Thiophene-Fused Bisdehydro[12]annulene That Undergoes Transannular Alkyne Cycloaddition by Either Light or Heat

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S *Supporting Information*

ABSTRACT: A new bisdehydro[12]annulene derivative having a thiophene-fused structure has been synthesized. This highly twisted π-conjugated macrocycle with two acetylene moieties in close proximity produces a [2+2]-type alkyne cycloadduct by either photoirradiation or mild heating without any transition metals. Theoretical calculations reveal that the thermal reaction proceeds through successive 8π and 4π electrocyclic reactions, while the photochemical reaction is an asynchronous concerted [2+2] cycloaddition. The fused structure with the less-aromatic thiophene ring is crucial for achieving this reaction. The cycloadduct, thiophene-fused biphenylene, has significant potential as a new polycyclic π-scaffold for electronic applications.

Two or more carbon–carbon triple bonds that are constrained in close proximity can undergo unique oligomerizations upon photoirradiation or heating without the addition of any reagents. These reactions produce various π-conjugated skeletons, some of which have significant potential as scaffolds for optoelectronic materials. One example is the so-called topochemical polymerization of diacetylenes, which proceeds intermolecularly upon photoirradiation to yield poly(diacetylene)s (Figure 1a).[1] Intramolecular dimerizations of alkynes are also important as ways to synthesize polycyclic aromatic hydrocarbons (Figure 1b). For instance, thermal Bergman cyclization is a well-known method for the construction of a benzene ring.[2,3] The transannular cyclization of macrocyclic diynes with two acetylene moieties in close proximity can also be promoted by heating (Figure 1b).[4–6] A lesson from these examples is that the precise distance and orientation of the acetylene moieties in the preorganization determine the reaction modes as well as the reactivity.

A [2+2] cycloaddition is another possible reaction mode for alkyne dimerization, to construct a four-membered cyclobutadiene skeleton (Figure 1c). According to frontier orbital theory[7] and the principle of conservation of orbital symmetry,[8] the photochemical [2+2] cycloaddition of unsaturated bonds is a symmetry-allowed process. However, although numerous [2+2] cycloadditions of alkenes and/or carbonyl compounds have been reported, such a reaction between two alkynes promoted by photoirradiation is unprecedented. Most of the formal [2+2] alkyne cycloadditions reported to date have been
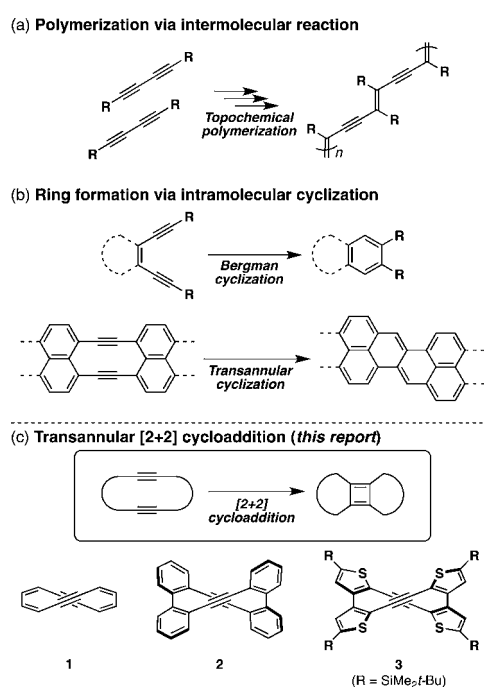
Figure 1. Several reaction modes of acetylene moieties in close proximity for the synthesis of π-electron systems. (a) Topochemical polymerization of diacetylenes. (b) Cyclization forming five- and/or six-membered rings. (c) [2+2] cycloaddition.

achieved by using transition metals via the formation of metallacyclopentadienes, by heating at a high temperature,[9] or by using activated substrates, such as electron-rich and electron-deficient alkynes[10] or highly strained alkynes.[11]

We now focus on bisdehydro[12]annulene (BD12A, **1**), a 12-membered-ring π-conjugated macrocycle with two acetylene moieties in close proximity, as a potential scaffold that enables [2+2] cycloaddition of alkynes.[12] The parent BD12A **1** was first reported in 1962 as a thermally unstable compound.[13] Later, it was demonstrated that the BD12A skeleton could be thermodynamically stabilized by the introduction of fused aromatic rings such as benzene[14] and thiophene.[15] Staab et al. studied the reactivity of the benzene-fused BD12A **2**, which

underwent a photoreaction in cyclohexane at room temperature to produce an insoluble product. Although they inferred the formation of a [2+2] cycloaddition product, the isolation as well as the structural characterization of the product remains unsolved. Since then, however, the reactivity of the BD12A derivatives has been almost untouched for several decades. Recently, Toyota et al. reported the mechanism of racemization of **2** via a planar conformer.[16]

To endow sufficient thermal stability to handle the BD12A skeleton without precaution, and to make the cycloaddition product soluble, we designed a thiophene-fused BD12A **3** bearing bulky silyl groups. We now report the synthesis of this compound and its transannular cyclization. Notably, cyclization of **3** is promoted not only by photoirradiation but also by mild heating to produce an identical [2+2]-type product.

The thiophene-fused BD12A **3** was successfully synthesized by oxidative ligand coupling of an organocuprate intermediate (Scheme 1).[17,18] Bis(3-bromo-2-thienyl)acetylene **4** was first

Scheme 1. Synthesis of Thiophene-Fused BD12A 3
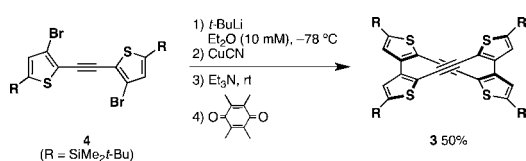
converted into the corresponding cyanocuprate *in situ* through dilithiation with *t*-BuLi followed by treatment with CuCN. Subsequent oxidation of the cuprate using tetramethyl-*p*-benzoquinone as oxidant afforded the target compound **3** in 50% yield. Notably, even when this reaction was conducted under a moderately dilute concentration of 10 mM, **3** was predominantly produced. Whereas some acyclic oligomers were also formed as minor products, purification by column chromatography easily gave **3** in a pure form.

The structure of **3** was verified by X-ray diffraction (Figure 2). The BD12A framework adopts a figure-eight geometry with helical chirality. The unit cell consists of a pair of enantiomers. Both the dithienylacetylene moieties and bithiophene moieties
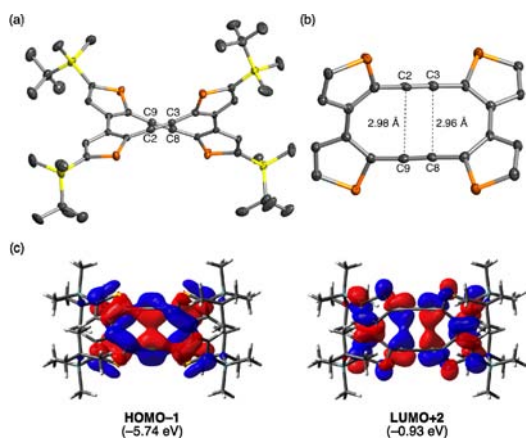
Figure 2. (a) Crystal structure of **3** (50% probability for thermal ellipsoids). Hydrogen atoms are omitted for clarity. One of the enantiomers is shown. (b) Geometry of the central thiophene-fused BD12A moiety and interatomic distances between the acetylene moieties. (c) Kohn−Sham molecular orbitals of **3** with transannular interactions, calculated at the B3LYP/6-31G(d) level.

have nonplanar geometries. While the dihedral angles between the thiophene mean planes in the di(2-thienyl)acetylene units are 63.55(10)° and 70.18(14)°, those in the 3,3′-bithiophene units are 28.42(23)° and 33.97(19)°. Consequently, the BD12A skeleton has a highly twisted geometry, similar to those of the BD12A derivatives already reported in the literature.[15b,19] This twisted structure reinforces the two acetylene moieties in close proximity. The interatomic distances of the acetylene carbons (C2---C9 2.98 Å; C3---C8 2.96 Å) are much shorter than the sum of the van der Waals radii of two carbon atoms (3.40 Å), indicative of the close spatial contact of the two acetylene moieties. Indeed, DFT calculations at the B3LYP/6-31G(d) level of theory[20] suggested the existence of significant through-space orbital interactions between them in the HOMO−1 and LUMO+2.[21]

Upon irradiation of a cyclohexane solution of **3** (10 mM) using a low-pressure mercury lamp, intramolecular cyclization proceeded slowly to produce a deep red-colored suspension. NMR study of the reaction mixture demonstrated that a [2+2]-type product, thiophene-fused biphenylene **5**, was exclusively produced (Condition A in Scheme 2). Purification by

**Scheme 2. Photochemical and Thermal Cycloaddition of 3**
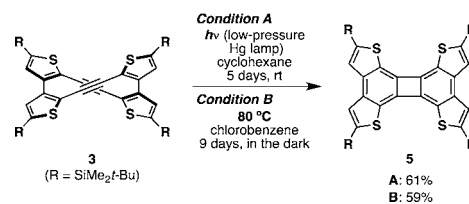
recrystallization in a preparative-scale synthesis after the photoirradiation for 5 days gave **5** in 61% isolated yield as red crystals. The structure of **5** was unequivocally determined by X-ray diffraction (*vide infra*). It is noteworthy that this alkyne dimerization to form a cyclobutadiene skeleton proceeds without the use of any transition metals. Theoretical calculations in the excited states by the time-dependent DFT (TD-DFT) method demonstrated that this photoreaction most likely proceeds through an asynchronous concerted [2+2] mechanism[22] (see SI). The close proximity of the two acetylene moieties in **3** should be crucial for this unprecedented reaction.

To our surprise, even mild heating of **3** at 80 °C also resulted in the same product **5**. After heating at this temperature for 9 days in the dark, **5** was obtained in 59% yield (Condition B in Scheme 2). This is in stark contrast to the analogous cycloaddition of 2,2′-bis(phenylethynyl)biphenyl, which requires a much higher temperature of 260 °C.[9] Thermal [2+2] cycloaddition is inherently a symmetry-forbidden process and thus should have a significantly high activation energy, in line with the conservation of orbital symmetry. The fact that **5** can be produced from **3** even under mild heating conditions is paradoxical and puzzling.

To elucidate the origin of the high reactivity of **3** under the thermal conditions, DFT calculations were also performed for a model compound, **3′**, in the ground state. The geometry optimization of **3′** and the corresponding cyclized product **5′** in the singlet state at the B3LYP/6-31G(d) level[20] demonstrated that the biphenylene **5′** is much more stable than the BD12A **3′** by 55.7 kcal/mol. Notably, the parent cyclobutadiene (C_4H_4) is also more stable than two acetylene molecules fixed in close proximity, as observed in **3′**. However, the energy difference

between these two compounds is only by 20.3 kcal/mol. These results suggest that the large stabilization in **5′** compared to **3′** is due to a gain of aromatic stabilization energy upon the formation of two benzene rings in the biphenylene skeleton. The significant stabilization is likely a driving force for the reaction under mild heating conditions.

To understand the mechanism of the thermal cyclization in more detail, the reaction pathways were investigated by geometry optimization of possible intermediates and transition states as well as intrinsic reaction coordinate (IRC) calculations.[23] The results suggested that neither a concerted pathway through symmetry-forbidden [2+2] cycloaddition, nor a stepwise pathway via a biradical intermediate, is a feasible mechanism.[24] Instead, the first step is the 8π electrocyclic reaction of the 2,2′-diethynyl-3,3′-bithiophene substructure in the thiophene-fused BD12A framework, as shown in Figure 3.
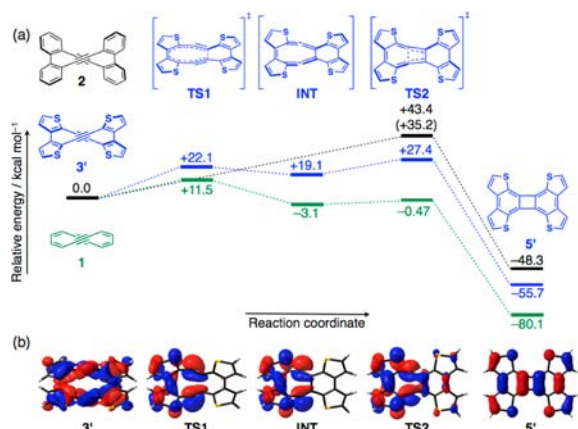

Figure 3. (a) Energy profiles for the transannular cyclization of **3′**, parent BD12A **1**, and benzene-fused BD12A **2** in the ground state calculated at the B3LYP/6-31G(d) level. For **2**, the energy of the other possible transition state in the triplet state is shown in the parentheses. All energy values are given relative to the initial BD12A derivatives. (b) Kohn−Sham HOMOs along the reaction coordinate.

The reaction produces the di(allenyl) intermediate **INT** via transition state **TS1**. The *s-cis*-butadiene moiety in **INT** further undergoes the 4π electrocyclic reaction via transition state **TS2** to afford the formal [2+2] cycloaddition product **5′**. Notably, inspection of the change in the spatial distributions of the HOMOs along the reaction course (i.e., from **3′** to **TS1** to **INT** and from **INT** to **TS2** to **5′**) confirms that both of the electrocyclic reactions proceed in a conrotatory motion. Thus, the BD12A skeleton provides the backbone that allows the symmetry-allowed 8π and 4π electrocyclic reactions to proceed in a successive manner. This two-step reaction pathway is in remarkable contrast to the concerted [2+2] cycloaddition mechanism under the photochemical conditions.

What is the role of the thiophene-fused structure for the intriguing reactivity of BD12A? To gain insight into this issue, we theoretically compared the reactivity of **3′** with those of the parent BD12A **1** and the benzene-fused **2**. The energy profiles for the reaction courses of **1** and **2** were determined by DFT calculations at the same level (Figure 3a). For reaction of the benzene-fused BD12A **2**, although we could find neither a transition state nor an intermediate corresponding to **TS1** and **INT**, we found **TS2** with a significantly high activation energy of +43.4 kcal/mol. Another transition state, with a structure similar to **TS2**, was also found in the triplet state (see SI), but

its activation energy (+35.2 kcal/mol) is still much higher than in the case of **3′**. In contrast, the parent BD12A **1** can undergo the reaction along an energy profile similar to that of **3′**. The activation energy of +11.5 kcal/mol for the first cyclization is significantly lower than in the reaction with **3′**. The high reactivity is consistent with the fact that **1** decomposes even at room temperature, as described by Sondheimer.[13] These comparisons clearly demonstrate that the key issue for the transannular cycloaddition is the loss of aromaticity of the fused rings along the reaction course.[25] In particular, the first 8π electrocyclization requires loss of aromaticity for two fused rings at the same time. The higher activation energy for **2** than **3′** should be due to the higher aromaticity of benzene than thiophene. In other words, the moderate aromaticity of thiophene renders the BD12A skeleton not only stable enough to handle, but also reactive enough to undergo the transannular reaction under mild heating conditions.

The tetrathienobiphenylene **5** is attractive as a new polycyclic π-conjugated scaffold. X-ray crystallographic analysis of **5** demonstrates that the seven-ring-fused skeleton has a highly coplanar geometry, with the dihedral angles between adjacent thiophene rings of 4.80° (Figure 4), indicative of the effective
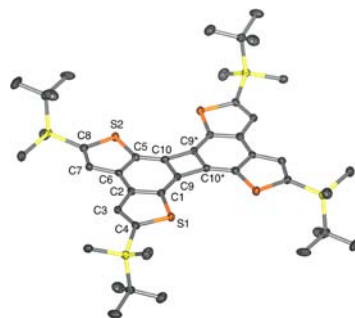
Figure 4. Crystal structure of **5** (50% probability for thermal ellipsoids).

extension of π-conjugation over the entire skeleton. In addition, the biphenylene skeleton has a greater contribution of a [4]radialene-like resonance form in the central four-membered ring than a cyclobutadiene form, even at the expense of losing aromaticity in the thiophene rings (Table S4).[26,27]

Compound **5** shows a set of characteristic electronic properties. First, **5** exhibits a bright red color in THF (Figure S10), in contrast to the yellow color of the parent biphenylene.[26,27a] In the UV/vis absorption spectrum, **5** shows a weak absorption band with λ_{max} = 529 nm (ε = 750), accompanied by the vibronic structure with the absorption edge wavelength of 650 nm. TD-DFT calculation at the B3LYP/6-31G(d) level suggested that this absorption band can be assigned to a symmetry-forbidden HOMO→ LUMO transition with an oscillator strength of 0.0006. Second, the tetrathienobiphenylene showed multiple reversible redox processes in cyclic voltammetry (Figure S11). Thus, **5** showed reversible redox waves, with first and second oxidation potentials of $E_{1/2}$ = +0.08 and +0.61 V and first and second reduction potentials of $E_{1/2}$ = −2.00 and −2.44 V (vs Fc/Fc$^+$). The significantly low first oxidation potential suggests a high-lying HOMO. The high redox stability is presumably due to the pronounced Hückel aromaticity of the resulting dication and dianion. These results demonstrate the significant potential of

this skeleton as a π scaffold with both high redox stability and significant electron-donating ability.

In summary, we have disclosed the synthesis, structure, and reactivities of thiophene-fused bisdehydro[12]annulene. This compound undergoes direct or formal [2+2] cycloaddition of alkynes by photoirradiation or mild heating, respectively, without using any transition metals. The photochemical [2+2] cycloaddition of alkynes seems to be an ordinary textbook reaction, but is in fact a long-sought reaction. To attain high reactivity in the thermal cyclization, the thiophene-fused structure plays a crucial role. The lesser aromaticity of the thiophene rings suppresses the detriment caused by the loss of aromaticity during the reaction. The tetrathienobiphenylene thus produced is a promising π scaffold with electron-donating character as well as multiple redox properties. Facile functionalization on the thiophene rings guarantees versatility of this skeleton for producing attractive organic dyes and semiconducting materials. Further investigation along this line is in progress in our laboratory.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information
Experimental procedures, characterization data for all new compounds, additional spectra, results of theoretical calculations, and crystallographic information (CIF) files of compounds 3 and 5. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

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(24) We also examined a concerted or stepwise pathway via tetrahedrane as an intermediate, which was initially postulated by Staab et al., as the other possible reaction pathway. However, this process was energetically unfavorable. See SI for details.

(25) It is known that tetrathieno-fused structure facilitates racemization of the twisted BD12A skeleton, proceeding through a planar transition state.[16] This structural effect might also facilitate the transannular cycloaddition of 3′, since TS1 and TS2 have rather planar geometries.

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1734

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