Cyclic Trimers of Phosphinic Acids in Polar Aprotic Solvent: Symmetry, Chirality and H/D Isotope Effects on NMR Chemical Shifts

V.V. Mulloyarova,[1] I.S. Giba,[1,2] M.A. Kostin,[2] G.S. Denisov,[2] I.G. Shenderovich,[3] P.M. Tolstoy[1,*]

[1] Institute of Chemistry, St.Petersburg State University, Russia

[2] Department of Physics, St.Petersburg State University, Russia

[3] Faculty of Chemistry and Pharmacy, University of Regensburg, Germany

* – corresponding author, peter.tolstoy@spbu.ru

Contents

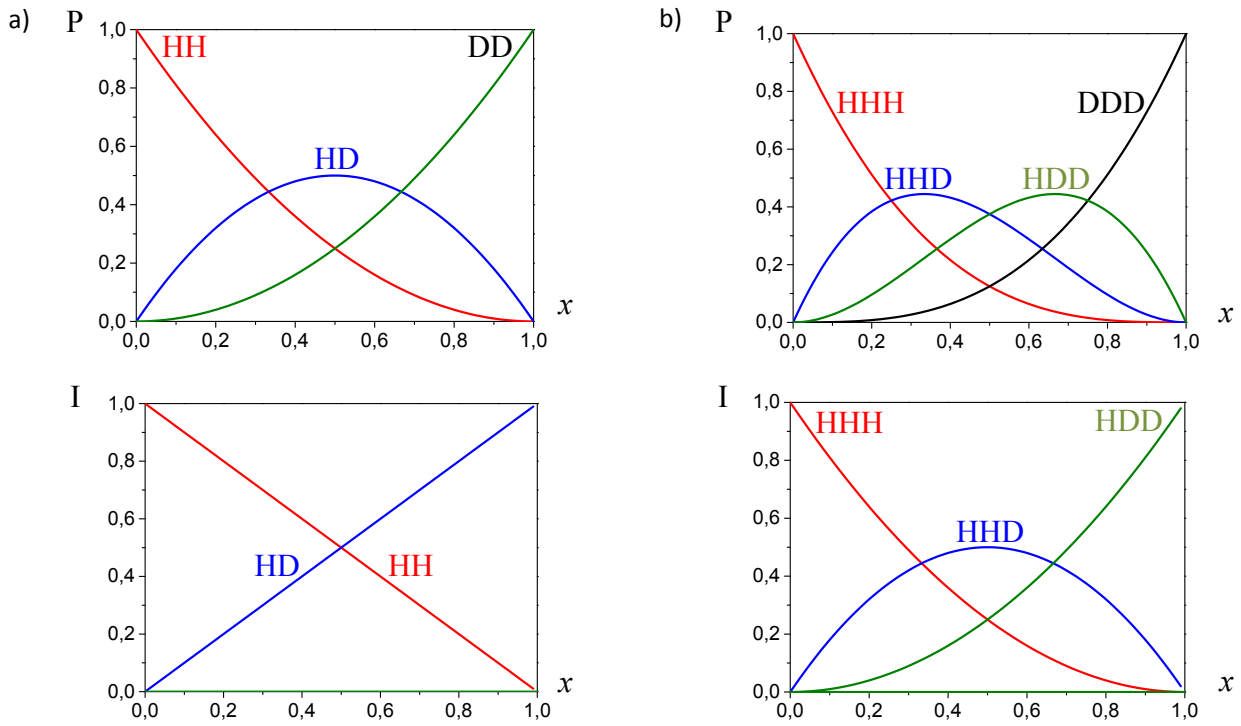

Figure S1. The dependencies of the probabilities *P* and relative signal intensities *I* (in ^{1}H NMR spectra) on the degree of deuteration *x* for cyclic dimers (a) and cyclic trimers (b). The curves for dimers and trimers are presented in color; for dimers (a): red color corresponds to the HH form; blue – to the HD form; green – to the DD form; for trimers (b): red color corresponds to the HHH form; blue – to the HHD form; green – to the HDD form; black – to the DDD form.

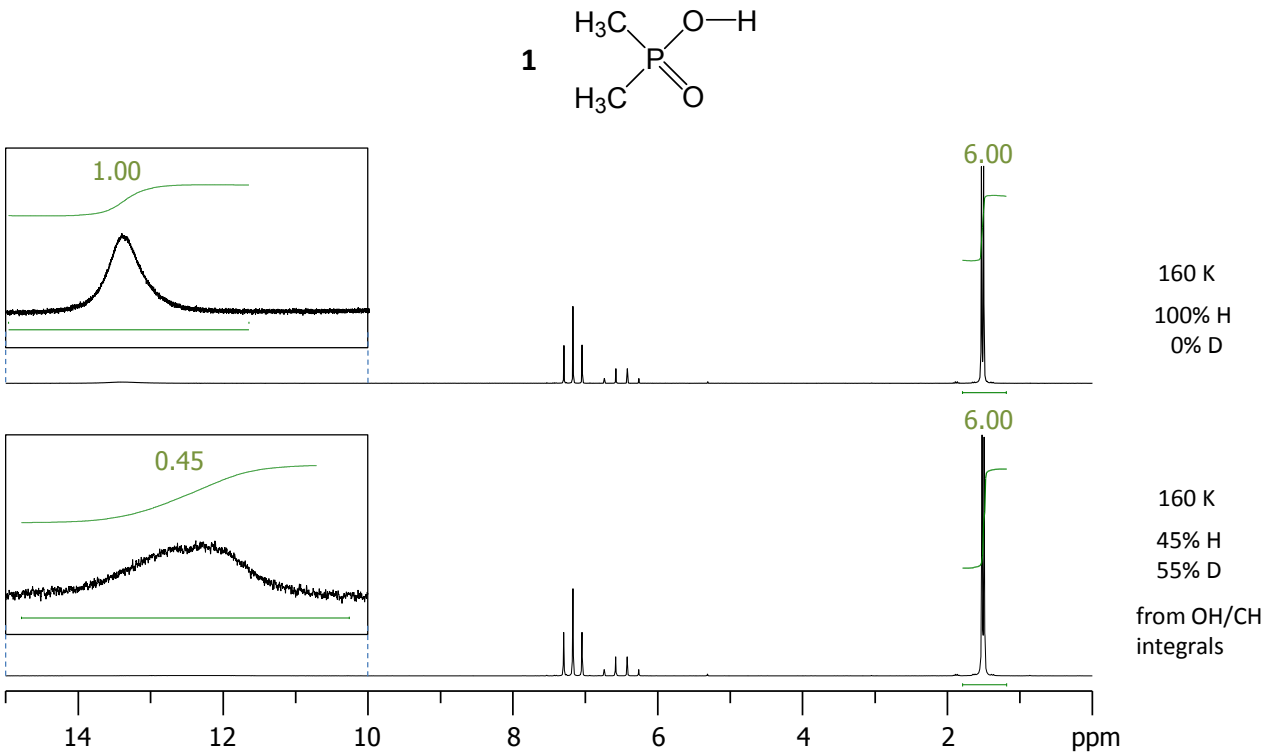

Figure S2. ^{1}H NMR spectra of solutions of dimethylphosphinic acid **1** in $CDF_3/CDClF_2$ mixture at 160 K. Top spectrum corresponds to the sample without deuteration; bottom spectrum – with deuteration. The OH signals are shown in insets. The degree of deuteration of the sample estimated from OH/CH integrals is 55%.

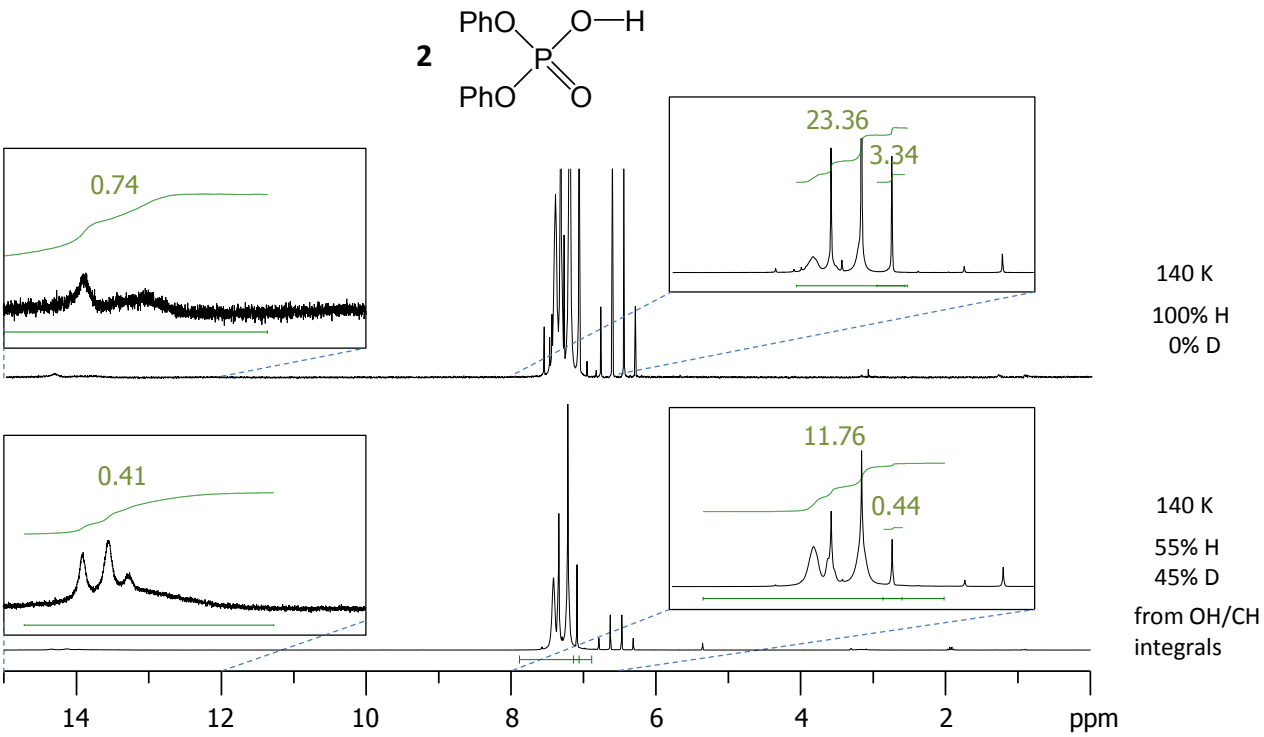

Figure S3. ^{1}H NMR spectra of solutions of diphenylphosphoric acid **2** in $CDF_3/CDClF_2$ mixture at 140 K. Top spectrum corresponds to the sample without deuteration; bottom spectrum – with deuteration. The OH and CH signals are shown in insets. The degree of deuteration of the sample estimated from OH/CH integrals is 45%.

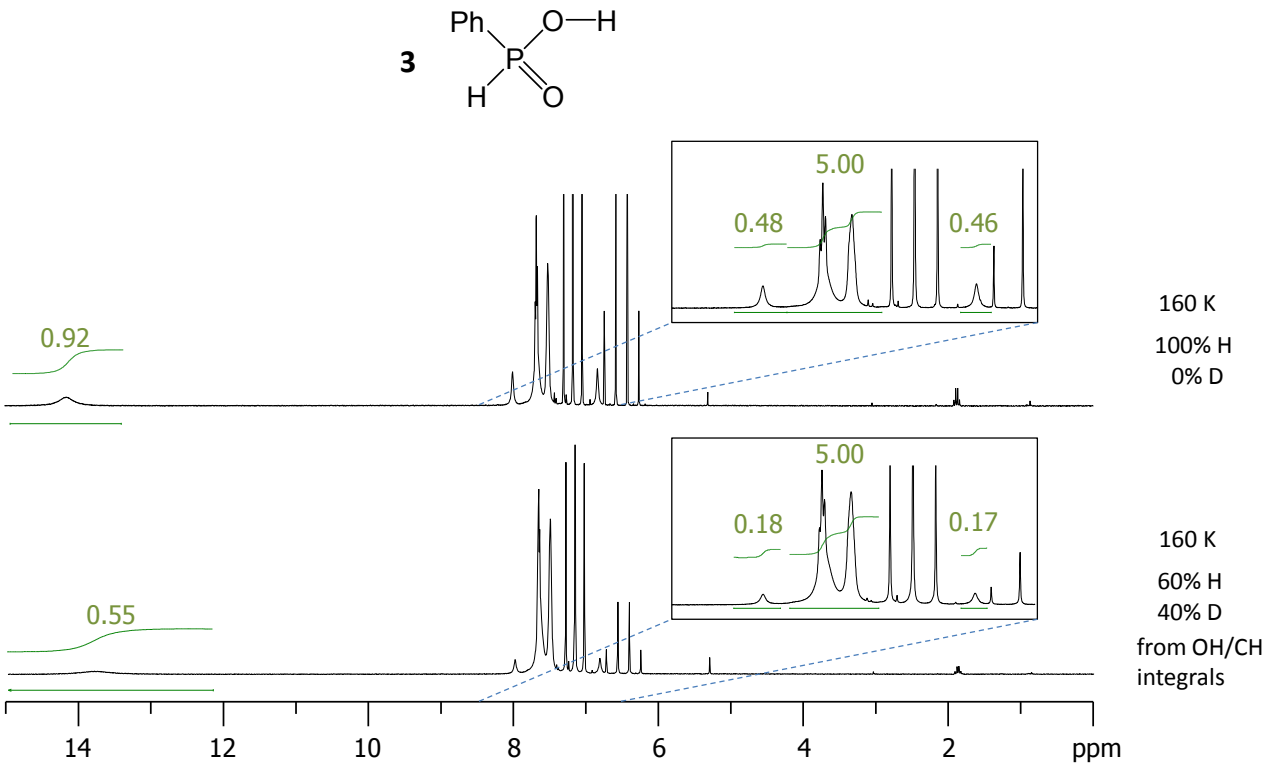

Figure S4. ^{1}H NMR spectra of solutions of phenylphosphinic acid **3** in $CDF_3/CDClF_2$ mixture at 160 K. Top spectrum corresponds to the sample without deuteration; bottom spectrum – with deuteration. The CH signals are shown in insets. The degree of deuteration of the sample estimated from OH/CH integrals is 40%.

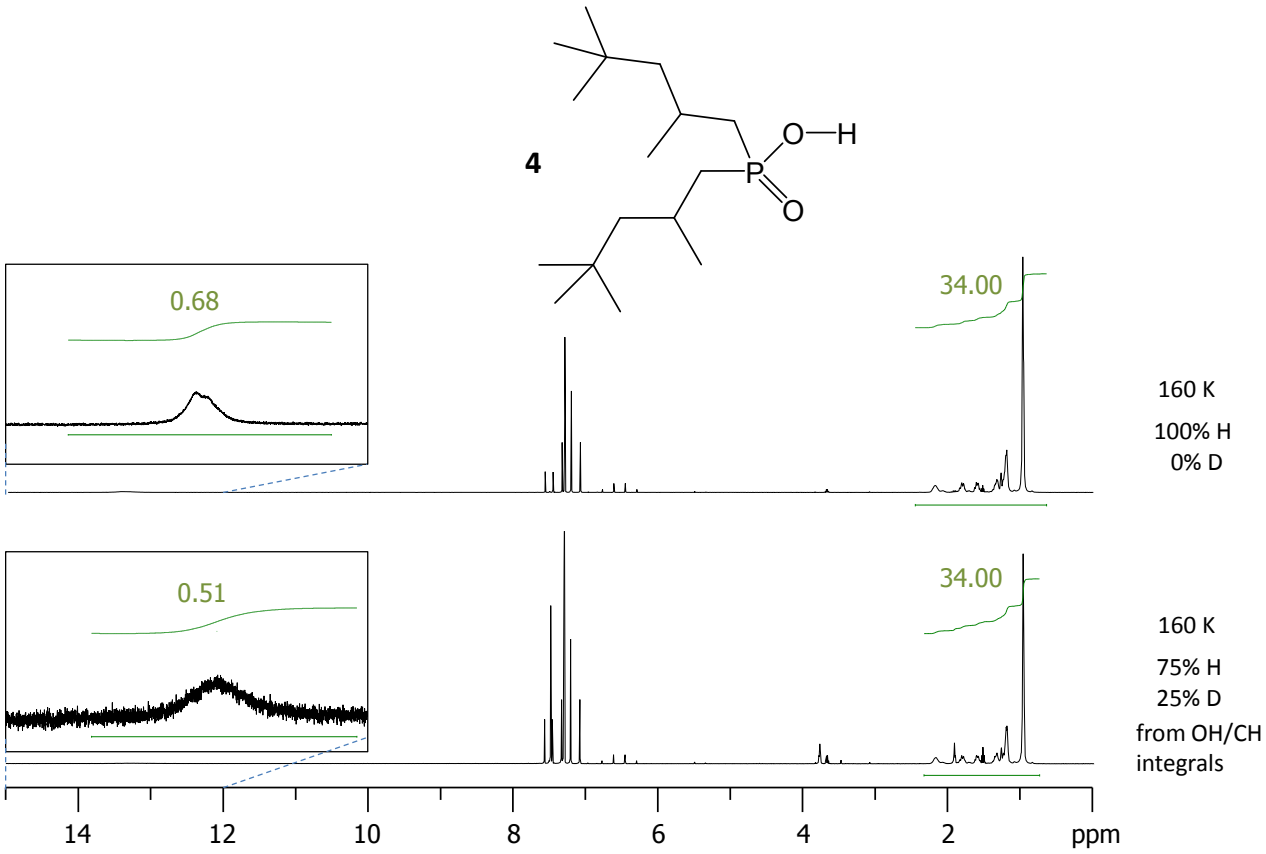

Figure S5. ^{1}H NMR spectra of solutions of bis(2,4,4-trimethylpentyl)phosphinic acid **4** in $CDF_3/CDClF_2$ mixture at 160 K. Top spectrum corresponds to the sample without deuteration; bottom spectrum – with deuteration. The OH signals are shown in insets. The degree of deuteration of the sample estimated from OH/CH integrals is 25%.

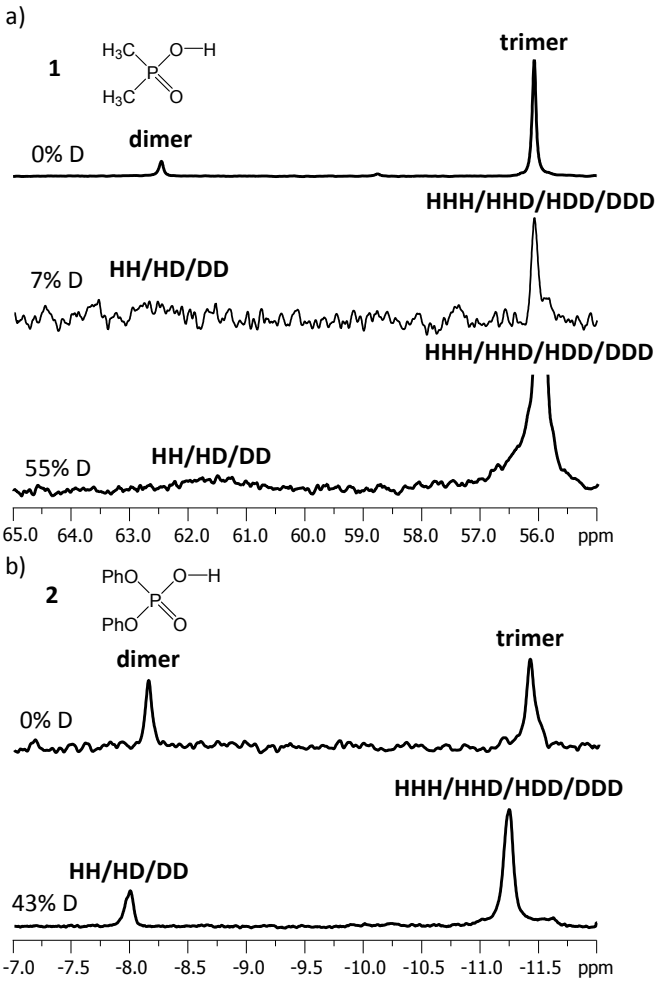

Figure S6. $^{31}P\{^{1}H\}$ NMR spectra of solutions of (a) dimetylphosphinic acid **1** and (b) diphenylphosphoric acid **2** in $CDF_3/CDClF_2$ mixture at 100 K. Top spectra correspond to the samples without deuteration; bottom and middle spectra – with deuteration. The degrees of deuteration of the samples were (a) 7% and 55%, (b) 43%.

Two signals with different integrated intensities are observed in these spectra at low temperature. The ratio of integrated intensities coincides with that for ^{1}H NMR signals presented in Figure 2a,b in the main text. Therefore, two types of associates with non-equivalent phosphorus atoms are formed in solution. The signals at lower field were assigned to cyclic dimers and the ones at higher field to cyclic trimers. The values of ^{31}P chemical shifts of dimers and trimers in deuterated samples and samples without deuteration do not match perfectly and vary by several tenths of ppm. This is probably due to the sensitivity of the ^{31}P chemical shifts to the small changes in temperature and to the composition of the solvent, which varies from synthesis to synthesis. The number of signals in spectra does not change after partial deuteration of samples. Thus, the H/D isotope effects in $^{31}P\{^{1}H\}$ spectra due to the OH/OD substitution are not observed.

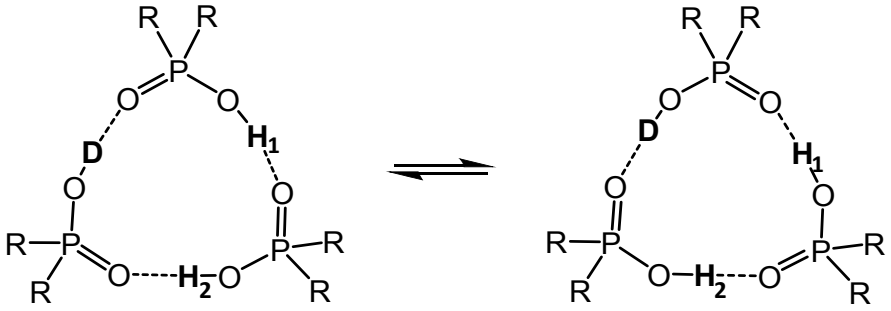

Figure S7. The triple reversible proton (deuterium) transfer in the cyclic mono-substituted trimer of a phosphinic/phosphoric acid.

The H_1 and H_2 protons in the left structure are not chemically equivalent and should give rise to two separate signals in ^1H NMR spectrum of the HHD isotopolog. However, in case of a fast (in the NMR time scale) triple proton (deuterium) transfer one obtains the structure shown in the right part of the figure. The left and right structures are equivalent except for H_1 and H_2 proton exchanging their chemical shifts. Thus, the existence of only one proton signal from the HHD isotopolog proves the fast reversible triple proton (deuterium) transfer in the trimer.

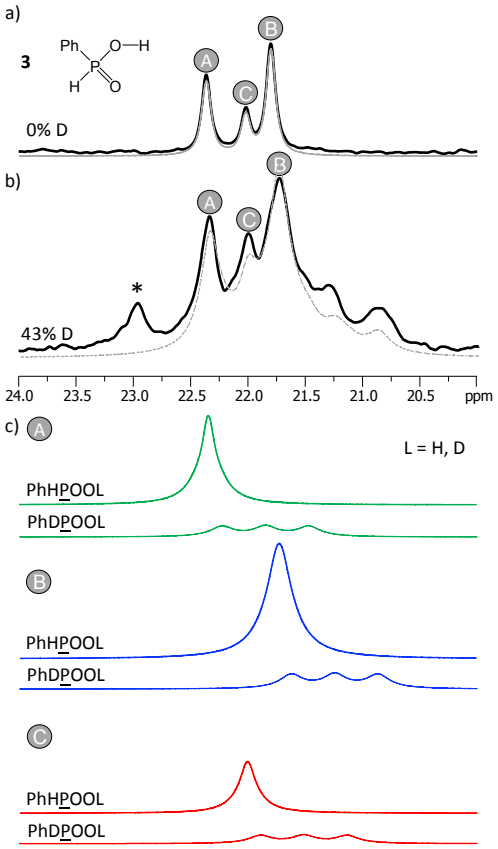

Figure S8. $^{31}P\{^{1}H\}$ NMR spectra of solution of phenylphosphinic acid (**3**) in $CDF_3/CDClF_2$ mixture at 100 K. The spectrum (a) corresponds to the sample without deuteration; the spectrum (b) – with deuteration. The degree of deuteration of the sample was 43%. The grey dashed line (b) correspond the fitted spectrum of three phosphorus atoms of isotopologs PhHPOOL and PhDPOOL (L = H, D); in green, blue and red color (c) are presented the subspectra of individual phosphorus atoms A, B and C of two isotopologs, respectively.

Three signals with different integrated intensities (labelled A, B and C) are observed at low temperature (a). Thus, the cyclic trimers with three types of non-equivalent ^{31}P atoms are formed in solution. Similar to what was observed in ^{1}H NMR spectra, we assume that $\delta^{31}P$ exhibits sensitivity to the orientation of substituents in neighboring molecules (see Figure S9 below). The spectrum becomes more complicated after the partial deuteration (b). The deuteration occurs both in OH and PH groups. The H/D substitution in OH group does not lead to measurable isotope effects, while PH/PD substitution leads to isotope effects and three new signals from each types of the phosphorus atoms are presented in NMR spectrum. The signals are heavily overlapped and for further analysis we have performed a deconvolution of the spectrum into three subspectra of A, B and C phosphorus atoms, presented in (c) in green, blue and red color, respectively. The isotope effect values are $\delta PD - \delta PH = -0.49$ ppm in all three cases. The $^{1}J_{PD} = 76$ Hz. The grey dashed line (b) correspond the fitted spectrum of three types of phosphorus atoms combined. The signal that labeled in asterisk was not assigned.

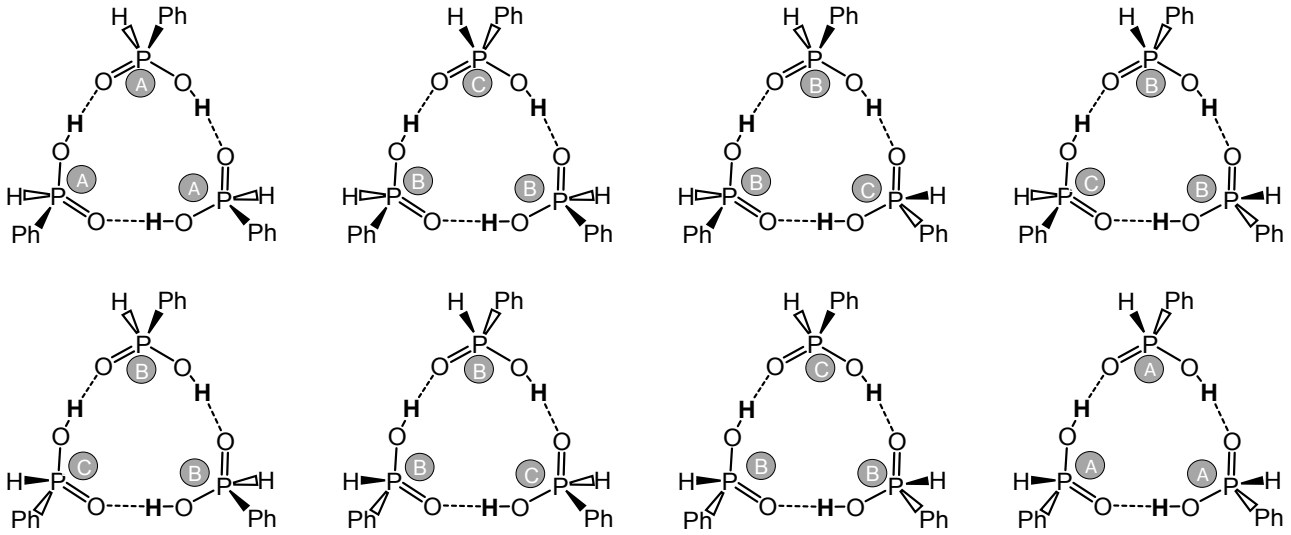

Figure S9. Eight equivalent in energy structures of phenylphosphinic (**3**) acid cyclic trimer with different mutual orientations of substituents. The chemically non-equivalent phosphorus atoms are marked in letters (A, B and C).

There are eight structures of phenylphosphinic acid **(3)** cyclic trimer with different orientations of substituents with respect to the "ring" of hydrogen bonds. Since in our interpretation the ^{31}P NMR chemical shift is sensitive to the orientation of substitutes in two other molecules of the trimer, there are three non-equivalent combinations one has to consider. Namely, with respect to the molecule containing the given phosphorus atoms, the phenyl groups in neighboring molecules could be oriented both in the same direction, (relative to the "plane" of hydrogen bonds; case A) both in the opposite direction (case C) and, finally, one phenyl could be oriented in the same direction and the other in the opposite one (case B).

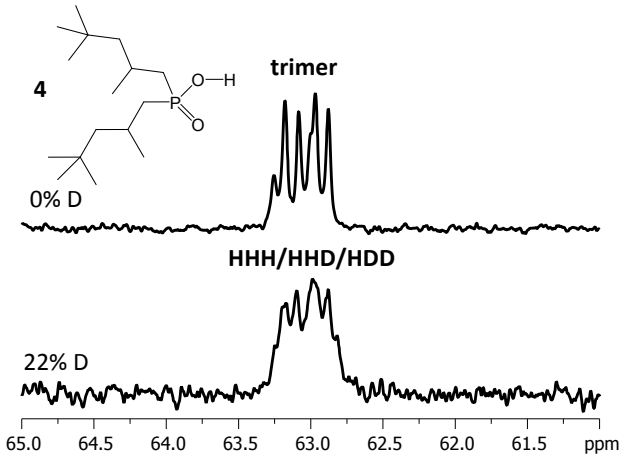

Figure S10. $^{31}P\{^{1}H\}$ NMR spectra of solution of bis(2,4,4-trimethylpentyl)phosphinic acid (**4**) in $CDF_3/CDClF_2$ mixture at 120 K. Top spectra correspond to the sample without deuteration; bottom spectra – with deuteration. The degree of deuteration was 22%.

At least six signals with different integrated intensities are observed in the spectrum at low temperature as shown in Figure S10 (top). Thus, a minimum of six types of non-equivalent phosphorus atoms are formed in solution. This is due to the fact that the monomer of this acid has four stereoisomeric forms (*RR*, *SS*, *RS* and *SR*) and in the racemic mixture cyclic trimers are formed by different combinations of these forms. Overall, there are $4^3 = 64$ combinations. If we assume that the ^{31}P NMR chemical shift is sensitive to the type and orientation of substituents in two neighboring molecules of the trimer, then the number of combinations one has to consider drops but it remains hard to interpret the $^{31}P\{^{1}H\}$spectrum (more on that in Figure S11). The spectrum is further complicated as a result of partial deuteration of the sample (Figure S10, bottom). The signal assignment is difficult due to the strong overlapping.

The fast proton tautomerism is depicted as O--H--H--O

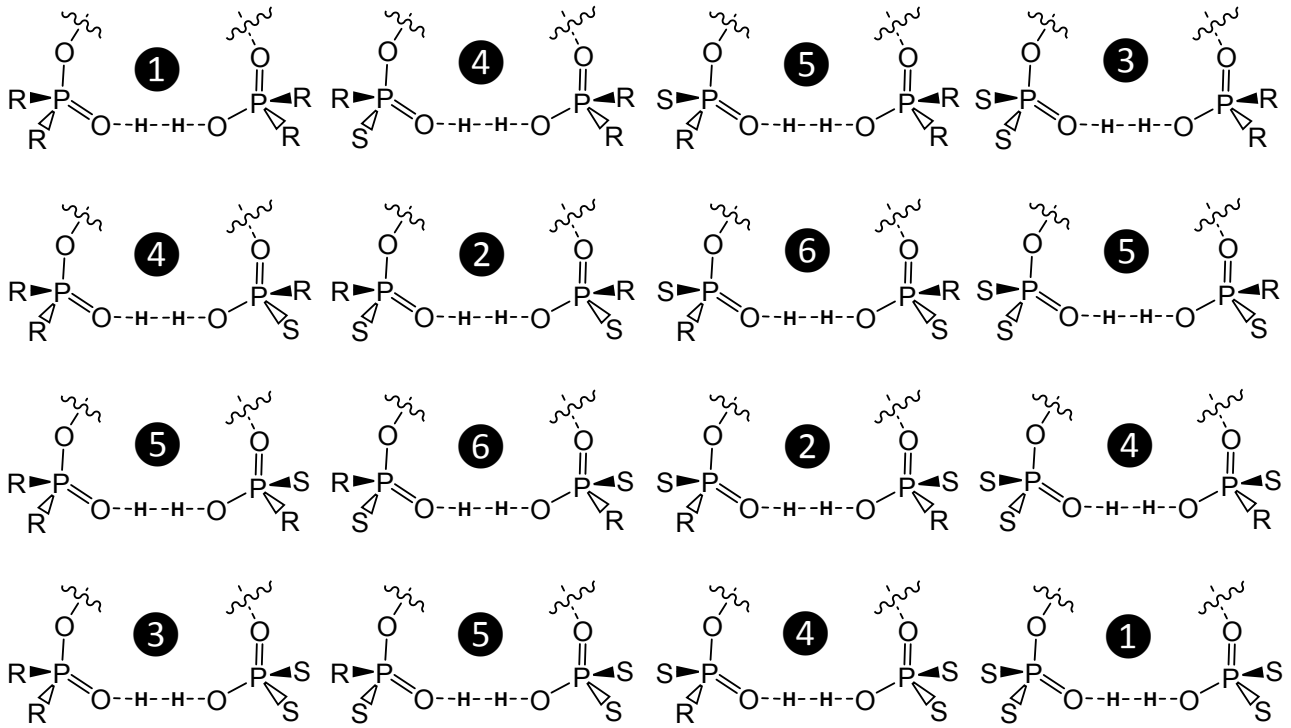

Figure S11. Sixteen stereoisomeric structures of fragment of cyclic trimer of bis(2,4,4-trimethylpentyl)phosphinic acid (**4**) with different mutual orientations of *S*- and *R*-forms of substituents. Assuming that the chemical shift of the bridging proton depends only on the combinations of isomers in donor and acceptor molecules of the acid, there are 6 chemically non-equivalent combinations which are marked in numeric (1–6).

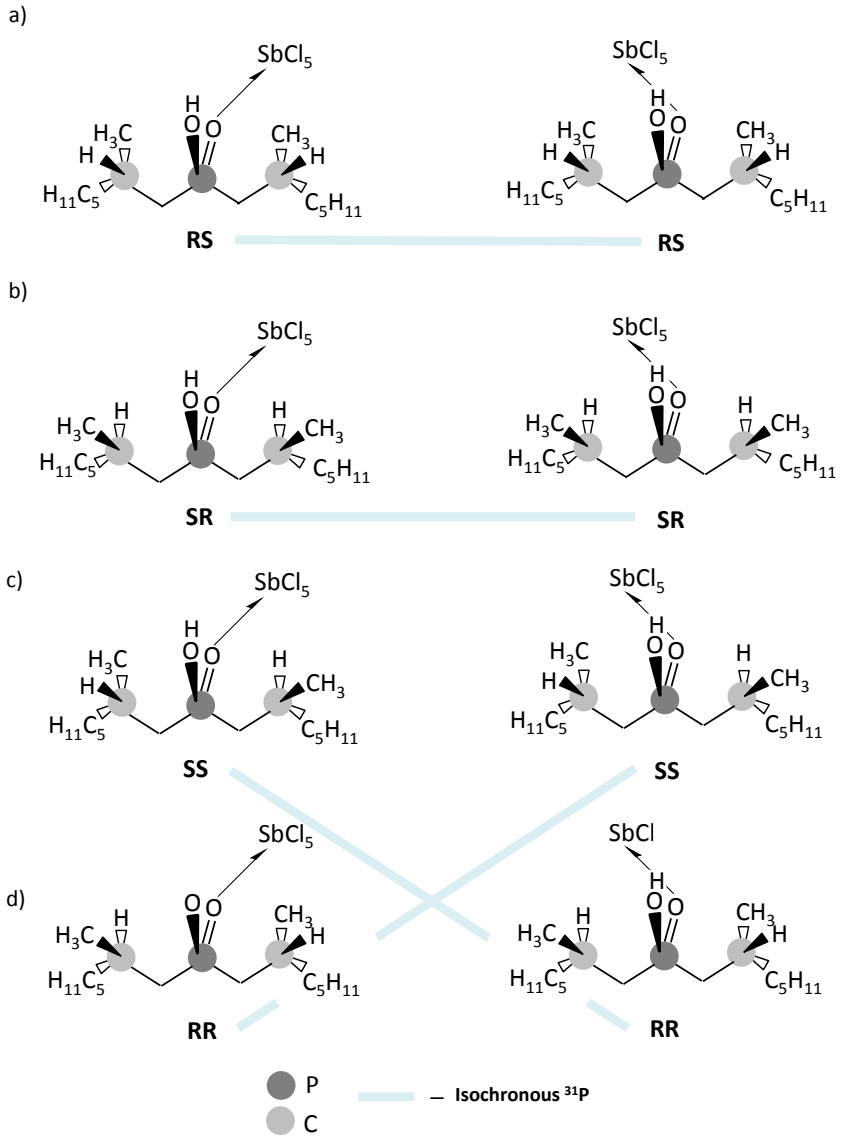

Figure S12. (a-d) Eight isomers of complex **5**, which would coexist in case of asymmetric binding of $SbCl_5$ to a molecule of **4**. The structures with isochronous ^{31}P atoms are linked by light blue lines. For more details see the main text.

When $SbCl_5$ flips from one side to the other the phosphorous atoms are isochronous for two conformations of *RS* isomer, for two conformations of *SR* isomer and also in a pairwise fashion for *RR* and *SS* isomers, as schematically shown in Figure S8, resulting in four ^{31}P NMR signals in total.

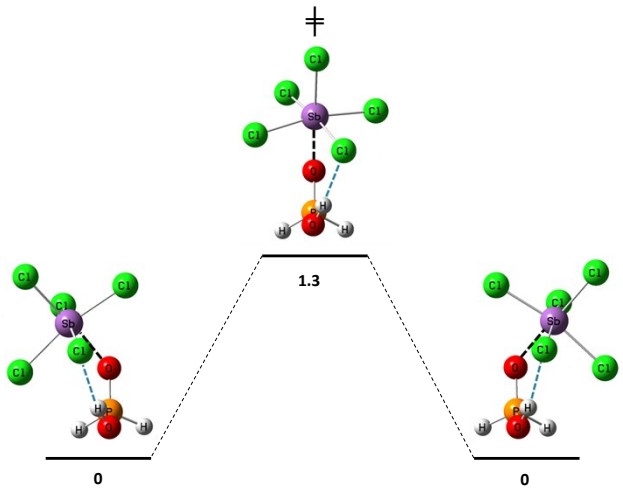

Figure S13. The equilibrium structures and transition state between two isotopologs of model complex $H_2POOH{\cdot}SbCl_5$. Energy is given in kcal/mol.

The asymmetric binding of $SbCl_5$ in principle looks like a viable option, because the partial $P^+–O^–$ character of the PO bond could promote such asymmetry. The quantum-chemical calculations performed for the model non-chiral $H_2POOH{\cdot}SbCl_5$ complex in vacuum (B3LYP/Def2-TZV) have resulted in the asymmetric structure with the 1.3 kcal/mol energy barrier for $SbCl_5$ flips, which is too low to explain the resolved signals of isomers in experimental NMR spectra. The dashed line in Figure S13 shows the hydrogen bond between the OH proton and one of the chlorine atoms of the $SbCl_5$.