

Structures and Rotational Barriers of a Diiodobinorsnoutane: Energetic Preference for *Gauche* Conformation

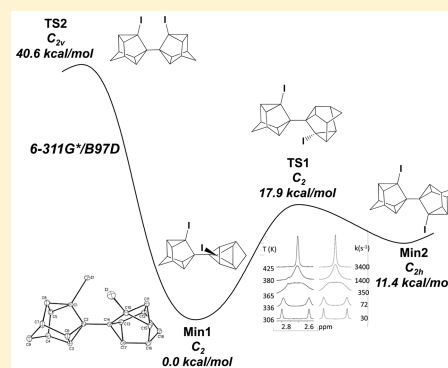
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Supporting Information

ABSTRACT: The diiodobinorsnoutane, bi(5-iodopentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]-non-4-yl) (**5**), exists in a sterically hindered *gauche* conformation rather than an *anti* or an averaged (freely rotating) C_{2v} structure. Density functional theory (DFT) predictions place the *gauche* conformation 11 kcal/mol more stable than the *anti* conformation with a barrier of 17 kcal/mol connecting the minima. These are consistent with variable-temperature NMR (17.1 ± 0.8 kcal/mol) estimates and X-ray analysis. Predictions of the torsional profiles of the yet-unsynthesized bromo-, chloro-, and fluoro- analogues show a progressive lowering of the barriers.



We previously reported that pentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]-non-4-ene (**1**), one of the most highly pyramidalized alkenes known, may be generated in solution and trapped as its Diels–Alder adduct via dehalogenation of diiodopentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]nonane (**2**) with alkylolithiums such as *n*-butyl- and *tert*-butyllithium. In these reactions, however, the various alkylolithiums present in the reaction mixture add to the pyramidalized double bond of **1** to yield several side products, including the dimer bi(5-iodopentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]-non-4-yl) (**5**) (Scheme 1). In the dehalogenation reaction with *tert*-butyllithium and in the absence of a trapping agent, bi(5-iodopentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]-non-4-yl) (**5**) is the major product, comprising nearly half of the isolable products.¹

When we initially isolated **5** from the aforementioned product mixtures of the reaction of diiodide **2** with *n*-butyllithium or *tert*-butyllithium, the ¹H and ¹³C NMR spectra of this compound showed less symmetry than expected. For a freely rotating compound, an averaged C_{2v} symmetry is expected for **5**. This would mean only five types of hydrogen atoms and six types of carbon atoms; however, in the corresponding NMR spectra we detected eight types of hydrogens and nine types of carbons (Figure 1). Thus, the number of observed proton and carbon signals is concordant for a situation in which **5** does not possess any planes of symmetry but rather only a C₂ axis. This makes both halves of the molecule equivalent, while all of the hydrogens and carbon atoms of each half are nonequivalent. We suspected that the lack of expected symmetry in **5** was likely the result of hindered rotation around the C4–C4' bond, which connects the two halves of the molecule.

To examine the conformations in more detail, density functional theory (DFT) was used to compute the gas phase structures and energies along the torsional profile of the C–C bond connecting the pentacyclononane subunits of **5**. Specifically, the B97D method was used to account explicitly for potential dispersion effects (see the Supporting Information for comparisons to additional computations). Figure 2 summarizes the torsional potential energy surface of **5** consisting of two energy minima and the transition states connecting them. Each of the stationary points was fully optimized within their respective point group symmetry. The lowest energy structure (Min1) has C₂ symmetry with the iodine substituents in a *gauche* arrangement. A second minimum (Min2) approximately 11 kcal/mol higher in energy is predicted to have C_{2h} symmetry with the iodine substituents in an *anti* conformation. The transition state connecting them (TS1) has C₂ symmetry and lies approximately 18 kcal/mol above the global minimum energy structure. Consistent with the sterics of the bulky iodine substituents, torsional rotation through the *syn* conformation is energetically disfavored. This transition state (TS2) has C_{2v} symmetry and lies approximately 40 kcal/mol above the C₂ *gauche* minimum.

The predicted energy barrier via TS1 (17.9 kcal/mol) was further assessed by performing variable-temperature NMR studies (Figure 3). The theoretically predicted gas-phase estimate of the activation barrier to rotation (17.9 kcal/mol) is in close agreement with that inferred via NMR via application

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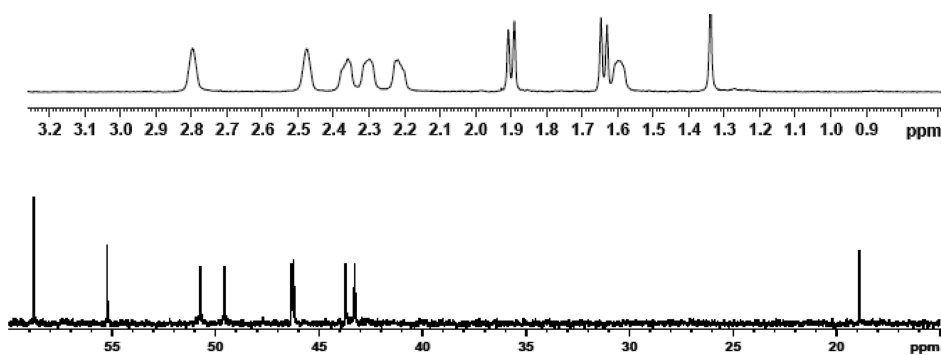
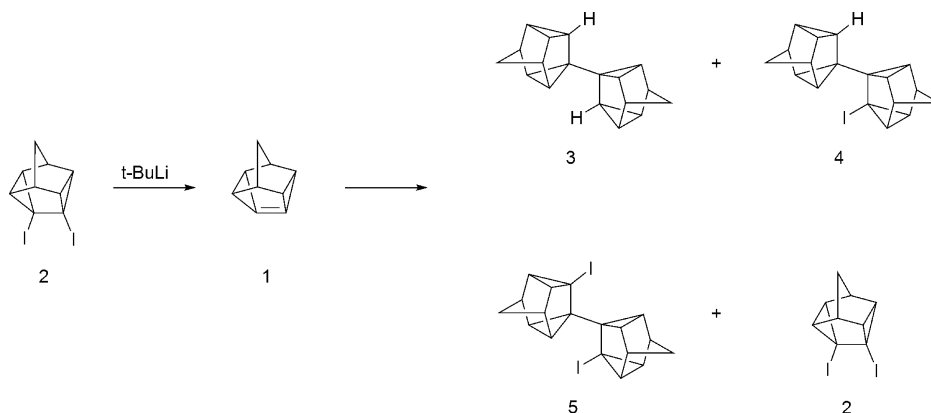
Scheme 1. Synthesis of Bi(5-iodopentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]non-4-yl) (5)

Figure 1. ^1H (500 MHz) and ^{13}C NMR (125 MHz) spectra for bi(5-iodopentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]non-4-yl) (5) in 1,2 dichlorobenzene- d_4 at 304 K.

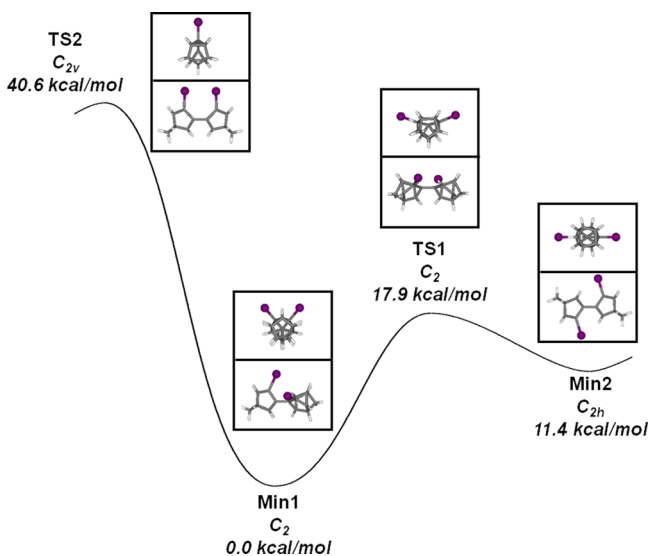


Figure 2. Computed (6-311G*/B97D, gas phase) free energy torsional profile of 5. The C_2 conformation with iodine substituents in the *gauche* orientation (Min1) is energetically preferred, while the C_{2h} *anti* orientation (Min2) lies approximately 11 kcal/mol higher. The C_2 TS1 transition state approximately 18 kcal/mol above Min1 is consistent with the energy barrier derived from temperature-dependent NMR studies (17.1 ± 0.8 kcal/mol). Rotation via the C_{2v} TS2 transition state with the iodines in a *syn* orientation is disfavored (barrier of approximately 40 kcal/mol).

of the Eyring equation (17.1 ± 0.8 kcal/mol, Figure 3) upon determination of the coalescence of the singlet signals.

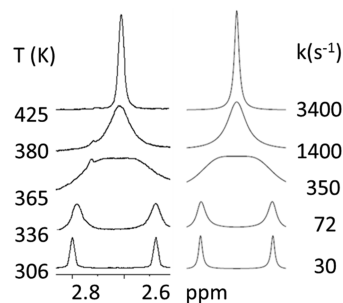


Figure 3. (Left) Temperature dependence of the ^1H C4 and C7 (or C12 and C16) signals of 5 (500 MHz in dichlorobenzene- d_4). (Right) Line-shape simulations with rate constants. The coalescence temperature of 346.8 K corresponds to an approximate interconversion barrier of 17.1 ± 0.8 kcal/mol via application of the Eyring equation.

Finally, the single-crystal X-ray crystal structure was determined for 5 (Figure 4). The iodine atoms diffract strongly at higher θ angles, and while additional frames at higher angles are desirable, the high angle data are unlikely to alter the structure significantly. Similarly, higher residual density is also located on the iodine atoms, but this is also not expected to affect the quality of the structure significantly. The X-ray structure also shows the iodine atoms to be in a *gauche* conformation, and key structural features are consistent with those predicted using DFT. The C2–C14 bond connecting the pentacyclononane subunits is 1.49 Å in the crystal structure (and also 1.49 Å from 6-311G*/B97D), and the iodine–iodine distance is 4.28 Å (4.22 Å using 6-311G*/B97D). The relatively short C2–C14 bond further suggests some degree

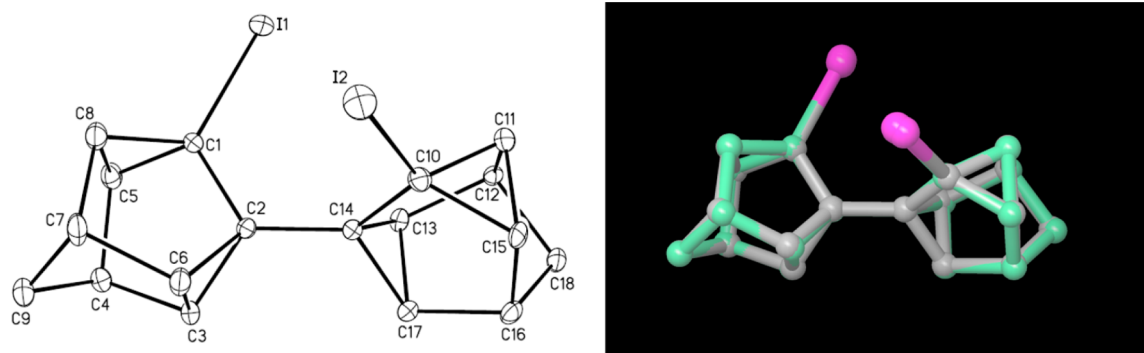


Figure 4. (Left) Single-crystal X-ray structure of **5**. The solid state structure illustrates that the iodine substituents exist in a *gauche* orientation. (Right) Overlay of the crystal structure (gray carbons) and the DFT structure (green carbons). The X-ray structure C2–C14 bond is 1.49 Å, in good agreement with the DFT structure (also 1.49 Å), and is somewhat shorter than the C–C bond in the X-ray structure of ethane (1.53 Å),³ suggesting some degree of attractive force between the pentacyclononane subunits. The computed C–C bond distance of the C_{2h} *anti* conformer of **5** is closer to that of a typical C–C single bond (1.51 Å). See the [Supporting Information](#) for a full CIF of **5**.

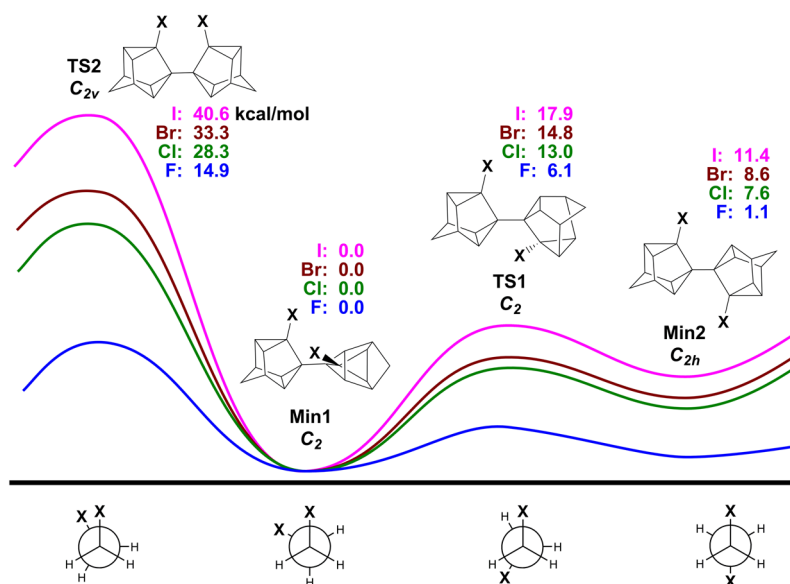


Figure 5. Computed (6-311G*/B97D, gas phase) relative energies (kcal/mol) along the torsional profiles of the halogen congener series of **5**. The transition states are lowered from I > Br > Cl >> F, with the fluoro analogue predicted to have a relatively low (ca. 6 kcal/mol) barrier between the *gauche* and *anti* forms, which are essentially isoenergetic using this theoretical method.

of attractive forces between the subunits, perhaps with contributions from hyperconjugation. Additionally, intermolecular interactions within the lattice are evident, including two typical C–I...I–C halogen bonds (3.71 and 3.75 Å) and a series of C–H...I hydrogen bonds that work together to lock the unit in place (see the [Supporting Information](#) for an additional figure as well as ref 2 for context). The solid-state crystal structure of ethane has a C–C bond length of 1.53 Å compared to that of **5** (1.49 Å).³ Conversely, the computed (6-311G*/B97D) C–C bond length of the C_{2h} *anti* conformer of **5** (1.51 Å) is closer to that of a typical C–C single bond. While there is good agreement between the X-ray structure and the computed structure in this case, molecular motion within the crystal can sometimes significantly contribute to the apparent shortening of bonds (for example in 3-ethynylcyclopropane)^{4–6} and cannot be ruled out as a contributing factor. The treatment of dispersion is evident when compared to the iodine–iodine bond distance in the optimized structure with no empirical accounting for dispersion: the iodine–iodine distance using 6-311G*/B3LYP is 4.37 Å, or 0.15 Å longer than that in the X-

ray structure. For some additional experimental perspective, the iodine–iodine distance in **5** is significantly longer than the shortest iodine–iodine intermolecular distance (3.56 Å) within the sheets of the crystal structure of solid iodine (I_2) but is comparable to the shortest intermolecular distance between sheets of the I_2 crystal structure (4.35 Å).⁷

Finally, the periodic trends of yet-unsynthesized halogen analogues were also examined computationally to gauge the degree of rotational hindrance of smaller halogens. On the basis of sterics alone, the barriers between energy minima are expected to decrease upon changes from I → Br → Cl → F. Indeed, it is also conceivable that the C_{2h} (*anti*) minimum could become energetically preferred with smaller substituents. The periodic trends illustrating the progressive lowering of energy barriers are summarized in [Figure 5](#). While the bromo and chloro analogues are predicted to have TS1 barriers of >10 kcal/mol, the fluorine analogue is predicted to have a significantly lower barrier (ca. 6 kcal/mol) between the *gauche* and *anti* structures, which are essentially isoenergetic. These estimated structures and relative energetics provide initial

Table 1. Computed (6-311G*/B97D) C2–C14 Bond Lengths for Minima and Transition States

6-311G*/B97D optimized structures, X =	Min1 C–C bond (Å)	TS1 C–C bond (Å)	Min2 C–C bond (Å)	TS2 C–C bond (Å)
iodine	1.49 [X-ray: 1.49]	1.53	1.51	1.59
bromine	1.49	1.52	1.51	1.58
chlorine	1.49	1.52	1.51	1.57
fluorine	1.48	1.51	1.50	1.53

guidance for interpretation if attempts are made to synthesize these halogen analogues.

The congeneric series also allows for a further examination of steric and electronic effects on the C–C bond connecting the subunits. Table 1 shows the relative invariance of the C–C bond in the I → Br → Cl → F series. If anything, the C–C bond shortens even more as the substituents become smaller and more electronegative. This C–C bond is nearly invariant across halogens at the TS1 transition state and the Min2 conformation. However, TS2 is influenced by sterics, as expected when the halogens are in closest proximity.

The combination of data from temperature-dependent NMR, density functional theory computations, and X-ray crystallography all converge to characterize **5** as having a sterically hindered C_2 *gauche* conformation with a barrier of ~17 kcal/mol to the C_{2h} *anti* conformation that lies ~11 kcal/mol above the minimum energy structure along the torsional profile. The dibromo and dichloro analogues are predicted to have similar torsional profiles, albeit with slightly lower barriers. However, the difluoro analogue is predicted to have a relatively low barrier (6 kcal/mol) connecting to the *anti* conformer, which is essentially isoenergetic to the *gauche* conformer.

EXPERIMENTAL SECTION

Materials. For synthesis and isolation of the title compound **5**, see ref 1.

Computations. Absolute energies, free energies, equilibrium structures, and harmonic vibrational frequencies were determined for each stationary point described. The 6-311G* basis set was used for all computations.^{8–11} All results are shown using the B97D exchange-correlation density functional, which includes an explicit accounting for potential dispersion contributions.¹² Comparisons to structures and energies computed using B3LYP^{13,14} and CAM-B3LYP¹⁵ are provided in the Supporting Information. Minima and transition states were optimized within the given point group symmetry via analytic gradients until the residual root-mean-square gradient was less than 10^{-4} hartree/bohr. The mass-weighted Hessian matrix, and hence the harmonic vibrational frequencies, were determined analytically. Minima and transition states were confirmed by the presence of zero or one imaginary frequency, respectively, and the torsional nature of each transition state was confirmed via normal-mode analyses. All computations were carried out with the GAUSSIAN03¹⁶ program package.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b01204.

X-ray crystallographic data for compound **5** (CIF)

Description of X-ray structure, thermal ellipsoid plot, views of crystal lattice, and key intermolecular interactions of compound **5**; full description of computational methods, Cartesian coordinates, and total energies for all DFT computations (PDF)

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Notes

The authors declare no competing financial interest.

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