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COOPERATIVE ENHANCEMENT OF INTRAMOLECULAR HYDROGEN BOND IN COMPLEXES OF *o*-HYDROXY-SUBSTITUTED AROMATIC ACIDS WITH PROTON ACCEPTORS

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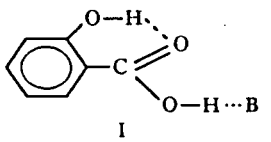
From the ^1H NMR and IR spectra of salicylic, 3-hydroxy-2-naphthoic, and 2,6-dihydroxybenzoic acids and their complexes with proton acceptors we established successive enhancement of the intramolecular hydrogen bond OH···O=C when passing from the cyclic dimer to the monomer and with increasing strength of the intermolecular bond in the complexes. The strength of the intramolecular OH···O< bond in 2,6-dihydroxybenzoic acid weakens upon decomposition of the cyclic dimer and increases upon formation and strengthening of the complexes. In the anion the two intramolecular hydrogen bonds become equivalent.

Compounds with an intramolecular hydrogen bond are convenient subjects for studying second-order effects in the energetics of the hydrogen bond, arising from mutual influence of the nearby active centers. When proton-donor and/or proton-acceptor groups that participate in the intramolecular H bond could simultaneously be donors (or acceptors) in an intermolecular H bond, there appears a possibility of purposefully affecting the strength of the intramolecular H bond via interactions of these groups with an external proton acceptor (donor). Such systems are convenient for studying mutual effects of hydrogen bonds in complex associates, since they allow one to widely vary the strength of the intermolecular H bond by appropriate selection of partner molecules, whereas the strength of the intramolecular H bond can be varied by changing the substituents [1]. The reasonableness of this approach, when IR spectroscopy was applied as a diagnostic method, was demonstrated [2] with OH···OH···B type complexes of 1,4-butanediol with acceptors as an example. With increasing strength of the intermolecular H bond OH···B the intramolecular H bond OH···O is successively enhanced; the low-frequency shift of the ν_{OH} band (from the OH···O group) was taken as a measure of the strength of the intramolecular interaction. Cooperative enhancement of the intramolecular hydrogen bond NH···O=C in complexes of anthranilic acid and its fluorinated analog with proton acceptors of the type RCOOH···B was studied in [3] by IR spectroscopy. We also demonstrated [4] the suitability of low-temperature ^1H NMR spectroscopy for studying cooperative phenomena in complexes with two hydrogen bonds, when signals from nonequivalent nuclei in the proton-donor groups are observed separately; the mutual effects were quantitatively evaluated from the shifts of the corresponding signals.

In the present work we examined the IR and low-temperature ^1H NMR spectra of RCOOH···B type complexes of salicylic acid with various B acceptors in order to study the effect of the intermolecular hydrogen bond on the intramolecular hydrogen bond OH···O=C. Some IR experiments were also carried out with the structurally related 3-hydroxy-2-naphthoic and 2,6-dihydroxybenzoic acids.



I

In CCl_4 and other aprotic solvents that do not exhibit pronounced proton-acceptor power, the acids under study exist as centrisymmetrical cyclic dimers with two hydrogen bonds. These dimers do not dissociate into monomers completely even upon ~10^{-3} M dilution at room temperature. It is convenient to monitor the relative content of the acid dimers and their complexes with proton acceptors by the $\nu_{C=O}$ band; in doing so one finds a concentration of the acceptor such that all the acid would be bound in complexes (I), but without rupture of the intramolecular H bond (which is possible, in

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Table 1. ^{1}H NMR Chemical Shifts (ppm) and IR Frequencies (cm^{-1}) in the Spectra of Salicylic and 3-Hydroxy-2-naphthoic Acids and Their Complexes RCOOH···B with Proton Acceptors

B acceptor	Salicylic acid				3-Hydroxy-2-naphthoic acid	
	^{1}H NMR spectrum[a]		IR spectrum[b]			
	δ_{OH}	δ_{COOH}	ν_{OH}	$\nu_{C=O}$	ν_{OH}	$\nu_{C=O}$
Acid dimer	10.9	13.6	3280	1665	3340	1670
Monomer	–	–	3230	1698	3300	1705
Acetonitrile	11.1	12.2	–	1690	–	–
Dimethyl ether	11.5	12.8	–	–	–	–
Diethyl ether	–	–	3200	1681	–	–
Tetrahydrofuran	11.6	13.5	3200	1678	3200	1690
Dimethyl sulfoxide	11.8	14.5	3060	1668	–	–
HMPT	11.9	15.3	3070	1666	3170	1680
4-Methylpyridine N-oxide	12.9	18.5	3070	1663	–	–
Tributylammonium cation	14.4	–	3070	1640	–	–
Dibutylammonium cation	14.6	–	3030, 3060	1640	–	–

Notes. a) In C_2D_5Cl, −130°C. b) In CCl_4, 25°C.

principle, with a considerable excess of a strong acceptor).

With strong acceptors such as HMPT and aliphatic amines, at a working concentration of the acid of ~0.02 M, even a slight excess of the acceptor over its stoichiometric concentration was sufficient to ensure that bands from complex (I) predominated in the IR spectra. However, with the weakest acceptor, acetonitrile, it was necessary to use solutions of the acid directly in the acceptor. Table 1 gives frequencies of phenolic hydroxyl ν_{OH} and salicylic acid $\nu_{C=C}$ in complexes with various acceptors. The ν_{OH} band has a low intensity and considerable width even in the spectrum of the monomer. Upon complex formation, its width grows, and the intensity (at the maximum) falls; therefore, even its mere identification becomes difficult, the more so if it is located at the edge of the broad structurized band due to ν_{OH} of the carboxyl group of the complex. The observation of this band can be somewhat improved (via elimination of overlapping by the ν_{CH} band) by using deuterated proton acceptors $(CD_2)_4O$, $(CD_3)_2SO$, $(CD_3)_6N_3PO$; however, its position could not be determined with proper accuracy, especially in the case of the strongest complexes. Table 1 gives the positions of the center of the hydroxyl band with an accuracy of about 10 cm^{-1}. Complexes of the acid with aliphatic amines have the structure of an ion pair with the interionic hydrogen bond $NH^+\cdots O^-$. In these complexes the strength of the intramolecular $OH\cdots{}^-O{=}C$ bond is the greatest, because of the enhanced proton-acceptor power of the oxygen due to the increased negative charge in the anion. We observed no appreciable difference between the intramolecular H bond parameters in the ion pairs with tri- and dibutylamines, as was the case with alkylammonium salts of anthranilic acid [3]. The values of ν_{OH} alone demonstrate only qualitatively the enhancement of the intramolecular hydrogen bond when passing from the monomeric acid to

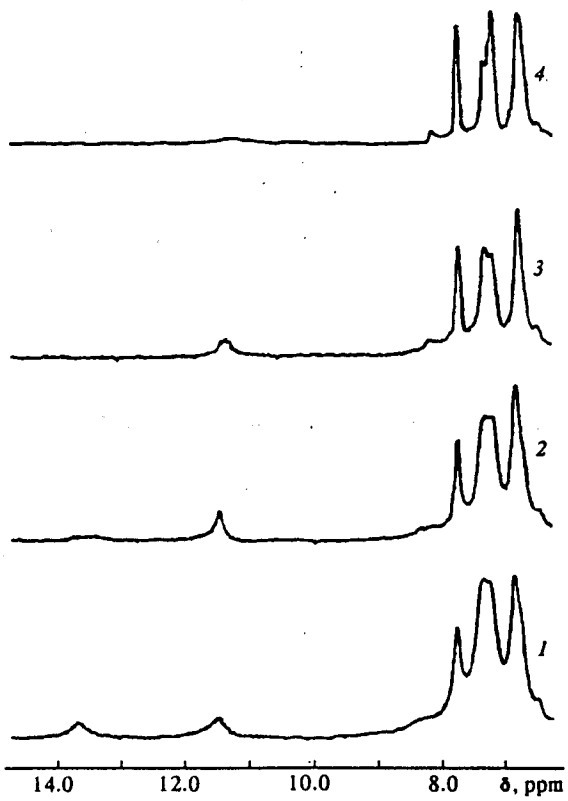


Fig. 1. ^{1}H NMR spectrum of the salicylic acid–$(CD_3)_2SO$ system, solution in CD_2Cl_2. Concentration of the acid $1\cdot10^{-3}$, of the acceptor $2\cdot10^{-3}$ M. Temperature, K: 190 (*1*), 200 (*2*), 230 (*3*), and 250 (*4*).

complexes with acceptors. However, the changes in the $\nu_{C=O}$ frequencies allows us to correlate the cooperative effect with the proton-acceptor power of B and to conclude that these quantities change in parallel.

The low-temperature ^1H NMR spectra are considerably more informative. In this case exchange processes are retarded, and the signals from the hydroxyl and the carboxyl protons are observed separately. The spectra of complexes in the salicylic acid—acceptor system under conditions of slow exchange can be observed in ethyl chloride C_2D_5Cl or in a $CDFCl_2$+CDF_2Cl Freon mixture at —70 to —140°C. The procedure for sample preparation and experimental technique are reported in [5]. At low temperatures only a slight excess of an acceptor is sufficient to bind all the acid into a complex, although with insufficient B acceptor both the complex and the dimer can appear in the spectrum. Figure 1 gives the spectrum of a solution of salicylic acid and a slight excess of dimethyl sulfoxide in the OH region. The temperature at which separation of the hydroxyl and carboxyl proton signals occurs depends on the proton acceptor and component concentrations. However, below —110°C in all systems both signals appear separately as sharp singlets. Table 1 gives chemical shifts of these signals for the complexes of salicylic acid with acceptors. These data show that the hydroxyl proton signal is gradually displaced downfield with increasing strength of the intermolecular COOH···B bond, which can be evaluated by the chemical shift of the carboxyl proton [6]. This indicates enhancement of the intramolecular hydrogen bond OH···O=C, resulting from shift of the electron density in the carboxyl group toward the oxygen atom under the influence of B acceptor. These changes correlate with changes in the $\nu_{C=O}$ frequencies and, qualitatively, with those in ν_{OH}. However, one should keep in mind that lowering of $\nu_{C=O}$ in these complexes is caused by two factors acting unidirectionally: (i) decrease in the force constant of the C=O bond upon complex formation and (ii) enhancement of the intramolecular H bond. These factors can probably be distinguished only by quantum-chemical calculations.

Comparison of the hydroxyl ν_{OH} of the acid monomer and dimer (NMR spectrum of the monomeric acid with separated signals could not be obtained) shows that the intramolecular hydrogen bond weakens upon dimerization. Obviously, in cyclic dimer, the carboxyl group participates in two intermolecular H bonds, with its OH group as a proton donor and the carboxyl oxygen as proton acceptor. The first of these increases the electron density near the unshared electron pair that participates in the intramolecular H bond, whereas the second decreases it due to polarization of the oxygen electron shell. The effect of the second bond, which is formed directly with the oxygen atom that participates in the intramolecular hydrogen bond, is stronger than that of the first H bond, which is transmitted through the HOCO chain. As a result, the intramolecular H bond weakens. A similar effect was noted previously [3,7] for dimers of *ortho*-substituted benzoic acids.

Similar results were also obtained with 3-hydroxy-2-naphthoic acid (Table 1). The concentration range was in this case limited by the poor solubility of the acid. However the spectra of its saturated solutions in CCl_4 showed two distinct bands in the ν_{OH} region, at 3340 and 3300 cm^{-1}. The first of these belongs to ν_{OH} of the dimer and disappears upon dilution, and the second to ν_{OH} of the monomer. The state of the monomer—dimer equilibrium was monitored, as with salicylic acid, by the $\nu_{C=O}$ band. Upon complex formation with proton acceptors, the ν_{OH} frequency of the intramolecularly

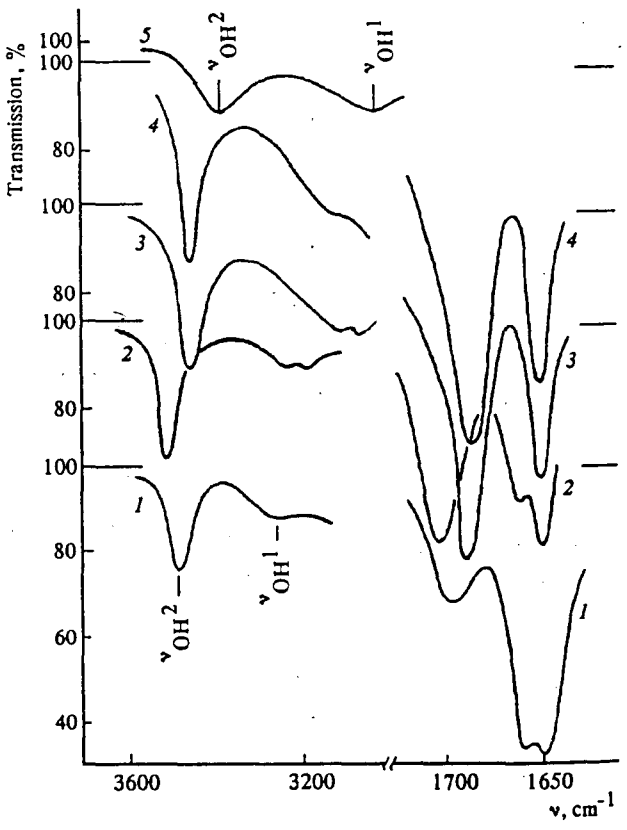


Fig. 2. IR spectra of solutions of 2,6-dihydroxybenzoic acid in CCl_4 (*1*, *2*) and mixtures of CCl_4 with diethyl ether (*3*), tetrahydrofuran (*4*), and HMPT (*5*). Concentrations, M, of the acid: 0.005 (*1*, *2*), 0.02 (*3*, *4*), 0.01 (*5*); of diethyl ether: 0.36; of tetrahydrofuran 0.2; and of HMPT 0.03. Temperature, °C: 25 (*1*, *3*–*5*), 72 (*2*).

protons at 11.3 ppm. At ~150 K the latter is resolved into two signals, at 10.2 and 12.4 ppm, which belong to the $OH^2\cdots O<$ and $OH^1\cdots O=C$ groups respectively. We have shown [4] that the acceptor more strongly affects the chemical shift of the $OH^2\cdots OH$ proton (weak H bond) than that of the $OH^1\cdots O=C$ proton (strong H bond), which is determined by the distance to the perturbation center. As with salicylic acid, the complexes of the stronger 2,6-dihydroxybenzoic acid with aliphatic amines have ion-pair structures. The intramolecular hydrogen bonds become stronger upon deprotonation, and the strongest bonds, as follows from the signal positions of the hydroxyl protons, are formed in the ion pair with the quaternary ammonium cation, in which the interionic H bond $NH^+\cdots O^-$ that weakens the proton-acceptor power of the oxygen in intramolecular $OH\cdots O^-$ bonds is absent.

With the IR spectra we succeeded in observing the different behavior of the two intramolecular H bonds when passing from the monomer to dimer, which is impossible with the NMR spectra, since the ^1H NMR spectrum of the monomer could not be obtained at low temperatures. Figure 4 shows the spectrum of 2,6-dihydroxybenzoic acid in CCl_4 in the regions of ν_{OH^2} and $\nu_{C=O}$. The spectrum of a saturated solution (c ~0.005 M, Fig. 4, *1*), in which the dimer content is still high (the dimer $\nu_{C=O}$ band at 1655 cm^{-1} overlaps the band at 1640

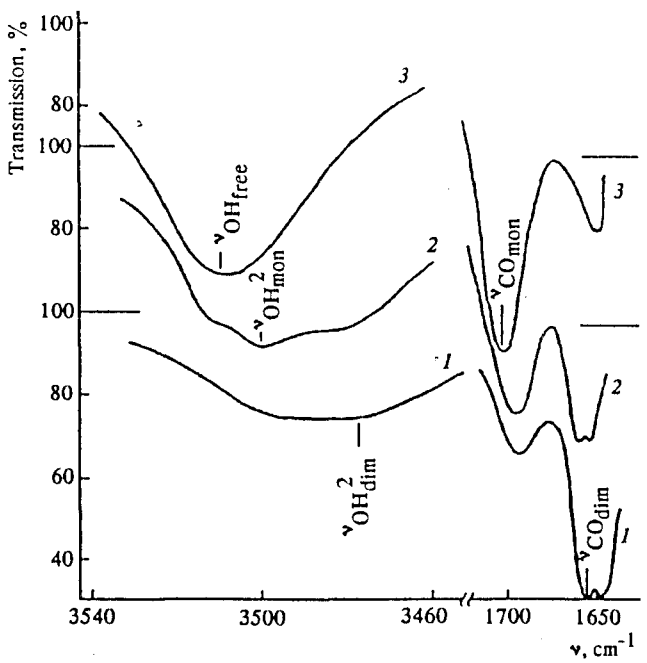
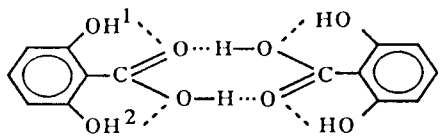


Fig. 4. IR spectra of solutions of 2,6-dihydroxybenzoic acid in CCl_4. Concentrations 0.005 (*1*) and 0.001 M (*2*, *3*). Temperature 25 (*1*, *2*) and 72°C (*3*).

cm^{-1}, which does not change its position with change in the temperature and concentration and presumably arises from the ring vibrations), contains a broad band consisting of at least two components. Upon dilution, it exhibits three absorption maxima, the highest-frequency of which at 3508 cm^{-1} becomes predominant at an elevated temperature, when the dimer $\nu_{C=O}$ band is no longer observed in an explicit form. This band belongs to the ν_{OH} vibrations of the free carboxyl group of the monomeric acid. The two low-frequency bands, at 3497 and 3480 cm^{-1}, belong to the ν_{OH^2} vibrations of the hydroxyl group that forms a weak intramolecular H bond in the dimer and monomer respectively. Upon dilution, as well as at elevated temperature, the intensities of these bands are redistributed in favor of the higher-frequency band (3497 cm^{-1}). Therefore, the intramolecular hydrogen bond $OH^2\cdots OH$ in cylcic dimer (II) is stronger than in the monomer.



II

Each carboxyl group in dimer (II) participates in four hydrogen bonds, two intermolecular and two intramolecular, so that each intramolecular H bond in the dimer is oppositely affected by the two intermolecular H bonds. The resulting effect is determined by the nearest intermolecular H bond. As the $OH^1\cdots O=C$ bond in the dimer weakens (as with all mono-*o*-hydroxy- or -amino-substituted aromatic acids, because this bond is formed with the oxygen atom that directly participates in the intermolecular H bond as proton acceptor), the intramolecular hydrogen bond $OH^2\cdots OH$ (which is formed with the oxygen of the hydroxyl group that is proton donor) is enhanced; the opposite effect on this bond from the second intermolecular H bond only weakens the effect from the first one but does not change its direction.

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Experimental

The ^1H NMR spectra were recorded on a Bruker AC-200 spectrometer (200.13 MHz), with field stabilization by the deuterium signal from the solvent. The temperature was controlled with a BVT-1000 unit with an accuracy of ±0.5 K (above 170 K) and ±1 K (below 170 K). Below 200 K the

ampul in the NMR probe was rotated by a stream of nitrogen passed through a column of silica gel. At a concentration of the complexes of $\sim 10^{-3}$ M about 200 FID scans were necessary to attain a signal-to-noise ratio of ~100:1.

The IR spectra of solutions of the acids and acceptors in CCl_4 were recorded on a UR-20 spectrophotometer. Thermostated cells with an electric heater were used. The temperature was measured with a copper—constantan thermocouple with an accuracy of ±0.5°C. The results were treated taking account of the temperature dependence of the density of solutions.

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