JOC*Note*

On the Existence of Uncharged Molecules with a Pyramidally Coordinated Carbon: The Cases of Pentacyclo[4.3.0.0^{2,9}.0^{3,8}.0^{7,9}]non-4-ene and Heptacyclo[7.6.0.0^{1,5}.0^{5,15}.0^{6,14}.0^{10,14}.0^{10,15}]pentadecane†

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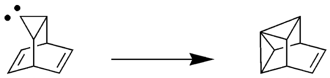
Received September 1, 2005



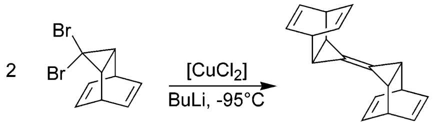
3 **4**

B3LYP/6-31G(d) and MP2 calculations predict interactions between the divalent carbon and one double bond in tricyclo[3.2.2.0^{2,4}]nona-6,8-dien-3-ylidene (**3**). Carbene **3** easily forms the more stable **4**, a species with a pyramidal geometry. Moreover, the kinetic stability of **4** has been investigated, and some of its decay products are described. Interestingly, 3,3-dibromotricyclo[3.2.2.0^{2,4}]nona-6,8-diene (**1**), the precursor of carbenoid **3**, has already been reported and shown to undergo a formal dimerization to give **2**. In addition, **15**, a compound structurally related to **4,** is expected to have a substantially greater stability toward further rearrangement.

A foiled carbene[1] is a divalent carbon intermediate for which an ostensibly facile intramolecular reaction is thwarted due to a prohibitively strained geometry within the resultant product.[2] Typically, an extraordinary energy stabilization is established via nonclassical interaction with either pendant n- or π-donors.[3] For example, singlet carbenes are stabilized by the π-complex formed between the π-orbital of the double bond (HOMO) and the empty p-orbital of the divalent carbon (LUMO).[4] Even cyclopropane rings can participate in this kind of delocalization. Recently, the nature of this stabilization was described in more detail.[5]

Strained molecules having a planar, inverted, or even pyramidal geometry have been theorized.[6] Some of these molecules, like [1.1.1]propellane—an unusually stable compound with an inverted C atom—have been synthesized.[7] Among the compounds with a pyramidal-tetracoordinate carbon, tetracyclo[2.1.0.0^{2,5}.0^{3,5}]pentane (pyramidane) has been particularly well described.[8] It should be kinetically stable because 24.0 kcal/mol (CCSD(T)/TZ2P) is needed for its rearrangement to tricyclo[2.1.0.0^{2,5}]pent-3-ylidene—its most accessible isomer.[8b,9] However, pyramidane has never been synthesized. In this paper, we examine two suitable molecular topologies in which the divalent carbon and double bond are close enough to interact strongly and drive the 1,2-addition forward to give a pyramidal intermediate.

SCHEME 1. Reaction of 1 with BuLi and CuCl$_2$[10a]



1 **2**

3,3-Dibromotricyclo[3.2.2.0^{2,4}]nona-6,8-diene (**1**) was first synthesized via dibromocarbene addition to barrelene with a yield of 80%.[10a] *gem*-Dibromide **1** should generate the carbenoid tricyclo[3.2.2.0^{2,4}]nona-6,8-dien-3-ylidene (**3**) under suitable conditions. Indeed, when **1** was treated with butyllithium in THF at −95 °C in the presence of CuCl$_2$, a formal dimerization of **3** giving 3,3′-bi(tricyclo[3.2.2.0^{2,4}]nona-6,8-dien-3-ylidene) (**2**) in 23% yield was reported (Scheme 1).[10] 1-Bromo-1-lithiocyclopropanes generated from 1,1-dibromocyclopropanes at temperatures of −90 °C and lower in the literature[11] often have been called carbenoids.[12] However, in general, these are organometallic compounds. At those temperatures, the carbon carrying the metal atom reacts as a *nucleophile*. Thus, on treatment with CO$_2$ and CH$_3$I the corresponding carboxylic acids and methyl compounds, respectively, are formed.

On warming, the 1-bromo-1-lithiocyclopropanes at certain temperatures generate more or less coordinated cyclopropylidenes. The actual temperature depends on the solvent used and on the position of any atoms such as O, N, S, etc. possibly present in the molecule. For example, the "decomposition temperature" of the organometallic species in THF is higher than in diethyl ether.[11] The lithiated carbon atom now shows a partial positive charge.[13,14] Toward reaction partners these cyclopropylidenoids behave like *electrophiles*.

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† Carbene Rearrangements. 61. For Part 60, see: Krois, D.; Brecker, L.; Werner, A.; Brinker, U. H. *Adv. Synth. Catal.* **2004**, *346*, 1367.

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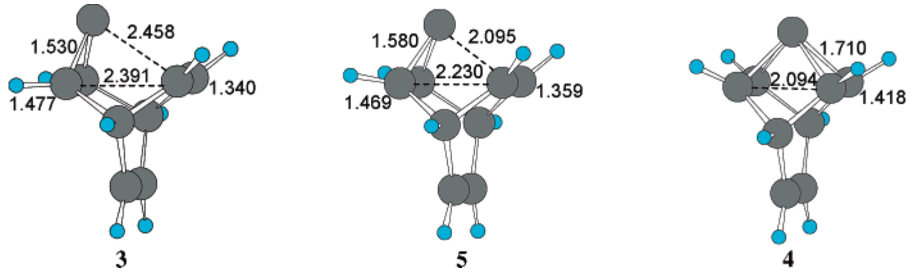
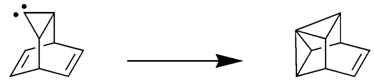
10.1021/jo051847m CCC: $30.25



3 **5** **4**

FIGURE 1. B3LYP/6-311+G(d,p)-optimized geometries for carbene **3** and its stabilization to **4**.

SCHEME 2. Putative Intramolecular Reaction of 3



3 **4**

Reactions of 1,1-dibromocyclopropanes with methyllithium at −100 °C afford 1-bromo-1-lithiocyclopropanes. ^{13}C NMR spectroscopy[15] of these species supports the notion of a loosened C−Br bond.[16] Carbenoids generated by the organometallic route in their intramolecular reactions largely correspond with those of "free" cyclopropylidenes.[17,18,19] Therefore, hereafter we speak of cyclopropylidenes, even if these species are coordinated with lithium halides, alkyllithium, and solvent, respectively.

As stated before, the dimerization of **3** leading to **2** is a *formal* dimerization. There are examples in the literature where at temperatures of about −80 °C two geminal bromolithiocyclopropanes form a double bond between the cyclopropane rings by undergoing two consecutive Wurtz-type LiBr eliminations.[11,20] The first elimination leads to a single bond, the second to the double bond. No real cyclopropylidenes seem to be involved in these cases.

As outlined (vide supra), at a *higher* temperature, intramolecular 1,2-addition of singlet[21] cyclopropylidene **3** should generate the secondary intermediate pentacyclo-[4.3.0.0^{2,9}.0^{3,8}.0^{7,9}]non-4-ene (**4**), which comprises a pyramidally coordinated carbon (Scheme 2). Bishomo square-pyramidal species **4** should then cascade further to the reactive intermediates described in the following paragraphs.

We performed B3LYP and MP2 calculations on carbene **3** and found that it can easily form the symmetrical π-complex **4** with the structure shown in Figure 1. Initial geometry optimizations were obtained using the Spartan'02 program.[22] Gaussian 03[23] was then used for density functional theory calculations employing Becke's[24] three-parameter hybrid method and the exchange functional of Lee, Yang, and Parr (B3LYP).[25] Geometries were optimized at the B3LYP/6-31G(d) level of theory and the stationary points were characterized by vibrational analysis. The so-obtained geometries were optimized again at the B3LYP/6-311+G(d,p) level. Unless otherwise stated, all values in the text refer to B3LYP/6-311+G(d,p) calculations. The calculations show that **4** is about 1.1 kcal/mol more stable than **3** and the transition state **5** lies only 0.5 kcal/mol above **3**. Compound **4** was confirmed to be a minimum at the MP2 level as well.[26]

Two distinct reaction paths were investigated for the intramolecular decay of **4** (Scheme 3). The first one proceeds in a retro-addition back to **3** leading to products typical for a cyclopropylidene,[19] i.e., formation of allene **6**. The activation energy for the ring opening of **3** to **6** is with 6.0 kcal/mol relatively high for this type of reaction. The high value is probably due to the fact that the cyclopropylidene moiety is attached to two six-membered rings.[21] Such systems are known to only reluctantly undergo the cyclopropylidene−allene rearrangement.[19] The second path takes into account that the pyramidal structure in **4** also can be obtained from carbene **7**, which exists in two conformations. The first structure obtained is the foiled carbene **7a**, where the divalent carbon is

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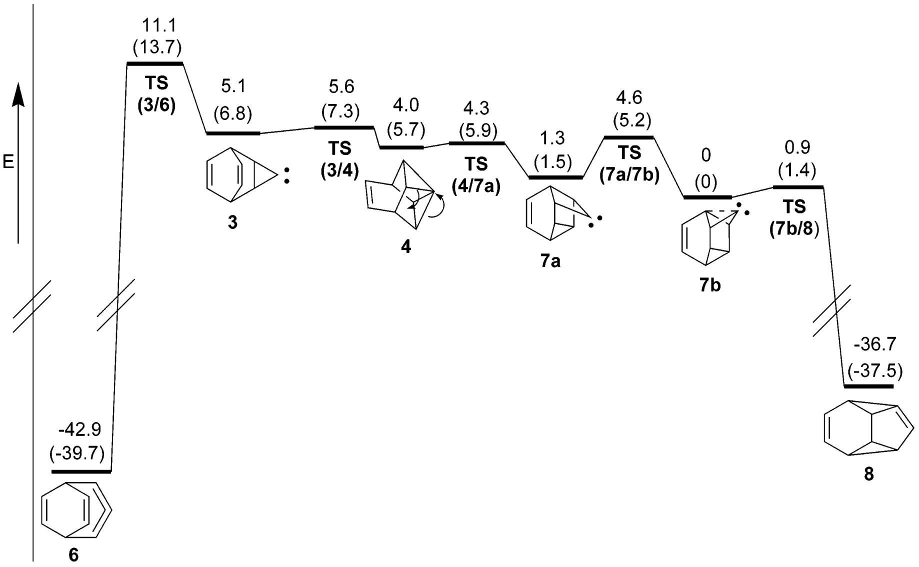
[26] All attempts to locate an energy minimum for **3** using MP2/6-31G(d) calculations led directly to **4**.

SCHEME 3. Schematic Presentation of the Relative Energies (in kcal/mol) of the C_9H_8 Isomers 3, 4, 6, 7a, 7b, and 8[a]



[a] B3LYP/6-311+G(d,p) and B3LYP/6-31G(d) (in parentheses).

TABLE 1. Relative Energies of 6, 3, 4, 7a, 7b, and 8 (kcal/mol)

	6	3	4	7a	7b	8
B3LYP/6-31G(d)	−45.4	+ 1.1	0	−4.2	−5.7	−43.2
B3LYP/6-311+G(d,p)	−46.9	+ 1.1	0	−2.7	−4.0	−40.7
MP2/6-31G(d)	−40.2		0	−1.8	−1.2	−39.9
MP2/cc-pVDZ	−37.3		0	+1.0	−0.6	−36.1
MP2/cc-pVTZ	−35.9		0	+0.4	+ 2.9	−34.9

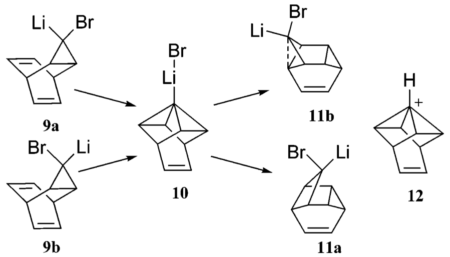
stabilized by the Walsh orbitals of the three-membered ring. However, the nonclassical cyclobutylidene structure **7b** is 1.3 kcal/mol more stable than **7a** at the B3LYP/6-311+G(d,p) level of theory. **4** opens to **7a** with almost no barrier (0.3 kcal/mol). The typical reaction of the cyclobutylidene[27] incorporated in **7b**, i.e., the rearrangement to an alkylidenecyclopropane[28] affording **8** also should be considered. Indeed, B3LYP calculations predict **8** to be the major product from **3**, since all transition states for this reaction sequence are lower than the one for the formation of allene **6**. Other intramolecular reaction paths lead to even more strained products. All these reactions require activation energies larger than 18 kcal/mol.

If we compare the relative free energies of structures **6**, **3**, **4**, **7a**, **7b**, and **8** or take their zero-point energies in consideration, no big differences are observed and the order of stability of these structures is not changed (Table 2). In all cases, **4** is more stable than **3**. **4** was confirmed to be a minimum at the MP2/6-31G(d), MP2/cc-pVDZ, and MP2/cc-pVTZ levels of theory (Table 1). However, in these computations, **3** does not exist anymore and optimizes to **4**. With the larger basis sets, the pyramidally coordinated structure is relatively more stabilized, especially in comparison with the cyclobutylidene structures. At the MP2/cc-pVTZ level, **4** represents the most stable species of the **3**−**4**−**7a**−**7b** manifold.

TABLE 2. Relative Energies of 6, 3, 4, 7a, 7b, and 8 (kcal/mol) at the B3LYP/6-311+G(d,p) Level of Theory

	6	3	4	7a	7b	8
E	−46.9	+ 1.1	0	−2.7	−4.0	−40.7
E + ZPVE	−46.3	+ 0.9	0	−1.9	−3.4	−39.6
H (298 K)	−46.4	+ 0.9	0	−2.3	−3.7	−40.0
G (298 K)	−46.1	+ 0.9	0	−1.5	−3.0	−39.2

SCHEME 4. Intramolecular Reactions of 9



Moreover, it should also be considered that cyclopropylidenes most of the time are generated by treatment of *gem*-dihalides with alkyllithium below room temperature.[19] We therefore investigated the stability of 3-bromo-3-lithiotricyclo[3.2.2.0^{2,4}]nona-6,8-dienes (**9**), precursors for carbene **3** (Scheme 4). If the bromine atom and the double bond are positioned as depicted in **9a**, the bromine atom is expected to be easily freed, due to anchimeric assistance by the double bond. Indeed, **9a** could not be energetically optimized and lead directly to **10**, which was found to be 13.9 kcal/mol more stable than **9b**, 4.0 kcal/mol more stable than **11a**, and 2.2 kcal/mol more stable than **11b**. However, these values should be taken with caution, since they have been calculated only for the gas phase. In contrast to hydrocarbon **4**, **10** is the most stable species of the C_9H_8BrLi manifold resulting from **9**. The geometries of carbenoids differ in solution, where they

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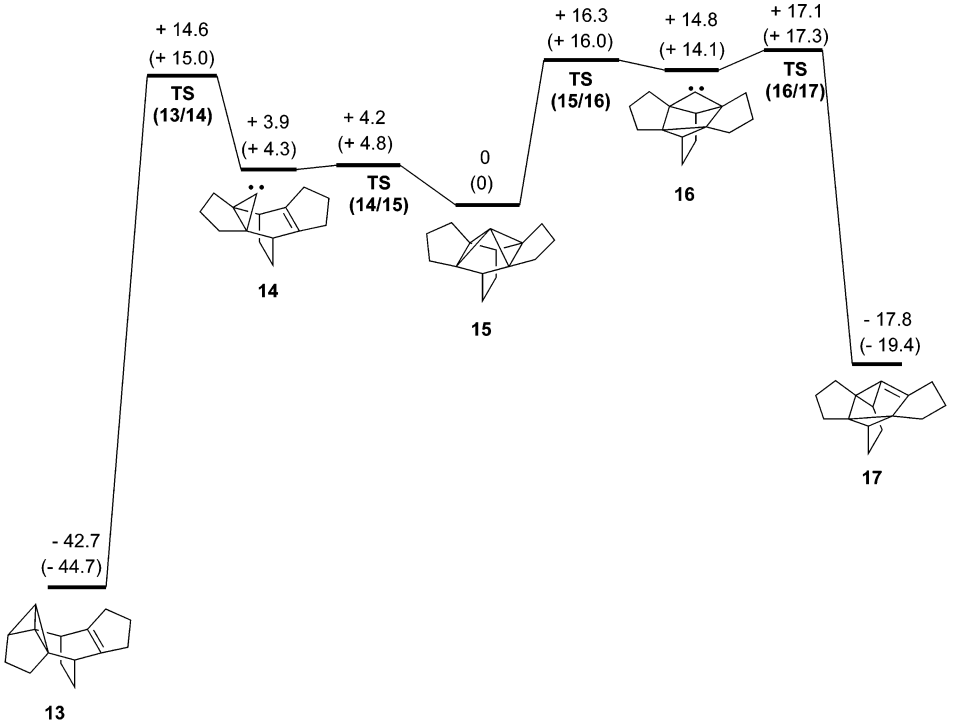
SCHEME 5. Decomposition of 15 to 13 and 17 via 14 and 16[a]



[a] Relative energies (in kcal/mol): B3LYP/6-311+G(d,p) and B3LYP/6-31G(d) (in parentheses).

can form clusters and interact with the solvent.[29] **10** has a similar structure as the pyramidal carbonium ion **12**,[30] which was described at the MP2/6-31G(d) level.[31] In contrast to the manifold of neutral species **4**, **7a**, **7b**, it was found that cation **12** only exists with a bishomo square-pyramidal geometry; the cation corresponding to **7a** is not a minimum.[31]

We then looked for derivatives of **4** with an increased stability toward intramolecular reactions. The first condition to be fulfilled is that the pyramidally coordinated structure should be more stable than the corresponding cyclobutylidene and the cyclopropylidene structures (vide supra). Second, any substituent should be chosen so that rearrangements of the resulting carbenes are disfavored. Thus, the cyclopropylidene-allene rearrangement can easily be blocked, if the cyclopropylidene becomes part of a bicyclic system like in pentacyclo[5.5.2.$1^{2,6}$. $0^{2,6}$.$0^{8,12}$]-pentadec-8(12)-en-15-ylidene (**14**) because the resulting allene would be excessively strained.[19] Indeed, the allene incorporated into a six-membered ring is 34.1 kcal/mol less stable than **14**. As shown in Scheme 5, heptacyclo-[7.6.0. $0^{1,5}$.$0^{5,15}$.$0^{6,14}$.$0^{10,14}$.$0^{10,15}$]pentadecane (**15**) is more stable than the corresponding carbenes **14** and **16** and sits in a fairly deep well with barriers of 14.6 and 17.1 kcal/mol toward rearrangement to **13** and **17**. It is separated from the thermodynamically more stable bicyclobutane **13**, which results from **14** by 1,3-C−H insertion. Alternatively, the decomposition of **15** may occur through cyclobutylidene **16**, which lies 14.8 kcal/mol above **15**, followed by a cyclobutylidene-alkylidenecyclopropane rearrangement to hexacyclo-[6.5.2.$0^{2,6}$.$0^{2,13}$.$0^{7,9}$.$0^{9,13}$]pentadec-6-ene (**17**) with a barrier of 17.1 kcal/mol above **15**. Compound **16** was found to exist only in the bicyclobutane-like conformation;[28b] all attempts to locate a minimum for a foiled cyclobutylidene only led to **15**. Other insertions into C−H bonds and C-migrations were also calculated. However, for all of them, the predicted transition states were at least 22 kcal/mol higher in energy than **15**.

In conclusion, attempts have been made to generate carbene **3** in solution.[10] According to the calculations presented here, its divalent carbon easily forms a π-complex with one of the double bonds. This leads to the formation of **4** comprising a bishomo square-pyramidal geometry. B3LYP/6-311+G(d,p) calculations also predict **4** to preferably decompose to tetracyclo[4.3.0.$0^{2,9}$.$0^{5,7}$]-nona-3,7-diene (**8**) instead of giving bicyclo[3.2.2]nona-2,3,6,8-tetraene (**6**). Moreover, **15**, a compound structurally related to **4**, is expected to have a substantially greater stability toward rearrangement.

Acknowledgment. Calculations with Gaussian 03 were performed on the Schrödinger II Linux cluster at the University of Vienna. We thank a reviewer for helpful comments.

Supporting Information Available: Cartesian coordinates and thermodynamic data for all stationary points for **3**−**17**. This material is available free of charge via the Internet at http://pubs.acs.org.

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