APPLICATION OF THE RELAXATION REAGENT Gd(FOD)$_3$ (1,1,1,2,2,3,3-HEPTAFLUORO-7,7-DIMETHYL-4,6-OCTANEDIONATE)-GADOLINIUM(III) IN ^{1}H-NMR SPECTROSCOPY OF ADAMANTOID COMPOUNDS

Jiří KARHAN[a], Milan HÁJEK[b], Zbyněk KSANDR[a] and Luděk VODIČKA[b]

[a] *Department of Analytical Chemistry and*
[b] *Laboratory of Synthetic Fuels,*
Prague Institute of Chemical Technology, 166 28 Prague 6

Received February 28th, 1978

The spin-lattice relaxation times T_1 of protons in the presence of the shift reagent Eu(FOD)$_3$-D$_{27}$ and the relaxation reagent Gd(FOD)$_3$ were employed for the structure analysis of 1-adamantanol, 4-diamantanol, adamantanone, and 2,2-dioxy-2-thiaadamantane. The structure models of the complex adducts of the substrates with Gd(FOD)$_3$ are discussed. The dependence of the corrected spin-lattice relaxation rates on the relaxation reagent concentration is linear only in the region of low concentration.

The NMR shift reagents have found wide application in the structure analysis[1-4]. Information on the structure can be obtained also from the spin-lattice and spin-spin relaxations of the nuclei of the substrate under study, affected by the presence of paramagnetic ions. Among paramagnetic ions there are such which affect selectively both relaxation mechanisms. These ions are used as the central atoms of the so-called relaxation reagents, and they must satisfy the following requirements[3,5-7]: *a*) they must possess a long electron relaxation time T_1^e, responsible for a strong relaxation effect, *b*) they must possess an isotropic electronic **g**-tensor, allowing to introduce some simplifications of the expressions for the calculations, and *c*) the complex of the substance measured with the relaxation reagent must be axially symmetrical.

For practical applications of a relaxation reagent, a method has been suggested[8,9] based on the simultaneous use of a shift reagent and a relaxation reagent. The shift reagent effects a resolution of the NMR signals of the various nuclei in the molecule, whose broadening or relaxation times, affected by the relaxation reagent, can be then readily measured.

For the correlation of the measured spin-lattice relaxation times of the substrate protons, the equation

$$(1/T_{1i})^R = K \cdot r_i^{-6} \qquad (1)$$

is usually employed[2,3,7,10]; here the left-side term is the corrected relaxation rate of the i-th proton, defined by the relation $(1/T_{1i})^R = (1/T_{1i})^{S+R} - (1/T_{1i})^S$, where the superscripts S and R refer to the systems with the shift and relaxation reagents, respectively.

For the testing of the applicability of Eq. (*1*) to structure analysis, the following monofunctional derivatives of adamantane were chosen: 1-adamantanol (*I*), 4-diamantanol (*II*) adamantanone (*III*), and 2,2-dioxy-2-thiaadamantane (*IV*); they feature rigid and symmetrical molecular structure.

We confronted the structure conclusions arrived at in this work with those obtained from the measurements of the induced broadening of the proton NMR signals of these substrates.

EXPERIMENTAL

The compounds *I*—*IV* were prepared by the standard method[11] at the Laboratory of Synthetic Fuels of the Prague Institute of Chemical Technology. All chemicals were stored in a vacuum dessicator over solid P_2O_5.

The shift reagent Eu(FOD)$_3$-D_{27} was a commercial chemical of MSD, Canada, the relaxation reagent Gd(FOD)$_3$ was a commercial preparation of Willow Brooks Labs., Wisconsin, U.S.A.

As the solvent served either a mixture of 75% vol. $CDCl_3$ and 25% vol. C_6F_6, or pure $CDCl_3$, always with TMS as the internal standard. The solvents were dried by means of a molecular sieve Nalsit 4 Å, preparation of Fluka, Switzerland[12].

The nonselective method Inversion-Recovery[13] was applied to the measurement of the spin-lattice relaxation times T_1 of the protons. The experiments were performed at the temperature 40°C on an adapted NMR spectrometer Varian DA-60 (60 MHz) with the ^{19}F heterolock system[14], controlled by an on-line computer VARIAN 620/L-100 with a 16 k memory and equipped with a disc unit DIABLO, and on a routine FT NMR spectrometer Bruker WP-80 (80 MHz) at the temperature 32°C.

The NMR signals were narrow enough to allow their intensities to be approximated by their heights with a sufficient accuracy. The individual T_1 relaxation times were calculated by using the linear regression method[14]. The error of determination of T_1 did not exceed 5% rel.

The effective positions of the Gd atom in the complex adducts were calculated by employing modified programs of the PSEUDO series in the language FORTRAN IV (ref.[15]), applying the nonlinear regression method[16]. The calculations were carried out on a computer ICL-4-72. The results were evaluated by using the optimization criterion P_{T_1} defined as

$$P_{T_1} = [\sum(1/T_{1i}^{obs} - 1/T_{1i}^{cal})^2/\sum(1/T_{1i}^{obs})^2]^{1/2}, \qquad (2)$$

where the superscripts obs and cal refer to the relaxation rates obtained from the measurements and the optimization calculation, respectively.

The coordinates x, y, z of the protons, requisite for the solution of Eq. (*1*), were calculated by employing the program KARTSOUR[15,17].

RESULTS AND DISCUSSION

For the description of the various structure models of the complex adducts it appeared convenient to introduce the term"effective position of the paramagnetic ion", meaning the position of the paramagnetic ion obtained upon the optimization solution of Eq. (*1*).

For the calculation, the substrate molecule was orientated in the cartesian coordinate system so that the heteroatom of the functional group was located in the origin. The position of the Gd atom is described by polar coordinates, *i.e.* by the magnitude of the radius vector R and the angles φ and ψ in the planes X-Y and X-Z, as shown for the substance *IV* in Fig. 1.

It turned out that the model involving a single effective position of Gd on the prolonged axis of the bond carbon–heteroatom was not appropriate for all the substrates examined. We performed therefore the calculations also for the model with two effective Gd positions, for simplicity's sake symmetrical with respect to the X axis. During the optimization calculation a set of calculated $(1/T_{1_i})^R$ values was sought such that the optimization criterion P_{T_1} attained the lowest possible value[17]. The model with a single Gd position is very well suited to 1-adamantanol and 4-diamantanol, slightly more poorly to adamantanone. For 2,2-dioxy-2-thiaadamantane this model does not suite at all (the value of the optimization criterion was greater than 1). The measured spin-lattice relaxation rates and the parameters calculated from them

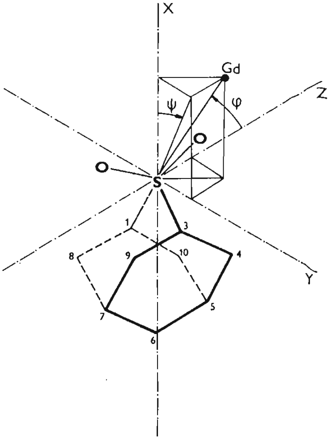


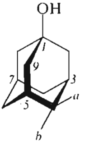
FIG. 1

Orientation of the Coordinate System for the Compound *III*

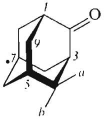
The oxygen atoms of the functional group lie in the X—Z plane.

for different Gd/Eu molar ratios are given in Tables I–III for the substances *I–III*, respectively. The optimization criterion values indicate a very good agreement between the measured and calculated sets of $(1/T_{1i})^R$.

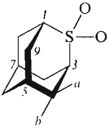
The substrate *IV* is very well described by the model with two effective Gd positions. The observed and calculated parameters are given in Table IV. This model accounts also better for the faster relaxation of the protons 4, 8, 9, 10 as compared with the protons 1, 3, which the model with one effective position does not.



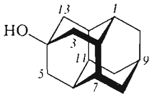
I



II



III



IV

TABLE I

Longitudinal Relaxation Rates $1/T_1$ (s^{-1}) of Protons of 1-Adamantanol with Eu(FOD)$_3$-D$_{27}$
Adamantanol concentration 0·45 mol l^{-1}, $R_p = 0.49$, measurement temperature 32°C, instrument Bruker WP 80.

Molar ratio Gd/Eu . 10^3	Protons				Effective distance Gd–O, nm	Optimization criterion P_{T_1}
	2,8,9	3,5,7	4,6,10(*a*)	4,6,10(*b*)		
0·0	1·46	0·78	1·05	1·06	—	—
6·3	71·23	9·74	10·54	7·71	0·330	0·025
11·6	150·0	19·53	20·72	14·36	0·283	0·03
23·3	287·1	37·69	38·08	27·59	0·250	0·04
34·9	370·9	50·54	—	37·84	0·250	0·05
61·3	708·2	73·05	—	53·67	0·250	0·02

With the substrate *IV*, experiments were also carried out employing the shift reagent Yb(FOD)$_3$ solely which itself affects significantly the relaxation of the nuclei, in contrast to Eu(FOD)$_3$. The measured $1/T_{1i}^{obs}$ values and the calculated parameters in dependence on the R_p value are given in Table V. The shift reagent Yb(FOD)$_3$ does not satisfy the requirements *a*) and *b*) as stated in the introduction; in the applied shift reagent concentration region, however, the results were found to be equally well applicable to structure analysis as those obtained with Gd(FOD)$_3$, in accordance with the results found with other substrates[10,18].

The model with two effective Gd positions was applied also to the substrate *III*, because the model with one effective position afforded relatively poorer results. It can be assumed that the oxygen lone electron pairs may be responsible for the occurrence of the two effective Gd positions, as suggested in the case of tert-butyl methyl ketone[19]. The parameters calculated for this case are given in Table III.

The lowering of the value of the optimization criterion P_{T_1} corroborates the above assumption of the two effective Gd positions. No change of this value has been observed on the use of the induced signal broadening of the adamantanone protons under the same assumptions[20].

Inasmuch as it was desirable to mutually compare the results obtained from the T_1 measurements and those from the measurements of the induced signal broadening, experiments were also performed with higher concentrations of the relaxation reagent, *viz.* with the Gd/Eu molar ratios $6 \cdot 1 \cdot 10^{-3} - 4 \cdot 93 \cdot 10^{-2}$. The dependence of the corrected relaxation rates for the individual protons of *III* was not found linear over the whole concentration region. The correlation coefficient of the dependence of

TABLE II

Longitudinal Relaxation Rates $1/T_1$ (s^{-1}) of the Protons of 4-Diamantanol with Eu(FOD)$_3$-D$_{27}$

Diamantanol concentration 0·18 mol l^{-1}, $R_p = 0 \cdot 35$, measurement temperature 40°C, instrument VARIAN DA-60.

Molar ratio Gd/Eu . 10^3	Protons			Effective distance Gd—O, nm	Optimization criterion P_{T_1}
	3,5,13	1,2,6,7,11,12	8,10,14,9[a]		
0·00	1·16	0·57	0·79	—	—
0·28	3·05	0·84	0·90	0·310	0·036
0·65	5·32	1·03	0·90	0·275	0·012
1·05	9·8	1·55	1·05	0·300	0·015
1·8	14·49	2·06	1·22	0·300	0·017

[a] The protons 9 remained unresolved at 60 MHz and the R_p applied.

TABLE III

Longitudinal Relaxation Rates $1/T_1$ (s^{-1}) of the Protons of Adamantanone with $Eu(FOD)_3$-D_{27}

Adamantanone concentration: A 0·59 mol l^{-1}, B 0·5 mol l^{-1}; R_p: A 0·49, B 0·47; measurement temperature: A 40°C, B 32°C; instrument: A VARIAN DA-60, B BRUKER WP-80.

Molar ratio Gd/Eu . 10^3	Protons				
	1,3	4,8,9,10(*a*)	4,8,9,10(*b*)	5,7	6
			A		
0·0	1·16	0·99	0·96	0·75	1·06
0·47	6·21	2·25	1·38	1·03	1·27
0·86	10·80	3·50	1·90	1·39	1·61
1·72	19·23	5·76	2·92	2·16	2·24
			B		
0·0	0·96	0·79	0·77	0·57	0·79
6·1	66·8	24·03	11·37	7·86	7·11
10·2	112·1	39·36	19·24	14·36	12·46
25·8	[c]	88·30	43·28	32·99	27·91
30·4	[c]	107·4	52·77	42·14	34·72
49·3	[c]	126·8	72·93	60·04	50·45

[a] Structure model with one effective Gd position; [b] structure model with two effective Gd positions; [c] signals very broadened; [d] calculation performed without taking into account the protons 1,3.

TABLE IV

Longitudinal Relaxation Rates $1/T_1$ (s^{-1}) of the Protons of 2,2-Dioxy-2-thiaadamantane with $Eu(FOD)_3$-D_{27}

Substrate concentration 0·52 mol l^{-1}, $R_p = 0·58$, measurement temperature 40°C, instrument VARIAN DA-60.

Molar ratio Gd/Eu . 10^3	Protons					Effective distance Gd–S, nm	Angle φ deg	Optimization criterion P_{T_1}
	1,3	4,8,9,10(*a*)	4,8,9,10(*b*)	5,7	6			
0·0	1·03	2·04	1·85	0·95	1·65	—	—	—
0·24	3·58	4·90	2·22	1·28	1·88	0·475	46·2	0·1
0·53	5·92	7·73	2·84	1·80	2·21	0·487	32·3	0·04
1·00	10·75	11·90	3·82	2·42	2·56	0·480	47·0	0·03
1·82	16·39	18·53	4·93	3·36	3·08	0·500	45·0	0·04

TABLE III
(*Continued*)

Model *I*[a]		Model *II*[b]		
effective distance Gd–O, nm	optimization criterion P_{T_1}	effective distance Gd–O, nm	angle Ψ deg	optimization criterion P_{T_1}
		A		
—	—	—	—	—
0·241	0·27	0·323	57·1	0·16
0·272	0·28	0·255	59·1	0·06
0·277	0·28	0·355	57·0	0·17
		B		
—	—	—	—	—
0·300	0·20	0·283	51·7	0·09
0·253	0·20	0·300	45·0	0·13
0·260[d]	0·23	0·310	48·0	0·21
0·259[d]	0·24	0·380	59·3	0·19
0·275[d]	0·31	0·370	64·3	0·25

TABLE V

Longitudinal Relaxation Rates $1/T_1$ (s^{-1}) of the Protons of 2,2-Dioxy-2-thiaadamantane with Yb(FOD)$_3$
Substrate concentration 0·95 mol l^{-1}, measurement temperature 40°C, instrument VARIAN DA-60.

R_p[a]	Protons					Effective distance Yb–S, nm	Angle φ deg	Optimization criterion P_{T_1}
	1,3	4,8,9,10(*a*)	4,8,9,10(*b*)	5,7	6			
0·00	0·39	0·54	0·56	0·57	—	—	—	—
0·028	3·66	4·04	1·40	1·06	—	0·501	42·0	0·03
0·082	9·26	10·23	2·77	2·11	1·82	0·450	45·0	0·09
0·144	15·55	16·88	4·31	3·14	2·65	0·520	44·4	0·06
0·23	23·92	27·03	6·3	4·83	3·88	0·455	44·1	0·06
0·45	42·02	55·23	11·11	8·26	5·71	0·510	50·0	0·08

---

[a] The ratio of the molar concentrations of the shift reagent (Yb(FOD)$_3$) and the substrate (2,2-dioxy-2-thiaadamantane).

$(1/T_{1,i})^{R}$ on the Gd/Eu molar ratio in the region 0·2 . 10^{-3} to 1·72 . 10^{-3} was 0·999 for all protons, whereas in the Gd/Eu molar ratio region 6·1 . 10^{-3} to 4·93 . 10^{-2} it was only 0·98. The dependence is linear only up to the molar ratio approximately 2·5 . 10^{-2}, hence approximately 6 . 10^{-3}M solution of the relaxation reagent. The dependence of $(1/T_{1,i})^{R}$ for the protons of the substance *III* in the examined range of the relaxation reagent concentrations are shown in Figs 2 and 3. The calculations performed for the whole region of the Gd(FOD)$_3$ concentrations showed that the final structure conclusions were independent of the concentration of the relaxation reagent. The nonlinearity of the plot of $(1/T_{1,i})^{R}$ *versus* the Gd/Eu molar ratio is probably due to the equilibrium processes in the system investigated, which are very complicated.

It can be concluded that use can be made of the spin-lattice relaxation times for the structure analysis of adamantane derivatives as successfully as of the induced chemical shifts[15,21,22] and of the induced NMR signal broadening[20]. In the case of adamantanone, the spin-lattice relaxation times were found to respond more sensitively to the choice of the structure model of the complex adduct.

The results of this work confirmed that the simple relation (*1*) and the structure models can be used for the interpretation of the relaxation data under the same conditions and assumptions as for the interpretation of the chemical shifts. It was also confirmed that an improvement of the method of measurement results in a lowering

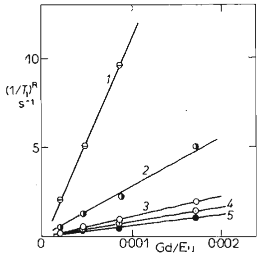


FIG. 2

Dependence of the Relaxation Rate $(1/T_1)^R$ on the Concentration of the Relaxation Reagent for the Protons of the Compound *III*

Protons: *1* 1,3, *2* 4,8,9,10(a), *3* 4,8,9,10(b), *4* 5,7, *5* 6.

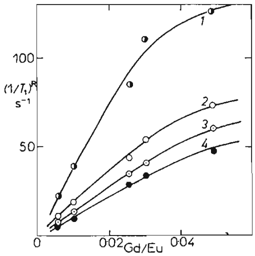


FIG. 3

Dependence of the Relaxation Rate $(1/T_1)^R$ on the Concentration of the Relaxation Reagent for the Protons of the Compound *III*

Protons: *1* 4,8,9,10(a), *2* 4,8,9,10(b), *3* 5,7, *4* 6.

of the optimization criteria values, which implies that the conclusions derived from the results are also more reliable.

The authors wish to thank Professor Dr R. R. Ernst, Laboratorium für physikalische Chemie ETH, Zürich, for enabling them to perform most of the relaxation experiments at his laboratory, and for valuable discussions of the problem under study.

REFERENCES

1. Hinckley C. C.: J. Amer. Chem. Soc. *91*, 5160 (1969).
2. Reuben J.: *Paramagnetic Lanthanide Shift Reagents in NMR Spectroscopy.* Pergamon Press, Oxford 1973.
3. LaMarr G. N., Horrocks W. DeW. jr, Holm R. H.: *NMR of Paramagnetic Molecules.* Academic Press, New York 1973.
4. Sievers R. E.: *Nuclear Magnetic Resonance Shift Reagents.* Academic Press, New York 1973.
5. Mohyla I., Ksandr Z., Hájek M.: Chem. Listy *69*, 1148 (1975).
6. Levy G. C., Komorski R. A.: J. Amer. Chem. Soc. *96*, 678 (1974).
7. Solomon I.: Phys. Rev. *99*, 559 (1955).
8. LaMarr G. N., Faller J. W.: J. Amer. Chem. Soc. *95*, 3817 (1973).
9. Faller J. W., LaMarr G. N.: Tetrahedron Lett. *1973*, 1381.
10. Reuben J., Leigh J. S. jr: J. Amer. Chem. Soc. *94*, 2789 (1972).
11. Eisentraut K. J., Sievers R. E.: J. Amer. Chem. Soc. *87*, 5254 (1965).
12. Karhan J., Hájek M., Ksandr Z.: Sb. Vys. Šk. Chemicko-Technol. Praze H *11*, 213 (1976).
13. Vold R. L., Waugh J. S., Klein M. P., Phelps D. E.: J. Chem. Phys. *48*, 3831 (1968).
14. Welti D.: *Thesis* No 5701. ETH, Zürich 1976.
15. Hájek M.: *Thesis.* Prague Institute of Chemical Technology, Prague 1974.
16. Ingri N., Sillen L. G.: Archiv Kemi *23*, 97 (1974).
17. Howel J. M.: Stud. Univer. Babes-Balyai, Sec. Chemia *1*, 87 (1970).
18. Lenkinski R. E., Reuben J.: J. Magn. Resonance *21*, 47 (1976).
19. Lenkinski R. E., Reuben J.: J. Amer. Chem. Soc. *98*, 4065 (1976).
20. Hájek M., Mohyla I., Ksandr Z., Vodička L.: This Journal *41*, 3591 (1976).
21. Willcott M. R., Davis R. E.: J. Amer. Chem. Soc. *94*, 1742 (1972).
22. Mohyla I., Ksandr Z., Hájek M., Vodička L.: This Journal *39*, 2935 (1973).

Translated by P. Adámek.