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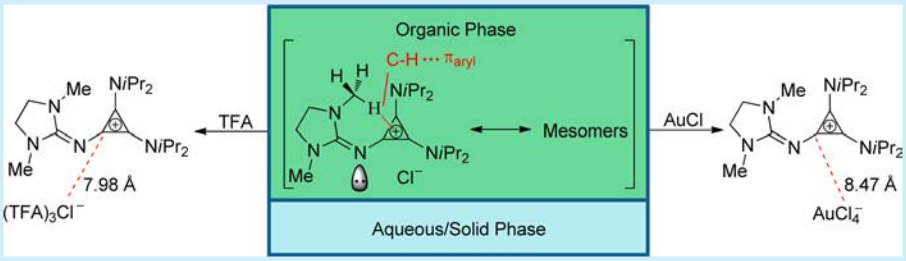
A Class of Phase-Transfer Catalyst with Interionic Strain: Insight into the Bonding of Disubstituted N- vs Carbene-Stabilized N^{I}-Centered Cations

Roya Mirabdolbaghi, Travis Dudding,* and Theocharis Stamatatos

Department of Chemistry, Brock University, 500 Glenridge Avenue, St. Catharines, Ontario L2R1H1, Canada

S Supporting Information



ABSTRACT: The straightforward synthesis of a class of nitrogen-based phase-transfer catalysts (PTCs) having markedly dissociated anions due to interionic donor−donor “ion pair strain” and use for catalyzing benzylation and benzylic fluorination is reported. Provided also is insight into the bonding of disubstituted N- vs so-called divalent carbene-stablized N^{I}-centered cations and the unprecedented finding of a cyclopropenium based C−H⋯π_{aryl} interaction.

The chemistry of low-valent group 14 based complexes, such as the so-called ylidones L: → E ← :L (L: = donor, E = C − Pb), has seen a bourgeoning level of interest in the past decade due to their peculiar electronic structures and unique reactivity, which has led to recent controversy.[1a−h] Emerging from the study of these complexes has been the nonintuitive, yet chemically relevant, view that the acceptor atom (E) retains its valence electrons in the form of two lone pairs, and the two ligands are coordinated through dative donor−acceptor interactions. As an exemplary case, carbodicarbenes (**1**) (also termed carbones), one of the most well-studied classes of ylidones, are thought to have “hidden” double lone-pair character, leading them to be regarded as “latent” C(0) compounds or zerovalent species (Figure 1).[2a−c] Notably, the observed nonlinear L: → E ← :L bond angles of carbones (ranging from 122−156°) and computational calculations support this assertion.[1a−c,2b,c]

On the other hand, p-block (group 15) donor−acceptor ylidone complexes have received far less attention and only recently have studies related to these systems begun to surface. In this regard, Alcarazo, Frenking, and others have reported divalent nitrogen species that are formally isoelectronic with carbodicarbenes. Moreover, several computational and experimental reports have appeared in which these compounds were depicted as possessing dative bonding character.[3a−g] Although questionable, this bonding scenario corresponds to a divalent carbene-stablized N^{I}-centered cation such as L: → N^{I} ← :L. Case in point, Alcarazo et al. prepared nitrogen polycations stabilized by cyclopropenylidene substituents from readily available onium precursor chlorocyclopropenium tetrafluoroborate, using an “inverse onio-substituent-transfer” strategy.[3a] In a related context, Lyapkalo et al. prepared a series of 2-amino-*N*,*N*′-dialkyl-4,5-dimethylimidazolium cations that were employed as phase-transfer catalysts (PTCs).[4] Likewise, Tan and co-workers have advanced a structurally similar class of chiral phase-transfer catalysts which they termed “pentanidium”.[5] Interestingly, the central nitrogen of pentanidiums and 2-amino-*N*,*N*′-dialkyl-4,5-dimethylimidazoliums are isoelectronic with the N^{I}-centered cations reported by Alcarazo and thus can be considered as coordinated by two N-heterocyclic carbenes (NHC).

Intrigued by the recent reports of carbene stabilized N^{I} centered complexes, as well as our interest in catalysis we were drawn toward the possibility of preparing structurally related complexes for applications in synthesis. As a result of this endeavor reported herein is the synthesis, X-ray characterization, and DFT calculations of **5**·X (X = AuCl$_4^-$, (TFA)$_3$Cl$^-$) as well as the use of **5**·Cl$^-$ as a PTC for benzylation and benzylic fluorination. Notably, due to donor−donor “ion pair strain” originating from a strong repulsive closed-shell interaction between the electron-rich anion and electron-excessive cyclo-

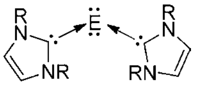


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Figure 1. Structure of carbodicarbene C(NHC)$_2$ (NHC = N-heterocyclic carbene).

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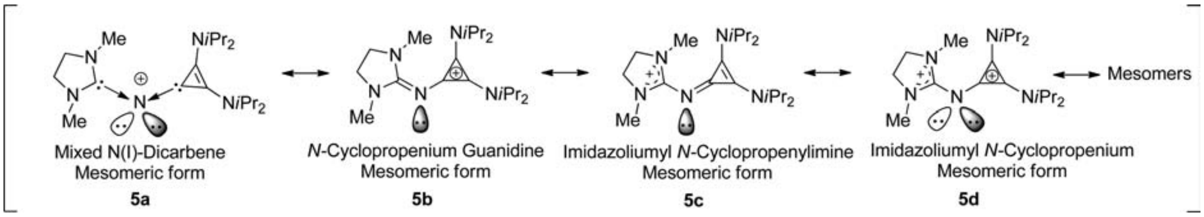
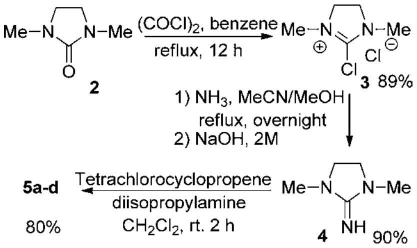
Scheme 1. Mesomeric Forms of Cation 5



propenylium ring of 5·X, the anion of these compounds is highly dissociated with the tell-tale signs of being a “naked anion”,[6a,b] providing an interesting feature for the design of PTC. With the secondary aim of applying 5 as a potential ligand for metal-based catalysis, the coordination properties of 5·Cl$^-$ with a number of metals is also reported. Given that cation 5 embodies what can be viewed as a divalent N^{I} adduct, coordinated by two different well-known carbenes (i.e., NHC and cyclopropenylidene carbene ligands), it offers insight into the bonding of so-called nitrogen centered low-valent complexes. In this regard, a salient feature of 5 is the mesomeric forms that may be invoked to describe the bonding in the parent cation: (1) a heteroleptic donor−acceptor complex of an imidazole-based NHC and cyclopropenylidene stabilized N^{I}-cation **5a**; (2) an *N*-cyclopropenium guanidine **5b**; (3) an imidazoliumyl *N*-cyclopropenylimine **5c**; and (4) imidazoliumyl *N*-cyclopropenium **5d**, etc. (Scheme 1). As outlined in Scheme 2, 5·Cl$^-$ was prepared as a bench stable solid from guanidine **4** (synthesized in three-steps) and tetrachlorocyclopropene, which is a commercially available reagent that can also be synthesized from inexpensive precursors.

Scheme 2. Synthesis of 5·Cl$^-$, Reagents, And Conditions



Having 5·Cl$^-$ in hand, based on Bharatam’s in silico findings[3d−g] related to structurally similar N^{I} complexes which were predicted to coordinate metals, the ligation of 5·Cl$^-$ to several metals (e.g., Ag^{I}, Cu^{II}, Pd^{0}, Au^{I}, In^{I}) was subsequently investigated. To this end, despite numerous failed attempts to isolate an *N*-ligated metal complex of 5·Cl$^-$, we were able to obtain a single crystal of 5·AuCl$_4^-$ suitable for X-ray diffraction from a mixture of 5·Cl$^-$ and AuCl (Figure 2).[7] Apparent from the X-ray structure of 5·AuCl$_4^-$ was the noticeable displacement of the AuCl$_4^-$ anion at a N(3)···Au(1) distance of 8.47 Å. A further characteristic feature of 5·AuCl$_4^-$ was the C(1)−N(3)−C(4) bond angle of 125° as it was similar to that of carbones and consistent with Alcarazo’s reported bis-cyclopropenium N^{I}-cations. Further telling were the N(3)−C(1) and N(3)−C(4) bond distances of 1.34(4) and 1.30(6) Å, which were in line with partial double-bond character as supported by the computed Wiberg bond indices of 1.25 and 1.40 obtained from the DFT-optimized X-ray coordinates of 5·AuCl$_4^-$. Meanwhile, the natural atomic orbital (NAO) charges of C(1), C(2), and C(3) ($\Sigma_{i=1}^{3} C_i$ = 0.714*e*) suggested the presence of an aromatic cyclopropenium cation, while the bridging N(3) atom had a high negative partial charge of −0.649 e.

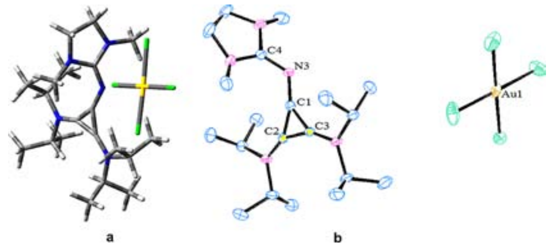


Figure 2. (a) Optimized structure of 5·AuCl$_4^-$ computed at the B3LYP/SDD level. (b) X-ray structure of 5·AuCl$_4^-$.

Given the failure of 5·Cl$^-$ to bind Au, we turned to the frontier molecule orbitals (FMOs) of this complex to gain a clearer understanding of its electron distribution. Apparent from the HOMO, was the presence of a pure *π*-type orbital at N(3) that shared an antibonding relationship with respect to the MO density of the two adjacent ring systems, while no orbital density was present on the AuCl$_4^-$ counterion. Further still, a detailed inspection of the lower lying HOMO−3 and HOMO−5, which are more stable than the HOMO (E = −6.68, −6.86 vs −5.62eV) and thus less available for bonding, revealed the presence of a small *σ*-type lone pair. On the other hand, the LUMO resided totally on the AuCl$_4^-$ counterion. In view of these trends, and the modest HOMO−LUMO gap of 2.09eV of 5·AuCl$_4^-$, as well as the negative partial charge of N(3), it would appear that N(3)-Au bond formation is in part disfavored by sterics (Figure 3).

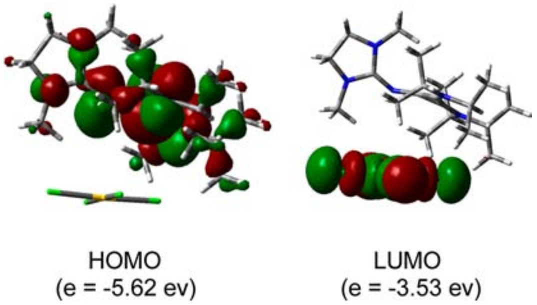


Figure 3. Plot of the HOMO and LUMO of 5·AuCl$_4^-$. Orbital energies were computed at the B3LYP/SDD level of theory.

Taken that steric hindrance represented a potential obstacle of 5·Cl$^-$ to bind metals, the protonation of 5·Cl$^-$ was attempted using trifluoroacetic acid (TFA). Accordingly, an excess of TFA was added to a solution of 5·Cl$^-$ in DCM that after stirring for 1 h was concentrated to afford a solid which exhibited three ^{15}N NMR signals at δ = 120.96, 108.11, and 82.68 ppm in comparison to 128.58, 105.50, and 81.28 ppm for the compound 5·Cl$^-$. Intrigued by these chemical shift differences we attempted to obtain a X-ray structure that despite exhaustive efforts proved challenging, yet ultimately did allow for a tentative structural assignment as **5**·(TFA)$_3$Cl$^-$ from a low quality X-ray structure, the coordinates of which were used as a starting point for DFT calculations (see the Supporting Information for X-ray coordinates).

The DFT-optimized structure of **5**·(TFA)$_3$Cl$^-$ revealed that the Cl$^-$ resided far from the parent cation **5** at a N(1)···Cl(1) distance of 6.63 Å (Figure 4). Contributing to the marked displacement of Cl$^-$ anion (average C(12,13,20)···Cl(1) distance = 7.98 Å) presumably was cyclopropenylium-based "ion pair strain", which in combination with the presence of a well-organized network of TFA-based H-bonds ultimately displaces the Cl$^-$ towards the adjacent heterocyclic ring system of cation **5**.

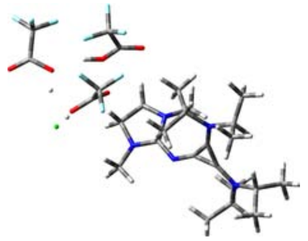
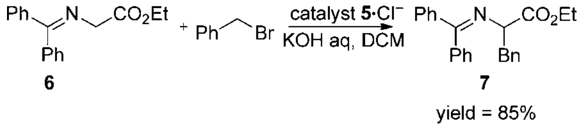


Figure 4. 3D optimized geometry of **5**·Cl(TFA)$_3^-$ computed at the B3LYP/6-311G(d) level of theory.

As for perhaps the most salient bonding feature of computed **5**·(TFA)$_3$Cl$^-$, Wiberg bond indices provided nearly equivalent bond orders of 1.31 and 1.30 for N(1)−C(7) and N(1)−C(12), consistent with partial double-bond character. Instructive as well was the insight gained from atoms in molecules (AIM) theory which supported the Wiberg bond order assignment of partial double bond character to N(1)−C(7) and N(1)−C(12). More specifically, AIM revealed that the N(1)−C(7) and N(1)−C(12) bonds were covalent in nature with a degree of π-bonding character based on the Laplacian ($\nabla^2\rho_{\mathrm{bcp}}$) values of −0.246 and −0.271, electron densities (ρ_{bcp}) of 0.346 and 0.342, and the total electronic energies (H_{bcp}) −0.469 and −0.471 at the corresponding (3, −1) bond critical points (BCPs) defining these bonds, respectively.[8] Also diagnostic of partial π-bonding were the calculated ellipticities (π) of 0.130 and 0.080 at these two BCPs, with the N(1)−C(7) bond having a greater degree of double bond character than that of N(1)−C(12), thus suggesting the bonding in **5**·(TFA)$_3$Cl$^-$ was more weighted toward mesomeric form **5b** (vide supra). AIM theory as well revealed the presence of a bond path between H(10a) and C(12) (ρ = 0.01, $\nabla^2\rho_{\mathrm{bcp}}$ = 0.0094) with a (3, −1) BCP located closer to the atomic basin of H(10a), suggesting the presence of an C−H(10a)···π_{aryl} interaction. Furthermore, application of Schleyer's nucleus independent chemical shift (NICS) method indicated that the cyclopropenylium ring of **5**·(TFA)$_3$Cl$^-$ had appreciable aromatic character (NICS (0) = −30.5, NICS (−1) = 9.2, NICS (1) = −8.9), consistent with the existence of an C−H(10a)···π_{aryl} interaction. Moreover, the summed NAO charges of C(12), C(13), and C(20) ($\Sigma_{i=1}^{3} Ci = 0.714\ e$) supported the presence of an aromatic cyclopropenium cation. Given the importance of C−H···π_{aryl} interactions in crystal packing,[9] structures of biological molecules,[10a−c] molecular recognition processes,[11a−d] and as directing elements in asymmetric reactions,[12] it is noteworthy that the involvement of a cyclopropenium ring system in such an interaction is unprecedented to the best of our knowledge.

At that stage, given the lipophilic nature of the cation of **5**·Cl$^-$ this ion pair was applied to phase-transfer catalysis. To this end, the benzylation of **6** catalyzed by **5**·Cl$^-$ (1 mol %) under hydroxide-initiated PTC conditions[13] using a biphasic aqueous KOH (50%)/dichloromethane system was conducted which to our delight after 4 h at rt afforded **7** in 85% yield (Scheme 3), whereas a control reaction without **5**·Cl$^-$ gave unreacted starting material.

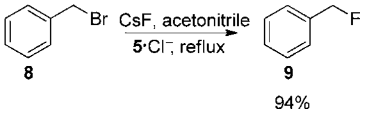
Scheme 3. Benzylation of Schiff Base 6 Using KOH Aqueous Catalyst 5·Cl$^-$ Phase-Transfer Conditions



Notably, this transformation represents the first example of a PTC reaction using a mixed imidazoliumyl *N*-cyclopropenylium substituted N-centered catalyst, which is additionally notable as the related pentanidium and 2-amino-*N*,*N*′-dialkyl-4,5-dimethylimidazolium PTCs that have been reported are symmetrically substituted. Given this promising result, we are currently investigating the use of chiral derivatives in asymmetric phase transfer catalysis (APTC).[14a−d] The relative stability of **5**·Cl$^-$ to concentrated biphasic (50% KOH) PTC conditions as well deserves mention as it along with the X-ray data and DFT findings presented herein are more consistent with the two heterocyclic rings of cation **5** being covalently bonded as opposed to datively coordinated as carbene ligands to the central nitrogen. Accordingly, based on the finding herein the structure of **5** is perhaps best described as mainly a composite of mesomers **5b**-**5c** with a small contribution from **5d**. This point should be appreciated as it provides in many ways clarification regarding the current questionable views of bonding in N-centered cations.

Lastly, given the successful application of **5**·Cl$^-$ as a PTC and the current demand for fluorination methodologies, especially metal-free approaches, we applied **5**·Cl$^-$ as a catalyst for benzylic fluorination. Thus, a heterogeneous acetonitrile solution of benzyl bromide (**8**) (1 equiv), cesium fluoride (4 equiv), and catalyst **5**·Cl$^-$ were refluxed for 9 h to afford, to our delight, benzyl fluoride (**9**) in 94% yield (Scheme 4). However, when the reaction of benzyl bromide was performed under the same conditions in absence of catalyst **5**·Cl$^-$ only a trace amount of the fluorinated product was obtained (~5% yield). A salient feature of this protocol was the column-free purification of the product and recovery of the catalyst that could be used for subsequent reaction cycles with no apparent loss in catalytic reactivity (up to 5 cycles attempted); see the Supporting Information for details. Attesting to the reliability of this fluorination protocol as well was the reaction of several other substitution benzyl bromides which afforded the corresponding fluorinated adducts in high yields (Figure 5); see the Supporting Information for reaction conditions. It is additionally noteworthy that in comparison to

Scheme 4. Fluorination of Benzyl Bromide Using Phase-Transfer Catalyst 5·Cl$^-$ in Acetonitrile



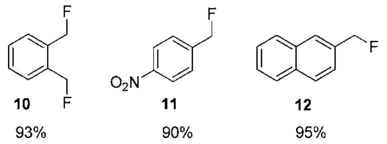


Figure 5. Examples of fluorination products derived from bromide substrates.

anhydrous TBAF based fluorination of benzylic substrates the approach introduced herein affords higher yields and does not require prior reagent preparation.[15] Furthermore, when compared with the alternative use of semimolten mixtures of tetrabutylammonium bromide and alkali metal fluorides it deserves mention that fluorination with catalyst $5\cdot\text{Cl}^-$ could be achieved under much milder conditions.[16]

Taken together, a structural class of phase-transfer catalysts offering fundamental insight into the chemical bonding of disubstituted N- vs so-called divalent carbene-stablized N^{I}-centered cations was presented. A marked feature of these PTC was the presence of a highly dissociated anion resulting from interionic donor−donor “ion pair strain”. Notably, this structural attribute provides what potentially is a unique design element for catalytic activity. In this context, congener $5\cdot\text{Cl}^-$ was applied as a catalyst for benzylation and benzylic fluorination. Emerging from DFT calculations was the finding that the central nitrogen had a measurable degree of negative charge and a significant amount of partial double bonding with respect to the adjacent ring systems, providing convincing evidence against divalent carbene-stablized N^{I} character. Of interest as well was the unprecedented finding of a $\text{C−H}\cdots\pi_{\text{aryl}}$ interaction between the cyclopropenium ring and a proximal hydrogen in one of these systems. Accordingly, efforts in our laboratory are currently focusing on the advancement and applications of chiral congeners of these PTC and the further development of systems with cyclopropenium based $\text{C−H}\cdots\pi_{\text{aryl}}$ interactions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Experimental details for the synthesis of $5\cdot\text{X}$ ($\text{X} = \text{Cl}^-$, AuCl_4^-, $(\text{TFA})_3\text{Cl}^-$), spectroscopic data of $5\cdot\text{Cl}^-$, DFT calculations, and crystallographic (CIF) data for $5\cdot\text{X}$ ($\text{X} = \text{AuCl}_4^-$, $(\text{TFA})_3\text{Cl}^-$). This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: tdudding@brocku.ca.

Notes

The authors declare no competing financial interest.

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