Piers’ Borane-Induced Tetramerization of Arylacetylenes

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Abstract: We herein report that the reaction of Piers’ borane, i.e. HB(C6F5)2, with an excess of arylacetylenes at room temperature leads to tetramerization of the acetylene and the diastereoselective formation of boryl-substituted tetra-aryl-tetrahydropentalenes. The reaction mechanism was investigated by isotope labeling experiments and DFT computations. These investigations indicate that a series of 1,2-carboboration reactions form an octetaene that undergoes an electrocyclization. Two skeletal rearrangements then presumably lead to the formation of the tetrahydropentalene core. Overall, this intricate and unprecedented transformation comprises five carbon-carbon bond formations in a single reaction.

Building molecular complexity from simple starting materials is paramount for synthetic chemistry. Boranes are in this context usually considered as reagents for transition metal-catalyzed C–C and C-Het couplings.[1,2] However, transformations of organic molecules, including skeletal rearrangements and C–C bond formations induced by highly Lewis acidic boranes have been reported recently. Prime examples are the 1,1-carboboration of alkynes and ary allenes by tris(perfluoro)phenylborane (BCF).[3,4] Furthermore, the Piers’ borane-induced catalytic trimerization of allyl alkenes and the dimerization of ary allenes were reported by Erker and co-workers.[5] These reactions are initiated by the hydroboration of the allene. When introducing HB(C6F5)2 as a highly electrophilic borane reagent in 1995, Piers and co-workers described the stoichiometric hydroboration of phenylacetylene by this reagent that leads to the corresponding alkynylborane.[6] We herein report the unexpected finding that the reaction of Piers’ borane with an excess of phenylacetylene yields cis-2-boryl-1,3,3a,5-tetraphenyl-tetrahydropentalene 1a (Scheme 1).

Scheme 1. Formation of cis-2-boryl-1,3,3a,5-tetraphenyl-tetrahydropentalene 1a upon reaction of Piers’ borane with five equivalents phenylacetylene. The yield was determined by NMR with trimethoxybenzene as internal standard. The yield of the isolated product is given in parenthesis.

Tetrahydropentalenes are frequently used as ligands in transition-metal catalyzed reactions. Examples are the rhodium-mediated formation of hydropentalenyl complexes from terminal alkynes and the palladium-induced cyclotetramerization of acetylenes have been reported.[8] However, the transition-metal free tetramerization of alkynes is to the best of our knowledge unprecedented. Upon reaction of Piers’ borane with five equivalents of phenylacetylene at r.t. in DCM, 1a is obtained after two days in an in situ yield of 56 % as determined by NMR. We were not able to detect a diastereomer of 1a. Subsequently, 1a was isolated in 41 % yield upon crystallization from n-hexane and fully characterized. Furthermore, crystals suitable for single-crystal X-ray diffraction (SCXRD) were grown from a saturated n-hexane solution. The molecular structure derived from SCXRD supports the structural assignment and confirms the cis-relationship of the substituents at the bridgehead positions (Figure 1).

Notably, the reaction also takes place if Piers’ borane is reacted with two equivalents phenylacetylene. In this case, hydroboration of the phenylacetylene is observed, followed by the slow formation of 1a while unreacted alkynylborane remains.[9] The reaction is not limited to phenylacetylene as the substrate: Treatment of alkynes 2b–i with Piers’ borane furnishes the cis-2-boryl-1,3,3a,5-tetra-aryl-tetrahydropentalenes 1b–i in NMR yields ranging from 32 %–55 % (Scheme 2).

Erker and co-workers demonstrated that boranes with perfluorophenyl substituents can be engaged in transition-
metal catalyzed coupling reactions. To prove that 1a is a suitable substrate for a Suzuki-Miyaura coupling, we reacted 1a with phenyl iodide and 2-iodothiophene in the presence of catalytic amounts tetrakis(triphenylphosphine) palladium. This allowed us to isolate the penta-aryl-tetrahydropentalenes 3a and 3b in very good yields (Scheme 3). Furthermore, 1a can be protodeborylated by the addition of acetic acid at room temperature yielding the tetrahydropentalene 4 in very good yield (Scheme 3). The oxidation of 1a with H2O2 and NaOH leads to the corresponding ketones 5a and 5b. The diastereoselectivity of this reaction can be controlled by the amount of NaOH added. Both products were isolated as single diastereomers in moderate to good yields and fully characterized including NOESY NMR (Scheme 3).

The structural assignments of 4 and 5b are further supported by SCXRD analysis (Scheme 3).

To elucidate the mechanism of the transformation that leads to the formation of 1a, we performed a series of isotope labeling experiments. Hydroboration of deuterated phenylacetylene with Piers’ borane yielded, as expected, the mono-deuterated alkenylborane 6-d (Scheme 4a). The reaction of 6-d with four additional equivalents of deuterated phenylacetylene lead to the formation of 1a-d, with protium exclusively in the 1-position of the pentalene core. On the other hand, the reaction of 6-d with four equivalents non-deuterated phenylacetylene led to 1a-d with deuterium incorporation in the 6a-position. These experiments, therefore, show that the hydrogen of the initial Piers’ borane ends up in the 1-position while the hydrogen of the first equivalent of phenylacetylene is incorporated in the 6a-position of 1a. Furthermore, the labeling

Figure 1. Molecular structure of cis-2-boryl-1,3,3a,5-tetraphenyl-tetrahydro-pentalene 1a derived from SCXRD (50% probability ellipsoids, all hydrogens attached to phenyl rings are omitted and C6F5 rings are shown in stick representation for clarity). Selected bond lengths and angles: C1–C2: 1.533(2) Å, C2–C3: 1.357(2), C3–C3a: 1.542(2) Å, C3a–C4: 1.513(2) Å, C4–C5: 1.338(3) Å, C5–C6: 1.509(3) Å, C2–C6a: 1.535(3) Å, C6a–C1: 1.540(2) Å.

Scheme 2. Tetramerization of aryl allenes by Piers’ borane (a) yields determined by 1H NMR with trimethoxybenzene as internal standard. The yields have an estimated error of +/−5% (see Supporting Information for details).

Scheme 3. Follow-up reactivity of 1a in a Suzuki-Miyaura coupling, oxidations, and protodeborylation (yields of isolated products given). The insets show the molecular structure for 4 and 5b derived from SCXRD analysis (all hydrogens attached to phenyl rings are omitted for clarity).

Scheme 4. a) Isotope labeling experiments that reveal the position of hydrogen from Piers’ borane and that of the initially hydroborated phenylacetylene in the final product. b) NMR experiment that disclosed the position of the non-deuterated phenyl moiety of 6 in the final product 1a-d15. Deuterium incorporation in the indicated position in each case was at least 88%, as determined by 1H NMR.
experiments suggest that the carbon atoms in the 1- and 6α-positions of 1a originate from phenylacetylene that was hydroborated in the first step of the reaction. To substantiate this hypothesis, we reacted alkenylborane 6 with four equivalents of phenylacetylene bearing fully deuterated phenyl rings (Scheme 4b). As a result, all aromatic 1H NMR signals except those originating from 6 could be suppressed. This enabled us to determine the position of the phenyl moiety of 6 in the product 1a-d15 by long-range COSY and NOESY NMR. This experiment revealed that the phenyl moiety of the alkenylborane which is formed upon initial hydroboration eventually ends up in the 1-position of the final product 1a.

The position of the first equivalent of phenylacetylene in the final product suggests a reaction that consists of an initial hydroboration and four 1,2-carboborations followed by electrocyclic ring closure of the formed octatetraene. Therefore, we investigated the initial steps computationally at the PCM(DCM)-revDSD-PBEP86-D4/def2-QZVPP//PCM(DCM)-PBh-3c level of theory (Figure 2). Furthermore, we considered the barrier for a 1,1-carboboration. According to the computations, the exergonic hydroboration of phenylacetylene by Piers' borane via TS6 requires a Gibbs free energy of activation of 9.0 kcal mol⁻¹. The 1,2-carboboration of phenylacetylene by alkenylborane 6 is asynchronous: The formation of the C–B bond is further advanced in the transition state structure (see inset in Figure 2). This is certainly a result of the high Lewis acidity of 6 and explains the preference of transition state TS6/7 over TS'. In the latter, the positive charge arising as a result of asynchronous bond formation is not stabilized by a phenyl substituent. Consequently, the 1,2-carboboration should lead to the diene 7 in which the phenyl substituents are in a 1,3-distance. The barrier for the 1,1-carboboration is computed to be 4.8 kcal mol⁻¹ higher than the one for the 1,2-carboboration.

We note that the computed transition state structure for the 1,1-carboboration is structurally similar to the one reported by Grimme and Erker for the 1,1-carboboration of alkynes by BCF. While the barrier for the 1,2-carboboration via TS6/7 is surmountable at r.t., the computed barriers for the carboxborations via TS' (28.8 kcal mol⁻¹) and TS1,1-carboboration (27.4 kcal mol⁻¹) are conflicting with the experimental observation that the tetramerization occurs at ambient conditions. The findings that the formation of 1a is also observed when Piers’ borane is

![Figure 2. Schematic PES of the formation of the cyclooctatriene 10 and barriers for the 1,2- and 1,1-carboboration of phenylacetylene by 6 computed at PCM(DCM)-revDSD-PBEP86-D4/def2-QZVPP//PCM(DCM)-PBh-3c. The insets show the computed transition state structures of the 1,2-carboboration leading to 7 and the 8π-electrocyclization leading to cyclooctatriene 10.](image)
reacted with only two equivalents phenylacetylene and that no intermediate except alkynylborane 6 can be detected by 1H NMR reaction monitoring further indicate that this initial 1,2-carboboration is rate-determining.\textsuperscript{[16]} Indeed, the computed barriers for the subsequent 1,2-carboborations (TS\textsubscript{7/8} and TS\textsubscript{8/9}) are lower than the one for the initial carboboration. An 8π-electrocyclization of the tetrane 9 via TS\textsubscript{9/10} yields then the cyclooctatetraene 10. The computed barrier of 20.8 kcal mol\textsuperscript{-1} for the 8π-electrocyclization of 9 does not differ substantially from the barrier obtained experimentally for the electrocyclization of unsubstituted octatetraene (17.0 kcal mol\textsuperscript{-1}) and permits this step to occur readily at r.t.\textsuperscript{[17]} Although a fourth 1,2-carboboration via TS\textsuperscript{a} is slightly disfavored compared to the electrocyclization via TS\textsubscript{9/10}, both transition states are close in energy so that further oligomerizations could be a possible side reaction. The sequence of 1,2-carboborations and electrocyclization would locate the first equivalent of phenylacetylene in the relative position to the boryl substituent that was deduced from the isotope labeling experiments. The thermal and photochemical rearrangements of cyclooctatetraenes to semibullvalenes were reported.\textsuperscript{[18,19]} An analogous \( \pi_1 + \pi_2 \) rearrangement of 10 would lead to tricycle 11 (Scheme 5).

A vinylcyclopropane-cyclopentene rearrangement of 11 would form 12. These rearrangements usually require high activation energies.\textsuperscript{[18,20]} However, it was shown that Lewis acids can lower the barrier for vinylcyclopropane-cyclopentene rearrangements significantly.\textsuperscript{[21]} Thus, we assume that this transformation is catalyzed by Lewis acidic boranes present in the reaction. Additionally, the electrophilic perfluorophenyl substituted boranes could serve as one-electron acceptors and promote the rearrangement from 10 to 11 via a (di)radical pathway.\textsuperscript{[22]} Finally, a simple proton shift can convert 12 into the experimentally observed product 1a. According to our computations at PCM(DCM)-revDSD-PBEP86-D4/def2-QZVPP//PCM(DCM)-PBeh-3c, formation of 1a from 10 is exergonic by 28.2 kcal mol\textsuperscript{-1}. We note that the relative position of the phenyl substituents in 1a that would result from the proposed \( \pi_1 + \pi_2 \) rearrangement and the vinylcyclopropane-cyclopentene rearrangement agrees with the experimentally determined one. However, it must be stressed that other reaction pathways cannot be excluded at present and further computational and experimental investigations to clarify the mechanistic details of the formation of 1a are ongoing.

In summary, we have documented the unprecedented tetramerization of simple arylacetylenes by Piers’ borane. We expect this finding to stimulate the development of new methods for organic synthesis that rely on the oligomerization of alkynes by Lewis acidic boranes.

Experimental Section
See the Supporting Information for details.

Deposition Numbers 2107142, 2121641 and 2124445 contain the supplementary crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe Access Structures service.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available in the supplementary material of this article.

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