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Isolation of a Metastable Geometrical Isomer of a Hexacoordinated Dihydrophosphate: Elucidation of Its Enhanced Reactivity in Umpolung of a Hydrogen Atom of Water

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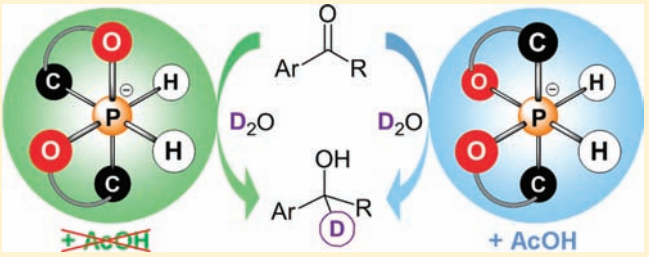
Supporting Information

ABSTRACT: Two of five conceivable geometrical isomers of a hexacoordinated dihydrophosphate bearing two sets of a bidentate ligand were investigated. X-ray crystallographic analysis of both of isomers, **1a-TPP** and **1b-TEA**, revealed their octahedral geometries of C_2 and C_1 symmetry, respectively, which were consistent with the NMR spectra. The isomer **1b-TEA** underwent both hydride reduction of an aldehyde and proton exchange with water at room temperature in DMSO without any additive. A one-pot reaction of both of the reactions of **1b-TEA** with D_2O and an aldehyde or a ketone under the above conditions proceeded successfully to give the deuterated alcohol. Thus, umpolung of a hydrogen atom of water with **1b-TEA** was achieved under much milder conditions than those used in the reaction with another isomer, **1a-TEA**. Quantitative isomerization of **1b-TEA** to **1a-TEA** occurred in methanol at room temperature. Calculations on the five conceivable geometrical isomers of the anionic part of the dihydrophosphate revealed their relative stability, which reasonably explained the isomerization, and the larger negative charge at the atoms located at the trans positions of the oxygen atoms. The smaller coupling constants of the P−H and P−C bonds located at the rear of an oxygen atom in the NMR spectra resulted in the smaller s character of these bonds. The differences in both hydride-donation and proton-exchange reactivities between **1a-TEA** and **1b-TEA** could be explained by the differences in the atomic charge of the hydrogen atom and the stability difference of the initially formed phosphorane intermediates, respectively.

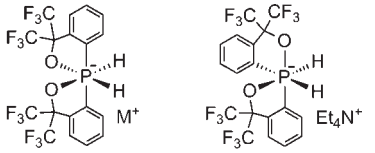


INTRODUCTION

Umpolung,[1] the reversal of polarity of an atom in a functional group, is one of the most useful concepts in organic synthesis. Umpolung of a hydrogen atom is relatively difficult because a proton source, such as water ($H^{\delta+}-OH$), undergoes a reaction with the product of the umpolung ($H^{\delta-}-Z$) to give molecular hydrogen. If umpolung of a hydrogen atom of a water molecule could be achieved, it would provide deuteride ion (D^-) and tritide ion (T^-) donors from heavy water (D_2O or T_2O). This method should be useful for isotope labeling,[2] which is widely used in the study of biomolecules and reaction mechanisms, because heavy water is cheap and easy to use. Although a number of studies have reported on the development of isotope-labeling methods using D_2O under strongly acidic conditions, at high temperatures, or in the presence of transition metal catalysts, the deuterium does not work as a deuteride ion in those cases.[3]

We recently reported the synthesis of novel hexacoordinated phosphates **1a-TEA** and **1a-TPP** and their application to hydride reduction of carbonyl compounds in a preliminary communication (Chart 1).[4] Interestingly, a hydrogen atom on the phosphorus atom of **1a-TEA** was not only reactive as a hydride but also exchangeable for a proton of water, resulting in umpolung of a hydrogen atom of water. However, the reactivity is low, so the reactions needed heating or additives. Considering that geometrical isomerism of some pentacoordinated organophosphorus compounds results in different stability, bonding properties, and reactivities,[5] another geometrical isomer of the hexacoordinated phosphorus compounds is expected to show enhanced reactivities. Here, we report the synthesis and isolation of hexacoordinated dihydrophosphate **1b-TEA**, in which the phosphorus atom forms bonds with two Martin ligands[6] and two hydrogen atoms in a spatial arrangement different from that of **1a-TEA**. The newly isolated isomer **1b-TEA** has higher reactivity than **1a-TEA** for both the hydride reduction and the proton exchange, and thus, umpolung of a deuterium atom in D_2O was achieved at room temperature without any additive.

Chart 1. Dihydrophosphates 1a-TEA, 1a-TPP, and 1b-TEA



1a-TEA (M = Et_4N)
1a-TPP (M = Ph_4P)

1b-TEA

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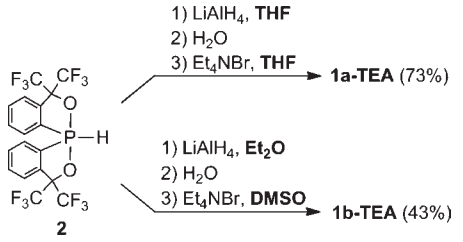
Scheme 1. Synthesis of 1a-TEA and 1b-TEA



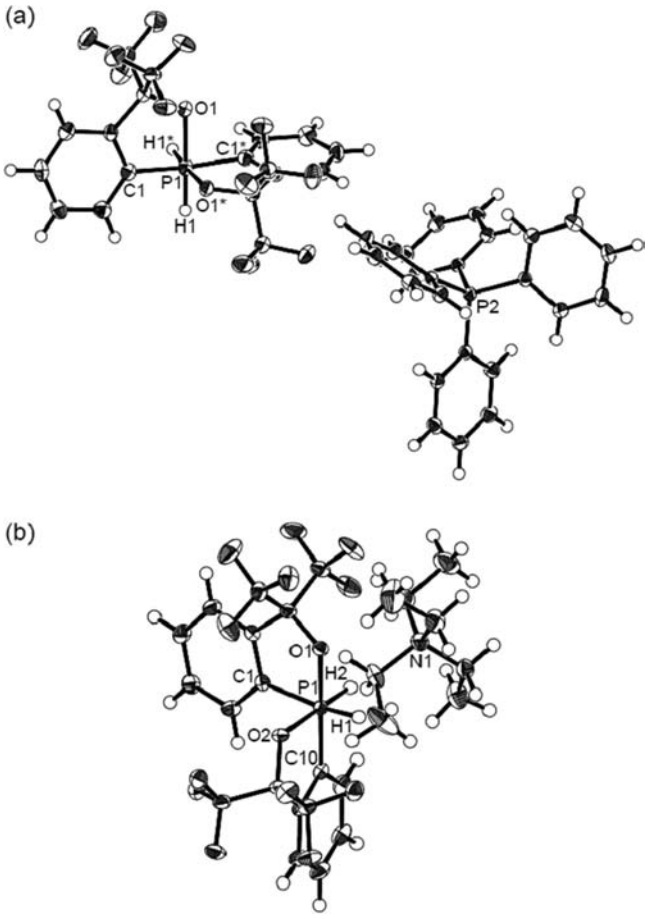


Figure 1. ORTEP drawings of (a) **1a-TPP** and (b) **1b-TEA** (50% probability thermal ellipsoids).

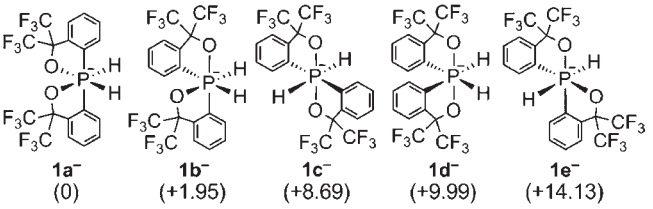
RESULTS AND DISCUSSION

In our previous paper, we reported that we obtained hexacoordinated dihydrophosphate **1a-TEA** from hydrophosphorane **2** using THF as a solvent (Scheme 1).[4] Here, we succeeded in synthesizing dihydrophosphate **1b-TEA** by changing solvents from THF to diethyl ether and dimethyl sulfoxide (DMSO) in the reduction and cation exchange, respectively. X-ray crystallographic analysis of **1b-TEA** revealed that it is a geometrical isomer of **1a-TEA** with a differently arranged bidentate ligand (Figure 1, Table 1). Although two different geometrical isomers have been successfully isolated in some pentacoordinated organophosphorus compounds,[5] this is the first example for a hexacoordinated phosphate as far as we know.[7] The phosphate anion moiety of **1b-TEA** shows C_1 symmetry, while **1a-TEA** and

Table 1. Crystallographic Data for 1a-TPP and 1b-TEA

	1a-TPP	1b-TEA
color	colorless	colorless
formula	$C_{42}H_{30}F_{12}O_2P_2$	$C_{26}H_{30}F_{12}NO_2P$
fw	856.60	647.48
temp/K	120(2)	120(2)
cryst syst	monoclinic	monoclinic
space group	$P2/n$	$P2_1/c$
a/Å	13.8932(17)	18.436(4)
b/Å	7.3216(9)	16.567(3)
c/Å	18.572(3)	20.034(5)
β/deg	98.415(3)	114.4158(7)
V/Å^3	1868.8(4)	5572(2)
Z	2	8
d_{calcd}/g cm^{-3}	1.522	1.544
unique reflns	11 729	12 690
R indices [$I > 2\sigma(I)$]	0.0377	0.0354
R indices (all data)	0.1047	0.0956
GOF	1.064	1.044

Chart 2. Five Possible Geometrical Isomers of the Dihydrophosphate Bearing Two Martin Ligands[a]



[a]Numbers in parentheses are relative energies (kcal mol^{-1}) calculated at the MP2/6-31+G(d,p)//B3PW91/6-31+G(d,p) level.

1a-TPP show C_2 symmetry for their anion moiety. Therefore, both of the crystallographically symmetric bonds of the P−H, P−O, and P−C bonds in **1a-TPP** naturally show the same length, whereas they do not in **1b-TEA**. For example, both of the P−H bond lengths of **1a-TPP** are 1.354(18) Å, whereas the P−H bond lengths of **1b-TEA** are 1.382(16) and 1.318(14) Å.

The ^{1}H, ^{13}C, ^{19}F, and ^{31}P NMR spectra (DMSO-d_6) of **1b-TEA** indicate that it has the same structure as that in the crystalline state, as described below. In the ^{31}P NMR spectrum, **1b-TEA** showed a doublet of doublets at δ_P −177.7 ppm with two nonequivalent coupling constants between the ^{31}P and the ^{1}H nuclei ($^1J_{PH}$ = 661, 319 Hz) while **1a-TEA** showed a triplet at δ_P −169.1 ppm ($^1J_{PH}$ = 343 Hz). Both signals in the very high field region indicated the hexacoordinated state of both phosphorus atoms in solution. Observation of the aforementioned nonequivalence in coupling constants of **1b-TEA** as well as two signals due to two nonequivalent protons (δ 6.85, 7.13 ppm) in the ^{1}H NMR spectrum supported a **1b**$^-$ structure among the five possible geometrical isomers, **1a**$^-$−**1e**$^-$, for the present hexacoordinated phosphate anion (Chart 2). The four other isomers do not correspond to the observations because their two protons binding to the phosphorus atom are equivalent in **1a**$^-$ and **1c**$^-$−**1e**$^-$. In addition, the **1b**$^-$ structure of **1b-TEA** was supported by observation of four quartets of nonequivalent trifluoromethyl groups in both the ^{13}C and the ^{19}F NMR spectra.

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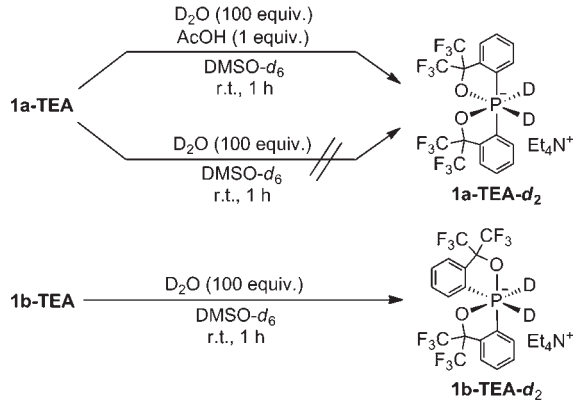
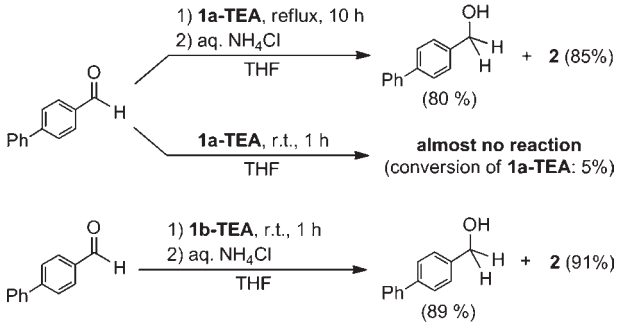
Scheme 2. H−D Exchange Reaction of 1a-TEA and 1b-TEA



Scheme 3. Hydride Reduction of an Aldehyde Using 1a-TEA or 1b-TEA as a Hydride Donor



Dihydrophosphate **1b-TEA**, a geometrical isomer of **1a-TEA**, is expected to have different reactivities from those of **1a-TEA**. As we already reported, treatment of **1a-TEA** with deuterium oxide in the presence of acetic acid gave deuterated phosphate **1a-TEA-d_2**, showing its proton-exchange reactivity.[4] Deuteration did not occur at all without such an acid. In contrast, **1b-TEA** was deuterated by treatment with deuterium oxide alone (Scheme 2). Hence, the geometrical isomerism was found to affect the reactivity of the proton exchange because deuteration of **1b-TEA** occurred much more easily than that of **1a-TEA**. This is a remarkable reactivity, because organophosphorus compounds with a P−H bond scarcely exchange the hydrogen as a proton with neutral water because of their weak acidity and basicity,[8] whereas many alcohols and amines easily exchange their protons with water.

Another important reactivity of **1a-TEA** was its hydride-reducing capability. In the case of reduction of 4-phenylbenzaldehyde to the corresponding alcohol using **1a-TEA** as a hydride donor, the reaction was completed after refluxing for 10 h in THF, while the reaction at room temperature for 1 h resulted in almost no reaction (only 5% conversion) (Scheme 3). However, a similar reaction using **1b-TEA** as a hydride donor was completed under much milder conditions (1 h at room temperature), and the alcohol product was obtained in a good yield (89%). Therefore, **1b-TEA** turned out to be more reactive in both proton exchange and hydride donation than its geometrical isomer, **1a-TEA**.

There are two requirements to achieve the umpolung of water by using the dihydrophosphate. First, a hydrogen atom of water has to be exchanged as a proton with hydrogens on the phosphorus of the phosphate, and second, the P−H groups of the phosphate have to show hydridic reactivity. Because the dihydrophosphate **1b-TEA** was found to satisfy both of these requirements, it was subjected to successive reactions without any separation process to demonstrate its utility for the umpolung. A one-pot reaction of the H−D exchange from **1b-TEA** to **1b-TEA-d_2** using D_2O followed by reduction of 4-PhC_6H_4CHO proceeded successfully at room temperature in DMSO without any additive to give the deuterated alcohol (76% yield, 94% D) and hydrophosphorane **2** (91%) (Scheme 4), while the one-pot reaction using **1a-TEA** needed addition of acetic acid.[4] The one-pot reaction using a ketone and **1b-TEA** similarly proceeded without any additive, although the yield and D content declined to some extent.

Scheme 4. One-Pot Reaction

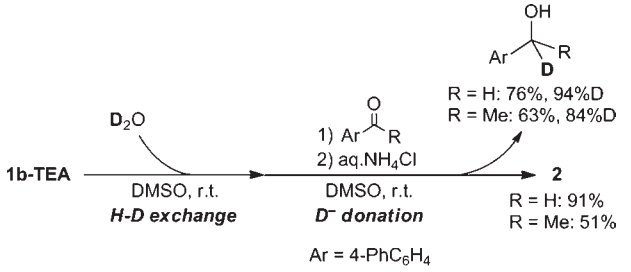
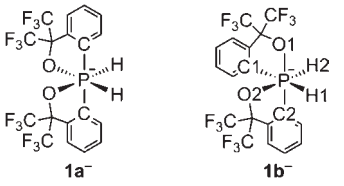


Table 2. Calculated Atomic Charges (q) and P−H and P−C Coupling Constants (J)



	q_P	q_O	q_C [a]	q_H [a]	J_{PC} (Hz) [a]	J_{PH} (Hz) [a]
1a⁻	1.54	−0.90	−0.31	**−0.13**	115	**260**
1b⁻	1.55	−0.89 (O1)	−0.30 (C1)	−0.07 (H1)	123 (P−C1)	576 (P−H1)
		−0.90 (O2)	**−0.35** (C2)	**−0.14** (H2)	**13** (P−C2)	**231** (P−H2)

[a] The bold numbers are the values for the nuclei located at the position trans to the oxygen atoms.

The difference in the reactivities of the P−H bond between these geometrical isomers should be explained by the physical properties of each isomer, such as atomic charges of the hydrogen atoms. Atomic charges (q) and coupling constants (J) of the phosphate anions **1a**$^-$ and **1b**$^-$, which are the anionic parts of **1a-TEA** and **1b-TEA**, respectively, were calculated at the MP2/6-31+G(d,p)//B3PW91/6-31+G(d,p) level for atomic charge and B3PW91/6-31+G(d,p) level for coupling constants (Table 2).[9] The calculated atomic charges of the central phosphorus atoms (q_P) of **1a**$^-$ and **1b**$^-$ were almost the same. However, the negative charges of the hydrogen atoms of **1a**$^-$ (−0.13) and of the H2 atom of **1b**$^-$ (−0.14) were somewhat larger than that of the H1 atom of **1b**$^-$ (−0.07). The hydrogen atoms with relatively high negative charges are located at the positions trans to the oxygen atoms. Similarly, the coupling constants were also influenced by the atoms located at the trans positions. The calculated P−H

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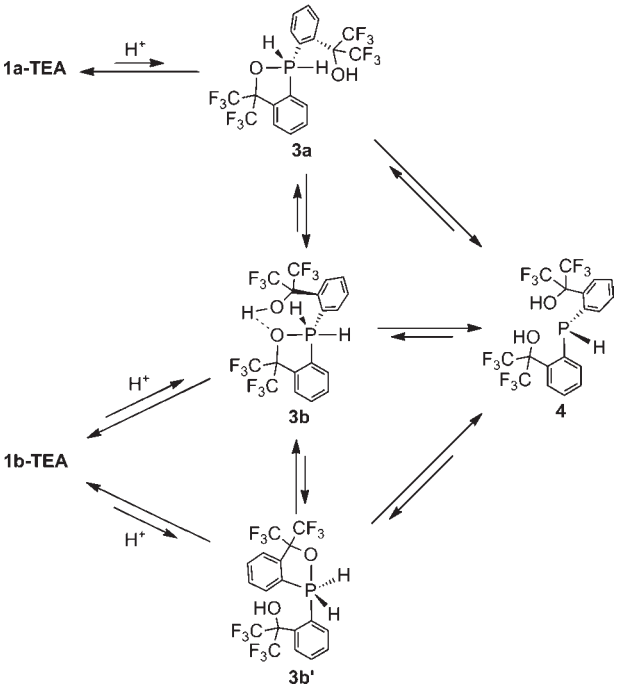
coupling constants of **1a**$^-$ (260 Hz) and the P−H2 coupling constant (trans to oxygen) of **1b**$^-$ (231 Hz) were also much smaller than the P−H1 coupling constant (576 Hz) of **1b**$^-$ (trans to carbon). These tendencies were also found in the experimental values from the NMR measurements (**1a-TEA**, $^1J_{PH}$ = 342 Hz; **1b-TEA**, $^1J_{PH}$ = 319, 661 Hz), although the calculated values were somewhat smaller than the experimental values. These results clearly indicate the strong influence of oxygen atoms on the atomic charges of the hydrogen atoms at the trans positions and the coupling constants between the hydrogen and the phosphorus nuclei. This is also true for atomic charges of the carbon atoms and the P−C coupling constants, as shown in Table 2.

The difference in the physical properties of each isomer reflects the stability. The relative stabilities of all five conceivable geometrical isomers of the dihydrophosphate bearing two Martin ligands were calculated at the MP2/6-31+G(d,p)//B3PW91/6-31+G(d,p) level. The most stable isomer, **1a**$^-$, corresponds to the anion moiety of **1a-TEA** (Chart 2). Isomer **1a**$^-$ was calculated to be 1.95 kcal/mol more stable than **1b**$^-$. The newly isolated isomer **1b-TEA** corresponds to the second stable isomer. Consideration of the solvation effect was expected to provide a reason for the formation of **1b-TEA** by changing the solvent in the synthetic procedures. Single-point calculations on **1a**$^-$ and **1b**$^-$ using the integral equation formalism−polarizable continuum model (IEFPCM) method[10] were carried out to estimate effects of the solvation of each isomer by THF and diethyl ether, which were used for the syntheses, on the relative energies. Isomer **1a**$^-$ was calculated to be 1.32 and 1.44 kcal/mol more stable than **1b**$^-$ in THF and diethyl ether, respectively. Therefore, selective isolation of the products cannot be explained by solvation only, and any stronger interaction with the phosphates must be taken into account to explain formation of **1b-TEA**. Judging from the experimental procedure for the synthesis of **1a-TEA** and **1b-TEA**, phosphates **1a**$^-$ and **1b**$^-$ must exist as lithium salts with some molecules of water used for workup before the cation exchange. Therefore, we carried out calculations of complexes **1a-Li−OH$_2$** or **1b-Li−OH$_2$**, which are composed of a lithium cation, one water molecule, and **1a**$^-$ or **1b**$^-$, respectively, at the MP2/6-31+G(d,p)//B3PW91/6-31+G(d,p) level and found that **1b-Li−OH$_2$** is 2.06 kcal/mol more stable than **1a-Li−OH$_2$**.[11] Thus, interaction with the lithium cation is considered to invert the relative stability of **1a**$^-$ and **1b**$^-$. When the solvation was considered using the IEFPCM method, **1b-Li−OH$_2$** was more stable than **1a-Li−OH$_2$** in both THF and diethyl ether.[11] Lithium salt **1b-Li−OH$_2$** prefers to exist as a contact ion pair in diethyl ether and, following cation exchange, would give **1b-TEA**. In THF, the phosphate would behave as a free anion rather than the contact ion pair because THF strongly solvates the lithium cation. Therefore, formation of the more stable **1a**$^-$ would be favored in THF.

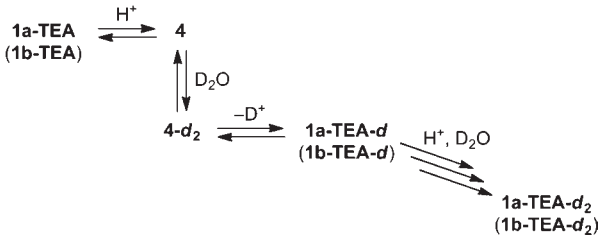
Quantitative isomerization of **1b-TEA** to **1a-TEA** occurred within 10 min after dissolving it in methanol. The reverse reaction was not observed. Therefore, **1b-TEA** is less stable than **1a-TEA** in methanol, consistent with the above calculations on free anions. In addition, the rate of isomerization was strongly dependent on the solvent used: No detectable isomerization occurred in either anhydrous THF or DMSO for 1 h. The active proton of methanol would assist the isomerization (see below).

The experimental results indicate that active protons play an important role in the isomerization. Protonation of **1a-TEA** gives dihydrophosphorane **3a**, which undergoes tautomerization

Scheme 5. Plausible Mechanism of Isomerization from 1b-TEA to 1a-TEA in a Protic Solvent



Scheme 6. Plausible Mechanism for the H−D Exchange Reaction of 1a-TEA or 1b-TEA



to afford phosphine **4** (Scheme 5). Similarly, the isomer **1b-TEA** would afford **3b** and **3b′** by protonation at the oxygen atoms trans to the carbon and hydrogen atoms, respectively, and their tautomerization also gives phosphine **4**. Isomerization from **1b-TEA** to **1a-TEA** in a protic solvent such as methanol would proceed via pseudorotation and/or tautomerization among these protonated intermediates.

Considering the calculated negative charge of the hydrogen atoms of **1a**$^-$ and **1b**$^-$, it is reasonable to suppose a reaction mechanism involving interconversion of the P−H moiety to an O−H moiety in the proton-exchange reactions of **1a-TEA** and **1b-TEA**. During the process from **1a-TEA** or **1b-TEA** to **4**, one of the hydrogen atoms on the phosphorus migrates to the oxygen by protonation, being protic and exchangeable for water. Therefore, the equilibration between **1a-TEA** or **1b-TEA** and **4** in the presence of D_2O allows deuteration of both dihydrophosphates **1a-TEA** and **1b-TEA** (Scheme 6). However, the H−D exchange experiments showed a difference in the exchange reactivity between **1a-TEA** and **1b-TEA**. To elucidate the reason for the difference, the relative energies of **3a**, **3b**, **3b′**, and **4** were studied

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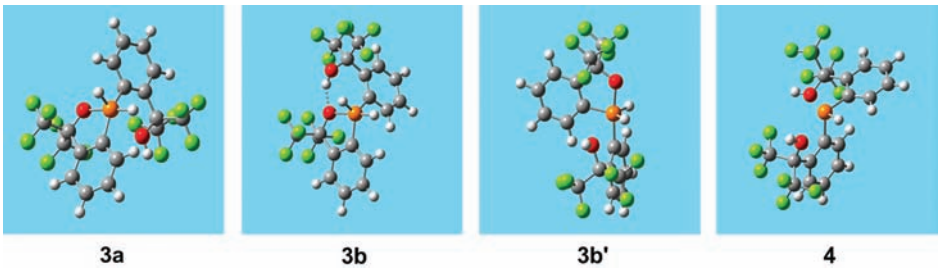


Figure 2. Optimized structures of **3a**, **3b**, **3b′**, and **4** at the MP2/6-31+G(d,p)//B3PW91/6-31+G(d,p) level: orange, phosphorus; red, oxygen; gray, carbon; green, fluorine; white, hydrogen.

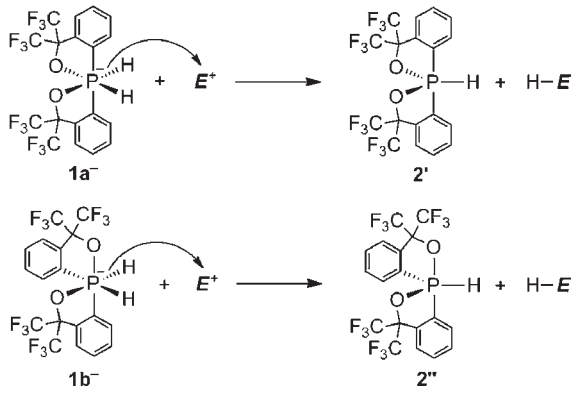
Table 3. Calculated Relative Energies (kcal mol^{-1}) of 3a, 3b, 3b′, and 4 at the MP2/6-31+G(d,p)//B3PW91/6-31+G(d,p) Level Using the IEFPCM Method

solvent	3a	3b	3b′	4
none	+3.41	0	+2.44	+1.50
DMSO	+6.17	+3.49	+2.62	0
MeOH	+4.50	+2.75	+3.60	0

by calculations at the MP2/6-31+G(d,p)//B3PW91/6-31+G(d,p) level as free molecules and as solvated molecules using the IEFPCM method considering solvation by DMSO and methanol (Figure 2). Phosphorane **3b**, the protonated form of **1b**$^-$, was calculated to be 3.41 kcal/mol more stable without solvation than **3a**, the protonated form of **1a**$^-$ (Table 3). The calculated structure of **3a** indicated distortion from the idealized trigonal bipyramidal structure, as indicated by the wide C−P−C angle (143°). The calculated structure of **3b** did not show such a distortion, and **3b** had a hydrogen bond between the OH group and the other oxygen atom. Phosphorane **3b′**, another protonated form of **1b**$^-$, was calculated to be 0.97 kcal/mol more stable than **3a**, because **3b′** adopted the more stable C-apical conformation without distortion. Both **3b** and **3b′** were calculated to be more stable than **3a** in the cases of solvation by DMSO and methanol, although the relative energies were different. In addition, **1b**$^-$ was less stable than **1a**$^-$, as described above. Comparison of the calculated relative energies of both the dihydrophosphates and the intermediate phosphoranes indicates that protonation of **1b**$^-$ is easier than that of **1a**$^-$. Therefore, it can be reasonably understood that proton exchange of **1a-TEA** required assistance of a relatively strong acid, acetic acid, while the similar reaction of **1b-TEA** proceeded without assistance from such an acid. In addition, the higher energy barrier of more than 6.17 kcal mol^{-1}, the energy difference from **4** to **3a**, would inhibit isomerization of **1b-TEA** to **1a-TEA** in DMSO, and only the H−D exchange reaction of **1b-TEA** proceeded without isomerization. In methanol, the difference in the energy barriers from **4** to **3a** and to **3b** or **3b′** is expected to be smaller. In addition, protonation of **1b**$^-$ in methanol is easier than in DMSO with a small amount of water, because the proton activity in methanol should be higher than that in the latter system, judging from the comparison of the pK_a values of MeOH (15.50) and water in DMSO (31.4).[12] Thus, isomerization from **1b-TEA** to **1a-TEA** in methanol occurred easily, although isomerization was not observed in DMSO with a small amount of D_2O during the H−D exchange reaction.

The differences in the reactivities of the hydride reduction of **1a-TEA** and **1b-TEA** are interpreted as follows. In the hydride reduction, the higher reactivity of **1b-TEA** than **1a-TEA** can be explained by the higher hydride-donating ability of **1b-TEA** compared with **1a-TEA**. The hydride-donating ability is suggested by the negative atomic charge of one hydrogen atom of **1b-TEA** (−0.14) being higher than that of **1a-TEA** (−0.13) (Table 2), although the difference is small. In addition, it is clearly reflected by the s character of the P−H bond. Judging from the fact that one of the P−H coupling constants J_{PH} of **1b-TEA** ($^1J_{PH}$ = 319 Hz) is smaller than that of **1a-TEA** ($^1J_{PH}$ = 342 Hz), the s character of the corresponding P−H bond of **1b-TEA** is smaller than that of **1a-TEA**. As a result, the hydridicity increases to produce the higher hydride-donating ability of **1b-TEA**.[13] From the viewpoint of the reverse relationship between the hydride-donating ability and the P−H coupling constant, it is reasonable that other previously reported hydrophosphates and dihydrophosphates with larger P−H coupling constants than **1a-TEA** and **1b-TEA**, such as F_5PH^- ($^1J_{PH}$ = 955 Hz),[14a] $F_4PH_2^-$ ($^1J_{PH}$ = 936 Hz),[14b] $Ph_4PH_2^-$ ($^1J_{PH}$ = 446 Hz),[14c] and $CH_3PF_4H^-$ ($^1J_{PH}$ = 966 Hz),[14d] have not been used as hydride donors.

Scheme 7. Plausible Reaction Mechanism of Hydride Donation from 1a$^-$ or 1b$^-$ to an Electrophile (E$^+$)



Another factor affecting the hydride-donation reaction rate would be the stability of intermediate products of the hydride donation. The intermediate products of **1a-TEA** and **1b-TEA** would be pentacoordinated phosphoranes **2′** and **2″**, respectively, which are unstable isomers of **2** (Scheme 7). They would give **2** under the reaction conditions. Phosphorane **2″** is considered to be more stable than **2′** because it has an oxygen atom at the apical position,[15] and therefore, **1b-TEA** would work as a more active hydride donor.

CONCLUSION

In summary, we synthesized and isolated a metastable geometrical isomer of a hexacoordinated dihydrophosphate and

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investigated its properties and reactivities. The newly synthesized dihydrophosphate **1b-TEA** showed higher reactivity for both proton exchange and hydride reduction, which are essential to achieve umpolung of a hydrogen atom of water, than **1a-TEA**. The two reactivities, proton exchange and hydride reduction, are usually thought to be opposite reactivities based on the opposite polarity of a hydrogen atom, and therefore, it is intriguing that both reactivities can be controlled by geometrical isomerism in this case. Demonstration of reactivity differences by taking advantage of the geometrical isomerism of hexacoordinated phosphorus species is important for phosphorus chemistry, in which the geometrical isomerism of pentacoordinated phosphorus species in particular has been studied. The higher reactivities of **1b-TEA** are explained by the larger negative charge of the hydrogen atom and higher stability of the reaction intermediate, with both changes caused by differences in the spatial arrangement of the ligands of **1a-TEA** and **1b-TEA**. The enhanced reactivities of **1b-TEA** enabled one-pot deuteration of an aldehyde and a ketone with D_2O at room temperature without any additive. This reductive deuteration of carbonyl compounds under mild conditions will be useful for isotope labeling of some compounds that are intolerant to acidic or basic conditions and thermal conditions.

EXPERIMENTAL SECTION

General Procedure. Solvents were dried and purified before use by an MBRAUN MB-SPS solvent purification system. All reactions were carried out under argon atmosphere. All NMR spectra were measured with a JEOL AL400 spectrometer. Tetramethylsilane was used as an external standard for ^{1}H (400 MHz) and ^{13}C NMR (100 MHz) spectra. CF_3CO_2H (δ −77.7 ppm) and 85% H_3PO_4 were used as external standards for ^{19}F (376 MHz) and ^{31}P NMR (202 MHz) spectra, respectively. FAB-mass spectral data were obtained on a JEOL JMS-700P. Infrared (IR) spectra were recorded on a JASCO FT/IR-420. Melting points were recorded with a Yanaco micromelting point apparatus and uncorrected. Elemental analyses were performed by the Microanalytical Laboratory of Department of Chemistry, Faculty of Science, The University of Tokyo.

Caution: Contact with skin and eyes of hexafluorocumyl alcohol, a reagent used for the synthesis of hydrophosphorane ***2****, and inhalation of its vapor or mist should be avoided. Dihydrophosphates* ***1a-TPP*** *and* ***1b-TEA*** *should be handled carefully because such organophosphorus compounds are potentially toxic.*

Dihydrophosphate 1b-TEA. A diethyl ether solution (20 mL) of phosphorane **2** (1.03 g, 2.0 mmol) was added to lithium aluminum hydride (0.15 g, 4.0 mmol) at room temperature. After stirring for 1 h, the reaction mixture was cooled to 0 °C and slowly quenched with water (1 mL). After stirring for 30 min, the reaction mixture was filtered and the residue was washed with diethyl ether (3 × 10 mL). The combined filtrate and washings were evaporated to give a colorless solid. The solid was redissolved in diethyl ether and evaporated again, and the process was repeated two times. The resulting solid was dissolved in dimethyl sulfoxide (20 mL), and a dimethyl sulfoxide solution (20 mL) of tetraethylammonium bromide (0.63 g, 3.0 mmol) was added to the solution. Water (10 mL) was slowly added to the reaction mixture with cooling by a water bath to generate a colorless solid. The resulting solid was filtered and washed with water and chloroform. Recrystallization of the solid from acetone/ether gave dihydrophosphate **1b-TEA** (0.56 g, 43%). Colorless crystals, mp 107−109 °C (decomp). ^{1}H NMR (400 MHz, DMSO-d_6) δ 1.15 (tt, $^3J_{HH}$ = 7.3 Hz, $^3J_{NH}$ = 1.7 Hz, 12H), 3.19 (q, $^3J_{HH}$ = 7.3 Hz, 8H), 6.00−6.09 (m, 1H), 6.85 (dd, $^1J_{PH}$ = 318.7 Hz, $^2J_{HH}$ = 20.8 Hz, 1H), 6.88−6.95 (m, 1H), 7.03−7.09 (m, 1H), 7.13 (dd, $^1J_{PH}$ = 661.4 Hz, $^2J_{HH}$ = 20.8 Hz, 1H), 7.21−7.28 (m, 1H), 7.38−7.57 (m, 4H). ^{13}C{^{1}H} NMR (101 MHz, DMSO-d_6) δ 7.2 (s), 51.6 (t, $^1J_{NC}$ = 3 Hz), 75.9 (sept, $^2J_{CF}$ = 29 Hz), 81.4 (sept, $^2J_{CF}$ = 28 Hz), 123.6 (d, J_{PC} = 15 Hz), 123.8 (q, $^1J_{CF}$ = 287 Hz), 124.0 (q, $^1J_{CF}$ = 288 Hz), 124.2 (q, $^1J_{CF}$ = 289 Hz), 124.5 (q, $^1J_{CF}$ = 291 Hz), 124.8 (d, J_{PC} = 8 Hz), 125.3 (d, J_{PC} = 17 Hz), 125.9 (d, J_{PC} = 2 Hz), 127.1−127.5 (m), 128.0 (d, J_{PC} = 16 Hz), 128.3−128.5 (m), 132.5 (d, J_{PC} = 16 Hz), 150.1 (d, J_{PC} = 53 Hz), 152.6 (d, J_{PC} = 167 Hz). ^{19}F NMR (376 MHz, DMSO-d_6) δ −76.22 to −76.07 (br, 3F), −76.85 (q, $^4J_{FF}$ = 9.2 Hz, 3F), −75.54 (q, $^4J_{FF}$ = 9.5 Hz, 3F), −75.00 (q, $^4J_{FF}$ = 9.2 Hz, 3F). ^{31}P NMR (162 MHz, DMSO-d_6) δ −177.7 (dd, $^1J_{PH}$ = 661.4, 318.7 Hz); IR (KBr, cm^{-1}) 2078, 2205 (P−H). Anal. Calcd for $C_{26}H_{30}F_{12}NO_2P$: C, 48.23; H, 4.67; N, 2.16. Found: C, 47.97; H, 4.77; N, 1.98.

H−D Exchange Experiments of Dihydrophosphate 1b-TEA with D_2O. Deuterium oxide (0.02 mL, 1.1 mmol) was added to a DMSO-d_6 solution (0.5 mL) of **1b-TEA** (6.5 mg, 0.010 mmol). After standing the reaction mixture for 30 min at room temperature, its ^{1}H, ^{19}F, and ^{31}P NMR spectra showed signals due to dihydro-d_2-phosphate **1b-TEA-*d*$_2$** (96%, 97%D, estimated by ^{1}H spectroscopy).

Reduction of Carbonyl Compounds with Dihydrophosphate 1b-TEA. A mixture of **1b-TEA** (130 mg, 0.20 mmol) and 4-phenylbenzaldehyde (37 mg, 0.20 mmol) was dissolved in THF (5 mL) and stirred for 1 h. ^{19}F NMR monitoring showed that consumption of **1b-TEA** was more than 90%. After addition of an aqueous solution of ammonium chloride, extraction with diethyl ether and evaporation gave a crude solid. The solid was separated by silica-gel chromatography to give **2** (94 mg, 91%) and 4-phenylbenzyl alcohol (33 mg, 89%). The products were identified by comparison of the data of ^{1}H NMR, GC-MS, and TLC with those of authentic samples.

Attempted Reduction of 4-Phenylbenzaldehyde with Dihydrophosphate 1a-TEA. A mixture of **1a-TEA** (130 mg, 0.20 mmol) and 4-phenylbenzaldehyde (37 mg, 0.20 mmol) was dissolved in THF (5 mL) and stirred for 1 h. ^{19}F NMR monitoring showed that consumption of **1a-TEA** was 5%.

One-Pot Reaction of the H−D Exchange of Dihydrophosphate 1b-TEA and Reduction of Cabonyl Compounds. *4-Phenylbenzaldehyde.* Deuterium oxide (0.4 mL, 22 mmol) was added to a DMSO solution (5 mL) of **1b-TEA** (130 mg, 0.20 mmol) at room temperature. After stirring for 30 min, a DMSO solution (2 mL) of 4-phenylbenzaldehyde (37 mg, 0.20 mmol) was added to it, and the reaction mixture was stirred for 2 h at room temperature. After addition of an aqueous solution of ammonium chloride, extraction with hexane and evaporation gave a crude solid. The solid was separated by silica-gel chromatography to give **2** (94 mg, 91%) and α-*d*-4-biphenylmethanol (28 mg, 76%, 94%D).

4-Acetylbiphenyl. After H−D exchange using deuterium oxide (0.4 mL, 22 mmol) and **1b-TEA** (130 mg, 0.22 mmol) in DMSO (5 mL), a DMSO solution (2 mL) of 4-acetylbiphenyl (39 mg, 0.20 mmol) was added to the solution and the reaction mixture was stirred for 50 h at room temperature. The above workup and chromatography gave α-*d*-1-biphenylethanol (25 mg, 63%, 84%D) together with **2** (53 mg, 51%).

X-ray Crystallographic Analysis. Colorless single crystals of **1a-TPP** and **1b-TEA** were obtained by recrystallization from CH_2Cl_2 and used for X-ray diffraction data collection on a Rigaku Mercury charge-coupled device diffractometer with a graphite-monochromated Mo Kα radiation. Data were collected and processed using CrystalClear (Rigaku). Data were corrected for Lorentz and polarization effects. The structures were solved by direct methods (SHELXS-97) and expanded using Fourier techniques.[16] The non-hydrogen atoms were refined anisotropically. The hydrogen atoms at the benzene rings of **1a-TPP** and **1b-TEA** and ethyl groups of **1b-TEA** were assigned by calculation and refined isotropically by using a riding model. The hydrogen atoms at the phosphorus atom of **1a-TPP** and **1b-TEA** were assigned by Fourier method and freely refined isotropically. Crystal data are summarized in

Table 1. More crystal data are available at the Cambridge Crystallographic Data Centre, deposition nos. CCDC 729102 (**1a-TPP**) and CCDC 814230 (**1b-TEA**).

Theoretical Calculation. Geometries of phosphate anions **1a**$^-$−**1e**$^-$, lithium phosphate **1a-Li**−**OH$_2$** and **1b-Li**−**OH$_2$**, dihydrophosphoranes **3a**, **3b**, and **3b′**, and phosphine **4** were fully optimized with density functional theory at the B3PW91/6-31+G(d,p) level, and single-point calculation was performed at the MP2/6-31+G(d,p) level using the GAUSSIAN 03 suite of programs.[9] The solvent was taken into account using the IEFPCM method.[10] The Cartesian coordinates in their optimized geometries are shown in Tables S1−S11 in the Supporting Information. Calculated atomic charges and P−H and P−C coupling constants are shown in Table S12, Supporting Information. Calculated relative energies using the IEFPCM method are shown in Tables S13 and S14, Supporting Information.

■ ASSOCIATED CONTENT

Supporting Information. X-ray crystallographic data of **1a-TPP** and **1b-TEA** in cif format; spectral data of **1b-TEA** and theoretical calculation data for phosphate anions **1a**$^-$−**1e**$^-$, lithium phosphate **1a-Li**−**OH$_2$** and **1b-Li**−**OH$_2$**, dihydrophosphoranes **3a**, **3b**, and **3b′**, and phosphine **4**. This material is available free of charge via the Internet at http://pubs.acs.org.

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