Organic LETTERS

Letter

pubs.acs.org/OrgLett

# Preorganization in a Cleft-Type Anion Receptor Featuring Iodo-1,2,3-Triazoles As Halogen Bond Donors

Ronny Tepper,[†,‡] Benjamin Schulze,[†,‡,∥] Helmar Görls,[§] Peter Bellstedt,[†,§] Michael Jäger,[†,‡] and Ulrich S. Schubert*[,†,‡]

[†]Laboratory of Organic and Macromolecular Chemistry (IOMC), Friedrich Schiller University Jena, Humboldtstrasse 10, 07743 Jena, Germany

[‡]Jena Center for Soft Matter (JCSM), Friedrich Schiller University Jena, Philosophenweg 7, 07743 Jena, Germany

[§]Laboratory of Inorganic and Analytical Chemistry, Friedrich Schiller University Jena, Lessingstrasse 8, 07743 Jena, Germany

Supporting Information

**ABSTRACT:** Preorganization *via* intramolecular hydrogen bonds was applied in a cleft-type receptor by exploiting the excellent halogen bond donor ability as well as hydrogen bond acceptor function of iodo-1,2,3-triazoles. As investigated by isothermal calorimetric titrations, the restriction of conformational freedom causes an enhanced entropic contribution resulting in a strongly increased binding affinity. This efficient way to improve the binding strength of 5-halo-1,2,3-triazoles paves the way for applications of new charge-neutral halogen bond donors in solution.


The halogen bond (XB) is a highly directional supramolecular interaction between a Lewis-acidic region of a covalently bound halogen ($\sigma$-hole) and a Lewis-base.[1] When compared to the hydrogen bond (HB), the XB features a higher preference for linearity[2] as well as a higher bond strength,[3] which constitutes the basis for application of XBs in selective anion detection[4] and transport,[5] organocatalysis,[6] and anion-templated construction of interlocked structures.[7] Beside cationic halo-imidazolium[4b,6a,8] and halo-1,2,3-triazolium[3b,4a,9] moieties, also charge-neutral systems based on perfluoroiodo arenes[2a,6b,10] and halo-1,2,3-triazoles[3b,7b−d,f,11] have been established as excellent XB donors.

While cationic XB donors achieve very high anion affinities due to charge assistance, their interaction with anions is less directional because of the isotropic nature of the additional Coulomb attraction.[11c] Evidently, this benefit only applies to anionic species. In addition, highly competitive solvents are usually required to dissolve the receptors and/or to prevent precipitation of the formed complex,[12] which lowers the effective binding strength in case of cationic XB donors. In contrast, charge-neutral XB donors offer an increased solubility in less competitive solvents and allow for a more directional binding. These characteristics of neutral systems might be advantageous when designing strong and selective receptors, *e.g.*, for application in asymmetric organocatalysis.[6b] For the latter, the use of charge-neutral catalysts is crucial, as the binding of anionic intermediates (*e.g.*, oxo-anions) or products (*e.g.*, halides) instead of the neutral substrate would be highly preferred in case of cationic receptors, *i.e.*, the catalyst would be blocked.[6f]

In particular, 5-halo-1,2,3-triazoles have been established as versatile, charge-neutral XB donors due to their good accessibility *via* facile and modular copper(I)-catalyzed cycloaddition reactions as well as their sufficient electron-withdrawing character.[11c,13] Nevertheless, the polarization of the XB donor atom and, consequently, the size of the $\sigma$-hole in this neutral unit is much smaller than that of positively charged halo-triazolium moieties.[3b] Hence, additional concepts as for instance chelation through polydentate donors[4c,6f,10a,d,11b] are required to increase the binding affinity. Furthermore, the concept of preorganization *via* intramolecular HBs represents a very efficient method to improve the binding affinity.

The 1,2,3-triazole ring is ideally suited to establish intramolecular preorganization as it offers both donor and acceptor function. In the case of HB-based receptors, this has been demonstrated by the seminal work by Flood *et al.*[14] Notably, the preorganization by intramolecular HBs does not only screen the entropic penalty for the binding event, but also increases the effective binding enthalpy since the free receptor cannot adopt a relaxed conformation and because the polarization of the 1,2,3-triazole is enhanced (dipole moment of 4.4 D[11c] and 6.1 D[14b] for the flexible and preorganized triazole, respectively). However, to

**Received:** September 24, 2015
**Published:** November 20, 2015



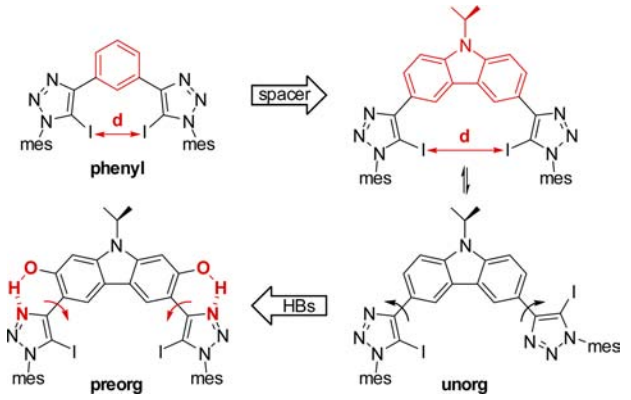


DOI: 10.1021/acs.orglett.5b02760
*Org. Lett.* 2015, 17, 5740−5743

the best of our knowledge, no comparative XB-based system has been published to date.[15]

Because of the strict linearity of XBs as well as the large size of the XB donor atom, the design of efficient polydentate XB-based receptors is not trivial.[3b] In contrast to flexible receptors, which can adapt to the size of the binding partner, the design of preorganized receptors is more challenging. In this case, the cavity of the preorganized receptor molecule has to match the size of the guest, otherwise the breaking of the intramolecular HB upon binding would hinder the binding event. In this contribution, we demonstrate that the carbazole spacer is ideally suited to enable a bidentate binding of halides by two iodo-1,2,3-triazoles in a coplanar fashion (Scheme 1, top).[16] Building on this finding, we demonstrate the effect of preorganization in XB donors based on iodo-triazoles (Scheme 1, bottom).

**Scheme 1. Schematic Representation of Studied Receptors**[a]



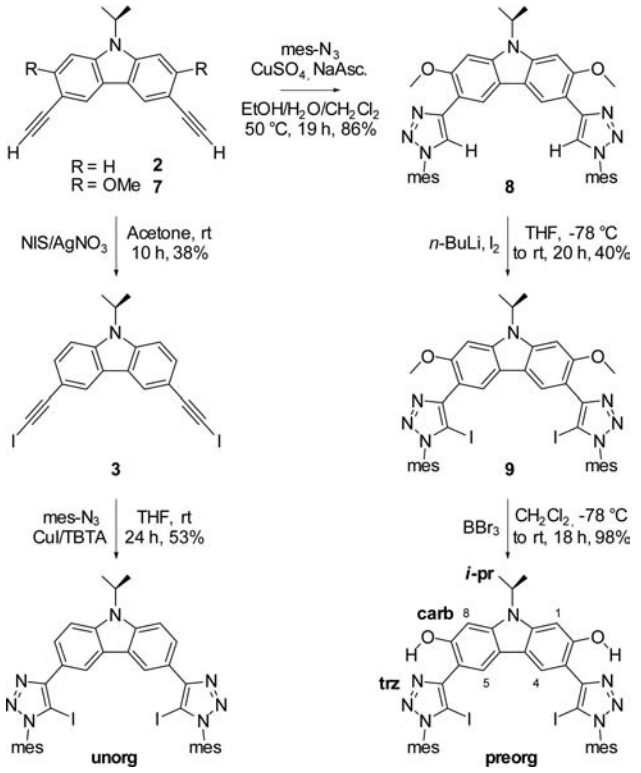

[a]Top: influence of spacer unit 1,3-benzene (**phenyl**) or 3,6-carbazole (**unorg**) on distance (*d*) between two donor moieties. Bottom: preorganization via intramolecular HBs (**preorg**).

Besides the already established phenyl-based receptor system (**phenyl**),[3b] the two carbazole-based receptors were synthesized using copper(I)-catalyzed cycloaddition reactions. **Unorg** was prepared directly from the corresponding iodo-alkyne (**3**) and mesityl azide in moderate yields (Scheme 2). In the case of the preorganized receptor, the 1,2,3-triazoles were formed first (**8**) and the iodination was achieved by metalation using *n*-BuLi and subsequent treatment with iodine to obtain the methoxy-decorated precursor (**9**). Remarkably, even in the presence of the iodo-1,2,3-triazoles, the final receptor **preorg** was obtained in excellent yields by $BBr_3$-induced ether cleavage. In addition, the formation of intramolecular HBs in case of **preorg** was revealed by selective ROESY studies as well as $^1$H NMR experiments in solvents with different polarity.[17]

To discuss the influence of the receptor design in the solid state, single crystals of free and complexed receptors were grown by slow vapor diffusion of different nonsolvents into a concentrated solution.[17] Obviously, because of the conformational freedom of **unorg**, the anti/anti or syn/anti conformation of the XB donors can be adapted in the free receptor.[18] In contrast, the formation of intramolecular HBs in **preorg** leads to a limitation of the rotational freedom, and thus, the required syn/syn conformation for the bidentate complexation is already preformed, which could be also supported by quantum chemical calculations using density functional theory (DFT).[17]

Furthermore, all three receptors revealed the expected cleft-type complexation of the anion through the formation of two

**Scheme 2. Schematic Representation of the Synthesis of Receptors unorg and preorg**




nearly linear XBs, which are significantly shorter than the sum of the van der Waals radii (I···Cl 3.73 Å).[19] Moreover, the preorganization of **preorg** led to an additional binding process (*vide infra*).

Comparing the 1:1 complexes of **phenyl** and **unorg** with chloride (Figure 1), the larger distance (*d*) between the two

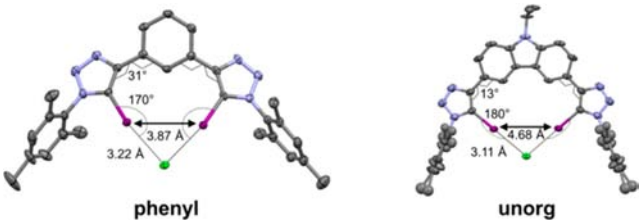



**Figure 1.** Molecular structure of **phenyl** (left) and **unorg** (right) interacting with chloride (thermal ellipsoids at 50% probability level, hydrogen atoms, counterions, and solvent molecules are omitted for clarity).

iodine atoms in the carbazole-based receptor enables an improved coplanarization (dihedral angle of 31° and 13°, respectively), which allows an increased linearity of the XBs and, as a net result, a decreased I···Cl distance.

Isothermal titration calorimetry (ITC) experiments were performed with the three receptors and two different tetra-*n*-butylammonium ($TBA^+$) halides to obtain a detailed understanding of the complex stoichiometry, the binding affinity, and the thermodynamic effect of preorganization in solution (Table 1). All titrations were performed in the guest-into-host setup in THF. In addition, also inverse titrations, *i.e.*, addition of a host solution into a guest solution, were performed to confirm the reliability of the calculated values.[17] Unfortunately, a direct



DOI: 10.1021/acs.orglett.5b02760
*Org. Lett.* 2015, 17, 5740−5743

**Table 1. Thermodynamic Parameters for the Complexation of Various Receptors with Different TBA$^+$ Halides**[a]

| host | guest | $K$ [M$^{-1}$] | $\Delta H$ [kJ mol$^{-1}$] | $T\Delta S$[kJ mol$^{-1}$] | $N$ |
|---|---|---|---|---|---|
| **phenyl** | Br$^-$ | $2.22 \times 10^3$ | −24.5 | −5.1 | 0.99 |
| | Cl$^-$ | $3.52 \times 10^3$ | −22.9 | −2.3 | 1.08 |
| **unorg** | Br$^-$ | $1.58 \times 10^3$ | −27.4 | −8.8 | 1.03 |
| | Cl$^-$ | $2.34 \times 10^3$ | −24.9 | −5.4 | 1.05 |
| **preorg**[b] | Br$^-$ | $3.85 \times 10^3$ | −7.2 | 13.6 | 0.52 |
| | | $5.45 \times 10^4$ | −23.5 | 4.0 | 0.89 |
| | Cl$^-$ | $3.17 \times 10^3$ | −15.1 | 5.3 | 0.45 |
| | | $7.09 \times 10^4$ | −17.8 | 10.3 | 0.90 |

[a]Thermodynamic parameters calculated from guest-into-host titrations in THF at 303 K. [b]The formation of a 2:1 complex (host−guest) could be further supported by a solid-state structure and selective NOESY experiments (*vide infra*).

comparison between **preorg** and **9** was not possible because of the insufficient solubility of **9** in THF.

In line with the binding in the solid state, a cleft-type complexation of the halides by **phenyl** and **unorg** in solution was deduced from the ITC titration experiments. For **unorg**, a slightly increased enthalpic contribution toward the binding was revealed, which may be due to the optimized XB formation (Figure 1). On the other hand, the entropic term is decreased for **unorg**, which is tentatively explained by a smaller extent of desolvation of the receptor and/or the anion upon binding. However, there are only subtle differences in the overall binding affinities of **phenyl** and **unorg** and the effect of the spacer unit seems to be negligible for the two flexible receptors.

Comparing the complexation of chloride and bromide, the trend for the $K$ values (Table 1) shows a general preference for the more charge-dense/basic chloride, which allows a stronger electrostatic as well as charge-transfer interaction.[3b,8b] For the same reason, the solvent interaction is more pronounced for chloride, resulting in a reduced enthalpic contribution toward the binding, which is, however, overcompensated by a more favorable entropic term due to the enhanced desolvation upon anion complexation.[20]

When comparing **unorg** and **preorg**, the tendency to form a 1:1 complex with chloride is enhanced by a factor of about 30 for the preorganized receptor ($K_1^{\text{unorg}} = 2.34 \times 10^3$ M$^{-1}$ and $K_1^{\text{preorg}} = 7.09 \times 10^4$ M$^{-1}$). As a result of the increased anion affinity, even a 2:1 complex is formed (*vide infra*). The same behavior is observed for bromide. Regarding the overall chloride affinity, the accumulated binding constant has to be considered, which even amounts to $K_1K_2 = 2.24 \times 10^8$ M$^{-2}$, corresponding to $\Delta G = -48.5$ kJ mol$^{-1}$. Notably, in contrast to the association constants, the observed binding enthalpy for the formation of a 1:1 complex with **unorg** cannot be directly compared to the binding enthalpy of a 1:1 complex with **preorg** since a 2:1 complex is formed simultaneously in the case of the latter. Thus, the released heat accounts for two processes both being related to the complexation of a single anion. Furthermore, the observed enthalpies for the formation of 1:1 and 2:1 complexes depend on the titration setup (guest-to-host *vs* host-to-guest).[21] However, the sum of both enthalpies, which corresponds to the total interaction with the anion, is the same irrespective of the titration order and is slightly more negative in the case of **preorg**. This slightly enhanced enthalpic contribution is attributed to the preorganization, which prevents a relaxation of the free receptor, *i.e.*, the preorganized receptor is spring-loaded for complexation. Additionally, the polarization of the triazole rings may be slightly enhanced;[14b] however, no significant difference of the computed $\sigma$-hole was observed.[17,22] Most importantly, however, the entropic term for the complexation with **preorg** is positive, while it is negative for **unorg**. This striking difference can be explained by the restriction of rotational freedom already in the uncomplexed **preorg** due to the intramolecular HBs. Consequently, the entropy penalty for the complexation is screened in the preorganized receptor[14b] and the desolvation of host and guest give rise to a positive entropic term.

The formation of a 2:1 complex could also be observed in the solid state (Figure 2A).[17] Accordingly, the anion is complexed in

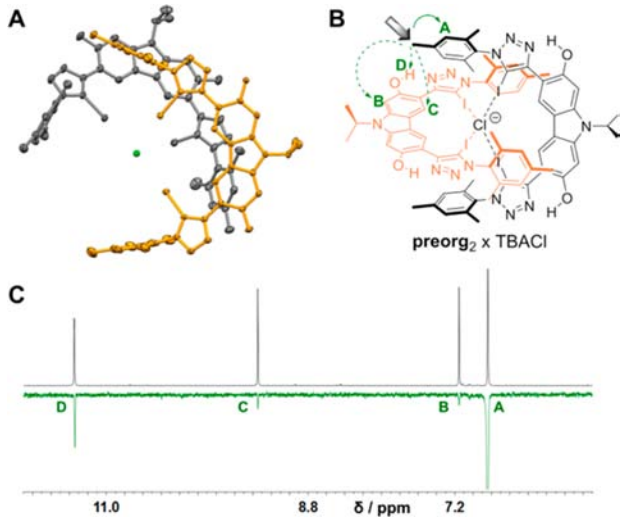



**Figure 2.** (A) Molecular structure of **preorg** interacting with chloride forming a 2:1 complex (thermal ellipsoids at 50% probability level, hydrogen atoms, counterions, and solvent molecules are omitted for clarity). (B) Schematic representation of the NOE contacts; the excited protons are marked with a shaded arrow and strong and medium contacts are indicated with solid and dashed arrows, respectively. (C) $^1$H NMR and selective ROESY spectra for **preorg** in the presence of 0.5 equiv of TBACl in THF-$d_8$.

a *bis*-bidentate fashion *via* four highly directional XBs (167° to 177°), which are all significantly shorter than the sum of the van der Waals radii (3.09−3.23 Å).[17] Moreover, the hydroxyl groups serve only as intramolecular HB donors and are not involved in the anion complexation.

This coordination mode is also present in solution as revealed by selective ROESY experiments (Figure 2B, C). For this experiment, a 2:1 mixture of the receptor and the anion was dissolved in THF-$d_8$ and the NOE signals after excitation of the methyl group of the mesityl substituent ($CH_3$-4$^{\text{mes}}$) were recorded. Beside a strong contact to the adjacent aromatic proton, further contacts to the central carbazole spacer and the hydroxyl groups were visible (Figure 2B, C). These additional NOE signals are not observed for the free receptor[17] and can only be explained by an orthogonal arrangement of two receptors within a *bis*-bidentate complex.

In conclusion, three different bidentate XB-based anion receptors were synthesized using facile and modular copper(I)-catalyzed cycloaddition reactions. Subsequently, the halide complexation was characterized by ITC experiments, X-ray diffraction, and selective ROESY experiments. While **phenyl** and **unorg** showed only moderate association constants, a strongly increased binding affinity was revealed for **preorg** *via* formation of intramolecular HBs between the central carbazole spacer and


DOI: 10.1021/acs.orglett.5b02760
*Org. Lett.* 2015, 17, 5740−5743

the adjacent iodo-1,2,3-triazoles, a rigid bidentate XB donor was formed, which enabled a strong complexation of halides without entropic penalty. Notably, the central carbazole is an almost ideal spacer for this assignment as it enables a bidentate complexation by a nearly planar receptor system. Following these building principles, charge-neutral, cleft-type receptors with high anion affinities can be designed. Owing to the highly directional and strong XBs as well as to the absence of isotropic Coulomb interactions, these receptors offer great potential for application as organocatalysts.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.5b02760.

DFT data and crystal structures (CIF)
Experimental details, NMR spectra, binding studies (PDF)

## ■ AUTHOR INFORMATION


### Corresponding Author

*E-mail: ulrich.schubert@uni-jena.de.

### Present Address

[‖]B.S.: Novaled GmbH, Tatzberg 49, 01307 Dresden, Germany


### Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

The authors are grateful to the Deutsche Forschungsgemeinschaft (DFG) for financial support (Grants SCHU 1229/24-1 and SPP 1568). We also thank C. Friebe, W. Günther, G. Sentis, T. Schlotthauer, as well as N. Fritz (all Friedrich Schiller University Jena, IOMC, Germany) for discussions and performing experiments.

## ■ REFERENCES


(1) (a) Gale, P. A.; Caltagirone, C. *Chem. Soc. Rev.* **2015**, *44*, 4212. (b) Metrangolo, P.; Resnati, G. *Science* **2008**, *321*, 918. (c) Desiraju, G. R.; Ho, P. S.; Kloo, L.; Legon, A. C.; Marquardt, R.; Metrangolo, P.; Politzer, P.; Resnati, G.; Rissanen, K. *Pure Appl. Chem.* **2013**, *85*, 1711. (d) Beale, T. M.; Chudzinski, M. G.; Sarwar, M. G.; Taylor, M. S. *Chem. Soc. Rev.* **2013**, *42*, 1667. (e) Erdelyi, M. *Chem. Soc. Rev.* **2012**, *41*, 3547. (f) Gilday, L. C.; Robinson, S. W.; Barendt, T. A.; Langton, M. J.; Mullaney, B. R.; Beer, P. D. *Chem. Rev.* **2015**, *115*, 7118. (g) Clark, T.; Hennemann, M.; Murray, J. S.; Politzer, P. *J. Mol. Model.* **2007**, *13*, 291.

(2) (a) Chudzinski, M. G.; McClary, C. A.; Taylor, M. S. *J. Am. Chem. Soc.* **2011**, *133*, 10559. (b) Kilah, N. L.; Wise, M. D.; Beer, P. D. *Cryst. Growth Des.* **2011**, *11*, 4565.

(3) (a) Politzer, P.; Lane, P.; Concha, M. C.; Ma, Y.; Murray, J. S. *J. Mol. Model.* **2007**, *13*, 305. (b) Tepper, R.; Schulze, B.; Jäger, M.; Friebe, C.; Scharf, D. H.; Görls, H.; Schubert, U. S. *J. Org. Chem.* **2015**, *80*, 3139. (c) Priimagi, A.; Cavallo, G.; Metrangolo, P.; Resnati, G. *Acc. Chem. Res.* **2013**, *46*, 2686.

(4) (a) Zapata, F.; Caballero, A.; Molina, P.; Alkorta, I.; Elguero, J. *J. Org. Chem.* **2014**, *79*, 6959. (b) Caballero, A.; White, N. G.; Beer, P. D. *Angew. Chem., Int. Ed.* **2011**, *50*, 1845. (c) Sarwar, M. G.; Dragisic, B.; Sagoo, S.; Taylor, M. S. *Angew. Chem., Int. Ed.* **2010**, *49*, 1674.

(5) Vargas Jentzsch, A.; Emery, D.; Mareda, J.; Metrangolo, P.; Resnati, G.; Matile, S. *Angew. Chem., Int. Ed.* **2011**, *50*, 11675.

(6) (a) Takeda, Y.; Hisakuni, D.; Lin, C.-H.; Minakata, S. *Org. Lett.* **2015**, *17*, 318. (b) Kniep, F.; Jungbauer, S. H.; Zhang, Q.; Walter, S. M.; Schindler, S.; Schnapperelle, I.; Herdtweck, E.; Huber, S. M. *Angew. Chem., Int. Ed.* **2013**, *52*, 7028. (c) Jungbauer, S.; Walter, S.; Schindler, S.; Rout, L.; Kniep, F.; Huber, S. M. *Chem. Commun.* **2014**, *50*, 6281. (d) Castelli, R.; Schindler, S.; Walter, S. M.; Kniep, F.; Overkleeft, H. S.; Van der Marel, G. A.; Huber, S. M.; Codée, J. D. C. *Chem. - Asian J.* **2014**, *9*, 2095. (e) Walter, S. M.; Kniep, F.; Herdtweck, E.; Huber, S. M. *Angew. Chem., Int. Ed.* **2011**, *50*, 7187. (f) Kniep, F.; Rout, L.; Walter, S. M.; Bensch, H. K. V.; Jungbauer, S. H.; Herdtweck, E.; Huber, S. M. *Chem. Commun.* **2012**, *48*, 9299. (g) Jungbauer, S. H.; Huber, S. M. *J. Am. Chem. Soc.* **2015**, *137*, 12110. (h) Bruckmann, A.; Pena, M. A.; Bolm, C. *Synlett* **2008**, *2008*, 900.

(7) (a) Caballero, A.; Swan, L.; Zapata, F.; Beer, P. D. *Angew. Chem., Int. Ed.* **2014**, *53*, 11854. (b) Mullaney, B. R.; Thompson, A. L.; Beer, P. D. *Angew. Chem.* **2014**, *126*, 11642. (c) Robinson, S. W.; Mustoe, C. L.; White, N. G.; Brown, A.; Thompson, A. L.; Kennepohl, P.; Beer, P. D. *J. Am. Chem. Soc.* **2015**, *137*, 499. (d) Cornes, S. P.; Davies, C.; Blyghton, D.; Sambrook, M.; Beer, P. D. *Org. Biomol. Chem.* **2015**, *13*, 2582. (e) Gilday, L. C.; Lang, T.; Caballero, A.; Costa, P. J.; Félix, V.; Beer, P. D. *Angew. Chem., Int. Ed.* **2013**, *52*, 4356. (f) Mullaney, B. R.; Partridge, B. E.; Beer, P. D. *Chem. - Eur. J.* **2015**, *21*, 1660.

(8) (a) Zapata, F.; Caballero, A.; White, N. G.; Claridge, T. D. W.; Costa, P. J.; Félix, V.; Beer, P. D. *J. Am. Chem. Soc.* **2012**, *134*, 11533. (b) Walter, S. M.; Kniep, F.; Rout, L.; Schmidtchen, F. P.; Herdtweck, E.; Huber, S. M. *J. Am. Chem. Soc.* **2012**, *134*, 8507. (c) Cametti, M.; Raatikainen, K.; Metrangolo, P.; Pilati, T.; Terraneo, G.; Resnati, G. *Org. Biomol. Chem.* **2012**, *10*, 1329.

(9) (a) Lim, J. Y. C.; Beer, P. D. *Chem. Commun.* **2015**, *51*, 3686. (b) Mercurio, J. M.; Knighton, R. C.; Cookson, J.; Beer, P. D. *Chem. - Eur. J.* **2014**, *20*, 11740.

(10) (a) Dimitrijevic, E.; Kvak, O.; Taylor, M. S. *Chem. Commun.* **2010**, *46*, 9025. (b) Jungbauer, S. H.; Bulfield, D.; Kniep, F.; Lehmann, C. W.; Herdtweck, E.; Huber, S. M. *J. Am. Chem. Soc.* **2014**, *136*, 16740. (c) Takezawa, H.; Murase, T.; Resnati, G.; Metrangolo, P.; Fujita, M. *Angew. Chem., Int. Ed.* **2015**, *54*, 8411. (d) Jungbauer, S. H.; Schindler, S.; Herdtweck, E.; Keller, S.; Huber, S. M. *Chem. - Eur. J.* **2015**, *21*, 13625.

(11) (a) Langton, M. J.; Robinson, S. W.; Marques, I.; Félix, V.; Beer, P. D. *Nat. Chem.* **2014**, *6*, 1039. (b) Gilday, L. C.; White, N. G.; Beer, P. D. *Dalton Trans.* **2013**, *42*, 15766. (c) Schulze, B.; Schubert, U. S. *Chem. Soc. Rev.* **2014**, *43*, 2522.

(12) Schulze, B.; Friebe, C.; Hager, M. D.; Günther, W.; Köhn, U.; Jahn, B. O.; Görls, H.; Schubert, U. S. *Org. Lett.* **2010**, *12*, 2710.

(13) Hua, Y.; Flood, A. H. *Chem. Soc. Rev.* **2010**, *39*, 1262.

(14) (a) McDonald, K. P.; Ramabhadran, R. O.; Lee, S.; Raghavachari, K.; Flood, A. H. *Org. Lett.* **2011**, *13*, 6260. (b) Lee, S.; Hua, Y.; Park, H.; Flood, A. H. *Org. Lett.* **2010**, *12*, 2100. (c) McDonald, K. P.; Qiao, B.; Twum, E. B.; Lee, S.; Gamache, P. J.; Chen, C.-H.; Yi, Y.; Flood, A. H. *Chem. Commun.* **2014**, *50*, 13285.

(15) In the course of our investigations, Beer *et al.* published an interesting study including iodo-1,2,3-triazoles which were preorganized by the help of a covalent metal coordination: Mole, T. K.; Arter, W. E.; Marques, I.; Félix, V.; Beer, P. D. *J. Organomet. Chem.* **2015**, *792*, 206 Nevertheless, there is no detailed characterization of the effect of preorganization.

(16) In the course of our investigations, Beer *et al.* published rotaxane systems with related cationic XB donors based on a carbazole spacer. See references 7b and 7f.

(17) See the Supporting Information for more detailed explanations.

(18) Zornik, D.; Meudtner, R. M.; El Malah, T.; Thiele, C. M.; Hecht, S. *Chem. - Eur. J.* **2011**, *17*, 1473.

(19) Bondi, A. *J. Phys. Chem.* **1964**, *68*, 441.

(20) Schmidtchen, F. P. *Chem. Soc. Rev.* **2010**, *39*, 3916.

(21) Dobrawa, R.; Ballester, P.; Saha-Möller, C. R.; Würthner, F. In *Metal-Containing and Metallosupramolecular Polymers and Materials*; American Chemical Society: Washington, DC, 2006; Vol. *928*, Chapter 4.

(22) Electrostatic potential calculations were performed for **unorg** and **preorg** to visualize the $\sigma$-hole.




DOI: 10.1021/acs.orglett.5b02760
*Org. Lett.* 2015, 17, 5740−5743