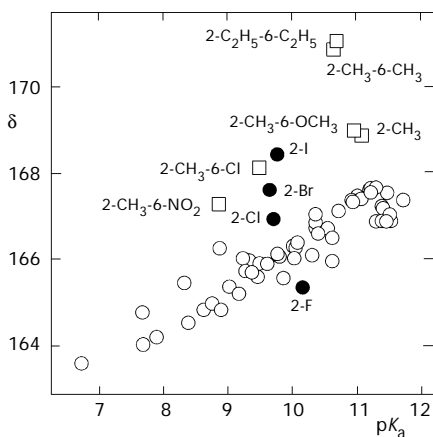


FIG. 1  
Dependence of  $^{13}\text{C}$  NMR chemical shifts ( $\delta$ ,  $\text{DMSO}-d_6$ ) of the carboxylic carbon in mono- and disubstituted benzoic acids upon their  $\text{p}K_{\text{a}}$  (● 2-halogen substituted derivatives, □ 2- or 2,6-disubstituted derivatives with alkyl groups, ○ other derivatives)

The dependence according to Eq. (9) does not show deviating points any longer and represents an average fit<sup>2,3,8,28</sup>. The anisotropy caused by methyl or ethyl group at *ortho* position is a fact that has been confirmed several times in the present paper. The different chemical shifts of carboxylic carbon in 2-halogenobenzoic acids, whose  $pK_a$  values are almost the same, are most probably caused by the steric effects associated with different extents of shielding of the carbon measured. Similar excesses were also found in the case of *ortho*-substituted nitrobenzenes<sup>28</sup> in their correlation with substituent constants. From Eq. (9), it follows that the magnitude of the chemical shift value of carboxylic carbon decreases with increasing acidity of the acid. This result could be expected since a substituent that stabilises the dissociated carboxylate must also lower the electron density at the carbon atom of non-dissociated carboxylic group.

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## REFERECES

1. Craik D. J., Brownlee R. T. C.: *Prog. Phys. Org. Chem.* **1983**, 14, 1.
2. Exner O., Buděšínský M.: *Magn. Reson. Chem.* **1989**, 27, 27.
3. Buděšínský M., Exner O.: *Magn. Reson. Chem.* **1989**, 27, 585.
4. Buděšínský M., Johnels D., Edlund U., Exner O.: *Collect. Czech. Chem. Commun.* **1991**, 56, 368.
5. Exner O., Buděšínský M.: *Collect. Czech. Chem. Commun.* **1991**, 56, 2234.
6. Exner O., Dahn H., Péchy P.: *Magn. Reson. Chem.* **1992**, 30, 381.
7. Bromilow J., Brownlee R. T. C., Lopez V. O., Taft R. W.: *J. Org. Chem.* **1979**, 44, 4766.
8. Bromilow J., Brownlee R. T. C., Craik D. J., Sadek M., Taft R. W.: *J. Org. Chem.* **1980**, 45, 2429.
9. Bromilow J., Brownlee R. T. C., Craik D. J., Sadek M.: *Magn. Reson. Chem.* **1986**, 24, 862.
10. Bromilow R. T. C., Brownlee D. J., Craik P. R., Fiske J. E., Rowe J. E., Sadek M.: *J. Chem. Soc., Perkin Trans. 2* **1981**, 753.
11. Kosugi Y., Furuya Y.: *Tetrahedron* **1980**, 36, 2741.
12. Guilleme J., Diez E., Garrigos L., Esteban A. L.: *Org. Magn. Reson.* **1984**, 22, 140.
13. Balakrishnan P., Baumstark A. L., Boykin D. W.: *Org. Magn. Reson.* **1984**, 22, 753.
14. Jones R. G., Wilkins J. M.: *Org. Magn. Reson.* **1978**, 11, 20.
15. Fong C. W., Grant H. G.: *Aust. J. Chem.* **1981**, 34, 1205.
16. Brownlee R. T. C., Sadek M.: *Magn. Reson. Chem.* **1986**, 24, 821.
17. Bromilow J., Brownlee R. T. C.: *Tetrahedron Lett.* **1975**, 25, 2113.
18. St. Amour T. E., Burgar M. I., Valentine B., Fiat D.: *J. Am. Chem. Soc.* **1981**, 103, 1128.
19. Dhami K. S., Stothers J. B.: *Can. J. Chem.* **1965**, 43, 479.
20. Rislely J. M., DeFrees S. A., Van Etten R. L.: *Org. Magn. Reson.* **1983**, 21, 28.
21. Frahm A. W., Hambloch H. F.: *Org. Magn. Reson.* **1980**, 14, 444.

22. Solčániová E., Toma Š., Gronowitz S.: *Org. Magn. Reson.* **1976**, 8, 439.
23. Happer D. A. R.: *Aust. J. Chem.* **1976**, 29, 2607.
24. Happer D. A. R., McKerrov S. M., Wilkinson A. L.: *Aust. J. Chem.* **1977**, 30, 1715.
25. Happer D. A. R.: *Aust. J. Chem.* **1982**, 35, 21.
26. Reynolds W. F., Gomez A., Maron A., McIntyre D. W., Maunder R. G., Tanin A., Wong H. E., Hamer G. K., Peat I. R.: *Can. J. Chem.* **1983**, 61, 2367.
27. Slater C. D., Robinson C. N., Bies R., Bryan D. W., Chang K., Hill A. W., Moore W. H., Otey T. G., Poppelreiter M. L., Reisser J. R., Stablein G. E., Waddy V. P., Wilkinson W. O., Wray W. A.: *J. Org. Chem.* **1985**, 50, 4125.
28. Rasala D., Gawinecki R.: *Magn. Reson. Chem.* **1992**, 30, 740.
29. Mezzina E., Spinelli D., Chimichi S., Frenna V., Lamartina L.: *Magn. Reson. Chem.* **1996**, 34, 1019.
30. Pytela O., Kulhánek J., Ludwig M., Říha V.: *Collect. Czech. Chem. Commun.* **1994**, 59, 627.
31. Pytela O., Kulhánek J., Ludwig M.: *Collect. Czech. Chem. Commun.* **1994**, 59, 1637.
32. Pytela O., Liška J.: *Collect. Czech. Chem. Commun.* **1994**, 59, 2005.
33. Kulhánek J., Pytela O.: *Collect. Czech. Chem. Commun.* **1995**, 60, 829.
34. Kulhánek J., Pytela O.: *Collect. Czech. Chem. Commun.* **1997**, 62, 913.
35. Exner O.: *Korelační vztahy v organické chemii*. SNTL, Praha 1981.
36. Charton M. in: *Similarity Models in Organic Chemistry, Biochemistry and Related Fields* (R. I. Zalewski, T. M. Krygowski and J. Shorter, Eds), p. 629. Elsevier, Amsterdam 1991.