Additivity of Carbon-13 Spin–Lattice Relaxation Times

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Abstract: Carbon-13 spin–lattice relaxation times have been measured for a number of isomeric alcohols in order to explore the relationships between T_1 and molecular dynamics and conformations. Systematic trends were observed in the relaxation times so that an empirical relationship could be derived which allows one to estimate the T_1 of a given carbon atom by summing additivity parameters based on the location of the given carbon relative to the hydroxyl group, to methyl groups, and to centers of branching. These additivity parameters throw considerable light on the structure factors which affect carbon relaxation times. Specifically we have made precise measurements of the relaxation times of the 89 primary, secondary, and tertiary carbons of the 18 isomeric six-carbon monohydric aliphatic alcohols. These measurements include eight primary, eight secondary, and two tertiary alcohols. A linear multiple regression analysis on the T_1's allows T_1's to be calculated by summing appropriate combinations of 12 regression coefficients. The multiple correlation coefficient for this regression analysis is 0.9575, and the standard deviation in the predicted T_1's is 0.65 s. A separate regression analysis on just the 37 methyl carbons allows methyl T_1's to be calculated using 7 regression coefficients. Relationships between T_1's and the effective correlation times, τ_{eff}, for each carbon atom and molecular dynamics and conformation are discussed.

The relative ease with which ^{13}C spin–lattice relaxation times can be measured with Fourier transform methods provides a wealth of information on molecular motions and molecular dynamics of organic molecules in the liquid phase.[1] Detailed qualitative interpretations of results often have been based on data from just one or two compounds of a given type. This information is applied quite empirically to molecules dominated by dipole–dipole relaxation. The purpose of the present work is to investigate the relaxation behavior of the individual carbons in a series of molecules having identical molecular weights and functional groups with a view to refining the application of T_1 measurements to problems of molecular structure and motion.

In this work we have made precise measurements of the relaxation times of the 89 primary, secondary, and tertiary carbons of the 18 isomeric six-carbon monohydric aliphatic alcohols in order to ascertain just what factors contribute to the relaxation time of a given carbon atom. These alcohols afford a wide variety of conformational and structural situations involving eight primary, eight secondary, and two tertiary alcohols. There are 95 magnetically distinct carbon nuclei in this set of molecules. Their ^{13}C chemical shifts were analyzed previously by a linear regression procedure involving 15 independent variables.[2] These regression coefficients include chemical shift parameters which yield additive contributions to the shift of a particular carbon nucleus (C_k) from the surrounding carbons in the molecule at various positions relative to the *k*th carbon and corrective terms which describe the relationship of the *k*th carbon to the hydroxyl group and indicate the type of carbon (methylene, methine, etc.) at the adjacent position. A multiple correlation coefficient R of 0.9983 and a standard deviation in predicted ^{13}C chemical shifts equal to ±1.11 ppm was achieved in this analysis. In addition the average solution conformations of these molecules were determined by using NMR shift reagent methods.[2] This well-characterized system was therefore chosen to study the regularities that might exist in the T_1 values of the carbons. Quaternary carbon atoms were omitted from this study since their relaxation times (ca. 35 s) are much longer than those of the protonated carbons. This leaves a total of 89 magnetically distinct nuclei which were the subject of this study. Their relaxation times range from 3 to 15 s.

Experimental Section

Carbon-13 spectra were accumulated by employing continuous proton decoupling with a JEOL FX-90Q Fourier transform NMR spectrometer operating at a centerband frequency of 22.5085 MHz. The peak assignments for all these compounds were determined from the chemical shifts previously reported.[2] All samples were of equal volume and were prepared in 10 mm o.d. tubes at a concentration of 25.0% by volume in CDCl₃. These solutions were degassed by 5 freeze–pump–thaw cycles and the tubes sealed off under vacuum. All spectra were run at a temperature of 29 ± 0.5 °C.

The ^{13}CH nuclear Overhauser enhancement (NOE) factor was measured for each resonance in 2-hexanol, 2-ethyl-1-butanol, and 2,3-dimethyl-2-butanol and was found to be the maximum value (2.98 ± 0.10) for all the protonated carbon atoms.

The spin–lattice relaxation times (T_1) of individual spectral lines in a particular sample were measured simultaneously via the inversion-recovery method.[3] Both the precision and the time expended for the measurement can be optimized by choosing a calculated set of pulse intervals and a pulse delay time determined by the range of T_1 values to be measured.[4] In the present investigation, involving 17 samples and the measurement of 89 different T_1 values ranging from 3 to 15 s, a standard deviation of less than 5% has been achieved by averaging 3 to 8 determinations. These experimental relaxation times are given in Table I.

Results

Perusal of the relaxation time data in Table I reveals very few easily discernible relationships between structure and T_1. One such correlation, noted by Allerhand for 1-decanol,[5] is that T_1's for methylenes increase with increasing distance from the hydroxyl group. This is seen in 1-hexanol, 2-hexanol, and 3-hexanol, and it is a result of the hydroxyl-bearing carbon being anchored, to some extent, by hydrogen bonding to another alcohol or to the solvent. The longer T_1's are the result of increased freedom of motion of the carbons in moving away from the hydroxyl group. But even this simple correlation breaks down in 2-methyl-1-pentanol where carbons 21 and 22 are seen to have the same value of T_1.

In order to reveal hidden regularities and relationships between these T_1's and molecular structure we have subjected these data to a linear regression analysis. We find that the T_1 of a given carbon atom can be calculated by summing parameters which reflect the proximity of the carbon in question to methyl groups, to the hydroxyl, and to centers of branching. The linear multiple

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regression analysis shows that these relaxation times can be described by an equation of the type

$$T_1(\text{k}) = A + \sum_i B_i x_{ik} \tag{1}$$

where $T_1(k)$ is the relaxation time of the kth carbon, A is a constant, and the B_1's are the coefficients of the variables which apply X_{ik} times for the kth carbon. If a particular variable is not applicable for a given kth carbon then $X_{ik} = 0$, and if it is applicable $X_{ik} = 1$ and in some cases 2 or 3.

In Table II are given the results of this analysis along with the 12 variables and their corresponding coefficients. These variables specify the type of carbon atom (methyl, methylene, methine), the type of carbon it is adjacent to (tertiary, quaternary), and its proximity to the hydroxyl group and the methyl groups in the molecule. The constant term for this regression analysis is 5.06 s, and it applies to all methylene carbons. As an example, the T_1 of carbon 32 in 4-methyl-1-pentanol is calculated to be 5.78 s which is the sum of the constant term (5.06 s), the fact it is adjacent to a tertiary carbon (−1.37 s), γ to a hydroxyl (−0.53 s), and β to two methyl groups (2(1.31 s)). The experimentally determined value is 5.87 s.

The multiple correlation coefficient for this regression analysis is 0.9575, and the standard deviation in the predicted T_1's is 0.65 s. The mean value of all T_1's is 6.63 s, therefore on the average the standard deviation in predicted T_1's is only 10%. Seventy-five percent of the calculated T_1's lie within the standard deviation of ±0.65 s, and in only two cases do they lie outside two standard deviations. This degree of internal consistency has been achieved by paying close attention to the caveats of Levy and Peat[6] regarding such matters as constancy of sample concentration, sample volume, temperature, etc., and the careful exclusion of oxygen from all samples.

None of the regression coefficients apply to the α-carbon in 1-hexanol, and so its relaxation time should equal the constant term, 5.06 s. For all other carbons in these molecules at least one regression coefficient applies in calculating T_1's from the data in Table I. Thus these regression coefficients reflect differences in T_1 for a given carbon relative to the methylene α-carbon in 1-hexanol.

A regression analysis was run on the T_1's of the 37 methyl carbons in these 18 alcohols. Their T_1's can be calculated by summing the appropriate combinations of seven additivity parameters (see Table III). The correlation coefficient for this regression analysis is 0.9656, and the standard deviation in the calculated relaxation times is 0.28 s.

Discussion

The tumbling times of these alcohols are much smaller than the reciprocal of the Larmor frequency of the spectrometer used to measure their ^{13}C spectra. Therefore the resonances of these molecules are observed in the motional narrowing limit. In the motional narrowing limit the dipolar NOE is maximal and independent of the Larmor frequency. The relaxation rate, assuming isotropic motion of the molecule, is given by[5]

$$\frac{1}{T_1} = \sum_{i=1}^{N} \frac{\gamma_H^2 \gamma_C^2 \hbar^2}{r_{CH_i}^6} \tau_c^{\text{eff}} \tag{2}$$

where γ_H and γ_C are the magnetogyric ratios of hydrogen and carbon, respectively, and $\hbar$ is Planck's constant divided by 2π.

Neglecting the methyl group which can relax by rapid internal rotation, the T_1's of methine carbons are predicted by eq 2 to be twice as long as the T_1's of methylene carbons. Although this is true for many molecules, it will be noted in Table I that the relaxation time of the methine carbon 20 is exactly the same as that of the methylene carbon 21 in 2-methyl-1-pentanol. From this it is obvious that the generalization that CH carbons have longer relaxation times than CH$_2$ carbons does not always hold and any NMR pulse scheme that purports to distinguish between methine and methylene carbons on the basis of their relaxation

times should be used with great caution.

The relaxation rate is very sensitive to the distance, r_{CH}, between a given carbon atom and nearby hydrogens. It is a function of the contributions made by all nearby protons:

$$1/T_1 = \sum_j 1/T_{ij} \tag{3}$$

For protonated carbons the contribution to the relaxation rate from directly bonded protons dominates this expression but nearby protons make, as we shall see, not insignificant contributions. It is effects such as these that can make the T_1's of CH and CH$_2$ carbons equal as seen for carbons 20 and 21.

A regression analysis of the data for these alcohols should consider explicitly the number of directly bound protons, the number of nearest neighbor protons, next nearest neighbor protons, etc. Since the hydroxyl group, through hydrogen bonding, restricts the motion of one end of the molecule, its location relative to the carbon of interest must also be accounted for in the regression analysis. Independent variables in the regression equation (the x_{ik}'s of eq 1) can be assigned in a number of different ways and still correlate the data. We have analyzed these data in three different ways in order to bring out slightly different information regarding the relationships between the T_1's and molecular motions in these molecules.

In the first approach nearby protons and the location of the hydroxyl group relative to the kth carbon were chosen as independent variables in the regression analysis. Although a hydroxyl ϵ to the kth carbon was entered into the analysis, it was found to produce a statistically insignificant regression coefficient, but locations β, γ, and δ to kth carbon decrease T_1 0.65, 0.53, and 0.38 s, respectively. This means that the anchoring effect of the hydroxyl group on T_1 of the kth carbon in these alcohols extends no further than the position δ to the hydroxyl. When positions ϵ and more remote are entered into the regression analysis, they are found to be statistically insignificant, as judged by their inability to improve the correlation coefficient for the overall analysis. In order to count directly bonded protons, we have arbitrarily used methylenes as our base and considered primary and tertiary carbons as independent variables. It is not surprising to find that if the kth carbon is tertiary instead of secondary T_1 increases by 2.13 s since T_1 is inversely proportional to the number of directly bound protons. If the kth carbon is primary it is of course a methyl group and spin rotation can contribute to its relaxation, consequently the regression coefficient for a primary carbon is 1.06 s. The effect of nearest neighbor protons on the relaxation time of the kth carbon atom is reflected in the negative contributions which an adjacent tertiary center (−1.37 s) or an adjacent quaternary center (−2.27 s) make. Lack of protons on those carbons leads to a decrease in T_1 of the kth carbon.

Perhaps the most interesting numbers to come out of this regression analysis are the ones reflecting the proximity of the kth carbon to methyl groups. In conformationally flexible molecules such as these, molecular motions bring the terminal methyl in close proximity to other carbons in the chain. A methyl in the γ position contributes 0.59 s to T_1 of the kth carbon. This γ effect of a methyl group is quite striking. When the methyl is one more carbon removed, in the δ position, the effect falls to 0.13 s. This large γ effect is an example of Newman's "rule of six"[7] which he formulated to explain the rates of certain addition and hydrolysis reactions. This is the same steric effect which is responsible for the low-frequency shift of a methylene ^{13}C atom in a γ relationship to another carbon atom.

Consider the tertiary carbon in an isopropyl group. Two methyls in the α position contribute 2(1.74) s to the relaxation time and the fact that the carbon is tertiary contributes another 2.13 s. In this way the regression analysis accounts for the empirical observation that terminal branched carbons have long relaxation times. A large regression coefficient ($3°(4°) = 3.7$ s) is needed to account for the relaxation time of the tertiary carbon adjacent
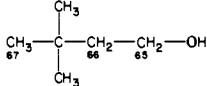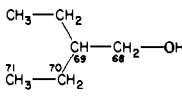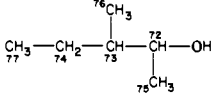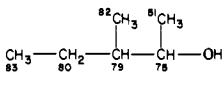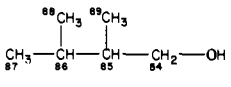
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Table I. Carbon-13 Relaxation Times and Effective Correlation Times in Six-Carbon Alcohols

sample	observation no.	$1/\tau_{eff}$ [a]	T_1 [b]	structure	$\tau(1,2)$ [c]	CH3
1-hexanol	1	0.194	4.56	CH3(6)—CH2(5)—CH2(4)—CH2(3)—CH2(2)—CH2(1)—OH	9.12	6
	2	0.208	4.89			
	3	0.228	5.37			
	4	0.265	6.23			
	5	0.312	7.35			
	6	0.422	6.62			
2-hexanol	7	0.185	8.70	CH3(12)—CH2(11)—CH2(9)—CH2(8)—CH(7)(OH)—CH3(10)	17.86	10
	8	0.213	5.01		9.76	12
	9	0.253	5.96			
	10	0.241	3.78			
	11	0.298	7.01			
	12	0.400	6.28			
3-hexanol	13	0.183	8.64	CH3(17)—CH2(16)—CH2(14)—CH(13)(OH)—CH2(15)—CH3(18)	10.08	17
	14	0.214	5.03		6.07	18
	15	0.207	4.88			
	16	0.272	6.41			
	17	0.371	5.83			
	18	0.372	5.84			
2-methyl-1-pentanol	19	0.196	4.61	CH3(24)—CH2(22)—CH2(21)—CH(20)(CH3 23)—CH2(19)—OH	6.98	23
	20	0.146	6.87		8.98	24
	21	0.292	6.87			
	22	0.292	6.87			
	23	0.289	4.54			
	24	0.403	6.33			
3-methyl-1-pentanol	25	0.217	5.12	CH3(30)—CH2(28)—CH(27)(CH3 29)—CH2(26)—CH2(25)—OH	9.67	29
	26	0.232	5.47		5.88	30
	27	0.206	9.71			
	28	0.269	6.33			
	29	0.310	4.86			
	30	0.439	6.89			
4-methyl-1-pentanol	31	0.200	4.71	CH3(35)—CH(34)(CH3 35)—CH2(32)—CH2(33)—CH2(31)—OH	12.65	35
	32	0.249	5.87			
	33	0.221	5.20			
	34	0.242	11.40			
	35	0.321	5.04			
2-methyl-2-pentanol	36	0.235	5.54	CH3(39)—CH2(38)—CH2(36)—C(OH)(CH3 37)(CH3 37)	9.90	39
	37	0.251	3.94			
	38	0.279	6.56			
	39	0.380	5.96			
4-methyl-2-pentanol	40	0.215	10.12	CH3(44)—CH(42)(CH3 45)—CH2(41)—CH(40)(OH)—CH3(43)	17.92	43
	41	0.245	5.76		10.52	44
	42	0.218	10.28		10.45	45
	43	0.271	4.25			
	44	0.313	4.92			
	45	0.314	4.93			
2-methyl-3-pentanol	46	0.229	10.78	CH3(51)—CH2(48)—CH(46)(OH)—CH(47)(CH3 50)—CH3(49)	9.46	49
	47	0.214	10.08		7.89	50
	48	0.258	6.07		6.35	51
	49	0.320	5.02			
	50	0.341	5.35			
	51	0.415	6.52			
3-methyl-3-pentanol	52	0.272	6.40	CH3(54)—CH2(52)—C(OH)(CH3 53)—CH2—CH3	4.93	54
	53	0.317	4.98			
	54	0.474	7.45			
2,2-dimethyl-1-butanol	55	0.271	6.38	CH3(58)—CH2(56)—C(CH3)(CH3 57)—CH2(55)—OH	4.66	58
	56	0.270	6.36			
	57	0.337	5.29			
	58	0.485	7.61			
3,3-dimethyl-2-butanol	59	0.320	15.05	CH3(60)—C(CH3)(CH3)—CH(59)(OH)—CH3(61)	9.50	61
	60	0.409	6.42			
	61	0.425	6.67			
2,3-dimethyl-2-butanol	62	0.282	13.30	CH3(64)—CH(62)(CH3)—C(OH)(CH3 63)(CH3)	6.58	64
	63	0.370	5.81			
	64	0.434	6.82			

Table I (*Continued*)

sample	observation no.	$1/\tau_{eff}{}^a$	$T_1{}^b$		$\tau(1,2)^c$	CH_3
3,3-dimethyl-1-butanol	65	0.278	6.54			
	66	0.310	7.31			
	67	0.295	4.63			
2-ethyl-1-butanol	68	0.210	4.94		5.57	71
	69	0.181	8.52			
	70	0.245	5.76			
	71	0.424	6.66			
3-methyl-2-pentanol (erythro)	72	0.215	10.14		12.66	75
	73	0.212	10.00		7.56	76
	74	0.278	6.54		6.86	77
	75	0.294	4.62			
	76	0.345	5.41			
	77	0.424	6.65			
3-methyl-2-pentanol (threo)	78	0.217	10.20		13.53	81
	79	0.194	9.16		6.07	82
	80	0.278	6.54		6.95	83
	81	0.290	4.56			
	82	0.359	5.64			
	83	0.422	6.62			
2,3-dimethyl-1-butanol	84	0.225	5.30		7.97	87
	85	0.209	9.82		7.55	88
	86	0.192	9.03		7.06	89
	87	0.317	4.98			
	88	0.324	5.09			
	89	0.350	5.50			

^{a} ps^{-1}, calculated from T_1 according to eq 4. ^{b} s, measured. ^{c} ps, calculated from $\tau_{eff}{}^{-1}$ for the indicated methyl and $\tau_{eff}{}^{-1}$ for the carbon adjacent to the methyl according to eq 7.

Table II. Multiple Regression Analysis of Relaxation Times in Six-Carbon Alcohols

no. of observations: 89
no. of independent variables: 12
multiple correlation coefficient R: 0.9575
standard deviation in predicted T_1: ±0.65 s
constant term: 5.06 ± 0.50 s

variables and coefficients^a (s)		no. of observations affected by variable
type of carbon		
primary	1.06 ± 0.50	37
tertiary	2.13 ± 0.65	18
type adjacent		
CH (tertiary)	−1.37 ± 0.42	41
Q (quaternary)	−2.27 ± 0.88	13
position to hydroxyl		
β	−0.65 ± 0.42	26
γ	−0.53 ± 0.47	25
δ	−0.38 ± 0.55	16
position to Me groups		
α	1.74 ± 0.51	28
β	1.31 ± 0.37	41
γ	0.59 ± 0.24	44
δ	0.13 ± 0.34	24
3° (4°)	3.70	2

^{a} 95% confidence.

Table III. Multiple Regression Analysis of Methyl Carbon Relaxation Times in Six-Carbon Alcohols

no. of observations: 37
no. of independent variables: 7
multiple correlation coefficient R: 0.9656
standard deviation in predicted T_1: ±0.28 s
constant term: 6.25 ± 0.24 s

variables and coefficients (s)		no. of observations affecting variable
type adjacent		
CH (tertiary)	−2.14 ± 0.32	18
Q (quaternary)	−2.70 ± 0.79	6
position to hydroxyl		
β	−0.33 ± 0.41	8
γ	−0.42 ± 0.25	12
position to other Me groups		
β	0.86 ± 0.32	13
γ	0.83 ± 0.15	19
δ	0.18 ± 0.19	16

to a quaternary carbon in 3,3-dimethyl-2-butanol and 2,3-dimethyl-2-butanol. The tertiary carbons of these two molecules have the longest relaxation times of all the carbon nuclei investigated, indicating these molecules are tumbling very rapidly compared to less highly branched analogues. These two molecules are roughly spherical, measuring about 4.8 Å in the longest dimension. This compares with about 9.2 Å for the overall length of 1-hexanol in the completely staggered conformation. Thus the 3.7 s regression coefficient for a tertiary carbon adjacent to a quaternary carbon is probably a measure of the faster correlation time for the two molecules having this structure compared with those which do not.

In our second approach to analyzing these T_1 data a linear multiple regression analysis was run on just the methyl carbons of these 18 isomeric hexanols. There are a total of 37 magnetically distinct methyl carbons in this series of molecules and only 7 of the original regression coefficients are required for the analysis. Specifying the type of carbon atom is not necessary, and the corrective term 3°(4°) does not apply. Two adjacent (directly bonded) methyl groups is not a possibility in these compounds and, therefore, the variable which designates the number of methyl groups at the α position relative to the kth carbon is not applicable. The correlation coefficient for this regression analysis is 0.9656 with a standard deviation in calculated T_1's of 0.28 s. This is equal to 5% of the mean T_1 value of these 37 carbons. Table III lists the regression coefficients for this analysis.

Perusal of the regression coefficents in Table III reveals several interesting observations. A methyl attached to a quaternary carbon is expected to have a shorter relaxation time than a methyl attached to a tertiary carbon atom, whether the methyl is at the end of a chain or not. A methyl in a position β to the kth methyl

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contributes 0.86 s to the relaxation time, but a methyl one more carbon removed, in the γ position, gives almost the same contribution, 0.83 s. Note that the contribution of a methyl in the δ position drops to 0.18 s.[8] This is another manifestation of the γ effect on relaxation times. Our conclusions regarding this γ effect are exactly the opposite of those of Ng,[8] who recently measured the T_1's of a variety of alkyl-substituted compounds.

Our third approach to analysis of the relaxation times of these molecules is to consider the correlation times of the individual carbons. In this we follow the treatment of Lyerla et al. in their analysis of alkane motions.[9] Since we have established that the carbons relax primarily by the dipolar mechanism and that we are within the extreme narrowing limit, an effective correlation time connecting the directly bonded C and H bonds is given by[5]

$$\tau_{eff} = r_{CH}6/KT_1N_H \qquad (4)$$

where r_{CH} is the internuclear distance (1.09 Å), T_1 is the spin-lattice relaxation time, N_H is the number of directly attached hydrogens, and K is a constant equal to 3.56×10^{10} Å^6 s^{-2}. This equation neglects contributions from other nearby protons.

Since τ_{eff} is proportional to T_1 we could have run a regression analysis on τ_{eff} for each carbon and obtained regression coefficients in terms of τ_{eff}. This we did not do.

A single correlation time describes the reorientation of the CH vector in a rigid spherical molecule, but in the alcohols under consideration here a distribution of correlation times is usually required to describe the motions of the various CH vectors because of motions of individual carbons within the molecule and reorientation of the molecule as a whole (which may be anisotropic). Therefore the single correlation time calculated by eq 1 is actually a weighted average of the correlation times, t_i, which characterize the motions of the CH vector, i.e., $\tau_{eff} = \sum c_i t_i$. The coefficients, c_i, depend upon the probability that the motion associated with t_i occurs and the orientation of the CH vector with respect to the rotation axes.

Lyerla et al. proposed that the rotational motion of an internuclear CH vector in alkane chains be analyzed in terms of an overall rotation of the molecule (considered rigid) with average rotational rate $(\tau_o)^{-1}$ and internal motion due to rotation about individual carbon–carbon bonds in the chain with rate $(\tau_i)^{-1}$ which is largest at the chain ends. For rapid overall rotation (i.e., (τ_o^{-1}) large) as found in these alcohols, $(\tau_{eff})^{-1}$ is approximately equal to $(\tau_o)^{-1}$. The rotational reorientation of the jth carbon in the molecule, $(j\tau_{eff})^{-1}$, is a sum of rates for internal and overall rotations, i.e.

$$(j\tau_{eff})^{-1} = (j\tau_i)^{-1} + (j\tau_o)^{-1} \qquad (5)$$

Some justification for this separation of relaxation contributions into a tumbling plus an internal motion term has come from the stochastic dynamics calculations of Levy et al.[10] They calculated the relaxation times of butane and heptane in aqueous solution and found a gradient in T_1 along the heptane chain in agreement with experiment.

Consider the rate $(\tau(1,2))^{-1}$ defined as the difference in the rates which characterize the motion of the terminal methyl and the adjacent carbon in a given alcohol, i.e.

$$(\tau(1,2))^{-1} = (^1\tau_{eff})^{-1} - (^2\tau_{eff})^{-1} \qquad (6)$$

Substitution of eq 5 into eq 6 yields

$$[\tau(1,2)]^{-1} = (^1\tau_i)^{-1} - (^2\tau_i)^{-1} \qquad (7)$$

The right side of eq 7 involves only internal correlation times since the overall correlation times of all carbons in a given alcohol are equal, by definition, and the terms involving τ_o cancel. Therefore in each alcohol the difference in internal rates, $(\tau(1,2))^{-1}$, should represent the rate of methyl group rotation alone, since the total

methyl motion is the result of all rotations that affect its neighboring carbon plus its rotation about the terminal C1–C2 bond. This value, $\tau(1,2)$, should be independent of molecular weight.

Perusal of Table I indicates that τ_{eff} increases monotonically in going from the methyl to the hydroxyl in 1-, 2-, and 3-hexanol just as it increases in going toward the center of the chain in heptane.[9] In 2-methyl-1-pentanol, however, both carbons 21 and 22 have the same values for τ_{eff}. Lyerla et al. found for straight-chain alkanes ranging from C_7 to C_{20} that $\tau(1,2)$ was independent of the molecular weight of the alkane with values ranging from 6.5 to 7.9 ps.[9] In the present work this generalization holds for the first four compounds and 2-methyl-2-pentanol where $\tau(1,2)$ varies from 8.98 to 10.1 ps. Each of these compounds has a terminal propyl group. The constancy of these values indicates that the terminal methyl group has virtually the same freedom of motion in all of these compounds. In molecules having a terminal ethyl group $\tau(1,2)$ varies from 4.66 to 6.95 ps. This variation is undoubtedly due to steric effects.

While ethyl group steric effects have not been extensively investigated in the past, methyl group rotations have received considerable attention since they are amenable to theoretical calculation.[10] In Table I $\tau(1,2)$ is seen to vary from 6.07 to 17.92 ps for methyl groups attached to a tertiary carbon atom. We expect the τ_{eff} values for these carbons to be greater than those for the unbranched molecules because of slower motions due to the increase in mass. If the separation of τ_{eff} into overall and methyl group rotation terms is still applicable for these methyls, then we can relate $\tau(1,2)$ to a rotational potential barrier (V_r) for thermally activated rotation according to

$$\tau(1,2) = A \exp(V_r/RT) \qquad (8)$$

where A, the preexponential factor, is taken as the $\tau(1,2)$ value for a methyl group in the gas phase, $(kT/I_{Me})^{1/2}$. Employing this relationship Lyerla et al.[9] calculated V_r to be 2.6 kcal/mol for the terminal methyls of alkanes and 2.9 kcal/mol for the branched methyls in 2-methylnonadecane. Better values for barriers to methyl group rotation are obtained from Arrhenius plots of $\tau(1,2)$ as a function of temperature as done by Lyerla and Horikawa[12] for 10-methylnonadecane and by Ericsson et al.[11f] for the methyls in four bicyclic terpenes, but Eq 8 is, nevertheless, useful in seeing trends in barriers to methyl rotation.

The large variation in $\tau(1,2)$ for methyls attached to tertiary carbons in these 18 alcohols seems to indicate large differences in steric hindrance to rotation in these molecules. The largest values for $\tau(1,2)$ and hence to the barrier to methyl rotation are found for methyls adjacent to the hydroxyl group in 2-hexanol and 4-methyl-2-pentanol (17.8 and 17.9 ps). These values are in contrast to 3,3-dimethyl-2-butanol where $\tau(1,2)$ is only 9.50 ps. Our regression analysis tells us that the short $\tau(1,2)$ in the latter compound is the result of the hydroxymethyl group being adjacent to a tertiary butyl group. The tertiary butyl group presents a ninefold barrier to the adjacent methyl group, hence no one conformation of the methyl has significantly lower energy, an effect noted previously in methyl-substituted aromatic compounds.[11]

Terminal methyls which are part of an isopropyl group have $\tau(1,2)$ values ranging from 6.58 to 12.65 ps. Again the lowest value of $\tau(1,2)$ is found for the methyls adjacent to a quaternary carbon (in 2,3-dimethyl-2-butanol) where they may be experiencing a sevenfold barrier to rotation against the two adjacent methyls and the hydroxyl group. The largest value of $\tau(1,2)$ is found for the two methyls in 4-methyl-1-pentanol, where we must argue, on the basis of eq 8, that rotation barriers are high. Final resolution of these questions will come with the availability of T_1

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measurements on these compounds as a function of temperature.

Since the present work has been restricted to compounds having just six carbons, we do not observe those effects peculiar to longer chains such as segmental motion and kinks in the alkane chain.[12] As we extend this work to include molecules of higher molecular weight, we expect those effects to enter the regression analysis.

It is interesting to note that diastereotropic methyl groups have different values for T_1, and hence different values for τ_{eff} and $\tau(1,2)$. In 4-methyl-2-pentanol the difference in $\tau(1,2)$ is not great, 10.4 vs. 10.5 ps, but in 2-methyl-3-pentanol one methyl has a $\tau(1,2)$ of 7.89 ps and the other a $\tau(1,2)$ of 9.49 ps. From our shift reagent work[2] we know the assignments for these two methyls and the average conformation of the molecule. Methyl-50, with the shorter $\tau(1,2)$, is the more crowded and hence may be subject to a threefold barrier to rotation and thus have a reduced barrier to rotation compared to methyl-49.

Conclusion

Careful measurement of the spin–lattice relaxation values for most of the carbons in these 18 isomeric alcohols followed by regression analysis of the results has given new insight into the relationships between T_1, molecular structure, and molecular dynamics. No general applicability can be claimed for the regression coefficients determined in this work since they are a function of such things as solvent, concentration, temperature,

the functional groups present, and the solution viscosity; however, the trends observed should have general applicability. We expect to be able to extend these correlations to include some of these other factors as we measure the relaxation times of higher homologues. Variable-temperature measurements will clarify the energetics of methyl group rotation. Ultimately theoretical calculations, which can be compared with the experimental results of the present work, will clarify the interactions responsible for the observed values of the carbon spin–lattice relaxation times in these molecules.

Sodium Cation Complexation by Large Crown Ethers: 23Na NMR Chemical Shifts and Longitudinal and Transverse Relaxation Rate Studies of Sodium Tetraphenylborate–Dibenzo-24-crown-8 Complexes in Nitromethane

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Abstract: The complexation of sodium tetraphenylborate by dibenzo-24-crown-8 has been studied in nitromethane solutions by Na-23 nuclear magnetic resonance spectroscopy at three different fields. Chemical shifts show the presence in solution of two major cationic species: solvated sodium and the 1:1 sodium/crown complex. Longitudinal relaxation rates are field-independent and indicate the formation of higher aggregates whose stoichiometry is plausibly $(n + 1)/n$ sodium/crown. An aggregation model based on this stoichiometry is proposed, and equilibrium constants for the aggregation have been calculated. The average number of crowns in the species varies from 1 to 3.8 which confirms that Na-23 relaxation times belong to the extreme-narrowing limit. Only 2% of the total sodium concentration is distributed among the aggregated species with a maximum contribution for $n = 1$. Transverse relaxation rates are field-dependent. The temperature variation of $\ln T_1^{-1}$ and $\ln T_2^{-1}$ shows that the T_2's are affected by two relaxation mechanisms which can be separated: quadrupolar and chemical exchange.

Naturally occurring cyclic antibiotic ionophores such as valinomycin, a 36-membered cyclic dodecadepsipeptide can highly discriminate between K^+ and Na^+.[1] Valinomycin folds around the potassium cation, being stabilized by intramolecular N–H···O=C hydrogen bonds. Other cyclic antibiotic ionophores, such as enniatin, form 1:1 and 2:1 ionophore/cation complexes[1b,c] and display lower cation selectivity than valinomycin. These cryptand-like three-dimensional complexes differ strikingly from the synthetic cryptands[2] or spherands[3] by their higher lability; the decomplexation rate is faster in the case of the wrapped ionophore complex[4a] than in the case of the encaging cryptand.[4b] This is one of the reasons why synthetic models have been designed,

incorporating a crown cavity and a potentially folding side arm capable of complexing the cation.[5] Such "lariat ethers" form three-dimensional labile cryptand-like complexes.[6] Large 24-

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