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Kinetic study of the proton transfer reaction between 1-nitro-1-(4-nitrophenyl)alkanes and P_1-*t*-Bu phosphazene base in THF solvent

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Abstract

The rates of proton transfer reactions between C-acids of the series of nitroalkanes with increasing bulk of R = H, Me, Et, *i*-Pr substituents as 4-nitro-phenylnitromethane (**1**), 1-(4-nitrophenyl)-1-nitroethane (**2**), 1-(4-nitrophenyl)-1-nitropropane (**3**), 2-methyl-1-(4-nitrophenyl)-1-nitropropane (**4**) and the P_1-*t*-Bu phosphazene have been measured in THF at pseudo-first-order conditions. The product of the proton transfer reaction with P_1-*t*-Bu is associated into ion pair. The equilibrium constants decrease along with growing bulk of alkyl substituent in the reacting C-acid: > 100 000, 1170, 590, and 11.8 for **1**, **2**, **3**, **4**, respectively. The second order rate constants (k_{2H}) for this very strong base and C-acids are rapidly declining: 9357, 2.31, 0.66, 0.09 $dm^3\ mol^{-1}\ s^{-1}$ for **1**, **2**, **3**, **4**, respectively, and could not be accounted for the small values of the enthalpies of activation $\Delta H^{\neq}_{H} = 6.1, 18.0, 20.7$ and 11.1 $kJ\ mol^{-1}$. The appropriate values of the entropies of activation were all negative and relatively large $\Delta S^{\neq}_{H} = -149.7, -176.5, -178.7, -227.8$ $J\ mol^{-1}\ deg^{-1}$ indicating an importance of steric and ordering effects in forming the transition state. The primary deuterium kinetic isotope effects are large showing tendency of reverse relation towards steric hindrance of the reacting C-acids, k_H/k_D = 15.8, 13.6, 13.2 for **1**, **2**, and **3**, respectively. The explanation of the unusual slow proton transfer abstraction caused by this extremely strong base is undertaken.

Keywords: Proton transfer; C-acids; Phosphazene; Rate constants; Kinetic isotope effects

1. Introduction

The introduction of a new, strong sterically hindered base *tert*-Butylimino-tris(dimethylamino)phosphorane, commonly known as P_1-*t*-Bu phosphazene [1], gives an additional opportunity to study the factors influencing the mechanism of proton transfer reactions in solution. In our previous papers we already took an advantage using commercially available two very strong bicyclic guanidines TBD and MTBD of similar basicity ($pK_{TBDH^+} = 24.7$ or 25.96; $pK_{MTBDH^+} = 24.97$ or 25.43) [2,3], differing by just one frontal methyl group. The mechanistic study of the proton transfer between C-acids of the series of nitroalkanes with increasing bulk of R = H, Me, Et, *i*-Pr substituents as: 4-nitrophenylnitromethane (**1**), 1-(4-nitrophenyl)-1-nitroethane (**2**), 1-(4-nitrophenyl)-1-nitropropane (**3**), 2-methyl-1-(4-nitrophenyl)-1-nitropropane (**4**) and the TBD and MTBD bases in acetonitrile [4] and THF [5] solvents unexpectedly show very different rate constants, always larger with the TBD than with MTBD base. The ratios of k_{TBD}/k_{MTBD} varied from 50 to 160 in MeCN [4] and 120 to 291 in THF [5] for **2**, **3**, and **4**, respectively. Initially, very different rate constants for these bases of almost equal strength were discussed in terms of a little larger basicity of TBD, steric hindrance brought to reaction center by the MTBD molecule caused by the methyl substituent of the nitrogen atom of the latter base, and finally the hypothetical additional hydrogen bond formed in the transition state (TS) of the TBD reaction [4,5]. For the reaction of TBD the remarkable blue shift that was observed for the reaction product species suggests double hydrogen bonding of the nitronate group by protonated base $TBDH^+$ [4,5].

The equilibrium constant for the TBD reaction has been found larger than 11000 M^{-1} and is considerably greater than that of 44 M^{-1} for MTBD reaction. This shows that the Brønsted relationship does not hold for the reactions of nitroalkanes with bicyclic guanidines. Such breakdowns frequently indicate the importance of steric hindrance but in the case of TBD base it results from an additional hydrogen bond, formed both in the TS and in the product [4,5].

Generally, along with growing crowding in the vicinity of reaction center due to steric hindrance brought by the bulk

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of alkyl substituents in the C-acid: **2**, **3**, **4** and MTBD base, significant reduction of the rate constants was observed [4] which is consistent with earlier observations made by Bordwell [6,7]. This points out that the steric factors play an important role and cannot be neglected in considering the planarity of the carbanion formed and, most of all, the different structure of the transition state [5].

Usually the primary deuterium kinetic isotope effects KIE increase with the steric hindrance [8], either by removal of the solvent molecules from the vicinity of the reaction site or a steeper energy barrier that favours proton tunneling [9]. However, just reverse effect we have already found. One can states that the steric hindrance in both the base and C-acid may also reduces the KIE. These unusual values of KIE we found for the reaction of studied series of C-acids with MTBD base where they are declining with the increase of bulk of the R substituents [10] in both acetonitrile [4] and THF [5] solvents. We, undoubtedly found, that in case of the TBD and MTBD reactions with this series of C-acids the reaction of MTBD proceeds with different structure of the transition state. Actually, two factors influencing KIE values have been found. Firstly, the additional stabilization of the TS in the case of TBD reaction by a hydrogen bond and secondly the planarity of the nitro group towards the proton transfer axis giving the dihedral HCNO angle dependent on the bulk of the R substituent [4]. The growing bulk of R substituent in the C-acid causes a decrease in HCNO dihedral angle what is manifested in the larger KIE values. Generally, for the reaction of nitroalkanes with guanidine bases, the KIE values increase when the structure of the transition state is less product-like. In conclusion, we say that the KIE values are greatly influenced by the factor resulting from the structure of the transition state complex which is formed with the hydrogen bonds between a base and oxygen atoms of nitro groups of the reacting C-acid. This is evidently confirmed by the ab initio predictions and the energetics we estimated for the structures of the complexes of 1-nitro-1-(4-nitrophenyl)ethane and TBD and MTBD bases [4,11].

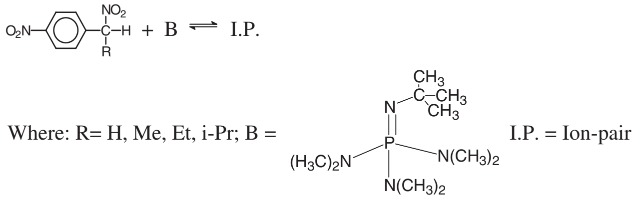
The further study of the mechanism of proton transfer may utilize the very strong phosphazene P_1-*t*-Bu base ($\mathrm{p}K_{\mathrm{a}}^{\mathrm{MeCN}}=26.88$ [1]) which is the weakest in the phosphazene's family [1,3,12], however, stronger than TBD and MTBD by one order of pK_{a} unit ($\mathrm{p}K_{\mathrm{a\,TBD}}^{\mathrm{MeCN}}=25.96$ or 24.7) [2,3] ($\mathrm{p}K_{\mathrm{a\,MTBD}}^{\mathrm{MeCN}}=25.43$ or 24.97) [2,3] and even three pK_{a} units stronger compared to DBU ($\mathrm{p}K_{\mathrm{a\,DBU}}^{\mathrm{MeCN}}=23.9$) [13].

Moreover, phosphazene P_1-*t*-Bu is much less nucleophilic in comparison with DBU and not sensitive towards hydrolysis revealing particularly useful properties for deprotonation [14]. The use of this neutral, strong and most of all highly hindered nitrogen base seems to be promising in our study of the factors influencing the structure of the transition state and mechanisms of the proton transfer reactions in solutions [4,15].

2. Results and discussion

1-Nitro-1-(4-nitrophenyl)alkanes are moderately strong acids (p$K_{\mathrm{a}}=20.39$, 23.24, 23.57 and 25.73 for **1**, **2**, **3**, and **4**, respectively) [16] with gradually increasing bulk of alkyl R substituents: H (**1**), Me (**2**), Et (**3**), *i*-Pr (**4**). These properties combined with large steric hindrance of very strong base *tert*-Butylimino-tris(dimethylamino)phosphorane, named P_1-*t*-Bu phosphazene ($\mathrm{p}K_{\mathrm{a}}^{\mathrm{MeCN}}=26.88$ [1]) offers a new ability to study the factors influencing mechanism of the proton transfer reaction.

The reaction carried out in low polarity solvent THF proceeds the Scheme 1:



Scheme 1. Reaction between 1-nitro-1-(4-nitrophenyl)alkanes and phosphazene P_1-*t*-Bu.

The product of the proton transfer reactions (Scheme 1) in THF of $\lambda_{\max}=484$, 496, 498, and 496 nm for **1**–**4**, respectively, appears to be an ion pair as indicated by a blue shift ∼20 nm compared to that of free anions previously found in acetonitrile solvent of $\lambda_{\max}=508$–515 nm [4,17,18]. Such a blue shift is an indication of a strong stabilization by the interaction with countercation [10]. The appropriate chemical shifts found in ^{1}H and ^{13}C NMR spectra are given in Tables 1 and 2. The ^{1}H NMR spectrum of the reaction of **1** with P_1-*t*-Bu, mixture 1:1 shows the complete conversion of the carbon acid **1** into its anion manifested by the shift of the signal of the acidic proton s, $\delta=$ 5.740 to 6.790. The intensity of the band found is equivalent to the loss of the one C_{α} proton. There were insignificant shifts of the bands attributed to ortho ($2H_{2,6}$) and meta ($2H_{3,5}$) hydrogen atoms (Table 1).

The ^{13}C NMR spectrum for the same reaction products shows a significant shift for acidic α-carbon atom equal to 31.664, and much smaller for the $2C_{2,6}$ carbon atoms of the anion and only insignificant changes for other carbon atoms (Table 1). The shift of the signals towards the lower field suggests the strong olefinic character of the exocyclic carbon atom. Hence the dominant structure of the anion in its resonance hybrid has the negative charge localized on the oxygen atoms of the exocyclic nitro group of the sp^{2} hybridization of the C_{α} atom.

The ^{1}H NMR spectrum of the reaction of **4** with P_1-*t*-Bu, mixture 1:1 shows the signals derived from both the C-acid and its anion (Table 2). Taking into account the integrated signals of the aromatic protons, one can assume ∼30% of the conversion of the C-acid **4** to its anionic form. The same conclusions can be drawn by analyzing the signals of ^{13}C corresponding to the P_1-*t*-Bu phosphazene base and the cation of **4** (Table 2). This amount of conversion is not so well observable in the equilibrium experiments carried out by spectrophotometry, where a similar degree of conversion has been noted only for the larger than 1:1 concentration of the base. The shifts assigned to the ortho and para protons $2H_{2,6}$ and $2H_{3,5}$ shows merely insignificant shift as was already observed for the reaction of **1** (Table 2).

Generally the spectrum of ^{13}C NMR of the 1:1 mixture of **1** and P_1-*t*-Bu phosphazene base is not clear perhaps due to low

Table 1
Chemical shifts (δ) found for the reaction of 4-nitrophenylnitromethane **1** and P_1-*t*-Bu phosphazene in THF

1		1 anion		P_1-*t*-Bu		P_1-*t*-BuH^+	
^1H (δ-ppm rel. to TMS)							
$2H_{2,6}$	m, $\delta=7.739$	$2H_{2,6}$ $\Delta\delta=-0.052$	m, $\delta=7.791$	9H, C–CH_3,	d, $\delta=1.146$	9H, C–CH_3, $\Delta\delta=-0.200$	d, $\delta=1.346$
$2H_{3,5}$	m, $\delta=8.285$	$2H_{3,5}$ $\Delta\delta=0.368$	m, $\delta=7.917$	18H, N–CH_3,	m, $\delta=2.582$	18H, N–CH_3, $\Delta\delta=-0.184$	m, $\delta=2.766$
$1H_\alpha$	s, $\delta=5.740$	$1H_\alpha$, $\Delta\delta=-1.050$	s, $\delta=6.790$				
^{13}C (δ-ppm rel. to TMS)							
$1C_\alpha$	$\delta=78.707$	$1C_\alpha$	s, 110.371	3C (C–CH_3)	d, 36.197	3C (C–CH_3) $\Delta\delta=4.634$	s, 31.563
$2C_{2,6}$	$\delta=132.370$	$2C_{2,6}$	s, 122.400	6C (N–CH_3)	d, 38.128	6C (N–CH_3) $\Delta\delta=0.251$	d, 37.877
$2C_{3,5}$	$\delta=124.541$	$2C_{3,5}$	s, 124.354	1C (C–CH_3)	d, 49.732	1C (C–CH_3) $\Delta\delta=-3.109$	s, 52.841
$1C_1$	$\delta=138.154$	$1C_1$	s, 141.509				
$1C_4$	$\delta=149.704$	$1C_4$	s, 145.061				

concentration of the anion. Nevertheless the signals assigned to free P_1-*t*-Bu phosphazene base as well as its cation in the amount adequate to converted amount of C-acid **4** are visible (Table 2).

The conductometric titration of the C-acid **1** with P_1-*t*-Bu phosphazene base in THF solvent shows rather low, however, distinct changes of the conductance (Fig. 1). The molar conductivity at the stoichiometric point is 0.72 Ω^{-1} cm^2 mol^{-1}. This is a direct and convincing indication of the ion-pair product taking into account that values of conductance obtained for the system of reaction made of C-acid **1** and MTBD base in acetonitrile solvent was larger by two orders of magnitude 80.15 Ω^{-1} cm^2 mol^{-1} [19].

The plots of k_{obs} vs base concentration show a measurable intercepts for the reactions of **2**, **3**, and **4** while for the reaction of **1** the intercept is zero within two standard deviations. Then the equilibrium constants calculated as the ratio of the rate constants for the forward and reverse reactions $K=k_f/k_b$ are large 315, 273 and 9.5 M^{-1} for **2**, **3**, **4**, respectively. The appropriate values of the equilibrium constants derived from equilibrium using Benesi and Hildebrand [20] formalism are in good agreement (Table 4), indicating that the ion-pair products are not involved in any side reactions.

Since we presume that hydrogen bonds between the carbon acid and P_1-*t*-Bu base with the hydrogen that was initially attached to α-carbon atom of the C-acid, lags behind the proton transfer from this carbon, then the pK_a values of the C-acids and P_1-*t*-Bu base, even though not measured in THF solvent, may in fact reflect the reactivity better than the equilibrium constants for their reactions in THF. For our purpose it is useful to accept pK_a values found in acetonitrile [1,16] as a measure of 'inherent' basicity providing the appropriate equilibrium constants $K^{25^\circ}\geq 1.6\times 10^5$ M^{-1}, $K^{25^\circ}=1170$, 590 and 12 M^{-1} for the reaction of phosphazene P_1-*t*-Bu with carbon acids **1**, **2**, **3**, and **4**,

Table 2
Chemical shifts (δ) found for the reaction of 2-methyl-1-(4-nitrophenyl)-1-nitropropane **4** and P_1-*t*-Bu phosphazene in THF

4		4, anion		P_1-*t*-Bu		P_1-*t*-BuH^+	
^1H (δ-ppm rel. to TMS)							
$2H_{2,6}$	m, $\delta=7.822$	$2H_{2,6}$ $\Delta\delta=-0.096$	m, $\delta=7.918$	9H, C–CH_3	d, $\delta=1.146$	9H, C–CH_3 $\Delta\delta=-0.032$	d, $\delta=1.178$
$2H_{3,5}$	m, $\delta=8.280$	$2H_{3,5}$ $\Delta\delta=0.204$	m, $\delta=8.076$	18H, N–CH_3	m, $\delta=2.582$	18H, N–CH_3	m, not legible
$1H_\alpha$	s, $\delta=5.429$	$1H_\alpha$	not present				
1H, CH	m, $\delta=2.556$–2.824	1H, CH	m, $\delta=3.356$				
3H, CH_3	d, $\delta=0.757$	3H, CH_3	d, $\delta=0.754$				
3H, CH_3	d, $\delta=1.105$	3H, CH_3	d, $\delta=1.104$				
^{13}C (δ-ppm rel. to TMS)							
$1C_\alpha$	$\delta=97.502$	$1C_\alpha$	d, $\delta=$not observed	3C (C–CH_3)	d, $\delta=36.197$	3C (C–CH_3) $\Delta\delta=5.246$	s, $\delta=30.951$
$2C_{2,6}$	$\delta=130.251$	$2C_{2,6}$ $\Delta\delta=3.809$	s, $\delta=126.442$	6C (N–CH_3),	d, $\delta=38.128$	6C (N–CH_3) $\Delta\delta=0.127$	d, $\delta=38.001$
$2C_{3,5}$	$\delta=124.507$	$2C_{3,5}$ $\Delta\delta=1.721$	s, $\delta=122.786$	1C (C–CH_3),	d, $\delta=49.732$	1C (C–CH_3)	s, $\delta=$not observed
$1C_1$	$\delta=141.470$	$1C_1$	s, $\delta=$not observed				
$1C_4$	$\delta=149.629$	$1C_4$	s, $\delta=$not observed				
1C (C)	$\delta=33.672$	1C (C) $\Delta\delta=-2.340$	$\delta=36.012$				
1C (CH_3)	$\delta=18.402$	1C (CH_3) $\Delta\delta=-0.698$	$\delta=19.100$				
1C (CH_3)	$\delta=19.858$	1C (CH_3)	$\delta=19.528$				

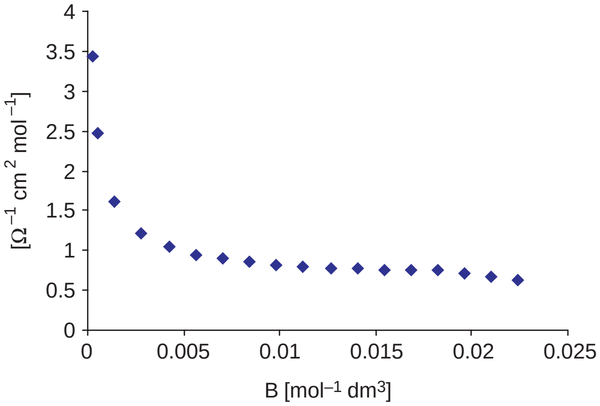


Fig. 1. Conductometric titration of 4-nitrophenylnitromethane **1** with P_1-*t*-Bu phosphazene in THF solvent.

Table 3

Observed and second order rate constants for proton/deuteron transfer reactions between 1-nitro-1-(4-nitrophenyl)alkanes $O_2NC_6H_4C(L)NO_2R$; R = H, Me, Et, *i*-Pr; L = H, D* and P_1-*t*-Bu phosphazene in THF

T (°C)	P_1-*t*-Bu × 10^3 (M)	$k_{obs} \times 10^2$ (s^{-1})	k_f ($dm^3\ mol^{-1} s^{-1}$)	k_H/k_D
*1-Nitro-1-(4-nitrophenyl)methane (**1**), (L=H)*				
10	0.5–2.5	369–1818	7336 ± 111	
15	0.5–2.5	400–1925	7718 ± 115	
25	0.5–2.5	429–2290	9357 ± 118	
35	0.5–2.5	507–2527	10218 ± 238	
45	0.5–2.5	564–2694	10718 ± 113	
*1-Nitro-1-(4-nitrophenyl)methane (**1**), (L=D)*				
10	0.5–2.5	23–106	401 ± 23	18.3 ± 1.1
15	0.5–2.5	23–123	474 ± 36	16.3 ± 1.2
25	0.5–2.5	27–150	592 ± 32	15.8 ± 0.8
35	0.5–2.5	38–186	723 ± 24	14.1 ± 0.5
45	0.5–2.5	51–251	995 ± 18	10.8 ± 0.2
*1-Nitro-1-(4-nitrophenyl)ethane (**2**), (L=H)*				
10	5–25	1.0–4.5	1.74 ± 0.03	
15	5–25	1.3–5.1	1.90 ± 0.01	
25	5–25	1.9–6.5	2.31 ± 0.05	
35	5–25	2.7–9.5	3.59 ± 0.06	
*1-Nitro-1-(4-nitrophenyl)ethane (**2**), (L=D)*				
10	5–25	0.05–0.21	$0.08 \pm 0.00_4$	20.8 ± 1.1
15	5–25	0.07–0.27	$0.10 \pm 0.00_2$	18.6 ± 0.4
25	5–25	0.11–0.45	$0.17 \pm 0.00_1$	13.6 ± 0.4
35	5–25	0.18–0.70	0.26 ± 0.01	13.8 ± 0.3
*1-Nitro-1-(4-nitrophenyl)propane (**3**), (L=H)*				
10	5–25	0.24–1.10	0.43 ± 0.02	
15	5–25	0.37–1.27	0.45 ± 0.01	
25	5–25	0.57–1.88	0.66 ± 0.01	
35	5–25	0.96–2.81	0.92 ± 0.03	
*1-Nitro-1-(4-nitrophenyl)propane (**3**), (L=D)*				
10	5–25	0.01–0.06	$0.02 \pm 0.00_1$	19.7 ± 0.9
15	5–25	0.02–0.08	$0.03 \pm 0.00_1$	15.3 ± 0.7
25	5–25	0.03–0.14	$0.09 \pm 0.00_2$	13.2 ± 0.6
35	5–25	0.06–0.26	$0.10 \pm 0.00_1$	9.6 ± 0.1
*2-Methyl-1-(4-nitrophenyl)propane (**4**), (L=H)*				
15	19.6–187.1	0.55–1.81	$0.07_5 \pm 0.00_1$	
20	19.6–187.1	0.83–2.17	$0.08 \pm 0.00_1$	
25	19.6–187.1	1.08–2.52	$0.09 \pm 0.00_1$	
35	19.6–187.1	2.06–3.88	$0.11 \pm 0.00_1$	

*Concentrations of C-acids 2.5×10^{-5} mol dm^{-3}.

respectively. The equilibrium constant for the reaction of C-acid **1**, is only roughly estimated using Benesi–Hildebrand formalism, for the increments of absorbance of the product, as a function of the base concentration were small and charged with a large error. Taking into account very large steric hindrance attributed to the phosphazene P_1-*t*-Bu, these values seem to harmonize with the values of equilibrium constants already found for DBU base using Benesi–Hildebrand method K^{THF} = 2060, 560, and 3.7 M^{-1} for **2**, **3**, and **4**, respectively [10]. The largest equilibrium constant for the reaction of **4** has been found for TBD base K^{THF} = 11000 M^{-1} while with MTBD was only 44 M^{-1}, however, this last was 10 times larger than that with DBU [10] base K^{THF} = 3.7 M^{-1} and P_1-*t*-Bu K^{THF} = 11.8 M^{-1} (Table 4). These show that the Brönsted relationship does not hold for the reactions of nitroalkanes with bicyclic guanidines/amidines [10] and P_1-*t*-Bu bases. This effect could be a result of a steric crowding in the vicinity of the reaction center, however, the alterations are extremely dramatic, then we say that this is an indication of the different structure of the transition state TS and consequently, the mechanism of reaction for each base (DBU [10], TBD [5], MTBD [5], and finally P_1-*t*-Bu) in THF solvent.

This is undoubtedly visible for the present kinetic experiments. The rate constants for the reaction of 1-nitro-1-(4-nitrophenyl)alkanes **1**, **2**, **3**, **4** are collected in Table 3. The fastest reaction in the group takes place for the least hindered C-acid **1** $k_2^{25°} = 9357\ dm^3\ mol^{-1}\ s^{-1}$. The replacement of the hydrogen atom on the α carbon atom by the Me group (C-acid **2**), causes the dramatic decrease of the second-order rate constants by more than three orders of magnitude (Table 3).

The ratio of k_2^1/k_2^2 is large equal to 4050.7. The gradual increase of the bulk of R substituents on the α carbon atom of the C-acid results in a further decrease of the rate constants, however the reduction is not so large. The ratio of the rate constants are only $k_2^2/k_2^3 = 3.5$ and $k_2^3/k_2^4 = 7.7$. These changes are the indication of the steric factor, which plays in this system of reaction a dominant role. However, it is clearly seen that the replacement of the Me by the Et and *i*-Pr caused a decrease of the rate constant only by a factor of 3.5 and 7.7. Then the most dramatic change is observed while comparing the proton transfer abstraction with P_1-*t*-Bu phosphazene from not substituted **1**, and Me substituted **2** C-acids. Consequently, taking into consideration this way of changes we claim that the steric inhibition reached a particular level for the reaction of **2**, as a further increase of the bulk of alkyl substituents effected moderate changes of the rate constants. This trend is reflected in the values of the activation parameters collected in Table 5.

The smallest value of the enthalpy of activation has been found for the reaction of **1**, $\Delta H_H^{\neq} = 6.1\ kJ\ mol^{-1}$, while

Table 4

Equilibrium constants for proton transfer reactions between 1-nitro-1-(4-nitrophenyl)alkanes $O_2NC_6H_4CHNO_2R$ and P_1-*t*-Bu phosphazene in THF at 25°

R	λ_{max} (nm)	k_f/k_b	K_r ($mol^{-1}\ dm^3$)	ϵ ($cm^{-1}\ mol^{-1}\ dm^3$)
H	484	$k_b \cong 0$	> 100 000	16200 ± 90
Me	496	315 ± 36	1170 ± 150	13200 ± 80
Et	498	273 ± 23	590 ± 60	28500 ± 280
i-Pr	496	9.5 ± 0.2	11.8 ± 0.1	19900 ± 200

Table 5
Activation parameters for proton/deuteron transfer reactions between 1-nitro-1-(4-nitrophenyl)alkanes $O_2NC_6H_4C(L)NO_2R$ and P_1-*t*-Bu phosphazene in THF

R	$\Delta H^{\neq}_{H}$ (kJ mol^{-1})	$\Delta S^{\neq}_{H}$ (J mol^{-1} deg^{-1})	$\Delta H^{\neq}_{D}$ (kJ mol^{-1})	$\Delta S^{\neq}_{D}$ (J mol^{-1} deg^{-1})	$\Delta G^{\neq}_{H}$ (kJ mol^{-1})	$\Delta G^{\neq}_{D}$ (kJ mol^{-1})	$\Delta H^{\neq}_{D}-\Delta H^{\neq}_{H}$ (kJ mol^{-1})
H	6.1 ± 1.1	-149.7 ± 3.5	16.0 ± 1.1	-138.0 ± 3.6	50.7 ± 1.5	57.2 ± 1.5	9.9 ± 1.1
Me	18.0 ± 3.6	-176.5 ± 12.3	31.4 ± 1.0	-154.3 ± 3.5	70.6 ± 5.14	77.4 ± 1.5	13.4 ± 3.7
Et	20.7 ± 2.5	-178.7 ± 8.4	39.9 ± 1.7	-135.4 ± 5.8	74.0 ± 3.5	80.3 ± 2.4	19.2 ± 3.0
i-Pr	11.1 ± 1.5	-227.8 ± 5.1			80.0 ± 2.1		

the reaction with more hindered C-acids **2**, **3** and **4** have much larger enthalpies of activation reaching $\Delta H^{\neq}_{H} = 18.0, 20.7$ and 11.1 kJ mol^{-1}, respectively. The enthalpy of activation for the reaction of **1** is unusually small $\Delta H^{\neq}_{H} = 6.1$ kJ mol^{-1}, characteristic for diffusion controlled reactions. Unexpectedly the rate of proton abstraction for this reaction found is relatively slow $k_{2H} = 9357$ dm^3 mol^{-1} s^{-1} (Table 3), allowing for stopped flow measurements.

The large, negative values of the entropy of activation $\Delta S^{\neq}_{H} = -149.7, -176.5, -178.7, -227.8$ J mol^{-1} deg^{-1}, respectively indicate considerable ordering of the transition state (Table 5). However, a visible difference between $\Delta S^{\neq}_{H}$ values for the least hindered C-acid **1** and two other carbon acids **2** and **3**, for which they are almost equal within the range of standard deviation while the reaction of the C-acid **4** has much more negative value (Table 5). Then the large differences in the enthalpy of activation between the reaction of **1** and the phosphazene base and other C-acids (**2** and **3**), of $\Delta\Delta H^{\neq}_{H} =$ 12 and 14.6 kJ mol^{-1} and only $\Delta\Delta H^{\neq}_{H} = 5$ kJ mol^{-1} for the reaction of (**4**) respectively are compensated by the negative entropies of activation in the way that the appropriate values of free enthalpy of activation are similar for **2**, **3** $\Delta G^{\neq}_{H} \cong 70$ kJ mol^{-1}, much smaller for the reaction of **1** $\varDelta G^{\neq}_{H} \cong$ 50 kJ mol^{-1} and definitely larger for the reaction of **4** $\Delta G^{\neq}_{H} = 80$ kJ mol^{-1}. Then the differentiation in the rate constants $k_2^{25^\circ} = 9357$ dm^3 mol^{-1} s^{-1} and $k_2^{25^\circ} = 2.31$, 0.66 and 0.09 dm^3 mol^{-1} s^{-1} for **1**, **2**, **3** and **4**, respectively (Table 3) is certainly attributed to the increase in the energy of the transition state for more hindered carbon acid and the solvation effects, particularly meaningful for the reaction of **4**.

As can be seen (Table 3), the reaction of **1** with P_1-*t*-Bu is very fast $k_2^{25^\circ} = 9357$ dm^3 mol^{-1} s^{-1}, however, still measurable by the stopped flow method, while the reactions with much weaker bases DBU, TBD and MTBD were unexpectedly faster and out of range of this method (Table 6) [5,10].

The comparison of the second-order rate constants for the reactions carried out with DBU, MTBD, TBD and P_1-*t*-Bu is puzzling as the fastest reaction takes place for TBD base while for the strongest P_1-*t*-Bu base is the slowest in the group. The exceptional acceleration of the proton transfer reaction we already found for the reaction of TBD while for MTBD, of nearly equal pK_a, was two orders of magnitude slower (Table 5). This effect was attributed to the stronger stabilization of the TS by an additional hydrogen bond present in the TBD complex. The MTBD and DBU bases are not capable to form such cyclic structures of the TS so the influence of the net steric hindrance brought by these bases is visible. The reaction with MTBD is slower than with DBU, which is a weaker base but with less steric crowding in the vicinity of reaction center [5,10]. Then the unusual deceleration of the proton transfer induced by very strong P_1-*t*-Bu phosphazene reflects very large sterical restraints which suddenly grow after the hydrogen has been replaced by methyl group in the reacting C-acid (Tables 3 and 5).

The values of the primary deuterium kinetic isotope k_{2H}/k_{2D} are large ranging from 15 to 13 at 25 °C for this series of C-acids **1**–**4** (Table 3). These values are a little larger than those already found for the reaction with DBU [10], MTBD and TBD [5] (Table 6). The k_{2H}/k_{2D} are indistinctly larger for the least hindered C-acid **1**, while for more hindered substrates **2**, **3**, and **4** are smaller, at least at 25 °C (Tables 3 and 6). This decrease of the KIE values, together with the increasing steric hindrance brought by reacting C-acids was already found for the system of reactions between MTBD base and sterically hindered 1-nitro-1-(4-nitrophenyl)alkanes [5], and (2,6-dialkyl-4-nitrophenyl)phenylcyano-methanes [15]. However, this trend is weaker for the present systems of reactions, although the temperature dependence of k_{2H}/k_{2D} is much visible since the 25 °C increase of temperature caused significant reduction of the KIE values, larger for more sterically hindered C-acids.

Table 6
Comparison of second-order rate constants and primary deuterium kinetic isotope effects k_H/k_D for reactions of 1-nitro-1-(4-nitrophenyl)alkanes $O_2NC_6H_4C(L)NO_2R$; R = H(**1**), Me(**2**), Et(**3**), *i*-Pr(**4**); L = H, D with DBU, MTBD, TBD and P_1-*t*-Bu in THF at 25 °C

R	Base							
	DBU k_2 (dm^{3}mol^{-1}s^{-1}) pK_a = 23.9	k_H/k_D	MTBD k_2 (dm^{3}mol^{-1}s^{-1}) pK_a = 25–25.4	k_H/k_D	TBD k_2 (dm^{3}mol^{-1}s^{-1}) pK_a = 24.7–26	k_H/k_D	P_1-*t*-Bu k_2 (dm^{3}mol^{-1}s^{-1}) pK_a = 26.9	k_H/k_D
H	–	–	–	–	–	–	9357	15.8
Me	800	11.4	161	10.9	19000	9.7	2.31	13.6
Et	219	12.1	46	10.1	6800	12.1	0.66	13.2
i-Pr	7.75	9.7	3.05	8.5	880	14.8	0.09	

These reduction covered 6.3, 7.0, and 10.1 KIE units for **1**, **2**, and **3**, respectively (Fig. 2).

Such a distinctive temperature dependence we already observed in our earlier paper [15] and was confirmed by Leffek et al. [21]. However, this is not expected to be extremely large effect and would be offset by some steric inhibition of C–H and C–D vibration frequencies in the initial state [22].

The sudden decrease of the rate constants k_f found for the reactions of more hindered C-acids **2** and **3** (Table 3) is insignificantly reflected in the KIE values as they remain constant within experimental error.

In the extreme case of a complete loss of the C–H stretching frequency and two C–H bending frequencies during the activation process, the maximum isotope effect on the activation parameters is 8.8 kJ mol^{-1} for $\Delta H^{\neq}_{D} - \Delta H^{\neq}_{H}$ and 5.9 J mol^{-1} K^{-1} for $\Delta S^{\neq}_{D} - \Delta S^{\neq}_{H}$. Since our results are in excess of these maximum values $\Delta H^{\neq}_{D} - \Delta H^{\neq}_{H} = 9.9$, 13.4, and 19.2 kJ mol^{-1} (Table 5), it is clear that there is a significant contribution from tunneling effect. One can assume that most proton transfer goes via tunnel effect as we accepted the maximum energy loss for three frequency modes instead of stretching vibrations, commonly used for estimation of the maximum value of the enthalpy differences. In such a case the maximum value of the enthalpy difference would be 5.4 kJ mol^{-1} only, so the above values exceed much the predicted value for the complete loss of C–H stretching frequency during the activation process. The largest contribution from the tunneling could be attributed for the reaction of 1, $k_{2H}/k_{2D} = 15.8$ with $\Delta H^{\neq}_{H} = 6.1$ kJ mol^{-1} while for the reactions of more hindered C-acids k_{2H}/k_{2D} remain unchanged 13.6 and 13.2 at 25 °C respectively confirming our suggestion that in our system of reactions the steric inhibition reached a particular level after the hydrogen atom in the carbon acid **1** has been replaced by methyl or more bulky substituents. The most distinct alteration, however is manifested for the entropy changes $\Delta S^{\neq}_{D} - \Delta S^{\neq}_{H} = 11.7$, 22.2, and 43.3 J mol^{-1} K^{-1} (Table 5) indicating predominant influence of steric and solvation effects visible for sudden decrease of the rate constants found for the reaction of **2** and **3**.

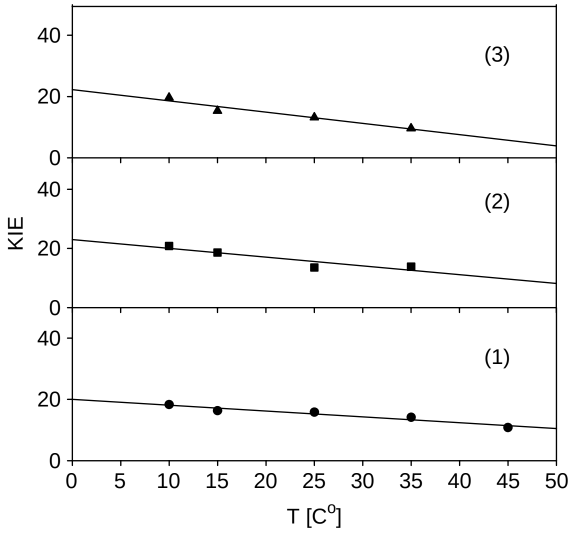


Fig. 2. Temperature dependence of KIE for the proton transfer reactions from 1-nitro-1-(4-nitrophenyl)methane **1**, 1-nitro-1-(4-nitrophenyl)ethane **2**, 1-nitro-1-(4-nitrophenyl)propane **3** to P$_1$-*t*-Bu phosphazene in THF

Our general conclusion is that the effect of steric hindrance in the vicinity of reaction center brought by both reacting C-acid and a base may conceal other important effects including Brønsted relationship obviously valid for most systems of proton transfer reactions [5,8,23–25].

3. Experimental

Spectroscopic grade THF (Aldrich) was dried with CaH$_2$ and fractionally distilled in the apparatus filled with argon. The middle fraction of THF (66±05°) was collected and kept under argon to prevent moisture and oxygen. The purity of THF was controlled by UV spectra to meet standards [26]. The influence of extraneous water on the rate constants of the proton transfer reaction between phosphazene P$_1$-*t*-Bu and the most hindered C-acid **4** has been tested by measuring the kinetics using commercial, anhydrous, packed under nitrogen THF by Aldrich (water content < 0.003%).

Previously prepared samples of C-acids: 4-nitrophenylnitromethane (**1**) [27], 1-(4-nitrophenyl)-1-nitroethane (**2**), 1-(4-nitrophenyl)-1-nitropropane (**3**), 2-methyl-1-(4-nitrophenyl)-1-nitropropane (**4**) were used [10]. The melting points and spectra after recrystallization from ethanol were in accordance with the literature. The deuterated analogues of **1**, **2**, **3**, and **4** were prepared by the modified exchange method in which the neutralization of the anion of the appropriate C-acid was effected using acetate buffer instead of concentrated DCl in D$_2$O [28], which eliminates the noxious Nef's reaction of the nitronic acid formed. The degree of deuteration of the α-carbon was better than 98% as showed by ^{1}H NMR spectra (disappearence of δ_H signals at 5.74, **1** (1 H, s), 5.74, **2** (1 H, q, J 6.95 Hz, CHNO$_2$), 5.49, **3** (1 H, m, CHNO$_2$), 5.43, **4** (1 H, d, J 10.94 Hz, CHNO$_2$).

Phosphazene P$_1$-*t*-Bu distributed by Fluka was used without any further purification. The stock solutions of commercial phosphazene P$_1$-*t*-Bu and C-acids (1×10^{-2} M) were freshly prepared before each kinetic or equilibrium experiment and kept under argon, to protect the system against atmospheric CO$_2$, O$_2$, and moisture. The purity of the base was satisfactory as tested by ^{1}H NMR and titration methods [2]. The working solutions of the C-acids and the base were made up by dilution of stock solutions. All operations with the solutions of the carbon acids and the base were accomplished under a positive pressure of argon.

Electronic absorption spectra were completed on a Hewlett–Packard 8452A diode array spectrophotometer using a thermostat cell holder. All spectra were recorded at 25 °C.

The kinetic measurements were performed using a stopped flow spectrophotometer made by Applied Photophysics and a Hewlett–Packard 8452A diode array depending on the rate of reaction. The values of k_{obs} were measured using 2.5×10^{-5} mol dm^{-3} concentration of C-acid and a varying, five concentration of phosphazene P$_1$-*t*-Bu base, always in a large excess over carbon acid to ensure pseudo-first-order kinetics (Table 3). From the kinetic curves the pseudo-first-order rate constants $k_{\rm obs}$ measured by 'stopped flow' method have been achieved by an 'end point method', but for slower reaction of deuteron transfer, measured by means of 'diode array' spectrophotometer were calculated by Guggenheim method.

The observed rate constants for proton transfer reaction were a function of base concentration according to the following equation:

$$k_{\rm obs} = k_{\rm f}^{\rm H} c_{\rm B} + k_{\rm b}^{\rm H} \qquad (1)$$

where $k_{\rm f}^{\rm H}$ and $k_{\rm b}^{\rm H}$ are the rate constants for the forward and reverse reactions respectively and $c_{\rm B}$ is the concentration of the base. The second-order rate constants are the calculated slopes of $k_{\rm obs}$ versus base concentration. The intercepts for proton transfer reaction are the rate constants of the backward reaction $k_{\rm b}^{\rm H}$. For reactions with deutero analogues of C-acids the initial part of the curves was ignored to minimize the possible error caused by contamination of C-D-acid with not deuterated C–H acid in accordance with Bergson [29] and Melander and Saunderss [22] who suggested that this procedure reduces the probability of results being distorted. The remaining part of Guggenheim plot was a good straight line. Then Eq. (1) was applied in order to determine second order rate constants $k_{\rm f}$.

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References

[1] R. Schwesinger, Angew. Chem. 105 (1994) 1420.

[2] G. Schroeder, B. Leska, A. Jarczewski, B. Nowak-Wydra, B. Brzezinski, J. Mol. Struct. 344 (1995) 77.

[3] R. Schwesinger, Chimia 39 (1985) 269.

[4] I. Grzeskowiak, W. Galezowski, A. Jarczewski, Can. J. Chem. 79 (2001) 1128.

[5] W. Galezowski, I. Grzeskowiak, A. Jarczewski, J. Chem. Soc., Perkin Trans. 2 (1998) 1607.

[6] F.G. Bordwell, H.E. Fried, Tetrahedron Lett. (1977) 1121.

[7] F.G. Bordwell, J.E. Bartmess, J.A. Hautala, J. Org. Chem. 43 (1978) 3107.

[8] E.S. Lewis, L.H. Funderburk, J. Am. Chem. Soc. 89 (1967) 2322.

[9] A. Jarczewski, C.D. Hubbard, J. Mol. Struct. 649 (2003) 287.

[10] W. Galezowski, A. Jarczewski, Can. J. Chem. 68 (1990) 2242.

[11] A. Jarczewski, J. Koput, I. Nowak, Crystal structure and infrared spectra of dicesium *trans*-tetraaquadichlorochromium (III) chloride, J. Mol. Struct. 708 (2004) 105–111.

[12] R. Schwesinger, Nachr. Chem. Tech. Lab. 38 (1990) 1214.

[13] K.T. Leffek, P. Pruszynski, K. Thanapaalasingham, Can. J. Chem. 67 (1989) 590.

[14] R. Schwesinger, J. Willaredt, H. Schlemper, M. Keller, D. Schmitt, H. Fritz, Chem. Ber. 127 (1994) 2435.

[15] K. Minksztym, A. Jarczewski, J. Mol. Struct. 631 (2003) 203.

[16] M. Stanczyk-Dunaj, W. Galezowski, A. Jarczewski, Can. J. Chem. 80 (2002) 1259.

[17] W. Galezowski, A. Jarczewski, J. Chem. Soc., Perkin Trans. 2 (1989) 1647.

[18] W. Galezowski, M. Stanczyk, I. Grzeskowiak, A. Jarczewski, J. Chem. Soc., Perkin Trans. 2 (1996) 2647.

[19] I. Nowak, PhD Thesis, University of A. Mickiewicz, Poznań, Poland, 2001, pp. 121.

[20] H.A. Benesi, J.H. Hildebrand, J. Am. Chem. Soc. 71 (1949) 2703.

[21] K.T. Leffek, P. Pruszynski, Can. J. Chem. 66 (1988) 1454.

[22] L. Melander, W.H. Saunders Jr., Reaction Rates of Isotopic Molecules, Wiley, New York, 1980, pp. 287–291 (Chapter X).

[23] R.P. Bell, The Proton in Chemistry, second ed., Chapman & Hall, London, 1973 (Chapters 7, 10, 12).

[24] F. Terrier, L. Xiao, P.G. Farrell, D. Moscowitz, J. Chem. Soc., Perkin Trans. 2 (1992) 1259 (and refs therein).

[25] P. Pruszynski, A. Jarczewski, J. Chem. Soc. Perkin Trans. 2 (1986) 1117.

[26] Uvasol®, Solvents and Auxiliaries for Spectroscopy, E. Merck, Rahway, 1980, pp. 98.

[27] E.F. Caldin, A. Jarczewski, K.T. Leffek, Trans. Faraday Soc. 67 (1971) 110.

[28] A. Jarczewski, P. Pruszynski, K.T. Leffek, Can. J. Chem. 61 (1983) 2029.

[29] G. Bergson, Chem. Scr. 8 (1975) 145.