Light-Induced On/Off Switching of the Surfactant Character of the o-Cobaltabis(dicarbollide) Anion with No Covalent Bond Alteration

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Abstract: Cobaltabis(dicarbollide) anion ([o-COSAN]) is a well-known metallacarborane with multiple applications in a variety of fields. In aqueous solution, the cisoid rotamer is the most stable disposition in the ground state. The present work provides theoretical evidence on the possibility to photoinduce the rotation from the cisoid to the transoid rotamer, a conversion that can be reverted when the ground state is repopulated. The non-radiative decay mechanisms proposed in this work are coherent with the lack of fluorescence observed in 3D fluorescence mapping experiments performed on [o-COSAN]− and its derivatives. This phenomenon induced by light has the potential to destruct the vesicles and micelles cisoid [o-COSAN]− typically forms in aqueous solution, which could lead to promising applications, particularly in the field of nanomedicine.

The cobaltabis(dicarbollide) anion, [3,3′-Co(1,2-C$_2$B$_9$H$_{11}$)$_2$]− abbreviated as [o-COSAN]−, is a 3D-aromatic metallabisdicarbollide,\textsuperscript{[1]} that can be viewed as if two $nido$-[C$_{2}$B$_{9}$H$_{11}$]$^{2−}$ units sandwich a Co$_{III}$ atom.\textsuperscript{[2]} In the last decades, a vast number of studies have described its physical and chemical properties, highlighting its thermal and chemical stability, most probably due to its strong aromatic character.\textsuperscript{[3]} These and other properties, in conjunction with its facile synthesis\textsuperscript{[4]} and derivatization,\textsuperscript{[5]} make this molecule highly attractive for the development of multiple applications in a plethora of fields,\textsuperscript{[4−5]} including catalysis,\textsuperscript{[6−7]} redox chemistry,\textsuperscript{[8]} (bio)sensors,\textsuperscript{[9−11]} medicine,\textsuperscript{[5,12−16]} metal-organic frameworks,\textsuperscript{[17]} conducting polymers,\textsuperscript{[18,19]} and surfactants,\textsuperscript{[20,21]} among others.\textsuperscript{[5,22]}

Recently, Malaspina et al\textsuperscript{[20]} rationalized the peculiar ability of [o-COSAN]− to form vesicles and micelles in bulk water, finding that the molecule has indeed very well differentiated hydrophobic and hydrophilic regions. The former corresponds to the surface spanned by the four carbon atoms, characterized by a low net charge density, whereas the latter is ascribed to the geometrically opposed boron atoms, that localize the net negative charge of the molecule. [o-COSAN]− exists in three different rotamers, namely transoid-[o-COSAN]−, gauche-[o-COSAN]−, and cisoid-[o-COSAN]−. Their relative populations in water solution at 298 K, estimated through the Boltzmann thermodynamic equilibrium distribution, are 1.4%, 12.8%, and 85.8%, respectively.\textsuperscript{[20]} The surfactant properties of [o-COSAN]− in water solution are thus explained by the preference for the cisoid rotamer, which orients the four carbon atoms toward the same side of the molecule, generating amphiphilic properties.\textsuperscript{[20]} Following this reasoning, it is rational to expect that the transoid rotamer, in which the two couples of adjacent carbon atoms face opposite sides, will lack these surfactant properties.

This work is thus aimed to find whether light could be used to stabilize, kinetically and/or thermodynamically, other isomers rather than the thermally stable cisoid [o-COSAN]− rotamer in aqueous solution. Apart from the fundamental interest in the discovery of novel molecular rotors, as reported for the related Ni$^{III}$ metallabis(dicarbollide),\textsuperscript{[23]} this hypothesis, if correct, could have potential practical relevance as on/off light switchable surfactants having significant applications in multiple relevant fields, for example, in drug delivery. Nanomedicine often fails to translate efficacies from preclinical trials to clinical administration due to heterogeneity in enhanced permeability and retention in human cancer cells.\textsuperscript{[24]} A photo-responsive nanocarrier formed by self-assembly of small molecules, [o-COSAN]−, wherein each individual molecule is a photo-responsive surfactant, can possibly enhance efficacy in clinical trials.

This hypothesis is motivated by the recent finding of Guerrero et al,\textsuperscript{[25]} which characterized the bright excited state of [o-COSAN]− as an electronic promotion from the carbaborane skeleton to the cobalt atom (ligand-to-metal charge transfer or LMCT),\textsuperscript{[1]} and the usual antibonding character of empty d orbitals of first-row transition metals, that could elongate the metal-boron coordination bonds, thus diminishing the steric hindrance for the relative rotation of the [C$_2$B$_9$H$_{11}$]$^{2−}$ units, as suggested in a previous work.\textsuperscript{[25]}

Herein, results are obtained through a combination of density functional theory (DFT),\textsuperscript{[26]} time-dependent (TD)-DFT,\textsuperscript{[27]} multiconfigurational complete-active-space second-order perturbation theory (CASPT2) calculations,\textsuperscript{[27]} and 3D...
fluorescence experiments. Full computational details and method validations can be found in the Supporting Information (SI).

The absorption properties of cisoid- and transoid-[α-COSAN] are shown in Figure S4. The CASSCF/CASPT2 method describes the most intense absorption in the UV wavelengths as LMCT transitions, confirming previous TD-DFT studies.[7] CASPT2 determinations predict smaller absorption capacities for cisoid-[α-COSAN]− with respect to the transoid rotamer. The latter is responsible of the intense band recorded at \( \approx 293 \text{ nm} \), whereas the absorption in the visible region (\( \approx 450 \text{ nm} \)) is ascribed solely to triplet absorptions of the cisoid-[α-COSAN]−. This result suggests that the presence of cisoid and transoid rotamers could be tracked at \( \approx 450 \) and \( \approx 293 \text{ nm} \), respectively.

Figure 1 displays the photochemical landscape of the cisoid and transoid rotamers. According to Kasha’s rules,[28] the optically active state populated upon light absorption vibrationally decays to the lowest singlet or triplet excited states via fast internal conversions and intersystem crossing events, also favoured by the high density of states and the large singlet-triplet spin-orbit couplings (SOCs) (see Tables S1–S3 and S5). In both rotamers, optimization of the \( S_1 \) state (coordinate 7) elongates all Co-B and Co-C coordination bonds due to the antibonding character of the LMCT state in this region of the molecule (Figure S4). Interestingly, \( T_1 \) state relaxation (coordinate 13) is characterized by a further elongation of a Co–C bond and a Co-B connection in cisoid-[α-COSAN]− and the two Co–C bonds in transoid-[α-COSAN], while the remaining coordination bond distances decrease. Table S5 lists the bond distances for all rotamers and Figure 1c illustrates the \( S_1 \) and \( T_1 \) minima stretchings. As shall be discussed below, the increase of the distance between the two \([\text{C}_2\text{B}_9\text{H}_{11}]^{2−}\) units correlates with lower energy rotation barriers between each [α-COSAN]− rotamers, as compared to those in the ground state.

For [α-COSAN], the large SOCs between singlet and triplet states (Table S6), typical of molecular systems bearing transition metal[9,30] strongly support the population of triplet states during the excited-state relaxation. By inspection of Figure 1, it becomes apparent that the \( T_1 \) and \( T_2 \) states lie at significantly lower energies with respect to the \( S_1 \) surface, indicating that these triplet states will mediate the excited state decay, especially at the \( T_1 \) equilibrium structure (coordinate 13). This region is, however, markedly different for both rotamers. Whereas the cisoid structure has a \( T_1-S_0 \) energy gap of 0.61 eV (14.1 kcal mol−1), the transoid isomer displays an energy difference of only 0.21 eV (4.8 kcal mol−1) and can be considered a singlet-triplet crossing (STC) region. Highly accurate CASPT2 results confirm this finding (see Table S7). The potential energy surfaces shown in Figure 1 suggest a longer excited state lifetime for the cisoid-[α-COSAN]−, as compared to transoid-[α-COSAN], due to the higher energy gap and thus smaller probability of ground-state repopulation via \( T_1\rightarrow S_0 \) intersystem crossing. The predicted longer excited-state lifetime allows the possibility to rotate to the transoid arrangement, clearly the most favorable rotamer in the excited state (Figure 2 and Table S8). In the transoid arrangement, the non-radiative \( T_1\rightarrow S_0 \) decay is more efficient, and will be followed by a thermal rotation back to the dominant cisoid disposition, the most stable rotamer in the ground state.[31]

The relative stabilities of the [α-COSAN]− rotamers in water have been re-assessed in the \( S_1 \) and \( T_1 \) excited states (see Figure 2). Table S8 compiles the energies both in solution and in the gas phase, at the TD-B3LYP and CASPT2 levels of theory, whereas the dipole moment modules \( || \) of each rotamer are compiled in Table S9. In solution, the gauche rotamer, intermediate between cisoid and transoid, is the most stable isomer in the \( S_1 \) state. Meanwhile, in the \( T_1 \) state, accessible through large singlet-triplet SOC values, the transoid rotamer is clearly the most stable rotamer by \( \approx 4 \text{ kcal mol}^{-1} \). In the gas phase, the stabilization is even larger (\( \approx 7 \text{ kcal mol}^{-1} \)). This indicates that the photoexcitation of cisoid-[α-COSAN]− in water solution increases the distance...
between the two \([\text{C}_2\text{B}_{9}\text{H}_{11}]^2\) ligands, facilitating the rotation of the two units favouring the transoid species, thus inducing a cisoid-to-transoid photoinduced rotation at a photochemical (fast) scale. To the best of our knowledge, this feature has not been explored until now.

The energy barriers associated to the rotation are reported in Figure 2a. It can be readily seen that the results corroborate the premise made above based on the antibonding character of the orbitals populated upon photoabsorption. Thus, energy barriers of ca. 2 kcal mol\(^{-1}\) are obtained for the \(S_1\) and \(T_1\) excited states, while those found for the ground state exceed 4 kcal mol\(^{-1}\). In vacuo, the CASPT2 method (Figure S7c) provides a very similar description to TD-DFT profiles (Figure S7b), even though the gauche and transoid rotamers are stabilized by \(\approx 1\) kcal mol\(^{-1}\) in the ground state by the multiconfigurational method. Note that the relative energies between the \(S_0\), \(S_1\) and \(T_1\) states at each point of the dihedral angle scan cannot be directly compared, since each curve has different energy reference (the energy of each state at the cisoid disposition).

The excited-state rotation and decay mechanism are confirmed through state-of-the-art\(^{[36-37]}\) non-adiabatic molecular dynamics\(^{[36-37]}\) performed in a model system, including only the first three singlet and four triplet states in the simulations, initially exciting the \(S_i\) state. Full simulation details can be found in the SI. As expected, populations analysis reveals a fast population of the triplet states within a few hundreds of fs (Figure S9a), with a characteristic time constant for the net triplet population (from both \(S_i\) and \(S_2\) states) that is of 343 fs (Figure S9b), totally coherent with the large singlet-triplet SOCs.

Time evolution of the B-B-C dihedral angle (as defined in Figure 2b) reveals that, within our simulation time (\(\approx 1\) ps), \(\approx 24\%\) of the molecules undergo a photoinduced rotation (Figure 3). In particular, \(\approx 14\%\) reach gauche disposition and \(\approx 10\%\) already display transoid arrangement. Whereas some of the rotations clearly take place in the triplet state, followed by the decay to the ground state when the system reaches the gauche or transoid regions (as stated above), others occur in the singlet state, even after decay to \(S_0\), indicating that the triplet state population is not a prerequisite for the photoinduced rotation and that the vibrational excess of energy can also drive the rotation. Meanwhile, this phenomenon is not observed when the dynamics are propagated in the \(S_0\) state (Figure S10), showing the influence of the excited state in inducing the rotation. The most active vibrational normal mode in the excited-state dynamics is characterized by transversal displacements of each carborane cage toward opposite directions (Figures S11–S18).

While the non-adiabatic dynamics performed in this work serve as a proof of concept of the photoinduced rotation and allow an estimation of its yield and timescale, these results shall be considered as a lower bound of the actual rotation properties. More rotations are expected with longer simulation times since the majority of trajectories (64%) remain in the excited state after 1 ps from excitation. On the other hand, only a few excited states are included in the dynamics, while higher energy states can be populated increasing the wavelength range of UV/Vis radiation. The higher excitation energy (and thus vibrational energy) and the presumably longer excited-state lifetimes are expected to increase the rotation yields.

The non-radiative decay mechanisms described in this work, mediated by the population of triplet excited states, explain the absence of luminescence measured for [o-COSAN] in 3D fluorescence experiments. Figure 4a shows the emission spectrum recorded for the sodium salt of [o-COSAN] in aqueous solution, of predominant cisoid configuration, irradiated from 300 to 550 nm. No emission signal is detected. The same result is obtained for [o-COSAN] in...
acetone (Figure S24). In contrast, Figure 4b reveals the well-known emission band of quinine sulfate, which serves as a control experiment in this work. Similar to [o-COSAN]−, some of its methyl, phenyl, and chlorinated derivatives, of predominant cisoid disposition due to the presence of the bulky substituents and/or lone pairs at the substituents, have no emission properties either (Figures S25–S29).

This Communication explores the ability of [o-COSAN]− cluster to constitute a light-induced molecular rotor, a feature that could have consequences in some of its vastly studied properties.[22] For example, the supramolecular vesicle nanostructures typical of the cisoid disposition,[23] could be disaggregated acting as precisely drug delivery systems under exposition to UV light. Mass spectrum measurements in photocatalysis experiments indicate that [o-COSAN]− is mostly stable upon irradiation,[7] The present theoretical predictions are also valuable given the experimental difficulties in disentangling the optical and spectroscopic properties of each rotamer. Nonetheless, future experimental set ups able to detect the rotamer population transfers in aqueous solution, for instance through time-resolved spectroscopy, are highly encouraged.

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Conflict of Interest

The authors declare no conflict of interest.

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[1] J. Poater, C. Viñas, I. Bennour, S. Escayola, M. Solà, F. Teixidor, J. Am. Chem. Soc. 2020, 142, 9396 – 9407.
[2] M. F. Hawthorne, D. C. Young, T. D. Andrews, D. V. Howe, R. L. Pilling, A. D. Pitts, M. Reintjes, L. F. Warren, P. A. Wegner, J. Am. Chem. Soc. 1968, 90, 879 – 896.
[3] I. Bennour, A. M. Cioran, F. Teixidor, C. Viñas, Green Chem. 2019, 21, 1925 – 1928.
[4] J. Pleseck, Chem. Rev. 1992, 92, 269 – 278.
[5] N. S. Hosmane, R. D. Eaging, Handbook Of Boron Science: With Applications In Organometallics Catalysis, Materials And Medicine, Vol. 4, World Scientific, Singapore, 2018.
[6] I. Guerrero, C. Viñas, X. Fontrodona, I. Romero, F. Teixidor, Inorg. Chem. 2021, 60, 8898 – 8907.
[7] I. Guerrero, Z. Kelemen, C. Viñas, I. Romero, F. Teixidor, Chem. Eur. J. 2020, 26, 5027 – 5036.
[8] M. Lupa, A. Zaulet, F. Teixidor, E. Ruiz, C. Viñas, Chem. Eur. J. 2015, 21, 6888 – 6897.
[9] A.-I. Stoica, C. Viñas, F. Teixidor, Chem. Commun. 2008, 6492 – 6494.
[10] A.-I. Stoica, C. Viñas, F. Teixidor, Chem. Commun. 2009, 4988 – 4990.
[11] D. Kodr, C. P. Yenice, A. Simonova, D. P. Saftic, R. Pohl, V. Sýkorová, M. Ortiz, L. Havran, M. Foja, Z. J. Lesnikowski, et al., J. Am. Chem. Soc. 2021, 143, 7124 – 7134.
[12] I. Fuentes, T. García-Mendiola, S. Sato, M. Pita, H. Nakamura, E. Lorenzo, F. Teixidor, F. Marques, C. Viñas, Chem. Eur. J. 2018, 24, 17239 – 17254.
[13] E. Hao, M. G. H. Vicente, Chem. Commun. 2005, 1306 – 1308.
[14] E. Hey-Hawkins, C. V. Teixidor, Boron-Based Compounds: Potential and Emerging Applications in Medicine, Wiley, Hoboken, 2018.
[15] P. Cigler, M. Kožošek, P. Řezáčová, J. Brynda, Z. Otwinowski, J. Pokorná, J. Plešek, B. Grünner, L. Dolečková-Marešová, M. Máša, et al., Proc. Natl. Acad. Sci. 2005, 102, 15394 – 15399.
[16] Y. Zheng, W. Liu, Y. Chen, H. Jiang, H. Yan, I. Kosenko, L. Chekulaeva, I. Sivaev, V. Bregadze, X. Wang, Organometallics 2017, 36, 3484 – 3490.
[17] M. J. Hardie, J. Chem. Crystallogr. 2007, 37, 69 – 80.
[18] C. Masalles, S. Borrós, C. Viñas, F. Teixidor, Adv. Mater. 2000, 12, 1199 – 1202.
[19] R. Núñez, I. Romero, F. Teixidor, C. Viñas, Chem. Soc. Rev. 2016, 45, 5147 – 5173.
[20] D. C. Malaspina, C. Viñas, F. Teixidor, J. Faraujo, Angew. Chem. Int. Ed. 2020, 59, 3088 – 3092; Angew. Chem. 2020, 132, 3112 – 3116.
