Synthesis and ^{13}C NMR Spectroscopy of ^{13}C-Labeled α,ω-Diphenylpolyynes

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Dedicated to Dr. Tom Nakashima for a lifelong commitment to NMR spectroscopy

Abstract: The synthesis of three ^{13}C-labeled α,ω-diphenylpolyynes is described. The known positions of the labeled carbon atoms allow assignment of the resonances in the ^{13}C NMR spectra and identification of trends in the chemical shifts.

Key words: alkynes, carbenes, ^{13}C labeling, polyynes, Fritsch–Buttenberg–Wiechell rearrangement

α,ω-Diphenylpolyynes (**Ph[*n*]**, where *n* is the number of acetylene units, Scheme 1) were among the first series of polyynes to be targeted synthetically, and these efforts emerged with a flurry in the early 1950s.[1] The aromatic stability of terminal phenyl rings, that is, their ability to tolerate a range of harsh conditions, was ideal for syntheses of the time, since all involved a sequence of addition and elimination reactions.[2] The synthesis and study of diphenylpolyynes has continued during the ensuing 60 years, targeting new synthetic methods, physical properties, or both.[3] For example, diphenylpolyynes have been explored by theory,[4] as nonlinear optical (NLO) materials,[3d] as molecular wires,[5] for their electronic structure (absorption and emission),[6] in supramolecular complexes,[7] and for their chemical reactivity.[8]

For some time, we have taken an interest in the synthesis of polyyne molecules, and particularly the evolution of physical properties as a function of polyyne length. This is, as one would expect, not a new endeavor. Indeed, the earliest investigations asked the same question: what happens to the spectroscopic properties as polyynes become longer?[2] Surprisingly, however, little has been done to confirm acetylenic NMR resonances via ^{13}C labeling, even though ^{13}C NMR spectroscopy is a mainstay method of characterization for polyynes, because the protons found on terminal end-capping groups change little versus length. Chemical shifts in triisopropylsilyl end-capped[9] and *tert*-butyl end-capped[10] polyynes have been examined for a handful of molecules, but aside from these examples, little else is known.

Many of the polyynes from our studies can be prepared via the Fritsch–Buttenberg–Wiechell (FBW) rearrangement, which has proven to be a procedurally straightforward and efficient protocol for polyyne formation.[11] The Fritsch–Buttenberg–Wiechell approach is well suited for the incorporation of ^{13}C labels, using reasonably inexpensive, or easily synthesized precursors, such as carbon tetrabromide or benzoic acid, as the source of the ^{13}C labeling. We report herein the synthesis of diphenylpolyynes with ^{13}C labeling at selected positions of the acetylenic framework. Using these compounds, we outline trends in the ^{13}C NMR chemical shifts as a function of polyyne length.

The synthesis of triyne **Ph[3]** started from the known ketone **1**,[12] which was first subjected to Ramirez dibromoolefination[13] using a mixture of carbon tetrabromide–^{13}C-labeled carbon tetrabromide (CBr_4–$^{13}CBr_4$, ca. 5:1) and triphenylphosphine. This afforded the labeled dibromoolefin **2** in 79% yield.[14] The ^{13}C NMR spectrum of **2** is consistent with that of the unlabeled analogue and also confirms the chemical shift of Cα, the labeled carbon, at 107.6 ppm. The identity of Cβ is also revealed at 114.1 ppm, due to the strong coupling observed to Cα, with $^1J = 97$ Hz.

Fritsch–Buttenberg–Wiechell rearrangement of dibromoolefin **2** via reaction with *n*-butyllithium under standard conditions[15] produced triyne **Ph[3]** in 62% yield. Due to the labeling of compound **2** at Cα, rearrangement of the intermediate alkylidene carbene **3** resulted in only product **Ph[3]**, that is, the same isotopomer was formed regardless of which phenylacetylene group migrated in intermediate **3** to form triyne **Ph[3]**.

The assignment of the three unique acetylenic carbons of **Ph[3]** proved reasonably straightforward based on the presence of the ^{13}C-enriched sp-carbon at C3, which is observed at 66.4 ppm with $^1J = 163$ Hz to C2. Carbon C2 is then identified at 74.4 ppm, based on the doublet with reciprocal one-bond coupling to C3 ($^1J = 164$ Hz), as well as a doublet resulting from two-bond coupling between C3↔C2′ with $^2J = 20$ Hz. The final alkyne carbon, C1, is assigned at 78.5 ppm, showing a doublet with $^2J = 18$ Hz (C1↔C3), as well as a three-bond correlation to H_A as observed in the heteronuclear multiple bond correlation (HMBC) spectrum.[16]

The predicted chemical shifts of **Ph[3]** have been reported, calculated using the GIAO-B3LYP/6-31G* method.[17] In this study, the calculated chemical shifts of C2 and C3, at 73.7 and 64.3 ppm, respectively, are quite close to those measured in solution (74.4 and 66.4 ppm, respectively).

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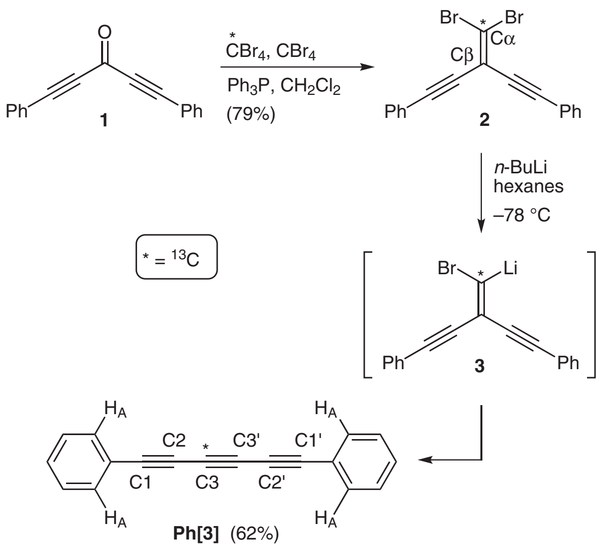
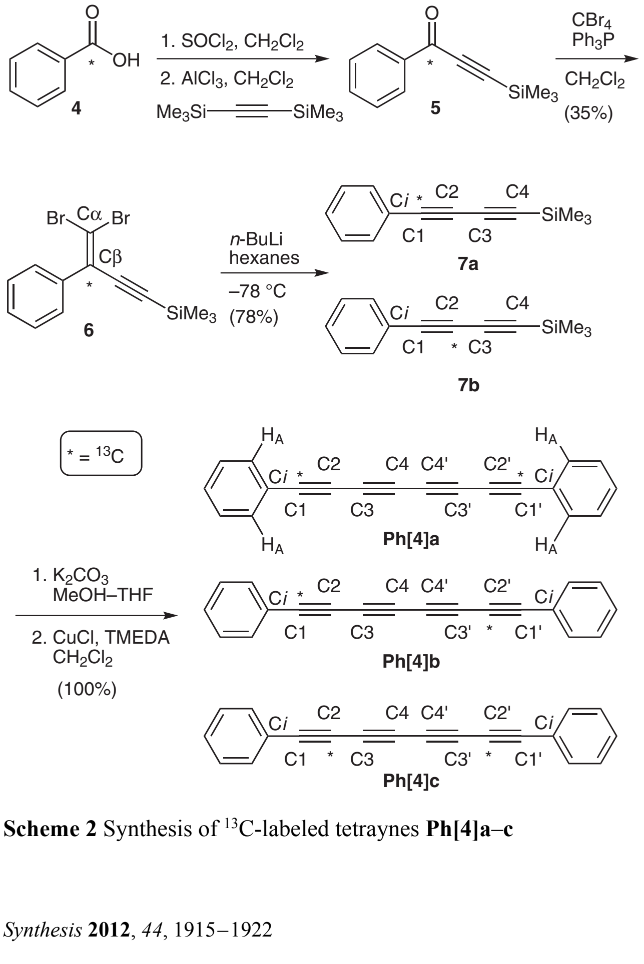


Scheme 1 Synthesis of ^{13}C-labeled triyne **Ph[3]**

Noteworthy, however, is the fact that the predicted shift of C1 (72.2 ppm) deviates quite significantly from the experimental value determined here (78.5 ppm).

The formation of labeled tetraynes **Ph[4]a**–**c** as a mixture of isotopomers was accomplished from C1-labeled benzoic acid (**4**) (100% ^{13}C enrichment, Scheme 2). The reaction of **4** with thionyl chloride in dichloromethane gave the corresponding acid chloride, which underwent Friedel–Crafts acylation with 1,2-bis(trimethylsilyl)ethyne in the presence of the Lewis acid aluminum trichloride ($AlCl_3$). This gave ketone **5**, which was subsequently used in the Ramirez reaction to produce dibromoolefin **6** in 35% yield as a pale-yellow oil.[18] It is worth noting that the formation of **6** proceeds more efficiently than the yield would suggest. Unfortunately, however, extensive purification by column chromatography was required to remove impurities with ^{13}C labeling that would likely complicate interpretation of the ^{13}C NMR spectra of the polyyne products in subsequent steps. In the ^{13}C NMR spectrum of **6**, the ^{13}C label assigns Cβ at 131.0 ppm, while Cα appears at 103.3 ppm, based on the observed one-bond coupling constant $^1J = 88$ Hz (Cα↔Cβ).



Scheme 2 Synthesis of ^{13}C-labeled tetraynes **Ph[4]a**–**c**

Lithium–halogen exchange at –78 °C in hexanes using dibromoolefin **6** and *n*-butyllithium induced the Fritsch–Buttenberg–Wiechell rearrangement to form diynes **7a**,**b** as an isotopic mixture. In this reaction, either the alkyne or the phenyl group can migrate to form either **7a** or **7b**, respectively, placing the labeled carbon at either C1 or C2. The ratio of products is typically close to 1:1.[18]

The ^{13}C NMR chemical shifts of the acetylenic carbons of **7a**,**b** can be assigned based on the sequence of C↔C coupling constants. The *ipso*-carbon (C*i*) is observed as two doublets centered at 121.4 ppm, with $^1J = 92$ Hz (C*i*↔C1 in **7a**) and $^2J = 14$ Hz (C*i*↔C2 in **7b**). This then sets the chemical shift of C1 as 76.7 ppm based on the observed common coupling constant to C*i* ($^1J = 92$ Hz). The C1 signal at 76.7 ppm also shows a second doublet with observed $^1J = 196$ Hz, as a result of C1↔C2 coupling. This reveals the chemical shift of C2 at 74.2 ppm (C2↔C1, $^1J = 203$ Hz). The C2 signal shows a second doublet with $^1J = 141$ Hz, due to one-bond C2↔C3 coupling, identifying the resonance of C3 at 87.8 ppm, which shows a reciprocal coupling ($^1J = 148$ Hz). The final resonance at 90.6 ppm, C4, shows a doublet due to two-bond C2↔C4 coupling in **7b** ($^2J = 14$ Hz), and a singlet from the isotopomer **7a**.[19]

In the final synthetic steps, desilylation of diynes **7a**,**b** gave the terminal diynes, which were carried on directly to an oxidative homocoupling reaction under standard Hay[20] conditions. The result of this reaction is a mixture of isotopomers **Ph[4]a**–**c**, where the labeled carbons are found at C1/C1′ for **Ph[4]a**, at C1/C2′ for **Ph[4]b**, and C2/C2′ for **Ph[4]c**.

Assignment of the resonances of the four unique sp carbons C1–C4 of **Ph[4]a**–**c** is complicated slightly due to second order coupling between C1 and C2[21] and the approximately equal distribution of the ^{13}C label between C1 and C2. The signal for C*i* is observed as two doublets centered at 120.6 ppm with $^1J = 91$ Hz and $^2J = 14$ Hz (both of equal intensity), as expected for coupling of C*i*↔C1 and C*i*↔C2, respectively. The reciprocal coupling constants are not, however, evident for the labeled carbons at 77.7 and 74.5 ppm. The lack of a clear coupling pattern complicates assignment of C1 and C2, although a correlation observed in the HMBC spectrum between H_A and the signal at 77.7 ppm suggests this resonance should be C1.[16]

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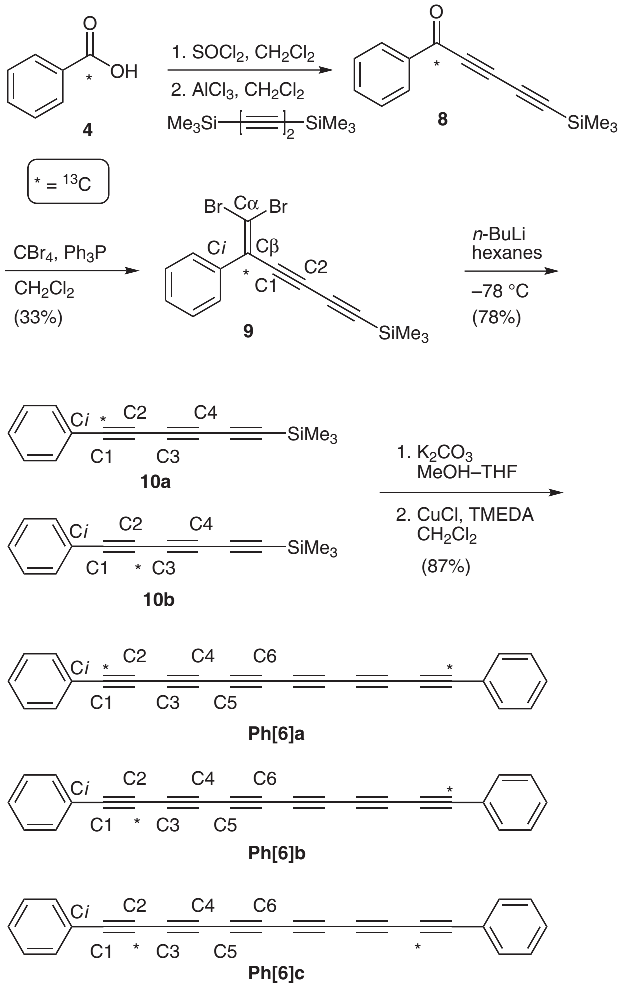
Selective homonuclear decoupling, however, provides the answer.[16] Acquisition of a $^{13}C\{^{1}H\}$ spectrum with selective decoupling (irradiation) of the signal at 77.7 ppm collapses the C*i* signal into a singlet and a doublet ($^{2}J = 13$ Hz), and hence the signal at 77.7 ppm is confirmed as that of C1. Conversely, the selective decoupling experiment with irradiation of the signal at 74.5 ppm shows C*i* as a singlet and a doublet ($^{1}J = 86$ Hz), confirming the chemical shift of C2 at 74.5 ppm. Irradiation at 77.7 ppm (C1) also results in a pseudo-doublet at 63.5 ppm (d, $J = 158$ Hz),[16] the consequence of one-bond coupling between C3↔C2, and thus the chemical shift of C3 is established. The final alkyne resonance, C4, is observed as a second order multiplet in the acquired spectra for **Ph[4]a**–**c** centered at approximately 67.2 ppm.

The synthesis of labeled hexaynes **Ph[6]a**–**c** was also accomplished starting from ^{13}C-labeled benzoic acid (**4**) (100% ^{13}C enrichment, Scheme 3), as previously reported for the unlabeled analogue.[3d] Acid **4** was first converted into the corresponding acid chloride, and this was followed by a Friedel–Crafts acylation with 1,4-bis(trimethylsilyl)butadiyne. This produced ketone **8**, which was quickly carried on without further purification to the dibromoolefination reaction. This gave dibromoolefin **9** as an off-white solid in 33% yield over the three steps from **4**. In the ^{13}C NMR spectrum of **9**, the ^{13}C label assigns the Cβ resonance at 129.9 ppm, and Cα appears at 102.6 ppm, based on $^{1}J = 91$ Hz coupling (Cα↔Cβ). Subsequent Fritsch–Buttenberg–Wiechell rearrangement of **9** results in triynes **10a**,**b** as an approximate 1:1 mixture of isotopomers.

The ^{13}C chemical shifts of the alkyne carbons of triynes **10a**,**b** can be assigned using an analysis similar to that employed for **7a**,**b**. The *ipso* carbon, C*i*, of **10a**,**b** is observed as two doublets centered at 120.8 ppm, with $^{1}J = 92$ Hz (C*i*↔C1) and $^{2}J = 14$ Hz (C*i*↔C2). The common coupling constant observed for C1↔C*i* ($^{1}J = 93$ Hz) sets C1 as 76.9 ppm. The C1 resonance also shows a doublet with observed $^{1}J = 197$ Hz, as a result of C1↔C2 coupling, revealing the chemical shift of C2 as 74.3 ppm. The C2 signal shows a second doublet with $^{1}J = 163$ Hz, due to one-bond C2↔C3 coupling, which assigns the resonance at 61.5 ppm (observed $^{1}J = 163$ Hz) as C3. While C4 can be identified by the two doublets centered at 66.8 ppm ($J = 21$ Hz and $J = 16$ Hz), it is not possible to distinguish C5 and C6.

Finally, removal of the silyl group and homocoupling under Hay[20] conditions converted **10a**,**b** into a mixture of hexayne isotopomers **Ph[6]a**–**c** in excellent yield. In the ^{13}C NMR spectrum of **Ph[6]a**–**c**, C*i* is observed at 120.1 ppm, again coupling to both labeled C1 ($^{1}J = 91$ Hz) and C2 ($^{2}J = 14$ Hz). Carbon C1 appears at 77.5 ppm, as one of the two enhanced signals and is identified by an HMBC correlation to H_A.[16] The other labeled carbon, C2, is observed at 74.3 ppm, showing one-bond coupling constants of 198 Hz and 165 Hz to C1 and C3, respectively.[21] This then sets the resonance of C3 at 62.5 ppm because of coupling to C2 ($^{1}J = 165$ Hz). The resonance at 67.2 ppm is observed as a doublet with $^{2}J = 19$ Hz, consistent with that expected for C4 due to C4↔C2 coupling. The signal at 63.6 ppm shows a weak coupling constant ($J = 5$ Hz), suggesting assignment as C5, and this leaves the last resonance, a slightly broadened singlet at 64.6 ppm, assignable as the central carbon C6.



Scheme 3 Synthesis of ^{13}C-labeled tetraynes **Ph[6]a**–**c**

Table 1 Summary of the Chemical Shifts for **Ph[1]**–**Ph[8]**

Ph[*n*]	Chemical shift (ppm, in $CDCl_3$)[a]							
	C1	C2	C3	C4	C5	C6	C7	C8
Ph[1]	89.4	–	–	–	–	–	–	–
Ph[2]	81.6	73.9	–	–	–	–	–	–
Ph[3]	78.5	74.4	66.4	–	–	–	–	–
Ph[4]	77.7	74.5	63.7	67.2	–	–	–	–
Ph[5]	77.5	*74.4*	*62.8*	*67.3*	*64.5*	–	–	–
Ph[6]	77.5	74.3	62.5	67.2	63.6	64.6	–	–
Ph[8]	77.6	*74.3*	*62.6*	*67.2*	*63.3*	*64.5*	*63.4*	*63.6*

[a] Values in italic font are tentative assignments. The value C*n* for each **Ph[*n*]** used in Figure 3 is highlighted in gray.

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In all cases for the **Ph[*n*]** polyynes, HMBC experiments[16] help to identify carbon C1 due to the correlation between C1 and H_A of the phenyl ring.[22,23] Combined with the labeling studies above, it can be seen that the chemical shift of C1 shows the most dramatic shift as a function of length, from 89.4 ppm in diphenylacetylene **Ph[1]** to 77.6 ppm for **Ph[8]** (Figure 1, Table 1).[24] The chemical shift of carbon C2, on the other hand, shows virtually no change as a function of polyyne length, appearing at circa 74.3 ppm in all cases except for **Ph[2]**. The signal for C3 appears at 66.4 ppm for **Ph[3]**, and then shifts steadily upfield to 63.7 ppm (**Ph[4]**) and 62.8 ppm (**Ph[5]**), and holds constant at approximately 62.5 ppm for **Ph[6]** and **Ph[8]**. Conversely, the C4 resonance appears consistently at 67.3–67.2 ppm.

Unambiguous assignment of the resonances for polyyne **Ph[8]** has not been possible, so the trends for C7–C8 are speculative, but a general alternating pattern seems quite clear. Thus, each additional acetylene unit brings two new resonances, and the new 'odd' carbon resonance appears slightly upfield from the accompanying 'even' resonance, such as for **Ph[6]**, where the C5 and C6 signals are found at 63.6 and 64.6 ppm, respectively. Continuation of this trend then places the C7 and C8 signals of **Ph[8]** at 63.4 and 63.6 ppm, respectively, and suggests that for longer **Ph[*n*]** derivatives, the NMR chemical shift values should coalesce between 63.4–63.6 ppm, providing an estimate of the chemical shift of the carbyne.

The chemical shifts of acetylenic carbons in the diphenylpolyyne series **Ph[*n*]** can be compared with the series endcapped with triisopropylsilyl groups **TIPS[*n*]**, the spectra of which have been reported previously (Figure 2).[9] Similar to the **Ph[*n*]** polyynes, the resonance of the terminal carbon of the polyyne chain, C1, is also the most influenced by the polyyne length in the **TIPS[*n*]** series, and C1 shifts from 82.2 ppm for **TIPS[2]** to 88.8 ppm for **TIPS[10]**.[25]

The most striking difference between the two series **Ph[*n*]** and **TIPS[*n*]** is the apparent reversal of polarization of the carbon chain, as evidenced by the relative positions of C1 and C2 in the **TIPS[*n*]** polyynes in comparison to those in **Ph[*n*]**. More specifically, within the **Ph[*n*]** series, the C1 resonance is the most downfield, followed by the resonance of C2, which appears consistently at approximately 74 ppm. For the **TIPS[*n*]** polyynes, however, the C2 resonance occurs farthest downfield at approximately 90 ppm, followed by C1. It is notable that the C3 and C4 resonances are also reversed for **TIPS[*n*]** versus **Ph[*n*]**, that is, for the **Ph[*n*]** polyynes the C3 resonance appears upfield relative to C4, while conversely for **TIPS[*n*]**, C4 is found upfield from C3.

An interesting trend is observed in the series **Ph[*n*]** for the chemical shift of carbon C*n*, that is, the signal of the central-most carbon in the polyyne. As can be seen in Figure 3, there is a consistent decrease in chemical shift of C*n* as a function of length. On closer inspection, it is also clear that the chemical shift values for C*n* oscillates along a mean curve, with shifts of C*n* for odd *n* (*n* = 3 and 5) that clearly fall below the trend established by the values for C*n* with even *n* (*n* = 2, 4, 6 and 8). It is interesting to con-

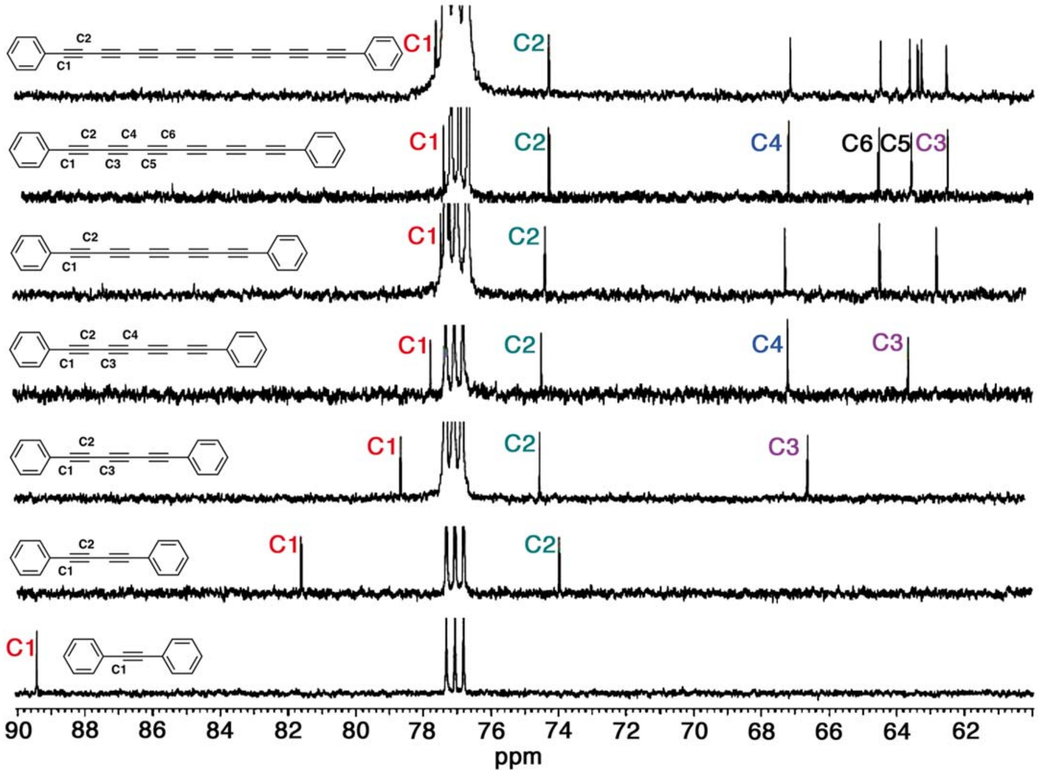

Figure 1 ^{13}C NMR spectra of polyynes **Ph[*n*]** with unambiguous assignments shown when possible ($CDCl_3$)[24]

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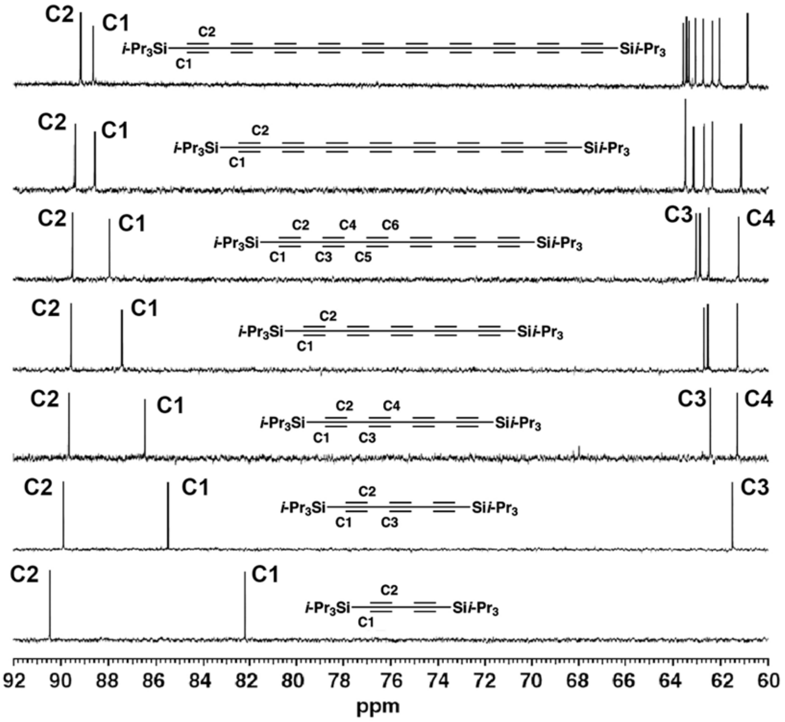

Figure 2 ^{13}C NMR spectra of polyynes **TIPS[*n*]** with unambiguous assignments shown when possible (CD_2Cl_2), from the literature[9]

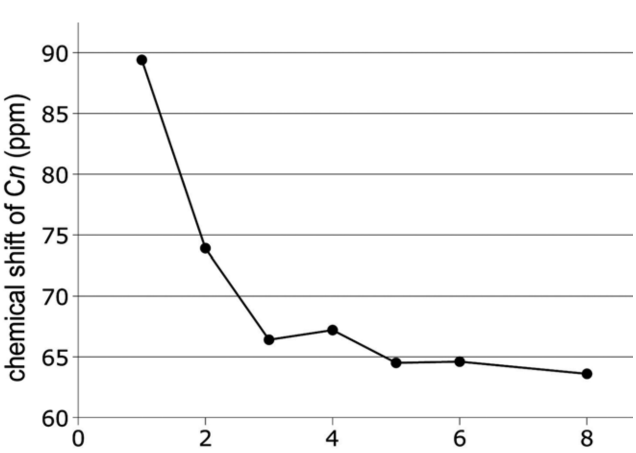

Figure 3 Plot of chemical shift of C*n* versus *n* for **Ph[*n*]**, where *n* is the number of acetylene units (see Table 1 for values and Figure 1 for numbering scheme)

sider if this trend is somehow linked to Hückel aromaticity in polyynes, as suggested by Chauvin and co-workers,[26] but this prospect awaits further study.

Similar to that of the **Ph[*n*]** series, for the **TIPS[*n*]** polyynes there seems to be a consistent appearance of new signals in the narrow range of circa 62–63 ppm suggesting convergence of the chemical shift values within this range. The estimates for both **Ph[*n*]** and **TIPS[*n*]** are in line with those suggested earlier for other polyynes, such as those end-capped with platinum,[27] dendrimers,[28] and adamantyl groups.[29] They are, however, slightly lower than the chemical shift of 63.7 ppm, as suggested from analysis of the longest series of polyynes reported to date, the **Tr*[*n*]** series (Figure 4).[30]

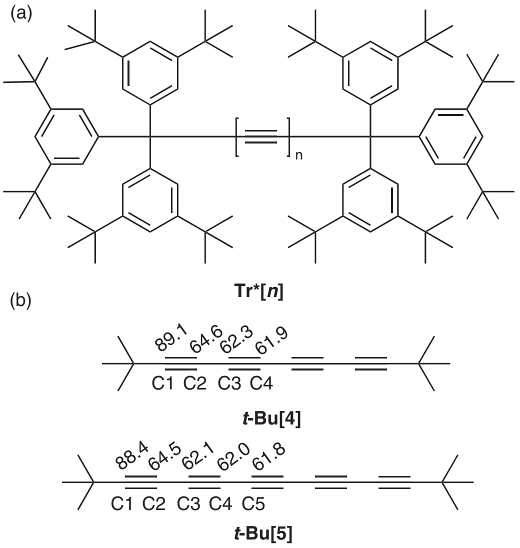

Figure 4 (a) Chemical structure of 'super-trityl' polyynes from reference 30, and (b) chemical shifts in ppm for the *tert*-butyl polyynes from the literature[10]

One final observation requires explanation. Members of both the **Ph[*n*]** and **TIPS[*n*]** series appear to show an alternating upfield–downfield pattern for the two resonances of each new acetylene added to the chain, as mentioned above. For example, excluding C1 and C2, **Ph[6]** shows a

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sequence of C4→C6→C5→C3 from high-to-low chemical shift values. The **TIPS[*n*]** series also appears to show a similar trend for C3→C5/C6→C4, although not definitive because the shifts of C5 and C6 are not known. Conversely, the chemical shifts reported for *tert*-butyl end-capped polyynes show a consistent trend to lower chemical shift values such as the resonances for ***t*-Bu[5]**, C1→C2→C3→C4→C5 (Figure 4), based on labeling studies by Bohlmann and Brehm.[10] While no labeling studies have been performed, a similar trend is suggested for the parent polyyne series, H–(C≡C)$_n$–H based on coupling constants.[31] To date, the origin of this difference remains unknown.

In conclusion, phenyl end-capped polyynes have been synthesized with incorporation of ^{13}C label(s) in the acetylenic framework. Using NMR spectroscopic techniques, the chemical shifts of individual carbons are identified, typically through ^{13}C–^{13}C coupling patterns and constants. Chemical shift trends for **Ph[*n*]** polyynes show that the pattern of resonances is similar to those for **TIPS[*n*]** polyynes, although the polarization of the polyyne chain appears to be opposite. The chemical shift trend for **Ph[*n*]** polyynes is, however, quite different than those proposed for **H[*n*]** and ***t*-Bu[*n*]** polyynes, which show a consistent trend in values from higher-to-lower chemical shift moving from the terminal carbon of the polyyne (C1) toward the center of the chain C*n*.

Reagent grade reactants and solvents were used without further purification. All reactions were performed using standard dry glassware under an inert atmosphere of N_2 unless otherwise noted Anhydrous $MgSO_4$ was used as the drying agent after aqueous work-up. Thin-layer chromatography (TLC) was performed on aluminum sheets coated with silica gel F_{254} (Whatman); visualization was achieved with UV light or by $KMnO_4$ staining. Column chromatography was performed on silica gel-60 (230–400 mesh) obtained from General Intermediates of Canada. Evaporation and concentration in vacuo was performed at H_2O-aspirator pressure. ^{13}C NMR spectra were obtained using Varian Gemini 400 or 500 instruments, at r.t. in $CDCl_3$; residual solvent peaks (δ = 7.24 ppm for ^{1}H and δ = 77.0 ppm for ^{13}C) were used as references. The asterisk (*) refers to ^{13}C-labeled carbons.

^{13}C-Labeled [3-(Dibromomethylene)penta-1,4-diyne-1,5-diyl]dibenzene (2)

CBr_4 (541 mg, 1.63 mmol), $^{13}CBr_4$ (109 mg, 0.315 mmol) and Ph_3P (1.02 g, 3.91 mmol) were added to CH_2Cl_2 (10 mL) at 0 °C and the resulting soln stirred for ca. 10 min until the mixture turned bright orange. Ketone **1** (187 mg, 0.814 mmol),[12] dissolved in CH_2Cl_2 (ca. 3 mL), was added in one portion. The mixture was allowed to warm to r.t. and the progress of the reaction was monitored by TLC analysis until the ketone was no longer observed (ca. 3 h). When the reaction was complete, the solvent was reduced to ca. 5 mL, hexanes (50 mL) was added, the non-homogeneous mixture filtered through a plug of Celite layered on top of silica gel, and the resulting filtrate concentrated in vacuo. Column chromatography (silica gel, hexanes) gave compound **2** (187 mg, 79%) as a colorless solid. Spectral data were consistent with those published for the unlabeled analogue.[12b]

^{13}C NMR (100 MHz, $CDCl_3$): δ = 131.6, 129.1, 128.3, 122.0, 114.1 (s and d, ^1J = 97 Hz, Cβ), 107.6 (s and d, ^1J = 94 Hz, Cα*), 95.7, 85.9.

^{13}C-Labeled 1,6-Diphenylhexa-1,3,5-triyne (Ph[3])

Dibromoolefin **2** (244 mg, 0.633 mmol) was dissolved in a mixture of anhyd toluene (4 mL) and anhyd hexanes (4 mL), and the soln cooled to –78 °C. *n*-BuLi (2.5 M in hexanes, 1.7 mL, 0.68 mmol) was added dropwise. The mixture was stirred at –78 °C for 30 min, and then warmed to r.t. for 30 min. Et_2O (10 mL) and sat. aq NH_4Cl soln (10 mL) were added. The organic phase was separated, washed with brine (2 × 10 mL), and dried over $MgSO_4$. Solvent removal and purification by column chromatography (silica gel, hexanes) afforded **Ph[3]** (89 mg, 62%) as a colorless solid. Spectral data were consistent with those published for the unlabeled analogue.[3b]

^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.9, 129.6, 128.4, 120.9, 78.5 (s and d, ^2J = 18 Hz, C1), 74.4 (s and d, ^1J = 164 Hz, and d, ^2J = 20 Hz, C2), 66.4 (s and d, ^1J = 163 Hz, C3*).

^{13}C-Labeled (4,4-Dibromo-3-phenylbut-3-en-1-yn-1-yl)trimethylsilane (6)

Dibromoolefin **6** was prepared using the procedure described in the literature.[18]

^{13}C-Labeled Trimethyl(phenylbuta-1,3-diyn-1-yl)silanes (7a) and (7b)

Dibromoolefin **6** (126 mg, 0.352 mmol) was dissolved in anhyd hexanes (8 mL), the resulting soln cooled to –78 °C and *n*-BuLi (2.5 M in hexanes, 0.16 mL, 0.40 mmol) added dropwise. The mixture was stirred at –78 °C for 30 min, and then warmed to r.t. for 30 min. Et_2O (10 mL) and sat. aq NH_4Cl soln (10 mL) were added. The organic phase was separated, washed with brine (2 × 10 mL), and dried over $MgSO_4$. Solvent removal and purification by column chromatography (silica gel, hexanes) afforded a ca. 1:1 mixture of diyne isotopomers **7a** and **7b** (54.1 mg, 78%) as a yellow oil. Spectral data were consistent with those published in reference 18.

^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.7 (d, J = 2 Hz), 129.3, 128.4 (s and d, J = 6 Hz), 121.4 (d, ^1J = 92 Hz and d, ^2J = 14 Hz, C*i*), 90.6 (d, ^2J = 14 Hz, C4), 87.8 (d, ^1J = 148 Hz and d, ^2J = 18 Hz, C3), 76.7 (d, ^1J = 196 Hz and d, ^1J = 92 Hz, C1*), 74.2 (d, ^1J = 203 Hz and d, ^1J = 141 Hz, C2*), –0.4.

^{13}C-Labeled 1,8-Diphenylocta-1,3,5,7-tetraynes (Ph[4]a–c)

A mixture of diynes **7a**,**b** (54.1 mg, 0.279 mmol) was dissolved in wet THF–MeOH (3 mL, 1:1), K_2CO_3 (50 mg, 0.36 mmol) was added, and the resulting soln stirred at r.t. until TLC analysis indicated complete conversion into the desilylated intermediate. Et_2O (10 mL) was added, and the resulting soln washed with sat. aq NH_4Cl soln (2 × 10 mL) and brine (2 × 10 mL), and then dried over $MgSO_4$. The soln was reduced to ca. 1 mL and added to a soln of the Hay catalyst [CuCl (50 mg, 0.50 mmol) and TMEDA (0.1 mL) in CH_2Cl_2 (5 mL), previously stirred until homogeneous] and a stream of O_2 was bubbled into the reaction mixture until the soln turned blue. This mixture was stirred at r.t. under O_2 until TLC analysis no longer showed the presence of the starting diynes (ca. 3 h). Et_2O (30 mL) and sat. aq NH_4Cl soln (2 × 20 mL) were added. The organic layer was separated, dried over $MgSO_4$, and the solvent removed. Column chromatography (silica gel, hexanes) afforded **Ph[4]a–c** (35 mg, 100%) as a light-yellow crystalline solid. Spectral data were consistent with those published for the unlabeled analogue.[32]

^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ = 133.3 (s and d, J = 2 Hz), 130.0, 128.6 (s and d, J = 6 Hz), 120.6 (d, ^1J = 91 Hz and d, ^2J = 14 Hz, C*i*), 77.7 (d, ^1J = 207 Hz, C1*; other couplings were obscured by $CDCl_3$ signals), 74.5 (d, ^1J = 198 Hz and d, ^1J = 164 Hz, C2*), 67.2 (m, C4), 63.7 (pseudo d, ^1J = 167 Hz and d, J = 14 Hz, C3).

^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$, irradiation at C1, 77.7 ppm): δ = 133.1, 129.9, 128.5, 120.4 (s and d, ^2J = 13 Hz, C*i*), 74.4 (C2*), 67.0 (m, C4), 63.5 (s and pseudo d, ^1J = 158 Hz, C3).

^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$, irradiation at C2, 74.5 ppm): δ = 133.1, 129.9, 128.5 (s and d, J = 6 Hz), 120.4 (s and d, ^1J = 86 Hz, C*i*), 77.8 (C1), 67.0 (m, C4), 63.5 (m, C3).

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^{13}C-Labeled (6,6-Dibromo-5-phenylhexa-5-en-1,3-diyn-1-yl)trimethylsilane (9)

^{13}C(1)-benzoic acid (**4**) (184 mg, 1.49 mmol) was dissolved in CH_2Cl_2 (1 mL) and $SOCl_2$ (49 mg, 4.1 mmol) was added. The mixture was stirred overnight and the excess $SOCl_2$ was removed in vacuo to yield the corresponding acid chloride, which was used directly in the next step. The acid chloride was dissolved in anhyd CH_2Cl_2 (15 mL), 1,4-bis(trimethylsilyl)buta-1,3-diyne (290 mg, 1.49 mmol) added, and the temperature of the soln lowered to –20 °C. $AlCl_3$ (239 mg, 1.79 mmol) was added portion-wise, and the mixture warmed to r.t. over 3 h. The reaction was carefully quenched by addition of the reaction soln to a mixture of 10% HCl (50 mL) and ice (50 mL). **CAUTION:** exothermic. Et_2O (70 mL) was added and the organic layer was separated, washed with sat. aq $NaHCO_3$ soln (2 × 20 mL) and brine (2 × 20 mL), dried over $MgSO_4$, and the resulting soln reduced to ca. 5 mL to afford the intermediate ketone **8** (R_f = 0.2, hexanes–CH_2Cl_2, 6:1) that was carried on without further purification. CBr_4 (744 mg, 2.24 mmol) and Ph_3P (1.17 mg, 4.47 mmol) were added to CH_2Cl_2 (14 mL) at 0 °C and the soln stirred for ca. 10 min until the mixture turned bright orange. Ketone **8**, dissolved in CH_2Cl_2 (ca. 3 mL), was added in one portion. The mixture was allowed to warm to r.t. and the progress of the reaction monitored by TLC analysis until the ketone was no longer observed (ca. 3 h). When the reaction was complete, the solvent was reduced to ca. 5 mL, hexanes (50 mL) was added, and the non-homogeneous mixture filtered through a plug of Celite layered on top of silica gel. The resulting filtrate was concentrated in vacuo. Column chromatography (silica gel, hexanes) gave dibromoolefin **9** (190 mg, 33%) as an off-white solid. Spectral data were consistent with those published for the unlabeled analogue.[3d]

^{13}C NMR (100 MHz, $CDCl_3$): δ = 137.1 (d, ^1J = 58 Hz, C*i*), 129.9 (d, ^1J = 97 Hz, d, ^1J = 91 Hz, and d, ^1J = 58 Hz, Cβ*), 128.7, 128.42, 128.38, 102.6 (d, ^1J = 91 Hz, Cα), 95.3 (C4), 87.2 (d, *J* = 4 Hz, C3), 82.0 (d, ^2J = 13 Hz, C2), 74.8 (d, ^1J = 97 Hz, C1), –0.7.

^{13}C-Labeled Trimethyl(phenylhexa-1,3,5-triyn-1-yl)silanes (10a) and (10b)

Dibromoolefin **9** (190 mg, 0.498 mmol) was dissolved in anhyd hexanes (15 mL), the resulting soln cooled to –78 °C and *n*-BuLi (2.5 M in hexanes, 0.24 mL, 0.60 mmol) added dropwise. The mixture was stirred at –78 °C for 30 min, and then warmed to r.t. for 30 min. Et_2O (10 mL) and sat. aq NH_4Cl soln (10 mL) were added. The organic phase was separated, washed with brine (2 × 10 mL), and dried over $MgSO_4$. Solvent removal and purification by column chromatography (silica gel, hexanes) afforded a ca. 1:1 mixture of triyne isotopomers **10a** and **10b** (86.7 mg, 78%) as a yellow oil. Spectral data were consistent with those published for the unlabeled analogue.[15b]

^{13}C NMR (100 MHz, $CDCl_3$): δ = 133.1 (d, *J* = 2 Hz) 129.8, 128.5 (s and d, *J* = 6 Hz), 120.8 (d, ^1J = 92 Hz and d, ^2J = 14 Hz, C*i*), 89.0 (d, *J* = 5 Hz and d, *J* = 3 Hz), 88.1 (d, *J* = 6 Hz and d, *J* = 3 Hz), 76.9 (d, ^1J = 197 Hz and d, ^1J = 93 Hz, C1*), 74.3 (d, ^1J = 197 Hz and d, ^1J = 163 Hz, C2*), 66.8 (d, ^2J = 21 Hz and d, *J* = 16 Hz, C4), 61.5 (d, ^1J = 163 Hz and d, ^2J = 19 Hz, C3), –0.5.

^{13}C-Labeled 1,12-Diphenyldodeca-1,3,5,7,9,11-hexaynes (Ph[6]a–c)

A mixture of triynes **10a**,**b** (8.6 mg, 0.387 mmol) was dissolved in wet THF–MeOH (3 mL, 1:1), K_2CO_3 (8 mg, 0.06 mmol) was added, and the resulting soln stirred at r.t. until TLC analysis indicated complete conversion into the desilylated intermediate. Et_2O (10 mL) was added, and the resulting soln washed with sat. aq NH_4Cl soln (2 × 10 mL) and brine (2 × 10 mL), and then dried over $MgSO_4$. The soln was reduced to ca. 1 mL and added to a soln of the Hay catalyst [CuCl (8 mg, 0.08 mmol) and TMEDA (0.1 mL) in CH_2Cl_2 (3 mL), previously stirred until homogeneous] and a stream of O_2 was bubbled into the reaction mixture until the soln turned blue. This mixture was stirred at r.t. under O_2 until TLC analysis no longer showed the presence of the starting triynes (ca. 3 h). Et_2O (30 mL) and sat. aq NH_4Cl soln (2 × 20 mL) were added. The organic layer was separated, dried over $MgSO_4$, and the solvent removed. Column chromatography (silica gel, hexanes) afforded **Ph[6]a**–**c** (5.0 mg, 87%) as an orange crystalline solid. Spectral data were consistent with those published for the unlabeled analogue.[3d]

^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$): δ = 133.5, 130.3, 128.6, 120.1 (d, ^1J = 91 Hz and d, ^2J = 14 Hz, C*i*), 77.5 (d, ^1J = 196 Hz, C1; other couplings were obscured by $CDCl_3$ signals), 74.3 (^1J = 198 Hz and d, ^1J = 165 Hz, C2), 67.2 (d, ^2J = 19 Hz, C4), 64.6 (C6), 63.6 (d, *J* = 5 Hz, C5), 62.5 (d, ^1J = 165 Hz and d, ^2J = 18 Hz, C3).

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Supporting Information for this article is available online at http://www.thieme-connect.com/ejournals/toc/synthesis.

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(23) For **Ph[2]**, the assignment of C1 and C2 is confirmed by ^{13}C labeling studies of Ph–C1≡C2–C3≡C4–C_6H_4Me, which shows acetylenic resonances at 81.2, 74.1, 73.3, and 81.9 ppm for C1–C4, respectively, see: Mabry, J.; Johnson, R. P. *J. Am. Chem. Soc.* **2002**, *124*, 6497.
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(25) The resonance for the two degenerate acetylenic carbons of **Ph[1]** ($\delta = 89.4$) and **TIPS[1]** ($\delta = 112.5$, see Supporting Information for spectrum) shows the most dramatic chemical shift deviation from the trend within each series, which presumably results from the influence of the end-capping groups. The position of this resonance relative to others in the series suggests that the distal end-group has a more significant influence on the chemical shift than the proximal group, that is, in the hypothetical case R–C1≡C1′–R′, the chemical shift of C1 is influenced mainly by R′, and reciprocally C1′ by R. We thank a reviewer for pointing out this observation.
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