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Efficient Synthesis of Biindenylidene Derivatives via a Domino-Heck-Type Double Cyclization of Diaryldienynes

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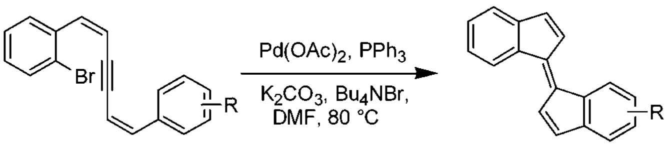
ABSTRACT

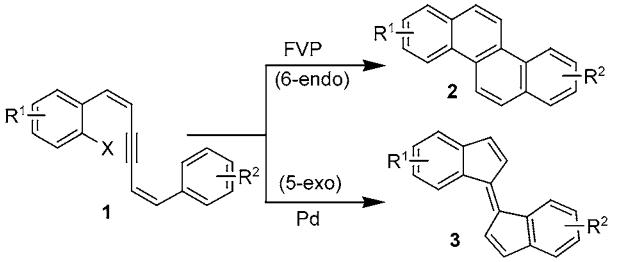


Synthesis of aromatic ring substituted (*E*)-1,1′-biindenylidene derivatives was achieved by a domino-Heck type double cyclization of (*Z,Z*)-1,6-diaryl-1,5-hexadien-3-ynes.

Extensively conjugated molecular and polymeric materials are critical components for a large number of advanced technologies utilizing nonlinear optical (NLO),[1] photo- and electroluminescent,[2] and molecule-based sensory devices.[3] As a part of our research program directed toward the synthesis of these materials, we are investigating the development of a general and versatile method for constructing highly extended π-systems composed by chrysene or indenylidene units. We designed a general synthetic scheme (Scheme 1), which is based on the tandem 6-endo or 5-exo cyclization of (*Z,Z*)-diaryldienynes to give chrysene (**2**) and indenylidene (**3**) derivatives, respectively.[4]

Because of their structural planarity, rigidity, and centrosymmetric nature, biindenylidene derivatives and some other benzo-fused fulvalenes are of considerable interest both as ligands in the preparation of organometallic complexes[5] and as precursors to materials with novel electronic and conductive properties.[6] Although (*E*)-1,1′-biindenylidene and some functionalized derivatives were accessed via mostly oxidative coupling of indene or indenyl derivatives,[7] no biindenylidene derivative with a functionalized aromatic ring(s) has been synthesized to date. We herein, report the first synthesis of aromatic ring-substituted biindenylidene derivatives via tandem cyclization of diaryldienynes.

Scheme 1



[†] 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) Nie, W. *Adv. Mater*. **1993**, *5*, 520. (c) Prasad, P. N.; Williams, D. J. *Introduction to Nonlinear Optical Effects in Molecules and Polymers*; Wiley: New York, 1991.

(2) Greenham, N. C.; Moratti, S. C.; Bradley, D. D.; Friend, R. H.; Holmes, A. B. *Nature* **1993**, *365*, 628.

(3) Swager, T. M.; Marsella, M. J. *Adv. Mater*. **1994**, *6*, 595.

(4) Recently, we reported the synthesis of chrysene from **1** via flash vacuum pyrolysis (FVP); see: Sonoda, M.; Itahashi, K.; Tobe Y. *Tetrahedron Lett*. **2002**, *43*, 5269.

(5) (a) McGovern, P. A.; Vollhardt, K. P. C. *J. Chem. Soc., Chem. Commun*. **1996**, 1593. (b) Waldbaum, B. R.; Kerber, R. C. *Inorg. Chim. Acta* **1999,** *291*, 109.

(6) Wennerström, O. *Macromolecules* **1985**, *18*, 1977.

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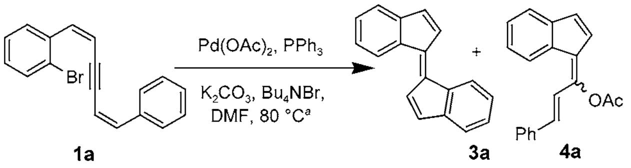
1,6-Diphenyl-1,5-hexadien-3-yne (**1a**)[4] was chosen for the optimization process of the tandem cyclization reaction (Table 1). Although we investigated a number of palladium catalysts,[8] only $Pd(OAc)_2$ furnished the desired product (*E*)-1,1′-biindenylidene (**3a**),[9] associated with a mixture of partly cyclized side-products **4a** ((*E*)- and (*Z*)-isomers).[13] We found that the reaction did not proceed at all in the absence of a base (entry 1), and exclusion of the ligand triphenylphosphine produced only a trace amount of **3a** (entry 2). Abrupt yield enhancement was not found by an increased catalyst loading from 10 to 20 mol % (entries 3 and 4). When the amount of base was increased to 3 equiv (entry 5), the yield improvement was not so significant.[11] However, a nearly 2-fold increase of yield was noted when the molar concentration of the substrate in DMF was reduced to 0.01 M, affording **3a** and **4a** in 54 and 15% yields, respectively (entry 6). Further increase of base (entry 7) provided a lower yield. When tri-*o*-tolylphosphine was employed as a ligand, yields of the products were reduced.

Table 1. Optimization of the Reaction Conditions



entry	$Pd(OAc)_2$[b] (mol %)	PPh_3 (mol %)	base (equiv)	DMF concentration (M)	yield (%)	
					3a	**4a**
1	10	20	none	0.05	no reaction	
2	30	none	K_2CO_3 (2)	0.05	trace	0
3	10	20	K_2CO_3 (2)	0.05	21	0
4	20	40	K_2CO_3 (2)	0.05	28	3
5	20	40	K_2CO_3 (3)	0.05	31	4
6	20	40	K_2CO_3 (3)	0.01	54	15
7	20	40	K_2CO_3 (6)	0.01	31	12
8	20	40[c]	K_2CO_3 (3)	0.01	24	5

[a] Optimum temperture was found to be 80 °C. While an elevated temperature accelerates decomposition of **3a**, below temperatures of 80 °C, a substantial amount of starting material remains unreacted. [b] Among the catalyst system, only $Pd(OAc)_2$ gave the desired product. [c] Tri-*o*-tolylphosphine was used as a ligand instead of PPh_3.

Next, different solvents and additives were investigated. Among the solvents investigated (CH_3CN, DMSO, DMA, DMI), only DMA gave the desired product, albeit in a slightly lower yield than that in DMF.[12] As shown in Table 2, changing the phase transfer catalyst from Bu_4NBr to Pr_4NBr/Bu_4NBF_4 or the base from K_2CO_3 to KOAc/Na_2CO_3/$CsCO_3$ produced various results with no increase of the yield of the desired product.[13]

Table 2. Investigation on Bases and Additives

entry	base	additive	yield (%)	
			3a	**4a**
1	K_2CO_3	Bu_4NBr	54	15
2	K_2CO_3	Pr_4NBr	36	trace
3	K_2CO_3	Bu_4NBF_4	47	nd
4	KOAC	Bu_4NBr	40	15
5	Na_2CO_3	Bu_4NBr	25	12
6	$CsCO_3$	Bu_4NBr	36	nd

With this optimization result in hand, we assumed that introduction of a substituent at an aromatic ring might increase or decrease the yield depending on its nature (electron withdrawing or electron releasing). Therefore, we synthesized a number of (*Z*,*Z*)-diaryldienynes as shown in Scheme 2. (*Z*)-Bromostyrenes **6b**−**e**, were synthesized selectively by a procedure similar to that of Uenishi.[14] The Sonogashira coupling of **6** with enyne **7**[4] gave the corresponding (*Z*,*Z*)-diaryldienynes **1b**−**e** in very good yields with a small amount of (*E*,*Z*)-isomers.[15] Similarly, **1f** was prepared from 1-naphthaldehyde via steps with very good yields (67% yield for three steps). However, a remarkable amount of (*E*,*Z*)-isomer of **1f** was produced (*ZZ*/*EZ* = 77/23). Pure (*Z*,*Z*)-isomers of **1a**−**f** were obtained by recyclable preparative HPLC.

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(7) For the synthesis of hitherto reported biindenylidene derivatives and other related dibenzofulvalenes, see: (a) Tani, H.; Toda, F. *Chem. Ind.* (London) **1963**, 1083. (b) Toda, F.; Tani, H. *Bull. Chem. Soc. Jpn*. **1964**, *37*, 915. (c) Anastassiuo, A. G.; Setlife, F. L.; Griffin, G. W. *J. Org. Chem.* **1966**, *31*, 2705. (d) Lacy, P. H.; Smith, D. C. *J. Chem. Soc. C* **1971**, 41. (e) Bergamasco, R.; Porter, Q. N. *Aust. J. Chem*. **1977**, *30*, 1051. (f) Escher, A.; Rutsch, W.; Neuenschwander, M. *Helv. Chim. Acta* **1986**, *69*, 1644. (g) Escher, A.; Neuenschwander, M.; Engel, P. *Helv. Chim. Acta* **1987**, *70*, 1623. (h) Priebsch, W.; Hoch, M.; Rehdar, D. *Chem. Ber*. **1988**, *121*, 1971. (i) Kelley, T. R.; Meghani, P. *J. Org. Chem*. **1990**, *55*, 3684. (j) Kerber, R. C.; Waldbaum, B. *Organometallics* **1995**, *14*, 4742. (k) Capparelli, M. V.; Machado, R.; De Sanctis, Y.; Arce, A. J. *Acta Cryst*. **1996**, *C52*, 947. (l) Taylor, B. M.; Joullie, M. M. *Tetrahedron* **1998**, *54*, 15121. (m) Stradiotto, M.; Hazendonk, P.; Bain, A. D.; Brook, M. A.; McGlinchey, M. J. *Organometallics* **2000**, *19*, 590. (n) Jonczyk, A.; Szymanek, P.; Juszczuk, C. *Pol. J. Chem*. **2000**, *74*, 985.

(8) We found that $Pd(PPh_3)_4$, $Pd(PPh_3)_2Cl_2$, $Pd(dppf)Cl_2$, $Pd(PhCN)_2Cl_2$, and $Pd_2(dba)_3 \cdot CHCl_3$ were ineffective.

(9) Similar type of domino-Heck double cyclization reaction was reported recently by Tietze and co-workers; see: (a) Tietze, L. F.; Heitmann, K.; Raschke, T. *Synlett* **1997**, 35. (b) Tietze, L. F.; Kahle, K.; Raschke, T. *Chem. Eur. J.* **2002**, *8*, 401.

(10) Compound **4a** consisted of an inseparable mixture (variable ratio) of two stereoisomers, which showed two methyl and two sets of trans-coupled vinyl proton signals in the ^1H NMR spectrum.

(11) Low yield of **3a** is due to a gradual decomposition of the product under the reaction conditions. This phenomenon was understood by subjection of pure **3a** to the reaction conditions.

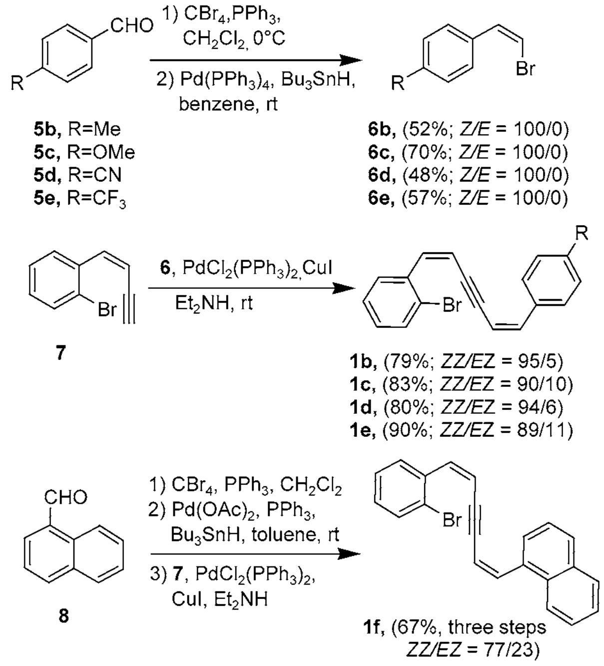
(12) While employment of CH_3CN as a solvent furnished a 2:1 mixture of **1a** and its (*Z*,*E*)-isomer, DMSO gave a complex mixture, and using DMA afforded **3a** and **4a** in 43 and 5% yields, respectively.

(13) Exactly the same reaction conditions utilized by Tietze were also applied for **1a**. While the reaction conditions using $Pd_2(dba)_3 \cdot CHCl_3/PPh_3/Ag_2O$/DMF described by Tietze[9a] were completely ineffective, utilization of $Pd(OAc)_2/PPh_3$/KOAc/Pr_4Br/DMF[9b] yielded **3a** in a relatively lower yield. Most probably, the substrates used by Tietze contained a free alkene with a terminal trimethylsilyl group, which facilitated the second step of cyclization compared to the aromatic ring present in **1a**.

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

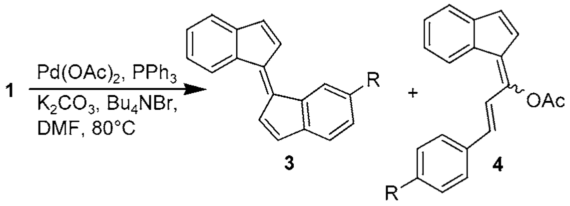
(15) Minor isomer formed was the (*E*,*Z*)-isomer. This assignment was accomplished by measuring the coupling constant of the vinyl proton signals in the ^1H NMR spectra and by comparing the change of the chemical shift values of the corresponding vinyl protons for (*E*)- and (*Z*)-isomerization. The (*E*,*Z*)-isomer was characterized by a set of trans-coupled ($J \approx 16$ Hz) and a cis-coupled ($J \approx 12$ Hz) vinyl proton signals.

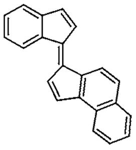
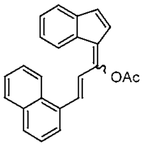
Scheme 2



The results of the domino-Heck-type tandem cyclization reaction of (*Z*,*Z*)-diaryldienynes to form biindenylidene derivatives are summarized in Table 3. A relatively larger scale reaction of **1a** yielded **3a** and **4a** (mixture) in 47 and 15% yields, respectively.[16] Electron-releasing substituents such as methyl and methoxy groups did not cause any significant alteration of yields (entries 2 and 3). A substrate bearing an electron-withdrawing CN group at the para position only gave the undesired acetates in 22% yield, and desired product **3d** was not accessible. Possibly, coordination of the cyano nucleophile with the Pd species discouraged the formation of **3d**. Introduction of a trifluoromethyl substituent afforded **3e**, albeit in a relatively lower yield. An extended π-system **3f** was also synthesized from **1f**, albeit in a lower yield (entry 6).[17]

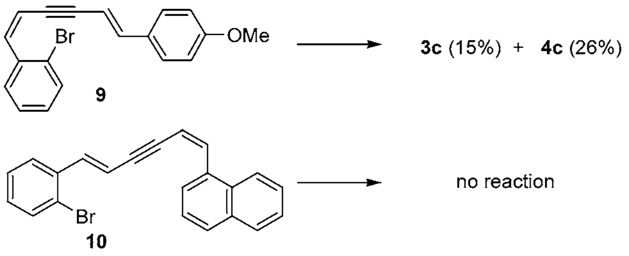
Table 3. Tandem Cyclization of (*Z*,*Z*)-Diaryldienynes



entry	substrate	R	products (yields %)	
1	**1a**	H	**3a** (47)	**4a** (15)
2	**1b**	Me	**3b** (45)	**4b** (15)
3	**1c**	OMe	**3c** (43)	**4c** (19)
4	**1d**	CN	**3d** (0)	**4d** (22)
5	**1e**	CF$_3$	**3e** (38)	**4e** (15)
6	**1f**	-	 **3f** (27)	 **4f** (8)

To explore the scope of this double-cyclization reaction and to understand the mechanistic clues, the (*Z*,*E*)-isomer of **1c**, compound **9**, was prepared[20] and subjected to the reaction conditions (Scheme 3). The desired product **3c** and the corresponding acetates **4c** were obtained in 15 and 26% yields, respectively. In contrast, the (*E*,*Z*)-isomer of **1f**, i.e., **10**, did not undergo this cyclization reaction and the starting material remained unchanged.

Scheme 3[a]



[a] Reaction conditions: Pd(OAc)$_2$, PPh$_3$, K$_2$CO$_3$, Bu$_4$NBr, DMF, 80 °C.

The reaction and the selective formation of (*E*)-1,1′-biindenylidene derivatives can be explained by a typical mechanism of Pd-catalyzed reactions (Scheme 4).[21] Oxidative addition of Pd^0 to **1** gave the aryl palladium species **11**, which was transformed to the intermediate **12** by the syn addition of the triple bond into the aryl palladium bond via a 5-*exo*-dig mode.[22] The second phase of cyclization would generate

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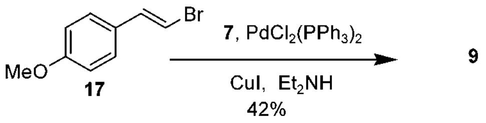
(16) **General Procedure.** A flame-dried flask was loaded with palladium acetate (20 mol %), triphenylphosphine (40 mol %), anhydrous potassium carbonate (3 eqiuv), and tetrabutylammonium bromide (1 equiv). A dilute solution (0.01 M) of diaryldieneyne was then added to the flask; the resulting mixture was heated to 80 °C for 20 min, and the reaction temperature was maintained at 80 °C until the reaction was complete. The reaction was cooled to room temperature, and water and ether were added sequentially. The mixture was extracted with ether three times. Organic layers were combined and washed with brine, dried over MgSO$_4$, and filtered. The filtrate was evaporated to give a dark residue, which was purified by column chromatography to yield the corresponding products.

(17) Formation of compound **3f** rather than the product with the phenafulvene substructure was judged by comparing the coupling constant of the olefinic proton signal of **3f** with those of the reported compounds. While the usual coupling constant for the olefinic protons of phenafulvenes occurs around 10 Hz,[18] that of indenylidenes occurs between 5 and 6 Hz.[19]

(18) Morita, N.; Asao, T. *Chem. Lett.* **1975**, 71.

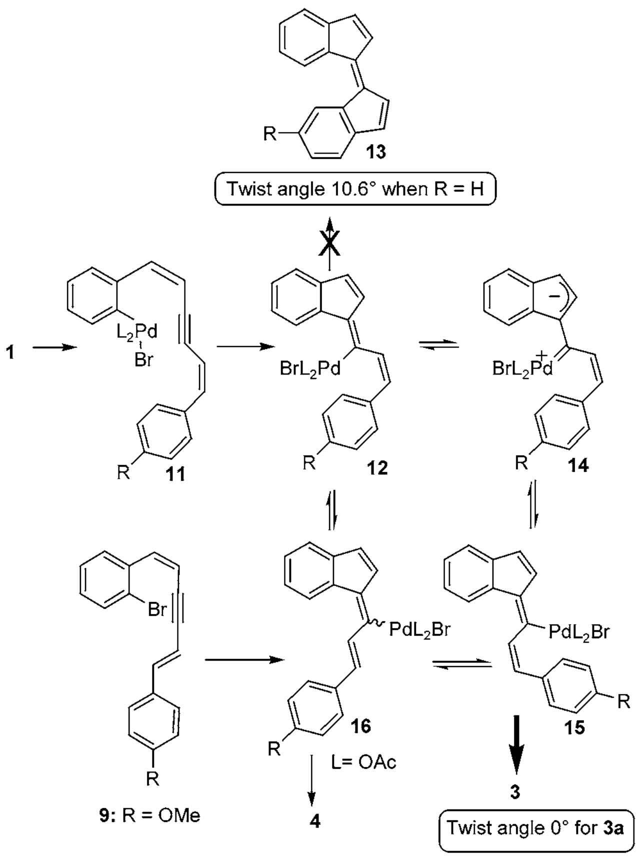
(19) See the coupling constant values for the pentacyclic olefinic protons in **3b**−**e** in Supporting Information. See also: Launikonis, A.; Sasse, W. H. F.; Willing, I. R. *Aust. J. Chem.* **1993**, *46*, 427.

(20) Compound **9** was prepared via the Sonogashira coupling of **7** and bromoalkene **17**.



(21) Tsuji, J. *Palladium Reagents and Catalysts*; John Wiley & Sons, Ltd.: Chichester, UK, 1995.

Scheme 4



the cis product **13**. However, this was not t the case and the trans isomer **3** was obtained selectively. Formation of **3** can be explained by the isomerization of the vinyl palladium species **12** to **15** via the zwitterionic resonance form **14.**[23] Selective generation of **3** was due to the fact that the activation energy for the cyclization of the vinyl palladium species **15** to **3** is lower than that of **12** to **13**. This is well understood by the twist angle of the central double bond of **3** and **13**. Whereas compound **3a** is calculated to be completely planar (twist angle of 0°), **13** is nonplaner (twist angle of 10° when R = H).[24]

Further isomerization of the pendant disubstituted double bonds of **12** and **15** might take place to give **16**, which can be transformed to **4** (mixture) by the attack of an acetate ligand. Isomerization of **12** or **15** to **16** is a reversible process, which is evident from the formation of **3c** from **9** in Scheme 3.

In conclusion, we have developed a general method for the synthesis of hitherto unknown aromatic substituted (*E*)-1,1-biindenylidene derivatives through a domino-Heck-type double-cyclization method. Further elaboration of this method toward the synthesis of more extended π-electronic and heterocyclic systems and subsequent measurement of photonic and electronic properties will be the subjects of future investigations.

Supporting Information Available: Experimental procedures and spectral data for **1b−f**, **3a−f**, **4a−f**, **9**, and **10** and ^{1}H NMR spectra of all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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[22] Formation of a six-membered ring was not observed. This could be explained by the low probability of a 6-*endo*-dig process.

[23] This type of zwitterionic resonance form might be generated from the formal donation of an electron pair by a d(8) palladium center. Resonance stabilization of the negative charge in the indene fragment of **14** might be responsible for the participation of **14** in the transformation of **12** to **15**. For isomerization via a zwitterionic resonance form, see: (a) Zargarian, D.; Alper, H. *Organometallics* **1991**, *10*, 2914. (b) de Vall, P.; Dedieu, A. *J. Organomet. Chem*. **1994**, *478*, 121. (c) Cacchi, S.; Fabrizi, G.; Marinelli, F.; Moro, L.; Pace, P. *Tetrahedron* **1996**, *52*, 10225. (d) Cacchi, S. *J. Organomet. Chem*. **1999**, *576*, 42. Participation of the zwitterionic species **14** in the cis−trans isomerization may be supported by the absence of such isomerization in the reaction of the related substrate with saturated chains reported by Tietze.[9] In addition, although we performed the reaction with a saturated system, 1-(2-bromophenyl)-6-phenyl-3-hexyn-2-ol, under similar conditions, neither the double-cyclization product nor the acetate was formed.

[24] Lee-Ruff, E.; Grant, A.; Stynes, D. V.; Vernik, I. *Struct. Chem.* **2000**, *11*, 245.