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Bifunctional Iodoazolium Salts: Searching for Cooperation Between Halogen Bonding and Hydrogen Bonding

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Non-covalent interactions play an important role in all sub-fields of chemistry, including catalysis, where interactions of different natures can work together to improve reactivity and selectivity. Several families of molecules that incorporate both hydrogen bond (HB) and halogen bonding (XB) donors have already been studied. However, there is a lack of data on how grafting HB donors to iodoazolium salts could impact their association and reactivity properties. Herein, we disclose the synthesis of a library of iodoazolium salts bearing varied HB

donors, along with a study of their physico-chemical properties using different techniques (X-ray diffraction, ³¹P NMR, ITC) and their behavior in catalysis. Even though no clear-cut evidence of cooperation between XB and HB could be obtained through physico-chemical evaluations, a iodoazolium salt bearing a urea function displayed better conversion and product selectivity in a Ritter reaction than all other activators lacking one or the other function.

Introduction

Attractive non-covalent interactions play an essential role in all fields of chemistry, and have received strong attention for the development of catalysts.^[1] In this context, the most studied non-covalent interaction is the hydrogen bond (HB),^[2] but many others such as pi-pi,^[3] anion-pi,^[4] or cation-pi^[5] interactions have also gained popularity. Among non-covalent interactions, the halogen bond (XB) has long received less attention, probably because of earlier difficulties in its precise identification.^[6] However, the recent years have seen tremendous developments, so that XB is now applied in fields of chemistry,^[7] including organocatalysis.^[8]

An interesting aspect of non-covalent interactions is that they can easily cooperate to increase both the rate and the stereoselectivity of the reaction.^[9] Examples of cooperation between XB and HB are known in biological systems,^[10] and have also found applications in synthetic chemistry, with four different scenarios (Figure 1):^[11]

(i) *Parallel cooperation of XB and HB* that separately interact with the same molecule of substrate or different ones: it is the case for urea-(polyfluoro)iodoarene such as **1** or **2**,^[12]

and in catenane and rotaxane systems developed by Beer and co-workers or in diaryliodolum salts (not shown).^[13]

- (ii) *HB-preorganized XB*: as reported by the group of Schubert, intramolecular HB within the structure of a bis-(iodoazole-phenol) containing structure **3** helps preorganizing this scaffold for improved XB properties.^[14]
- (iii) *HB-assisted XB*: for example, DFT calculations provided evidence that hydrogen-bond-assisted halogen bonding could exist between inorganic species: Br₂ and HF can create a complex network **4** when combined with the Lewis-basic NH₃.^[15] For organic molecules, Berryman (iodopyridinium ions bearing amine or amide functions **5** and **6**) and others have disclosed structures including external (to the backbone) or internal (to the iodine atom lone pairs) HB-assistance, respectively.^[16] In both cases, HB-assistance resulted in much stronger XB and improved catalytic activities.
- (iv) *XB-assisted HB*: recently, the group of Takemoto showed that the sulfur atom of Schreiner thiourea can interact as a Lewis base with an iodobenzimidazolium ring.^[17] The supramolecular assembly **7** becomes a very efficient catalyst for *N*-glycofunctionalization, whereas the two separated species are unable to perform the reaction.

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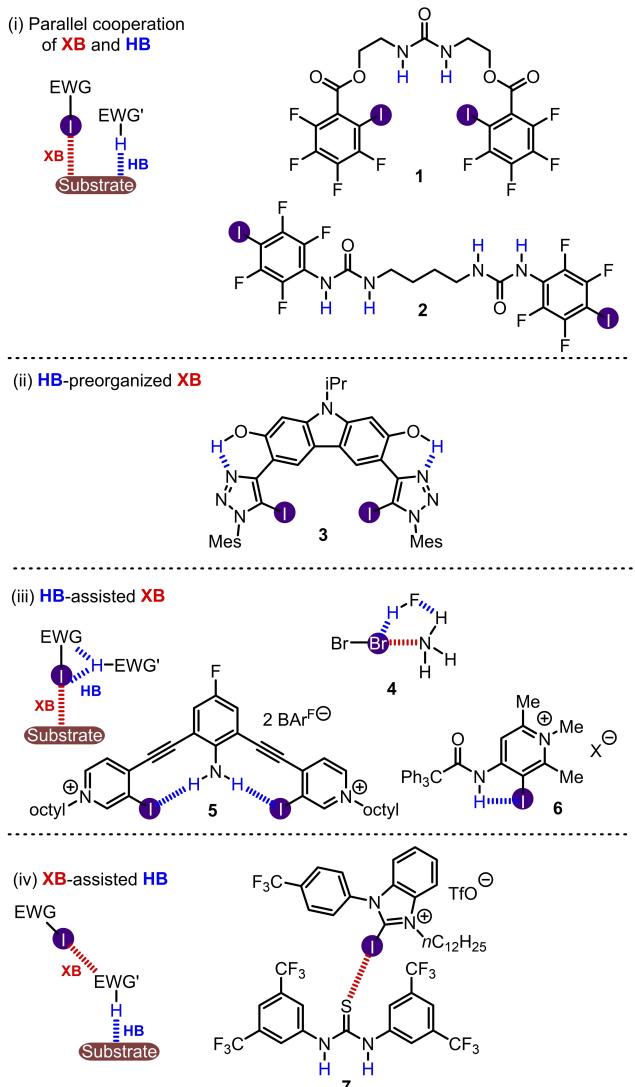


Figure 1. Four different scenarios for the cooperation between XB and HB.

Haloazolium ions represent a very interesting family of halogen-bond donors since they exhibit strong interaction with Lewis bases and a comparative reluctance to transfer their halogen atom.^[18] Much to our surprise, studies on the possibility to prepare haloazolium ions that incorporate a HB donor are extremely scarce,^[19] and the effect of their potential collaboration on association constants of catalytic efficiency is not documented. Herein, we wish to disclose our first attempts at preparing a family of bifunctional iodoazolium salts bearing a variety of HB donors, along with the study of their properties using physico-chemical methods and preliminary catalytic attempts.

Results and Discussion

Synthesis and Structure of Iodoazolium Salts Bearing Diverse HB Donors

Our experimental studies started with the design of a simple and flexible synthesis of original iodoazolium salts **10aa–cf·Br**– bearing diversified HB donors (Table 1). The key step consisted in a nucleophilic substitution between easily accessible 2-iodo-1-arylimidazole **8a–c** and functionalized benzyl bromides **9a–f**.^[20] The reaction proceeded smoothly at room temperature, delivering the expected products in reasonable yields and purities. Long reaction times (3 days) were required and heating could not help as it resulted in extensive degradation, notably deiodination and protonation. The aromatic substituent of **8a–c** incorporated either an electron-donating (–OMe) or an electron-withdrawing (–CF₃) group at position 4, or consisted of a mesityl ring to evaluate the effect of steric hindrance on XB.^[21] Benzylic bromides included the parent compound **9a** as a reference and other ones incorporating HB candidates such as a benzylic alcohol (**9b**), a carbamate (**9c**), a sulfonamide (**9d**), an urea (**9e**) and a squaramide (**9f**). Products were obtained in moderate to good purities after simple filtration, which could sometimes be improved by crystallization, but not by flash chromatography which caused extensive degradation.

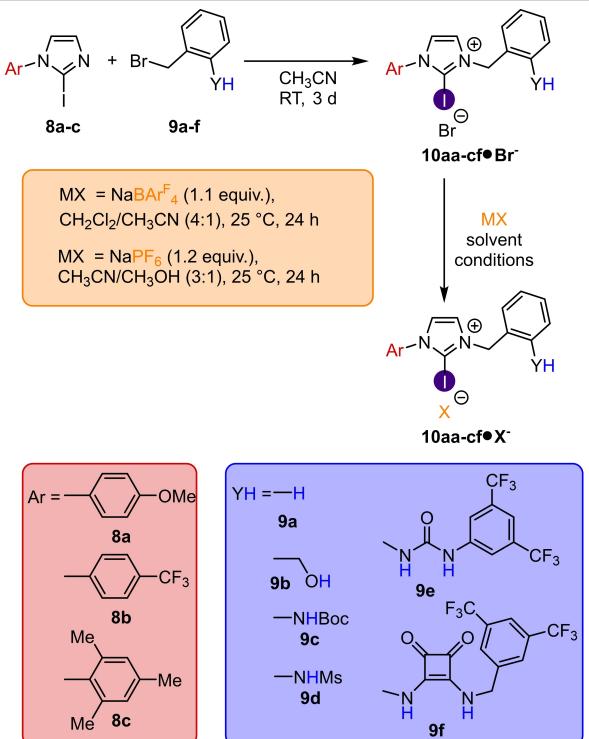
To avoid the interference of the bromide anion in the evaluation of the association between XB and HB, ion metathesis was performed with different counterions including $\text{BAr}^{\text{F}}_4^-$ and PF_6^- , to deliver the corresponding iodoazolium salts **10aa–cf·BAr}^{\text{F}}_4^-** and **10aa–cf·PF}_6^-**. An interesting feature of ion metathesis is that it increased product stabilities, allowing purification of the iodoazolium salts by flash chromatography to obtain pure materials.

Among all the prepared XB donors, monocrystals suitable for X-ray diffraction could be grown for three of them: **10aa·Br**–, **10ac·Br**– and **10ab·PF}_6^-** (Figure 2).^[20] The structure of **10aa·Br**– clearly establishes the existence of XB with a I–Br distance of 3.105 Å (81% of the sum of the van der Waals radii) with a C–I–B angle of 175.6°. The presence of a HB donor (NHBOC) in the structure of **10ac·Br**– did not seem to have a strong influence on its behavior in the solid state since no HB could be observed. XB remained largely unchanged with a I–Br distance of 3.041 Å (81% of the sum of the van der Waals radii) and a nearly perfect alignment between the three atoms involved in the interaction (178.7°). Lastly, the inertness of the weakly coordinating PF_6^- anion towards XB was confirmed by the structure of **10ab·PF}_6^-**, where the anion lies away from the iodine atom, with a non-directional electrostatic interaction with the cation.

Physico-Chemical Studies

Even though solid state analysis failed to provide any insight about the potential cooperation between XB and HB in our bifunctional iodoazolium salts, we wanted to evaluate their properties in solution, which might be very different. In order to

Table 1. Synthesis of iodoazonium salts $10\text{aa-cf}\cdot\text{Br}^-$ and counter-anion exchange to prepare $10\text{aa-cf}\cdot\text{BAr}_4^F^-$ and $10\text{aa-cf}\cdot\text{PF}_6^-$.



Entry	Product ^[a]	Yield for 1 st step (%) ^[b]	Yield for 2 nd step (%) ^[b]
1	$10\text{aa}\cdot\text{BAr}_4^F^-$	80	79
2	$10\text{aa}\cdot\text{PF}_6^-$		93
3	$10\text{ab}\cdot\text{BAr}_4^F^-$	76	85
4	$10\text{ab}\cdot\text{PF}_6^-$		90
5	$10\text{ac}\cdot\text{BAr}_4^F^-$	84	93
6	$10\text{ad}\cdot\text{BAr}_4^F^-$	58	81
7	$10\text{ae}\cdot\text{BAr}_4^F^-$	58	98
8	$10\text{af}\cdot\text{BAr}_4^F^-$	43	99
9	$10\text{ba}\cdot\text{BAr}_4^F^-$	71	86
10	$10\text{bb}\cdot\text{BAr}_4^F^-$	80	88
11	$10\text{bc}\cdot\text{BAr}_4^F^-$	62	89
12	$10\text{ca}\cdot\text{BAr}_4^F^-$	64	73
13	$10\text{cb}\cdot\text{BAr}_4^F^-$	91	72
14	$10\text{cc}\cdot\text{BAr}_4^F^-$	78	81

[a] Elucidation of product numbering: 10xy is prepared from 8x and 9y . [b] See SI for experimental details.

collect rapidly data for all the prepared compounds, we selected the Gutmann-Beckett method consisting in the saturation of a solution of triethylphosphine oxide (TEPO, 11) in CD_2Cl_2 and CH_2Cl_2 with a large excess of the XB/HB donor to measure the influence on the chemical shift in ^{31}P NMR (Table 2).^[22] This method seemed especially appealing because of its easy implementation and since it has been recently applied for the separate evaluation of both HB^[23] and XB,^[24] with higher $\Delta\delta(^{31}\text{P})$ values correlating with stronger attractive interactions. For comparison purposes, TEPO analysis was applied to bifunctional iodoazonium salts $10\text{aa-cf}\cdot\text{X}^-$ but also

to the corresponding azonium salts $12\text{ae-af}\cdot\text{BAr}_4^F^-$ and hydrogen bond donors 13ae-af .^[20] Reference compound $10\text{aa}\cdot\text{BAr}_4^F^-$ without HB donor showed a $\Delta\delta(^{31}\text{P})$ value of 6.70 ppm, in accordance with the literature data for other iodoazonium salts (5.68–6.25 ppm).^[24b] Placing a benzylic alcohol in the structure of $10\text{ab}\cdot\text{BAr}_4^F^-$ had no significant impact on $\Delta\delta(^{31}\text{P})$, in accordance with its relatively weak HB donor ability. Quite surprisingly, the NHBoc moiety of $10\text{ac}\cdot\text{BAr}_4^F^-$ decreased $\Delta\delta(^{31}\text{P})$ to 6.06 ppm. However, it is documented that NHBoc carbamates behave as stronger HB acceptors on the oxygen atom than HB donors.^[25] Therefore, we can imagine that they

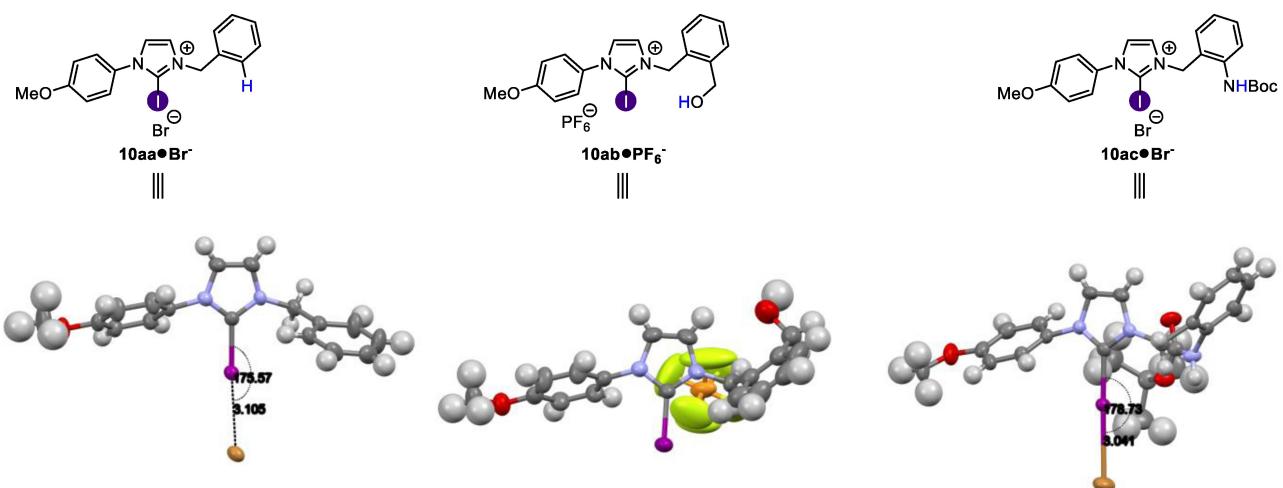


Figure 2. X-ray diffraction on monocrystals of several iodoazolium salts.

Table 2. TEPO analyses of bifunctional iodoazolium salts.

$\text{Et}^2\text{P}(\text{OEt})_2$ + $\text{X}^{\bullet}\text{B}/\text{HB}$ donor (10 equiv) $\xrightarrow[\text{CD}_2\text{Cl}_2, \text{CH}_2\text{Cl}_2]{}$ complex of TEPO with $\text{X}^{\bullet}\text{B}/\text{HB}$ donor (10 equiv)	
	$\Delta\delta^{(31)\text{P}} = ? \text{ ppm}^{[a]} / \text{AN}^{[b]}$
Evaluation of HB-donor	
$10\text{aa} \bullet \text{BAr}_4^-$: 6.70 / 35.9	$10\text{ab} \bullet \text{BAr}_4^-$: 6.71 / 35.9
$10\text{ac} \bullet \text{BAr}_4^-$: 6.05 / 34.5	$10\text{ad} \bullet \text{BAr}_4^-$: 6.16 / 34.7
$10\text{ae} \bullet \text{BAr}_4^-$: 7.95 / 38.7	$12\text{ae} \bullet \text{BAr}_4^-$: 8.37 / 39.6
13ae : 6.64 / 35.8 ^[c]	$14\text{ae} \bullet \text{BAr}_4^-$: 7.98 / 38.7
$10\text{af} \bullet \text{BAr}_4^-$: 10.10 / 43.4	$12\text{af} \bullet \text{BAr}_4^-$: 10.52 / 44.4
	13af : - / - ^[d]
Electronic and steric effects	
$10\text{ba} \bullet \text{BAr}_4^-$: 6.60 / 35.7	$10\text{bb} \bullet \text{BAr}_4^-$: 6.40 / 35.2
$10\text{bc} \bullet \text{BAr}_4^-$: 6.42 / 35.3	
$10\text{ca} \bullet \text{BAr}_4^-$: 5.80 / 33.9	$10\text{cb} \bullet \text{BAr}_4^-$: 5.90 / 34.1
	$10\text{cc} \bullet \text{BAr}_4^-$: 5.76 / 33.8
Counterions	
$10\text{aa} \bullet \text{PF}_6^-$: 4.53 / 31.1	$10\text{ab} \bullet \text{PF}_6^-$: 3.67 / 29.2

[a] A stock solution of TEPO (11, 83 mM) was prepared in CH_2Cl_2 . The compound to analyze (0.083 mmol, 10 equiv) was dissolved in a mixture of CH_2Cl_2 (250 μL) and CD_2Cl_2 (200 μL), and transferred into an NMR tube, followed by the addition of the suitable amount of TEPO solution (100 μL , 0.0083 mmol, 1 equiv). The sample was analyzed by ^{31}P NMR (300 MHz) and $\Delta\delta^{(31)\text{P}} = \delta^{(31)\text{P}}_{\text{sample}} - \delta^{(31)\text{P}}_{\text{TEPO}}$ with $\Delta\delta^{(31)\text{P}}_{\text{TEPO}} = 50.55 \text{ ppm}$. [b] Acceptor number AN = $2.21 * (\delta^{(31)\text{P}}_{\text{sample}} - 41.0)$ [c] Only 3 equiv. of compound to analyze, because of low solubility. [d] Solubility of 13 af was not sufficient to obtain a reliable result.

could rather compete with TEPO as XB acceptors than being HB donors. The same tendency was observed for the NHMs group of **10ad**· $\text{BAr}^{\text{F}}_4^-$.

To outcompete these unwanted interactions, we turned our attention towards better HB donors such as ureas^[26] and squaramides.^[27] Urea-containing iodoazolium salt **10ae**· $\text{BAr}^{\text{F}}_4^-$ indeed exhibited a stronger $\Delta\delta(^{31}\text{P})$ than the parent compound, but it was even higher for the corresponding azolium salt **12ae**· $\text{BAr}^{\text{F}}_4^-$ (8.37 ppm against 7.95 ppm). To verify the role of the urea function, compound **13ae** lacking the (iodo)azolium unit was prepared.^[20] When it was submitted to TEPO analysis, a $\Delta\delta(^{31}\text{P})$ value of 6.64 ppm was obtained,^[28] which is matching literature precedents.^[23a] These results lead us to elaborate two distinct scenarios to explain the observed high $\Delta\delta(^{31}\text{P})$ value for **10ae**· $\text{BAr}^{\text{F}}_4^-$:

- either it acts only as a strong double HB donor thanks to its urea function, whose ability is heightened by the electron-withdrawing effects of the cationic (iodo)azolium rings, with stronger intensity for the more electron-deficient azolium ring of **12ae**· $\text{BAr}^{\text{F}}_4^-$ than for the iodoazolium ring of **10ae**· $\text{BAr}^{\text{F}}_4^-$;
- or **10ae**· $\text{BAr}^{\text{F}}_4^-$ actually exhibits XB/HB cooperation, but with a geometry that is less favored than the HB/HB cooperation of **12ae**· $\text{BAr}^{\text{F}}_4^-$.

To discriminate between those two scenarios, ureido 2-methylazolium **14ae**· $\text{BAr}^{\text{F}}_4^-$, which lacks a strong interaction point at position 2 of the azolium ring (hydrogen bonding to the hydrogen atoms of the methyl group or to the positions 4 and 5 of the imidazolium ring cannot be ruled out), was also prepared.^[20] Its $\Delta\delta(^{31}\text{P})$ value of 7.98 ppm similar to **12ae**· $\text{BAr}^{\text{F}}_4^-$ seems to be in favor of the first scenario of electrostatic activation of the urea HB donor properties, and to rule out that an efficient XB/HB cooperation occurs for **10ae**· $\text{BAr}^{\text{F}}_4^-$.

The same trend was observed in the squaramide series, with once again a stronger $\Delta\delta(^{31}\text{P})$ for the non-iodinated **12af**· $\text{BAr}^{\text{F}}_4^-$ than for **10af**· $\text{BAr}^{\text{F}}_4^-$ (10.52 ppm against 10.10 ppm). The squaramide **13af** with no (iodo)azolium ring could not be compared because of its too low solubility.

We also wanted to evaluate whether the electronic and steric properties could have an impact on the XB and HB strengths. The iodoazolium salts bearing the trifluoromethyl substituent exhibited $\Delta\delta(^{31}\text{P})$ similar to the ones with the methoxy group, showing no evidence for an impact of this electron-withdrawing substituent. These values were reduced by a little bit less than 1 ppm in the mesyl series. Moreover, no strong positive influence of the alcohol or NHBoc HB donors could be observed, with only a slightly higher $\Delta\delta(^{31}\text{P})$ for **10cb**· $\text{BAr}^{\text{F}}_4^-$ compared to **10ca**· $\text{BAr}^{\text{F}}_4^-$ (5.90 ppm against 5.80 ppm). To finish, two compounds bearing a PF_6^- instead of $\text{BAr}^{\text{F}}_4^-$ as anion were evaluated. A $\Delta\delta(^{31}\text{P})$ reduced by 2 ppm was observed for **10aa**· PF_6^- , in accordance with the more coordinating nature of PF_6^- , with 1 additional ppm reduction for compound **10ab**· PF_6^- with the alcohol function.^[24b]

To complete the TEPO analyses, we also wanted to evaluate several of our compounds using a titration method.^[30] For about a decade, isothermal titration calorimetry (ITC) has established itself as the most powerful method to characterize the

association between XB donors and Lewis bases in solution.^[31] It notably has the advantage to be a global method (compared to NMR techniques which rely on local modifications, such as changes in the chemical shift of one selected proton). Moreover, ITC can give an access to all thermodynamic parameters of the equilibrium (stoichiometry N , dissociation constant K_D and its inverse, association constant K_A , variations of Gibbs free energy ΔG , enthalpy ΔH and entropy ΔS) in only one experiment. ITC analyses have been conducted on the three compounds **10ae**· $\text{BAr}^{\text{F}}_4^-$, **12ae**· $\text{BAr}^{\text{F}}_4^-$, **13ae** and **14ae**· $\text{BAr}^{\text{F}}_4^-$ that bear an urea function, which were combined with tetrabutylammonium bromide (TBABr) in CH_3CN (Table 3). The experiments were carried out at 1.00 mM of studied compound in the cell and 10.0 mM of TBABr in the syringe, delivering good quality titration curves.^[20] For the three compounds, only the fitting model with one set of sites allowed the regression to converge and furnish the thermodynamic parameters, pointing towards a scenario where the urea function is mostly responsible for ion sensing. The monofunctional urea **13ae** exhibited an association constant of $1.38 \cdot 10^3 \text{ M}^{-1}$ consistent with the literature value ($1.49 \cdot 10^3 \text{ M}^{-1}$) for Schreiner thiourea in related experimental conditions (Entry 3).^[31] The association constants of the three cationic compounds are about 10 times higher, with the iodinated compound being slightly less efficient: $1.55 \cdot 10^4 \text{ M}^{-1}$ for **10ae**· $\text{BAr}^{\text{F}}_4^-$, to be compared with $2.15 \cdot 10^4 \text{ M}^{-1}$ for **12ae**· $\text{BAr}^{\text{F}}_4^-$ and $2.00 \cdot 10^4 \text{ M}^{-1}$ for **14ae**· $\text{BAr}^{\text{F}}_4^-$ (Entries 1 to 3). It should also be noted that the interactions of the cationic compounds display similar profiles with strong entropic contributions, whereas the interaction with **13ae** seems to be more dominated by enthalpic factors. Last but not least, even though the two methods are completely different in their physico-chemical principles and nature of the Lewis bases, the ITC measured association constants and the TEPO $\Delta\delta(^{31}\text{P})$ values follow remarkably similar trends for these four ureas.

Table 3. ITC analyses in the urea series^[a].

Entry	Results
1	10ae · $\text{BAr}^{\text{F}}_4^-$ $N = 0.926^{\text{[b]}}$ $K_D = 6.44 \cdot 10^{-5} \pm 8.39 \cdot 10^{-6} \text{ M}$ $K_A = 1.55 \cdot 10^4 \text{ M}^{-1}$ $\Delta G = -23.9 \text{ kJ.mol}^{-1}$ $\Delta H = -7.28 \pm 0.22 \text{ kJ.mol}^{-1}$ $-\Delta S = -16.7 \text{ kJ.mol}^{-1}$
2	12ae · $\text{BAr}^{\text{F}}_4^-$ $N = 0.895^{\text{[b]}}$ $K_D = 4.66 \cdot 10^{-5} \pm 9.99 \cdot 10^{-7} \text{ M}$ $K_A = 2.15 \cdot 10^4 \text{ M}^{-1}$ $\Delta G = -24.7 \text{ kJ.mol}^{-1}$ $\Delta H = -7.03 \pm 0.03 \text{ kJ.mol}^{-1}$ $-\Delta S = -17.7 \text{ kJ.mol}^{-1}$
3	13ae $N = 0.995^{\text{[b]}}$ $K_D = 7.23 \cdot 10^{-4} \pm 1.12 \cdot 10^{-4} \text{ M}$ $K_A = 1.38 \cdot 10^3 \text{ M}^{-1}$ $\Delta G = -18.0 \text{ kJ.mol}^{-1}$ $\Delta H = -10.9 \pm 0.98 \text{ kJ.mol}^{-1}$ $-\Delta S = -7.1 \text{ kJ.mol}^{-1}$
4	14ae · $\text{BAr}^{\text{F}}_4^-$ $N = 0.778^{\text{[b]}}$ $K_D = 5.01 \cdot 10^{-5} \pm 8.25 \cdot 10^{-7} \text{ M}$ $K_A = 2.00 \cdot 10^4 \text{ M}^{-1}$ $\Delta G = -24.6 \text{ kJ.mol}^{-1}$ $\Delta H = -7.56 \pm 0.03 \text{ kJ.mol}^{-1}$ $-\Delta S = -17.0 \text{ kJ.mol}^{-1}$

[a] Parameters: cell: C(**10ae**· $\text{BAr}^{\text{F}}_4^-$, **12ae**· $\text{BAr}^{\text{F}}_4^-$, **13ae** or **14ae**· $\text{BAr}^{\text{F}}_4^-$) = 1.00 mM; syringe: C(TBABr) = 10.0 mM; solvent: CH_3CN ; $T = 25.1\text{--}25.2^\circ\text{C}$; fitting model: one set of sites Several fitting models were evaluated, with the one accounting for a 1:1 interaction providing the best correlation.

[b] Stoichiometry of the complex.

Reactivity Attempts

Despite physico-chemical studies that do not seem to show positive impact of the HB donors on the properties of the iodoazolium salts, we carried out some catalytic attempts. Indeed, catalytic processes are much more complex than the simple association with a Lewis base since they involve several consecutive steps that might be sensitive to very slight differences in the catalyst structure. Especially, stronger interactions from the catalyst are sometimes deleterious to the overall reaction as they might result in inhibition by the product.

Initially, efforts to perform a hetero-Diels–Alder reaction between imines and dienes, which had already been promoted by other mono-iodoazolium salts,^[21,32] were not conclusive. Imines possess only one lone pair on the nitrogen atom, so that concomitant XB and HB activation of this substrate is hard to conceive, leaving only the HB-activated XB scenario as possible. To test the scenario of parallel activation by XB and HB, we wanted to evaluate our bifunctional iodoazolium salts in a reaction where the Lewis base possesses several lone pairs.

For this, we retained the Ritter-type solvolysis of bromodiphenylmethane (15) in CD_3CN , which affords amide 16 in the presence of trace amounts of water (Table 4).^[33] This reaction is usually promoted by stoichiometric or sub-stoichiometric amounts of double XB-donors, and we wanted to assess the

possibility for the HB-donor to replace the second XB-donor. At first, the substrate was placed in CD_3CN , containing traces of water, at room temperature. After 72 h, 7% conversion to the final product 17 was observed (Entry 1). Using non-bifunctional iodoazolium salts $12\text{aa}\cdot\text{BAr}^{\text{F}}_4^-$ increased the conversion to 41%, with a product distribution of 80:20 between the Ritter product 16 and the product of direct hydrolysis 17 (Entry 2). Placing an alcohol function as HB donor in $10\text{ab}\cdot\text{BAr}^{\text{F}}_4^-$ had a positive impact on the conversion (52%) but also complicated the product distribution. Indeed, a third product 18 resulting from the trapping of the substrate by the alcohol function was also present (Entry 3).^[34]

Since urea- and squaramide-containing XB donors were more promising in terms of physico-chemical properties, we also evaluated them in the Ritter-type solvolysis. Pleasingly, $10\text{ae}\cdot\text{BAr}^{\text{F}}_4^-$ afforded a better conversion than all other compounds, with also a high ratio between the Ritter product 16 and benzhydrol alcohol 17 (Entry 4). Both the compound lacking the iodine atom $12\text{ae}\cdot\text{BAr}^{\text{F}}_4^-$ and the one without the azolium unit 13ae were not as efficient (Entries 5 and 6), pointing towards a positive impact of incorporating the iodoazolium and the urea motives within the structure of $10\text{ae}\cdot\text{BAr}^{\text{F}}_4^-$. Control experiment with the 2-methylazolium activator $14\text{ae}\cdot\text{BAr}^{\text{F}}_4^-$ resulted in less convincing results (lower conversion and selectivity, Entry 7), letting the iodinated

Table 4. Reactivity attempts in Ritter-type solvolysis.

Entry	Activating agent ^[a]	Conversion of 15 (%) ^[b]	Product distribution ^[b]
1	no activating agent	7%	Only 16
2	$10\text{aa}\cdot\text{BAr}^{\text{F}}_4^-$	41%	$16/17=80:20$
3	$10\text{ab}\cdot\text{BAr}^{\text{F}}_4^-$	52%	$16/17/18=57:7:35$
4	$10\text{ae}\cdot\text{BAr}^{\text{F}}_4^-$	61%	$16/17=96:4$
5	$12\text{ae}\cdot\text{BAr}^{\text{F}}_4^-$	45%	$16/17=85:15$
6	13ae	28%	$16/17=88:12$
7	$14\text{ae}\cdot\text{BAr}^{\text{F}}_4^-$	39%	$16/17=74:26$
8	$10\text{af}\cdot\text{BAr}^{\text{F}}_4^-$ ^[c]	61%	$16/17=81:19$
9	$12\text{af}\cdot\text{BAr}^{\text{F}}_4^-$ ^[c]	68%	$16/17=90:10$
10	13af ^[c]	38%	$16/17=67:33$
11	$10\text{ae}\cdot\text{BAr}^{\text{F}}_4^-$ ^[d]	40%	$16/17=89:11$

[a] Bromodiphenylmethane (15, 2.5 mg, 0.010 mmol, 1.0 equiv.), the activating agent (0.010 mmol, 1.0 equiv.) and CH_2Br_2 (1.9 mg, 0.86 μL , 0.010 mmol, 1.0 equiv.) as internal standard were dissolved in CD_3CN (0.50 mL), and the reaction mixture analyzed after 72 h at room temperature. [b] Conversions and product distributions were determined by ^1H NMR: substrate 15 (singlet at 6.44 ppm), expected product 16 (doublet at 6.23 ppm) and diphenylmethanol 17 (singlet at 5.78 ppm) and. [c] Reaction time: 96 h. [d] A sub-stoichiometric amount of activating agent $10\text{ae}\cdot\text{BAr}^{\text{F}}_4^-$ (0.004 mmol, 0.4 equiv.) was used and TMSOH (0.030 mmol, 3.0 equiv.) was added.

compound **10ae·BAr₄^F** as the clear best activating agent in the series. On the contrary, the results in the squaramide series were less interesting both in terms of yields and products distributions (Entries 8 to 10). At last, an attempt to achieve catalyst turnover was made (Entry 11), by adding an excess of TMSOH that could replace water as nucleophile and ensure catalyst regeneration by halide-induced desilylation.^[35] Unfortunately, a conversion that matched the catalyst loading was observed, along with a slight decrease of the product selectivity.

Conclusions

As a conclusion, we have developed the synthesis of a new family of bifunctional iodoazolium salts bearing diverse HB donors, in order to provide a first insight into the cooperation between XB and HB in the iodoazolium series. A convergent and efficient synthetic route consisting of the nucleophilic substitution of benzylic bromides was used to introduce alcohol, carbamate, sulfonamide, urea and squaramide functionalities. The bromide counterion could then be exchanged for less coordinating BAr_4^{F} and PF_6^- ions.

The bifunctional azolium salts were then submitted to different physico-chemical methods (X-ray diffraction, TEPO ³¹P NMR analyses, ITC analyses) and reactivity attempts (aza-Diels–Alder reaction, Ritter-type solvolysis). No clear-cut evidence of the XB/HB cooperation could be detected by physico-chemical methods. Actually: (i) the alcohol function seems to be too weak a HB donor; (ii) the carbamate function is likely to behave rather as a HB acceptor on its oxygen atom than as a HB donor; (iii) the urea and the squaramide seem to be too strong double HB donors that outcompete the interaction at the iodine atom. In this case, the cationic azolium ring increases the HB donor properties of the urea or squaramide moiety thanks to its electron-withdrawing effect. Nevertheless, our physico-chemical studies provide the first evidence of similar tendencies between TEPO ³¹P NMR and ITC analyses of XB donors.

On the contrary, reactivity studies were more encouraging, highlighting the fact that the stoichiometric or catalytic activation of a transformation is a much more complex process than a simple Lewis acid-base interaction. The bifunctional ureido iodoazolium salt **10ae·BAr₄^F** proved to be a significantly better activating agent than the corresponding monofunctional structures in the Ritter-type reaction, both in terms of conversion and product selectivity.

To finish, based on a very recent competing study in the 3-iodopyridinium series,^[16e] we feel like the linker between the XB and HB donors is likely to be too long and flexible to offer an efficient cooperation. Current studies are ongoing in our lab aiming at preparing other families of bifunctional iodoazolium salts with shorter linkers between the two active sites.

Experimental Section

Only general procedures are presented here. The syntheses and analytical descriptions of all compounds are provided in the supporting information.

General procedure A for the synthesis of (iodo)azolium bromides: In an oven dried Schlenk tube were dissolved iodoimidazole or imidazole derivative (1.0 equiv) and benzylic bromide (1.0 equiv.) in anhydrous MeCN (0.06 M) under argon atmosphere. The reaction mixture was stirred at room temperature (25 °C) for 72 h. The product was then purified according to the specified procedure.

General procedure B for $\text{Br}^-/\text{BAr}_4^{\text{F}}$ exchange: In an oven-dried Schlenk tube, iodoimidazolium or imidazolium bromide derivative (1.0 equiv.) and sodium tetrakis(3,5-bis(trifluoromethyl)phenyl)borate (1.1 equiv.) were dissolved under an argon atmosphere in a mixture of dry dichloromethane and dry acetonitrile (4:1, 0.05 M). The reaction mixture was stirred at room temperature for 24 h. The reaction mixture was then concentrated under reduced pressure and the residue was purified by silica gel column chromatography (DCM/MeOH 98:2 to 95:5).

General procedure C for $\text{Br}^-/\text{PF}_6^-$ exchange: In an oven dried Schlenk tube, iodoimidazolium bromide derivative (1.0 equiv.) and sodium hexafluorophosphate (1.2 equiv.) were dissolved under an argon atmosphere in a mixture of dry acetonitrile and dry methanol (3:1, 0.05 M). The reaction mixture was stirred at room temperature for 24 h. The reaction mixture was then concentrated under reduced pressure and the residue was purified by silica gel column chromatography (DCM/MeOH 99:1 to 98:2).

TEPO measurements: According to the literature,^[24b] all the NMR tubes were prepared and sealed in a glovebox. TEPO was solubilised with CH_2Cl_2 to make a stock solution with concentration of 83 mM. The host compounds **10ac-af·X**[−], **12ae-af·BAr₄^F**, **13ae-af** and **14ae·BAr₄^F** (0.083 mmol, 10 equiv, unless specified otherwise) were dissolved in CH_2Cl_2 (0.25 mL) and CD_2Cl_2 (0.2 mL). The solution was transferred into an NMR tube followed by addition of TEPO stock solution (0.1 mL, 8.3 μ mol, 1 equiv, unless specified otherwise). The ³¹P NMR spectrum of each sample was immediately measured at room temperature with 32 scans and chemical shifts were compared to a standard (TEPO solution in CH_2Cl_2 , 15 mM).

ITC measurements were performed on a MicroCal PEAQ-ITC (Malvern Instruments) with a 200- μ L sample cell and a 40- μ L titration syringe. The following parameters were used:

- host compounds **10ae·BAr₄^F**, **12ae·BAr₄^F**, **13ae** and **14ae·BAr₄^F** (1.00 mM solution in dry CH_3CN) in the cell;
- guest TBABr (10.00 mM solution in dry CH_3CN) in the syringe;
- temperature of 25 °C;
- stirring speed of 750 rpm;
- reference power of 10 μ cal.s^{−1};
- high-feedback mode;
- 1 injection of 0.4 μ L over 4 s (which was not considered for correlation), followed by 18 injections of 2 μ L over 4 s;
- intervals of 150 s between each injection;

Several fitting models were evaluated in the MicroCal PEAQ-ITC Panalytical software, with the single-site binding model accounting for a 1:1 interaction always providing the best correlation.

General procedure D for Ritter-type reaction: Bromodiphenylmethane (15, 2.5 mg, 0.010 mmol, 1.0 equiv.), the activating agent (0.010 mmol, 1.0 equiv.) and CH_2Br_2 (1.9 mg, 0.86 μ L, 0.010 mmol, 1.0 equiv.) as internal standard were dissolved in CD_3CN (0.50 mL), and the reaction mixture analyzed after 72 h at room temperature. Conversions and product distributions were determined by ¹H NMR.

substrate **15** (singlet at 6.44 ppm), expected product **16** (doublet at 6.23 ppm) and diphenylmethanol **17** (singlet at 5.78 ppm).^[33a] Even though this compound could not be isolated in its pure form, the presence of the cation **18** in the reaction depicted in Entry 3 was supported by HRMS analysis of the crude reaction mixture: HRMS (ESI): *m/z*: calcd for $[C_{31}H_{28}IN_2O_2]^+$ 587.1190; found 587.1189.

Supporting Information

Additional references cited within the Supporting Information.^[36–48]

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Conflict of Interests

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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- [1] a) C. A. Hunter, *Angew. Chem. Int. Ed.* **2004**, *43*, 5310; b) R. R. Knowles, E. N. Jacobsen, *Proc. Nat. Acad. Sci.* **2010**, *107*, 20678.
- [2] a) A. G. Doyle, E. N. Jacobsen, *Chem. Rev.* **2007**, *107*, 5713; b) T. Akiyama, Y. Arakawa, Y. C. Chen, H. L. Cui, L. Deng, J. Duschmalé, L. Z. Gong, Z. Y. Han, N. Haraguchi, T. Hashimoto, K. Hof, H. Imai, T. Inokuma, S. Itsuno, K. Izawa, H. B. Jang, M. Klussmann, K. M. Lippert, B. List, K. Maruoka, N. Momiyama, K. Nagasawa, T. Nishikawa, J. S. Oh, T. Ooi, I. Pápai, H. G. Park, P. R. Schreiner, S. Shirakawa, R. P. Singh, Y. Sohtome, C. E. Song, Y. Takemoto, M. Terada, T. Torii, D. Uraguchi, C. Wang, H. Wennemers, *Asymmetric Organocatalysis 2: Brønsted Base and Acid Catalysts, and Additional Topics*, Georg Thieme Verlag, Stuttgart, **2012**.
- [3] A. J. Neel, M. J. Hilton, M. S. Sigman, F. D. Toste, *Nature* **2017**, *543*, 637.
- [4] Y. Zhao, Y. Cotelle, L. Liu, J. López-Andarias, A.-B. Bornhof, M. Akamatsu, N. Sakai, S. Matile, *Acc. Chem. Res.* **2018**, *51*, 2255.
- [5] a) C. R. Kennedy, S. Lin, E. N. Jacobsen, *Angew. Chem. Int. Ed.* **2016**, *55*, 12596; b) S. Yamada, *Chem. Rev.* **2018**, *118*, 11353.
- [6] a) F. Guthrie, *J. Chem. Soc.* **1863**, *16*, 239; b) R. S. Mulliken, *J. Am. Chem. Soc.* **1950**, *72*, 600; c) O. Hassel, *Science* **1970**, *170*, 497; d) G. R. Desiraju, P. S. Ho, L. Kloo, A. C. Legon, R. Marquardt, P. Metrangolo, P. Politzer, G. Resnati, K. Rissanen, *Pure Appl. Chem.* **2013**, *85*, 1711.
- [7] a) P. Metrangolo, G. Resnati, *Halogen Bonding: Fundamentals and Applications*, Springer, Berlin, **2008**; b) T. M. Beale, M. G. Chudzinski, M. G. Sarwar, M. S. Taylor, *Chem. Soc. Rev.* **2013**, *42*, 1667; c) R. Wilcken, M. O. Zimmermann, A. Lange, A. C. Joerger, F. M. Boeckler, *J. Med. Chem.* **2013**, *56*, 1363; d) G. Cavallo, P. Metrangolo, R. Milani, T. Pilati, A. Priimagi, G. Resnati, G. Terraneo, *Chem. Rev.* **2016**, *116*, 2478; e) R. Tepper, U. S. Schubert, *Angew. Chem. Int. Ed.* **2018**, *57*, 6004; f) J. Y. C. Lim, P. D. Beer, *Chem* **2018**, *4*, 731; g) S. M. Huber, *Halogen Bonding in Solution*, Wiley-VCH, Weinheim, **2021**; h) R. Hein, P. D. Beer, *Chem. Sci.* **2022**, *13*, 7098.
- [8] a) D. Bulfield, S. M. Huber, *Chem. Eur. J.* **2016**, *22*, 14434; b) J. Bamberger, F. Ostler, O. G. Mancheño, *ChemCatChem* **2019**, *11*, 5198; c) R. L. Sutar, S. M. Huber, *ACS Catal.* **2019**, *9*, 9622; d) M. Kaasik, T. Kanger, *Front. Chem.* **2020**, *8*, DOI: 10.3389/fchem.2020.599064; e) H. Yang, M. W. Wong, *Molecules* **2020**, *25*, 1045; f) M. Breugst, J. J. Koenig, *Eur. J. Org. Chem.* **2020**, 5473.
- [9] A. S. Mahadevi, G. N. Sastry, *Chem. Rev.* **2016**, *116*, 2775.
- [10] Biological systems: R. K. Rowe, P. S. Ho, *Acta Crystallogr. Sect. B* **2017**, *73*, 255.
- [11] The competition between XB and HB has also been studied: a) C. C. Robertson, J. S. Wright, E. J. Carrington, R. N. Perutz, C. A. Hunter, L. Brammer, *Chem. Sci.* **2017**, *8*, 5392; b) J. C. Gamekkanda, A. S. Sinha, J. Desper, M. Đaković, C. B. Aakeröy, *New J. Chem.* **2018**, *42*, 10539.
- [12] a) M. G. Chudzinski, C. A. McClary, M. S. Taylor, *J. Am. Chem. Soc.* **2011**, *133*, 10559; b) L. Meazza, J. A. Foster, K. Fücke, P. Metrangolo, G. Resnati, J. W. Steed, *Nat. Chem.* **2013**, *5*, 42; c) R. Chutia, G. Das, *Dalton Trans.* **2014**, *43*, 15628; d) T. K. Ghosh, S. Mondal, S. Bej, M. Nandi, P. Ghosh, *Dalton Trans.* **2019**, *48*, 4538.
- [13] a) S. W. Robinson, C. L. Mustoe, N. G. White, A. Brown, A. L. Thompson, P. Kennepohl, P. D. Beer, *J. Am. Chem. Soc.* **2015**, *137*, 499; b) J. Y. C. Lim, I. Marques, V. Félix, P. D. Beer, *J. Am. Chem. Soc.* **2017**, *139*, 12228 and references included therein; c) M. V. Il'in, A. A. Sysoeva, A. S. Novikov, D. S. Bolotin, *J. Org. Chem.* **2022**, *87*, 4569.
- [14] R. Tepper, B. Schulze, H. Görls, P. Bellstedt, M. Jäger, U. S. Schubert, *Org. Lett.* **2015**, *17*, 5740.
- [15] P.-P. Zhou, W.-Y. Qiu, S. Liu, N.-Z. Jin, *Phys. Chem. Chem. Phys.* **2011**, *13*, 7408.
- [16] a) A. M. S. Riel, D. A. Decato, J. Sun, C. J. Massena, M. J. Jessop, O. B. Berryman, *Chem. Sci.* **2018**, *9*, 5828; b) J. Sun, A. M. S. Riel, O. B. Berryman, *New J. Chem.* **2018**, *42*, 10489; c) A. M. S. Riel, R. K. Rowe, E. N. Ho, A.-C. C. Carlsson, A. K. Rappé, O. B. Berryman, P. S. Ho, *Acc. Chem. Res.* **2019**, *52*, 2870; d) S. Kuwano, Y. Nishida, T. Suzuki, T. Arai, *Adv. Synth. Catal.* **2020**, *362*, 1674; e) D. A. Decato, A. M. S. Riel, J. H. May, V. S. Bryantsev, O. B. Berryman, *Angew. Chem. Int. Ed.* **2021**, *60*, 3685; f) S. Portela, I. Fernández, *Molecules* **2021**, *26*, 1885; g) M. Kaasik, J. Martonova, K. Erkman, A. Metsala, I. Järving, T. Kanger, *Chem. Sci.* **2021**, *12*, 7561; h) A. M. S. Riel, D. A. Decato, J. Sun, O. B. Berryman, *Chem. Commun.* **2022**, *58*, 1378; i) D. A. Decato, J. Sun, M. R. Boller, O. B. Berryman, *Chem. Sci.* **2022**, *13*, 11156; j) O. Berryman, J. Sun, D. A. Decato, E. A. John, V. Bryantsev, *Chem. Sci.* **2023**, DOI: 10.1039/D3SC02348F.
- [17] Y. Kobayashi, Y. Nakatsuji, S. Li, S. Tsuzuki, Y. Takemoto, *Angew. Chem. Int. Ed.* **2018**, *57*, 3646.
- [18] N. Tsuji, Y. Kobayashi, Y. Takemoto, *Chem. Commun.* **2014**, *50*, 13691.
- [19] F. Zapata, A. Caballero, P. Molina, I. Alkorta, J. Elguero, *J. Org. Chem.* **2014**, *79*, 6959.
- [20] See supporting information for further details.
- [21] R. Haraguchi, S. Hoshino, M. Sakai, S.-G. Tanazawa, Y. Morita, T. Komatsu, S.-I. Fukuzawa, *Chem. Commun.* **2018**, *54*, 10320.
- [22] a) U. Mayer, V. Gutmann, W. Gerger, *Monatsh. Chem.* **1975**, *106*, 1235; b) M. A. Beckett, G. C. Strickland, J. R. Holland, K. Sukumar Varma, *Polymer* **1996**, *37*, 4629.
- [23] a) K. M. Diemoz, A. K. Franz, *J. Org. Chem.* **2019**, *84*, 1126; b) Preliminary studies for thioureas with tri-*n*-butylphosphine oxide: A. R. Nödling, G. Jakab, P. R. Schreiner, G. Hilt, *Eur. J. Org. Chem.* **2014**, 6394.
- [24] a) R. J. Mayer, A. R. Ofial, H. Mayr, C. Y. Legault, *J. Am. Chem. Soc.* **2020**, *142*, 5221; b) Y.-P. Chang, T. Tang, J. R. Jagannathan, N. Hirbawi, S. Sun, J. Brown, A. K. Franz, *Org. Lett.* **2020**, *22*, 6647.
- [25] R. Wechsel, M. Źabka, J. W. Ward, J. Clayden, *J. Am. Chem. Soc.* **2018**, *140*, 3528.
- [26] A. Shukla, E. D. Isaacs, D. R. Hamann, P. M. Platzman, *Phys. Rev. B* **2001**, *64*, 052101.
- [27] a) A. P. Davis, S. M. Draper, G. Dunne, P. Ashton, *Chem. Commun.* **1999**, 2265; b) J. P. Malerich, K. Hagiwara, V. H. Rawal, *J. Am. Chem. Soc.* **2008**, *130*, 14416; c) L. A. Marchetti, L. K. Kumawat, N. Mao, J. C. Stephens, R. B. P. Elmes, *Chem.* **2019**, *5*, 1398.

[28] Value obtained with onyl 3 equivalents of **15ae** instead of 10 equivalents, because of its low solubility. Varying the amount of compound to study seemed to have a minimal impact on the experiment since similar $\Delta\delta(^3\text{P})$ values were obtained with 10 and 3 equivalents of **14ae**· BAr_4^- (8.37 ppm against 8.33 ppm, respectively). For this reason, we are confident that the $\Delta\delta(^3\text{P})$ of 6.64 ppm for **15ae** can be compared with those of the other ureas.

[29] Obtaining those results required the use of a tripled amount of TEPO so that its signal in ^{31}P NMR remains intense enough compared to the one of PF_6^- .

[30] P. Thordarson, *Chem. Soc. Rev.* **2011**, *40*, 1305.

[31] S. M. Walter, F. Kniep, L. Rout, F. P. Schmidtchen, E. Herdtweck, S. M. Huber, *J. Am. Chem. Soc.* **2012**, *134*, 8507.

[32] a) Y. Takeda, D. Hisakuni, C.-H. Lin, S. Minakata, *Org. Lett.* **2015**, *17*, 318; b) M. Kaasik, A. Metsala, S. Kaabel, K. Kriis, I. Järving, T. Kanger, *J. Org. Chem.* **2019**, *84*, 4294.

[33] a) S. M. Walter, F. Kniep, E. Herdtweck, S. M. Huber, *Angew. Chem. Int. Ed.* **2011**, *50*, 7187; b) S. H. Jungbauer, S. M. Huber, *J. Am. Chem. Soc.* **2015**, *137*, 12110.

[34] The presence of **18** was detected by HMRS analysis of the reaction mixture. However, it could not be independently prepared to fully ascertain its structure. See supporting information for further details.

[35] For other selected examples of the use of silylated nucleophiles to ensure XB catalyst turnover, see: a) F. Kniep, S. H. Jungbauer, Q. Zhang, S. M. Walter, S. Schindler, I. Schnapperelle, E. Herdtweck, S. M. Huber, *Angew. Chem. Int. Ed.* **2013**, *52*, 7028; b) M. Saito, N. Tsuji, Y. Kobayashi, Y. Takemoto, *Org. Lett.* **2015**, *17*, 3000.

[36] D. D. Perrin, W. L. F. Armarego, *Purification of Laboratory Chemicals*, Pergamon Press: Oxford, 3rd ed., **1988**.

[37] G. R. Fulmer, A. J. M. Miller, N. H. Sherden, H. E. Gottlieb, A. Nudelman, B. M. Stoltz, J. E. Bercaw, K. I. Goldberg, *Organometallics* **2010**, *29*, 2176.

[38] Y. Zhao, S. R. Gilbertson, *Org. Lett.* **2014**, *16*, 1033.

[39] M. Sarmah, A. Dewan, P.-K. Boruah, M.-R. Das, U. Bora, *Appl. Organomet. Chem.* **2020**, *34*, e5554.

[40] K. Nozawa-Kumada, S. Kurosu, M. Shigeno, Y. Kondo, *Asian J. Org. Chem.* **2019**, *8*, 1080.

[41] F. Jahani, M. Tajbakhsh, H. Golchoubian, S. Khaksar, *Tetrahedron Lett.* **2011**, *52*, 1260.

[42] C. Mukai, M. Kobayashi, S. Kubota, Y. Takahashi, S. Kitagaki, *J. Org. Chem.* **2004**, *69*, 2128.

[43] R. Bernárdez, J. Suárez, M. Fañanás-Mastral, J. A. Varela, C. Saá, *Org. Lett.* **2016**, *18*, 642.

[44] T. Ema, D. Tanida, T. Matsukawa, T. Sakai, *Chem. Commun.* **2008**, 957.

[45] Monocationic aggregates consisting of two iodoazolium cations and one bromide anions have been observed.

[46] H. Wu, Handoko, M. Raj, P. S. Arora, *Org. Lett.* **2017**, *19*, 5122.

[47] M. Ryuichi, A. Keisuke, *Tetrahedron* **2021**, *97*, 132381.

[48] P. Manesiots, A. Riley, B. Bollen, *J. Mater. Chem. C* **2014**, *2*, 8990.

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