

Rapid Solid-Phase Synthesis of Oligo(1,4-phenylene ethynylene)s by a Divergent/Convergent Tripling Strategy

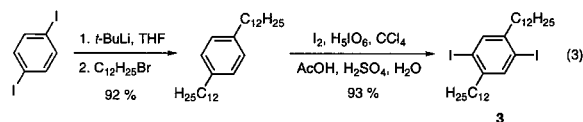
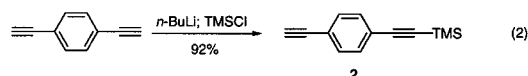
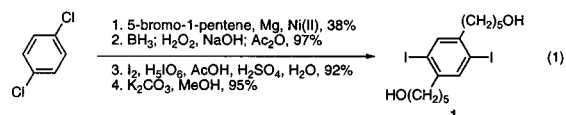
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Received December 2, 1998

The preparation of large conjugated molecules of precise length and constitution has attracted much interest recently.¹ These compounds can serve as models for the analogous bulk polymers, and they can be used for the construction of nanoarchitectures such as molecular wires and molecular-scale electronic devices.^{1,2} We and others previously used convergent/divergent doubling methodologies for oligomer growth where the iodide portions needed masking as diethyltriazenyl or bromide groups.³ We report here a new method for the preparation of oligo(1,4-phenylene ethynylene)s that more than triples the molecular length with each iteration and avoids the masking and unmasking steps often required for aryl iodides.

The syntheses of the three monomers were performed as shown in eqs 1–3.^{4–7}



The solid-phase iterative divergent/convergent synthetic approach is outlined in Scheme 1. 2-(Hydroxymethyl)-3,4-dihydro-2H-pyran was coupled to Merrifield's resin (1.0 mequiv of Cl/g, 2% DVB cross-linked, 200–400 mesh, Aldrich) in dimethylacetamide at room temperature to afford the dihydropyran-modified resin **4**.⁸ Compound **1** was then attached to **4** through the hydroxyl group using PPTS in dichloroethane to afford **5**. The loading level

was determined by cleaving the alcohol from the resin using PPTS in 1:1 *n*-butanol/1,2-dichloroethane at 80 °C.⁸ Compound **5** (0.48 mequiv of 1/g) was subjected to Pd/Cu-catalyzed coupling conditions⁹ with monomer **2** to afford the polymer-supported trimer **6** that was deprotected to yield polymer-supported trimer **7**. Attempts to generate **7** directly from **5** and 1,4-diethynylbenzene failed, possibly due to rapid homocoupling of 1,4-diethynylbenzene with trace oxygen present. Compound **7** was then cross-coupled with **3** (5–6 mol of **3** per mol of **7**) to afford polymer-supported pentamer **8**. Excess **3** was easily recovered by filtration. One portion of **8** was coupled with **2** to produce the polymer-supported heptamer **9** that was then desilylated to afford polymer-supported heptamer **10**. The remaining portion of polymer-supported pentamer **8** was treated with acid to liberate pentamer **11**. Treatment of **10** with the liberated pentamer **11** (6–8 mol of **11** per mol of **10**) under Pd/Cu cross-coupling conditions (23 °C for 24 h, then 60–70 °C for 24 h) afforded the polymer-supported 17-mer **12**. Directly heating the mixture of **10** and **11** caused a much lower yield, possibly due to decomposition of the polymer-supported α,ω -diyne **10**. Recovery of excess **11** was simply achieved by filtration from the beads, followed by passage through silica gel. Finally, treatment of **12** with acid liberated the 120-Å long 17-mer **13**.¹⁰ The overall yield was 20% for the seven-step sequence from **5**.¹¹

Completion of each polymer-supported reaction step was determined by FTIR analysis of the polymer-bound substrate.^{3b,d,12} Polymer-supported material was mixed with oven-dried KBr and ground to a powder, and an FTIR spectrum was acquired from the formed pellet. Absorptions at 3290 cm⁻¹ (strong) and 2110 cm⁻¹ (weak) are characteristic of the terminal alkynyl carbon–hydrogen and carbon–carbon stretches, respectively, and a strong absorption at 2150 cm⁻¹ is characteristic of the carbon–carbon stretch of the trimethylsilyl-terminated alkyne. As expected, we observed that the coupling reaction of a polymer-supported aryl diiodide with **2** was accompanied by the appearance of the 2150 cm⁻¹ absorption. The trimethylsilyl removal step was confirmed by the appearance of the 3290 cm⁻¹ band and the diminution of the 2150 cm⁻¹ band. The coupling reaction of a polymer-supported α,ω -dialkyne with aryl diiodide was accompanied by the disappearance of the 3290 cm⁻¹ band.^{3b,d,12}

While pentamer **11** afforded molecular ions by direct exposure via electron impact mass spectrometry (MS), neither this ioniza-

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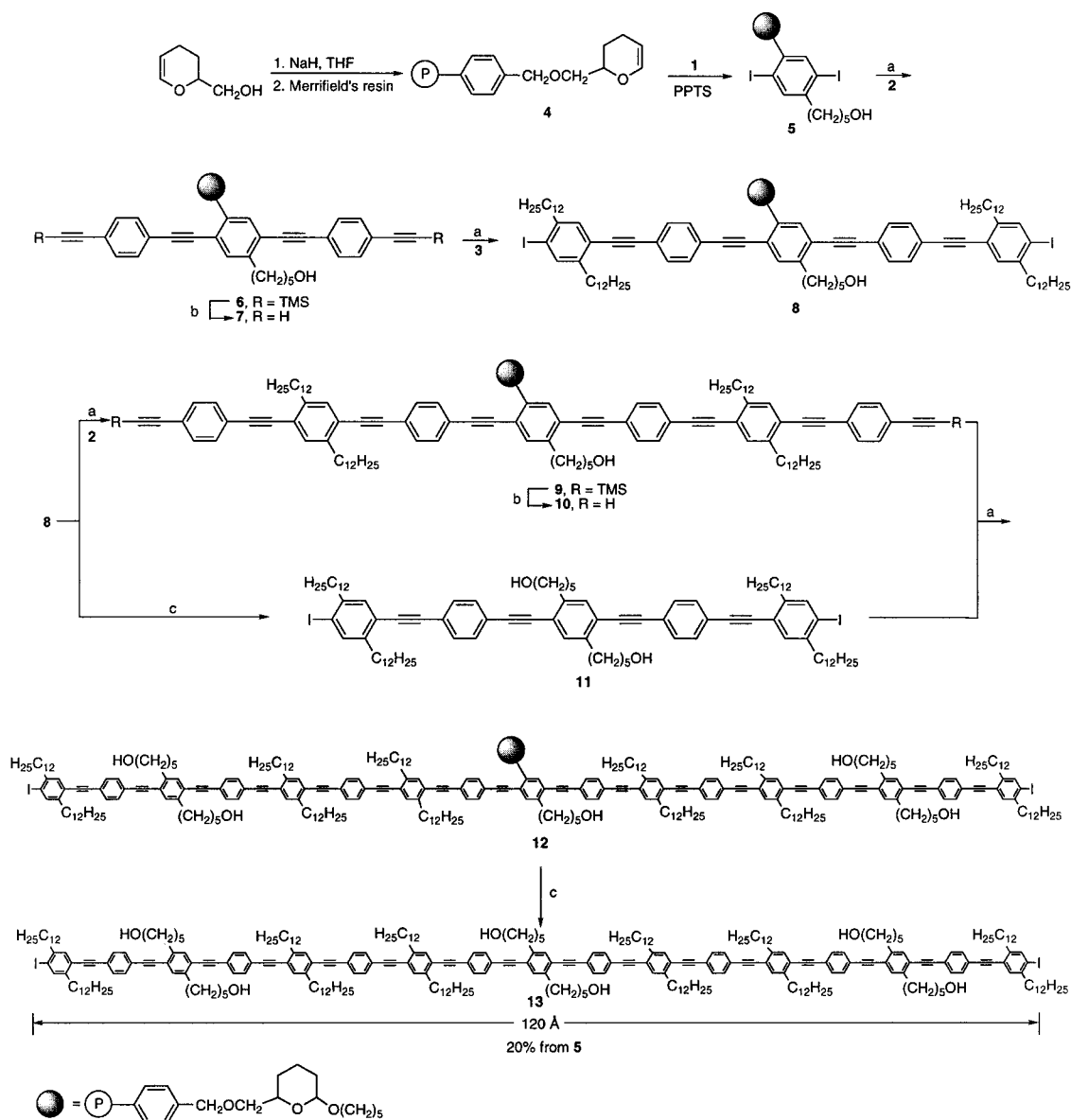
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(10) Compound **13** (310 mg yielding scale): FTIR (KBr) 3418, 2924, 2854, 1727, 1601, 1514, 1463, 1378, 1273, 1177, 1121, 1071, 894, 833, 721, 694 cm⁻¹. ¹H NMR (400 MHz, CDCl₃) δ 7.62 (s, 2 H), 7.49 (br s, 34 H), 7.36 (br s, 14 H), 3.65 (br t, *J* = 6.4 Hz, 12 H), 2.81 (m, 36 H), 1.8–1.2 (m, 282 H), 0.85 (m, 36 H). ¹³C NMR (100 MHz, CDCl₃) δ 142.19, 141.87, 139.38, 132.32, 132.25, 131.29, 123.00, 122.46, 94.22, 93.97, 93.81, 93.72, 90.48, 90.40, 90.28, 90.21, 64.20, 34.25, 34.15, 32.77, 32.04, 30.78, 30.45, 29.81, 29.78, 29.75, 29.67, 29.48, 25.73, 22.82, 14.27. λ_{abs} (CH₂Cl₂) 385 nm, ϵ (THF) = 1.1 × 10⁵. λ_{emis} (CH₂Cl₂, excitation at 385 nm) 415 nm. These assignments correlate well with oligo(phenylene ethynylene)s previously synthesized.³ The initial polydispersity index of **13** was 1.2, and all spectra were recorded at that purity level. Preparative TLC on a portion was used to sharpen the index to 1.06.

(11) The overall yields of the final 17-mer **13** was determined by comparing the loading of the monomer **1** on the polymer support (compound **5**) and the yield of the final oligomer when liberated from the polymer support: **5** (10.0 g, 4.8 mmol of loading of **1**) → **6** (10.5 g) → **7** (10.3 g) → **8** (13.9 g) of which only a 7.2% mass portion (1.00 g) was taken on in the polymer-supported form → **9** (1.03 g) → **10** (0.98 g) → **12** (1.30 g) → **13** (0.31 g, 0.069 mmol). Starting from 4.8 mmol of **1** in **5** and using only 7.2% mass of the material during the conversion of **8** → **9**, gives a theoretical yield of 0.35 mmol and an actual yield of 0.069 mmol (20%) for **13**.

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Scheme 1^a

^a Reagents: a. Pd(dba)₂, PPh₃, and CuI (5 mol %, 10 mol %, and 5 mol %, respectively, per iodide atom), Et₂NH/THF (1:4). b. TBAF, THF. c. PPTS, *n*-C₄H₉OH, ClCH₂CH₂Cl.

tion method nor FAB or electrospray MS sufficed for obtaining a molecular ion of 17-mer **13**. To obtain MS data on **13**, it was necessary to use matrix-assisted laser desorption/ionization mass spectrometry (MALDI-MS) using α -cyano-4-hydroxycinnamic acid matrix in positive ion mode. MALDI-MS of **13** afforded a peak that was 254 amu lower than the actual molecular weight of **13**, corresponding to the molecular ion minus the two iodides.

Size-exclusion chromatography (SEC) was conducted after benchtop chromatography on the obtained oligomers. The number average molecular weight (M_n) values of rigid rod oligomers should be significantly inflated relative to the randomly coiled polystyrene standards.^{1a} As expected, the M_n values of the pentamer **11** ($M_n = 2200$, PDI = 1.18, actual molecular weight = 1576), and 17-mer **13** ($M_n = 8000$, PDI = 1.06, actual molecular weight = 4468) were much greater than the actual molecular weights. Additionally, SEC on a crude reaction mixture was used to determine whether polymerization or oligomerization could ensue using this synthetic protocol.^{12d} The heptamer on **9** was cleaved from the polymer support, and the crude material was analyzed. As expected, the site isolation inhibited polymerization. However, in addition to the expected heptamer derived from **9** ($M_n = 2700$, PDI = 1.01), there was an equal area

broadened peak at slightly higher molecular weight which likely arose from undesired oligomer formation. This could have arisen from several inter-site interactions along the synthetic sequence, for example, coupling of **7** with **8** followed by capping with **2**. Therefore, although this technique inhibits polymer formation, the conformational flexibility of Merrifield resin does not allow the functionalized sites to be exclusively isolated from each other. We may be able to overcome this problem in the future by using a lower degree of loading and a more rigid matrix through higher DVB cross-link levels.^{12d} Additionally, although the final yield of the 17-mer **13** was relatively high for the size of the oligomer formed, using a more suitable polymer support would likely provide higher yields and higher purities of the final products by permitting definitive site isolation.

Acknowledgment. Financial support from the Office of Naval Research and the Defense Advanced Research Projects Agency is gratefully acknowledged. We thank FAR Research Inc. (Dr. I. Chester) for a gift of trimethylsilylacetylene, FMC for a gift of alkyllithium reagents, and Dr. Kevin Schey for obtaining the MALDI-MS data.

JA984138H