

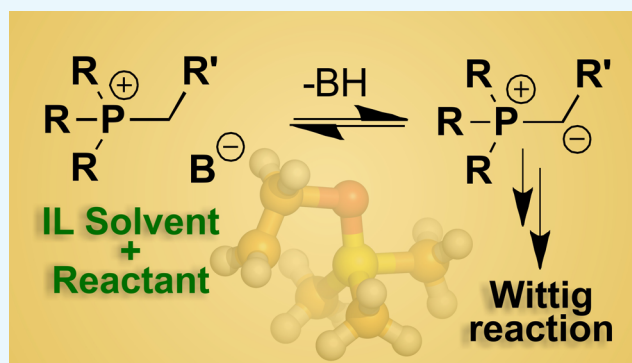
Basic Phosphonium Ionic Liquids as Wittig Reagents

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S Supporting Information

ABSTRACT: The possibility of designing a solvent/reagent for Wittig reactions from basic phosphonium salts is explored theoretically. In the suggested $R_4P^+PhO^-$ and $Ph_3PR^+PhO^-$ ionic liquids (ILs), the phenolate anion is prone to remove the α -proton from the alkyl chains, forming a phosphorous ylide. Significant hydrogen bonding between the oxygen atoms of the anions and α -hydrogen atoms of the cations were found by molecular dynamics simulations of these substances; therefore, proton transfer between the two ions is inherently supported by the structure of the liquid as well. The subsequent steps of the Wittig reaction from the phosphorous ylide were also found to be energetically possible. The mesoscopic structure of these materials exhibits a significant segregation into polar and nonpolar domains, which may also allow an easy dissolution of the substrates. The formation of a pentacoordinated phosphorous derivative through P–O bond formation was found to be also possible in the gas phase for both kind of compounds. Accordingly, having such basic anions in phosphonium-based ILs may produce such a neutral and therefore volatile species, which may hold further significant applications for these solvents in ion-exchange and separation techniques and in synthesis.



INTRODUCTION

The Wittig reaction continues to be of high importance in organic syntheses,^{1–5} as it is a convenient and versatile method for forming C=C double bonds, in many cases with good to excellent stereoselectivity. Among the many possible solvents that were applied in such reactions, ionic liquids (ILs) have shown great potential,^{6,7} similar to that in other catalytic transformations.^{8–10} The main advantage of using such an ionic solvent in Wittig reactions was the easier separation of the alkene and the phosphine oxide side product, whereas the reuse of the solvent was also found to be more efficient.⁶

Regarding the connection between Wittig reactions and ILs it is important to point out some of the chemical similarities between the related compounds. As shown in Figure 1, the Wittig reaction is initiated by the deprotonation of a suitable quaternary phosphonium cation at its α -position and the thereby formed phosphorous ylide reacts with the carbonyl derivative. On the other hand, phosphonium salts are widely applied as ILs, also as solvents in synthesis.^{8–12} Indeed, it has been reported that by dissolving strong bases in phosphonium-based ILs, the cation can be deprotonated to phosphorous ylides, which was observed by nuclear magnetic resonance spectroscopy in the solution.^{13,14} In tetraalkylphosphonium-phenolate and -azolate ILs, the anion itself has a significant inherent basicity.^{15,16} Although these ILs were designed for physical absorption of CO₂, chemisorption in a small amount via an intriguing carboxylation at the α -carbon atom of the cation occurred (Figure 2).^{15,16} The presence of this product could only be explained by the spontaneous formation of

phosphorous ylides in the solution, similarly to the carbene-like reactivity of 1,3-dialkylimidazolium acetate ILs.^{17–23} The reaction has also been investigated in detail by static density functional theory (DFT) calculations, proving the feasibility of the cation's CO₂ absorption potential via the formation of phosphorous ylides.¹⁶

Accordingly, it seems possible to access the chemistry of phosphorous ylides directly from the IL solvents, including the Wittig reaction. If these reactions were available from the phosphonium ILs with basic anions, then during the application of these solvents as absorbents for CO₂ the presence of carbonyl derivatives is necessary to avoid to prevent the degradation of the liquid. This is especially important to consider in the treatment of waste gases with incomplete combustion, in which partially oxidized carbon derivatives, such as aldehydes or ketones can be present. Thus, for CO₂ absorption processes, the potential of the solvent to undergo a Wittig reaction must be characterized.

Even more importantly, exploiting this chemical relationship between the Wittig reagents and ILs might allow the combination of the advantageous properties of these two chemistries, wherein the use of the reagent also as a solvent can, if the counterions are properly chosen, enable a greener process. In such an attempt, the use of an inherently basic IL shows clear advantages because the need for an external base,

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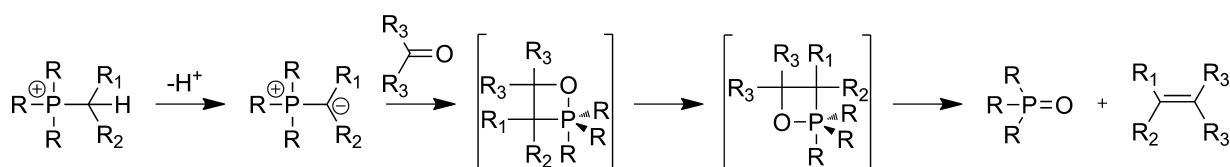


Figure 1. Mechanism of the Wittig reaction. For the sake of clarity, the possible stereochemical issues are omitted.

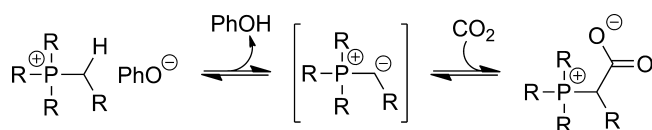


Figure 2. Chemical CO_2 absorption by the cation in $[\text{P}_{66614}][\text{PhO}]$ and $[\text{P}_{66614}][2\text{-CNPy}]$ ILs.^{15,16} The product suggests the involvement of the ylide, which was later proven by DFT calculations.¹⁶

and therefore an extra component in the synthesis can be also avoided. The aforementioned family of phosphonium-phenoate and -imidazolidine ILs could be an ideal choice for designing Wittig reagent solvents as a synthetically already available starting point.

The generally used tetraalkylphosphonium ILs that are substituted with more than one kind of side chain on the phosphorous can provide more than one possible product, which should be avoided in an efficient synthetic approach. This obstacle can be, however, easily overcome by employing phosphonium salts with four equivalent alkyl chains on the phosphorous atom. Another possible approach is to derive the IL cation from triphenylphosphine through alkylation, resulting in the most widely applied Wittig reagent, alkyl-triphenylphosphonium salts. Alkyl-triphenylphosphonium tosylate ILs have been investigated^{24,25} and were found to be excellent reaction media for hydroformylation reactions.²⁵ Moreover, alkyl-triphenylphosphonium cations are generally preferred for Wittig reactions as well, offering also the lack of variance in the possible products because there is only one transferable group at the phosphorous atom. Thus, while having the aforementioned advantageous solvent properties, the reactivity of these compounds is also promising for the present purposes.

In this theoretical contribution, we evaluate whether basic phosphonium-salt ILs can undergo a Wittig reaction, which might result in an efficient, solventless synthetic pathway for this synthetically highly important chemical transformation,

whereas the information gathered here also provides a better understanding on the analogous ILs used as CO_2 absorbents. To this end, according to the discussion above, we will investigate two groups of compounds: $\text{R}_4\text{P}^+\text{OPh}^-$ and $\text{Ph}_3\text{PR}^+\text{OPh}^-$ ILs, wherein R is ethyl, butyl, hexyl, or octyl. We will assess the reactivity of these ILs in the Wittig reactions by exploring the corresponding reaction energy profiles, and we will also characterize their liquid properties, providing a more detailed, multiscalar view on the structure of these ILs.

RESULTS AND DISCUSSION

To design an IL solvent that is a precursor and base in the Wittig reaction, one must assess the possibility of a proton transfer, feasibility of the reaction with different substrates, and also liquid structure and dynamics. First, the proton transfer was investigated by static quantum chemical calculations on an ion pair of each IL in a solvent model. To avoid the high number of conformations, and to allow the highly accurate coupled cluster calculations, the nonreacting aliphatic side chains were substituted by methyl groups, whereas the alkyl group that is directly involved in the proton transfer and Wittig reaction was modeled by a methyl and an ethyl group. Because the spectator alkyl substituents are far from the reaction site, the effect of this simplification should be minimal. Similarly, the electronic effect of the methyl group on the reacting methylene moiety should not be very different from that of the longer side chains, and therefore the present models will provide realistic results.

Interestingly, all of the investigated IL ion pairs can rearrange in a manner that a bond is formed between the phosphorous and oxygen atoms, forming a pentacoordinated phosphorous derivative. Such structures have not yet been observed in the ILs. The formation of this species is driven by the strength of the P-O bond and in the gas phase also by a decrease in the dipole moment, which sums up to a significant stabilization of 20–30 kJ mol^{-1} (Table 1). Clearly, the decrease in polarity will

Table 1. DLPNO-CCSD(T)/CBS//B3LYP-D3(BJ)/def2-TZVPP Gibbs Free Energies (in kJ mol^{-1}) at 298.15 K in the Different Media for the Formation of Phosphorous Ylide, As Shown in Figure 3^a

	medium	1	2	$\text{TS}_{2 \rightarrow 3}$	3	4	4'
$\text{Me}_4\text{P}^+\text{PhO}^-$	gas phase	−27.9	0.0	10.5	0.2	−20.8	
$\text{Me}_3\text{PEt}^+\text{PhO}^-$	gas phase	−22.7	0.0	21.3	13.0	−9.5	
$\text{Ph}_3\text{PMe}^+\text{PhO}^-$	gas phase	−28.8	0.0	8.3	−6.8	−26.7	
$\text{Ph}_3\text{PEt}^+\text{PhO}^-$	gas phase	−28.3	0.0	13.3	1.7	−22.4	
$\text{Me}_4\text{P}^+\text{PhO}^-$	THF	11.5	0.0	31.9	35.0	33.9	0.6
$\text{Me}_3\text{PEt}^+\text{PhO}^-$	THF	12.7	0.0	41.3	45.8	44.8	11.6
$\text{Ph}_3\text{PMe}^+\text{PhO}^-$	THF	−5.5	0.0	19.5	14.7	11.0	−22.2
$\text{Ph}_3\text{PEt}^+\text{PhO}^-$	THF	−4.4	0.0	26.9	24.2	17.1	−16.2
$\text{Me}_4\text{P}^+\text{PhO}^-$	IL	20.5	0.0	36.6	43.4	28.9	13.6
$\text{Me}_3\text{PEt}^+\text{PhO}^-$	IL	21.3	0.0	45.9	53.7	40.3	25.0
$\text{Ph}_3\text{PMe}^+\text{PhO}^-$	IL	−1.7	0.0	21.6	18.7	2.9	−12.2
$\text{Ph}_3\text{PEt}^+\text{PhO}^-$	IL	−1.0	0.0	29.0	27.7	8.3	−7.1

^aThe results for 420 K can be found in the Supporting Information (SI).

be energetically less favorable in an ionic^{26,27} or polar environment, and indeed, by applying a conductor-like screening model for realistic solvation (COSMO-RS) to represent tetrahydrofuran (THF) or the IL, the P–O bond formation is only slightly exothermic for the $\text{Ph}_3\text{PR}^+\text{PhO}^-$ ($\text{R} = \text{Me}, \text{Et}$) ILs and even endothermic for $\text{Me}_3\text{PR}^+\text{PhO}^-$ ($\text{R} = \text{Me}, \text{Et}$). Accordingly, in the liquid phase, the formation of the corresponding nonionic pentacoordinated phosphorous derivative is unfavorable for the R_4P^+ derivatives, but it is available in the presence of the bulky phenyl groups on the phosphorous atom, shielding the P–O bond from the apparently dissociating polar environment. Thus, these calculations indicate that the $\text{Ph}_3\text{PR}^+\text{PhO}^-$ salts are partly nonionic (Table 1).

Because ILs generally evaporate as single ion pairs,^{28–30} these results may have significant practical consequences. Because of the availability of these less polar structures in the liquid and stabilization^{31,32} of the ion pairs by the formation of these low-energy compounds in the gas phase, it might make the evaporation of the phosphonium-based ILs with basic/nucleophilic anions more facile. It would also be interesting to see whether this phenomenon could be applied in ion exchange or separation processes on the basis of the different affinities of the anions to form bonds with the phosphorous atoms.

In the ionic isomer, a hydrogen bond between the oxygen atom of the anion and the α -hydrogen atom of the cation can be observed (Figure 3). Thus, the proton that has to be mobile

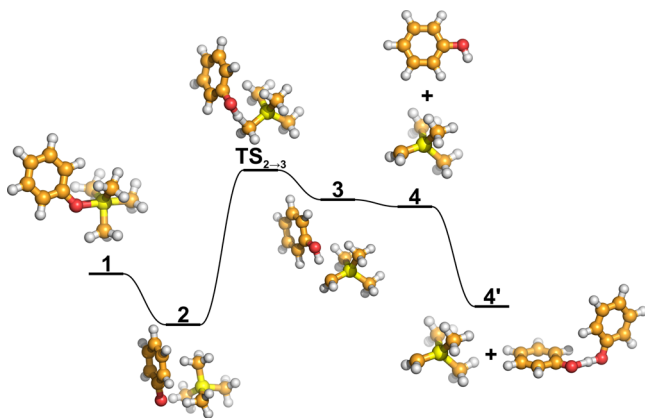


Figure 3. Numbering and ball-and-stick figures of the structures involved in the formation of phosphorous ylides from the phosphonium phenolate ILs (orange: carbon, yellow: phosphorous, red: oxygen, and white: hydrogen). For the relative Gibbs free energies at 298.15 K see Table 1, and for the data at 420 K, the SI. Please note that in the energy of the structures, 1–4, an infinitely separated PhO^- ion is also included.

for the formation of the phosphorous ylide (and hence for the Wittig reaction) is already interacting strongly with the basic anion. The proton transfer in the ionic isomer occurs via a relatively low barrier, resulting in 3. In 3, a hydrogen bond is present between the phosphorous ylide and phenol. In agreement with the trends in proton affinities of the corresponding ylides,^{33,34} the relative energy of this structure varies significantly with the substituents on the phosphorous: The presence of the phenyl groups stabilizes the ylide–PhOH complex compared with the ion pair, whereas the exchange of a hydrogen atom at the P-CH_2^- unit to a methyl group destabilizes the ylide–PhOH hydrogen-bonded assembly.

The Wittig reaction requires a bond formation between the carbon atom of the ylide and the carbonyl derivative substrate; therefore, the hydrogen bond donor phenol is clearly hindering the reaction. Accordingly, the reaction requires the dissociation of 3 into the free ylide and phenol. Despite the high basicity of the ylide and its related high hydrogen bond acceptor strength, the dissociation is exothermic (ca. -10 – 30 kJ mol^{-1} , see Table 1). Considering solvent effects makes the dissociation less favorable. However, in the liquid, the phenolate anion can form a very strong hydrogen bonding interaction with phenol (similar to the acetate–acetic acid system in analogous reactions^{18,20}), which stabilizes the dissociated species (cf. 4 and 4' in Table 1). Accordingly, the free ylide and the phenol–phenolate complex lie only somewhat higher in Gibbs free energy compared with the ion pair itself for the $\text{Me}_3\text{PR}^+\text{PhO}^-$ structures, and slightly lower for the $\text{Ph}_3\text{PR}^+\text{PhO}^-$ compounds. Clearly, assuming the formation of the phenol–phenolate complex, the availability of the phenolate anion to deprotonate further phosphonium cations is reduced, and therefore an upper limit of 50% is expected for the conversion, similar to that of the analogous reaction of imidazolium acetate ILs with CO_2 .²⁰

The phosphorous ylides formed in the process described above should easily react with the substrate if the reaction is to occur in an applicable manner. Although the mechanism of the Wittig reaction is well known,^{35,36} IL ions have not yet been considered as starting materials, neither the effects of the ionic solvent on the reaction mechanism. Thus, we performed a series of calculations on the Gibbs free energy profile of the full reaction mechanism for all four model systems, $\text{Me}_3\text{PR}^+\text{PhO}^-$ and $\text{Ph}_3\text{PR}^+\text{PhO}^-$ ($\text{R} = \text{Me}, \text{Et}$), with a COSMO-RS correction for the solvent effects of the IL. To provide a comparison for the solvent effects, we also performed these calculations with THF, which is often applied as a medium in the Wittig reaction.

The reaction follows the path that has been explored earlier³⁵ (see Figure 1): First, the initial van der Waals complex 5 is formed. From 5, the $[2 + 2]$ cycloaddition occurs to give the oxaphosphetane intermediate. Oxaphosphetane undergoes a Berry pseudorotation, relocating the P–C bond to the axial position, which allows the last step, cycloelimination into the products. The reaction-energy profile for the simplest example is shown in Figure 4, whereas the detailed energetic data can be found in Tables 2–5.

Apparently, the Gibbs free energy of the van der Waals complex is higher than that of the separated ylide and substrate by ca. 20 kJ mol^{-1} in all cases, which is due to the unfavorable entropy effects of the association, compensating the weak attraction between these molecules. From this complex, the reaction often follows a downhill path without a barrier to the oxaphosphetane, as the transition state, $\text{TS}_{5 \rightarrow 6}$, found on the potential energy surface has a lower Gibbs free energy than that of the initial van der Waals complex due to the differences in the $\text{E} \rightarrow \text{G}$ thermal correction values applied after the geometry optimization. The formation of the oxaphosphetane is highly exergonic; the relative Gibbs free energy of this intermediate is significantly lower than that of the ion pair and the isolated substrate (Table 1). The reaction Gibbs free energy shows clear substituent effects, as starting from the $\text{Me}_3\text{PR}^+\text{PhO}^-$ ILs the formation of the oxaphosphetane is less favorable energetically by ca. 20 kJ mol^{-1} than in the case of the $\text{Ph}_3\text{PR}^+\text{PhO}^-$ derivatives, whereas introducing a longer ethyl side chain also shows some increase in the reaction Gibbs free energies (Tables 2–5). Comparing the results for the THF and IL

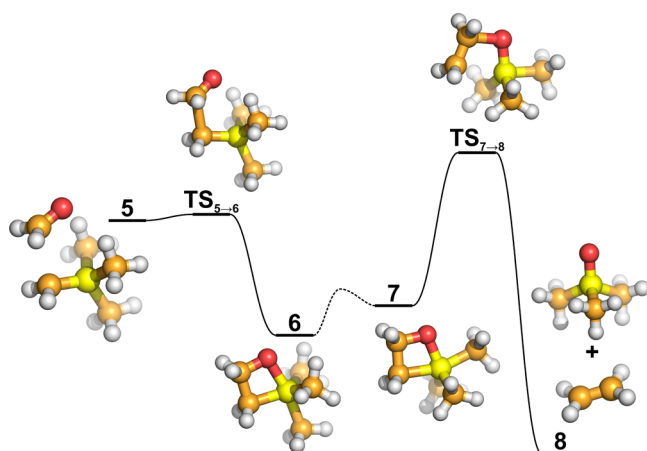


Figure 4. Numbering and ball-and-stick figures of the structures involved in the Wittig reaction from phosphonium phenolate ionic liquids (orange: carbon; yellow: phosphorous; red: oxygen; white: hydrogen).

models, it is apparent that although in THF the reaction is more exergonic by ca. 10 ($\text{Ph}_3\text{PR}^+\text{PhO}^-$ derivatives) and 15 kJ mol^{-1} ($\text{Me}_3\text{PR}^+\text{PhO}^-$ derivatives), the ionic solvent does not diminish the driving force of the reaction. Depending on the substituents of the carbonyl moiety of the substrate, the relative Gibbs free energy of the oxaphosphetane with respect to that of the ion pair and the separated substrate also varies significantly, by ca. 40 kJ mol^{-1} for each IL. Interestingly, the least exergonic reactions were found with acetophenone for all ILs, which should be due to combined stabilization of the +I effect of the methyl group and the π -conjugation between the phenyl group and the carbonyl unit. According to the reaction energy profiles obtained for all considered systems, the reaction of the solvent with a carbonyl compound should result readily in an oxaphosphetane.

The formation of oxaphosphetane determines stereochemistry of the product and thus the stereoselectivity of the process. For a highly stereoselective reaction, the barriers of the two paths that lead to the two products should be significantly different. However, in this case, the oxaphosphetane derivatives are all formed in a reaction step with low barriers (between 0

and ca. 40 kJ mol^{-1}), and the differences in the barrier heights between the paths that result eventually in cis or trans products are generally only 1–2 kJ mol^{-1} (see SI). Accordingly, these results do not indicate any significant selectivity for the Wittig reactions considered here.

The elusive transition states of the Berry pseudorotation were not located, but because this process is known to occur via a very low-energy transition state,³⁵ the lack of this barrier will not affect the conclusions of the present study. In many cases, oxaphosphetane isomer 7, with an axial P–C bond (which is, as mentioned above, required for the cycloelimination), was not found on the potential energy surface. After failing to optimize these structures from tentatively constructed geometries, we also tried to locate them by starting from the vicinity of the transition state TS_{7-8} . In all of these attempts, the geometry converged again into structure 6, with the P–O bond in an axial position. These findings can be rationalized, as these two isomers are not located in two separate minima on the potential energy surface; hence, the Berry pseudorotation and cycloelimination occur as a single step in the reaction mechanism. This reasoning is supported by the fact that 7, when found, is in all cases less stable than 6 by 10–20 kJ mol^{-1} .

TS_{7-8} exhibits the highest Gibbs free energy among all of the transition states and minima that were located on the potential energy surface. The rate-limiting step of the Wittig reaction is the cycloelimination; since, the energy difference between 6 and TS_{7-8} provides the highest barrier. Apparently, the barriers are in the range of 80–130 kJ mol^{-1} , depending on mostly the substituents on the phosphorous atom rather than on those on the carbonyl derivative. The $\text{Ph}_3\text{PR}^+\text{PhO}^-$ derivatives showed significantly lower barriers than those of the $\text{Me}_3\text{PR}^+\text{PhO}^-$ salts, which is in clear agreement with the preference in the experiments to choose triphenylphosphonium salts for the Wittig reactions. Considering that the rate-determining step in this reaction is the cycloelimination, wherein the anion does not play a role, the present reaction should behave similarly to the other Wittig reactions in the ILs. Knowing that such synthetic approaches have already been published before,^{6,7} it is reasonable to expect that the ILs investigated here would undergo the Wittig reactions, in agreement with the finding that the activation Gibbs free energies mentioned above are

Table 2. DLPNO-CCSD(T)/CBS//B3LYP-D3(BJ)/def2-TZVPP Gibbs Free Energy Profiles at (in kJ mol^{-1}) 298.15 K in THF for the Wittig Reaction of $\text{Me}_3\text{PR}^+\text{PhO}^-$ (R = Me, Et), with 2 and an Isolated $[\text{PhO}]^-$ as Reference, and Considering the Formation of $[(\text{PhO})_2\text{H}]^-$ ^a

	substrate	5	TS_{5-6}	6	7	TS_{7-8}	8
$\text{Me}_4\text{P}^+\text{PhO}^-$	CH_2O	12.3	10.9	−75.3	−58.3	10.1	−227.9
$\text{Me}_4\text{P}^+\text{PhO}^-$	CH_3CHO	19.8	28.8	−54.3	−35.2	40.3	−203.6
$\text{Me}_4\text{P}^+\text{PhO}^-$	$(\text{CH}_3)_2\text{CO}$	17.6	46.1	−38.8	−21.8	56.2	−185.8
$\text{Me}_4\text{P}^+\text{PhO}^-$	PhCHO	23.4	25.3	−48.4	−27.4	48.0	−207.3
$\text{Me}_4\text{P}^+\text{PhO}^-$	PhCMeO	20.5	41.9	−37.0	→	60.9	−189.7
$\text{Me}_4\text{P}^+\text{PhO}^-$	Ph_2CO	24.6	40.6	−40.9	→	61.8	−200.6
$\text{Me}_3\text{PEt}^+\text{PhO}^-$	CH_2O	16.9	8.8	−84.5	→	42.2	−253.4
$\text{Me}_3\text{PEt}^+\text{PhO}^-$	CH_3CHO^b	31.8	27.8	−63.1	→	42.8	−221.3
$\text{Me}_3\text{PEt}^+\text{PhO}^-$	$(\text{CH}_3)_2\text{CO}$	28.9	52.4	−47.6	→	61.7	−200.2
$\text{Me}_3\text{PEt}^+\text{PhO}^-$	PhCHO^b	32.2	22.9	−58.5	→	51.0	−228.5
$\text{Me}_3\text{PEt}^+\text{PhO}^-$	PhCMeO^c	33.3	71.8	−42.9	→	66.5	−202.9
$\text{Me}_3\text{PEt}^+\text{PhO}^-$	Ph_2CO	30.4	44.5	−50.2	→	58.8	−217.9

^aThe structures are shown in Figure 4. If the cis and trans products are available, only those reactions are shown here, which involve the lower energy oxaphosphetane intermediate. The results for 420 K are shown in the SI. ^bReaction Gibbs free energy profile for the formation of the trans structure.

^cReaction Gibbs free energy profile for the formation of the cis structure.

Table 3. DLPNO-CCSD(T)/CBS//B3LYP-D3(BJ)/def2-TZVPP Gibbs Free Energy Profiles (in kJ mol^{−1}) at 298.15 K in THF for the Wittig Reaction of Ph₃PR⁺PhO[−] (R = Me, Et), with 2 and an Isolated [PhO][−] as the Reference, and Considering the Formation of [(PhO)₂H]^{−a}

	substrate	5	TS _{5→6}	6	7	TS _{7→8}	8
Ph ₃ PMe ⁺ PhO [−]	CH ₂ O	−7.4	19.5	−93.2	→	−10.0	−261.4
Ph ₃ PMe ⁺ PhO [−]	CH ₃ CHO	−0.7	27.9	−69.8	−51.9	13.9	−237.1
Ph ₃ PMe ⁺ PhO [−]	(CH ₃) ₂ CO	−1.0	48.6	−52.4	−38.2	28.8	−219.3
Ph ₃ PMe ⁺ PhO [−]	PhCHO	5.1	25.5	−63.6	−39.9	26.6	−240.8
Ph ₃ PMe ⁺ PhO [−]	PhCMeO	−2.6	45.4	−52.3	−35.9	30.9	−223.2
Ph ₃ PMe ⁺ PhO [−]	Ph ₂ CO	5.5	36.4	−61.1	−34.7	32.7	−234.1
Ph ₃ PEt ⁺ PhO [−]	CH ₂ O	−6.3	10.3	−107.6	−90.1	−15.4	−290.7
Ph ₃ PEt ⁺ PhO [−]	CH ₃ CHO ^b	3.6	29.3	−82.3	−68.0	9.0	−258.5
Ph ₃ PEt ⁺ PhO [−]	(CH ₃) ₂ CO	6.1	65.4	−54.2	−50.2	26.1	−237.4
Ph ₃ PEt ⁺ PhO [−]	PhCHO ^b	8.9	21.0	−70.0	−61.8	14.7	−265.7
Ph ₃ PEt ⁺ PhO [−]	PhCMeO ^{b,c}	3.5	46.3	−57.3	−44.0	26.8	−240.2
Ph ₃ PEt ⁺ PhO [−]	Ph ₂ CO	0.4	41.6	−67.0	−44.7	25.7	−255.1

^aThe structures are shown in Figure 4. If the cis and trans products are available, only those reactions are shown here that involve the lower energy oxaphosphetane intermediate. The results for 420 K are shown in the SI. ^bReaction Gibbs free energy profile for the formation of the trans structure.

^cReaction Gibbs free energy profile for the formation of the cis structure.

Table 4. DLPNO-CCSD(T)/CBS//B3LYP-D3(BJ)/def2-TZVPP Gibbs Free Energy Profiles (in kJ mol^{−1}) at 298.15 K in the IL for the Wittig Reaction of Me₃PR⁺PhO[−] (R = Me, Et), with 2 and an Isolated [PhO][−] as Reference, and Considering the Formation of [(PhO)₂H]^{−a}

	substrate	5	TS _{5→6}	6	7	TS _{7→8}	8
Me ₃ P ⁺ PhO [−]	CH ₂ O	28.1	21.7	−59.3	−40.5	26.3	−215.0
Me ₃ P ⁺ PhO [−]	CH ₃ CHO	36.4	39.4	−37.9	−17.1	57.2	−190.3
Me ₃ P ⁺ PhO [−]	(CH ₃) ₂ CO	34.4	56.7	−22.0	−3.6	73.3	−172.3
Me ₃ P ⁺ PhO [−]	PhCHO	39.0	35.5	−32.4	−10.1	63.6	−195.2
Me ₃ P ⁺ PhO [−]	PhCMeO	36.7	52.7	−20.4	→	78.1	−177.1
Me ₃ P ⁺ PhO [−]	Ph ₂ CO	39.9	51.9	−24.6	→	77.6	−188.4
Me ₃ PEt ⁺ PhO [−]	CH ₂ O	30.0	19.4	−69.7	→	57.8	−241.4
Me ₃ PEt ⁺ PhO [−]	CH ₃ CHO ^b	47.0	38.2	−47.8	→	59.0	−208.8
Me ₃ PEt ⁺ PhO [−]	(CH ₃) ₂ CO	44.8	68.3	−32.2	→	77.8	−187.6
Me ₃ PEt ⁺ PhO [−]	PhCHO ^b	46.6	32.5	−43.8	→	66.6	−217.2
Me ₃ PEt ⁺ PhO [−]	PhCMeO ^c	48.2	81.7	−28.0	→	82.2	−191.1
Me ₃ PEt ⁺ PhO [−]	Ph ₂ CO	44.9	55.4	−35.0	→	74.1	−206.6

^aThe structures are shown in Figure 4. If the cis and trans products are available, only those reactions are shown here that involve the lower energy oxaphosphetane intermediate. The results for 420 K are shown in the SI. ^bReaction Gibbs free energy profile for the formation of the trans structure.

^cReaction Gibbs free energy profile for the formation of the cis structure.

Table 5. DLPNO-CCSD(T)/CBS//B3LYP-D3(BJ)/def2-TZVPP Gibbs Free Energy Profiles at (in kJ mol^{−1}) 298.15 K in IL for the Wittig Reaction of Ph₃PR⁺PhO[−] (R = Me, Et), with 2 and an Isolated [PhO][−] as Reference, and Considering the Formation of [(PhO)₂H]^{−a}

	substrate	5	TS _{5→6}	6	7	TS _{7→8}	8
Ph ₃ PMe ⁺ PhO [−]	CH ₂ O	4.4	27.7	−82.0	→	2.3	−251.9
Ph ₃ PMe ⁺ PhO [−]	CH ₃ CHO	11.3	38.8	−58.2	−39.1	29.1	−227.2
Ph ₃ PMe ⁺ PhO [−]	(CH ₃) ₂ CO	11.0	56.5	−40.7	−25.1	41.6	−209.0
Ph ₃ PMe ⁺ PhO [−]	PhCHO	16.7	33.8	−51.9	−28.0	38.8	−231.5
Ph ₃ PMe ⁺ PhO [−]	PhCMeO	9.0	53.9	−40.9	−23.1	43.2	−213.6
Ph ₃ PMe ⁺ PhO [−]	Ph ₂ CO	17.3	44.9	−49.5	−22.9	44.5	−224.7
Ph ₃ PEt ⁺ PhO [−]	CH ₂ O	3.4	17.4	−97.8	−79.3	−4.7	−282.5
Ph ₃ PEt ⁺ PhO [−]	CH ₃ CHO ^b	13.3	36.2	−72.2	−56.9	20.1	−249.9
Ph ₃ PEt ⁺ PhO [−]	(CH ₃) ₂ CO	16.1	72.2	−44.0	−38.9	37.1	−228.8
Ph ₃ PEt ⁺ PhO [−]	PhCHO ^c	13.8	27.0	−60.0	−41.0	36.3	−247.5
Ph ₃ PEt ⁺ PhO [−]	PhCMeO ^b	13.0	53.2	−47.1	−33.5	37.5	−231.9
Ph ₃ PEt ⁺ PhO [−]	Ph ₂ CO	10.3	49.5	−57.4	−34.8	36.0	−247.1

^aThe structures are shown in Figure 4. If the cis and trans products are available, only those reactions are shown here, which involve the lower energy oxaphosphetane intermediate. The results for 420 K are shown in the SI. ^bReaction Gibbs free energy profile for the formation of the trans structure.

^cReaction Gibbs free energy profile for the formation of the cis structure.

moderate. This is further supported by the fact that the differences between the barriers in THF and the IL for each system is marginal, generally within 1–2 kJ mol^{−1}, in good agreement with the observation that the ILs are efficient solvents for Wittig reactions,^{6,7} similar to THF.^{3–5} The relative energy of the product has lower energy and Gibbs free energy than those of any intermediate in all cases and in both solvents, which provides the necessary driving force for the reaction.

The results above indicate that the Me₃PR⁺PhO[−] and Ph₃PR⁺PhO[−] derivatives can be applied as reagents in the Wittig reaction. However, to be able to use these compounds also as solvents for the reaction, the liquid structures must also be characterized to ensure that they are indeed ILs. To this end, we performed classical molecular dynamics (MD) simulations on a series of compounds, R₄P⁺PhO[−] and Ph₃PR⁺PhO[−] (wherein R = Et, Pr, Bu, Hexyl, Octyl). Because ILs are often applied in a wide range of temperatures and because the present ILs (especially the Ph₃PR⁺PhO[−] derivatives) might be viscous at ambient conditions, we performed the calculations at two different temperatures, 298.15 and 420 K. Heating might result in the evaporation of the aldehyde substrate from the solvent, which can be counteracted by applying pressure to the system, but in the case of aldehydes with sufficiently large substituents, this should not be an issue, as already, for example, cyclohexanone has a boiling point of 429 K. Clearly, we did not investigate in the present article all of the possible substrates for the Wittig reaction in these ILs, but the energetically most relevant electronic effects are fully covered above by the three substituents that we considered (H, CH₃, Ph); therefore, the conclusions here should be transferrable to other substrates as well.

Although the structure exhibited only a slight change upon heating, the dynamic properties varied greatly. The data are shown in Table 6. Interestingly, the obtained viscosities are low;

Table 6. Dynamic Viscosity (η , in mPa s), the Diffusion Constants for the Cation (D^+ , in 10^{−10} m² s^{−1}), and the Anion (D^- , in 10^{−10} m² s^{−1}) Obtained in the Simulations for the Different IL Systems at 298.15 and 420 K Temperatures

ionic liquid	298.15 K			420 K		
	η	D^+	D^-	η	D^+	D^-
Et ₄ P ⁺ PhO [−]	1.76	0.370	0.367	0.77	6.11	8.27
Pr ₄ P ⁺ PhO [−]	2.09	0.051	0.065	0.83	3.71	5.32
Bu ₄ P ⁺ PhO [−]	2.01	0.012	0.021	0.94	1.61	2.69
Hex ₄ P ⁺ PhO [−]	1.71	0.009	0.013	0.96	0.67	1.22
Oct ₄ P ⁺ PhO [−]	1.15	0.007	0.011	0.98	0.32	0.42
Ph ₃ PEt ⁺ PhO [−]	2.46	0.009	0.010	1.14	2.21	2.65
Ph ₃ PPr ⁺ PhO [−]	2.33	0.005	0.009	1.20	1.47	1.91
Ph ₃ PBu ⁺ PhO [−]	2.50	0.005	0.012	1.15	1.28	2.09
Ph ₃ PHex ⁺ PhO [−]	2.56	0.005	0.009	1.17	1.00	1.82
Ph ₃ POct ⁺ PhO [−]	1.22	0.013	0.015	1.12	0.81	1.79

all are in the range of 1–3 mPa s, comparable to that of room-temperature water. At the higher temperature, the viscosities are notably lower, occasionally half of those at room temperature. Clearly, taking the absolute values for viscosities obtained from MD must be treated carefully, but the trends can nevertheless be discussed. The R₄P⁺PhO[−] ILs exhibit an increasing viscosity due to the longer alkyl chains, whereas the Ph₃PR⁺PhO[−] ILs do not show a clear trend in their viscosities. The diffusion constants also show a moderate ion mobility at the lower temperature, which is increased by 2 orders of

magnitude at the higher temperature (Table 6). Interestingly, the diffusion constants and viscosities show a completely different trend, which can be explained by the facile deformation of the longer side chains by shear forces, whereas the overall center of mass of the larger cations diffuses slower.

The data obtained from the MD simulations allow us not only to assess the aforementioned properties but also to gain a molecular and mesoscopic level^{37–39} insight into the structure of these liquids. The formation of the pentacoordinated species, **1**, is not possible in a classical MD environment because the bond-breaking and bond-formation processes are not described in the empirical potentials applied there. Although in ab initio MD (AIMD) simulations it is possible to describe the electronic structure explicitly and therefore the formation of the aforementioned P–O bond in **1** may be observed, the computational demand of these simulations prohibit the treatment of the bulk liquid phase of the large molecules that we investigated here. Thus, to check the availability of **1** in an explicit and dynamic liquid model, we performed AIMD simulations on an IL consisting of smaller cations, Et₃PBu⁺PhO[−]. This IL is applied by Brennecke and co-workers in CO₂ absorption and therefore is of practical use. The radial pair distribution function (RDF) for the P–O correlation shows a high first peak (Figure 5), but only at ca. 4 Å, which is too

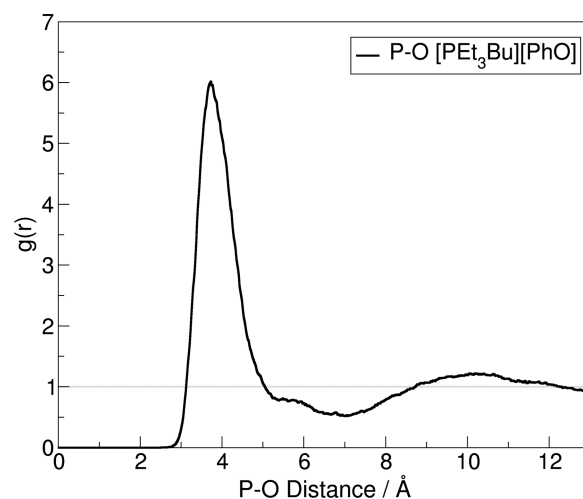


Figure 5. Radial pair correlation functions for the P–O distances in the AIMD calculation of Et₃PBu⁺PhO[−] (see Models and Methods section).

long a distance for a covalent bond. This suggests that in this particular liquid the formation of **1** is not very frequent, which is in good agreement with the results of the static quantum chemical calculations for Me₃PR⁺PhO[−] (R = Me, Et), shown in Table 1.

Hydrogen bonding is usually an important feature of ILs.^{40–43} In these cases, it is especially so because as it has been shown above, hydrogen-bond formation between the IL anion and cation is the starting point for the proton transfer that is necessary for the Wittig reaction. Hydrogen bonding is most relevant between the oxygen atom of the phenolate and partially most positive α -hydrogen atoms of the cation. Indeed, as it can be seen by the presence of the first peaks of the RDFs with a relevant height ($g(r) > 1$), at short distances in Figure 6 (above), the hydrogen bonding in these liquids is a characteristic feature as well. Interestingly, the hydrogen bonding is more expressed for the R₄P⁺ cations than for the Ph₃PR⁺ derivatives,

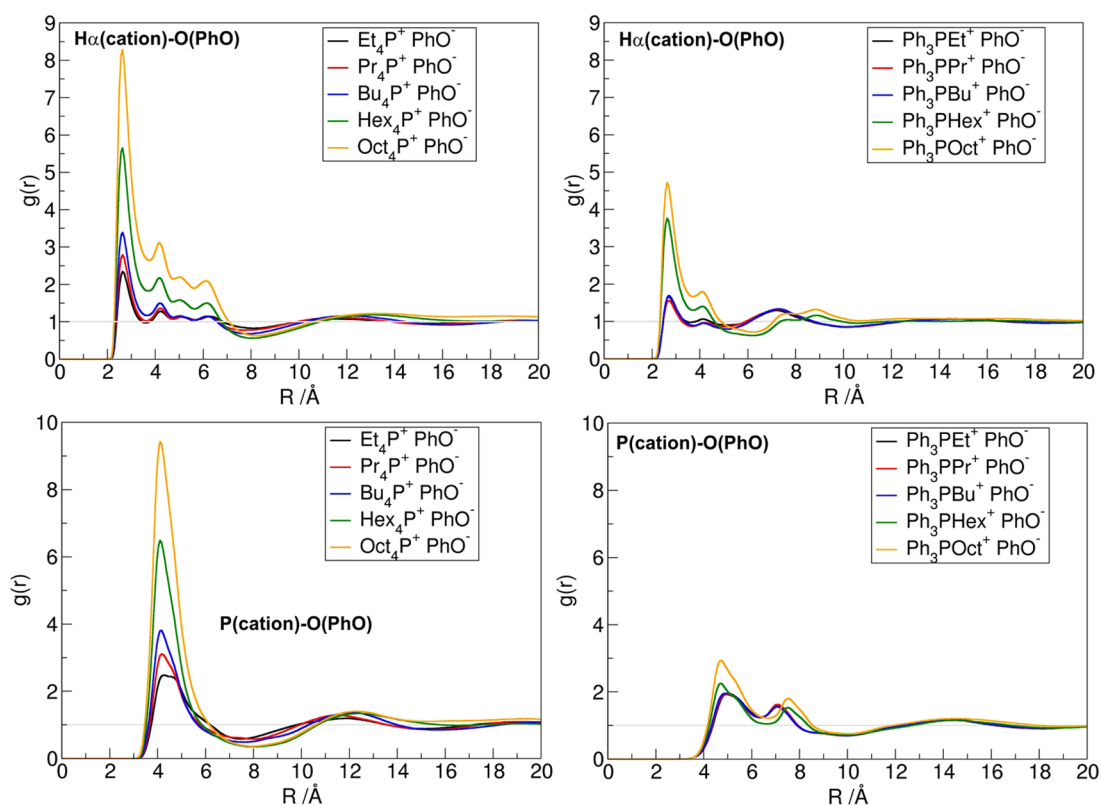


Figure 6. Relevant radial pair correlation functions for the liquid models investigated by classical MD simulations, describing the anion–cation interactions for the simulation boxes at 298.15 K (for the analogous graphs for the simulations at 420 K, please see SI).

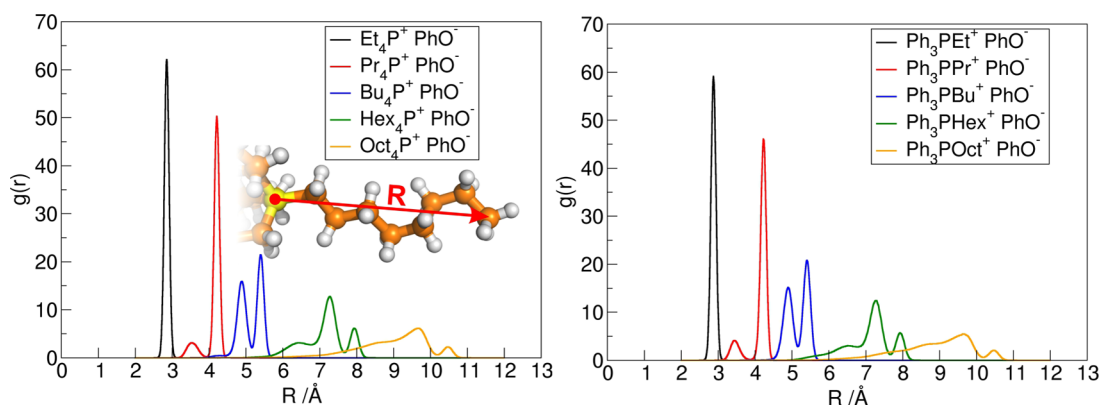


Figure 7. Distribution of the intramolecular distances between the phosphorous atom and terminal carbon atom of the side chains in the investigated ionic liquids at 298.15 K (for the analogous graphs for the simulations at 420 K, please see the SI).

which is apparently due to the fact that in the latter cases the positively polarized hydrogen atoms at the phenyl groups compete for these interaction sites. The $g(r)$ values show a significant increase at the first peaks when introducing the longest hexyl and octyl side chains. This sudden increase is possibly due to the increased microheterogeneity in these liquids (see below), which separates the polar and nonpolar moieties in a larger extent, which results in a stronger polar–polar interplay within the liquid.

In ILs, it is a known phenomenon that the side chains and polar parts of the molecules segregate into two microscopically separate units, a polar and a nonpolar domain.^{37–39} This feature can highly influence the properties of the liquid. Apart from changes in the rheological properties, the solubility and solvation mode of the solutes (i.e., the substrates) can be

altered. This is especially important from the point of view of the reaction because the potential microheterogeneous structure of these liquids can aid the solvation and dissolution of a substrate that is too lipophilic for dissolving in an ionic environment. For the formation of nonpolar domains, the alkyl groups have to assume a relatively straight conformation, wherein the C–C–C–C units are (almost) all in a trans configuration. The distribution of conformations can be easily evaluated by considering the intramolecular distances between the terminal carbon atom of the alkyl group and the phosphorous atom. The occurrences are plotted on Figure 7. It is observable in these graphs that the highest occurrences correspond to a stretched-out conformation, and therefore these side chains are not at all curled up close to the phosphorous atom. This important finding shows that the

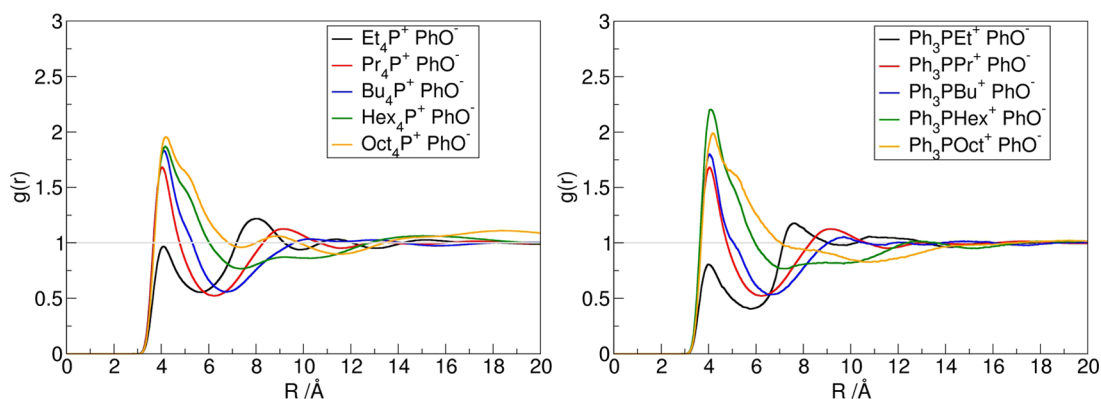


Figure 8. Radial pair correlation functions between the terminal carbon atoms of the side chains in the liquid models investigated by classical MD simulations at 298.15 K (for the analogous graphs for the simulations at 420 K, please see the SI).

phosphorous atom is not blocked by the coiled side chains but rather accessible, which is important for the substrate to react with the forming phosphorous ylides. The stretched-out alkyl chains also allow a significant microsegregation, as it is also shown by the strong correlation between the terminal carbon atoms in Figure 8. The microheterogeneity apparently increases as the side chains become longer, as one might expect from the increasing volume of the nonpolar moieties in the system. It is interesting to point out that the two groups of ILs tested here, namely R_4P^+ and Ph_3PR^+ , show similar alkyl conformations and microsegregations if the side chains are similar (see Figures 7 and 8).

SUMMARY AND CONCLUSIONS

In this study, we aimed at designing Wittig reagent ionic liquids (ILs), which can be used as a reagent and solvent for this synthetically important transformation. On the basis of the earlier literature data, we suggested that tetraalkylphosphonium and alkyl-triphenyl-phosphonium phenolate ionic liquids might be suitable targets for this purpose. Indeed, according to our quantum chemical calculations and in agreement with previous indirect experimental indications,¹⁶ the formation of ylides from the ion pairs of such ionic liquids is feasible. The forming ylides should react readily with the carbonyl-derivative substrate of the Wittig reaction, forming an oxaphosphetane intermediate without any significant barriers. Further steps of the Wittig reaction were also found to be possible, as the barriers in our calculations were almost identical to those in THF and the ILs.

The affinity of the phosphorous to oxygen atoms allows the formation of a neutral substance, with a pentacoordinated phosphorous atom from the IL ion pair. In the gas phase, these structures are dominant, which offers several applications, for example, easier distillation or the separation of more nucleophilic anions from phosphonium-based ILs. In the liquid phase, however, the stability of this compound is significantly reduced due to the ionic medium,^{26,27} which stabilizes the ion pair over this neutral isomer. Nevertheless, our calculations show that in triphenylphosphonium phenolates the formation of the P–O bond between the cation and anion occurs to a great extent. It will be interesting to see in a follow up study whether the change of the anion to one without an oxygen atom changes this behavior.

The classical MD simulations show that the viscosities of these compounds are low at both 298.15 and 420 K, and therefore they might be indeed used as solvents for the reaction they are also directly involved in. The molecular level details

from the MD simulations showed significant hydrogen bonding between the basic oxygen atom of the phenolate anion and the α -hydrogen atoms of the cation. Because these are the hydrogen atoms that have to be removed from the cation if the reaction is to happen, these hydrogen bonds show that the formation of the phosphorous ylides in this solution is inherently supported by the IL structure itself. The structure of the liquids exhibits a significant microheterogeneity already if propyl groups are attached to the phosphorous atom, which will be helpful for the solubility of the substrates for the reaction.

To apply such systems in the Wittig reaction as green processes, it might be desirable to exchange the phenolate to other, less toxic anions. The aforementioned reactivity is important to consider not only for the direct application of the Wittig reagent ILs but also if such ILs are applied in CO_2 absorption from waste gases. In the case of incomplete combustion, the partially oxidized products, that is, aldehydes and ketones, might decompose the IL absorbent, which is to be avoided in a sustainable process.

MODELS AND METHODS

Static DFT and Ab Initio Calculations. Unless specified otherwise, all static quantum chemical calculations were performed by the ORCA⁴⁴ program (version 3.0.3⁴⁵). The evaluation of relative Gibbs free energies for the substrates, products, intermediates, and transition states of the reaction requires taking into account different energetic contributions. Thus, we combined DFT and wave function theory, statistical thermodynamics, and a reliable solvation model. First, we conducted geometry optimization and subsequent frequency calculations on the considered structures at the B3LYP-D3(BJ)/def2-TZVPP(Grid 5) level of theory.^{46–48} The nature of the stationary point was evaluated by verifying the eigenvalues of the Hessian. Second, single point calculations were performed on the obtained geometries to obtain reliable electronic energies. For this purpose, we applied DLPNO-CCSD(T),⁴⁹ which provides the energies within an error of 1 kJ mol^{−1}.⁵⁰ The energy calculations were performed at the DLPNO-CCSD(T) level of theory with def2-TZVPP and def2-QZVPP basis sets. An additional basis set for correlational fitting was included in each case. We specified normal settings for the DLPNO calculations (TCutPairs 1×10^{-4} , TCutPNO 3.33×10^{-7} , TCutMKN 1×10^{-3}).

The extrapolation of the calculated energies to the complete basis set⁵¹ was undertaken separately for Hartree–Fock and DLPNO-CCSD(T) correlation energy as follows

$$E_{\text{HF}}^{\text{CBS}} = E_{\text{HF}}^{\text{TZ}} + \frac{E_{\text{HF}}^{\text{QZ}}}{\exp(7.88(\sqrt{4} - \sqrt{3})) - 1} \quad (1)$$

$$E_{\text{corr}}^{\text{CBS}} = \frac{3^{2.97} \cdot E_{\text{corr}}^{\text{TZ}} - 4^{2.97} \cdot E_{\text{corr}}^{\text{QZ}}}{3^{2.97} - 4^{2.97}} \quad (2)$$

$$E(\text{DLPNO} - \text{CCSD(T)}/\text{CBS}) = E_{\text{HF}}^{\text{CBS}} + E_{\text{corr}}^{\text{CBS}} \quad (3)$$

Third, we calculated the zero-point vibrational energies and thermal corrections from statistical thermodynamics calculations in the ideal gas state for finite temperatures at 298.15 and 420 K from the DFT geometries and frequencies according to the approach described in ref 52. The combination of the electronic energies and the thermal corrections to the finite temperature provides the Gibbs free energy in the gas phase. Finally, the Gibbs free solvation energies at infinite dilution were calculated from the COSMO-RS.^{53,54} The ionic liquid solvent was modeled by a 1:1 mixture of the corresponding cation and anion. The sum of the gas phase and solvation Gibbs free energies provides a good estimate for the reaction and activation Gibbs free energies in the solvents.

Classical MD Simulations. For all classical simulations, the optimized potential for liquid simulations (OPLS) potential form⁵⁵ was applied. For the PR_4^+ cations, the force field parameters were taken from the OPLS-based CL&P force field fitted for the structures by Pádúa and Canongia Lopes.⁵⁶ The Lennard-Jones parameters for the Ph_3PR^+ cations were taken from the OPLS force field.⁵⁵ The charges for the latter cations were obtained by first performing RESP fitting at the TPSS-D3/def-TZVPP level on the structures that were optimized at the same level by the CP2K program,⁵⁷ then consistently with the approach of Pádúa and Canongia Lopes for ionic liquids, a systematic set of charges was obtained that allows substitution by the OPLS functional groups. The obtained charges can be found in the SI. Because the force constants generally do not influence the structure of the liquid in a significant manner, all CA–P, CA–P–CA, and CA–P–CT force constants were taken from the CT–P, CT–P–CT, and CT–P–CT data,⁵⁶ respectively (CA: carbon atom in the phenyl ring, CT: an sp^3 carbon atom). The $V_{m,ijkl}$ Fourier constants of the dihedrals describing the rotation of the phenyl groups on the phosphorous atom around the CA–P bonds were all set to 0.0, which is as usual for molecules with such steric demand, assuming that the repulsive van der Waals forces will control these rotations. The reference bond lengths and angles that include the phosphorous were taken from the TPSS-D3/def-TZVPP optimized geometry of Ph_3PEt^+ , whereas for the rest the OPLS/AMBER parameters were taken.^{55,58} The bonding parameters for the phenolate anion were taken from the OPLS/AMBER force fields,^{55,58} whereas the charges were taken from the RESP fitting at the TPSS-D3/def-TZVPP level on the structure that was previously optimized at the same level by CP2K.⁵⁷

The classical MD simulations were performed using the LAMMPS program package,^{59,60} with periodic boundary conditions. The simulation boxes for classical MD simulations contained 250–360 ion pairs of the IL (see Table 7). The initial boxes were prepared to represent a density of ca. 0.6–0.8 g cm^{-3} using the packmol program.⁶¹ After 0.5 ns of initial equilibration at the simulation temperature in an NVT ensemble, 1 ns NpT simulation was run ($T = 298.15$ or 420 K; $p = 1$ bar). Over the last 0.5 ns the box volume was averaged, and the average volume was taken for the subsequent

Table 7. Number of Ionic Liquid Ion Pairs (N) in the Simulation Boxes, the Cell Vector, and the Corresponding Densities (ρ) for the Different Ionic Liquids at the Simulation Temperatures

ionic liquid	N	298.15 K		420 K	
		cell vector	ρ	cell vector	ρ
		Å	g cm^{-3}	Å	g cm^{-3}
$\text{Et}_4\text{P}^+\text{PhO}^-$	310	51.1179	0.7613	52.8172	0.8398
$\text{Pr}_4\text{P}^+\text{PhO}^-$	330	56.4577	0.7426	58.3251	0.8188
$\text{Bu}_4\text{P}^+\text{PhO}^-$	250	54.8031	0.7292	56.6475	0.8053
$\text{Hex}_4\text{P}^+\text{PhO}^-$	250	62.3344	0.7636	62.7781	0.7800
$\text{Oct}_4\text{P}^+\text{PhO}^-$	250	67.6686	0.7605	67.8542	0.7668
$\text{Ph}_3\text{PEt}^+\text{PhO}^-$	360	60.0808	0.9001	61.7393	0.9767
$\text{Ph}_3\text{PPr}^+\text{PhO}^-$	343	60.0245	0.8945	61.6449	0.9689
$\text{Ph}_3\text{PBu}^+\text{PhO}^-$	320	59.5487	0.8788	61.2250	0.9552
$\text{Ph}_3\text{PHex}^+\text{PhO}^-$	301	60.3565	0.8528	61.9971	0.9242
$\text{Ph}_3\text{POct}^+\text{PhO}^-$	250	59.4177	0.8889	59.8404	0.9080

simulations. The obtained cell vectors and densities are shown in Table 7. After 1 ns equilibration, a 10 ns production run was performed for both temperatures in the NVT ensemble ($T = 298.15$ or 420 K). The temperature and pressure were controlled by Nosé–Hoover chain thermostats and barostats,^{62–64} respectively. The time step was chosen to be 0.5 fs. The trajectory was saved in every picosecond. Viscosities were obtained by applying the Green–Kubo formula from the ensemble average of the stress tensor’s autocorrelation. All AIMD and classical MD trajectories were analyzed using the TRAVIS program.⁶⁵

AIMD Simulations. The cubic simulation box, containing 32 $\text{Et}_3\text{BuP}^+\text{PhO}^-$ ion pairs, was created by a short classical MD simulation (see Figure 9). The box length was calculated to be 27.234 Å so that it represents a realistic density for a phosphonium-derivative IL.

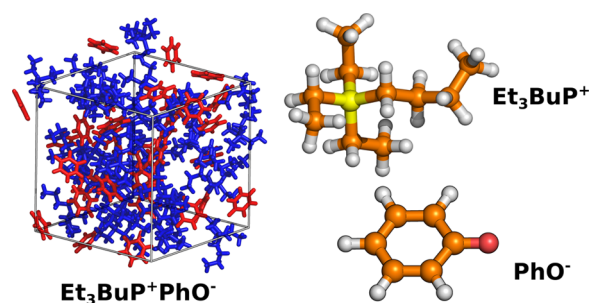


Figure 9. Left: Representative snapshot of the triethyl-butylphosphonium phenolate, $\text{Et}_3\text{BuP}^+\text{PhO}^-$ (cations are shown in blue, phenolate anion in red). Right: Ball-and-stick representation of the ions of the simulated IL (on the right, red: oxygen, orange: carbon, white: hydrogen, and yellow: phosphorus).

All AIMD simulations were carried out with the CP2K⁵⁷ program package using the QUICKSTEP module,⁶⁶ using hybrid Gaussian and plane wave basis sets.

For AIMD simulations, we utilized the BLYP functional^{67,68} and an empirical dispersion correction, with Becke–Johnson damping.^{47,48} For all atoms, the molecularly optimized double- ζ basis set (MOLOPT-DZVP-SR-GTH),⁶⁹ with corresponding Goedecker–Teter–Hutter pseudopotentials for core electrons,^{70–72} was applied. A 280 Ry density cutoff criterion, with the finest grid level, was employed together with multigrad

number 5 (NGRID 5 and REL_CUTOFF 40), using the smoothing for the electron density (NN10_SMOOTH) and its derivative (NN10).⁶⁶ For the energy calculations, the convergence criterion of 1.0E-5 was used.

The simulation temperature was regulated using Nosé–Hoover chain thermostats.^{62–64} A time step of 0.5 fs was chosen. The simulation boxes were equilibrated for 2.5 ps at a temperature of 450 K at a constant volume with a massive thermostat, with a time constant of 10 fs. The system was then simulated in a canonical ensemble for 81.5 ps at a temperature of 350 K, with a time constant of 100 fs.

■ ASSOCIATED CONTENT

■ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsomega.7b00230.

Detailed Gibbs free energy profiles at both 298.15 and 420 K for the Wittig reactions, including comparison of the formation of the cis and trans products, together with the optimized XYZ coordinates and total energies for all structures that were considered in this study, atomic partial charges for the Ph_3PR^+ and the PhO^- ions, RDFs obtained for the systems from the MD simulations at 420 K (PDF)

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Notes

The authors declare no competing financial interest.

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