

Vicinal H/D Isotope Effects in NMR Spectra of Complexes with Coupled Hydrogen Bonds: Phosphoric Acids¹

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The mutual influence of hydrogen bonds in complexes involving several coupled hydrogen bonds (many-particle, or cooperative, effects) has been extensively studied in recent years in connection to various problems of chemical bond theory, reactivity, and, especially, enzyme catalysis. The energies, equilibrium geometries, and vibrational frequencies of chainlike and cyclic associates and clusters including up to 10–15 simple molecules can be evaluated to a high accuracy by *ab initio* calculations [1], while laser spectroscopy provides the most selective experimental method for detecting such complexes [2]. The advantages of NMR spectroscopy in studying hydrogen bonds in complicated systems can be realized efficiently at temperatures as low as 100–150 K, where the slow proton and molecular exchange regime is achieved [3–5]. This makes it possible to separately observe NMR signals of different complexes and, therefore, to directly estimate the cooperativity effects, using their chemical shift differences [6, 7]. A useful technical approach to such studies is partial deuteration of complicated complexes on mobile proton sites. A slight weakening of the hydrogen bond as a result of H/D replacement leads to some changes in the strength of neighboring hydrogen bonds and to additional splitting in proton spectra due to the vicinal, or long-range, isotope effect [8, 9]. Measuring the spectra of partially deuterated samples provides information on the composition and chemical structure of a complex, on the sign and value of mutual influence of neighboring hydrogen bonds, as well as on fast degenerate multiple proton transfers in the complex.

In this paper, we report that this method allows one to determine the number n of AH molecules in a hydrogen-bonded cluster $(AH)_n$ and to decide whether the cluster is linear or cyclic. In addition, information on the proton sites in anionic clusters such as AHA^- or $AHAHA^-$ can be obtained. Actual experiments were performed on phosphoric acids R_2POOH , namely, dime-

thylphosphoric acid (dimethyl phosphate) with $R = CH_3O$ (**I**) and dimethylphosphinic acid with $R = CH_3$ (**II**). These acids form exceedingly strong H-bonds [10, 11], and substantial vicinal isotope effects can be expected. 1H and ^{31}P spectra at 110–140 K were recorded for solutions in a $CDF_3 + CDF_2Cl$ (1 : 3) Freon mixture, on a Bruker AMX-500 instrument, with the experimental technique described in [5]. Deuteration was performed by repeatedly adding CH_3OD followed by its vacuum evaporation and removal of residual water via azeotropic distillation with methylene chloride. The total deuterium percentage was determined by integrating the OH proton signals with respect to the methyl group signal.

The spectra of the two phosphoric acids studied qualitatively resemble each other; Fig. 1 depicts the spectra of **I**. Below 140 K, two OH proton signals are observed at 13.28 and 13.89 ppm. Further lowering the temperature results in an increase of the low-field signal intensity with respect to the high-field one, the position of the signals being unchanged. Increasing the concentration leads to the same result. It is natural to assign these signals to associates of different composition. In the spectrum of the partially deuterated sample, the high-field signal is split into the doublet, whereas the low-field one is transformed into the triplet. Thus, the first associate contains two and the second one contains three equivalent protons. In the sample, two proton-containing isotopomers of the first complex (HH, HD) and three isotopomers of the second complex (HHH, HHD, HDD) are present. Therefore, the signals belong to symmetric cyclic dimers and trimers (Fig. 1). The assignment of the signals was done using the dependence of their relative intensity on deuterium percentage. The presence of the averaged signal of the asymmetric form, HHD, indicates fast proton migration inside the trimer; otherwise two signals of this form would have been observed. The ^{31}P spectrum of the **I** solution exhibits two poorly resolved multiplets at 3.52 and 1.56 ppm with the intensities corresponding to the dimer and trimer proton signals, respectively. Deuteration causes no additional splitting of the phosphorus signals.

Both the position and the temperature dependence of the relative intensities of proton signals indicate that the trimer is more stable in terms of energy. According to the correlation between the hydrogen bond $OH \cdots O$

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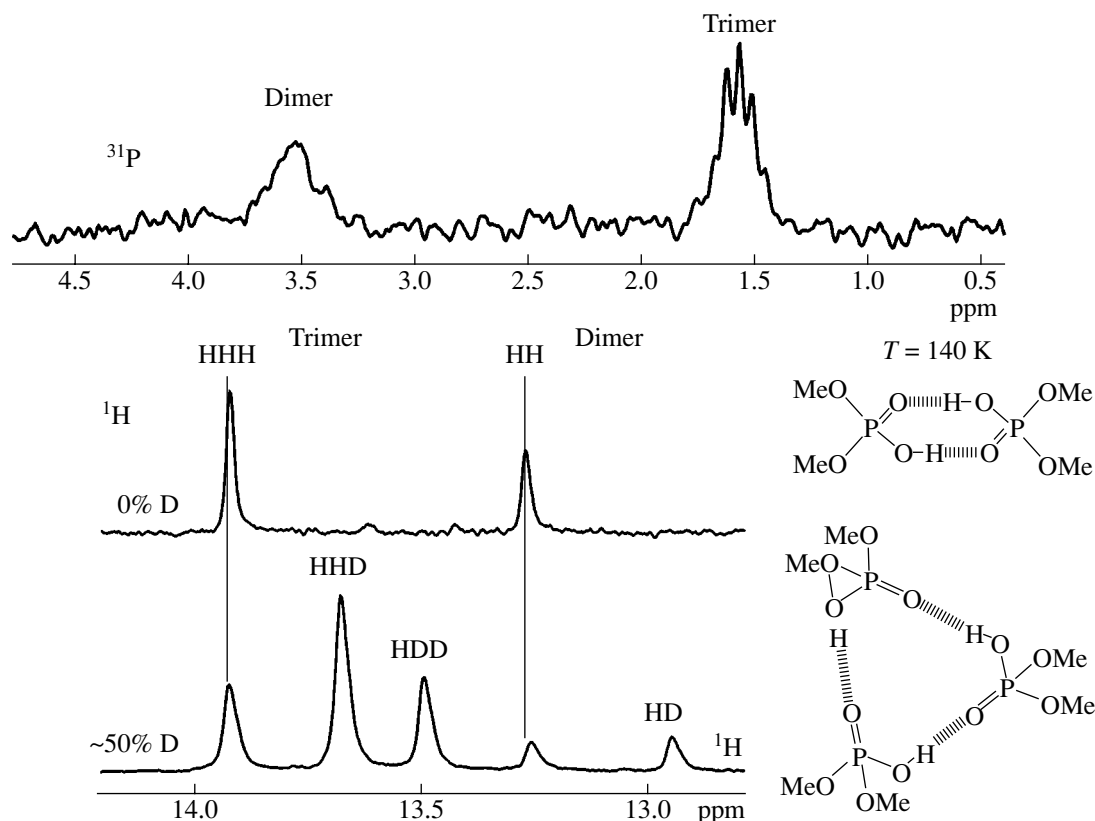


Fig. 1. ^1H and ^{31}P NMR spectra (500.13 and 202.47 MHz) of solutions containing 0.01 M dimethyl phosphate **I**, in a $\text{CDF}_3 + \text{CDF}_2\text{Cl}$ (1 : 3) mixture, at 140 K. ^{31}P chemical shift is referenced to $(\text{CH}_3\text{O})_3\text{PO}$ and recalculated to the usual H_3PO_4 scale.

enthalpy and proton chemical shift [12], each hydrogen bond strengthens by ~ 0.9 kcal/mol in going from dimer to trimer, obviously, due to increasing polarization of molecules in a cycle (see, e.g., [13]). The calculation [14] of cooperative hydrogen bond strengthening in the dimer of **II** gives practically the same value. The consideration of vicinal isotope effects on chemical shifts provides additional information on the mutual influence of the hydrogen bonds. The proton substitution for deuterium leads to the anharmonic contraction of the covalent O–D bond and some lengthening (weakening) of the OD \cdots O hydrogen bond. This results in the weakening of neighboring OH \cdots O bonds and in the upfield shift of their proton signals. For the dimer, this shift is as high as -0.31 ppm, and two isotope shifts in the trimer are -0.23 and -0.18 ppm, successively. Close results have been obtained for acid **II**. The dimer and trimer signals at 12.93 and 13.76 ppm are shifted upfield as compared to **I**, probably, due to weaker hydrogen bonds. However, the cooperative strengthening in the trimer, in comparison with the dimer, is more pronounced, $\Delta\delta = -0.83$ ppm. The ^{31}P chemical shifts of the trimer and dimer here are 55.8 and 62.7 ppm, respectively, also in agreement with acid **I**. The intensity of the dimer signal at 140 K is much lower than that of the trimer, and the dimer becomes unobservable with

further decrease in temperature. The vicinal effects, both in the dimer, -0.18 , and in the trimer, -0.23 and -0.18 ppm, differ only slightly from **I**. Thus, the negative (upfield) sign of the vicinal H/D effect can serve as a reliable indication of cooperative strengthening of hydrogen bonds in a complex.

Measuring the vicinal isotope effect in the spectra of complexes of phosphoric acids with their anions of the 2 : 1 composition allows one to determine the structure of such complexes and estimate the character of the cooperative coupling of two hydrogen bonds. In the proton spectrum of a solution containing the salt $(\text{CH}_3\text{O})_2\text{PO}_2^- \cdot \text{N}^+(\text{C}_4\text{H}_9)_4$ and an excess of the acid **I**, two singlets are observed at 17.10 and 15.38 ppm, assigned to acid salts of different composition (Fig. 2). Partial deuteration does not change the low-field peak but causes the doublet splitting of the high-field one. This makes it possible to assign the first peak to the homoconjugated ion with a formally symmetric hydrogen bond, $(\text{PO}\cdots\text{H}\cdots\text{OP})^-$, the second peak belongs obviously to the ion with two equivalent H-bonds, $(\text{POH}\cdots\text{OPO}\cdots\text{HOP})^-$. The positive sign of the vicinal H/D effect, $+0.45$ ppm, which corresponds to the downfield shift for the HD form, testifies to the mutual weakening of two hydrogen bonds in the 2 : 1 complex; this confirms its structure as dimethyl the phosphate anion

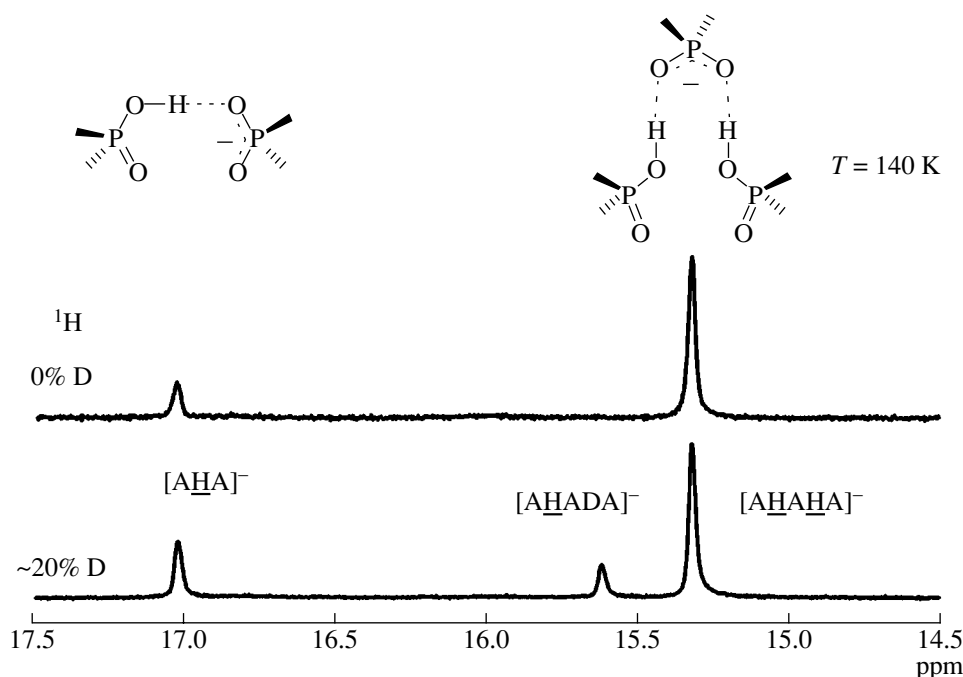


Fig. 2. ^1H NMR spectra (500.13 MHz) of solutions containing 0.02 M dimethyl phosphate and its tetrabutylammonium salt (concentration ratio 2.5 : 1) in $\text{CDF}_3 + \text{CDF}_2\text{Cl}$ (1 : 3) at 140 K.

interacting symmetrically with two acid molecules. In this case, the directions of the mutual electronic polarization of the two hydrogen bonds are opposite, so that the two bonds compete with and weaken each other.

The proton spectrum of a solution containing acid **II** and its tetrabutylammonium salt looks quite similar, namely, it shows two singlets at 16.97 and 15.05 ppm, and the latter one, assigned to the 2 : 1 complex, undergoes the positive vicinal shift by +0.42 ppm upon half-deuteration.

In conclusion, measuring the vicinal isotope effects on the NMR chemical shifts of partially deuterated complexes containing several coupled hydrogen bonds makes it possible to determine the type and the chemical structure of these complexes. Here, we obtained, for the first time, evidence for the existence of cyclic trimers of phosphoric and phosphinic acids, as well as of linear homoconjugated ions of these acids with the charge localized on the central anion.

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