# $^1H$ and $^{13}C$ NMR Spectra Simulation

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Received February 14, 1992

Similarities and differences between the systems for $^1H$ and $^{13}C$ NMR simulation of spectra are described. Both methods use semiempirical chemical shift calculation. Input for the simulation is the chemical structure edited by a two-dimensional structure editor. Both systems consist of tables of basic chemical shifts (for hydrogen or carbon atoms, respectively), tables containing different corrections and the coupling constants of protons, a LAOCOON program for higher-order spectra calculation, and programs for the graphical output of spectra.

## INTRODUCTION

The importance of simulation of different types of spectra can be clearly seen in any structure elucidation process. Due to the fact that structure identification cannot be accomplished in a straightforward manner:

different spectra → structure of the compound

simply by deducing the entire structure from the spectroscopic data, the process in the other direction:

candidate structures → simulated spectra

must also be possible. The principles of the spectral simulation process are theoretically more readily explained (vibrational analysis, resonance theory, etc.) than spectra-based structure identification. However, with the exception of relatively small molecules, the theoretical equations (Hamiltonians) with which the spectral features can be calculated from the structural data become excessively large and complex for "real-world" compounds. Spectra simulation procedures therefore are mainly carried out using correlation tables and different semiempirical methods, similar to those used in the structure elucidation process.

Consequently, the entire structure determination process must be performed iteratively, going from initial guesses of structural fragments and structural parts toward larger and larger structural groups until few final candidate structures are obtained. But even at this last step, having few molecules as possible candidates for the actual solution, the best way to select the correct one is to simulate all spectra of all candidates and search for the best agreement with the experiment.

Besides the structure elucidation process, where the spectral simulation plays a very important role as feedback information, the simulation of spectra is used for other purposes as well:

theoretical consideration
testing of hypotheses
checking of large databases for possible errors
aiding the isomer generation process
etc.

The above consideration of the structure elucidation process clearly shows that the more different spectroscopies are involved, the more structural information can be extracted from measurements. Therefore, the need for multispectroscopy simulation as a feedback corrective process is doubtless necessary.

In this paper, the simulation of $^1H$ and $^{13}C$ NMR spectra is discussed and the role of simulation in the structure elucidation process is shown in a short example.

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## SIMULATION OF NMR SPECTRA

In general, the simulation of any type of NMR spectrum, of $^1H$, $^{13}C$, or any other nucleus having a spin different from zero, is based on the evaluation of chemical shifts for all corresponding nuclei in the molecule (i.e., shifting of the resonance RF line with the respect to the standard line due to the magnetic field caused by the neighboring atoms). The chemical shifts can be observed only for the atomic nuclei having a spin different from zero.

Due to the fact that the hydrogen atom (spin $^1/_2$) is much more common in nature than the carbon isotope $^{13}C$ (spin $^1/_2$; $^{12}C$ has spin equal to zero) the $^1H$ NMR spectrum shows features different from those found in the $^{13}C$ NMR spectrum. The most significant influence in the $^1H$ NMR spectrum is the coupling of magnetic effects between different neighboring hydrogens. Due to a very low probability of $^{13}C$ carbon isotope atoms being neighbors in an molecule, the effect of spin–spin coupling is marginal in $^{13}C$ NMR spectroscopy.

**Decoupled Spectrum.** Each chemical shift $\sigma_{\text{nucleus } i}$ in the decoupled spectrum (i.e., a spectrum without coupling) can be calculated according to the same formula for any NMR spectroscopy:

$$\sigma_{\text{nucleus } i} = A_i + \sum_j Z_{ji} + \sum_k \text{corr}_k \qquad (1)$$

$A_i$ is the basic chemical shift of the nucleus $i$ for a given neighborhood (for example, a carbon in a benzene ring, proton in a $CH_3$- group, etc.). $Z_{ji}$ are changes of the basic chemical shift $A_i$ caused by the specific substituent $j$ in a given topological environment in the basic group with respect to the nucleus $i$. The last sum represents empirical corrections that should be applied in certain cases in order to obtain better agreement with the experimental data. These corrections are applied in the case when more substituents from the same substituting position have to be taken into account, in the case of conformations, and/or in the case of configurational corrections. One of the very important tasks of each NMR simulator is to detect *automatically* the cases where corrections $\text{corr}_k$ have to be applied.

For the simulation of the $^{13}C$ NMR spectrum, the values $A_i$, $Z_{ji}$, and $\text{corr}_k$ are stored in tables addressable according to the specific structural features. The program SIMULA[1-3] contains the chemical shifts for 39 basic environments (Table I) and 2479 values of increments $Z_{ji}$. Theoretically, for 150 substituents $j$ acting in all 39 basic environments $i$ from 2 to 7 different substituent positions ($\alpha$, $\alpha_1$, $\beta$, $\beta_1$, $\gamma$, $\gamma_1$, and $\delta$) 24 600 different corrections $Z_{ji}$ would be needed. Although

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**Table I.** All 39 Basic $^{13}C$ NMR Chemical Shifts $A_i$ (in ppm relative to TMS)

| functional group $i$ | $A_i$ (ppm) | functional group $i$ | $A_i$ (ppm) |
|---|---|---|---|
| alkane | −2.3 | structures with five-membered rings | |
| alkene | 123.3 | cyclopentane | 26.3 |
| alkyne | 71.9 | pyrrole $C_r$-2,5 | 118.0 |
| carboxylic acid, ester | 166.0 | pyrrole $C_r$-3,4 | 107.7 |
| amide | 165.0 | pyrrole N | |
| C=$C_r$=C | 213.5 | furan $C_r$-2,5 | 143.0 |
| $C_r$=C=C | 74.5 | furan $C_r$-3,4 | 109.9 |
| aldehyde, ketone | 193.0 | structures with six-membered rings | |
| CF | 75.2 | cyclohexane | 27.6 |
| $CF_3$ | 116.4 | benzene | 128.5 |
| CCl | 24.9 | pyridine $C_r$-2,6 | 149.8 |
| $CCl_2$ | 54.0 | pyridine $C_r$-3,5 | 123.6 |
| $CCl_3$ | 77.2 | pyridine $C_r$-4 | 135.7 |
| CBr | 10.2 | indole C-2 | 124.1 |
| $CBr_2$ | 21.4 | indole C-3 | 102.1 |
| $CBr_3$ | 12.1 | indole C-3a | 127.6 |
| CI | −20.7 | indole C-4 | 120.5 |
| structures with three-membered rings | | indole C-5 | 121.7 |
| cyclopropane | −2.8 | indole C-6 | 119.6 |
| oxirane | 39.8 | indole C-7 | 111.0 |
| structures with four-membered rings | | indole C-7a | 135.5 |
| cyclobutane | 23.1 | | |

**Table II.** Percentage of Available $Z_{ij}$ for All Basic Shifts

| functional group | possible no. | actual available | % |
|---|---|---|---|
| alkane | 600 | 467 | 77.8 |
| alkene | 300 | 116 | 38.7 |
| alkyne | 300 | 62 | 20.7 |
| carboxylic acid, ester | 600 | 153 | 25.5 |
| amide | 600 | 78 | 13.0 |
| C=$C_r$=C | 300 | 44 | 14.7 |
| $C_r$=C=C | 150 | 20 | 13.3 |
| aldehyde, ketone | 450 | 110 | 22.4 |
| CF | 600 | 2 | 0.3 |
| $CF_3$ | 600 | 10 | 1.7 |
| CCl | 600 | 20 | 3.3 |
| $CCl_2$ | 600 | 14 | 2.3 |
| $CCl_3$ | 600 | 21 | 3.5 |
| CBr | 600 | 23 | 3.8 |
| $CBr_2$ | 600 | 8 | 1.3 |
| $CBr_3$ | 600 | 3 | 0.5 |
| CI | 600 | 3 | 0.5 |
| cyclopropane | 300 | 39 | 13.0 |
| oxirane | 300 | 23 | 7.7 |
| cyclobutane | 450 | 24 | 5.3 |
| cyclopentane | 450 | 33 | 7.3 |
| pyrrole $C_r$-2,5 | 600 | 25 | 4.2 |
| pyrrole $C_r$-3,4 | 600 | 17 | 2.8 |
| pyrrole N | 300 | 6 | 2.0 |
| furan $C_r$-2,5 | 600 | 72 | 12.0 |
| furan $C_r$-3,4 | 600 | 44 | 7.3 |
| cyclohexane | 600 | 201 | 33.5 |
| benzene | 600 | 360 | 60.0 |
| pyridine $C_r$-2,6 | 750 | 92 | 12.3 |
| pyridine $C_r$-3,5 | 750 | 106 | 14.1 |
| pyridine $C_r$-4 | 450 | 60 | 13.3 |
| indole C-2 | 1 050 | 28 | 2.7 |
| indole C-3 | 1 050 | 27 | 2.6 |
| indole C-3a | 1 050 | 34 | 3.2 |
| indole C-4 | 1 050 | 27 | 2.6 |
| indole C-5 | 1 050 | 27 | 2.6 |
| indole C-6 | 1 050 | 26 | 2.5 |
| indole C-7 | 1 050 | 27 | 2.6 |
| indole C-7a | 1 050 | 27 | 2.6 |
| total | 24 600 | 2479 | 10.1 |

the number 2479 for different contributions (representing only 10% of all possible corrections $Z_{ji}$) seems to be small, the missing contributions are largely from the less-common substituents. As can be seen from Table II, the percentage of available corrections $Z_{ji}$ for the most frequent substituents like alkanes, alkenes, carboxylic acids and esters, ketones, benzenes, cyclohexanes, etc. are far above this average value.

Less than half of the data (1049 $Z_{ji}$ values) used by the SIMULA program were taken from the literature,[4-15] while the rest of them (1430) were obtained in our laboratory.[2,3]

In contrast to the $^{13}C$ NMR simulation, in the case of $^1H$ NMR spectra the decoupled approach (eq 1) is seldom used as a final result; its value is mainly as the starting or initial step for more complicated procedures. Due to the fact that the protons form a smaller number of basic structural environments than the carbon atoms do, the list of basic shifts (Table III) is shorter than the list in Table I (22 vs 39), and the list of substructures is smaller in the case of $^1H$ NMR compared to $^{13}C$ NMR (85 vs 150, Table IV). The same is true for the list of different topological positions of the substituents with respect to the basic group (4 vs 7).

**Simulation of First-Order Spectra.** When the coupling constants $J_{AB}$ between two nuclei A and B with the nonzero spins have to be taken into the account, the basic chemical shifts $\sigma_A$ and $\sigma_B$ of the particular two nuclei are always split into more peaks. In the first-order approximation **each** coupling constant $J_{AB}$ produces four peaks instead of two peaks $\sigma_A$ and $\sigma_B$:

$$\sigma_{1A} = {}^1/_2(J_{AB} + \sqrt{(J_{AB}{}^2 + (\sigma_A - \sigma_B)^2)})$$

$$\sigma_{2A} = {}^1/_2(-J_{AB} + \sqrt{(J_{AB}{}^2 + (\sigma_A - \sigma_B)^2)})$$

$$\sigma_{3B} = {}^1/_2(J_{AB} - \sqrt{(J_{AB}{}^2 + (\sigma_A - \sigma_B)^2)})$$

$$\sigma_{4B} = {}^1/_2(-J_{AB} - \sqrt{(J_{AB}{}^2 + (\sigma_A - \sigma_B)^2)}) \quad (2)$$

Each of the four peaks (eq 2) has the following relative intensity:

$$\text{intensity}(\sigma_{1A}) = 1 - J_{AB}/\sqrt{(J_{AB}{}^2 + (\sigma_A - \sigma_B)^2)}$$

$$\text{intensity}(\sigma_{2A}) = 1 + J_{AB}/\sqrt{(J_{AB}{}^2 + (\sigma_A - \sigma_B)^2)}$$

$$\text{intensity}(\sigma_{3B}) = 1 + J_{AB}/\sqrt{(J_{AB}{}^2 + (\sigma_A - \sigma_B)^2)}$$

$$\text{intensity}(\sigma_{4B}) = 1 - J_{AB}/\sqrt{(J_{AB}{}^2 + (\sigma_A - \sigma_B)^2)} \quad (3)$$

**Table III.** All 22 Basic $^1H$ NMR Chemical Shifts $A_i$ (in ppm relative to TMS)

| functional group $i$ | $A_i$ (ppm) | functional group $i$ | $A_i$ (ppm) |
|---|---|---|---|
| methyl ($-CH_3$) | 0.23 | benzene | 7.26 |
| ethyl ($-CH_2-CH_3$) | 0.86 | pyrrole ($H_1$-substituent) | 9.50 |
| *n*-propyl ($-CH_2-CH_2-CH_3$) | 1.33 | pyrrole ($H_2$-substituent) | 6.62 |
| *n*-propyl ($-CH_2-CH_2-CH_3$) | 0.91 | pyrrole ($H_3$-substituent) | 6.05 |
| isopropyl ($-CH(CH_3)_2$) | 1.33 | thiophene ($H_2$-substituent) | 7.20 |
| isopropyl ($-CH(CH_3)_2$) | 0.91 | thiophene ($H_3$-substituent) | 6.96 |
| *t*-butyl ($-C(CH_3)_3$) | 0.89 | pyridine ($H_2$-substituent) | 8.59 |
| other alkane ($CH_2R^1R^2$) | 1.25 | pyridine ($H_3$-substituent) | 7.38 |
| other alkane ($CHR^1R^2R^3$) | 1.50 | pyridine ($H_4$-substituent) | 7.75 |
| alkene | 5.25 | furan ($H_2$-substituent) | 7.38 |
| alkyne | 1.80 | furan ($H_3$-substituent) | 6.30 |

The first-order approximation is valid as long as the coupling constant $J_{AB}$ is considerably smaller than the absolute difference $\sigma_A - \sigma_B$. In one structure this condition for some nuclei may be met and may not be met for some others.

As was mentioned above, the coupling constants are of various sizes compared to the chemical shifts. Not only this, the coupling constants depend on many structural features such as C–C distance, dihedral angle, electronegativity of substituents, influence of Π-bond,[16] etc. Therefore, only the few most common and standard coupling constants are included in the database of our $^1H$ NMR spectra simulation program VODIK.[17,18]

Table V shows the coupling constants $J_{AB}$ between some most common protons A and B used in our progam VODIK for the simulation of $^1H$ NMR spectra. Due to the fact that the magnetic field strength heavily influences the splitting of the chemical shifts in the NMR spectrum one of the input data that must be provided by the chemist is the frequency of the field at which the NMR measurements are made (e.g., 60 MHz, 250 MHz, etc.).

At the initial step of simulation of $^1H$ NMR spectrum, the program VODIK enables the user to enter different coupling constants from those proposed by the program. If such "user-determined" coupling constants turn out to be better than the system's they can be easily exchanged and permanently stored in the program's data base.

**Spectra of Higher Order.** In cases where the coupling constants between the nuclei are comparable to the shifts and involve more nuclei with nonzero spin, the first-order ap-

**Table IV.** List of Substituents for $^{13}C$ and $^1H$ NMR Handled by Programs SIMULA and VODIK, Respectively[a]

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | -Csp$^3$ | | 51 | -Sn(R)$_2$ | | 101 | -CO-O-CO-R | |
| 2 | -CH$_3$ | * | 52 | -P(Ph)$_2$ | | 102 | -CS-R | |
| 3 | -CH$_2$-CH$_3$ | * | 53 | -CR=R$_2$ | * | 103 | -SO$_2$-R | * |
| 4 | -CH$_2$-CH$_2$-CH$_3$ | * | 54 | -CH$_2$-O-CH$_3$ | • | 104 | -aziridyl | |
| 5 | -CH$_2$-CH$_2$-CH$_2$-CH$_3$ | | 55 | -CHO | * | 105 | -N=N-R | * |
| 6 | -CH$_2$-O-CH$_2$-CH$_3$ | | 56 | -CO-R | * | 106 | -N=C=N-R | |
| 7 | -CR$_2$-Cl | * | 57 | -CO-CH$_3$ | • | 107 | -P(R)$_2$ | |
| 8 | -CR$_2$-Br | * | 58 | -CO-NH$_2$ | * | 108 | -CO-S-R | |
| 9 | -CR$_2$-I | * | 59 | -CO-NR$_2$ | * | 109 | -CS-OR | |
| 10 | -CH$_2$-OH | * | 60 | -CO-Cl | * | 110 | -NR-CS-OR | |
| 11 | -CH$_2$-NH$_2$ | • | 61 | -COOH | * | 111 | -S-CS-S-R | |
| 12 | -CH-CN | * | 62 | -COO$^-$ | * | 112 | -O-CS-OR | |
| 13 | -CH(CH$_3$)$_2$ | * | 63 | -COO-R | * | 113 | -S-CS-NR$_2$ | |
| 14 | -C(CH$_3$)$_3$ | * | 64 | -COO-CH$_3$ | * | 114 | -NR-CO-NR$_2$ | |
| 15 | -CF$_3$ | * | 65 | -COO-CH$_2$-CH$_3$ | | 115 | -N=C=S | |
| 16 | -OH | • | 66 | -CR=OHsyn | | 116 | -NR-CS-NR$_2$ | |
| 17 | -O$^-$ | * | 67 | -CR=OHanti | | 117 | -O-CO-NR$_2$ | |
| 18 | -O-R | * | 68 | -O-O-R | | 118 | -NR-CS-R | |
| 19 | -O-CH$_3$ | * | 69 | -N=C=O | | 119 | -CO-NR-CO-R | |
| 20 | -O-CH$_2$-CH$_3$ | | 70 | -N=O | | 120 | -C(R)$_2$F | • |
| 21 | -O-(CH$_2$)$_3$-CH$_3$ | | 71 | -N=N-Ph | * | 121 | -C(R)F$_2$ | * |
| 22 | -O-CO-R | * | 72 | -N=N=cyclohexyl | | 122 | -CH=CH$_2$ | |
| 23 | -O-CO-CH$_3$ | * | 73 | -NO$_2$ | * | 123 | -CR=N-OH | |
| 24 | -O-N=O | * | 74 | -SO-R | • | 124 | -C(R)Cl$_2$ | * |
| 25 | -O-Ph | * | 75 | -SO$_2$-Cl | • | 125 | -CCl$_2$ | • |
| 26 | -S-H | * | 76 | -SO$_2$-CH=CH$_2$ | | 126 | -Ph with substituent | * |
| 27 | -S-R | * | 77 | -SO$_2$-OH | * | 127 | -C(R)Br$_2$ | • |
| 28 | -S-CH$_3$ | * | 78 | -C≡C-R | * | 128 | -CBr$_3$ | • |
| 29 | -S-CH$_2$-CH$_3$ | * | 79 | -C≡C-H | * | 129 | -CO-Ph | * |
| 30 | -S-CH$_2$-Ph | * | 80 | -C≡N | * | 130 | -C(R)I$_2$ | * |
| 31 | -S-(CH$_3$)$_3$ | * | 81 | -N$^+$≡N | | 131 | -CI$_3$ | |
| 32 | -S-CO-R | • | 82 | -N$^+$≡C$^-$ | | 132 | -S-CS-R | |
| 33 | -S-CN | • | 83 | -cyclopropyl | | 133 | -pyrrolyl(2/5) | • |
| 34 | -NH$_2$ | * | 84 | -oxiryl | | 134 | -pyrrolyl(3/4) | * |
| 35 | -NR$_2$ | • | 85 | -pyridyl(2/6) | * | 135 | -indolyl(1) | |
| 36 | -N$^+$R$_3$ | | 86 | -Ph | * | 136 | -indolyl(2) | |
| 37 | -N$^+$H$_3$ | | 87 | -cyclohexyl | | 137 | -indolyl(3) | |
| 38 | -NHR | • | 88 | -N(CH$_3$)$_2$ | * | 138 | -indolyl(4) | |
| 39 | -N$^+$(CH$_3$)$_3$ | | 89 | -NR-CO-R | • | 139 | -indolyl(5) | |
| 40 | -NH-CH$_3$ | * | 90 | -CR=N-Ph | * | 140 | -indolyl(6) | |
| 41 | -N(CH$_2$-CH$_3$)$_2$ | | 91 | -Si(R)$_3$ | | 141 | -indolyl(7) | |
| 42 | -NH-CO-CH$_3$ | • | 92 | -CR=N-R | • | 142 | -cyclopentyl | |
| 43 | -NH-NH$_2$ | * | 93 | -O-CO-O-R | * | 143 | -cyclobutyl | |
| 44 | -N(Ph)$_2$ | * | 94 | -NC | | 144 | -NR-CO-O-R | |
| 45 | -F | * | 95 | -pyridyl(3/5) | • | 145 | -furyl(2/5) | • |
| 46 | -Cl | * | 96 | -pyridyl(4) | * | 146 | -furyl(3/4) | • |
| 47 | -Br | * | 97 | -CR=C=C(R)$_2$ | | 147 | -pyrrolyl(1) | * |
| 48 | -I | * | 98 | -CR=C=N-R | | 148 | -thienyl(2/5) | * |
| 49 | -Si(CH$_3$)$_3$ | | 99 | -CR=C=O | | 149 | -thienyl(3/4) | * |
| 50 | -Si(Cl)$_3$ | | 100 | -CR=N=N-R | | 150 | -cycloheptyl | |

[a] All listed substituents are for the $^{13}C$ NMR spectra simulation. Substituents marked with an asterisk are for the $^1H$ NMR spectra simulation.

**Table V.** All 27 Coupling Constants $J_{ij}$ (in Hz) Used in Program VODIK

| functional group | $J_{ij}$ (Hz) | functional group | $J_{ij}$ (Hz) |
|---|---|---|---|
| alkane (CH-CH) | 7.10 | thiophene ($H_2$-$H_4$) | 1.00 |
| alkene (gem substituent) | 2.00 | thiophene ($H_2$-$H_5$) | 2.80 |
| alkene (cis substituent) | 8.50 | thiophene ($H_3$-$H_4$) | 3.50 |
| alkene (trans substituent) | 15.0 | pyridine ($H_2$-$H_3$) | 5.00 |
| benzene (ortho substituent) | 8.40 | pyridine ($H_2$-$H_4$) | 1.30 |
| benzene (meta substituent) | 2.00 | pyridine ($H_2$-$H_5$) | 1.00 |
| benzene (para substituent) | 0.15 | pyridine ($H_2$-$H_6$) | 0.30 |
| pyrrole ($H_2$-$H_3$) | 2.60 | pyridine ($H_3$-$H_4$) | 8.00 |
| pyrrole ($H_2$-$H_4$) | 1.30 | pyridine ($H_3$-$H_5$) | 1.60 |
| pyrrole ($H_2$-$H_5$) | 2.10 | furan ($H_2$-$H_3$) | 1.80 |
| pyrrole ($H_2$-$H_1$) | 2.60 | furan ($H_2$-$H_4$) | 0.90 |
| pyrrole ($H_3$-$H_4$) | 3.50 | furan ($H_2$-$H_5$) | 1.50 |
| pyrrole ($H_3$-$H_1$) | 2.30 | furan ($H_3$-$H_4$) | 3.40 |
| thiophene ($H_2$-$H_3$) | 4.80 | | |

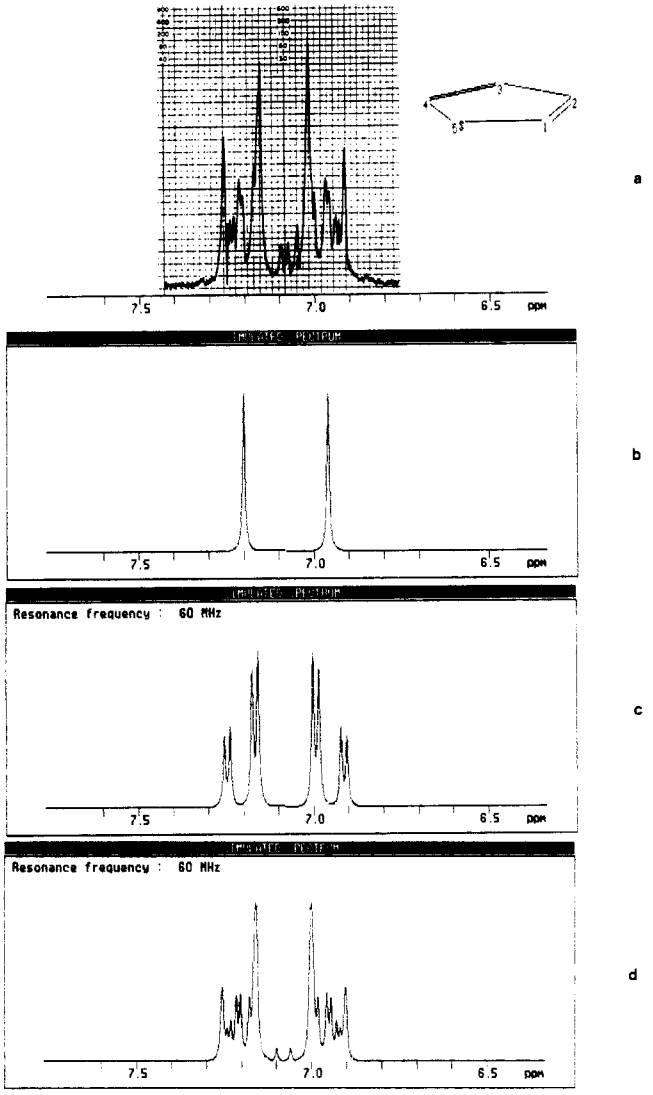



**Figure 1.** Comparison between the experimental (a) and simulated (d) $^1$H NMR spectra of thiophene. The simulation is made in a three-step process: decoupled (b), first-order (c), and higher-order (d) simulation.

proximation of the spectrum does not adequately simulate the experimental spectrum. For such, more realistic cases, the diagonalization of the wave function matrix with the Hamiltonian in the form[19]

$$H = \sum_{i=1}^{n} \nu_i I_{zi} + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} J_{ij} I_i I_j \qquad (4)$$

must be solved. The value $J_{ij}$ has the same meanings as in the above eqs 2 and 3. The value $\nu_i$ is the resonance frequency

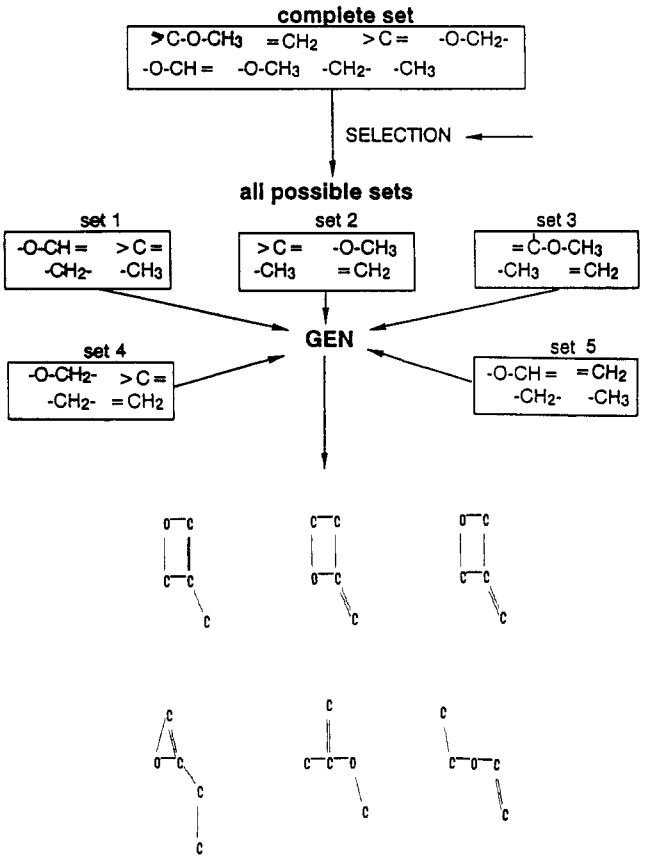
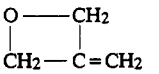
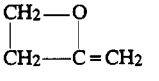
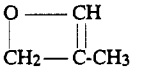
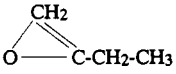
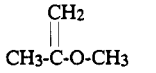



**Figure 2.** Selection of possible sets from the complete set, and the resulting possible structures are generated by the structure generator GENSTR.[24]

**Table VI.** Simulated $^1$H and $^{13}$C NMR Spectra for Six Possible Structures

| Structure | $^1$H NMR spectrum (in ppm) | $^{13}$C NMR spectrum (in ppm) |
|---|---|---|
|  | 3.55, 3.55, 5.22, 5.22 | 74.2, 74.2, 106.5, 149.1 |
|  | 2.05, 3.55, 3.83, 3.90 | 39.4, 60.9, 78.4, 164.8 |
|  | 1.80, 4.35, 6.23 | 13.4, 74.1, 110.3, 135.6 |
|  | 1.00, 2.00, 6.24 | 7.5, 27.7, 105.7, 130.9 |
|  | 1.80, 3.50, 3.82, 3.90 | 23.7, 51.1, 76.5, 163.3 |
| $C_2H_5$-O-CH=$CH_2$ | 1.30, 3.70, 4.04, 4.18, 6.47 | 14.8, 62.7, 83.5, 151.8 |
| Experimental | 2.2 T, 3.6 S, 3.8-4.1 | 20.8, 51.5, 76.7, 163.5 |

of nucleus $i$ in the absence of other nuclei and is linearly dependent from $\sigma_i$.[20] $I_i$ is the angular momentum operator and $I_{zi}$ is the $z$ component of angular momentum for the nucleus $i$.

The input values for this diagonalization program are actually the first-order spectrum and the chemical shifts of 'active' nuclei with mutual coupling constants. For two

different spin orientations ($\pm^1/_2$) of $n$ nuclei in the magnetic field there are $2^n$ different wave functions, and the energy of such a system is described by a $2^n \times 2^n$ dimensional matrix. The solutions of this system can be achieved using iterative programs like LAOCOON.[21]

Considering the symmetry of the active (nonzero spin) nuclei in each particular structure, the large $2^n \times 2^n$ dimensional matrix can be factorized into smaller parts. However, in spite of the factorization and rapidly increasing computational power of modern personal computer hardware and software, the simulation of complex spin systems is still limited to a small number of ($\leq 10$) nuclei with nonzero spins.

For such high-order calculations of $^1$H NMR spectra in VODIK, the well-known program LAOCN-4A[22] is used.

## SIMULATION BY THE PROGRAM VODIK

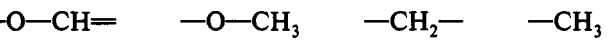
The structure of the compound for which the $^1$H NMR spectrum should be simulated is entered via the structure editor, which was already described elsewhere.[23] Next, the program VODIK finds and enumerates the active nuclei and calculates the first-order spectrum (eqs 2 and 3) as the initial approximation and passes the calculated result to the next step.

In the second step, the results of the first approximation simulation are handled by the LAOCN-4A program, and the result is displayed in Figure 1.

Before the first-order spectrum is calculated, the user has to give the radio frequency (RF in MHz) for which the simulation has to be performed. At this step the user can change the coupling constants as well. Where the output is concerned, the user can select the width of the peaks (resolution of the "instrument") and choose the way the spectra are displayed (with or without the integral, specific region of the spectrum, etc.).

## EXAMPLE OF USE OF THE SYSTEM

As an example of how the simulations can be used, a real case where both simulations ($^{13}$C and $^1$H NMR) were employed to solve the unknown structure will be presented in this paragraph. First, a $^{13}$C NMR spectrum consisting of four peaks (at 20.8, 51.5, 76.7, and 163.5 ppm relative to TMS) was recorded. Using the 'FRAGMENT' option in the system CARBON, the two most common fragments at each peak were selected:




From this set of eight fragments and the constraint that the resulting structure should have only four carbon atoms, the system GENSTR[24] has selected five possible sets:

—O—CH=, >C=, —$CH_2$—, and —$CH_3$

>C=, —O—$CH_3$, —$CH_3$, and =$CH_2$

=(C—)—O—$CH_3$, —$CH_3$, and =$CH_2$

—O—$CH_2$—, >C=, —$CH_2$—, and =$CH_2$

—O—CH=, =$CH_2$, —$CH_2$—, and —$CH_3$

out of which six different structures (Figure 2) were generated.

For all six possible structures, both the $^1$H NMR and the $^{13}$C NMR spectra were simulated, and the results are shown in Table VI. From the results obtained it is clearly seen that structure 5 has produced the best pair of spectra compared to the experimental ones.

## CONCLUSION

The simulation of different types of spectra has a very broad application in many fields of chemistry. On the market there are more and more powerful and user-friendly computer programs performing this tasks. Such software can be used in analytical, spectroscopic, chemometrics, and qualimetrics, and in other laboratories. The best performance is achieved if the simulation procedure is linked with other all-purpose chemistry-oriented packages as an additional stone in the mosaic of the particular computerized tool.

The described simulation programs VODIK and SIMULA are written in Turbo Pascal language and can handle VGA/EGA and Hercules graphics. Both can be used together with the general package CARBON[23] and GENSTR.[24]

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