^{17}O NMR Chemical Shifts of Polyoxides in Gas Phase and in Solution

Anan Wu,[†] Dieter Cremer,*[,†] and Jürgen Gauss[‡]

Department of Theoretical Chemistry, Göteborg University, Reutersgatan 2, S-41320 Göteborg, Sweden, and Institut für Physikalische Chemie, Universität Mainz, D-55099 Mainz, Germany

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The ^{17}O NMR chemical shift values of polyoxides HO_nH, CH_3O_nH, and $CH_3O_nCH_3$ ($n = 2, 3, 4$) were calculated using four different methods (GIAO-HF, GIAO-MP2, GIAO-CCSD(T), and IGLO-DFT) and various basis sets ranging from double to quadruple ζ quality. The ^{17}O shift values depend on the number of O atoms in the polyoxide chain and on the terminal group (H or alkyl) and are spread over a large range (200−600 ppm relative to H_2O) due to a (diamagnetic) shielding effect caused by electron attraction by the electronegative O atom and a (paramagnetic) deshielding effect caused by anomeric delocalization. Solvent shifts result from both nonspecific and specific solvation. Nonspecific solvation normally leads to a shielding of ^{17}O by up to 20 ppm, whereas specific solvation is strongly deshielding, causing a net effect of 20−36 ppm. An empirical scheme is suggested to predict measured values with an accuracy of better than 5 ppm using GIAO-MP2/qzp gas-phase values with GIAO-CCSD(T) estimates of higher-order correlation corrections as well as specific and nonspecific solvation corrections. Averaging of NMR chemical shifts due to the rotational flexibility of the polyoxides has little influence on the measured ^{17}O NMR chemical shifts.

1. Introduction

During the past years, research on polyoxides has been intensified, whereas specifically hydrogen trioxide, HOOOH, and alkyl hydrotrioxides, ROOOH, are at the focus of current investigations.[1−6] Increasing evidence shows that ozonation reactions with organic substrates lead to hydrotrioxides, as was already speculated for a long time.[7−9] Plesnicar and co-workers used ^{17}O-enriched ozone to verify the existence of HOOOH and ROOOH in the reaction mixture of ozone and isobutyl alcohol.[1] A recent publication showed that hydrogen trioxide can also be an intermediate in the hydrogen peroxide production from singlet oxygen and water by antibodies.[10] These findings have led to intensive work on peroxone (the combination of ozone and hydrogen peroxide) chemistry.[11−14] Peroxone is used to treat soil, groundwater, and wastewater contaminated with organic compounds, petroleum hydrocarbons, organic solvents, metals, munitions, trinitrotoluol, and other waste constituents.[15] Engdahl and Nelander[11] reported that a mixture of ozone and hydrogen peroxide produces when photolyzed considerable concentrations of HOOOH, which is relevant for peroxone chemistry and explains the production of the trioxide by antibodies.[10] Xu and Goddard[14] have suggested a mechanism for the generation of HOOOH in peroxone on the basis of quantum chemical calculations.

Polyoxides can be produced in processes involving ozone, oxygen, hydrogen peroxide, and water in various mixtures in connection with organic substrates. Hence they are important for chemical synthesis,[1−3,8,9,16] wastewater purification,[7,9] bleaching of polysaccharides (starch, cellulose, wood, pulp),[17] drinking water processing, toxicity studies of ozone, and activity studies of medical ozone.[18−22] In the polluted atmosphere reactions with alcohols and ozone only occur in the absence of OH radicals, which often react much faster with organic substrates than ozone.[23]

It is now considered to be a fact that in the ozonation reaction hydrogen trioxide, HOOOH,[24,25] its radical HOOO$^{\bullet}$,[26] or its anion $HOOO^-$ [5,6] are formed as important intermediates and that these species play also a role in ozonation reactions of biochemical compounds.

Because of the increased interest in HOOOH, ROOOR, and ROOOH compounds and because of the fact that the experimental detection of these compounds is heavily based on ^{17}O NMR spectroscopy, we report in this work ^{17}O NMR chemical shifts that provide a basis for identifying polyoxides in experimental investigations. One could expect that with increasing length of the polyoxide the individual O atoms get similar shift values and that it is in general difficult to distinguish peroxides from tri- or tetroxides. In this work we will show that a number of distinct electronic effects lead to a variation of the ^{17}O NMR chemical shifts to such an extent that ^{17}O NMR spectroscopy is probably the best tool to identify a specific polyoxide in solution. We will calculate ^{17}O NMR chemical shifts for HO_nH, CH_3O_nH, and $CH_3O_nCH_3$ ($n = 2, 3, 4$) in the gas phase. Since most NMR measurements of polyoxides can only be carried out in solution phase, we will also provide estimates for solvent shifts that are needed for the experimental work.

2. Computational Methods

In this work, density functional theory (DFT)[27] in connection with the B3LYP hybrid functional[28−30] and Pople's 6-31G(d,p) basis set[31] was used to calculate the equilibrium geometries of HO_nH, CH_3O_nH, and $CH_3O_nCH_3$ ($n = 2, 3, 4$) in the gas phase. In previous calculations,[32] we have found that this approach provides reasonably reliable although not absolutely correct geometries. However, contrary to CCSD(T)/large basis set calculations, it can be routinely applied to alkyl polyoxides, which are at the focus of experimental work. The geometry of all equilibrium structures was confirmed by vibrational frequency calculations to be minima on the conformational energy surface.

* Corresponding author. E-mail: cremer@theoc.gu.se.
[†] Göteborg University.
[‡] Universität Mainz.

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NMR chemical shifts have been computed at the Hartree−Fock (HF) and at second-order Møller−Plesset perturbation theory (MP2) level using gauge-including atomic orbitals (GIAO)[33,34] and the integral-direct algorithm as implemented in the quantum chemical program package TURBOMOLE.[35,36] For the purpose of checking the accuracy of the GIAO-MP2 calculations, additional chemical shift calculations have been performed for HOH, HOOH, and HOOOH at the GIAO-CCSD-(T) level.[37] Calculations have been carried out with the dzp ((8s4p1d/4s1p) → (4s2p1d/2s1p)), tzp ((10s6p1d/5s1p) → (6s3p1d/3s1p)), and qz2p (((11s7p2d/7s2p) → (6s4p2d/4s2p)) basis sets[38,39] which in earlier studies have proven well suited for the prediction of NMR chemical shifts.[34]

Sum-over-states density functional perturbation theory (SOS-DFPT)[40,41] based on the individual gauge for localized orbitals (IGLO) approach[42] was employed to calculate ^{17}O NMR chemical shifts for both the gas phase and the solution phase. For this purpose, a combination of Becke's exchange[28] and the PW91 correlation functional[43] rather than B3LYP was used since the former is known to lead to somewhat better shift values.[44] As an appropriate basis set the (9s5p1d/5s1p) → (5s4p1d/3s1p) set was employed, which is of valence triple-ζ plus polarization quality and which was designed for NMR chemical shift calculations with the IGLO method.[45] All DFT calculations were based on an accurate calculation of the Coulomb part and numerical integration of the exchange-correlation potential.[41] The well-known deficiencies of DFT methods to lead to occupied orbitals with relatively high energies and, accordingly, to an overestimation of paramagnetic contributions to chemical shifts[46] were compensated by adding appropriate level shift factors to orbital energy differences, as was first suggested by Malkin and co-workers[40] and studied in detail by Olsson and Cremer.[41]

The influence of a solvent on the ^{17}O NMR chemical shifts was investigated by using a reaction field with the self-consistent isodensity polarized continuum (SCIPCM) approach,[47] which provides an estimate of electrostatic solvent effects. In this approach, an isodensity surface defined by a value of 0.0004 au of the total electron density distribution is calculated at the level of theory employed. Such an isodensity surface has been found to define rather accurately the volume of a molecule,[48] and therefore, it should also define a reasonable cavity for the dissolved molecule within the polarizable continuum where the cavity can iteratively be adjusted when improving wave function and electron density distribution during a self-consistent-field (SCF) calculation at the DFT level of theory. The wave function obtained for the dielectric constant ϵ of water at 298 K (78.3 [ref 49]) was used with the same basis set and geometry to recalculate the ^{17}O NMR chemical shifts, which by comparison with the gas-phase NMR chemical shifts lead to the solvent effects Δ on the ^{17}O shifts.

Relative shifts δ were obtained by converting the computed shielding constants σ via

$$\delta = \sigma_{H_2O(gas)} - \sigma - 36.1$$

to the usual ^{17}O NMR scale, thereby using the fact that the relative shift of gaseous water is −36.1 ppm.[50] It should be stressed that the reference for the ^{17}O scale is liquid and not gaseous water, and that therefore a large correction of 36.1 ppm is necessary. However, it must be also realized that we obtain in this way from the computations gas-phase ^{17}O shift values for the compounds considered. To compare with experimental data which generally are obtained in solution phase, we need to account for solvent effects, and those cannot be ignored. We will in this work devise a stepwise procedure for converting gas-phase ^{17}O values to solution values.

The electronic structure of the polyoxides considered was investigated by determining atomic charges with the natural bond orbital (NBO) analysis of Weinhold and co-workers.[51] Calculations were carried out with the ab initio program packages TURBOMOLE[52] (GIAO-HF and GIAO-MP2 calculations), ACES II[53] (GIAO-CCSD(T) calculations), COLOGNE 2002[54] (IGLO-DFT), and Gaussian 98 (geometry optimizations).[55]

3. Results and Discussion

B3LYP geometries of HO_nH, CH_3O_nH, and $CH_3O_nCH_3$ (n = 2, 3, 4) are summarized in Figure 1. For HOOH, a dihedral angle of 118° is calculated, which is about 6° larger than the excepted value of 112°.[56] Otherwise, the geometry is reasonably described (R(OO) = 1.456 Å; expt: 1.452 Å[57]), which holds also for the two methyl derivatives (MeOOH: τ = 115°, R(OO) = 1.456 Å; MeOOMe: τ = 128.7°, R(OO) = 1.462 Å). HOOOH and MeOOOMe adopt a C_2-symmetrical form, where one substituent (H or Me) is above the other below the plane of the three O atoms so that part of a helix is formed. For HOOOH, this conformer is known to be 3.5 kcal/mol more stable than the C_s-symmetrical conformer with both substituents above (below) the OOO plane.[24,58] For HOOOOH again a helix form can be expected[58] (see Scheme 1); however, contrary to these predictions, a partial helix was found (Figure 1 and Scheme 1), in which electrostatic attraction between one of the terminal groups and a central O atom is found. This form is 3 kcal/mol more stable than the helix form.

In Table 1, ^{17}O NMR chemical shifts calculated at the HF and the MP2 level of theory with dzp, tzp, and a qz2p basis set are listed for HO_nH, CH_3O_nH, and $CH_3O_nCH_3$ (n = 2, 3, 4) in the gas phase. While for HOOH the influence of basis set and correlation effects are moderate extending not 9 ppm, these effects are substantial for the other polyoxides. In general, both extension of the basis and inclusion of correlation effects lead to a downfield shift of the ^{17}O shifts (more positive shift values) with just a few exceptions (for example, MP2 shifts for O(H) in MeOOH; Table 1). The downfield shifts due to correlation effects are substantial, ranging up to 80 ppm for the central O atoms, whereas the basis set effects are in general smaller. There is no possibility to extrapolate calculated ^{17}O shifts to the basis set limit, as the dzp basis seems to underestimate and the tzp basis set to overestimate the downfield shift in comparison to the qz2p values.

In view of the relatively large correlation effect, GIAO-MP2 calculations are a must for getting reasonable ^{17}O chemical shifts. At this level of theory, the tzp basis provides already reasonable shifts values, which differ for most polyoxides only by 2−4 ppm from the better GIAO-MP2/qz2p values. Since solvent effects can be substantially larger (see below), one might be satisfied with the tzp results; however, to be on the safe side, GIAO-MP2/qz2p values are preferable. There are ^{17}O shifts (e.g., for one of the central O atoms of MeO_4H; Table 1), which differ by 6 ppm and more when increasing the basis set from tzp to qz2p quality.

MP2 covers the important pair correlation effects but is far from giving a reliable description of higher-order electron correlation effects. For example, in polyoxides important multielectron correlation effects (repulsion between two electron lone pairs; anomeric effects) take place, which are difficult to describe. Kraka et al. have shown this, for example, for the FOOF molecule.[59] Because of these higher-order correlation

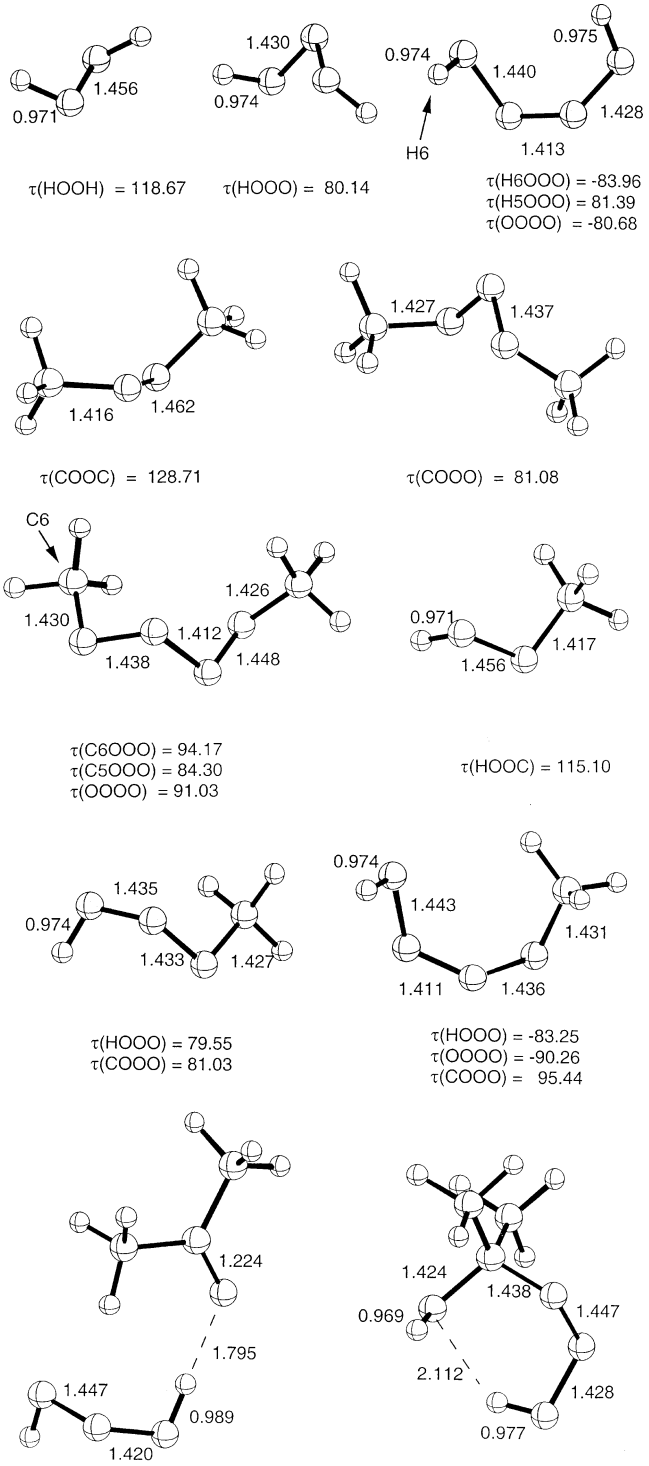


Figure 1. B3LYP/6-31G(d,p) geometries (distances in Å and angles in deg) of the polyoxides investigated.

effects, GIAO-CCSD(T)/dzp calculations were carried out for HOOH and HOOOH. The ^{17}O value of hydrogen peroxide changed by just 0.3 ppm to 158.6 ppm, which suggests that additional correlation corrections are here not important.

For the central O atom of HOOOH, the ^{17}O chemical shift changes from 392.2 ppm (GIAO-MP2/dzp, Table 1) to 378.3 ppm (GIAO-CCSD(T)/dzp), indicating 14 ppm additional shielding because of higher-order electron correlation effects. For the terminal O atom this value is 4.8 ppm (from 247.7, Table 1, to 242.9 ppm). Comparing these values with the changes in the ^{17}O chemical shift due to basis set improvements

SCHEME 1

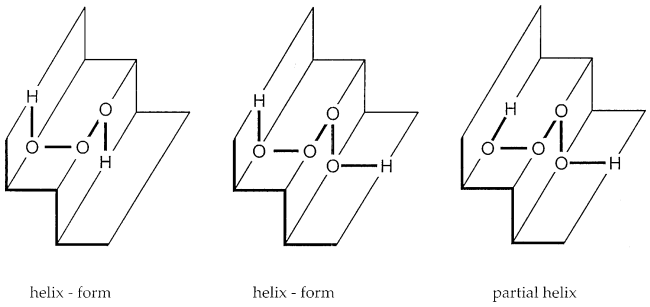


TABLE 1: ^{17}O NMR Chemical Shifts of Polyoxides in the Gas Phase As Obtained with Different Methods and Basis Sets[a]

		GIAO-HF			GIAO-MP2		
molecule	nucleus	dzp	tzp	qz2p	dzp	tzp	qz2p
H_2O_2	O	155.8	158.8	154.3	158.9	167.9	163.1
H_2O_3	O(c)	347.8	364.5	362.2	392.2	423.1	421.8
	O(t)	247.4	266.0	263.9	247.7	277.8	278.2
H_2O_4	O(1)	254.3	268.1	261.9	238.2	263.5	260.5
	O(2)	410.8	436.9	437.8	450.9	495.9	500.5
	O(3)	422.1	447.8	446.6	463.2	507.1	509.4
	O(4)	238.6	252.0	248.8	234.4	259.5	258.9
Me_2O_2	O	201.5	211.7	206.8	216.2	235.6	233.6
Me_2O_3	O(c)	424.8	448.3	445.9	480.2	523.7	527.6
	O(t)	229.6	243.9	239.8	233.0	258.9	257.7
Me_2O_4	O(1)	273.9	289.3	283.9	272.0	301.0	298.7
	O(2)	460.3	487.4	486.3	515.7	564.1	568.9
	O(3)	427.7	452.7	452.6	479.4	524.6	529.4
	O(4)	284.8	301.5	279.9	275.4	307.4	304.4
MeO_2H	O(oc)	164.3	171.5	165.8	173.9	187.9	182.1
	O(oh)	197.1	204.2	200.7	205.3	220.2	219.1
MeO_3H	O(c)	386.4	406.5	404.0	436.4	473.5	474.5
	O(oc)	252.2	273.0	269.4	252.0	285.2	285.2
	O(oh)	225.4	239.1	236.4	228.9	253.4	252.8
MeO_4H	O(oc)	288.1	307.3	300.1	274.0	308.3	305.5
	O(c1)	444.1	473.6	474.5	491.6	542.4	548.8
	O(c2)	421.6	445.4	444.1	471.7	513.9	515.9
	O(oh)	260.6	274.4	270.8	261.7	287.5	286.1

[a] ^{17}O NMR chemical shifts (in ppm) relative to liquid water as reference. The shielding constant of H_2O(liquid) is obtained as $\sigma(H_2O(\text{liquid})) = \sigma(H_2O(\text{gas})) - 36.1$ ppm from the calculated gas-phase value $\sigma(H_2O(\text{gas}))$, thereby using the experimental relative shift of -36.1 ppm for gaseous H_2O.[50] B3LYP/6-31G(d,p) geometries were used for the GIAO calculations. O(c), O(c1), and O(c2) denote central atoms, O(t) terminal atoms, O(oc) the O atom next to C, and O(oh) the O atom next to H. For the numbering of HOOOOH and MeOOOOMe, see Figure 1.

(Table 1), the latter are more important than the inclusion of higher-order correlation. However, a further remark is required in the current context. When we discuss electron correlation effects, we actually consider differences in correlation contributions, as the relative shifts depend on correlation corrections for both the reference and the actual target compound. It thus is not surprising that rather small correlation effects are observed for the terminal oxygens. Those resemble in the electronic environment more the oxygens in the reference compound H_2O than the central oxygens in the polyoxides for which much larger correlation effects are seen.

We performed also some comparative IGLO-DFT calculations for the gas phase (Table 2) with a basis set comparable to the tzp basis. All shift values obtained in this way are much more positive. This is a result of the well-known tendency of DFT to exaggerate paramagnetic contributions. Therefore, we will not discuss the IGLO results here in detail but just point

TABLE 2: ^{17}O NMR Chemical Shifts of Polyoxides in the Gas Phase and in Aqueous Solution As Calculated at the IGLO-DFT/BPW91 Level[a]

molecule	nucleus	δ(gas)	δ(water)[b]	Δ_E	δ(soln)[c]	expt[d]
H_2O_2	O	179.0	162.0	−16.9	146.2	180
H_2O_3	O(c)	474.3	454.6	−19.8	402.1	421
	O(t)	280.8	268.9	−11.9	266.2	305
H_2O_4	O(1)	262.8	251.5	−11.3	249.1	
	O(2)	523.1	512.4	−10.7	489.8	
	O(3)	536.9	521.5	−15.4	494.1	
	O(4)	257.6	258.2	+0.6	259.4	
Me_2O_2	O	251.4	248.5	−2.9	230.9	253
Me_2O_3	O(c)	563.3	553.7	−9.6	517.9	
	O(t)	265.7	265.7	+0.0	257.7	
Me_2O_4	O(1)	309.9	319.3	+9.4	308.2	
	O(2)	579.4	569.2	−10.2	558.7	
	O(3)	539.0	532.4	−6.6	522.8	
	O(4)	316.3	313.7	−2.7	301.7	
MeO_2H	O(oc)	209.3	199.4	−9.9	172.2	204
	O(oh)	229.0	218.3	−10.8	208.3	254
MeO_3H	O(c)	519.5	504.7	−14.8	459.7	
	O(oc)	297.1	293.5	−3.6	281.6	
	O(oh)	251.1	242.1	−9.0	243.8	
MeO_4H	O(oc)	320.4	315.0	−5.4	300.1	
	O(c1)	559.6	552.1	−7.6	541.2	
	O(c2)	536.3	521.7	−14.6	501.3	
	O(oh)	288.2	287.7	−0.5	285.6	

[a] All ^{17}O NMR chemical shifts are given in ppm relative to liquid H_2O as reference. For the conversion of absolute shieldings to relative shift, the calculated value for $\sigma(H_2O(gas))$ of 295.8 ppm (IGLO/BPW91/[5s4p1d/3s1p] as well as $\delta(H_2O(gas)) = -36.1$ ppm have been used. All calculations have been performed at B3LYP/6-31G(d,p) optimized geometries. [b] The ^{17}O NMR chemical shifts δ(water) are calculated at the IGLO/SCIPCM/ BPW91/[5s4p1d/3s1p] level of theory using the dielectric constant ϵ of water at 298 K (78.3 [ref 49]) and B3LYP/6-31G(d,p) geometries. The shift increment $\Delta_E = \delta(gas) - \delta(water)$ reflects the electrostatic influence of the solvent. [c] The ^{17}O NMR chemical shifts for a water solution δ(solution) estimated by combining GIAO-MP2/qz2p values for the gas phase with the solvent corrections Δ_E. [d] Experimental values from ref 61 (HOOH), ref 1 (HOOOH), ref 60 (EtOOEt for MeOOMe), and ref 60 (compound **10a** in Table 1, p 254: ROOH for MeOOH).

TABLE 3: Comparison of NBO Atomic Charges and GIAO-MP2/qz2p NMR Chemical Shifts $\delta(^{17}O)$[a]

molecule	type	NBO charge	$\delta(^{17}O)$
H_2O_2	O	−0.481	163.1
H_2O_3	O(c)	−0.033	421.8
	O(t)	−0.463	278.2
H_2O_4	O(1)	−0.447	260.5
	O(2)	−0.027	500.5
	O(3)	−0.018	509.4
	O(4)	−0.473	258.9
Me_2O_2	O	−0.308	233.6
Me_2O_3	O(c)	−0.047	527.6
	O(t)	−0.292	257.7
Me_2O_4	O(1)	−0.297	298.7
	O(2)	−0.027	568.9
	O(3)	−0.035	529.4
	O(4)	−0.277	304.4
MeO_2H	O(oc)	−0.298	182.1
	O(oh)	−0.487	219.1
MeO_3H	O(c)	−0.040	474.5
	O(oc)	−0.289	285.2
	O(oh)	−0.466	252.8
MeO_4H	O(oc)	−0.276	305.5
	O(c1)	−0.034	548.8
	O(c2)	−0.020	515.9
	O(oh)	−0.471	286.1

[a] NMR chemical shifts $\delta(^{17}O)$ from Table 1 in ppm. NBO charges in electrons.

out that trends in the ^{17}O values are parallel to those obtained with GIAO methods.

The ^{17}O NMR chemical shifts depend on the diamagnetic influence of the negative charges at the O atoms. Calculating NBO charges for the molecules considered, a clear distinction between terminal and central O atoms can be made (Table 3). The terminal O atoms have always substantially more negative charges (−0.3 to −0.5 e) than the central O atoms (−0.02 to −0.04 e) so that the terminal O atoms are more shielded and have ^{17}O chemical shifts between 170 and 310 ppm. The ^{17}O chemical shifts of the central O atoms are in the region 420−570 ppm. Hence, if a signal is missing in the latter region, a tri- or tetroxide will not have been formed.

In Figure 2, calculated ^{17}O shifts are shown to be dependent on the calculated NBO atomic charges. The shift values cluster in three regions: First, there are ^{17}O values of the O(H) atom which attract due to the electronegativity difference between O and H of −0.48 electron. Then, there is a cluster of ^{17}O values of O(C) atoms, which attract only −0.3 electron. Finally, there are the ^{17}O values of the central O atoms which possess only little negative charge.

Apart from this clustering of the ^{17}O values shown in Figure 2, there is no correlation between calculated O charges and NMR chemical shifts within the three clusters. This indicates that besides the diamagnetic effect also paramagnetic effects must play a role for the actual ^{17}O values. In a simple, qualitative picture, these effects are related to the existence of low-lying excited states or alternatively to low-lying unoccupied molecular orbitals. Structure and stability of the polyoxides depend on an anomeric effect. The skewed equilibrium conformation of HOOH, MeOOH, and MeOOMe is a direct consequence of the delocalization of the oxygen lone pair electrons into low-lying σ^*(OX) orbitals of adjoint bonds, as indicated in Scheme 2. The strength of the anomeric effect depends on the orbital energy difference $\epsilon(\sigma^*(OX)) - \epsilon$(lone-pair) and on the overlap between these orbitals. Hence, only the π-type lone pair at O makes a sufficient contribution, and the σ^*(OX) orbital must be parallel aligned to the lone-pair orbital to guarantee significant overlap.

For the peroxides, substituent−substituent interactions widen the anomeric angle of 90°−128° (Figure 1), whereas for the trioxides and tetroxides dihedral angles between 80° and 95° are found, reflecting the influence of the anomeric effect. With each new OO bond in the polyoxide the anomeric effect is increased because the σ^*(OO) orbital is lower in energy than the σ^*(OH) orbital. Also, lone pair repulsion in a polyoxide increases the energy of the π(lone pair) so that the energy difference $\epsilon(\sigma^*(OX)) - \epsilon$(lone pair) becomes smaller and the anomeric effect stronger. This can be verified by comparing OO bond lengths, which decrease from 1.456 Å (HOOH) to 1.430 Å (HOOOH) and 1.413 Å (shortest bond of HOOOOH, Figure 1).

The anomeric effect leads to a paramagnetic shift (to low field, i.e., more positive shift values) in the ^{17}O values. However, it has also an influence on the diamagnetic effect because it determines the charge distribution in a polyoxide. In any case, it is responsible for the fact that the calculated ^{17}O shifts do no possess a linear relationship with the calculated O charges. This makes it difficult to establish simple correlations between the ^{17}O shifts and any other molecular property.

This becomes especially clear when one compares ^{17}O chemical shifts and NBO charges for MeOOH and MeOOOH. According to the calculated NBO charges, one would assign the shift values for MeOOH in the opposite way as done in this work (Tables 2−4). However, anomeric delocalization is stronger from the OH group than that from the OMe group (Me

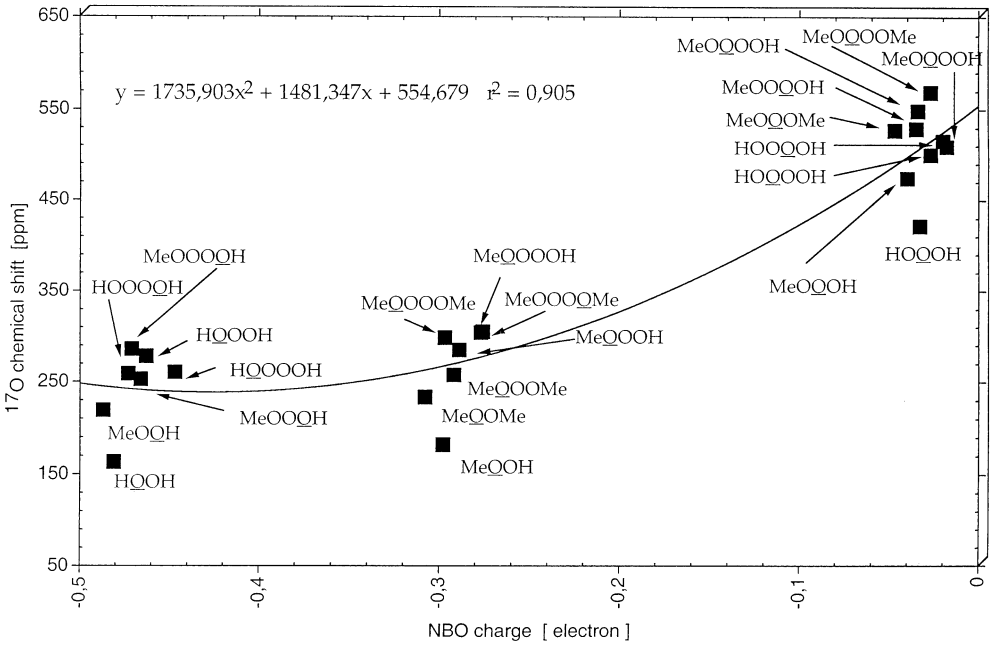
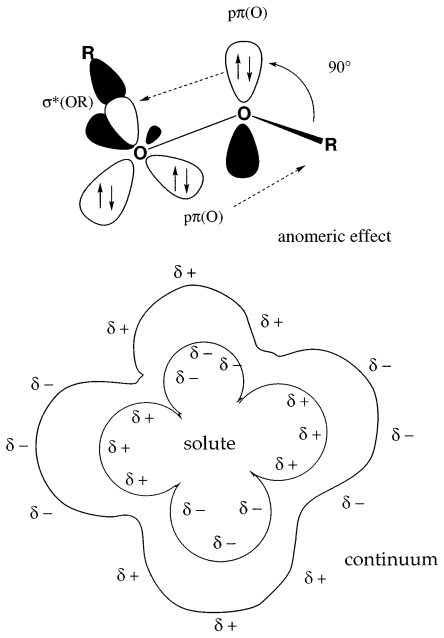


Figure 2. Dependence of the GIAO-MP2/qz2p ^{17}O NMR chemical shifts (relative to liquid water) on calculated NBO charges for the corresponding O atom.

SCHEME 2



possesses a somewhat larger electronegativity than H), thus effectively deshielding the O(oh) and shielding the O(oc) nucleus, which can be confirmed by considering calculated group charges (OH: 0.010; OMe: −0.010). The situation is different for MeOOOH because in this case the lone pair electrons at O(h) and O(c) both delocalize into σ^*(OO) orbitals that do not differ much. The difference in the NBO charges becomes now decisive for the ^{17}O shift values.

The calculated ^{17}O values stretch over such large regions in the gas phase (terminal O atoms: 163−305 ppm; central O atoms: 422−569 ppm; Table 1) that it should be possible to identify individual polyoxides by their ^{17}O values without any problem. Problematic is only the fact that all polyoxides investigated so far could only be measured in solution and that in solution the gas-phase values change considerably.

Effects of Rotational Averaging. Polyoxides can rotate at the OO bond. For HOOH cis- and trans-rotational barriers of 1 and 7 kcal/mol, respectively, have been determined.[57] HOOOH is a flip-flop rotator[24a,58] that by passing barriers of 6.5 kcal/mol can convert from its C_2-symmetrical equilibrium form (one OH bond above, one below the OOO reference plane) to a C_s-symmetrical form sitting at a local minimum and to another C_2-symmetrical equilibrium form, which is the mirror image of the first. Hence, both polyoxides as well as other polyoxides will undergo rapid internal rotations at room temperature. The measured NMR chemical shifts have to be understood as averaged shift values reflecting the population of the various conformational minima. In Figure 3, the changes in the ^{17}O shifts of HOOH dependent on the rotational angle are given.

For a rigid-rotor model, changes in the ^{17}O shift value are as large as 13 ppm, which reduce however for the more realistic flexible rotor model to less than 7 ppm. More important, the average value for the conformations densely populated (τ(HOOH) > 90°) hardly differs from the NMR chemical shift at equilibrium. For HOOOH, the local minimum form (C_s symmetry) possesses ^{17}O shift values that are just 2 ppm larger (terminal O) or smaller (central O) than those found for the global minimum form (C_2 symmetry). Following the flip-flop rotation reveals again that rotational averaging of ^{17}O shift values has hardly any influence on the measured value.

We have not considered in this work the rotational flexibility of the polyoxides in a solvent, which of course could significantly differ from that in the gas phase. First, the rotational flexibility of the polyoxides could change because of nonspecific solvation effects. Each polyoxide would be surrounded by one or more solvent shells, thus forming a cavity in which the conformational changes would take place. If due to the rotation the cavity would be strongly deformed, this would be accompanied by cavity work, thus increasing the rotational barriers. Second, the HO_nH and MeO_nH (n = 2, 3, 4) polyoxides can form H-bonded complexes with heteroatom-containing solvents such as acetone. The HOOOH complex with acetone has a stability of 6.4 kcal/mol (enthalpy difference at 298 K; B3LYP/6-311++G(3df,3pd) calculations with basis set super-

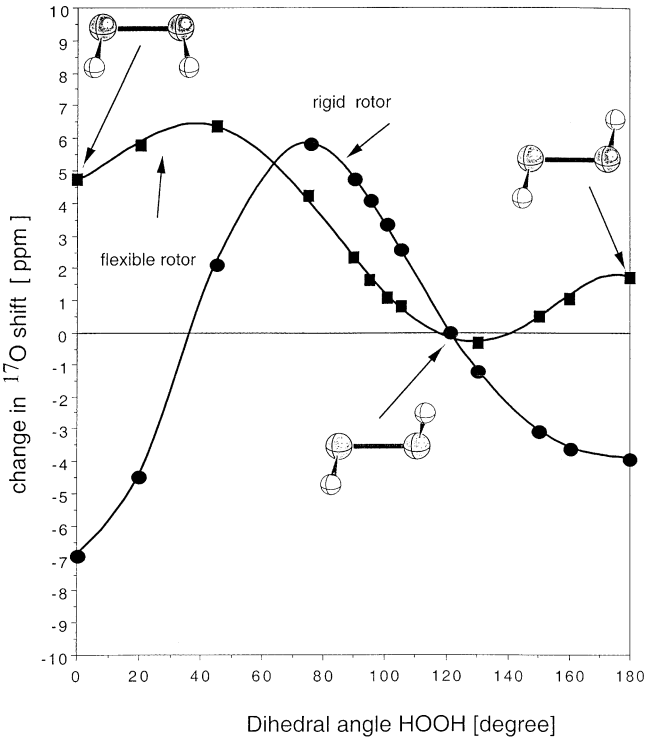


Figure 3. Dependence of the ^{17}O NMR chemical shift of HOOH on the dihedral angle τ(HOOH). Shift values are given relative to the ^{17}O shift at the equilibrium geometry of HOOH. Positive values correspond to deshielding and negative values to shielding. IGLO-DFT calculations at MP2/6-31G(d) geometries.

position error corrections; see Figure 1). Its rotational flexibility is considerably limited by the H-bond. We conclude that although internal rotation of the polyoxides in solution was not investigated in this work, its impact on the ^{17}O shift values will probably be smaller in a polar solvent than in the gas phase. Hence, rotational averaging should not have a significant influence on the measured ^{17}O value.

NMR Chemical Shifts in Solution. ^{17}O NMR chemical shifts have been measured in various solutions including acetone, methyl acetate, *tert*-butyl methyl ether, and water.[1,60,61] Since solvent−solute interactions can be strong, one has to consider relatively large solvent shifts to compare calculated with measured shift values. The NMR chemical shift in a solvent has been expressed by eq 1:[62]

$$\delta_{solv} = \delta_{gas} + \Delta_{\chi} + \Delta_{E} + \Delta_{exch-rep} + \Delta_{dis} + \Delta_{vdW} + \Delta_{HB} + ... \quad (1)$$

where Δ_{χ} denotes the chemical shift increment caused by the bulk susceptibility of the solvent, Δ_E the shift increment caused by the electrostatic properties of the solvent (polarity, etc.), $\Delta_{exch-rep}$ a shift increment caused by general exchange-repulsion, i.e., steric interactions between solvent and solute, Δ_{dis} a shift increment caused by general dispersion interactions between solute and solvent molecules, Δ_{vdW} a shift increment caused by specific van der Waals interactions between solvent and solute, and Δ_{HB} a shift increment caused by H bridging between solvent and solute molecules. In the case of the polyoxides, eq 1 can be simplified to eq 2 by neglecting $\Delta\chi$:

$$\delta_{solv} = \delta_{gas} + \Delta_{nonspec} + \Delta_{spec} \quad (2)$$

where $\Delta_{nonspec}$ accounts for all terms due to nonspecific solvation of the polyoxide

$$\Delta_{nonspec} = \Delta_{E} + \Delta_{exch-rep} + \Delta_{dis} \approx \Delta_{E} \quad (3)$$

which can be approximated by the electrostatic term, and Δ_{spec}

$$\Delta_{spec} = \Delta_{vdW} + \Delta_{HB} \quad (4)$$

for all terms due to specific solvation of the polyoxide molecules, for example via the formation of van der Waals or H-bonded complexes.

Nonspecific solvation effects can be modeled by a continuum approach. In Table 2, Δ_E solvent shifts are listed for all polyoxides investigated in this work. They vary between −20 and 9 ppm, indicating that there are significant differences between gas-phase and solvent values.

Clearly, nonspecific solvation as simulated by a continuum model leads to a stronger diamagnetic shielding as indicated in Scheme 2 by a schematic drawing of a cavity with a target molecule and surrounding polarizable continuum. At the cavity surface charges are induced with opposite sign to those of the solute molecule; i.e., the charges of the solute molecule are stabilized by Coulomb attraction. In an iterative process, the magnitude of these charges is enhanced until they reach their optimum value; i.e., the negatively charged O atoms become more negatively charged and therefore get a diamagnetic shift to higher field (more negative shift values).

For liquid water a high field effect of 18 ppm is found, which is opposite to the experimentally measured low field shift of 36 ppm[50] for the transition from gaseous water to liquid water. Calculations for ^{13}C chemical shift in solution reveal that Δ_E is reliably reproduced by a continuum model and that this should also be the case for ^{17}O.[63] However, in the case of the liquid structure of water H bonding plays an important role. By constructing a net of H bonds starting with the water dimer and then extending to the tetramer and to the hexamer, positive shift increments are found, which by extrapolation to an infinite net of H bonds in liquid water become larger than the measured low field shift increment of 36 ppm.[63] Hence, one can explain the measured ^{17}O shift of liquid water as the net effect of diamagnetic shielding given by $\Delta_E = -18$ ppm and paramagnetic deshielding given by $\Delta_{HB}{}^{17}O = 54$ ppm.

Similar opposing effects can be expected for the polyoxides in a solvent. The electrostatic shielding effect of the solvent should change depending on the dielectric constant of the solvent. In Figure 4, $\Delta_E{}^{17}$O of water is plotted as a function of the dielectric constant ϵ. A small increase of the polarity of the solvent leads to a rapid increase of the magnitude of $\Delta_E{}^{17}$O to a large negative value ($\epsilon = 10$, $\Delta_E{}^{17}O = -15$ ppm; Figure 4) while the maximum value of −18 ppm is asymptotically approached from above with increasing ϵ. Similar curves are found for polyoxides, which shows that it is sufficient to calculate $\Delta_E{}^{17}$O just for an aqueous solution ($\epsilon = 78.3$ [ref 49]) and to obtain in this way a maximum value, which is only slightly different from the $\Delta_E{}^{17}$O value obtained in acetone ($\epsilon = 20.7$ [ref 49]).

The solvent shifts caused by specific solvation can be assessed by investigating solvent−polyoxide complexes. In Figure 1, the H-bonded complex between acetone and HOOOH is shown. The electrostatic part of H bonding decreases the electron density at H and increases the negative charge at the donor O atom. For the H atom of a H bridge, downfield shifts (i.e., to more positive ^{1}H shift values) of 2 ppm and more have been measured.[64] Accordingly, strong upfield shifts corresponding to a diamagnetic shielding can be expected for the ^{17}O shift

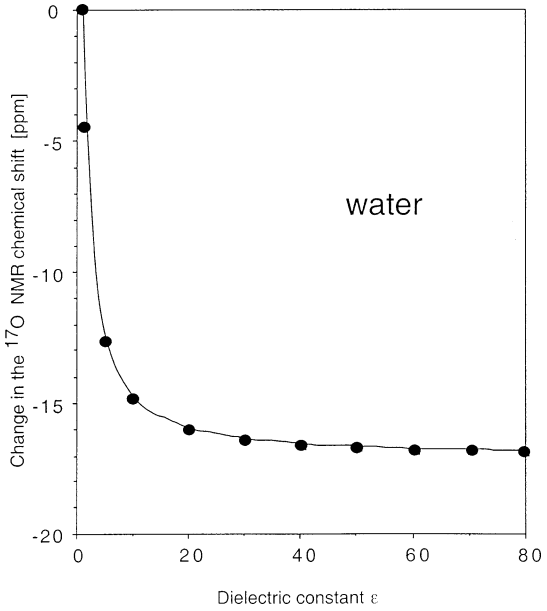
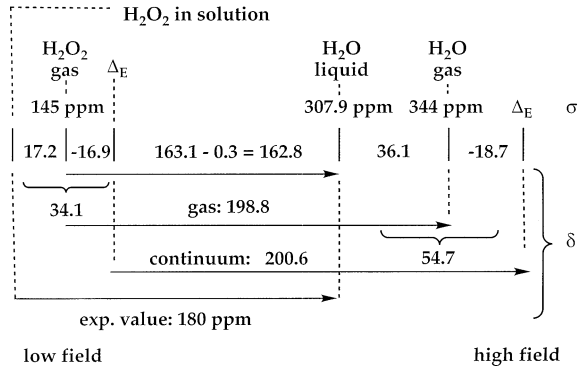


Figure 4. Dependence of the ^{17}O NMR chemical shift of water on the dielectric constant ϵ of the solvent. IGLO-DFT calculations with a continuum model at MP2/6-31G(d,p) equilibrium geometry.

value. The covalent part of the H bond leads, however, to a delocalization of the O−H bonding pair over three centers and, accordingly, decreases diamagnetic shielding (increases paramagnetic deshielding). We find a 9 ppm shift to lower field for the donor O atom of HOOOH (^{17}O shift value of O(1) from 278.2 to 287.5 ppm, Tables 1 and 4), suggesting that the covalent effect dominates in the gas phase. The second terminal O atom of the trioxide−acetone complex experiences a small shift of +3.5 ppm; i.e., it is hardly effected by complex formation. The central O atom has a diamagnetic shift of 10 ppm, half as large as that calculated for nonspecific solvation (Table 2).

The specific solvation effects will be smaller for polyoxides than those found for water. The attempt to obtain a suitable shift increment Δ_{HB} for acetone that covers bulk properties of the solvent requires molecular dynamics simulations, which are beyond the scope of the present work. Therefore, we used another approach using HOOH as a suitable reference and to reproduce its measured ^{17}O value of 180 ppm[61] by setting

SCHEME 3



$\Delta_{HB}{}^{17}O = 34$ ppm (see Scheme 3). Using this value as an empirical correction for HOOOH, its ^{17}O values in acetone solution were predicted in the following way:

$$\delta_{acetone} = \delta_{gas}(\text{GIAO-MP2/qzp}) + \Delta(\text{GIAO-CCSD(T)}) + \Delta_E(\text{polyoxide}) + \Delta_{HB}(\text{reference}) \quad (5)$$

where Δ_{HB}(HOOH) = 34.1 ppm is used for HOOOH in acetone solution. Utilizing eq 5, the NMR chemical shifts for the acetone−HOOOH complex were used to predict the measured ^{17}O shift for HOOOH. The central O atom is predicted to have a ^{17}O value of 421.2 ppm, which agrees well with the experimental one of 421 ppm (Table 4). For the two terminal O atoms values of 303.7 and 308.6 ppm are obtained while experimentally only one value of 305 ppm was found. This could mean that there is a rapid formation and cleavage of the acetone−HOOOH complex and an average over the ^{17}O values of the two terminal O atoms has to be taken. Alternatively, one HOOOH molecule may be H-bonded to two acetone molecules. In view of a calculated stability of 6.4 kcal/mol and a counteracting entropy factor, a rapid exchange of HOOOH molecules between the acetone molecules is likely, thus yielding an average ^{17}O value of 306.1 ppm, in close agreement with the experimental value of 305 ppm (Table 4).

For the alkyl hydrotrioxide $Me_2C(OH)OOOH$ found by Plesnicar and co-workers,[1] the application of eq 5 is less clear because specific CCSD(T) corrections are not known, and the

TABLE 4: Comparison of Calculated and Measured ^{17}O NMR Chemical Shifts for Some Polyoxides[a]

		IGLO-BPW91		GIAO-MP2			CCSD(T)		
molecule	nucleus	gas	water	gas, dzp	gas, tzp	gas, qz2p	correction	eq 5[b]	exp[c]
HOOH	O(1)	179.0	162.0	158.9	167.9	163.1	−0.3	180	180
MeOOH	O(oc)	209.3	199.4	173.9	187.9	182.1	−0.3	206	204
	O(oh)	229.0	218.3	205.3	220.2	219.1	−0.3	242	254
MeOOMe	O(1)	251.4	248.5	216.2	235.6	233.6	−0.3	253	253
acetone−HOOOH	O═C	553.3	520.8	526.0	552.7	552.4		554	523, 569
complex	O(1)	287.4	273.7	252.6	284.7	287.5	−4.8	306* (303.7)	305
	O(2)	458.7	448.1	376.6	411.8	411.6	−13.9	421	421
	O(3)	281.7	279.4	252.4	280.4	281.6	−4.8	306* (308.6)	305
$Me_2(OH)O_3H$	O(1)	289.2	278.6	262.9	291.5		−4.8	308	305
	O(2)	500.2	483.6	423.5	458.7		−13.9	440	445
	O(3)	347.7	348.2	306.2	348.1		−4.8	370	368
	OH	67.5	58.6	66.2	79.6			105	

[a] All ^{17}O NMR chemical shifts are given in ppm relative to liquid water as reference. The ^{17}O NMR chemical shifts δ(water) are calculated at the IGLO/SCIPCM/ BPW91/[5s4p1d/3s1p] level of theory using the dielectric constant ϵ of water at 298 K (78.3 [ref 49]). All calculations have been performed at B3LYP/6-31G(d,p) optimzed geometries. [b] For the calculation of ^{17}O NMR chemical shift values in acetone according to eq 5 the Δ_E value is taken from the IGLO-BPW91 data of columns 3 and 4. For HOOH, MeOOH, and HOOOH, Δ_{HB}(reference) is equal to 34.1 ppm; for ROOOH and MeOOMe Δ_{HB}(reference) is equal to 22.4 ppm. In the case of ROOOH, the specific solvation increments found for the acetone−HOOOH are used. The starred values are average values derived from the O(1) and O(3) shifts in parentheses. [c] Experimental values, all from refs 1 and 60. For acetone the value in neat liquid is 569 ppm and in aqueous solution 523 ppm.[60] For MeOOMe, the measured value for EtOOEt[60] was taken.

correction term Δ_{HB}(reference) has to be newly fixed. Taking the CCSD(T) corrections found for HOOOH, the complexation increments 9.4, −10.2, and 3.4 ppm found for the acetone−HOOOH complex and an average Δ_{HB}(reference) value of 22.4 ppm lead to the shift values listed in Table 4. Agreement is satisfactory as reflected by predicted values of 308, 440, and 370 ppm compared to measured values of 305, 445, and 368 ppm (see Table 4).

4. Conclusions

This work has shown that the prediction of ^{17}O NMR chemical shifts is a difficult task, especially if a prediction for solution-phase rather than gas-phase values is needed. Reliable gas-phase values can only be obtained if GIAO-CCSD(T) is used together with sufficiently large basis sets; alternatively, one can carry out GIAO-MP2 calculations and add to these values CCSD(T) correction increments as done in this work.

The ^{17}O values of the polyoxides result from a strong diamagnetic effect and a significant paramagnetic effect. The first is a result of the large electronegativity of the O atom, which attracts a negative charge, leading in this way to diamagnetic shielding. The shielding effect reflects the influence of a neighboring atom: H and C lead to relatively strong negative charges at O and therefore are the shift of terminal O atoms about 200 ppm at higher field than those of the central O atoms.

The paramagnetic effect is closely related to an anomeric delocalization of π-type lone pair electrons at O into properly aligned σ^*(OX) orbitals. It becomes stronger by increasing length of the O_n chain so that the ^{17}O values of a tetroxide are more positive than those of the corresponding trioxide and the latter are more positive than the corresponding peroxide. Methyl groups increase the anomeric effect, thus also shifting the ^{17}O values to lower field (more positive values). Considering both diamagnetic and paramagnetic effects, each O atom in a ployoxide molecule possesses a characteristic ^{17}O value.

Rotational flexibility of the polyoxides leads to the fact that measured ^{17}O NMR chemical shifts are averages reflecting the population of the most stable conformations. We have explored for HOOH and HOOOH these averaging effects and found that they lead to a small (1−2 ppm) paramagnetic shift of the ^{17}O values. Since the rotational flexibility of the polyoxides is reduced in solution, averaging will lead there to even smaller changes.

Identification of individual O atoms in a polyoxide with the help of the NMR chemical shifts presented in this work is however problematic because of the fact that NMR measurements have been exclusively performed in solution and that because of relatively strong solvent effects one cannot correlate in an easy way gas-phase and solution values. In this work, two solvent effects could be identified, namely a shielding effect caused by nonspecific solvation (a few exceptions were found, Table 2) and a H-bonding effect in the case of the hydropolyoxides. The electrostatic part of H-bonding leads again to shielding of the adjoint O nucleus while the covalent part causes deshielding. Without additional information obtained, for example, by extensive modeling of ployoxide−solvent clusters, it is not possible to predict the magnitude of the solvent effect due to H bonding (or specific solvation). However, it can be estimated using a suitable reference compound (e.g., HOOH).

Using eq 5, the ^{17}O NMR chemical shifts of HOOOH and $Me_2C(OH)OOOH$ measured in acetone solution[1] could be predicted within 5 ppm (Table 4) and explained as a result of specific and nonspecific solvation.

Despite this success, it is easy to see that more accurate values can only be obtained if the effects of specific solvation (H bonding) on the ^{17}O shifts can be explicitly modeled in the future. Molecular dynamics simulations in connection with quantum chemical NMR chemical shift calculations would help in this connection.

Previous investigations, which seemed to have obtained reasonable ^{17}O shifts by comparing calculated gas-phase values directly with measured solution-phase values without considering any solvent effects, have to be criticized. In view of the results of this work, the agreement obtained in these investigations must be considered as clearly fortuitous, without giving the chance for predicting the ^{17}O shifts for other polyoxides.

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