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Novel Synthesis of Bridged Phenylthienylethenes and Dithienylethenes via Pd-Catalyzed Double-Cyclization Reactions of Diarylhexadienynes

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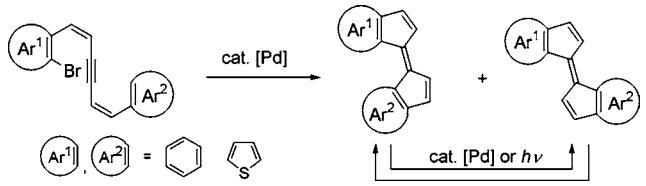
ABSTRACT



Bridged phenylthienylethenes and dithienylethenes were synthesized via Pd-catalyzed double-cyclization reactions of (*Z*,*Z*)-1,6-diaryl-1,5-hexadien-3-ynes. Pd-catalyzed as well as photoinduced *Z*/*E* isomerization of the products were also investigated.

Thiophene-based diarylethenes are considered as the key components of a number of advanced technologies including nonlinear optical, electronic, and photochromic devices.[1] Styrylthiophenes (phenylthienylethenes) having a donor substituent on the phenyl ring and an acceptor substituent on the thiophene ring are known to behave as good NLO-phores.[2] It has been shown that bridging between the double bond and the aryl ring of diarylethenes results in the enhancement of NLO properties and electric conductivity because of the enhanced capability of π-electron delocalization owing to enforced planarization and rigidification.[3] Dithienylethenes are among the most promising photochromic compounds.[4] Moreover, unsymmetrical bridged diarylethenes are attractive in view of their potential as novel molecular rotors and switches.[5]

We previously reported a versatile and convenient route to construct (*E*)-1,1′-biindenylidene (**1**) and its unsymmetrical derivatives possessing a bridged diarylethene structure from a series of diphenyldienyne derivatives via 5-exo tandem cyclization.[6a,7] In all cases, the (*E*)-isomers were obtained exclusively presumably via the isomerization of the vinylpal-

[†] On leave from the University of Dhaka, Bangladesh.

(1) (a) Munn, R. W.; Ironside, C. N. *Principles and Application of Nonlinear Optical Materials*; Chapman & Hall: London 1993. (b) Prasad, P. N.; Williams, D. J. *Introduction to Nonlinear Optical Effects in Molecules and Polymers*; Wiley: New York, 1991. (c) Balzani, V.; Venturi, M.; Credi, A. *Molecular Devices and Machines*; Wiley-VCH: Weinheim, 2003. (d) Feringa, B. L. *Molecular Switches*; Wiley-VCH: Weinheim, 2001.

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(3) (a) Hudson, R. D. A.; Manning, A. R.; Nolan, D. F.; Asselberghs, I.; Boxel, R. V.; Persoons, A.; Gallagher, J. F. *J. Organomet. Chem.* **2001**, *619*, 141. (b) Raimundo, J.-M.; Blanchard, P.; Gallengo-Planes, N.; Mercier, N.; Ledoux-Rak, I.; Hierle, R.; Roncali, J. *J. Org. Chem.* **2002**, *67*, 205 and references therein.

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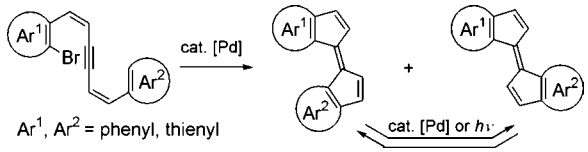
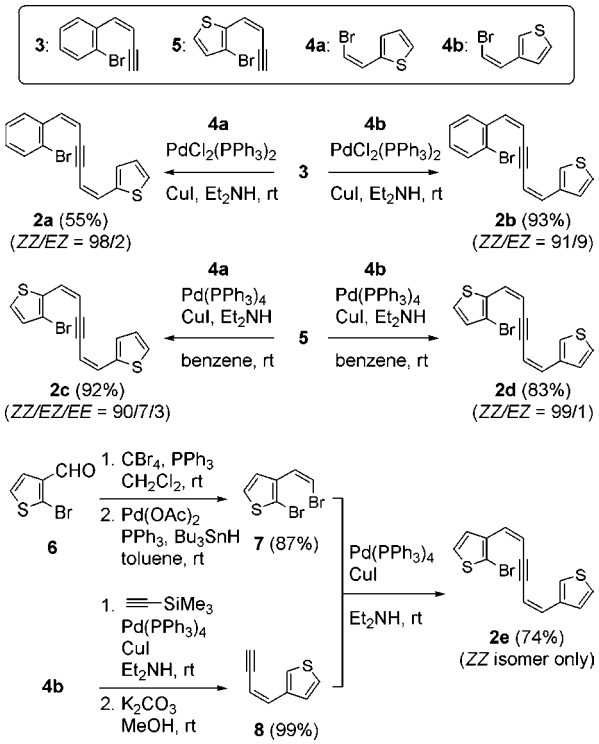
Scheme 1. Pd-Catalyzed Double Cyclization of Diaryldienynes



ladium intermediate because of steric hindrance in the (*Z*)-isomers.[6a,8] As an extension of our work, we planned to apply the reaction to (di)thienyldienynes because of the following possibilities in the cyclization products: (i) further elaboration of bridged diarylethenes containing (a) thiophene ring(s) to potentially useful materials as described above and (ii) formation of the (*Z*)-isomers owing to the absence of the inner peri hydrogen atoms.[9] The latter issue is indispensable for application of the products to photochromic systems. In this context, we report herein the efficient synthesis of phenylthienylethene and dithienylethene derivatives by Pd-catalyzed double cyclization reactions of readily available diarylhexadienynes and their *Z*/*E* isomerization catalyzed by a Pd catalyst or induced by photoexcitation (Scheme 1).

The preparations of the starting materials **2a**−**e** for the cyclization are shown in Scheme 2. For the preparation of phenylthienyldienynes **2a** and **2b**, bromothienylethene **4a**[10] or **4b** was prepared from the corresponding thiophenecarboxaldehyde in excellent yields through the Corey−Fuchs protocol[11] followed by the stereoselective hydrogenolysis reported by Uenishi.[12] The Sonogashira coupling of **4a** or **4b** with **3**[6a] afforded (*Z*,*Z*)-**2a** and **2b**, respectively, together with their (*E*,*Z*)-isomers as minor components.[13] Pure (*Z*,*Z*)-isomers were isolated by preparative GPC. Dithienyldienynes **2c** and **2d** were also synthesized by the coupling of bromothienylbutenyne **5** with **4a** or **4b**.[14] Compound **5** was prepared by the Sonogashira coupling of 1-bromo-2-(3-

Scheme 2



bromothienyl)ethene[15] with ethynyltrimethylsilane and subsequent deprotection of the trimethylsilyl group.

Dithienyldienyne **2e** was prepared from 1-bromo-2-(2-bromothienyl)ethene (**7**), derived from bromothiophenecarboxaldehyde (**6**)[16] by the same method as that used for the synthesis of **4a** and **4b**, and thienylbutenyne **8** derived from **4b** by the same method as that used for the synthesis of **5**. It should be noted that, by changing the position of the enyne bond formation, only (*E*,*E*)-isomer **2e** was obtained.

The tandem cyclization reactions of **2a**−**e** were conducted under the conditions optimized in the synthesis of **1**.[6a] When **2a** was treated with $Pd(OAc)_2$ (0.2 equiv), PPh_3 (0.4 equiv), Bu_4NBr (1 equiv), and K_2CO_3 (3 equiv) in DMF at 80 °C, the 5-exo cyclization proceeded readily to form the doubly cyclized products, bridged phenylthienylethene **9a**, as a mixture of (*E*)- and (*Z*)-isomers in 85% yield (*Z*/*E* = 75/25) (Figure 1). In contrast to the case of **1**, the (*Z*)-isomer was formed as a major product. Pure (*Z*)-**9a** and (*E*)-**9a** were

(6) (a) Rahman, S. M. A.; Sonoda, M.; Itahashi, K.; Tobe, Y. *Org. Lett.* **2003**, *5*, 3411. We also reported 6-endo tandem cyclization of diaryldienynes by flash vacuum pyrolysis (FVP): (b) Sonoda, M.; Itahashi, K.; Tobe, Y. *Tetrahedron Lett.* **2002**, *43*, 5269.

(7) A similar type of domino-Heck double cyclization reaction was reported: (a) Tietze, L. F.; Kahle, K.; Raschke, T. *Chem. Eur. J.* **2002**, *8*, 401. (b) Bruyère, D.; Bouyssi, D.; Balme, G. *Tetrahedron* **2004**, *60*, 4007. (c) Ohno, H.; Yamamoto, M.; Iuchi, M.; Tanaka, T. *Angew. Chem., Int. Ed.* **2005**, *44*, 5103.

(8) (*Z*)-Biindenylidenes should be deformed to a nonplanar conformation because of the steric hindrance between the two inner peri hydrogen atoms. According to the calculations by the DFT method at the B3LYP/6-31G** level, twist angles of the central double bond of (*E*)- and (*Z*)-biindenylidenes were estimated to be 0° and 14.9°, respectively.

(9) The DFT calculations at the B3LYP/6-31G** level predict that the twist angles of the central double bond of (*Z*)-isomers of **9a**, **9b**, and **9c** are 11.4°, 6.1°, and 8.4°, respectively, whereas those of both **9d** and **9e** are 0°. The corresponding angles of the (*E*)-isomers, (*E*)-**9a**−**e**, are essentially 0°.

(10) Recently, the synthesis of (*Z*)-vinylthiophenes was reported: Hayford, A.; Kaloko, J., Jr.; El-Kazaz, S.; Bass, G.; Harrison, C.; Corprew, T. *Org. Lett.* **2005**, *7*, 2671.

(11) Corey, E. J.; Fuchs, P. L. *Tetrahedron Lett.* **1972**, 3769.

(12) Uenishi, J.; Kawahama, R.; Yonemitsu, O.; Tsuji, J. *J. Org. Chem.* **1998**, *63*, 8965.

(13) The presence of (*E*,*Z*)-isomers was indicated by the ^{1}H NMR spectra, which showed sets of vinyl proton signals with $J \sim 16$ Hz (δ 7.45 and 6.43 ppm for (*E*,*Z*)-**2a** and δ 7.36 and 6.38 ppm for (*E*,*Z*)-**2b**) and those with $J \sim 12$ Hz (δ 6.96 and 5.73 ppm for (*E*,*Z*)-**2a** and δ 6.73 and 5.78 ppm for (*E*,*Z*)-**2b**).

(14) The ^{1}H NMR spectrum of **2c** showed two sets of vinyl proton signals with $J \sim 12$ Hz (δ 7.07, 6.97, 6.00, and 5.85 ppm) for the (*Z*,*Z*)-isomer. The presence of the other isomers of **2c** were confirmed clearly by the ^{1}H NMR spectrum of the residual fractions after isolation of pure (*Z*,*Z*)-isomer using preparative GPC. Thus, two doublet of doublet signals, due to the vinyl protons adjacent to the acetylenic carbons, with $J \sim 12$ Hz (δ 5.84 and 5.71 ppm) and four doublet of doublet signals with $J \sim 16$ Hz (δ 6.32, 6.25, 6.19, and 6.14 ppm) were assigned to the two (*E*,*Z*)- and (*E*,*E*)-isomers. The vinyl proton signals adjacent to aromatic rings, which appeared at lower field, were concealed by the aromatic proton signals. Simiarly, a doublet of doublet signal with $J \sim 16$ Hz at δ 6.27 ppm and that with $J \sim 12$ Hz at δ 5.85 ppm in the spectrum of **2d** were ascribed to (*E*,*Z*)-**2d**.

(15) Tietze, L. F.; Lücke, L. P.; Major, F.; Müller, P. *Aust. J. Chem.* **2004**, *57*, 635.

(16) Christophersen, C.; Begtrup, M.; Ebdrup, S.; Petersen, H.; Vedso, P. *J. Org. Chem.* **2003**, *68*, 9513.

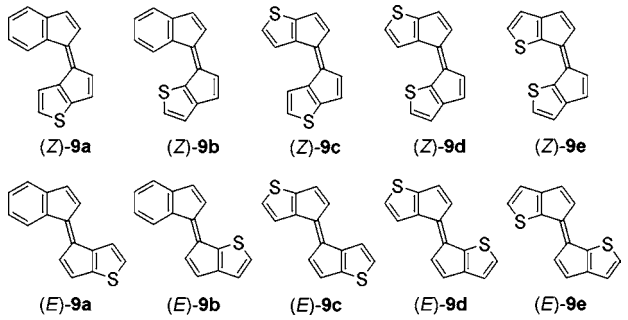


Figure 1. Phenylthienylethenes **9a**,**b** and dithienylethenes **9c**−**e**.

isolated by preparative GPC.[17] In the ^{1}H NMR spectrum of (*Z*)-**9a**, a diagnostic signal was observed at δ 8.30 ppm which was assigned to the inner peri hydrogen of the benzene ring. The prominent downfield shift relative to the corresponding proton of (*E*)-**9a** (δ 7.87 ppm) is ascribed to the anisotropic deshielding effect of the closely located thiophene ring. The stereochemical assignment of (*E*)-**9a** was secured by the observation of a nuclear Overhauser enhancement between the peri hydrogen and one of the vinyl hydrogens of the cyclopentadiene ring fused to the thiophene ring. The formation of (*Z*)-**9a** may be interpreted by the relatively diminished steric repulsion between the β-hydrogen of the thiophene ring and the inner peri hydrogen of the benzene ring in the diarylethene structure.[9] Interestingly, (*E*)-**9a** was obtained as the major product when the reaction was performed for a relatively long period (54% yield, Z/E = 35/65). In this case, the Z/E ratio of the products was found to be dependent on the reaction time, indicating that the isomerization is catalyzed by the palladium catalyst employed for the cyclization as described later. Hexadienyne **2b** was also converted efficiently to **9b** (89%, Z/E = 89/11). Though complete separation of (*E*)-**9b** and (*Z*)-**9b** was not achieved, samples enriched with either isomer were obtained.

Reactions of **2c**−**d** were less efficient, giving bridged dithienylethenes **9c** and **9d** in 38% (Z/E = 77/23) and 49% yields (Z/E = 83/17), respectively. As was the case with **9b**, the (*E*)- and (*Z*)-isomers of **9c** and **9d** could not be separated entirely. In the ^{1}H NMR spectra of the mixture of (*E*)- and (*Z*)-isomers of **9c** and **9d**, the signals of the β-hydrogen of the thiophene ring of the (*Z*)-isomers, which are located inside the U-shaped molecular framework, appear at relatively low field compared with the corresponding proton of the (*E*)-isomers. In both cases, the reactions proceeded slowly and a portion of the starting material was not consumed.[18] In remarkable contrast, in the case of **2e**, the tandem cyclization occurred efficiently and (*Z*)-**9e** was obtained exclusively in 87% yield. The reaction of **2e** took

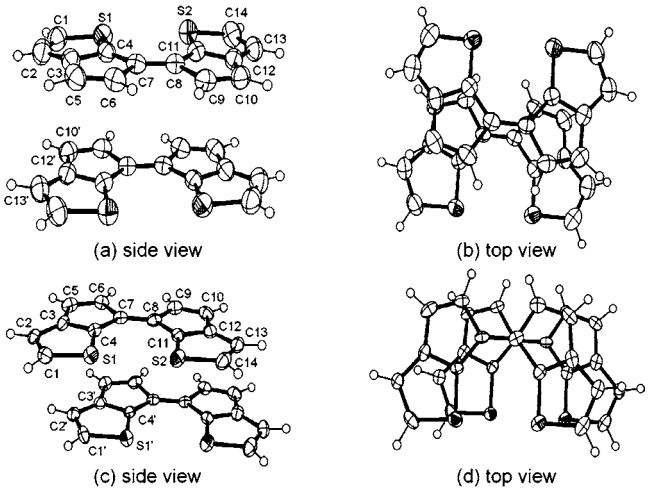


Figure 2. ORTEP drawings of (*Z*)-**9e**: (crystal A) (a) side view, (b) top view; (crystal B) (c) side view, (d) top view.

place even with a smaller amount of the catalyst (0.05 equiv) and the phosphine ligand (0.1 equiv) with similar efficiency.

The geometry of the double bond of (*Z*)-**9e** was confirmed by the X-ray crystallographic analysis of crystals obtained by recrystallization from chloroform/hexane (crystal A) or ether (crystal B) as shown in Figure 2. In both crystal structures, two molecules of (*Z*)-**9e** stacked to form a dimer. The closest interatomic distances between non-hydrogen atoms of the two molecules of crystals A and B are 3.56 (C(5)−C(12′)) and 3.45 Å (C(4)−C(3′)), respectively. The most striking difference between the two crystal structures is the orientation of the two molecules of (*Z*)-**9e**; it is antiparallel in crystal A while parallel in crystal B. In crystal B, the intermolecular S−S distance (S(1)−S(1′)) (3.80 Å) is slightly longer than the sum of the van der Waals distance (3.7 Å).[19] In both structures, the molecules adopt planar conformations with dihedral angles (C(4)−C(7)−C(8)−C(11)) of 1.1° and 0.2°, respectively. The intramolecular atomic distances between the two sulfur atoms (S(1)−S(2)) (3.26 Å in crystal A and 3.22 Å in crystal B) are smaller than the sum of the van der Waals radii, indicating the presence of S−S interaction,[20] which may be responsible for its exclusive formation.

The result of the reaction of **2a**, forming initially (*Z*)-**9a** and then (*E*)-**9a** with increasing reaction time, suggests that the former is kinetically favored and the latter is thermodynamically favored. Accordingly, we examined the isomerization reaction between the (*Z*)- and (*E*)-isomers for all products under the catalytic conditions. We also investigated photochemical isomerization between the isomers. The results are summarized in Table 1. When (*Z*)-**9a** (Z/E = 100/

(17) Dark unknown materials, which were insoluble in $CHCl_3$, were formed gradually on standing a solution of (*Z*)-**9a** in $CHCl_3$ (or $CDCl_3$). It was not possible, therefore, to measure the absorption spectrum of (*Z*)-**9a** accurately.

(18) The low yields of **9c** and **9d** were partly ascribed to the decomposition of the products under the reaction conditions.

(19) (a) Pauling, L. *The Nature of the Chemical Bond*, 3rd ed.; Cornell University Press: Ithaca, 1960. (b) Ladd, M. F. C. *Structures and Bonding in Solid State Chemistry*; Ellis Horwood: West Sussex, 1979.

(20) (a) Aso, Y.; Yui, K.; Ishida, H.; Otsubo, T.; Ogura, F.; Kawamoto, A.; Tanaka, J. *Chem. Lett.* **1988**, 1069. (b) Mazaki, Y.; Kobayashi, K. *J. Chem. Soc., Perkin Trans. 2* **1992**, 761.

Table 1. Isomerization between (*Z*)- and (*E*)-Isomers of **9a**−**e**[a]

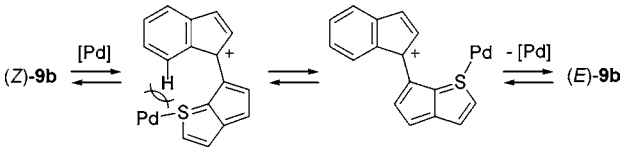
entry	conditions	substrate (*Z*/*E*)	time (h)	product[b] (*Z*/*E*)	yield[c] (%)
1	A[d]	**9a** (100/0)	1	**9a** (100/0)	ND[e]
2	A	**9a** (100/0)	3.5	**9a** (30/70)	85[f]
3	A	**9a** (0/100)	2	**9a** (0/100)	ND[e]
4	A	**9b** (89/11)	48	**9b** (59/41)	55[f]
5	A	**9e** (100/0)	12	**9e** (100/0)	ND[e]
6	B	**9a** (60/40)	6	**9a** (0/100)	56
7	B	**9b** (89/11)	1	**9b** (16/84)	73
8	B	**9c** (82/18)	2	**9c** (10/90)	72
9	B	**9d** (95/5)	12	**9d** (39/61)	86
10	B	**9e** (100/0)	3	**9e** (41/59)	76
11	B	**9e** (9/91)	2	**9e** (37/63)	83

[a] Conditions A: $Pd(OAc)_2$ (0.2 equiv), PPh_3 (0.4 equiv), DMF 80 °C. Conditions B: photoirradiation in THF with a high-pressure mercury lamp in a Pyrex tube. [b] Product ratio was determined by HPLC or ^1H NMR. [c] Yields were determined by ^1H NMR using an internal standard (1,4-dioxane). [d] Without the palldium catalyst. [e] Not determined. [f] Isolated yield.

0) was treated with $Pd(OAc)_2$ and PPh_3 in DMF at 80 °C, an *E*-enriched mixture of **9a** (*Z*/*E* = 30/70) was obtained in 85% yield (entry 2). In the absence of the palladium catalyst, no isomerization was observed (entry 1). The reverse mode of the isomerization, i.e., *E* to *Z*, did not proceed (entry 3). When **9b** (*Z*/*E* = 89/11) was subjected to the same catalytic reaction conditions, the isomerization occurred slowly (*Z*/*E* = 59/41) (entry 4). In the case of **9c** (*Z*/*E* = 77/23) and **9d** (*Z*/*E* = 83/17), decomposition of the substrates and the products precluded us from studying their isomerization.[18] In contrast, (*Z*)-**9e** (*Z*/*E* = 100/0) was inactive under the catalytic conditions (entry 5). A plausible mechanism for the isomerization process is shown in Scheme 3 for **9b**. Thus, the reaction is initiated by re-coordination of the sulfur atom of the (*Z*)-isomer to the palladium center, followed by isomerization of the centeral double bond and elimination of the palladium complex to form the (*E*)-isomer. The slow isomerization rate of (*Z*)-**9b** may be attributed to the steric hindrance between the inner peri hydrogen of the benzene ring and the palladium complex because the sulfur atom is located in the bay region of the U-shaped structure of (*Z*)-**9b**. In the case of (*Z*)-**9e**, chelation to the palladium center by the two sulfur atoms might stabilize the *Z*-form, preventing it from the isomerization.

In contrast to the catalytic method, photoisomerization of *Z*-enriched **9a** (*Z*/*E* = 60/40) proceeded smoothly by irradiation with a high-pressure mercury lamp to afford (*E*)-**9a** (*Z*/*E* = 0/100) (entry 6). Photoisomerization of *Z*-enriched **9b** (*Z*/*E* = 89/11) also proceeded smoothly to afford an *E*-enriched **9b** (*Z*/*E* = 16/84) (entry 7). Fast isomerization was observed in the case of **9c** (*Z*/*E* = from 82/18 to 10/90) (entry 8). *Z*-Enriched **9d** (*Z*/*E* = 95/5) isomerized slowly to give slightly *E*-enriched **9c** (*Z*/*E* = 39/61) (entry 9). Interestingly, isomerization of (*Z*)-**9e** (*Z*/*E* = 100/0), which was not effected under the catalytic conditions, proceeded smoothly to furnished a *Z*/*E* mixture of **9e** (*Z*/*E* = 41/59) (entry 10). This isomerization was proven to have reached at photostationary state from the result of the isomerization of *E*-enriched **9e** (*Z*/*E* = 9/91) (entry 11).

Scheme 3



In the UV−visible spectra, **9a**−**e**[17] show two absorption maxima in the area of 360−430 nm and weak absorptions extending to ca. 600 nm were observed, which are responsible for their deep red-brown color (Figure S1 in the Supporting Information). The absorption maxima of the samples enriched with the *E*-isomers showed bathochromic shifts (ca. 5−10 nm) relative to those of the corresponding *Z*-enriched samples. It is attributed to the better conjugation pathway and the higher planarity of the (*E*)-isomers than the (*Z*)-isomers.[9]

In conclusion, we have accomplished the first synthesis of bridged phenylthienylethenes and dithienylethenes. In contrast to the synthesis of (*E*)-biindenylidene (**1**), the (*Z*)-isomers of the products were obtained selectively, which could be transformed into the corresponding (*E*)-isomers by Pd-catalyzed or photoisomerizaion method. Further elaboration of this method to the synthesis of more extended heteroaromatic π-electronic systems with potential photonic and electronic applications is the subjects of our future investigation.

Supporting Information Available: Experimental procedures, characterization data, and NMR spectra of new compounds, UV−vis spectra of **9a**−**e**, and X-ray crystallographic data (CIF) of (*Z*)-**9e**. This material is available free of charge via the Internet at http://pubs.acs.org.

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