CALCULATION OF SOLVENT EFFECT ON CONFORMATION STABILITY AND ANOMERIC EFFECT IN DIMETHOXYMETHANE

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Solvent effect has been investigated on relative stability of the dimethoxymethane (DMM) conformers formed by rotation about the central C—O bonds. Potential energy of the isolated molecule in the whole conformation space determined by torsion angles (φ_1, φ_2) has been calculated by the PCILO semiempirical quantum-chemical method. For determination of potential energy of DMM in solvent environment the procedure by Sinanoglu has been used in which the solvation energy is divided into electrostatic, dispersion and cavity terms. The calculation predicts that DMM in CCl_4 solution as well as in vapour phase exists almost exclusively in its most stable (*sc*, *sc*) conformation with slight population of the (*ap*, *sc*) conformations. On the contrary, in aqueous solution an almost exclusive occurrence of the (*ap*, *ap*) conformation can be expected. The predicted abundances of the DMM conformers agree well with the available experimental data for DMM and similar molecules. Also the role of environmental factors on the anomeric (gauche) effect has been analyzed which makes itself felt in preference for *sc* to *ap* conformations in a number of polar molecules. It has been shown that the original intramolecular preference for the *sc* conformation can be compensated by intermolecular solute–solvent interactions, and the anomeric effect can disappear with increasing solvent polarity. The calculated solvation energies have been used for estimation of dilution enthalpies of DMM, too.

Recently various quantum-mechanical as well as classic molecular-mechanical method were successfully used for problems of theoretical prediction of stable conformations of isolated molecules *i.e.* in vacuum or in gas phase. Application of these methods to chemical and biochemical problems, however, necessitates their modification expressing explicitly the effect of environment on potential energy of the molecule. Recently several general procedures were developed enabling calculation of the intermolecular interactions between the solute molecule and its environment. The recently published conference proceedings[1] give a survey of almost all methods in this field along with their applications in theoretical conformational analysis. From methodological viewpoint most approaches to description of effects of medium on physical properties of molecules can be classified according to two diametrically opposed procedures. The first "supermolecular" approach respects the molecular structure of solvent, and the calculation concerns the system solute + solvent molecules. The second "continuous" approach considers the solvent as a continuum which can be characterized by its macroscopical properties. Each of the two general approaches (supermolecular and continuous) involves a number of various concrete calculation procedures differing in complexity and sophistication, efforts being obvious to join the both extreme approaches in description of the environmental effects.

Generally solvent effect on conformational stability and other physical properties of molecules is the greater the more polar they are. Whereas with *e.g.* saturated hydrocarbons the solvent effect on the conformation energies is relatively small, introduction of heteroatoms of the type of oxygen into the molecule results in a more marked solvent effect. On the contrary, some polar molecules containing two close polar bonds or an atom with lone electron pair close to a polar bond exhibit a particular stereochemical behaviour resulting in stabilization of the staggered gauche (synclinal) conformation as compared with the *trans* (antiperiplanar) conformation (*gauche* effect[2], anomeric effect[3]). There are several interpretations of this behaviour in literature[4-8] which are mostly based on quantum-chemical calculations of model substances containing two polar substituents X, Y at the central $-CH_2-$ group, the X, Y being most frequently F, OH, OCH_3, Cl. In our previous works we studied the nature of the anomeric effect in an isolated molecule of dimethoxymethane (DMM) – a model of acetal group[8-10]. The present communication deals with a theoretical study of conformational stability of DMM dissolved in solvents of various polarity. The obtained torsion potentials and maps of conformational energies of DMM in CCl_4 and in H_2O provide information about dependence of the anomeric effect on solvent.

RESULTS AND DISCUSSION

Model and Calculation Method

We examined the dependence of potential energy of DMM ($CH_3-O-CH_2-O-CH_3$) on rotation about the two central C—O bonds characterized by the dihedral angles φ_1 and φ_2. We presumed rigid geometry of the molecule with the parameters determined experimentally (see the geometry B in our previous communication[9]). The torsion angles φ_1 and φ_2 are defined as 180° and $\pm 60°$ for the *trans* (antiperiplanar, *ap*) and the *gauche* (synclinal, *sc*) positions, respectively. The hydrogen atoms in the methyl groups were fixed in the *sc* stable position. For determination of the conformational energy maps of the isolated molecule $E_{isol}(\varphi_1, \varphi_2)$ the semiempirical quantum-chemical method PCILO in original parametrization[11] was used. The PCILO method was not among the methods originally tested[9] for calculation of the isolated DMM molecule, it provides, however, for this molecule, results only slightly different from those of CNDO/2.

For evaluation of influence of medium on the conformational structure of DMM we used the continuous model of the environmental effects in the form given by Sinanoglu[12]. In the this approach it is presumed that the energy E of a solute in a solvent can be expressed as a sum of the intramolecular contribution (*i.e.* E_{isol}) and the solute–solvent interaction term (E_{solv}):

$$E = E_{isol} + E_{solv} . \qquad (1)$$

The second term (E_{solv}) can be expressed as a sum of several terms:

$$E_{solv} = E_{el} + E_{dis} + E_{cav} . \qquad (2)$$

In this equation the first two terms represent the contribution of electrostatic and dispersion interactions of solute–solvent type to the solvation free energy. The last term in Eq. (*2*) represents the free energy of formation of a cavity in the solvent of such a size that it could contain a solute molecule. For explicit expression of the individual contributions in Eq. (*2*) various procedures are used, however, generally this method was used successfully for prediction of conformations of solutes of various types[14-15]. The following calculations of solvation energy of DMM are restricted to only two solvents, CCl_4 and H_2O, which should represent extreme situations in magnitude of solute–solvent interactions for DMM. The individual terms of Eq. (*2*) were expressed as it follows:

Calculation of E_{el}; the electrostatic energy of solute with polarizable continuum (solvent) was estimated on the basis of the Onsager theory of reaction field. In contrast to the previous approaches[12-15] we did not restrict the calculation to only the dipolar term in the multipole expansion, but we took into account also the interaction of the solute quadrupole with the environment according to the procedure developed by Abraham[16,17]. The electrostatic contribution to the solvation energy (kJ/mol) in a medium characterized by the relative permittivity ε is given by Eq. (*3*)

$$E_{el} = -60{\cdot}25\mu^2 x(1 - 2\alpha x)^{-1} a^{-3} - 90{\cdot}37hx(5 - x)^{-1} a^{-5} , \qquad (3)$$

where μ is the permanent dipole moment of the solute, h is a function of the individua components of the solute molecular quadrupole, $x = (\varepsilon - 1)/(2\varepsilon + 1)$, a is radius of the spherical cavity, α is determined by the relation $\alpha = (n^2 - 1)/(n^2 + 2)$ where n is the refractive index of the solute (n = 1·358 for DMM)[18]. The effective radius of the cavity was determined on the basis of molecular volume (V) of DMM from the relation $a = (3V/4\pi)^{1/3}$. The molecular volume was calculated from the geometrical data (Cartesian coordinates of the extreme atoms plus 0·2 nm to each side) with the presumption that, the molecular volume of the solute can be approximated by a rectangular solid[13]. The origin of coordinates was located in the centre of gravity of DMM, and the coordinate system was oriented along the main axes of the tensor of the moment of inertia. The dipole moment and the components of the quadrupole moment of DMM were obtained on the basis of the charge distribution calculated by the PCILO method. The dipole moment in this method is determined as a sum of the moment due to pure charges and that due to contributions of the atomic hybridization dipoles[10,11]. In the calculation of the quadrupole

term net charges at the atoms only were used, and the components of the quadrupole moment were expressed in the same coordinate system as that used for calculation of the DMM volume. The values of relative dielectric permittivity $\varepsilon = 2{\cdot}24$ and 77·0 were used for CCl_4 and H_2O, respectively.

Calculation of E_{disp}. Out of all the terms in Eq. (*2*) the least reliable is the determination of the solute–solvent dispersion interactions in spite of the fact that there are several calculation procedures. We used the original procedure by Sinanoglu[12] which is based on determination of the effective interaction potential for the molecules of the solute surrounded by the solvent molecules. If, in a simplified form, we consider the integration over only the first discrete solvation layer and further only the continuous solvent model, then the dispersion term E_{disp} is given by Eq. (*4*) (refs[12,19]):

$$E_{disp} = = -f(\xi_s, l)\,\Delta_s D_s D \bar{B}_s \,. \qquad (4)$$

The Van der Waals dispersion interactions are given, according to this procedure, as a product of several functions whose values depend on molecular parameters of both the solvent and solute, ionization potential, I, polarizability, "core size" with the molecular parameters σ, l, ϱ and molecular volume V. A more detailed form of the individual functions of the right-hand side of Eq. (*4*) is described in original papers by Sinanoglu (see references cited in ref.[12]), and the variant used by us is given especially in the recent application of this theory to chromatography[19]. Values of the parameters are given in ref.[14] for the both solvents. For the "core size" parameters of the two solvents, CCl_4 and H_2O, the following respective values were used: σ_B 3·13 and 2·46, l_B 2·37 and 0·49, ϱ_B $6{\cdot}18 \,.\, 10^{-3}$ and $3{\cdot}33 \,.\, 10^{-3}$. The acentric factor ω was considered zero, and the other values were taken from the standard tables[20].

Calculation of E_{cav}: The energy needed for formation of spherical cavity with the radius a was determined from the molecular volume and from macroscopic physico-chemical properties of the solvents *viz.* surface tension, γ_s, thermal volume expansion coefficient A_s and thermal coefficient of surface tension $d\ln\gamma_s/d\ln T$. The analytical form used for calculation of E_{cav} was given by Beveridge and coworkers[13]. Using kJ/mol it is given in Eq. (*5*):

$$E_{cav} = 2{\cdot}913 \,.\, 10^{-2}\gamma_s V^{2/3} k_b(V_s/V)\,(1 - \delta\,\ln\gamma_s/\delta\,\ln T) - (2/3)\,A_s T) \,. \qquad (5)$$

For CCl_4 and H_2O we used respectively: γ_s (mN/m) 26·11 and 71·66; $d\ln\gamma_s/d\ln T$ −1·379 and −0·657; A_s (in $K^{-1} \,.\, 10^{-3}$) 1·22 and 2·57; coefficient $k_b(V_s/V)$ 0·629 and 1·272.

Maps of Conformational Energies

The conformational energy map obtained by the PCILO method for the isolated DMM molecule is very similar to the published CNDO/2 map[10,21], and, therefore, it is not given here. The both methods CNDO/2 and PCILO predict the (*sc*, *sc*) (60°, 60°) conformation to be the most stable with the DMM methyl groups oriented at the opposite sides of the O—CH_2— O plane. The further four conformations of the type (*ap*, *sc*) (180°, 50°) are less stable by 4·96 kJ/mol, and the last minimum at the energy hypersurface, the (*ap*, *ap*) conformation, lies 10·88 kJ/mol above the absolute minimum. Just in the (*ap*, *ap*) conformation region the conformation map of DMM obtained by the PCILO method deviates partially from that obtained by the CNDO/2 method which predicts a higher energy of the (*ap*, *ap*) conformation (15·78 kJ/mol)[10]. Qualitative correctness of the description is confirmed not only by the scarcely available results for DMM but also by theoretical conformational analysis with the *ab initio* method using various bases[22,23]:

The map of the conformational energies calculated for CCl_4 is given in Fig. 1. Its overall shape is not much different from that obtained for the isolated molecule. Two symmetrical regions of (*sc*, *sc*) conformations represent an energy minimum. Four minima of the type (*ap*, *sc*) are less marked in CCl_4 than in the isolated molecule and are shifted to the regions (50°, 160°), (310°, 200°) (and to the positions symmetrical therewith) with the energy 2·97 kJ/mol above the absolute minimum. The ideal (*ap*, *ap*) conformation in CCl_4 does not represent a local minimum, but it lies in four symmetrical points characterized by the angles (160°, 170°) with the energy higher than the absolute minimum by 10·47 kJ/mol.

An entirely different situation is found with H_2O as solvent (Fig. 2). Here the absolute minimum is shifted to the conformation (*ap*, *ap*), (180°, 180°) which lies in a deep potential well at the hypersurface. Further local minima of the (*sc*, *sc*) type lie at (70°, 70°) and (290°, 290°) higher by 10·55 kJ/mol, and four minima of the (*ap*, *sc*) type are placed 14·30 kJ/mol above the absolute minimum at this hypersurface.

Analysis of Individual Energy Terms of Solvation Energy

It is interesting to examine how the individual terms of Eq. (*2*) affect the solvation energy in the both solvents and, especially, to find which contribution is decisive for the stability order change of the (*ap*, *ap*) and (*sc*, *sc*) conformations when going from the isolated molecule to water solution. Values of the individual energy terms for the conformations (*ap*, *ap*), (*ap*, *sc*) and (*sc*, *sc*) are given in Table I for the both solvents.

The term E_{elst}: Stabilization of a solute with permanent dipole moment in a polar solvent represents the most simple and frequent correction for the presence of solvent,

the usual procedure starting from the equations for the reaction field of a point dipole surrounded by continuous medium. This approach was also used by Bonnet and coworkers[21] in conformational studies of DMM in vapour and liquid phases. Reinterpretation of the original results of Kubo and coworkers[24] for DMM in gas phase (from which it followed that the (*sc*, *sc*) conformation is the most stable, the (*ap*, *sc*) and (*ap*, *ap*) conformations being less stable by 7·12 and 14·24 kJ/mol, respectively) was carried out by the mentioned authors[21]. They found that the free energy differences between the given conformations in gas phase should be 8·08 and

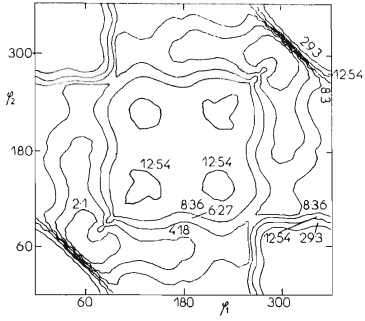

FIG. 1
Conformational Energy Map of DMM in CCl_4 (the energy contours in kJ/mol)

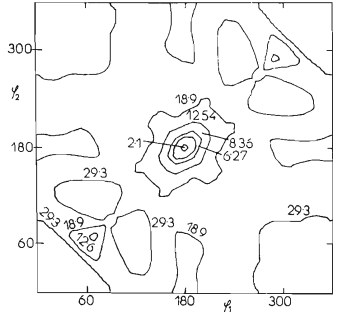

FIG. 2
Conformational Energy Map of DMM in H_2O (the energy contours in kJ/mol)

18·48 kJ/mol, if the value 22 is used for the infinite polarizability of DMM. Analyzing the experimental results for liquid phase these authors[21] found that the solvation enthalpies of the (*ap*, *sc*) and (*ap*, *ap*) conformations compared to (*sc*, *sc*) are −2·76 and −6·74, respectively, for the liquid DMM ($\varepsilon = 2{\cdot}6$) and −2·22 and −5·48, respectively, for the 1 : 1 mixture DMM–*n*-heptane (in kJ/mol).

The electrostatic stabilization of the both DMM conformations given in ref.[21] is somewhat lower than that calculated by us for the solvent of similar polarity, CCl_4 (Table I). This difference can be explained by our approach considering not only the interaction of the point dipole located in the spherical cavity with its environment but also similar interaction of the quadrupole according to the procedure developed by Abraham[16] in detail. The used way of calculation of E_{elst} provides reasonable values of stabilization of the solute (several kJ/mol), the stabilization of the conformation with greater dipole moment increasing with the solvent polarity, which is documented also by the values in Table I. The (*ap*, *ap*) conformation having the greatest dipole moment $\mu = 10{\cdot}90 \,.\, 10^{-30}$ mC (3·27 D) is destabilized by 10·90 kJ/mol with respect to the (*sc*, *sc*) conformation with $\mu = 0{\cdot}47 \,.\, 10^{-3}$ mC (0·14 D) (isolated molecules). If the contribution of E_{elst} in CCl_4 is taken into account, this destabilization is only 4·18 kJ/mol, and in water the order is reversed, (*ap*, *ap*) being more stable by 5·72 kJ/mol. In spite of the overall success of the E_{elst} calculation method this procedure involves a number of simplifications. Thus *e.g.* spherical shape of the cavity is presumed in accord with the original Onsager theory[12,16], although eliptical cavity would better fit the shape of the molecule frequently. Another problem is in localization of the cavity centre where location of both dipole and quadrupole is assumed. As the quadrupole moment value depends on choice of the coordinate system, the solvation energy depends on it, too. From this viewpoint it is advantageous to carry out the calculation within a fixed coordinate system whose centre is not changed on rotation and orientation of axes. On the contrary this can result in a situation in which the quadrupole can fall out of the cavity centre.

The E_{cav} *term*: The calculation of the energy needed for formation of the cavity in the solvent according to the method[13] used represents a mixed procedure which makes use of knowledge of the solute volume V determined on the microscopic level as well as the macroscopic quantities γ_s and temperature coefficients of γ_s and V. As γ_s and the temperature coefficients of γ_s and V are considered conformation-independent and affecting only the absolute value of the term E_{cav}, the conformation dependence of E_{cav} is determined exclusively by changes in the molecular volume with conformation. The E_{cav} term has different significance in determination of the overall character of the map and the energy of the local minima at the conformational energy map of the two solvents. Whereas for CCl_4 the conformational dependence of cavity term does not assume such values which would markedly influence position of the absolute minimum (Table I), the situation is reversed for H_2O. In the latter case (due also to great absolute value of γ_s) the E_{cav} term contributes substantially

to stabilization of the (*ap*, *ap*) conformation as compared with (*sc*, *sc*) or (*ap*, *sc*). From Table I it follows that rotation of the methyl group from the *ap* position to *sc* results, in the case of the (*ap*, *ap*) conformer, in an increase of the E_{cav} value by 21 kJ/mol. It is supposed that this great conformational change of E_{cav} can be due also to the approximation in calculation of the molecular volume. This conclusion seems to be confirmed also by the E_{cav} change during rotation of the second methyl group to *sc* position which causes a change of only about 2 kJ/mol.

The E_{disp} term: The conformational dependence of E_{disp} is determined as a complex function of molecular volume. The stabilizing contribution of the dispersion interactions is greater in the case of CCl_4 than that of H_2O. In the both solvents this contribution leads to destabilization of the (*ap*, *ap*) conformation and, hence, acts against the effects of E_{elst} and E_{cav}. In the case of CCl_4 this term is probably responsible for folding of the conformational energy map as compared with that of the isolated molecule, it does not, however, cause any shift of the absolute minimum.

Although it is generally presumed that the dispersion interactions make significant contribution to the solvation energy value, there exists no unambiguous procedure for their calculation in the case of more complex molecules. With respect to the approximations connected with the calculation of this term and that of the conformational dependence of the molecular volume we used a simplified version of the treat-

TABLE I

Conformational Energy of Isolated DMM Molecule and Solvation Energies in CCl_4 and in H_2O (in kJ/mol)

Parameter	CCl_4			H_2O		
	sc, *sc*	*sc*, *ap*	*ap*, *ap*	*sc*, *sc*	*sc*, *ap*	*ap*, *ap*
ΔE_{isol} [a]	0·0	4·96	10·90	0·0	4·96	10·90
E_{elst}	− 1·84	− 3·67	− 8·56	− 4·23	− 8·85	−20·85
E_{cav}	27·88	28·04	23·14	118·16	120·15	99·14
E_{dis}	−88·07	−88·41	−77·35	−74·28	−74·56	−65·49
E_{solv}	−62·03	−64·24	−62·77	39·65	36·74	12·80
ΔE_{tot} [a]	0·0	2·75	10·16	0·0	2·05	−15·95
r_{cav} [b]	0·32638	0·32732	0·29733			

[a] The values related to the (*sc*, *sc*) position, $\Delta E_{isol}(sc, sc) = -169\,557{\cdot}98$ kJ/mol; [b] the cavity radius in nm.

ment in which only the interaction of the solute with the first layer of the solvent were considered.

On the whole, detailed analysis of the individual terms of the solvation energy shows that a relatively reliable and accurate calculation of the E_{elst} term is combined with less satisfactory estimates of the terms E_{cav} and E_{disp}, although it is doubtless that these terms cannot be neglected, and the solvent effects cannot be simplified and restricted to only electrostatic interactions. Correctness of the both latter terms depends critically on the calculation method for the molecular volume and its conformational dependence. The highest possible correctness in determination of these quantities is one of the limiting steps in successful prediction of conformational dependences of the environmental effects.

Comparison with Experiment

If the calculated values of the conformational energies are used as the basis for the assessment of abundances of the individual conformers, then it can be concluded that DMM in vapour phase is present exclusively in (*sc*, *sc*) conformation, which was found by Kubo and coworkers[24] and confirmed later both experimentally and theoretically. In CCl_4 and other non-polar solvents DMM should also exist predominantly in the same conformation (*sc*, *sc*) with possible admixture of the (*ap*, *sc*) conformers. This conclusion is confirmed also by experimental values of dipole moments. The latter increase slightly with increasing polarity of the solvent, which would suggest increasing abundance of the conformer having greater dipole moment in the equilibrium mixture, although the increase of the induced dipole moment is obviously also contributing. The dipole moment of DMM measured in vapour phase and in n-hexane is $2{\cdot}23 \cdot 10^{-30}$ mC (0·67 D) (ref.[24]) in CCl_4 ($2{\cdot}46 \cdot 10^{-30}$ mC (0·74 D) (ref.[18,24]), in benzene $3{\cdot}30 \cdot 10^{-30}$ mC (0·99 D) ref.[25,26]). We have not found any experimental data in literature concerning conformation equilibria of DMM in more polar solvents and in water. The efforts to use the Raman spectroscopy for obtaining such information showed that the method could not differentiate the individual conformers in the case of pure liquid DMM or its solution in CCl_4 (ref.[27]). The calculations predict unambiguously that in aqueous DMM solutions abundance of the (*ap*, *ap*) conformer should be considerably greater than in non-polar solvents. However, we believe that the calculated stabilization of the (*ap*, *ap*) structure can be somewhat exaggerated with respect to the problems encountered in determination of the term E_{cav}. Arguments for the qualitatively correct prediction of stabilization of the (*ap*, *ap*) structure in polar solutions can also be found in studies of conformational structure of cyclic analogues of DMM. Experimental measurements of 2-methoxytetrahydropyrane and cognate molecules containing an acetal segment showed[3,28,29] that axial position of the methoxy group, which corresponds to the (*sc*, *sc*) conformation of DMM, represents the most stable position in non-polar

solvents. With gradual increase in the solvent polarity this position is destabilized, and abundance of the equatorial position is increased corresponding to the (*ap*, *sc*) and (*ap*, *ap*) conformations of the acetal segment in DMM.

Solvent Effect on Anomeric Effect

DMM is a typical example of a molecule containing two polar rotors bound to a common centre. Such molecules are found to be more stable in the *sc* conformation than in the *ap*. This phenomenon is called (due to its origin in stereochemistry of saccharides) anomeric effect[2,3] or *gauche* effect[2]. The results found for DMM show that it can depend on the environment whether or not a molecule will exhibit the anomeric effect. Whereas DMM in gas phase or in non-polar solvents exhibits the anomeric effect, the (*sc*, *sc*) conformation being the most stable, in polar solvents the preference of the *sc* position is lost, and the anomeric effect disappears. This fact is caused by the conformational dependence of the solvation energy according to Eq. (*2*), which, in polar solvents, compensates or even overbalances the intramolecular interactions causing the anomeric effect in the isolated molecule.

We showed before that the stabilization of the *sc* conformation in the anomeric effect is generally due to mutual subtle equilibrium between electrostatic and delocalization interactions in the molecule[30]. Calculation of the conformational dependences of delocalization[8] and electrostatic[10] interactions of lone electron pairs at the oxygen atoms in DMM led to a conclusion that in the case of the acetal segment the anomeric effect in an isolated molecule is due to intramolecular electrostatic interactions. In principle, solvent in the environment can affect the both mentioned types of interactions and, hence, contributes as a further important factor determining their equilibrium. Thus *e.g.* a polar solvent can stabilize the orbitals of the lone electron pairs at oxygen and, hence, change the conformational dependences of their interactions. On the other hand, the polar dielectric can diminish mutual electrostatic interactions of the dipoles of bonds and lone pairs inside the molecule. These two ideas represent the two antagonistic concepts used for qualitative interpretation of solvent effect[4,29] depending on whether the authors stressed the delocalization or the electrostatic nature of the anomeric effect. Within the framework of the continuous model of solvent effect used in the present communication the influence of solvent on the anomeric effect is expressed quantitatively by the conformational dependence of the solvation energy of the molecule according to Eq. (*2*). The anomeric effect is not affected by the environment in the only case of conformation-independent solvation energy. In all the other cases the interactions with the solvent environment modify the intramolecular preference for the *sc* conformation and, hence, either diminish the anomeric effect (as in DMM) or increase it. Direction of this action can, so far, be hardly predicted *a priori* from the structure of the solute molecule, and it necessitates always the particular calculation. Investigation of the

environmental influence on the anomeric effect is also important, because often its value is determined on the basis of measurements in polar solutions (*e.g.* saccharides). A comparison of the anomeric effect of two different solutes, in two different solvents does not give a relevant picture of intrinsic preferences of the *sc* conformation in the both molecules.

Comparison of Solvation Energies and Dissolution Heats

In calculation of the influence of solvent on stable conformations of molecules relative changes of the solvation energies with rotation only are important. It is also interesting to appreciate quality of the used method for calculation of absolute values of the solvation energies. For this purpose the most useful is to compare the calculated values with the standard dissolution enthalpy at infinite dilution ΔH_{dil}. If the difference between energy and enthalpy is neglected, then for ΔH_{dil} it follows:

$$\Delta H_{dil} = \Delta H_{sep} + \Delta E_{intra} + \Delta E_{solv} . \qquad (6)$$

The term ΔH_{sep} represents the enthalpy for separation of the solute molecules when the solution is formed, and it approximately equals evaporation enthalpy of the liquid solute or sublimation enthalpy of the solid solute. The term ΔE_{intra} expresses the change of the intramolecular energy of the solute transferred from gas phase to the solution, and it is determined by the energy difference ΔE_{isol} for the stable conformations in the both phases. This contribution is usually neglected[31,32], which can cause considerable error in the cases of the molecules the conformation structure of which is sensitive to the quality of solvent (*e.g.* DMM). The term ΔE_{solv} is defined in analogy to Eq. (*2*) and expresses both the energy needed for formation of the hole in the solvent and electrostatic and dispersion solute–solvent interactions. The latter are always exothermic, whereas the terms ΔE_{cav} and ΔH_{sep} are endothermic. If the solute can exist in the solution in several stable conformations, the individual terms of the right-hand side of Eq. (*6*) must be determined as the energy-weighted mean of contributions of all stable conformations. The term ΔH_{dil} defined by Eq. (*6*) gives the transfer enthalpy of the solute from pure liquid or solid to the solution of infinite dilution $\Delta H_{tr}(l \text{ or } s \rightarrow S)$. Analogously, the last two terms of Eq. (*6*) express the transfer enthalpy of the solute from gas phase to the solution of infinite dilution ΔH_{tr} $(v \rightarrow S)$. Both these transfer enthalpies can be used[31,32] also for expressing the transfer enthalpy from one solvent to another $\Delta H_{tr}(S_1 \rightarrow S_2)$.

The data in Table I enable calculation of ΔH_{dil} of DMM in CCl_4 and in water. The evaporation enthalpy of DMM is 28·88 kJ/mol at 298·15 K (ref.[33]). If, for simplicity, only the (*sc*, *sc*) and (*ap*, *ap*) conformations of DMM are considered in CCl_4 and H_2O, respectively, then the respective values ΔH_{dil} are −33·15 and 52·58 kJ/mol. For neither solvent we could find in literature experimental values enabling

direct comparison with the calculation. Only Guthrie[34] gives the value $-13{\cdot}30$ kJ/mol for dissolution enthalpy of DMM in 0·1 N-NaOH. The presence of NaOH prevents reliable comparison of this value with the calculated value for H_2O, but the calculation seems to give exaggerated endothermic ΔH_{dil} values. This fact can be due to neglect of specific interactions of the hydrogen bond type in the calculation of the solute–solvent interactions, as in the model used water serves rather for representation of a solvent with high relative permittivity. Introduction of the specific interactions should add a substantial exothermic contribution to ΔH_{dil}. Another reason of the exaggerated endothermic ΔH_{dil} value can be seen in overestimation of the contribution of the term ΔE_{cav} which, in the Sinanoglu method, is calculated directly from the macroscopic values of surface energy without correction for the microscopic values. It can be presumed that a more extensive comparison of the calculated and measured dissolution heats of the above-mentioned type for more types of solutes and solvents would enable a testing of the Sinanoglu method and its possible modification for use in calculation of the solvation energies and dissolution heats.

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REFERENCES

1. *Environmental Effect on Molecular Structure and Properties* (B. Pullman, Ed.). Reidel, Dordrecht 1976.
2. Wolfe S.: Accounts Chem. Res. *5*, 102 (1972).
3. Lemieux R. U.: Pure Appl. Chem. *25*, 257 (1971).
4. David S., Eisenstein O., Hehre W. J., Salem L., Hoffman R.: J. Amer. Chem. Soc. *95*, 3806 (1973).
5. Jeffrey G. A., Pople J. A., Radom L.: Carbohyd. Res. *25*, 117 (1972).
6. Lehn J. M., Kippf G.: J. Amer. Chem. Soc. *96*, 4048 (1974).
7. Wolfe S., Rank A., Tel L. M., Csizmadia I. G.: J. Chem. Soc. B, *1971*, 136.
8. Tvaroška I., Bleha T.: Can. J. Chem. *57*, 424 (1979).
9. Tvaroška I., Bleha T.: J. Mol. Struct. *24*, 249 (1975).
10. Tvaroška I., Bleha T.: This Journal *43*, 922 (1978)).
11. Diner S., Malrieu J. P., Jordan F., Gilbert M.: Theoret. Chim. Acta *15*, 160 (1969).
12. Sinanoglu O. in the book: *Molecular Associations in Biology* (B. Pullman, Ed.), p. 472. Academic Press, New York 1968.
13. Beveridge D. L., Kelly M. M., Randa J.: J. Amer. Chem. Soc. *96*, 3769 (1974).
14. Birnstock F., Hofmann H. J., Köhler H. J.: Theoret. Chim. Acta *42*, 311 (1976).
15. Rein R., Renugopalakrishnan V., Nir S., Swissler T. J.: Int. J. Quantum Chem.: Quantum Biol. Symp. No 2, *99* (1975).
16. Abraham R. J., Bretschneider E. in the book: *Internal Rotation in Molecules* (W. J. Orville-Thomas, Ed.). Wiley, London 1974.
17. Abraham R. J., Banks H. D., Eliel E. L., Hofer O., Kaloustian M. K.: J. Amer. Chem. Soc. *94*, 1913 (1972).
18. Riddick J. A., Bunder W. B.: *Organic Solvents*. Wiley, New York 1970.
19. Horváth C., Melander W., Molnár I.: J. Chromatogr. *125*, 129 (1976).

20. *Handbook of Chemistry and Physics*, 48th Ed. Cleveland. Chem. Rubber Co 1967/68.
21. Bonnet P., Rinaldi D., Marchal J. P.: J. Chim. Phys. Physicochim. Biol. *71*, 298 (1974).
22. Gorenstein D. G., Kar D.: J. Amer. Chem. Soc. *99*, 672 (1977).
23. Jeffrey G. A., Pople J. A., Bindkley J. S., Vishveshwara S.: J. Amer. Chem. Soc. *100*, 373 (1978).
24. Uchida T., Kurita A., Kubo N.: J. Polym. Sci. *29*, 365 (1956).
25. Krane J.: Unpublished results, quoted in ref.[26]
26. Astrup E. E.: Acta Chem. Scand. *25*, 1494 (1971).
27. van der Veken B.: Personal communication.
28. Hoog A. J., Buys H. R., Altona C., Havings E.: Tetrahedron *25*, 3365 (1965).
29. Eliel E. L., Giza A.: J. Org. Chem. *33*, 3754 (1968).
30. Tvaroška I., Bleha T.: Tetrahedron Lett. *249* (1975).
31. Moura Eamos J. J., Stien M. L., Reisse J.: Chem. Phys. Lett. *42*, 373 (1976).
32. Saluja P. P. S., Yonng T. M., Rodewald R. E., Fuchs F. H., Kohli D. H., Fuchs R.: J. Amer. Chem. Soc. *99*, 2949 (1977).
33. Cox J. D., Pilcher G.: *Thermochemistry of Organic and Organometallics Compounds*. Academic Press, London 1970.
34. Guthrie J. P.: J. Amer. Chem. Soc. *99*, 3991 (1977).

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