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In Search of 1,4-Diazabutatrienes, the Elusive Isocyanide Homodimers. The Superchameleonic F-NC

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Supporting Information Placeholder

ABSTRACT: Isocyanides might dimerize forming 1,4-diazabutatrienes, never isolated but eventually proposed as reaction intermediates. We herein disclose a computational study on the homo and heterodimerization of isocyanides, in particular on the influence of the substituents onto the structural and energetics parameters of these processes. As result we have identified some reaction partners that are predicted to give stable 1,4-diazabutatrienes by surpassing low energy barriers. Of special significance is the homodimerization of F-NC, in which this species revealed as an excellent acceptor and, quite surprisingly, also as a suitable donor.

Isocyanides were first isolated in 1859 by Lieke who described them as species with an unpleasant odor.¹ Since then, they have become valuable species in different fields as organic synthesis,² coordination chemistry³ or multicomponent reactions⁴ among others. These isomers of cyanides present two resonant forms **1** and **1'** (Figure 1a) which are responsible for their rich reactivity; its terminal carbon atom can exist in a divalent state reacting either with nucleophiles, electrophiles or radicals.⁵ The organometallic-mediated polymerization of isocyanides has been broadly studied,⁶ although much less attention has been devoted to its dimerization processes. Isocyanides could react in a head-to-head manner towards the 1,4-diazabutatriene homodimers R-N=C=C=N-R, but these species have been never isolated. Notwithstanding, such heterocumulenes have been proposed as putative reaction intermediates, not only in homodimerizations but also in heterodimerizations (two different reacting partners leading to R¹-N=C=C=N-R²) of diverse isocyanides⁷⁻¹⁵ and have been additionally postulated as plausible molecular wires.^{16,17} Whereas the C-C coupling of two molecules of hydrogen isocyanide affording ethenediimine (R = H) has been studied by theoretical methods¹⁸⁻²² no previous reports deal with computational studies on the dimerization of *N*-substituted isocyanides **1**,²³ a lack that might be reasonably associated to its challenging preparation. Motivated by this absence, by our long-standing interest in the chemistry of nitrogenated heterocumulenes,²⁴⁻²⁷ and by the fascinating per elusive nature of 1,4-diazabutatrienes,²⁸ we present here a computational study aimed to estimate which *N*-substituents have better opportunities of favoring the homodimerization of isocyanides **1** towards species **2** (Figure 1b). With such purpose, and also bearing in mind future attempts for the preparation of **2** by the herein discussed reactions, we combined commercial or synthetically accessible²⁹ isocyanides bearing groups of different electronic nature: H atom, electron donating groups (EDG) as Me, NH₂, NMe₂ and electron withdrawing groups (EWG) as CF₃, CHO and F. Although the preparation of F-NC is still

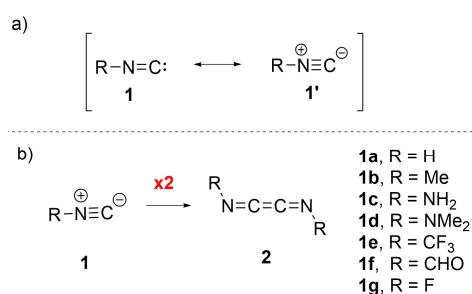


Figure 1. a) Resonant forms of isocyanides **1**; b) Homodimerization of isocyanides **1** to afford 1,4-diazabutatrienes **2**

unknown, we incorporated it in our study for evaluating the influence of the most electronegative element (F).

The homodimerization of isocyanides **1** might afford several structural isomers depending on its reactivity mode. The relative stabilities of all the C₂H₂N₂ isomers, putative dimers of hydrogen isocyanide **1a**, have been computed previously and the results show that (*Z*)-iminoformyl isocyanide [(*Z*)-HN=CHCN] is the most stable one, whereas the parent ethenediimine HN=C=C=NH **2aa** is of higher energy.^{20,22,30} Thus, we first evaluated the thermochemical stability of the diverse isomers resulting from the homodimerization of isocyanides, taking Me-NC **1b** and F-NC **1g** as models. The (*E*)-*N,N'*-disubstituted-1,4-diazabutatrienes **2bb** and **2gg** isomers, resulting from a C-C coupling reaction, were the most stable ones (see Supp. Info.). Afterward we computed the other diazabutatriene dimers **2** and a generalized representation is shown in Figure 2. There are minor structural differences among them: the C-C distances rank from 1.263 to 1.290 Å

whereas the N-C ones go from 1.228 to 1.244 Å, therefore lengthening that in the starting linear isocyanide **1** (1.162-1.170 Å). Interestingly, their two N-C-C bond angles, ranging from 161.0 to 171.1°, reveal the non-linearity of these heterocumulenes (Figure 2 and Supp. Info).

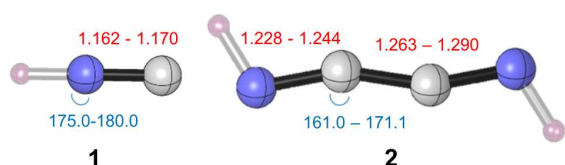


Figure 2. General representation of the computed isocyanides **1** and 1,4-diazabutatrienes **2**. Distances are shown in angstrom (Å, red) and bond angles in degrees (°, blue). The grey and blue spheres are the respective C and N atoms whereas the small pink one represents the R substituent

We further explored the potential energy surfaces of the homodimerizations of isocyanides **1a-g** towards the respective 1,4-diazabutatrienes **2**. Figure 3 shows the relative free energies of the transition structures **TS** (blue bars) and the products **2** (orange bars). In the next paragraphs we comment only on the most relevant aspects of our computational results (see Supp Info for a detailed energy description of the reactions). Compounds **2** are shown in Figure 3 ordered by decreasing values of energy from left to right. Most of the homodimerization processes are endergonic reactions, following the ranking **2bb** (Me, +104.3 kJ mol⁻¹) > **2ff** (CHO, +61.1 kJ mol⁻¹) > **2aa** (H, +47.7 kJ mol⁻¹) > **2ee** (CF₃, +40.1 kJ mol⁻¹) > **2cc** (NH₂, +0.3 kJ mol⁻¹), whereas the formation of diazabutatrienes bearing two identical NMe₂ (**2dd**) and F (**2gg**) substituents are exergonic, although notoriously different, by -8.1 kJ/mol and -158.6 kJ mol⁻¹ respectively, this latter 1,4-diazabutatriene **2gg** being by far the more stable one of the entire series. Our calculations also predict that the formation of **2** follows a different rank in kinetic terms. The homodimerization of **1b** is the most costly in energy terms ($\Delta G_{TSbb} = +142.5$ kJ mol⁻¹), followed by **2aa** with an energy penalty of +118.5 kJ mol⁻¹, whereas the formation of **2cc** and **2gg** are significantly more accessible showing the lowest energy barriers of +100.9 and +69.0 kJ mol⁻¹, respectively (Figure 3). These barriers were computed to be lower than those of the alternative isocyanide-cyanide isomerization processes, except for the case of HNC (see Supp. Info.)

Aiming to shed light on the reasons for these different energetic parameters we performed a structural and electronic analysis of the respective transition structures **TS** as well as of the reaction products **2**. The relevant geometrical parameters, Wiberg bond indexes and the stabilizing orbital charge transfers $E(2)$ of those stationary points were calculated and can be consulted in the Supp. Info. It is worth noting that, in general, both isocyanide units behave as two identical entities at the transition structure with the notorious exception of **TSgg** where each F-NC unit presents different structural and electronic features (see Figure 4 and Supp. Info.). The transition structures **TSaa-ff** are planar and show C₂ symmetry. Both isocyanide components approach each other in a non-linear trajectory, measured as the N-C-C angles, and the two N-C distances are equal and slightly longer than in the corresponding isocyanide **1a-f**. The computed side-

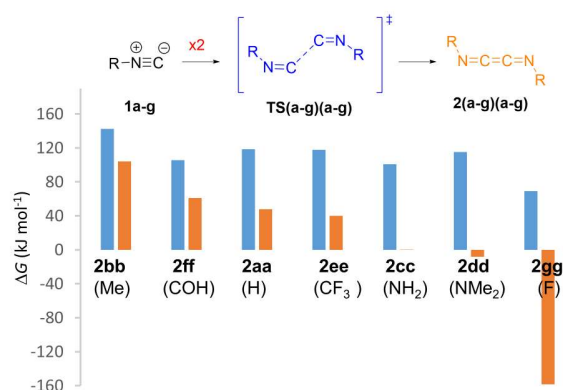


Figure 3. Computed relative Gibbs free energies (kJ mol⁻¹) of stationary points **TS** (blue bars) and dimers **2** (orange bars), referenced to the corresponding isolated monomer **1**, at the DLPNO-CSSD(T)/ma-def2-TZVPP//wB97XD/def2-TZVPD theoretical level

on approach of both isocyanide units resembles that found in dimerizations of singlet carbenes, where the repulsion of the lone pairs of the reacting carbon atoms is minimized in this way respect to the least motion trajectory.^{31,32} However, the structural symmetry is lost in case the of **TSgg** where both angular approaches of one isocyanide to the other are notably different, with N-C-C angles of 135.2° and 109.6°, whereas the two N-C bond lengths are also different, 1.166 Å and 1.208 Å (1.165 Å in **1g**). In addition, the forming C-C bond distance of 2.088 Å in **TSgg** is the longest one among all the computed. In fact, the C-C bond length at the planar transition structures **TSs** increases as the respective energy barrier decreases, a characteristic of early transition states. The energy penalty of the late **TSs** of some homodimerizations could be reasoned attending to the higher electronic repulsion between the bonding carbon atoms when both units become closer (see Figure S2).

The NBO second-order perturbation energies [$E(2)$] between the two isocyanides at the transition structures provide a vision on how the reactions are taking place in terms of charge transfer interactions between occupied and empty orbitals.³³ In these processes the most significant computed orbital interactions are those from the lone pair (LP) of the C atom of one isocyanide unit to the antibonding π -orbital of the N-C bond of the other. In all the transition structures **TSbb-ff** both isocyanide units contribute equally, whereas the two energy transfers from an isocyanide unit to the other are very different in **TSgg**, +246.7 and +89.0 kJ mol⁻¹, one of them playing the role of the electron-donor partner whereas the other is the electron-acceptor. Moreover, a minor stabilizing interaction of 1.3 kJ mol⁻¹ from the LP of the fluorine atom of the bent unit to the antibonding σ -orbital of the C2-N bond was computed, therefore contributing somehow to low the barrier energy of **TSgg** respect to the rest of **TSs**, in which this kind of orbital interaction is absent or non significant (as in **TSee**). In other words, the fluorine atom seems to be able to simultaneously modulate the uneven electronic characteristics (donor and acceptor) of both

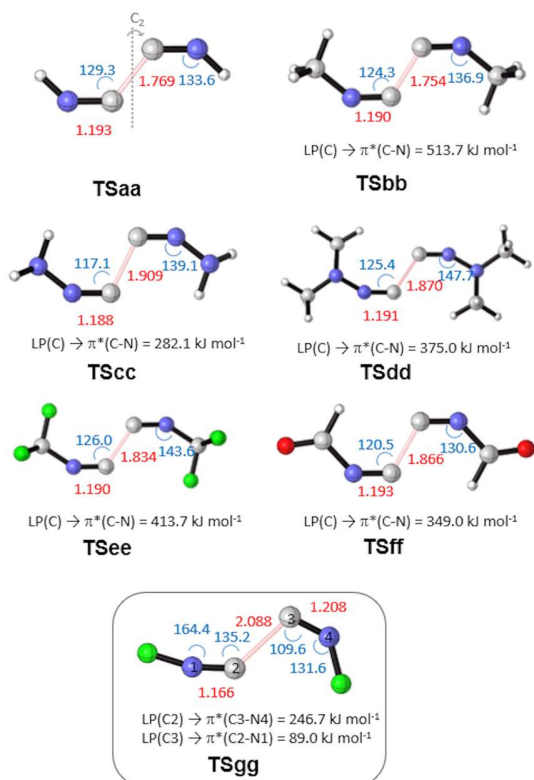


Figure 4. Distances (Å, red), angles ($^{\circ}$, blue) and stabilizing orbital charge transfer interactions $E(2)$ (kJ mol^{-1} , black) of computed transition structures **TSaa-gg** at the DLPNO-CSSD(T)/def2-TZVPP//wB97XD/ma-def2-TZVPD theoretical level³⁴

isocyanide units, a somewhat surprising situation. This dual behavior of F-NC is reflected in the quite different geometries of both units at the **TSgg**: the donor one more linear, showing a nearly sp -like nitrogen atom N1, and the acceptor one curved, with a more sp^2 -like nitrogen atom N4, as revealed by their respective F-N-C angles of 164.4 and 131.6 $^{\circ}$. Although it is well known that isocyanides are chameleonic species³⁵ that can react indistinctly with nucleophiles or electrophiles, *F-NC behaves as a superchameleonic isocyanide*, as it plays simultaneously a dual role, as donor and acceptor, *on reacting with itself!*

Prompted by the chameleonic character of F-NC, we wondered which role it would play in heterodimerization processes versus the rest of isocyanides explored herein. Thus, we next computed the reactions between **1g** (R = F) and the other six isocyanides **1a-f** (Figure 5). All of these combinations show lower energy barriers than that of the homodimerization of **1g** and, moreover, *all the processes are exergonic!* Among them, the formation of the diazabutatriene **2bg** (Me, F) is the less exergonic ($-51.2 \text{ kJ mol}^{-1}$), followed by **2fg** (CHO, F) and **2eg** (CF₃, F), whereas the combination of **1g** with **1d** (NMe₂) provides the thermodynamically most favorable heterodimer, $-103.2 \text{ kJ mol}^{-1}$. Furthermore, the heterodimerizations of **1g** with **1a-f** are more kinetically favored when the latter bears an H atom or an EDG group (NH₂, NMe₂, Me) rather than an EWG substituent (CF₃, CHO). As expected from the data above, the computed orbital charge transfer interactions from the **1a-f** unit towards the

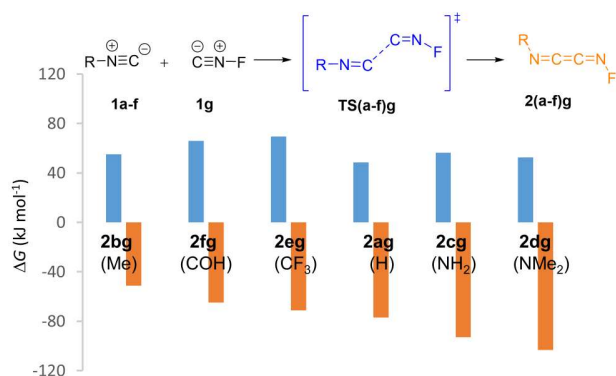


Figure 5. Computed relative Gibbs free energies (kJ mol^{-1}) of stationary points **TS(a-f)g** (blue bars) and dimers **2(a-f)g** (orange bars), referenced to **1a-f** plus **1g**, at the DLPNO-CSSD(T)/def2-TZVPP//wB97XD/def2-TZVPD theoretical level

fluorinated partner **1g** at all **TS(a-f)g** is always higher than in the reverse sense, showing that F-NC acts in all these cases as *an acceptor unit* (Figure 6). This is also evident by attending to the geometries of each isocyanide at the respective transition structures: whereas the F-NC fragment presents always a bent structure, associated to an sp^2 -like nitrogen and the acceptor role, the reacting counterparts show linear geometries typical of a more sp -like nitrogen and the donor role (Figure 6).

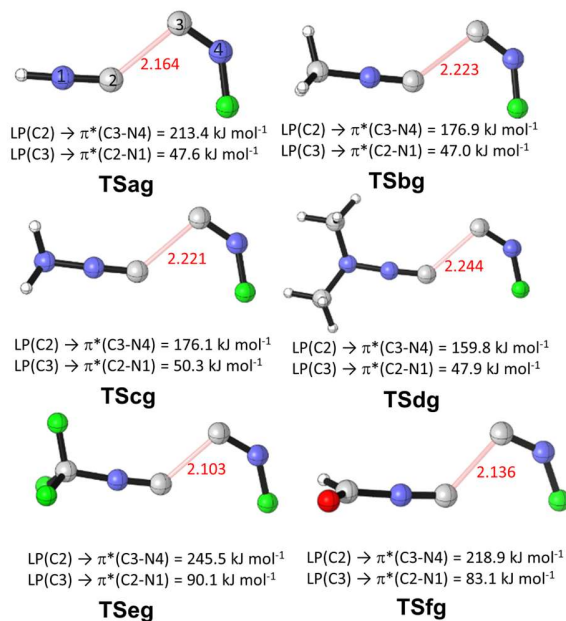


Figure 6. Distances (Å, red) and stabilizing orbital charge transfer interactions $E(2)$ (kJ mol^{-1} , black) of computed transition structures **TS(a-f)g** at the DLPNO-CSSD(T)/ma-def2-TZVPP//wB97XD/def2-TZVPD theoretical level. For clarity, bond angles have been omitted and can be consulted at the Supp. Info.

CONCLUSIONS

In summary, we disclose herein the influence of a range of *N*-substituents on the electronics of the homocoupling processes between two isocyanides towards the respective 1,4-diazabutatrienes. We computed that groups as F or NMe₂ directly attached to the N atoms contribute to turning exergonic these processes, which are endergonic in most of the cases. Although isocyanides are known as chameleonic species, reacting with both nucleophiles and electrophiles, we have shown herein for the first time that *F-NC behaves like a chameleon versus itself*, in its homodimerization process, acting simultaneously as donor and acceptor. This is why we qualify F-NC as a superchameleon. However it acts always as acceptor when confronted with the rest of isocyanides analyzed in the series of heterodimerization processes. In these latter cases, the choice of the better donor partners yielded more exergonic processes. We believe this study lays the foundations for future attempts of preparing the elusive 1,4-diazabutatrienes by homo and heterodimerization of isocyanides, apparently with more possibilities of success by this latter synthetic approach. Nevertheless, the striking characteristics of the superchameleonic F-NC are worth of remarking: its homodimer is still the most thermochemical stable one of all the herein computed 1,4-diazabutatrienes. New examples of similar superchameleonic isocyanides are being now the object of our studies and a full account of our results on this field will be reported in due course.

COMPUTATIONAL METHODS

The geometries of the molecules were fully optimized by using the wB97XD hybrid functional³⁶ in combination with the def2-TZVPD basis set.^{37,38} The nature of minimum and transition structure of all the stationary points found along the Potential Energy Surface was confirmed by performing a frequency analysis at the same level of theory. Thermochemical corrections at 298.15 K were calculated for all stationary points from unscaled vibrational frequencies. The stability of the wave functions was checked for all the optimized structures.³⁹ Single point calculations of the optimized geometries were performed at the DLPNO-CSSD(T)⁴⁰/ma-def2-TZVPP⁴¹ theoretical level and were combined with the previous computed thermochemical corrections to yield free energies G_{298} at 298.15 K. All calculations were performed by using both the Gaussian 09⁴² and the ORCA 4.0.1 programs.⁴³ Natural Bond Orbital analyses³³ were performed at the wB97XD/def2-TZVPD level with the NBO 7.0 software.⁴⁴ The structures were plotted by using the CYLview program.⁴⁵

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Computational data and cartesian coordinates (PDF)

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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