

Can the $\text{Ti}(\text{OiPr})_4/n\text{BuLi}$ Combination of Reagents Function as a Catalyst for [2+2+2] Alkyne Cyclotrimerisation Reactions?

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Dedicated to Prof. Janusz Zakrzewski of the University of Łódź, Poland, on the occasion of his 70th birthday.

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I. General information

Titanium(IV) isopropoxide was purchased from Sigma Aldrich, distilled under reduced pressure (≈ 70 °C at 2 mbar) and stored under argon for several months. *n*-butyllithium (2.5 M solution in hexanes) and isopropylmagnesium chloride (2.0 M solution in THF) were purchased from Sigma-Aldrich or Acros Organics and titrated once a month according to literature methods.^{1,2} Tetrahydrofuran (THF) was purified using a MB SPS-800 solvent purification system (MBRAUN). Petroleum ether (40–60 °C fraction) was distilled at 450 mbar before use. Other solvents and commercial reagents were used as received. The microwave-promoted experiments were run using a CEM Discover Microwave Synthesis System or an Anton Paar Monowave 300 Microwave Synthesis Reactor, with the temperature and time parameters indicated. For other reactions, the temperatures mentioned are the temperatures of the cold baths or the oil baths used. For all experiments, the glassware, septa, syringes and needles were dried in a desiccator under vacuum in the presence of CaCl₂ and silica gel with moisture indicator. The reaction vessels were further dried with a heat gun under a stream of argon. Flash column chromatography was performed on VWR Chemicals silica gel 60 (40–63 μm). Concentration under reduced pressure was carried out using rotary evaporators at 40 °C. NMR spectra were recorded with an AVANCE 400 Bruker spectrometer (¹H at 400.2 MHz, ¹³C at 100.6 MHz) or an AVANCE II 300 Bruker spectrometer (¹⁹F at 282.4 MHz). Chemical shifts δ are given in ppm, referenced to the peak of tetramethylsilane, defined at $\delta = 0.00$ (¹H NMR), or the solvent peak of CDCl₃, defined at $\delta = 77.0$ (¹³C NMR), or the peak of fluorobenzene used as an internal standard, defined at $\delta = -113.15$ (¹⁹F NMR). Multiplicities are abbreviated as follows: s (singlet), d (doublet), t (triplet), q (quartet), quint (quintet), m (multiplet), br (broad). Coupling constants *J* are given in Hz and are rounded to the closest multiple of 0.5. Melting points were determined using a Stuart SMP40 apparatus. Mass spectra were recorded using a JEOL GC-mate II (high-resolution EI) spectrometer.

1– H.-S. Lin, L. A. Paquette, *Synth. Comm.* **1994**, *24*, 2503–2506.

2– W. G. Kofron, L. M. Baclawski, *J. Org. Chem.* **1976**, *41*, 1879–1880.

II. General procedures

General procedure G1: Alkyne cyclotrimerisation reaction using $\text{Ti}(\text{O}i\text{Pr})_4/n\text{BuLi}$ in 2 : 3 ratio (in the case of liquid alkyne substrates).

$n\text{BuLi}$ (≈ 2.0 M solution in hexanes, 0.900 equiv, 2.70 mmol) was added dropwise, over 1 min, into a solution of $\text{Ti}(\text{O}i\text{Pr})_4$ (0.600 equiv, 1.80 mmol) in dry THF (4.0 mL), in a flame-dried 10 mL microwave vial, under argon at 0 °C. After 5 min of stirring at 0 °C, the alkyne substrate (1.00 equiv, 3.00 mmol) was then added dropwise. The septum on the vial was quickly replaced with the suitable sealed cap and the vial was immediately heated with the microwave synthesis reactor (100 °C, 15 min).

After cooling, either of the following work-up procedures was performed:

Work-up procedure W1: 2 M HCl aqueous solution (10 mL) was added. The mixture was stirred at r.t. for 15 min, then extracted with Et_2O (3×10 mL). The combined organic phases were dried over MgSO_4 , filtered and concentrated under reduced pressure to afford the crude product.

Work-up procedure W2: H_2O (0.5 mL) was added and the mixture was stirred at r.t. for 30 min, before being filtered through a short pad of sand, MgSO_4 , celite and sand (from bottom to top) (rinsing: Et_2O). The combined organic phases were dried over MgSO_4 , filtered and concentrated under reduced pressure to afford the crude product.

Note: when the conversion of volatile alkyne substrates had to be assessed by NMR, the pressure in the rotary evaporator was kept above 200 mbar (with a bath at 40 °C). More thorough concentration was later performed before purification of the adducts.

General procedure G1s: Alkyne cyclotrimerisation reaction using $\text{Ti}(\text{O}i\text{Pr})_4/n\text{BuLi}$ in 2 : 3 ratio (in the case of solid alkyne substrates).

$n\text{BuLi}$ (≈ 2.0 M solution in hexanes, 0.900 equiv, 2.70 mmol) was added dropwise, over 1 min, into a solution of $\text{Ti}(\text{O}i\text{Pr})_4$ (0.600 equiv, 1.80 mmol) in dry THF (3.5 mL), in a flame-dried 10 mL microwave vial, under argon at 0 °C. A solution of the alkyne substrate (1.00 equiv, 3.00 mmol) in THF (0.5 mL) was then added dropwise. The septum on the vial was quickly replaced with the suitable sealed cap and the vial was immediately heated with the microwave synthesis reactor (100 °C, 15 min).

After cooling, **work-up procedure W1** or **W2** was applied.

General procedure G2: Alkyne cyclotrimerisation reaction using $\text{Ti}(\text{O}i\text{Pr})_4/n\text{BuLi}$ in 1 : 2 ratio (in the case of liquid alkyne substrates).

$n\text{BuLi}$ (≈ 2.0 M solution in hexanes, 0.600 equiv, 1.80 mmol) was added dropwise, over 1 min, into a solution of $\text{Ti}(\text{O}i\text{Pr})_4$ (0.300 equiv, 900 μmol) in dry THF (4.0 mL), in a flame-dried 10 mL microwave vial, under argon at 0 °C. After 5 min of stirring at 0 °C, the alkyne substrate (1.00 equiv, 3.00 mmol) was then added dropwise. The septum on the vial was quickly replaced with the suitable sealed cap and the vial was immediately heated with the microwave synthesis reactor (100 °C, 15 min).

After cooling, **work-up procedure W1** or **W2** was applied.

General procedure G2s: Alkyne cyclotrimerisation reaction using $\text{Ti}(\text{O}i\text{Pr})_4/n\text{BuLi}$ in 1 : 2 ratio (in the case of solid alkyne substrates).

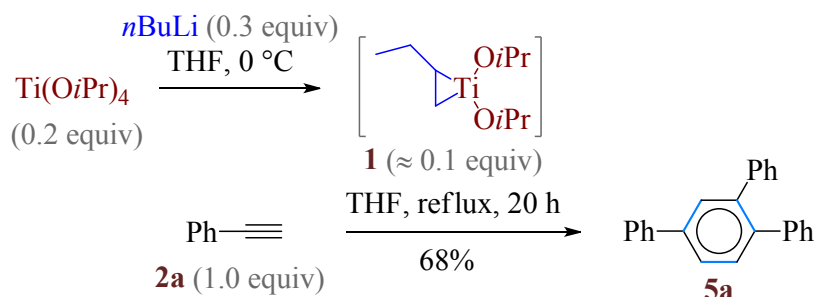
$n\text{BuLi}$ (≈ 2.0 M solution in hexanes, 0.600 equiv, 1.80 mmol) was added dropwise, over 1 min, into a solution of $\text{Ti}(\text{O}i\text{Pr})_4$ (0.300 equiv, 900 μmol) in dry THF (3.5 mL), in a flame-dried 10 mL microwave vial, under argon at 0 °C. A solution of the alkyne substrate (1.00 equiv, 3.00 mmol) in THF (0.5 mL) was then added dropwise. The septum on the vial was quickly replaced with the suitable sealed cap and the vial was immediately heated with the microwave synthesis reactor (100 °C, 15 min).

After cooling, **work-up procedure W1** or **W2** was applied.

III. Reactions of Table 1, Table 2 and Scheme 3

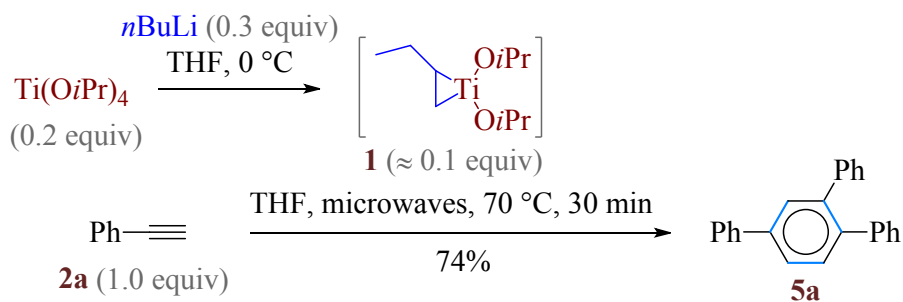
Typical experimental procedures: Table 1, entries 5 and 10; Table 2, entry 3; Scheme 3

a) Catalytic reaction performed at reflux (Table 1, entry 5)



*n*BuLi (2.14 M solution in hexanes, 0.300 equiv, 1.80 mmol, 841 μL) was added dropwise, over 2.5 min, into a solution of Ti(OiPr)_4 (0.200 equiv, 1.20 mmol, 355 μL) in dry THF (8.0 mL), under argon at 0 $^\circ\text{C}$. After 5 min of stirring at 0 $^\circ\text{C}$, the resulting solution was added dropwise, over 2.5 min, into a solution of phenylacetylene **2a** (1.00 equiv, 6.00 mmol, 660 μL) in THF (1.0 mL) at 15 $^\circ\text{C}$. The mixture was then heated at reflux for 20 h. After cooling, work-up **W1** was carried out (on 1.5-fold scale). ^{13}C NMR analysis of the crude product showed full conversion of the starting material and the production of 1,2,4-triphenylbenzene **5a** as the main product. The 1,3,5 isomer **5'a** was not detected. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 10%) afforded pure **5a** (418 mg, 1.36 mmol, 68%).

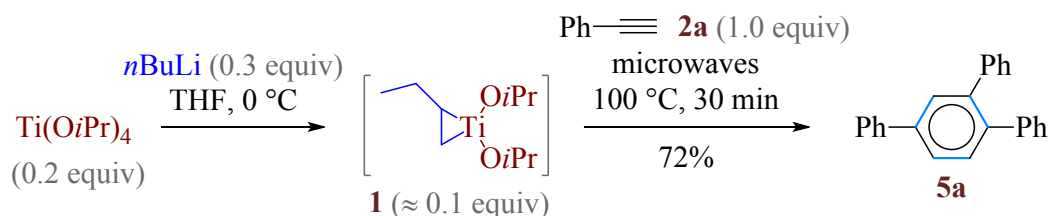
b) Catalytic reaction performed under microwave conditions (Table 1, entry 10)



*n*BuLi (2.27 M solution in hexanes, 0.300 equiv, 900 μmol , 397 μL) was added dropwise, over 1 min, into a solution of Ti(OiPr)_4 (0.200 equiv, 600 μmol , 178 μL) in dry THF (1.5 mL), under argon at 0 $^\circ\text{C}$. After 5 min of stirring at 0 $^\circ\text{C}$, the resulting solution was added dropwise into a solution of phenylacetylene **2a** (1.00 equiv, 3.00 mmol, 330 μL) in THF (3.0 mL) at 0 $^\circ\text{C}$. The total volume of the mixture was measured: $V = 5.4$ mL and part of it ($v = 2.0$ mL) was then introduced into a flame-dried 10 mL microwave vial, under argon at 0 $^\circ\text{C}$. The septum on the vial was quickly replaced with the suitable sealed cap and the vial was immediately heated with the microwave synthesis reactor (70 $^\circ\text{C}$, 30 min). After cooling, work-up **W1** was carried out, on half scale. ^{13}C NMR analysis of the crude product (343 mg) showed the production of 1,2,4-triphenylbenzene **5a** as the main product. The 1,3,5 isomer **5'a** was not detected. To destroy traces of diene **6a**, concentrated H_2SO_4 (0.5 mL) was added dropwise to the crude product at 0 $^\circ\text{C}$. After 20 min of stirring, H_2O (20 mL) was added dropwise at 0 $^\circ\text{C}$ and the mixture was extracted with Et_2O

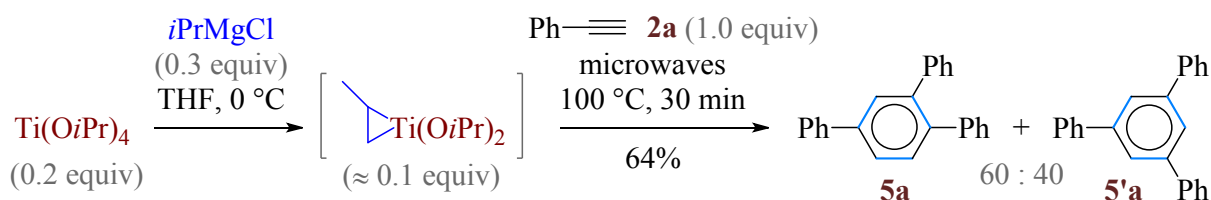
(3 × 10 mL). The combined organic phases were dried over MgSO₄, filtered and concentrated under reduced pressure to afford the crude product (143 mg). Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 2%) afforded pure **5a** (83.8 mg, 273 μmol, *i.e.* 27.3 × *V/v* ≈ 74% yield).

c) Catalytic reaction performed under microwave conditions, with a simplified procedure
(Table 2, entry 3 and Scheme 3, top)



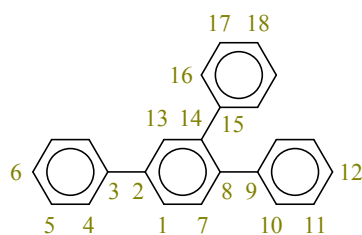
*n*BuLi (2.34 M solution in hexanes, 0.300 equiv, 900 μmol, 385 μL) was added dropwise, over 1 min, into a solution of Ti(OiPr)₄ (0.200 equiv, 600 μmol, 178 μL) in dry THF (4.5 mL), in a flame-dried 10 mL microwave vial, under argon at 0 °C. After 5 min of stirring at 0 °C, phenylacetylene **2a** (1.00 equiv, 3.00 mmol, 330 μL) was added dropwise. The septum on the vial was quickly replaced with the suitable sealed cap and the vial was immediately heated with the microwave synthesis reactor (100 °C, 30 min). After cooling, work-up **W1** was carried out. ¹³C NMR analysis of the crude product showed nearly full conversion of the starting material and the production of 1,2,4-triphenylbenzene **5a** as the main product. The 1,3,5 isomer **5'a** was not detected. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 2%) afforded pure **5a** (222 mg, 725 μmol, 72%).

d) Catalytic reaction performed under microwave conditions, with a simplified procedure using isopropylmagnesium chloride (Scheme 3, bottom)



*i*PrMgCl (1.73 M solution in THF, 0.300 equiv, 900 μmol, 520 μL) was added dropwise, over 1 min, into a solution of Ti(OiPr)₄ (0.200 equiv, 600 μmol, 178 μL) in dry THF (4.5 mL), in a flame-dried 10 mL microwave vial, under argon at 0 °C. After 5 min of stirring at 0 °C, phenylacetylene **2a** (1.00 equiv, 3.00 mmol, 330 μL) was added dropwise. The septum on the vial was quickly replaced with the suitable sealed cap and the vial was immediately heated with the microwave synthesis reactor (100 °C, 30 min). After cooling, work-up **W1** was carried out. ¹³C NMR analysis of the crude product (380 mg, brown sticky oil) showed full conversion of the starting material and the production of 1,2,4- and 1,3,5-triphenylbenzene **5a** and **5'a** in 60 : 40 ratio. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 2%) afforded a 58 : 42 mixture of **5a** and **5'a** (197 mg, 642 μmol, 64%).

1,2,4-Triphenylbenzene **5a**^{3,4}

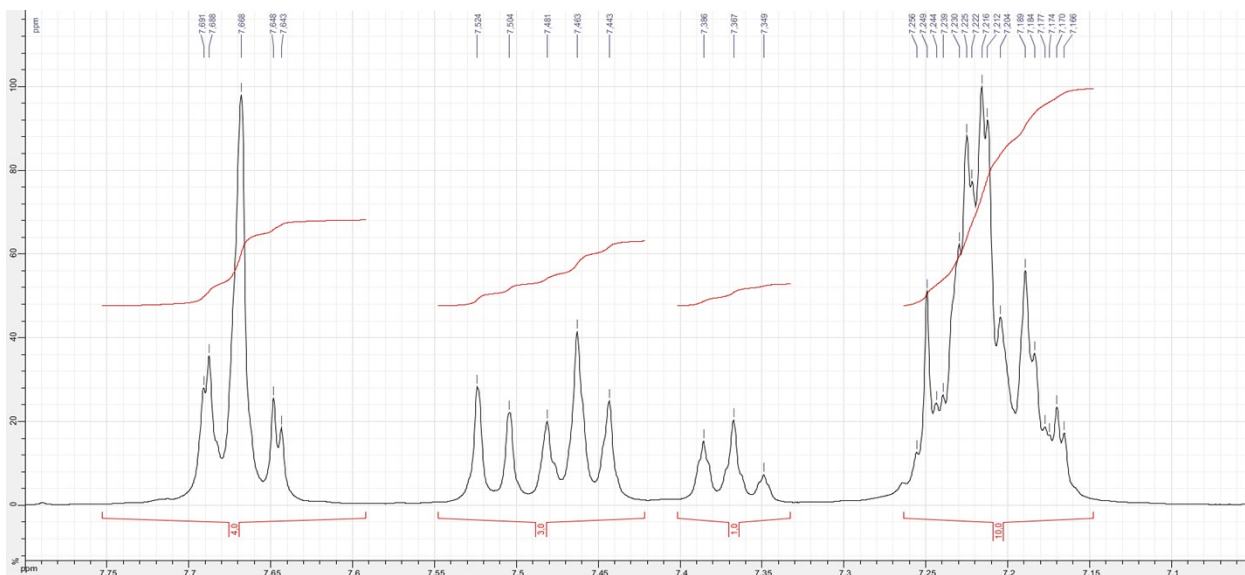


White solid. M.p. 116–118 °C (trituration in MeOH) [lit.⁵ two forms are reported: 99.5–100 °C (EtOH) and 119–120 °C (petroleum ether)]. R_f 0.5 (EtOAc/petroleum ether 2%, UV-active). ¹H NMR (CDCl₃, 400 MHz): δ 7.15–7.27 (10 H, m, H10–12, H16–18), 7.37 (1 H, br t, J 7.5, H6), 7.46 (2 H, br t, J 7.5, H5), 7.51 (1 H, d, J 7.5, H7), 7.63–7.70 (4 H, m, H1, H4, H13). ¹³C NMR (CDCl₃, 100.6 MHz): δ 126.1 (C13), 126.5, 126.6 (C12, C18), 127.1 (C4), 127.4 (C6), 127.88, 127.91 (C10, C16), 128.8 (C5), 129.4 (C1), 129.85, 129.88 (C11, C17), 131.1 (C7), 139.5 (C2), 140.3, 140.5 (C8, C14), 140.9, 141.1, 141.4 (C3, C9, C15). HRMS (EI): m/z 306.1396 (M^{+} C₂₄H₁₈⁺ requires 306.1403).

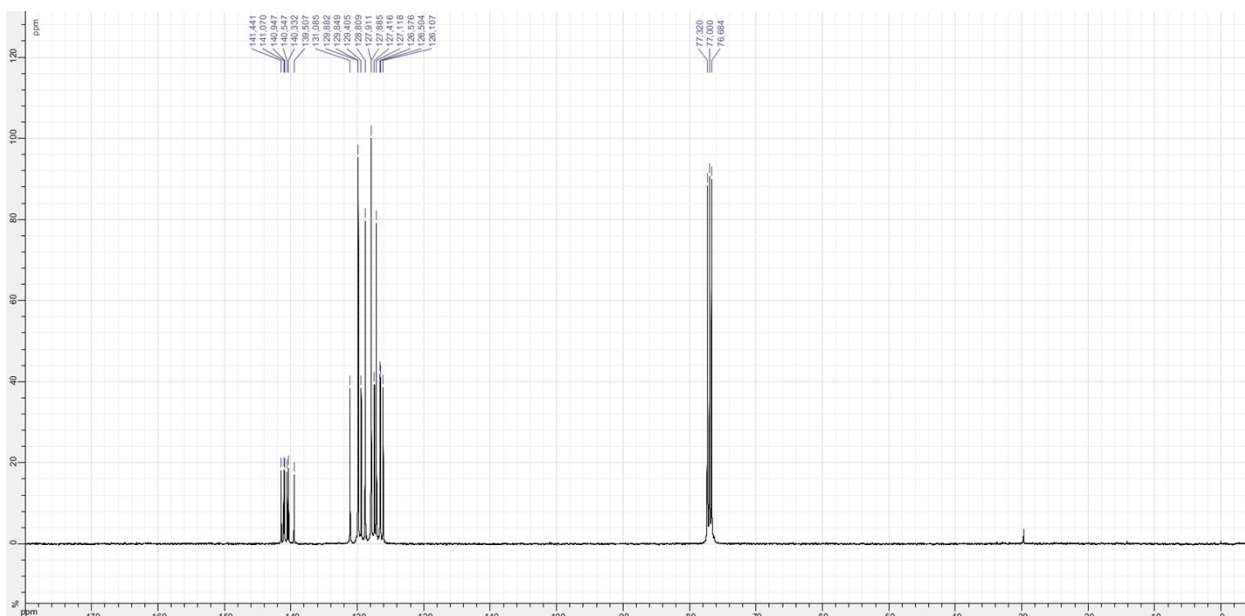


¹H NMR spectrum (CDCl₃, 400 MHz).

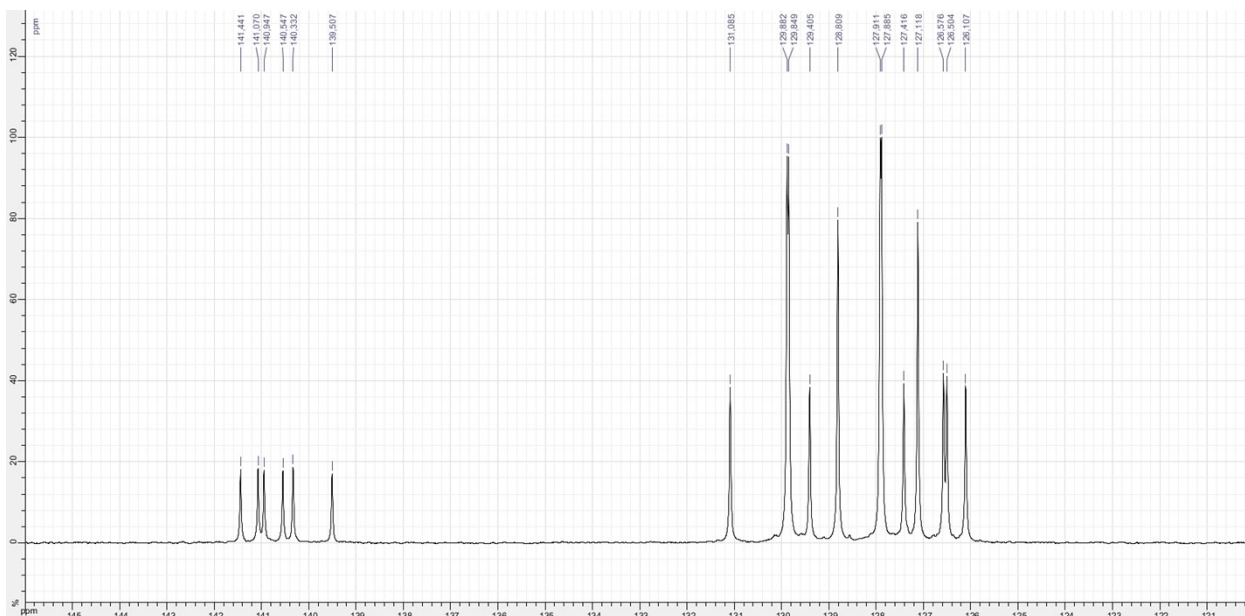
- 3– S. L. Kireev, V. A. Smit, B. I. Ugrak, O. M. Nefedov, *Izv. Akad. Nauk, Ser. Khim.* **1991**, 2565–2571; *Russ. Chem. Bull.* **1991**, 40, 2240–2246.
- 4– V. A. Rassadin, E. Nicolas, Y. Six, *Chem. Commun.* **2014**, 50, 7666–7669.
- 5– W. Herz, E. Lewis, *J. Org. Chem.* **1958**, 23, 1646–1653.



^1H NMR spectrum (selected extract) (CDCl_3 , 400 MHz).

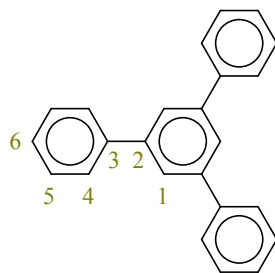


^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).



^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).

1,3,5-Triphenylbenzene **5'a**^{6,7}



R_f 0.5 (EtOAc/petroleum ether 2%, UV-active). ^1H NMR (CDCl_3 , 400 MHz): δ 7.40 (3 H, br t, J 7.5, H6), 7.49 (2 H, br dd, J 8.5, 7.5, H5), 7.71 (6 H, br d, J 8.5, H4), 7.79 (3 H, s, H1). ^{13}C NMR (CDCl_3 , 100.6 MHz): δ 125.2 (C1), 127.3 (C4), 127.5 (C6), 128.8 (C5), 141.1 (C3), 142.3 (C2).

Note: this compound was not obtained in pure form but as a mixture with **5a**.

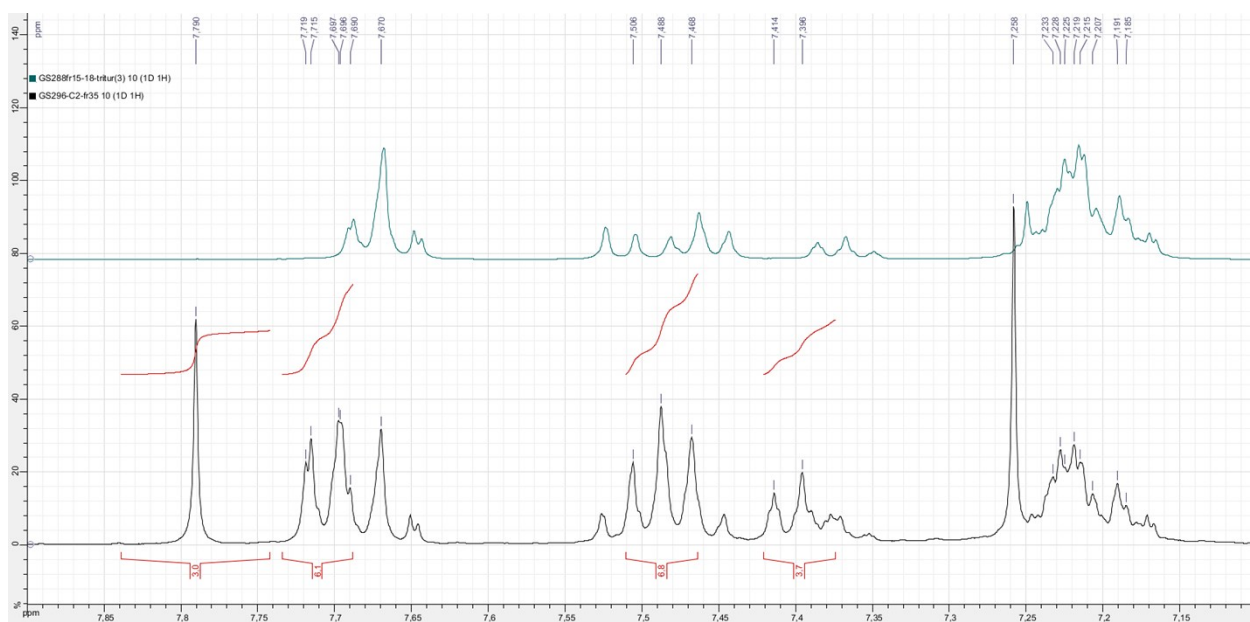


^1H NMR spectrum (CDCl_3 , 400 MHz).

Note: in black (bottom), spectrum of a mixture of **5'a** and **5a**; in green (top), spectrum of **5a** alone.

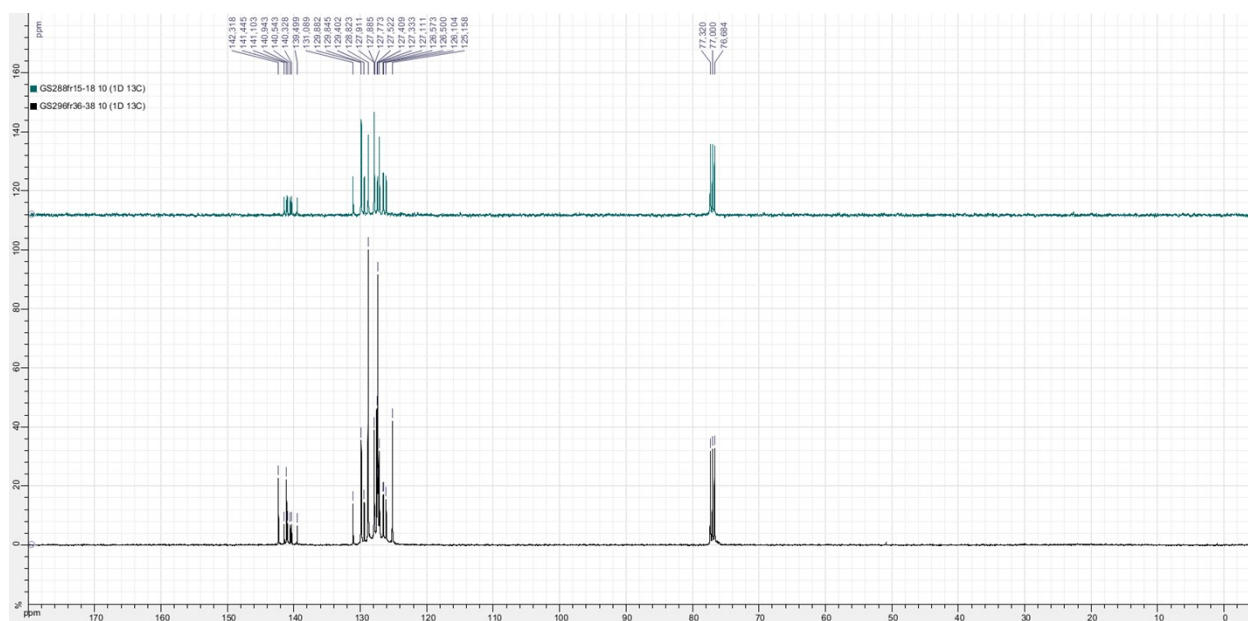
6- A. R. Butler, I. Hussain, *J. Chem. Soc., Perkin Trans. 2* **1980**, 229–231.

7- P. K. Thallapally, K. Chakraborty, H. L. Carrell, S. Kotha, G. R. Desiraju, *Tetrahedron* **2000**, *56*, 6721–6728.



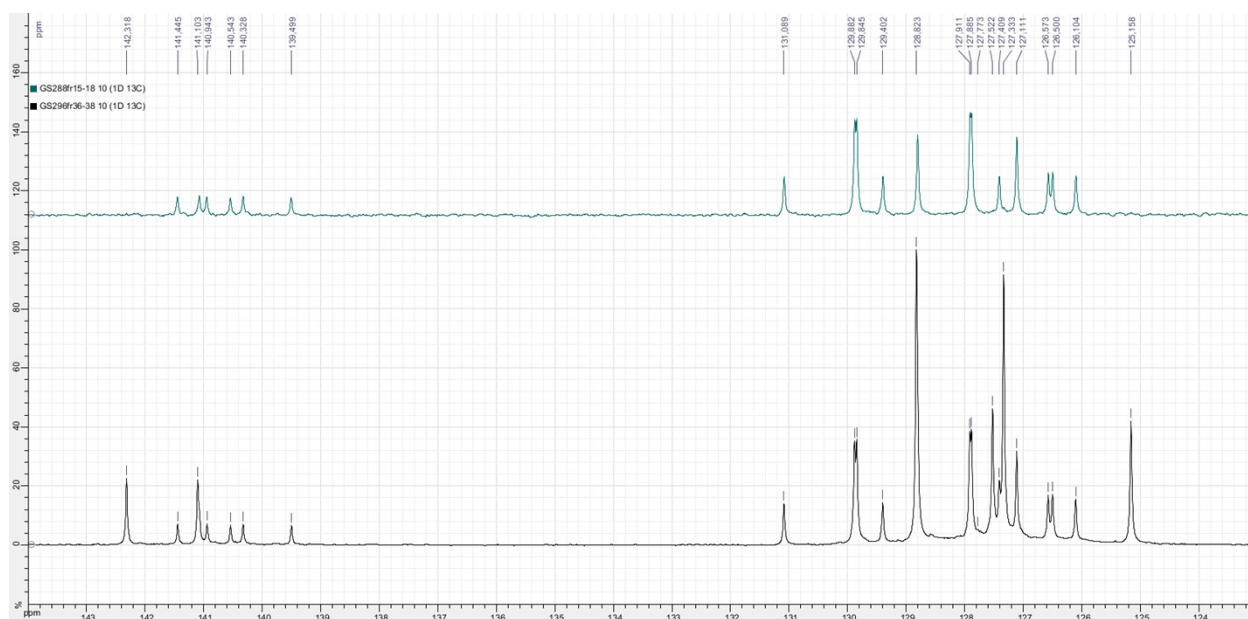
^1H NMR spectrum (selected extract) (CDCl_3 , 400 MHz).

Note: in black (bottom), spectrum of a mixture of **5'a** and **5a**; in green (top), spectrum of **5a** alone.



^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).

Note: this analysis was recorded with a $\approx 60 : 40$ mixture of 1,2,4 and 1,3,5 isomers of triphenylbenzene **5a** and **5'a**. For comparison, a spectrum of pure **5a** is displayed (top, in green).



^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).

Note: this analysis was recorded with a $\approx 60 : 40$ mixture of 1,2,4 and 1,3,5 isomers of triphenylbenzene **5a** and **5'a**. For comparison, a spectrum of pure **5a** is displayed (top, in green).

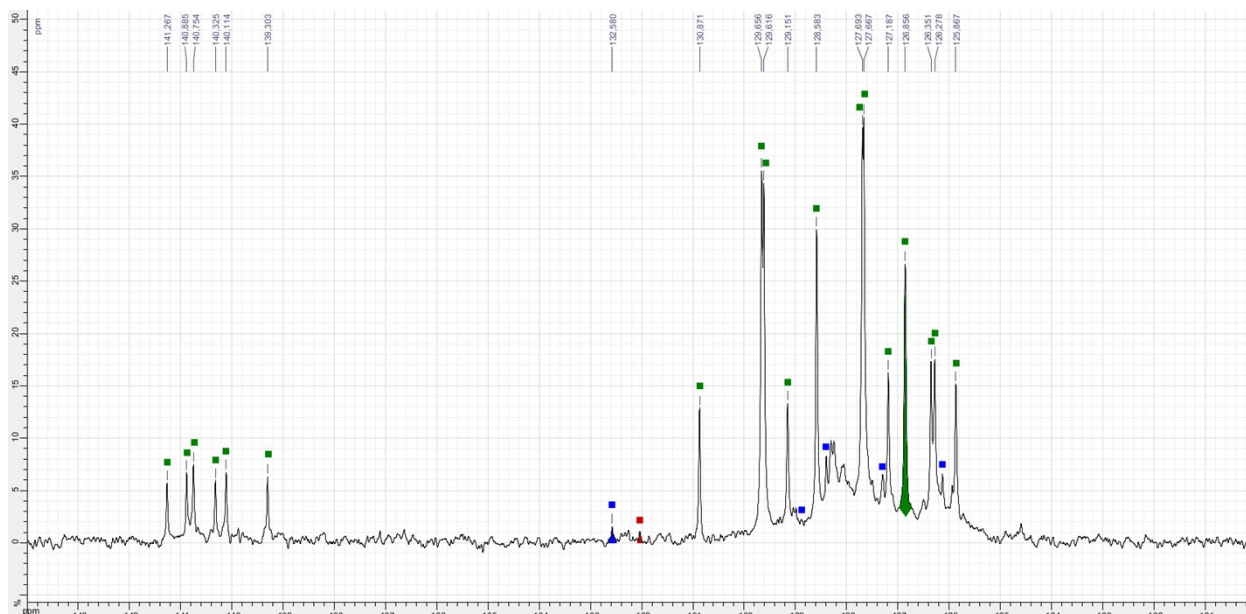
Analysis of the crude products starting from **2a**; determination of the ratio of compounds

a) Method used

The reactions of phenylacetylene **2a** generated 1,2,4-triphenylbenzene **5a**, often as the major product, with a smaller amount of 1,4-diphenylbuta-1*E*,3*E*-diene **6a**, sometimes also accompanied by starting material **2a** and various amounts of polymeric material (see next sub-section). In order to qualitatively establish the **5a/6a/2a** product distributions in the crude reaction products, ^{13}C NMR spectroscopy was used. The intensities of the following characteristic signals, accounting for two CH carbon atoms in all three molecules, **5a**, **6a** and **2a**, were measured: δ 127.1 (**5a**), 132.7 (**6a**)⁸ and 132.0 ppm (**2a**)⁸ (when significant amounts of polymeric material were detected, these intensities were not evaluated from the spectrum baseline but from the top of the polymeric signals). Simple normalisation calculations then gave the estimated **5a/6a/2a** ratio.

8– SDBSWeb: <http://sdfs.db.aist.go.jp> (National Institute of Advanced Industrial Science and Technology, accessed on the 29th of January 2018).

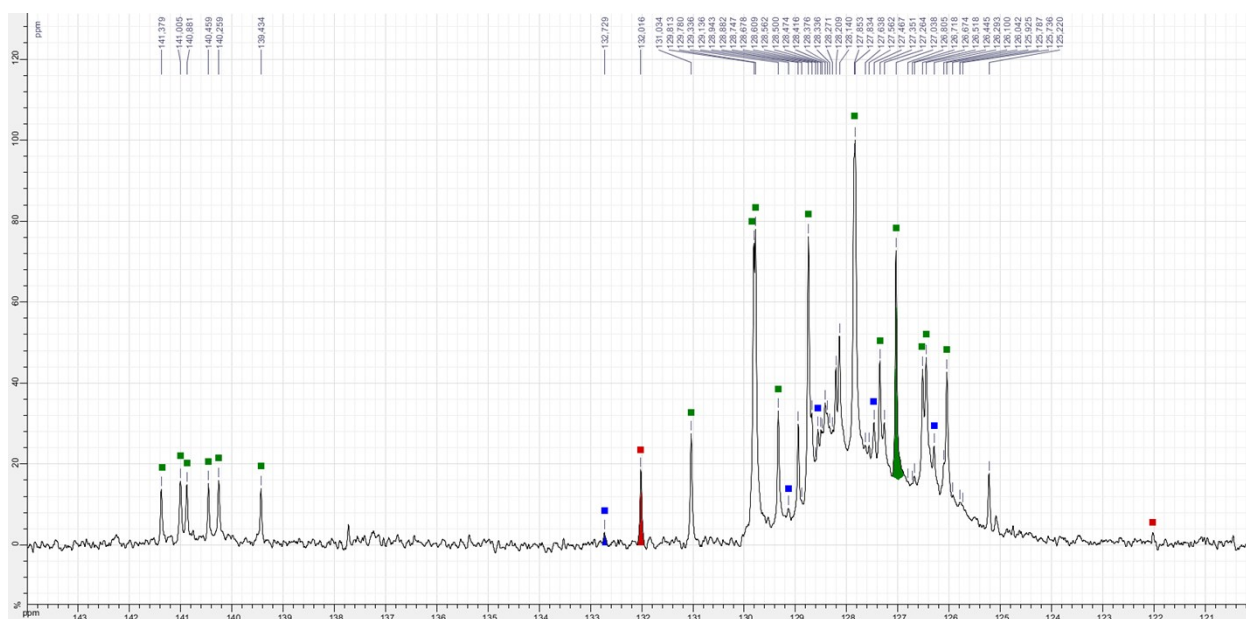
b) Examples



^{13}C NMR spectrum of the crude product of the reaction presented in Table 2, entry 3 (CDCl_3 , 100.6 MHz).

■ 1,2,4-cyclotrimer **5a**, ■ diene **6a**, ■ starting alkyne **2a**, (only the signals assigned with certainty are marked).
The peaks used for qualitative estimation of the compound distribution are coloured in the corresponding tint.

Crude intensity values measured: 24.1 (**5a**), 1.5 (**6a**) and 0.9 (**2a**), i.e. **5a/6a/2a** \approx 91 : 06 : 03.



^{13}C NMR spectrum of the crude product of the reaction presented in Table 1, entry 8 (CDCl_3 , 100.6 MHz).

■ 1,2,4-cyclotrimer **5a**, ■ diene **6a**, ■ starting alkyne **2a**, (only the signals assigned with certainty are marked).
The peaks used for qualitative estimation of the compound distribution are coloured in the corresponding tint.

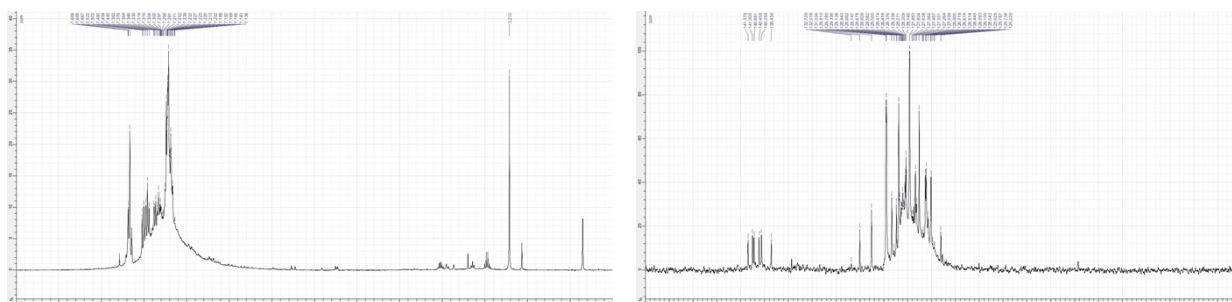
Note the higher content of polymeric material (see next paragraph).

Crude intensity values measured: 56.7 (**5a**), 3.3 (**6a**) and 18.8 (**2a**), i.e. **5a/6a/2a** \approx 72 : 04 : 24.

Observation of polymeric material in the crude products

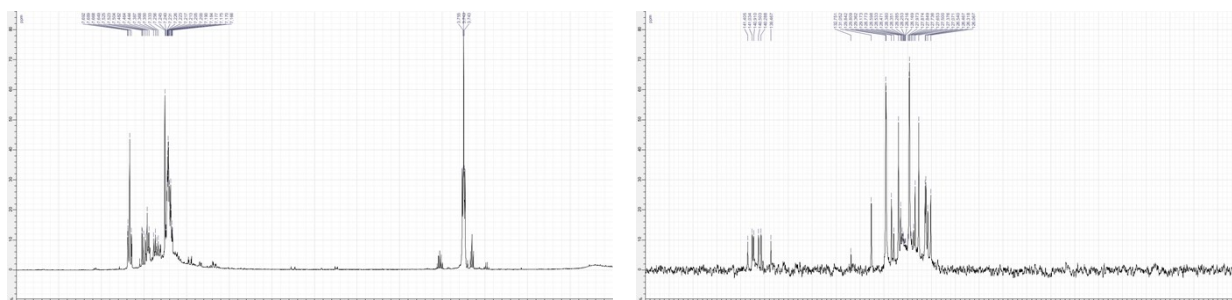
a) General comment

In the reactions of phenylacetylene **2a**, the results of which are presented in Tables 1 and 2, various amounts of undesired oligomeric or polymeric compounds were produced, as evidenced by ^1H and ^{13}C NMR spectroscopy. This phenomenon was characterised by the presence of enlarged signals in the aromatic regions, in the intervals 6.0–8.0 ppm (^1H NMR spectrum) and 124–130 ppm (^{13}C NMR spectrum). This is clearly illustrated by the extreme example of the NMR spectra of the crude product obtained when the reaction was carried out in *t*BuOMe (Table 1, entry 8):

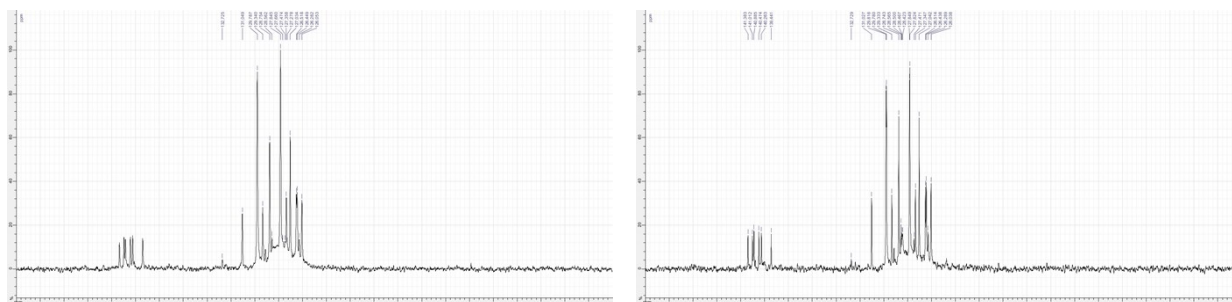


^1H (left) and ^{13}C (right) NMR spectra of the crude product of the reaction conducted in *t*BuOMe at reflux.

More typically, these unwanted by-products could be considered as minor components of the crude products. This was the case for the reactions run with addition of a pre-formed THF solution of **1** into a solution of **2a** in the same solvent, either under standard reflux conditions (Table 1, entries 3–5) or with microwave irradiation [Table 1, entry 10 (procedure A)]. The corresponding spectra are presented below.



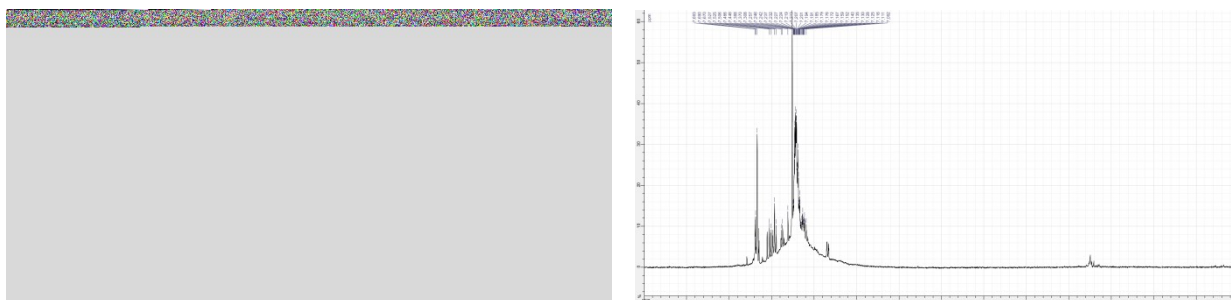
^1H (left) and ^{13}C (right) NMR spectra of the crude product of a reaction run in THF at reflux (Table 1, entry 3).



Comparison of ^{13}C NMR spectra of the crude products of reactions conducted in THF under standard reflux conditions (left, Table 1, entry 5) and under microwave irradiation conditions (right, Table 1, entry 10).

b) Effect of simplified procedures on the production of oligomeric/polymeric side-products

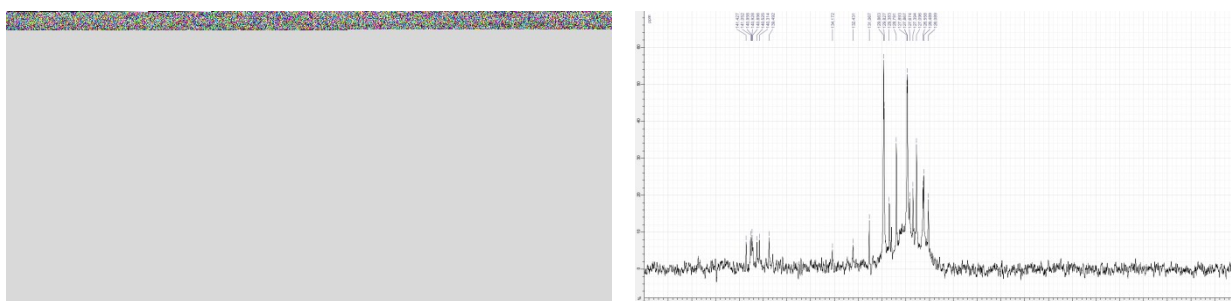
When *n*BuLi was directly added into a THF solution of Ti(O*i*Pr)₄ and **2a**, before heating at reflux (Table 1, entry 7), undesired oligomeric or polymeric compounds were produced in larger amounts, as qualitatively observed by NMR analysis:



Comparison of ¹H NMR spectra of the crude products of two reactions conducted in THF at reflux.

Left: with addition of a pre-formed solution of **1** into a solution of **2a** (Table 1, entry 5).

Right: with *n*BuLi having been directly added into a solution of Ti(O*i*Pr)₄ and **2a** (Table 1, entry 7).

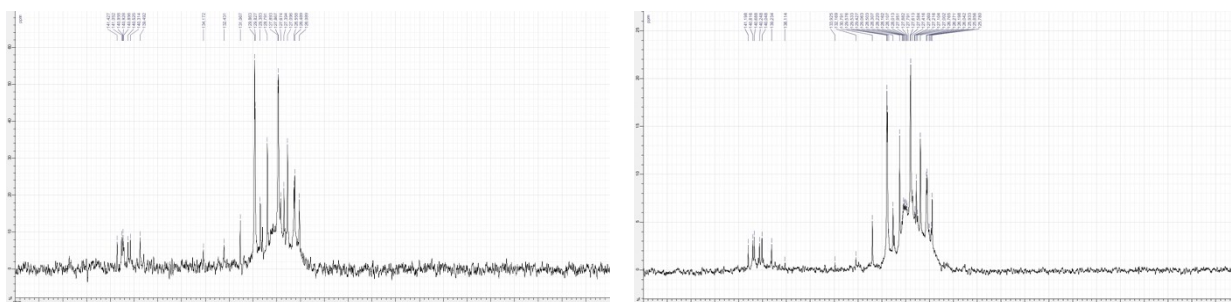


Comparison of ¹³C NMR spectra of the crude products of two reactions conducted in THF at reflux.

Left: with addition of a pre-formed solution of **1** into a solution of **2a** (Table 1, entry 5).

Right: with *n*BuLi having been directly added into a solution of Ti(O*i*Pr)₄ and **2a** (Table 1, entry 7).

Heating with microwave irradiation under otherwise identical conditions [Table 2, entry 2 (procedure B)] did not result in any improvement:

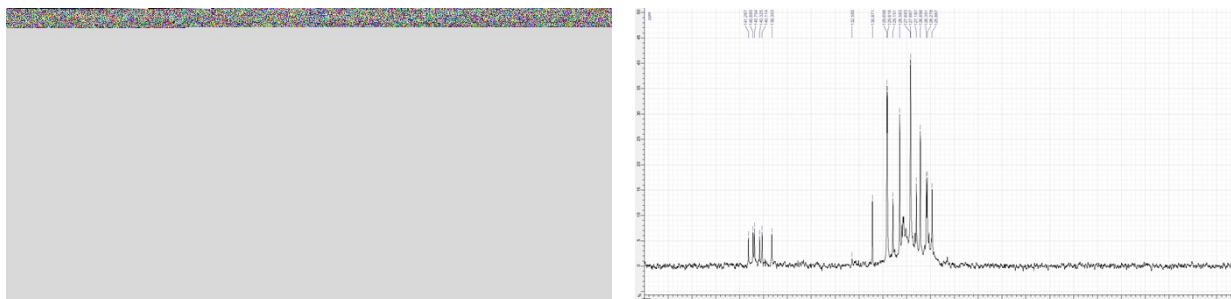


Comparison of ¹³C NMR spectra of the crude products of two reactions conducted in THF,

with *n*BuLi having been directly added into a solution of Ti(O*i*Pr)₄ and **2a**.

Left: heating at reflux (Table 1, entry 7). Right: heating by microwave irradiation (Table 2, entry 2).

Conversely, application of an alternative simplified one-pot procedure where **2a** was directly added into a pre-formed THF solution of **1** [Table 2, entry 3 (procedure C)] provided satisfactory results with respect to this problem. Comparison of the ^{13}C NMR spectrum with a spectrum recorded in the case the initial two-pot procedure [Table 2, entry 1 (procedure A)] does not reveal important qualitative changes:



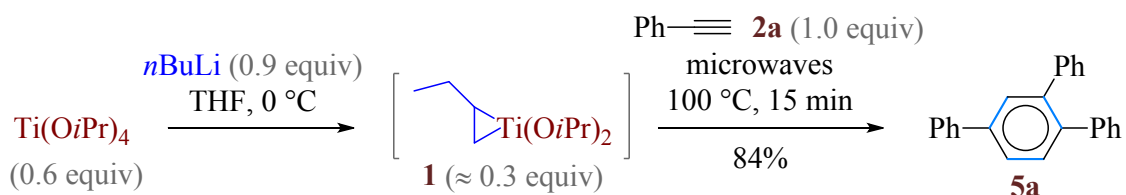
Comparison of ^{13}C NMR spectra of the crude products of two reactions run in THF under microwave conditions.

Left: with addition of a pre-formed solution of **1** into a solution of **2a** (Table 2, entry 1).

Right: with addition of neat **2a** into of a pre-formed solution of **1** (Table 2, entry 3).

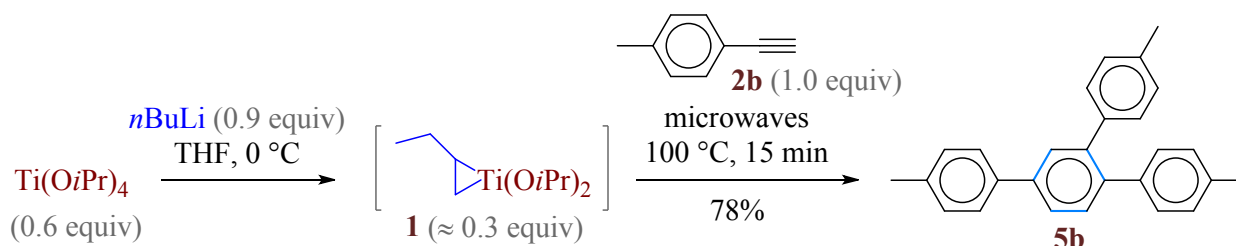
IV. Reactions of Table 3, Table 4 and Scheme 4

1,2,4-Triphenylbenzene **5a** and 1,3,5-triphenylbenzene **5'a**



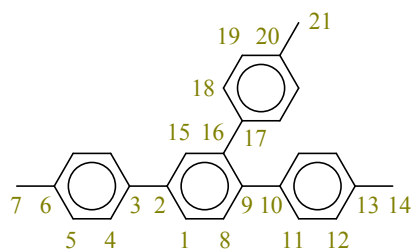
General procedure **G1** was applied with phenylacetylene **2a**. Work-up **W1** was carried out. ^{13}C NMR analysis of the crude product (420 mg, brown sticky oil) showed full conversion of the starting material and the production of 1,2,4-triphenylbenzene **5a**. The 1,3,5 isomer **5'a** was not detected. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 2%) afforded pure **5a** (257 mg, 839 μmol , 84%). A highly pure sample was obtained by trituration in MeOH.

1,2,4-Tris(*p*-tolyl)benzene **5b**



General procedure **G1s** was applied with 4-methylphenylacetylene **2b**. Work-up **W1** was performed. ^{13}C NMR analysis of the crude product showed full conversion of the starting material and the production of 1,2,4-tris(*p*-tolyl)benzene **5b**. The 1,3,5 isomer was not detected. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 2%) afforded pure **5b** (273 mg, 783 μmol , 78%). A highly pure sample was obtained by trituration in MeOH.

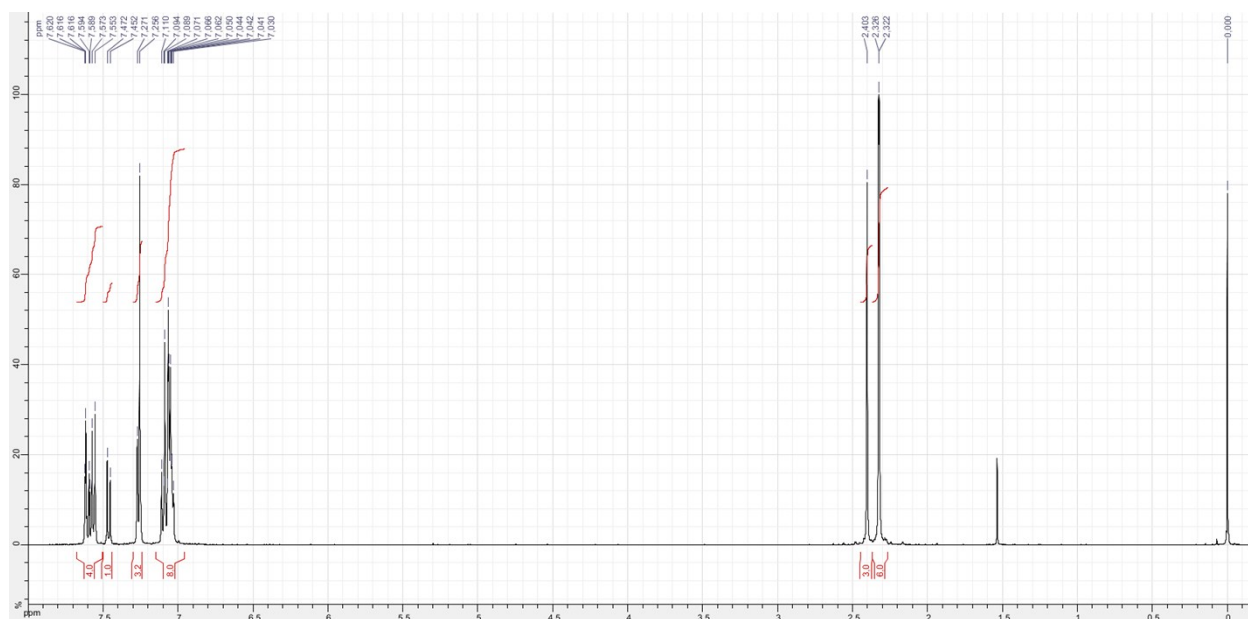
1,2,4-Tris(*p*-tolyl)benzene **5b**^{4,9}



White solid. M.p. 124–126 °C (trituration in MeOH) (lit. 75–77 °C;¹⁰ 122–123 °C¹¹).

R_f 0.5 (EtOAc/petroleum ether 2%, PMA, UV-active). ¹H NMR (CDCl₃, 400 MHz): δ 2.32 (3 H, s, H14 or H21), 2.40 (3 H, s, H7), 7.02–7.12 (8 H, m, H11–H12, H18–H19), 7.26 (2 H, br d, J 8.0, H5), 7.46 (1 H, d, J 8.0, H8), 7.56 (2 H, br d, J 8.0, H4), 7.60 (1 H, br dd, J 8.0, 2.0, H1), 7.62 (1 H, br d, J 2.0, H15). ¹³C NMR (CDCl₃, 100.6 MHz): δ 21.1, 21.1, 21.1 (C7, C14, C21), 125.7 (C15), 126.9 (C4), 128.6 (4 C, C11, C18), 129.2 (C1), 129.5 (C5), 129.7 (4 C, C12, C19), 131.1 (C8), 135.9, 136.0 (C13, C20), 137.0 (C6), 137.7, 138.3, 138.7 (C3, C10, C17), 139.1 (C2), 140.0, 140.7 (C9, C16).

HRMS (EI): m/z 348.1872 (M^{+} C₂₇H₂₄⁺ requires 348.1873).

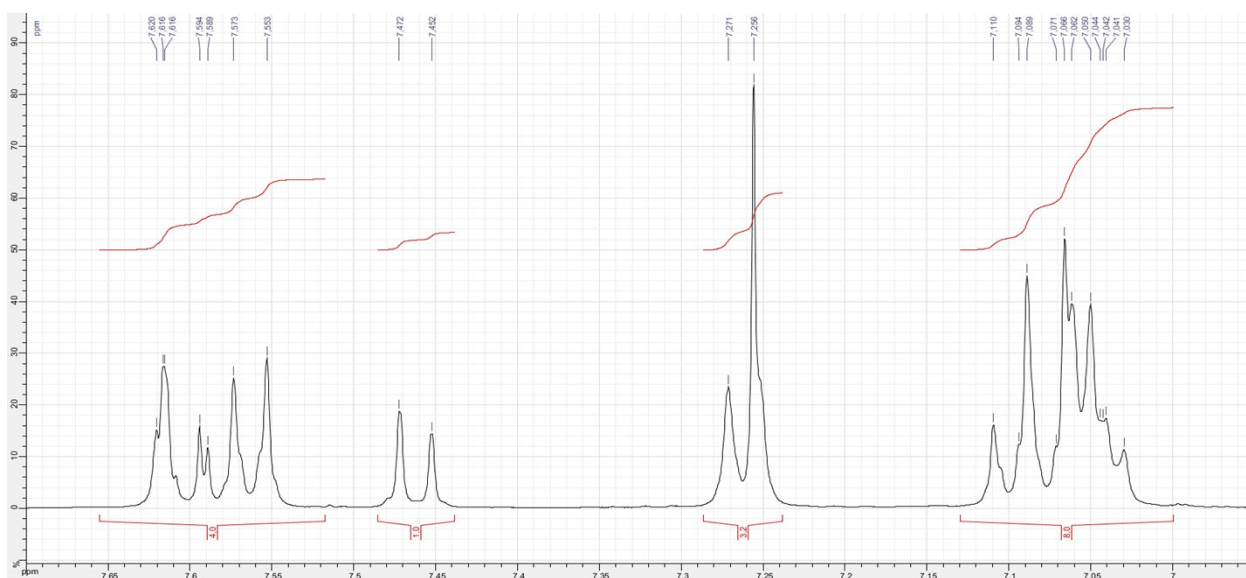


¹H NMR spectrum (CDCl₃, 400 MHz).

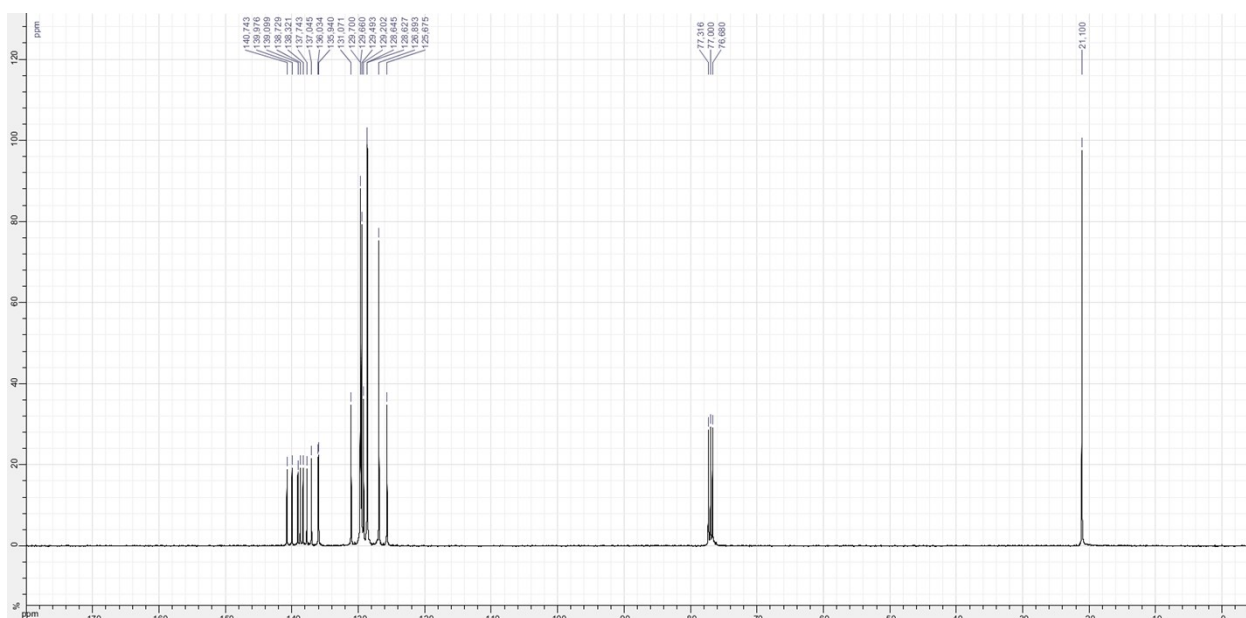
9– O. V. Ozerov, B. O. Patrick, F. T. Ladipo, *J. Am. Chem. Soc.* **2000**, *122*, 6423–6431.

10– M. Rehan, S. Maity, L. K. Morya, K. Pal, P. Ghorai, *Angew. Chem. Int. Ed.* **2016**, *55*, 7728–7732 (supporting information).

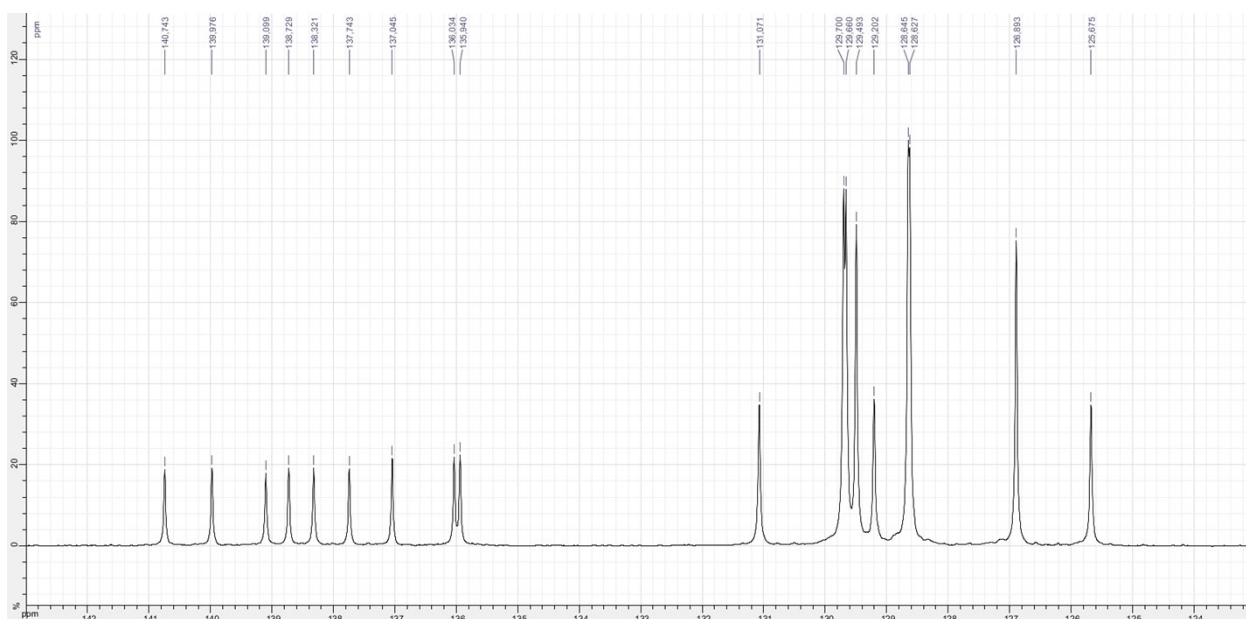
11– J. Liu, D. K. Das, G. Zhang, S. Yang, H. Zhang, X. Fang, *Org. Lett.* **2018**, *20*, 64–67 (supporting information).



^1H NMR spectrum (selected extract) (CDCl_3 , 400 MHz).

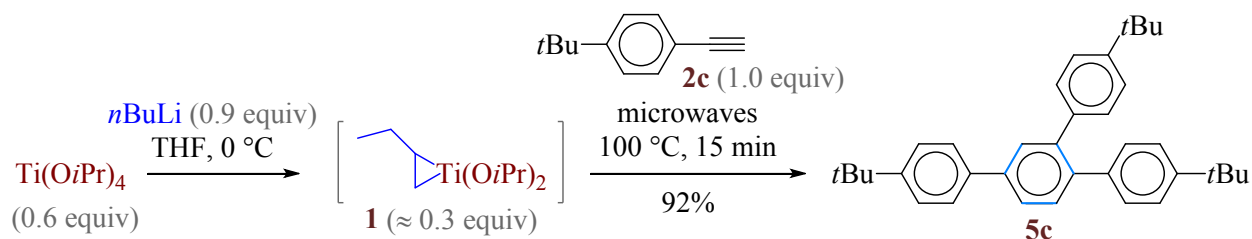


^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).



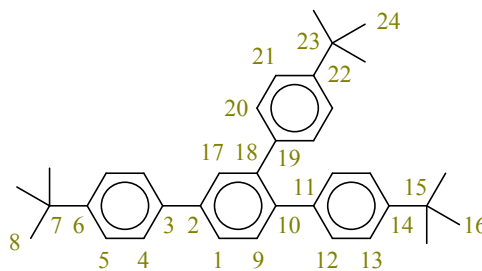
^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).

1,2,4-Tris(4-*tert*-butylphenyl)benzene **5c**



General procedure **G1** was applied with 4-*tert*-butylphenylacetylene **2c**. Work-up **W1** was carried out. ^{13}C NMR analysis of the crude product (685 mg, brown sticky oil) showed full conversion of the starting material and the production of 1,2,4-tris(4-*tert*-butylphenyl)benzene **5c**. The 1,3,5 isomer was not detected. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 2%) afforded pure **5c** (436 mg, 918 μmol , 92%). A highly pure sample was obtained by trituration in MeOH.

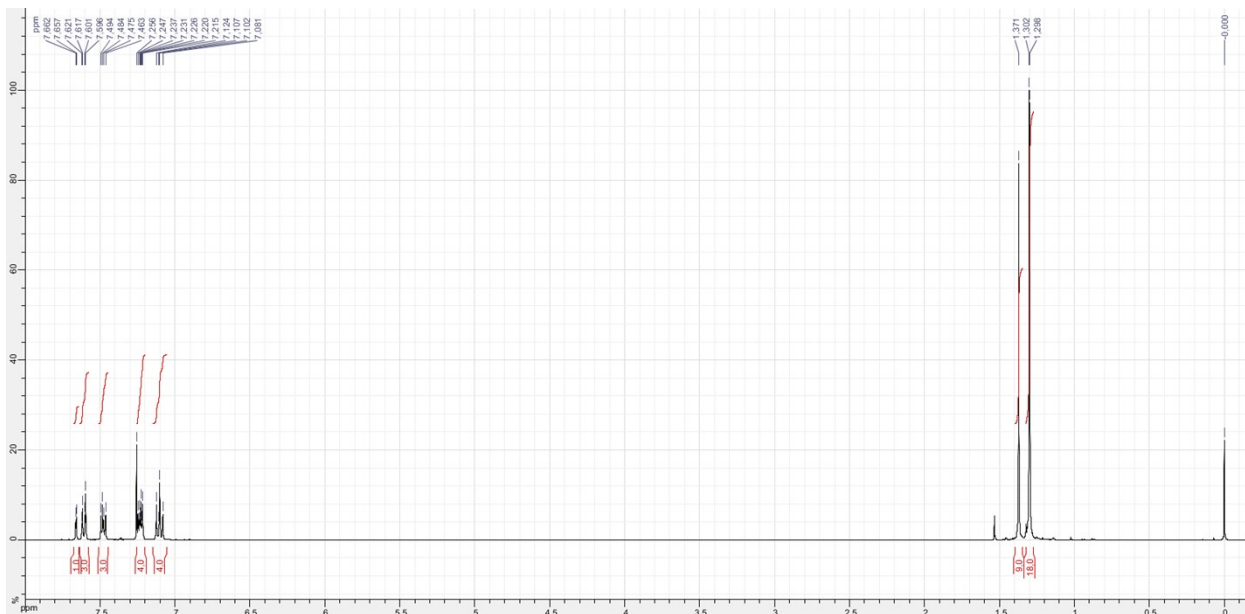
1,2,4-Tris(4-*tert*-butylphenyl)benzene **5c**¹²



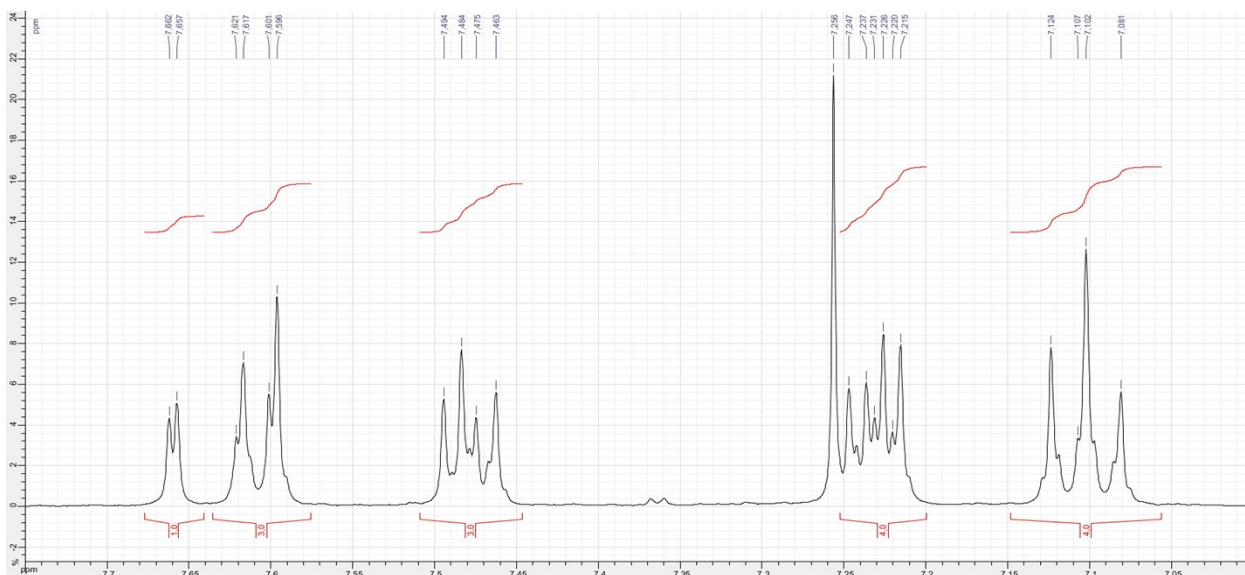
White solid. M.p. 152–154 $^\circ\text{C}$ (trituration in MeOH) (lit.¹² 145–146 $^\circ\text{C}$).

R_f 0.5 (EtOAc/petroleum ether 2%, UV-active). ^1H NMR (CDCl_3 , 400 MHz): δ 1.298 (9 H, s, H16 or H24), 1.302 (9 H, s, H16 or H24), 1.37 (9 H, s, H8), 7.11 (4 H, m, H13, H21), 7.23 (4 H, m, H12, H20), 7.45–7.51 (3 H, m, H5, H9), 7.61 (3 H, br d, J 8.0, H1, H4), 7.66 (1 H, s, H17).

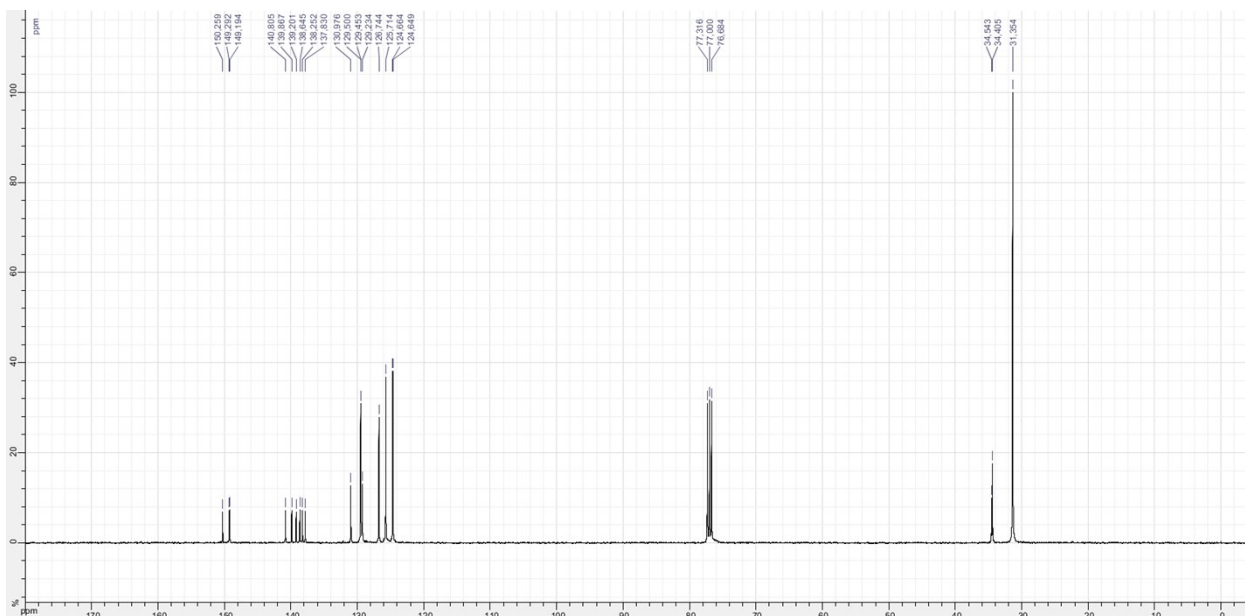
^{13}C NMR (CDCl_3 , 100.6 MHz): δ 31.4, 31.4, 31.4 (C8, C16, C24), 34.4 (C15, C23), 34.5 (C7), 124.65, 124.66 (C13, C21), 125.7, 125.7 (3 C, C5, C17), 126.7 (C4), 129.2 (C1), 129.45, 129.50 (C12, C20), 131.0 (C9), 137.8 (C3), 138.3, 138.6 (C11, C19), 139.2 (C2), 139.9, 140.1 (C10, C18), 149.2, 149.3 (C14, C22), 150.3 (C6). HRMS (EI): m/z 474.3279 (M^{++} $\text{C}_{36}\text{H}_{42}^{++}$ requires 474.3281).



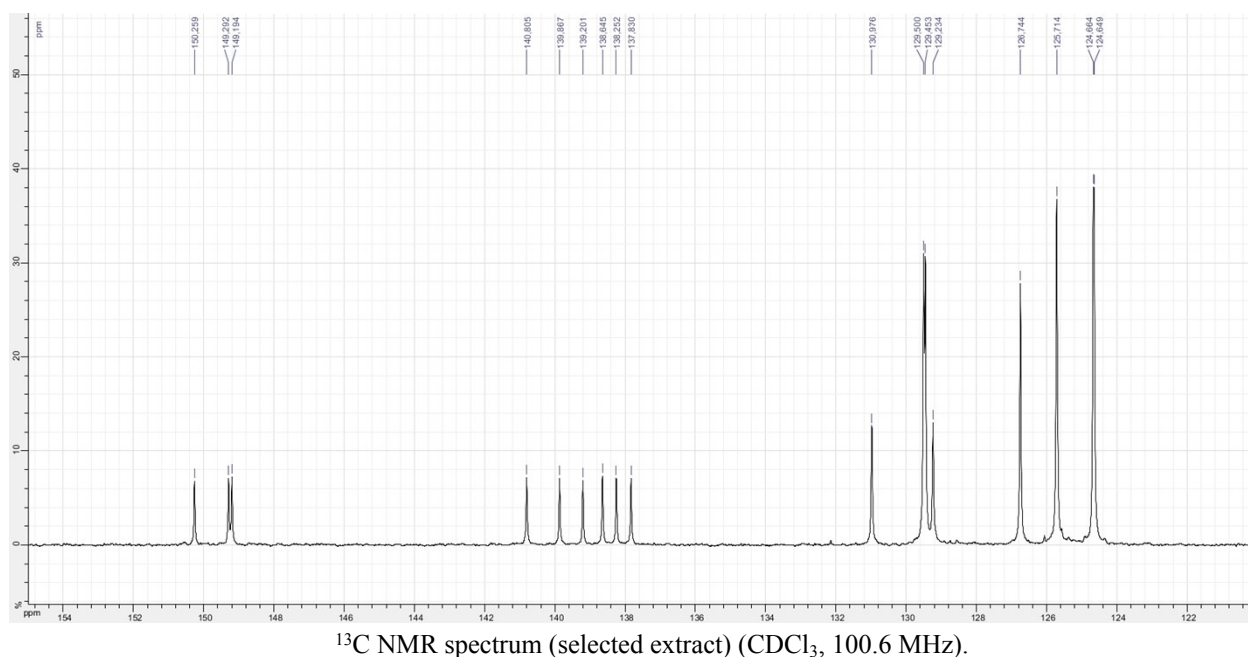
^1H NMR spectrum (CDCl_3 , 400 MHz).



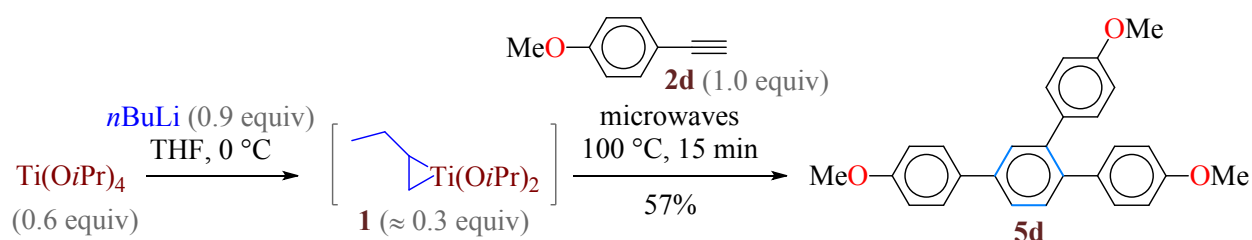
^1H NMR spectrum (selected extract) (CDCl_3 , 400 MHz).



^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).

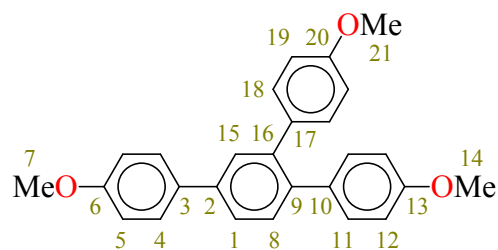


1,2,4-Tris(4-methoxyphenyl)benzene **5d**



General procedure **G1s** was applied with 4-methoxyphenylacetylene **2d**. Work-up **W1** was carried out. ¹³C NMR analysis of the crude product showed full conversion of the starting material and the production of 1,2,4-tris(4-methoxyphenyl)benzene **5d**. The 1,3,5 isomer was not detected. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 1 to 10%) afforded pure **5d** (225 mg, 567 μmol , 57%). A highly pure sample was obtained by trituration in MeOH.

1,2,4-Tris(4-methoxyphenyl)benzene **5d**^{4,13}



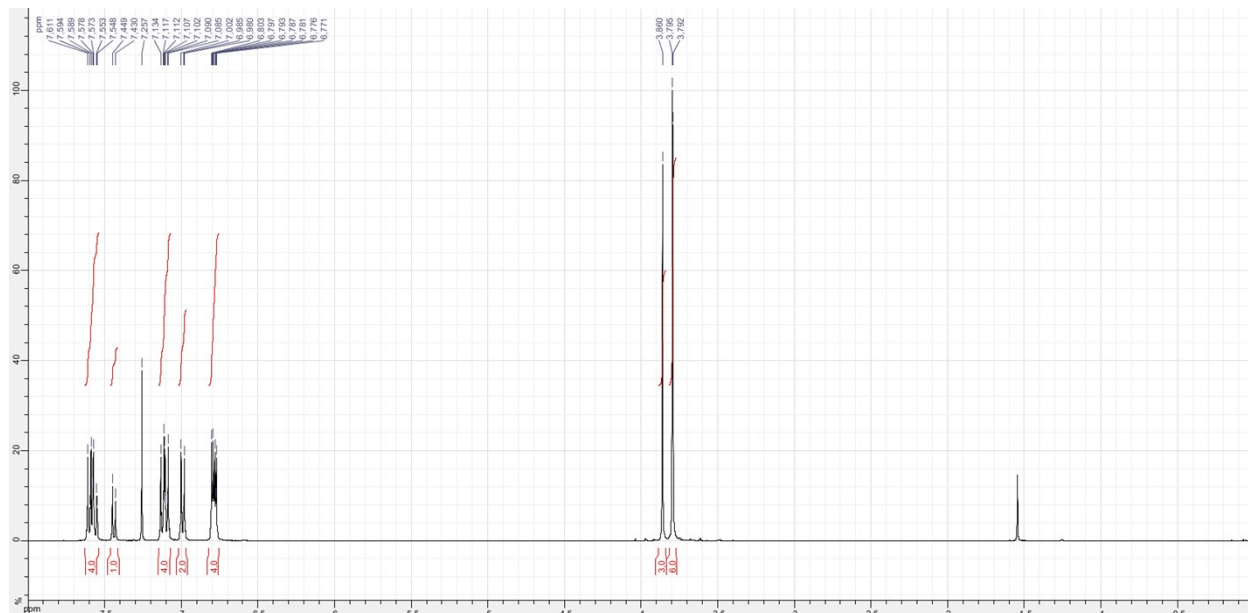
White solid. M.p. 116–117 $^\circ\text{C}$ (trituration in MeOH) (lit.¹⁰ 176–178 $^\circ\text{C}$).

R_f 0.2 (EtOAc/petroleum ether 5%, PMA, UV-active). ¹H NMR (CDCl₃, 400 MHz): δ 3.792 (3 H, s, H14 or H21), 3.795 (3 H, s, H14 or H21), 3.86 (3 H, s, H7), 6.78 (2 H, br d, J 8.5, H12 or H19), 6.79 (2 H, br d, J 8.5, H12 or H19), 6.99 (2 H, br d, J 9.0, H5), 7.10 (2 H, br d, J 8.5, H11 or H18), 7.12 (2 H, br d, J 8.5, H11 or H18), 7.44 (1 H, d, J 8.0, H8), 7.56 (1 H, br dd, J 8.0, 2.0, H1), 7.58

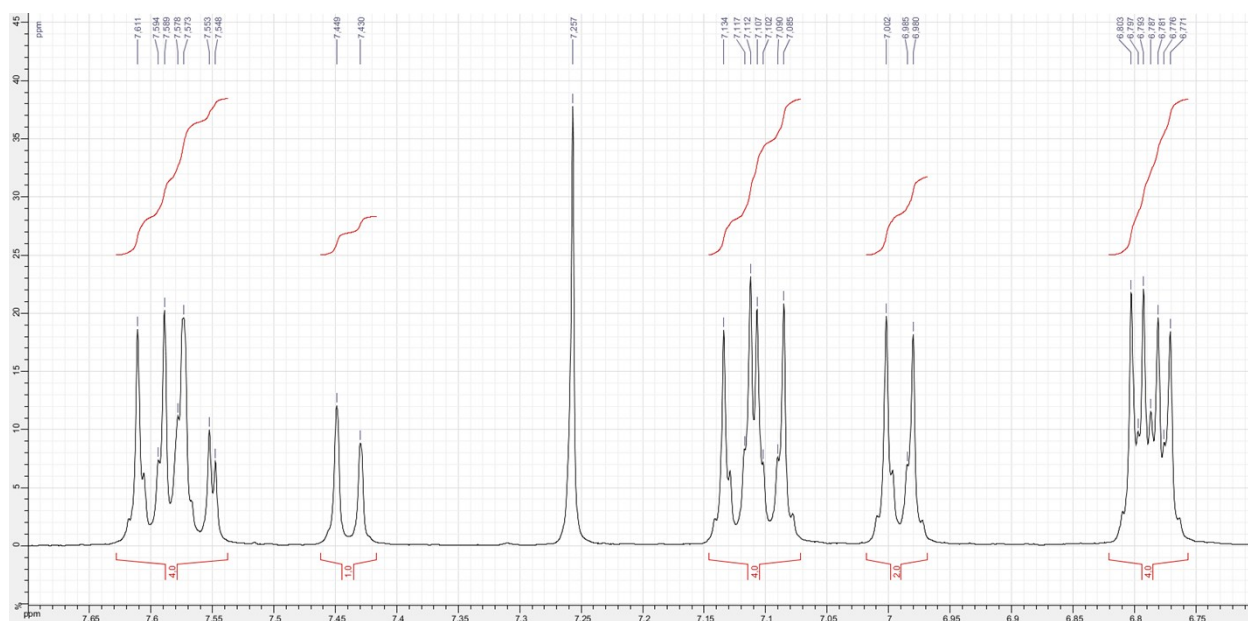
13– V. Cadierno, S. E. García-Garrido, J. Gimeno, *J. Am. Chem. Soc.* **2006**, *128*, 15094–15095.

(1 H, br d, J 2.0, H15), 7.60 (2 H, br d, J 9.0, H4). ^{13}C NMR (CDCl_3 , 100.6 MHz): δ 55.1 (2 C, C14, C21), 55.3 (C7), 113.34, 113.36 (C12, C19), 114.2 (C5), 125.3 (C15), 128.0 (C4), 128.8 (C1), 130.82, 130.86 (C11, C18), 131.0 (C8), 133.1 (C3), 133.6, 134.1 (C10, C17), 138.4 (C2), 139.5, 140.3 (C9, C16), 158.16, 158.24 (C13, C20), 159.1 (C6).

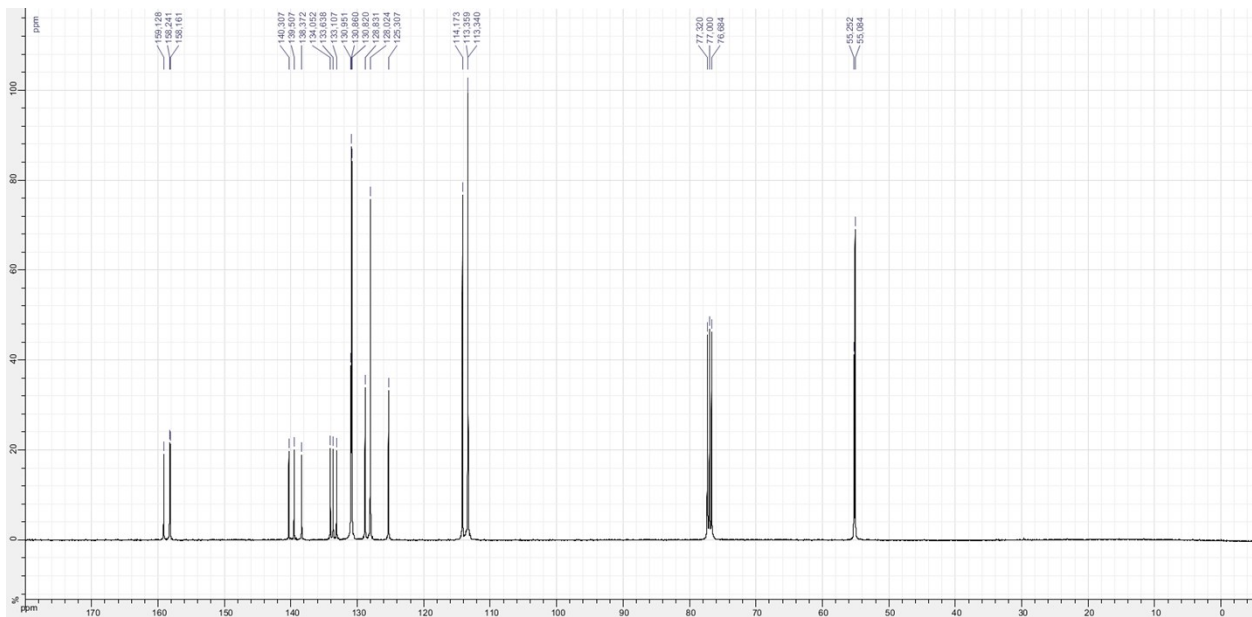
HRMS (EI): m/z 396.1722 (M^+ $\text{C}_{27}\text{H}_{24}\text{O}_3$ requires 396.1720).



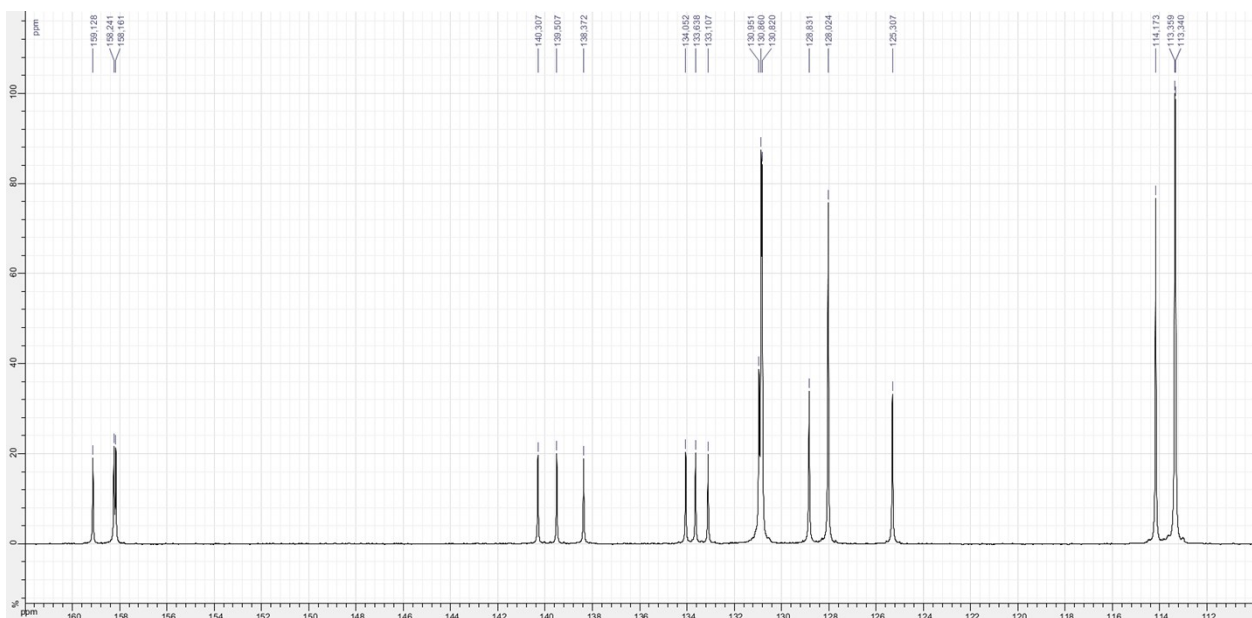
^1H NMR spectrum (CDCl_3 , 400 MHz).



^1H NMR spectrum (selected extract) (CDCl_3 , 400 MHz).



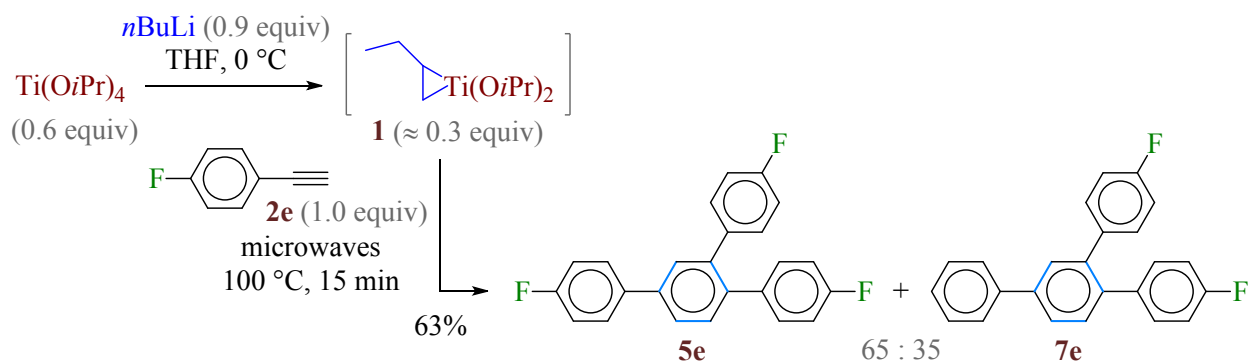
^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).



^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).

1,2,4-Tris(4-fluorophenyl)benzene **5e** and 1,2-bis(4-fluorophenyl)-4-phenyl-benzene **7e**

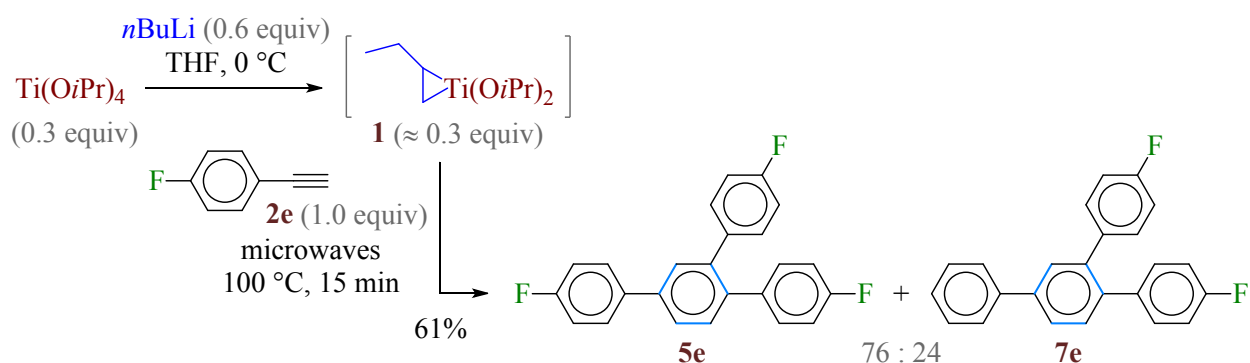
a) Using $\text{Ti}(\text{O}i\text{Pr})_4/n\text{BuLi}$ in 2 : 3 ratio



General procedure **G1s** was applied with 4-fluorophenylacetylene **2e**. Work-up **W1** was carried out. Analysis of the crude product (370 mg, brown sticky oil) by ^{13}C NMR spectroscopy showed full conversion of the starting material and the production of 1,2,4-tris(4-fluorophenyl)benzene **5e** and 1,2-bis(4-fluorophenyl)-4-phenyl-benzene **7e** in an estimated 65 : 35 ratio. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 5%) afforded pure **5e** (36.8 mg, 103 μmol , 10%) and a 55 : 45 mixture of **5e** and **7e** (as determined by ^{13}C NMR spectroscopy, 187 mg, 292 and 239 μmol respectively). The yields obtained for both compounds are thus 39% (**5e**) and 24% (**7e**). A highly pure sample of **5e** was obtained by trituration in MeOH.

Note: for the estimation of the **5e/7e** ratio by ^{13}C NMR spectroscopy, the intensities of the following peaks were used: δ 126.2 (1C of **5e**), 128.6 (d, J 8.0, 2C of **5e**), 127.1 (2C of **7e**) and 128.9 (2C of **7e**).

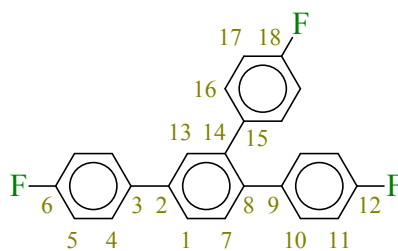
b) Using $\text{Ti}(\text{O}i\text{Pr})_4/n\text{BuLi}$ in 1 : 2 ratio



General procedure **G2s** was applied with 4-fluorophenylacetylene **2e**. Work-up **W1** was carried out. Analysis of the crude product by ^{13}C NMR spectroscopy showed full conversion of the starting material and the production of 1,2,4-tris(4-fluorophenyl)benzene **5e** and 1,2-bis(4-fluorophenyl)-4-phenyl-benzene **7e** in an estimated 76 : 24 ratio. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 2%) afforded pure **5e** (50.0 mg, 139 μmol , 14%) and a 64 : 36 mixture of **5e** and **7e** (as determined by ^{13}C NMR, 166 mg, 299 and 169 μmol respectively). The yields obtained for both compounds are thus 44% (**5e**) and 17% (**7e**).

Note: for the estimation of the **5e/7e** ratio, the method described further above was applied.

1,2,4-Tris(4-fluorophenyl)benzene **5e**¹⁰



White solid. M.p. 138–140 °C (trituration in MeOH) (lit. 136–137 °C;¹⁴ 155–157 °C¹⁰).

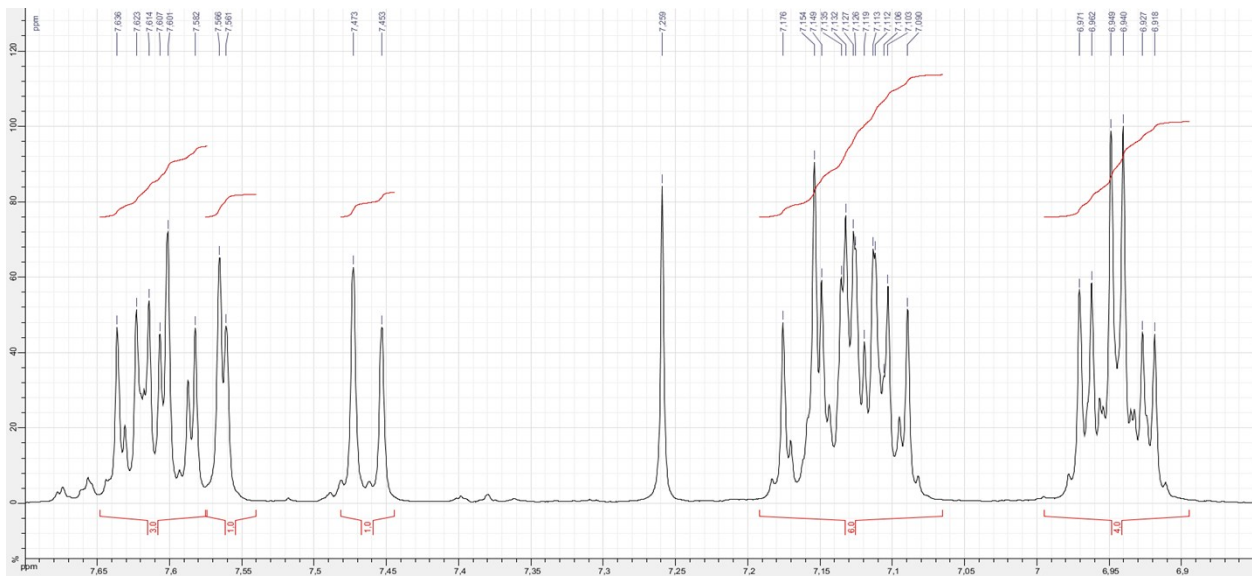
R_f 0.5 (EtOAc/petroleum ether 2%, PMA, UV-active). ¹H NMR (CDCl₃, 400 MHz): δ 6.93 (2 H, br dd, J 9.0, 8.5, H11 or H17), 6.96 (2 H, br dd, J 9.0, 8.5, H11 or H17), 7.07–7.19 (6 H, m, H5, H10, H16), 7.46 (1 H, d, J 8.0, H7), 7.55–7.65 (4 H, m, H1, H4, H13).

¹³C NMR (CDCl₃, 100.6 MHz): δ 115.01 (d, J 21.5, C11 or C17), 115.04 (d, J 21.5, C11 or C17), 115.8 (d, J 21.5, C5), 126.2 (C13), 128.6 (d, J 8.0, C4), 129.2 (C1), 131.1 (C7), 131.30 (d, J 8.0, C10 or C16), 131.34 (d, J 8.0, C10 or C16), 136.4 (d, J 3.0, C3 or C9 or C15), 136.7 (d, J 3.0, C3 or C9 or C15), 137.1 (d, J 3.0, C3 or C9 or C15), 138.5 (C2), 139.6, 140.0 (C8, C14), 161.80 (d, J 246.5, C12 or C18), 161.85 (d, J 246.5, C12 or C18), 162.6 (d, J 247.0, C6).

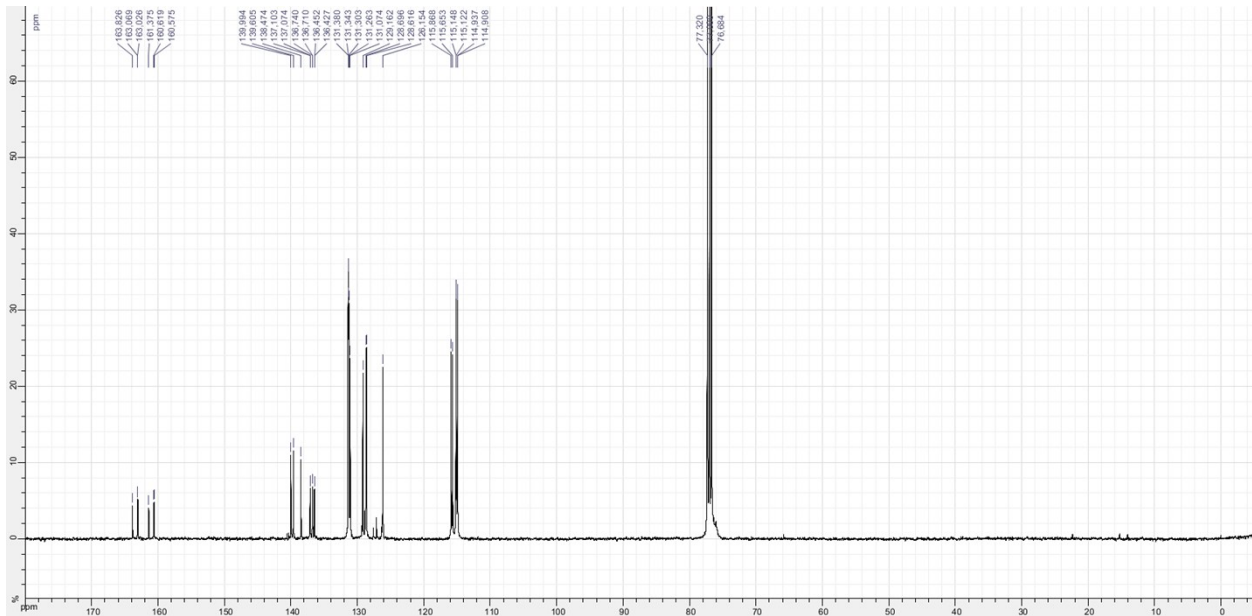
HRMS (EI): m/z 360.1135 (M^{+} C₂₄H₁₅F₃⁺ requires 360.1120).



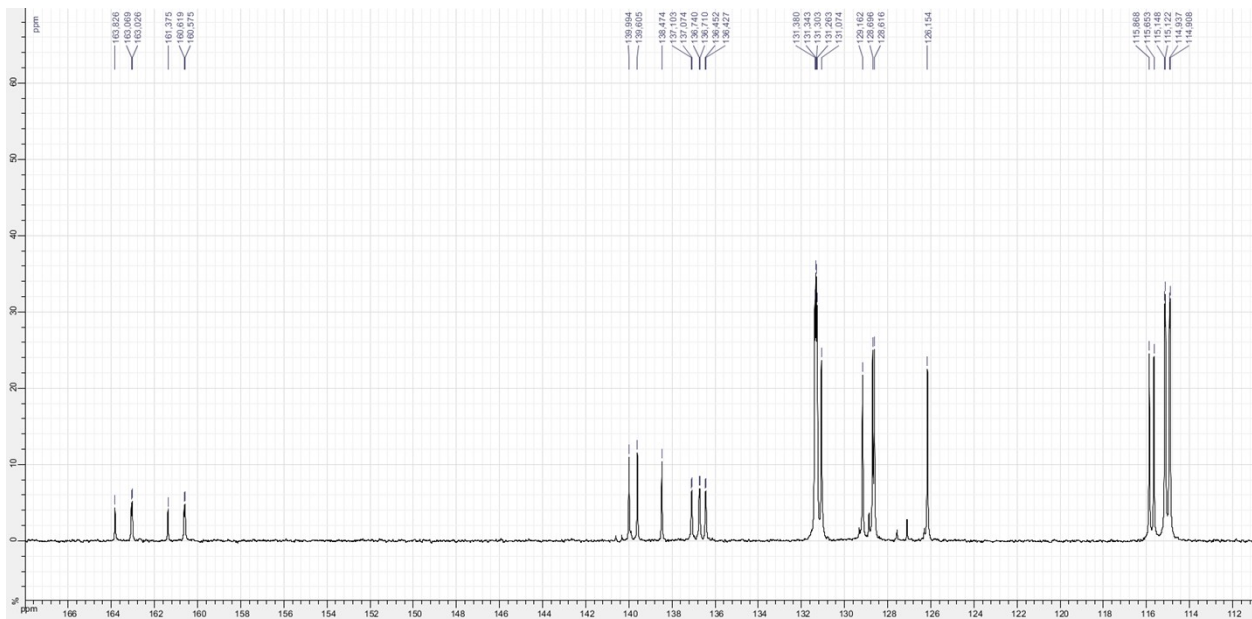
¹H NMR spectrum (CDCl₃, 400 MHz).



^1H NMR spectrum (selected extract) (CDCl_3 , 400 MHz).

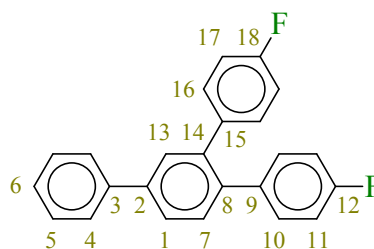


^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).



^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).

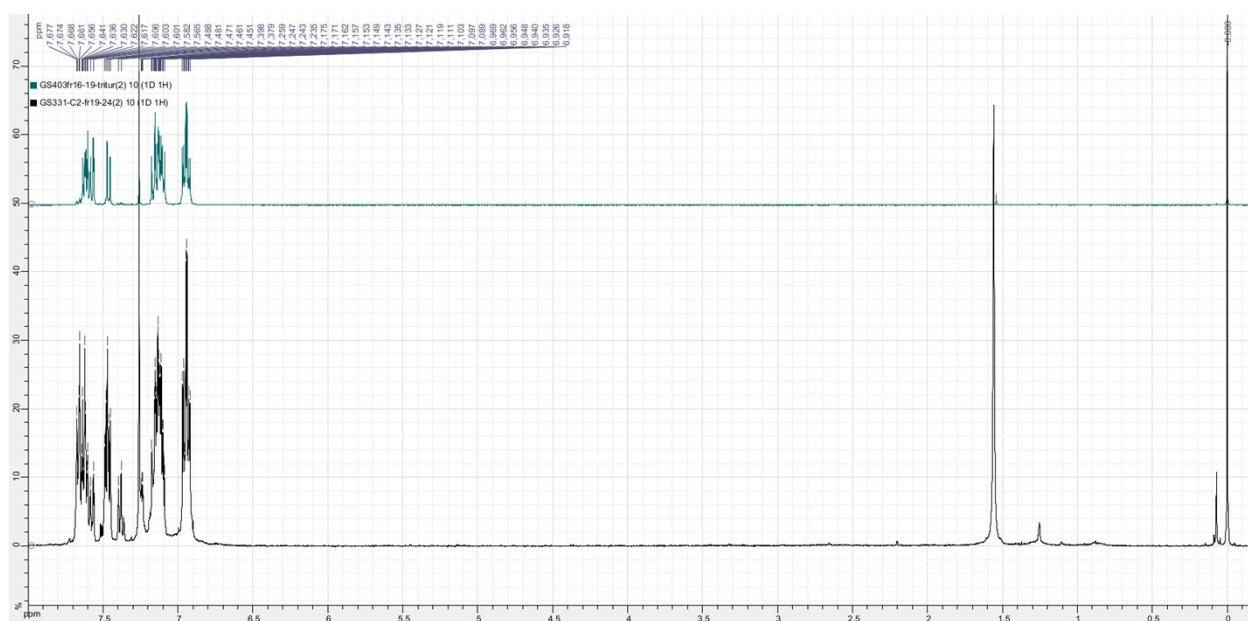
1,2-Bis(4-fluorophenyl)-4-phenyl-benzene **7e**



White solid. R_f 0.5 (EtOAc/petroleum ether 2%, PMA, UV-active).¹⁵

^1H NMR (CDCl_3 , 400 MHz): δ 6.94 (2 H, br dd, J 9.0, 8.5, H11 or H17), 6.95 (2 H, br dd, J 9.0, 8.5, H11 or H17), 7.09–7.16 (4 H, m, H10, H16), 7.38 (1 H, br t, J 7.5, H6), 7.47 (2 H, br t, J 7.5, H5), 7.47 (1 H, d, J 8.0, H7), 7.62 (1 H, br d, J 2.0, H13), 7.63 (1 H, br dd, J 8.0, 2.0, H1), 7.66 (2 H, br d, J 7.5, H4). ^{13}C NMR (CDCl_3 , 100.6 MHz): δ 115.0 (4 C, br d, J 21.5, C11, C17), 126.3 (C13), 127.1 (C4), 127.6 (C6), 128.9 (C5), 129.3 (C1), 131.0 (C7), 131.33 (d, J 8.0, C10 or C16), 131.38 (d, J 8.0, C10 or C16), 136.8 (d, J 3.0, C9 or C15), 137.2 (d, J 3.0, C9 or C15), 138.4 (C2), 139.9, 140.3 (C8, C14), 140.6 (C3), 161.80 (d, J 246.5, C12 or C18), 161.83 (d, J 246.5, C12 or C18). HRMS (EI): m/z 342.1209 (M^+ $\text{C}_{24}\text{H}_{16}\text{F}_2^+$ requires 342.1215).

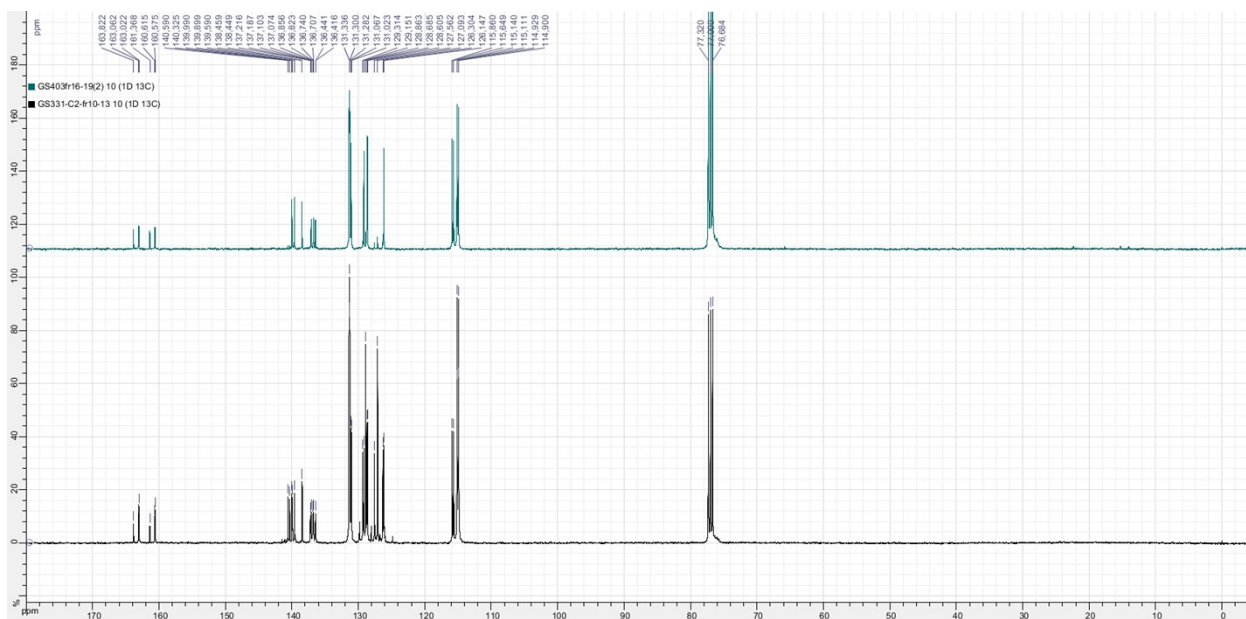
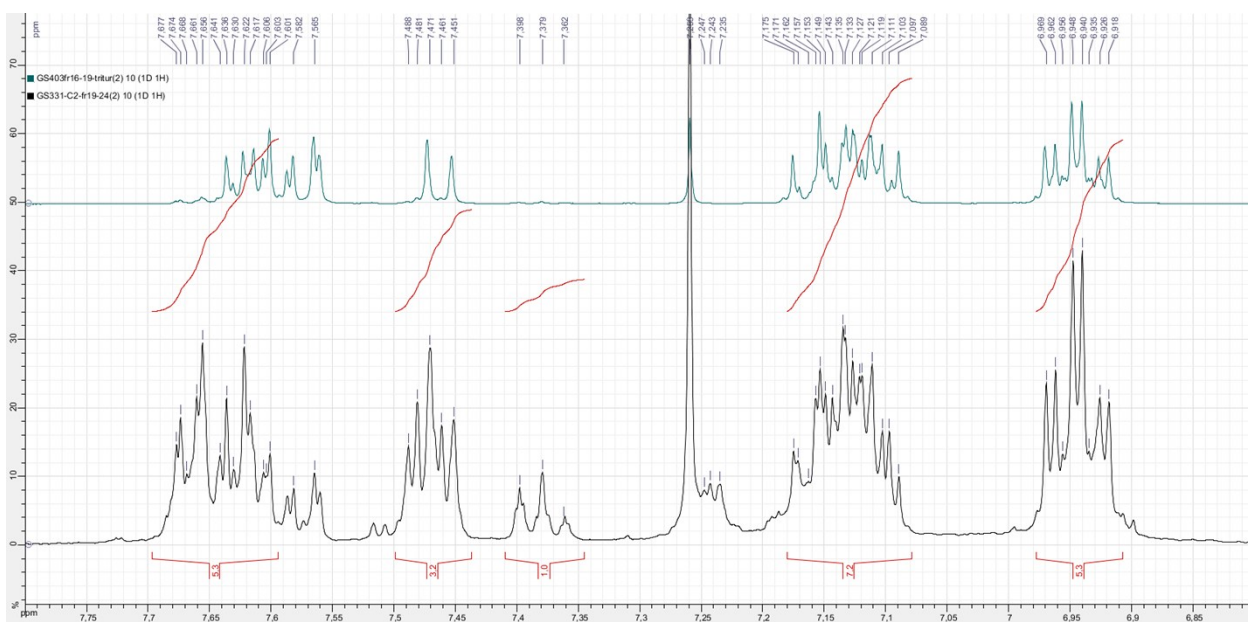
Note: this compound was not obtained in pure form but as a mixture with **5e**.

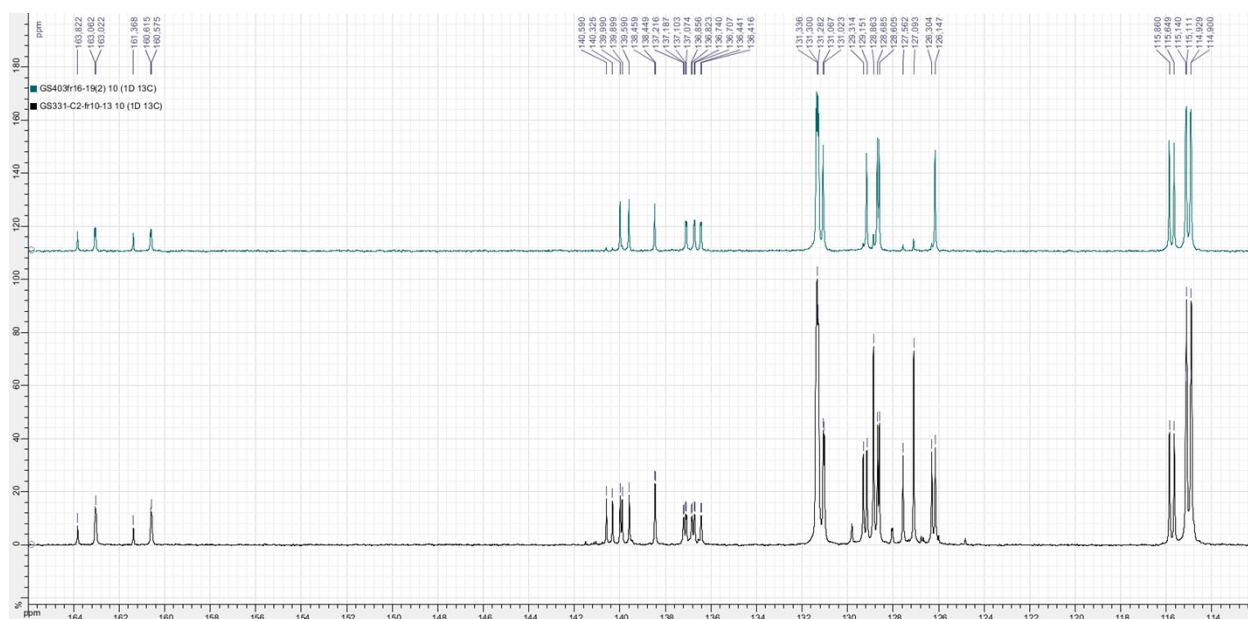


^1H NMR spectrum (CDCl_3 , 400 MHz).

Note: in black (bottom), spectrum of a mixture of **7e** (major) and **5e** (minor); in green (top), spectrum of **5e** alone.

15– 1,2-Bis(4-fluorophenyl)-4-phenylbenzene **7e** is slightly more polar than 1,2,4-tris(4-fluorophenyl)benzene **5e**.





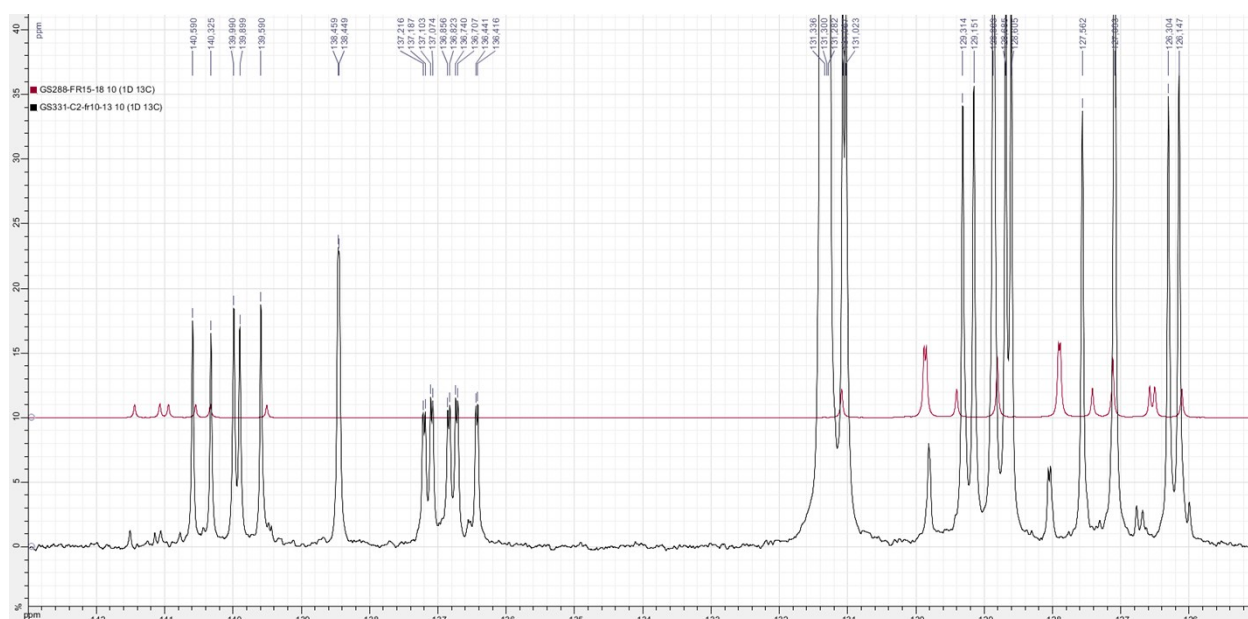
^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).

Note: in black (bottom), spectrum of a nearly equimolar mixture of **7e** and **5e**; in green (top), spectrum of **5e** alone.

Evidence for the formation of (an)other hydro-dehalo substitution product(s)

■ ^{13}C NMR spectroscopy.

In ^{13}C NMR spectra of fractions obtained after purification by flash column chromatography, small peaks were observed, corresponding to the presence of minor contaminants. In one particular sample (spectrum displayed below), a fairly good match was found between these signals and those of the NMR spectrum of the completely defluorinated compound 1,2,4-triphenylbenzene **5a**, suggesting high structural similarity, if not identity.

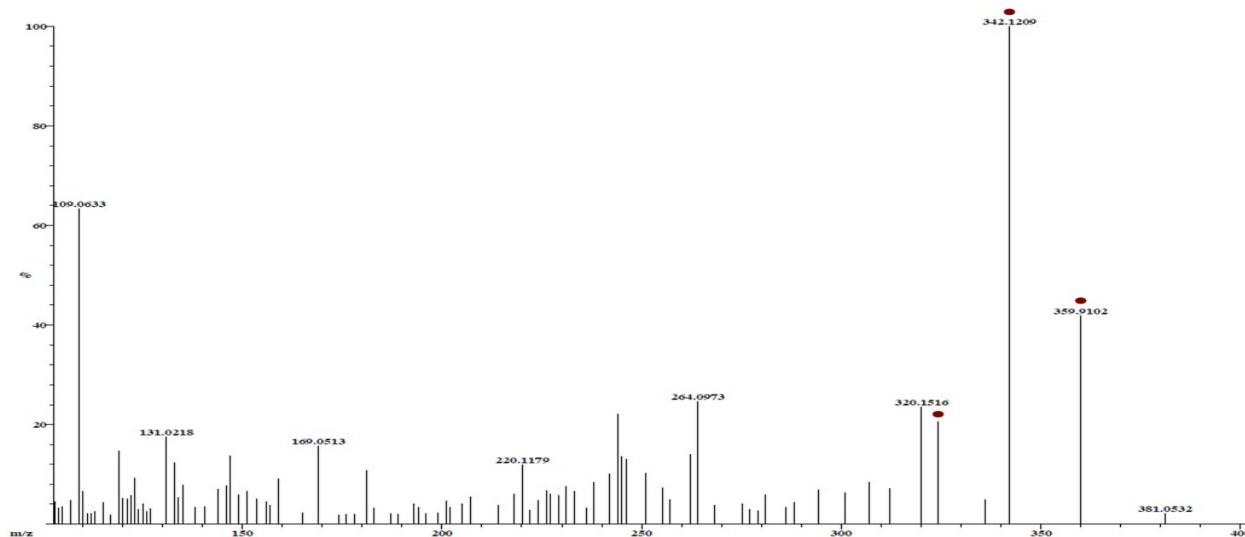


^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).

Note: in black (bottom), spectrum of a nearly equimolar mixture of **5e** and **7e**; in red (top), spectrum of **5a** alone.

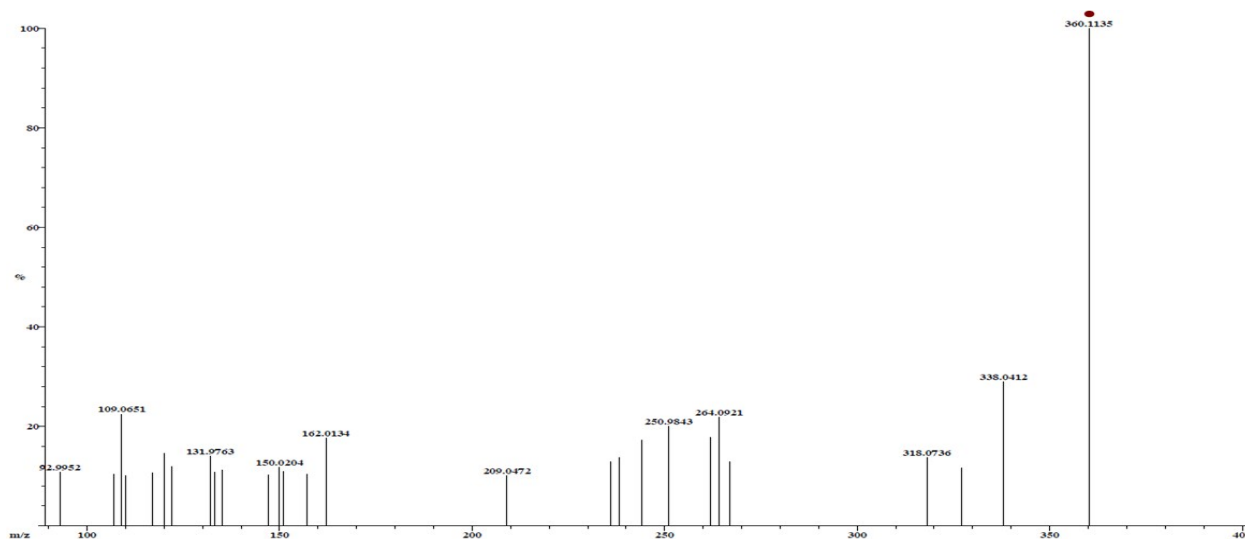
■ Mass spectrometry.

The spectrum shown below was recorded with another sample containing a $\approx 65:35$ mixture of **7e** and **5e**. The molecular peaks are clearly visible at m/z 360 (42%, **5e**⁺ C₂₄H₁₅F₃⁺) and 342 (100%, **7e**⁺ C₂₄H₁₆F₂⁺). A peak at m/z 324 is also observed (21%), which is in agreement with the presence of (a) monofluoro compound(s) in the sample (C₂₄H₁₇F⁺).



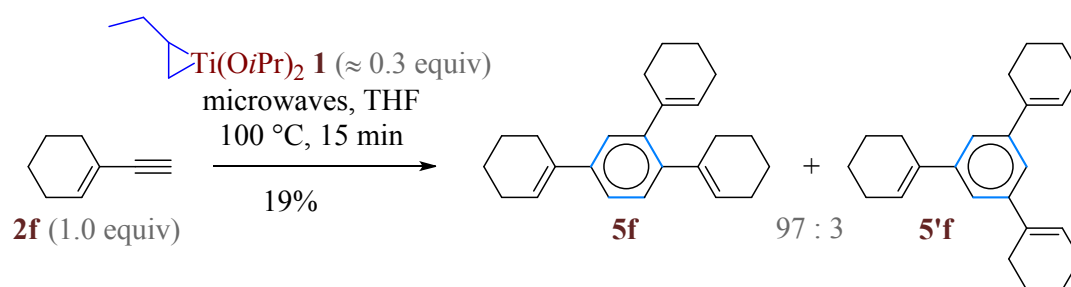
EI MS spectrum of a $\approx 65:35$ mixture of **7e** and **5e**.

For comparison, the electronic impact MS spectrum of the pure trifluoro compound **5e** is shown below. The molecular peak is clearly visible at m/z 360 (100%, **5e**⁺ C₂₄H₁₅F₃⁺). Importantly, no peaks at m/z 342 or 324 are observed, which indicates the absence of any difluoro or monofluoro compound in the sample.



EI MS spectrum of pure **5e**.

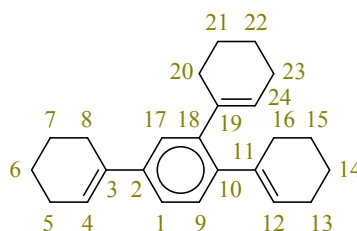
1,2,4-Tri(cyclohexen-1-yl)benzene **5f** and 1,3,5-tri(cyclohexen-1-yl)benzene **5'f**



Run 1: General procedure **G1** was applied with 1-ethynylcyclohexene **2f**. Work-up **W1** was carried out. ^1H NMR analysis of the crude product (426 mg) showed full conversion of the starting material and the production of 1,2,4- and 1,3,5-tris(1-cyclohexen-1-yl)benzene **5f** and **5'f** in 98 : 2 ratio. Flash column chromatography on silica gel (petroleum ether) only led to partial purification of **5f**, the fractions being typically contaminated with small amounts of unidentified by-products.

Run 2: The same reaction was repeated but work-up **W2** was carried out and *trans*-cinnamic acid (200 μmol , 29.6 mg) was added as an internal standard at the end of the work-up, just before concentration of the crude product under reduced pressure. ^1H NMR analysis, with comparison of the integrals of relevant signals, showed that **5f** and **5'f** had been produced in 19% yield (ratio 97 : 3).

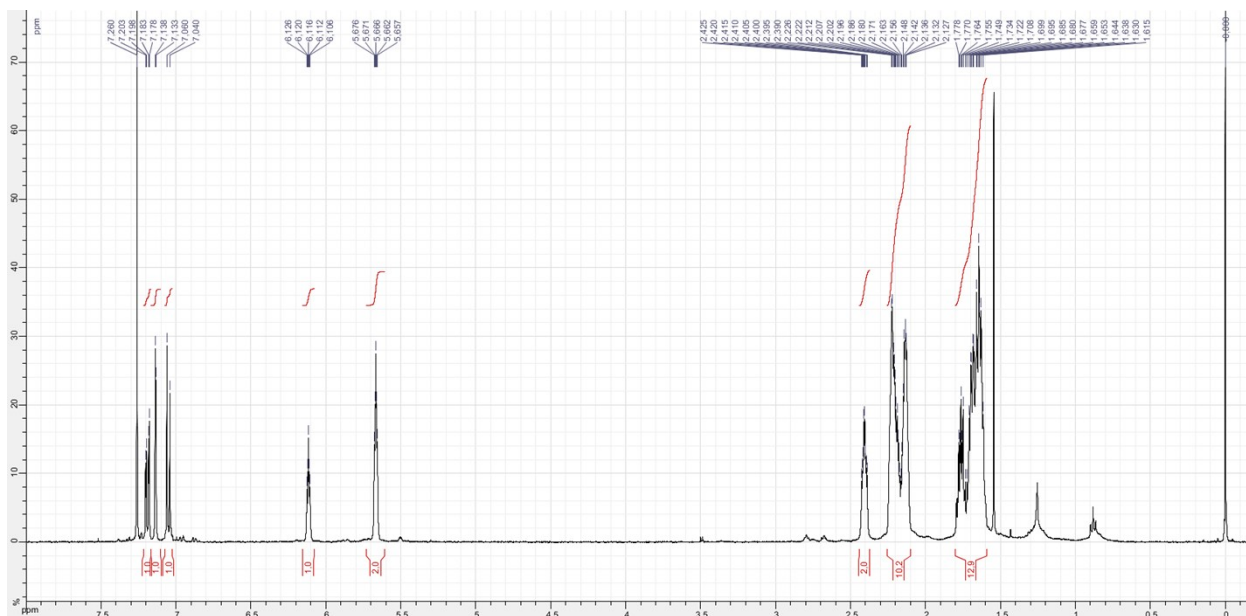
1,2,4-Tri(cyclohexen-1-yl)benzene **5f**¹⁶



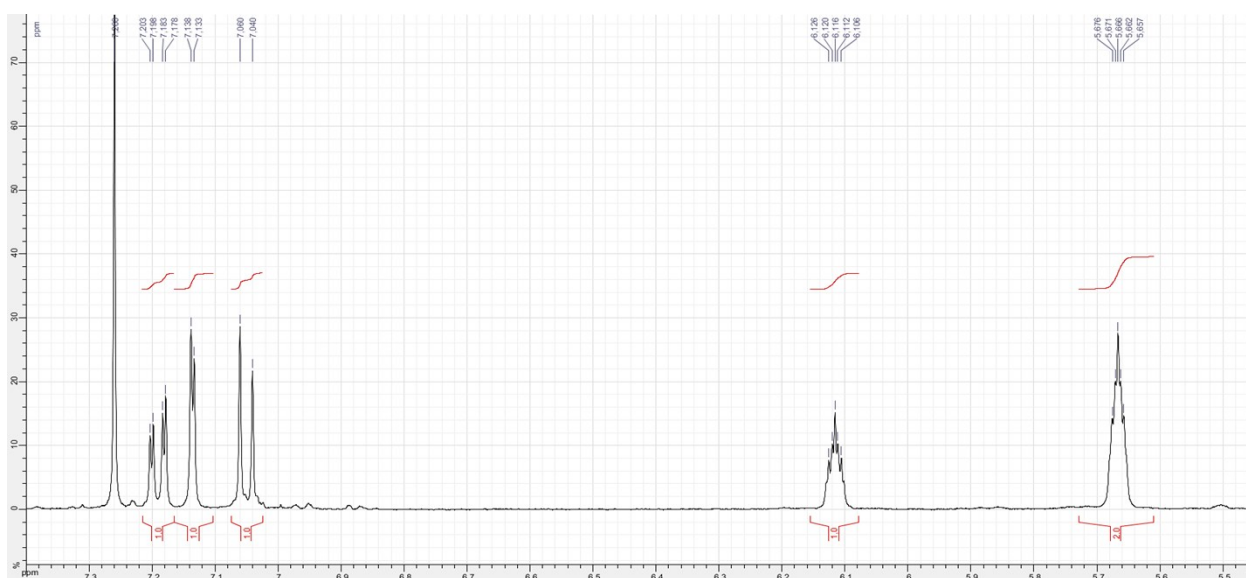
Colourless oil. *R*_f 0.7 (EtOAc/petroleum ether 1%, anisaldehyde, UV-active). ^1H NMR (CDCl_3 , 400 MHz): δ 1.59–1.80 (12 H, m, H6–H7, H14–H15, H21–H22), 2.10–2.25 (10 H, m, H5, H13, H16, H20, H23), 2.41 (2 H, m, H8), 5.67 (2 H, tt, *J* 4.0, 1.5, H12, H24), 6.12 (1 H, tt, *J* 4.0, 1.5, H4), 7.05 (1 H, d, *J* 8.0, H9), 7.14 (1 H, d, *J* 2.0, H17), 7.19 (1 H, dd, *J* 8.0, 2.0, H1).¹⁷ ^{13}C NMR (CDCl_3 , 100.6 MHz): δ 22.2 (3 C, C6, C14, C22), 23.1 (C7), 23.3 (2 C, C15, C21), 25.73, 25.74 (C13, C23), 25.9 (C5), 27.3 (C8), 29.48, 29.54 (C16, C20), 122.8 (C4), 124.2, 125.3 (C1, C9), 125.75, 125.78 (C12, C24), 128.4 (C17), 136.3 (C3), 139.1, 139.8 (C11, C19), 140.6, 141.0 (C10, C18), 142.4 (C2). HRMS (EI): *m/z* 318.2357 ($\text{M}^{+\bullet}$ $\text{C}_{24}\text{H}_{30}^{+\bullet}$ requires 318.2342).

16– K. Tanaka, K. Shirasaka, *Org. Lett.* **2003**, *5*, 4697–4699 (supporting information).

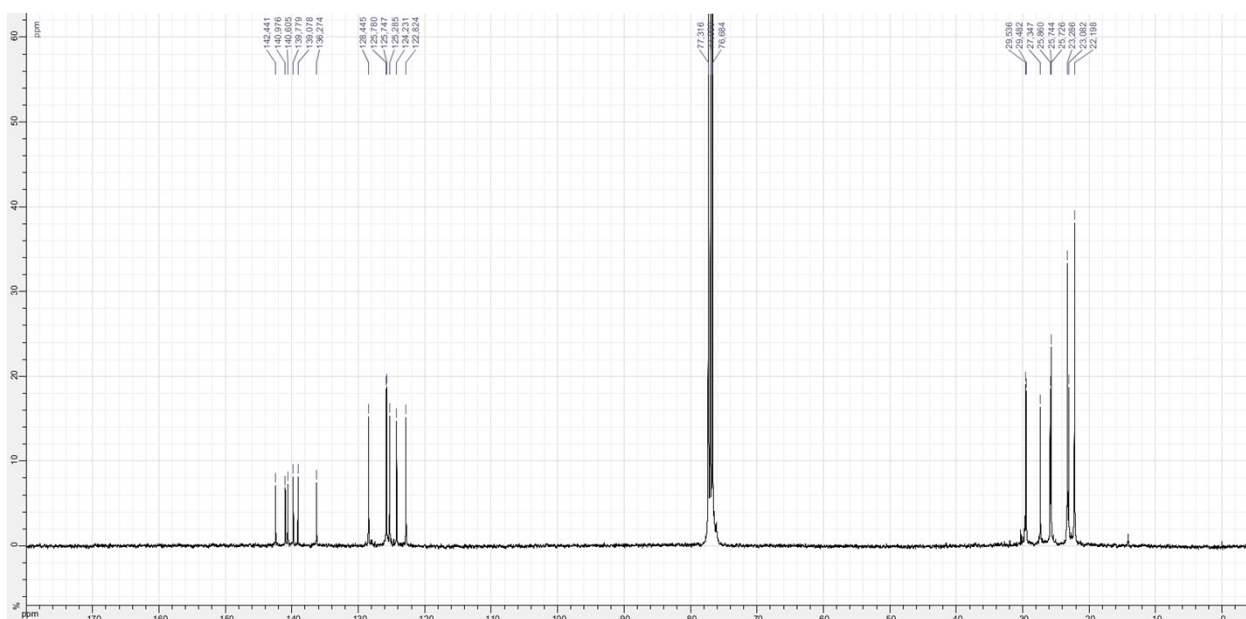
17– The signals of H1, H9 and H17 are an ABX system but are described in a simplified fashion for the sake of clarity.



¹H NMR spectrum (CDCl₃, 400 MHz).

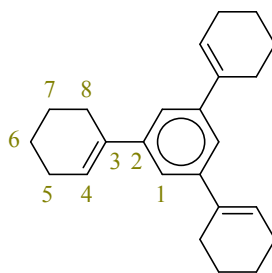


¹H NMR spectrum (selected extract) (CDCl₃, 400 MHz).

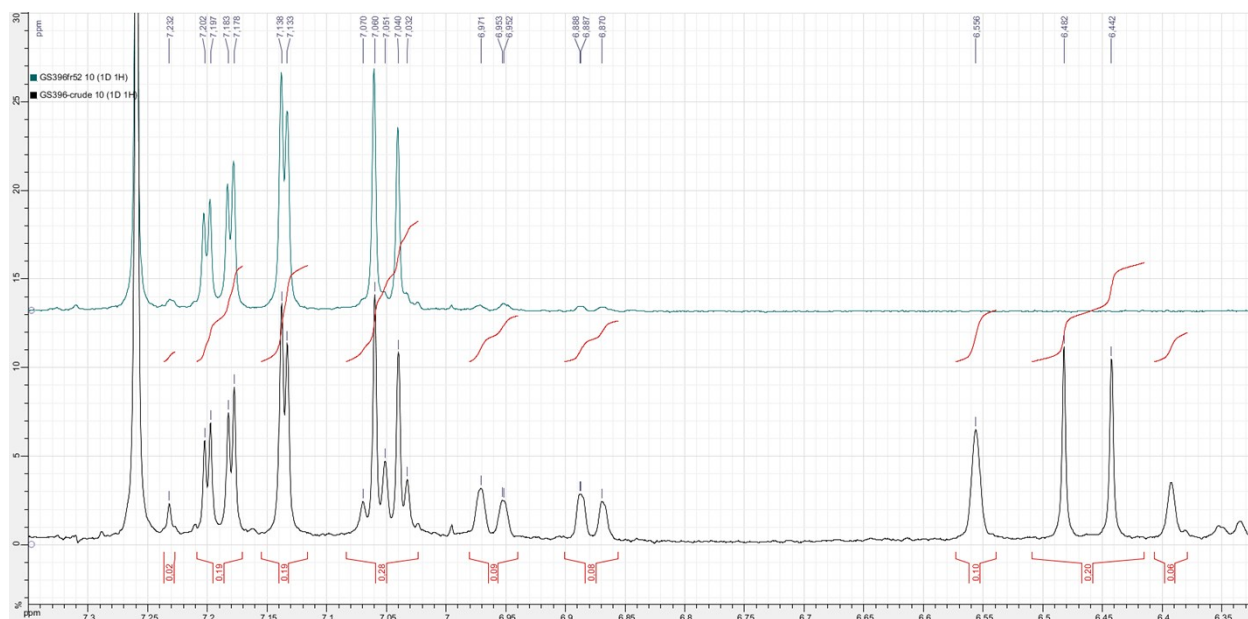


¹³C NMR spectrum (CDCl₃, 100.6 MHz).

1,3,5-Tri(cyclohexen-1-yl)benzene **5'f**¹⁶



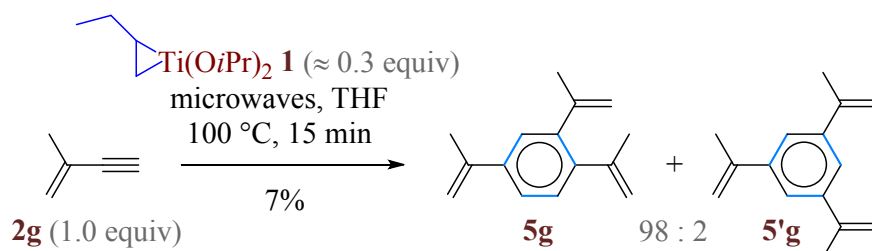
R_f 0.7 (EtOAc/petroleum ether 1%, anisaldehyde, UV-active).¹⁸ ¹H NMR (CDCl₃, 400 MHz), characteristic signals: δ 7.23 (s, 3H, C1)



¹H NMR spectrum of the crude product of **run 2** (selected extract) (CDCl₃, 400 MHz).

Notes: the doublet at δ 6.46 ppm belongs to *trans*-cinnamic acid and is used as a reference. For comparison, a spectrum of pure 1,2,4-tricyclopropylbenzene **5f** is displayed (top, in green). Signals of an unidentified by-product are visible at δ 6.88 (br d, *J* 7.5), 6.96 (br d, *J* 7.5) and 7.05 (t, *J* 7.5). A characteristic peak of **5'f** is visible at δ 7.23 ppm.

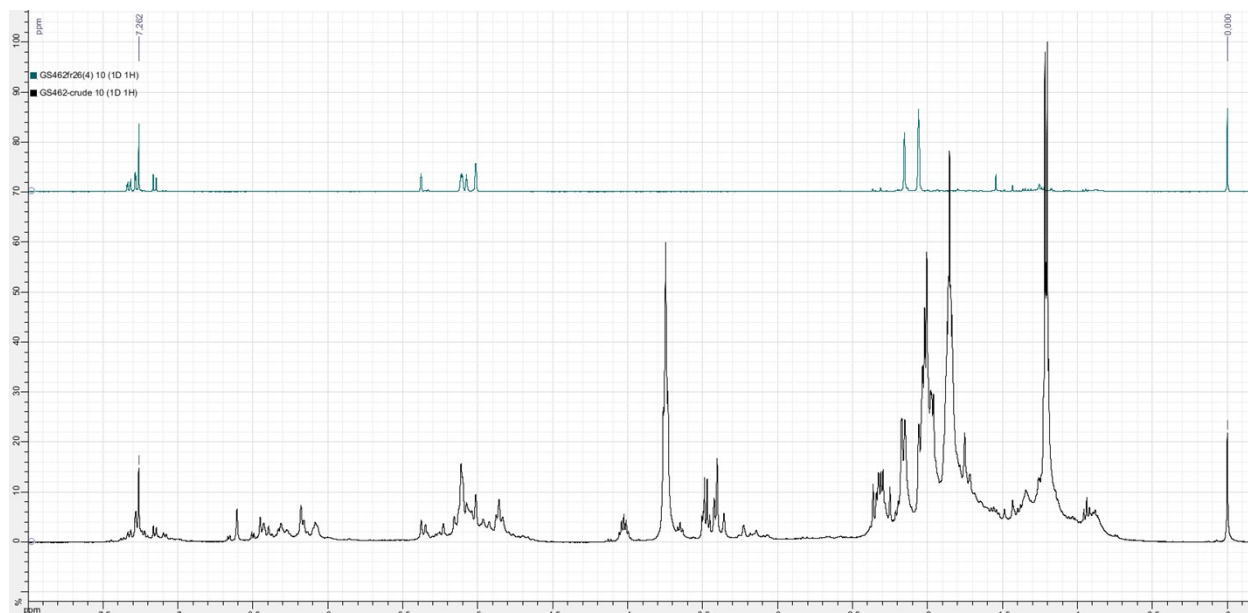
1,2,4-Triisopropenylbenzene **5g** and 1,3,5-triisopropenylbenzene **5'g**



Run 1: General procedure **G1** was applied with 2-methylbut-1-en-3-yne **2g**. Work-up **W1** was carried out. ¹H NMR analysis of the crude product (278 mg) showed production of 1,2,4- and 1,3,5-triisopropenylbenzene **5g** and **5'g** in 98 : 2 ratio. Conversion of the starting material was not determined. Purification by flash column chromatography on silica gel (pentane) afforded pure **5g** (11.2 mg) and a 90 : 10 mixture of **5g** and the 1,3,5 isomer **5'g** (3.0 mg). The total amount of triisopropenylbenzene isomers isolated is thus 13.2 mg (66.6 μmol, 7%).

¹⁸– 1,3,5-Triisopropenylbenzene **5'f** is slightly more polar than the 1,2,4 isomer **5f**.

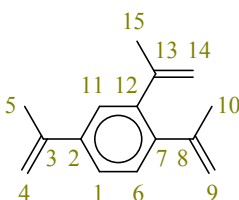
Run 2: The same reaction was repeated but work-up **W2** was carried out. ^1H NMR analysis of the crude product (196 mg) showed the production of **5g** and **5'g** in 97 : 3 ratio. Purification by flash column chromatography on silica gel (pentane) afforded a rather impure 98 : 2 mixture of the two *triisopropenylbenzene* isomers (21.5 mg; had the product been isolated in pure form, this would represent 106 μmol , 11%).



^1H NMR spectrum of the crude product (CDCl_3 , 400 MHz), showing that a complex mixture of compounds is obtained, containing only minor amounts of 1,2,4-triisopropenylbenzene **5g**.

For comparison, a spectrum of pure **5g** is displayed (top, in green).

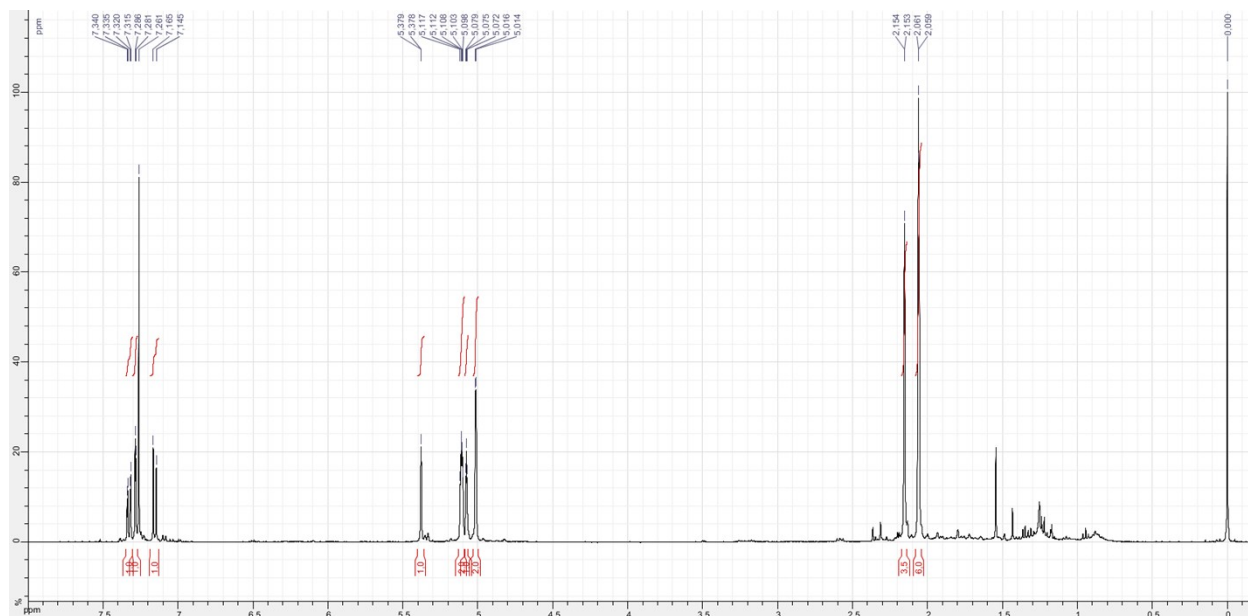
1,2,4-Triisopropenylbenzene **5g**^{19,20}



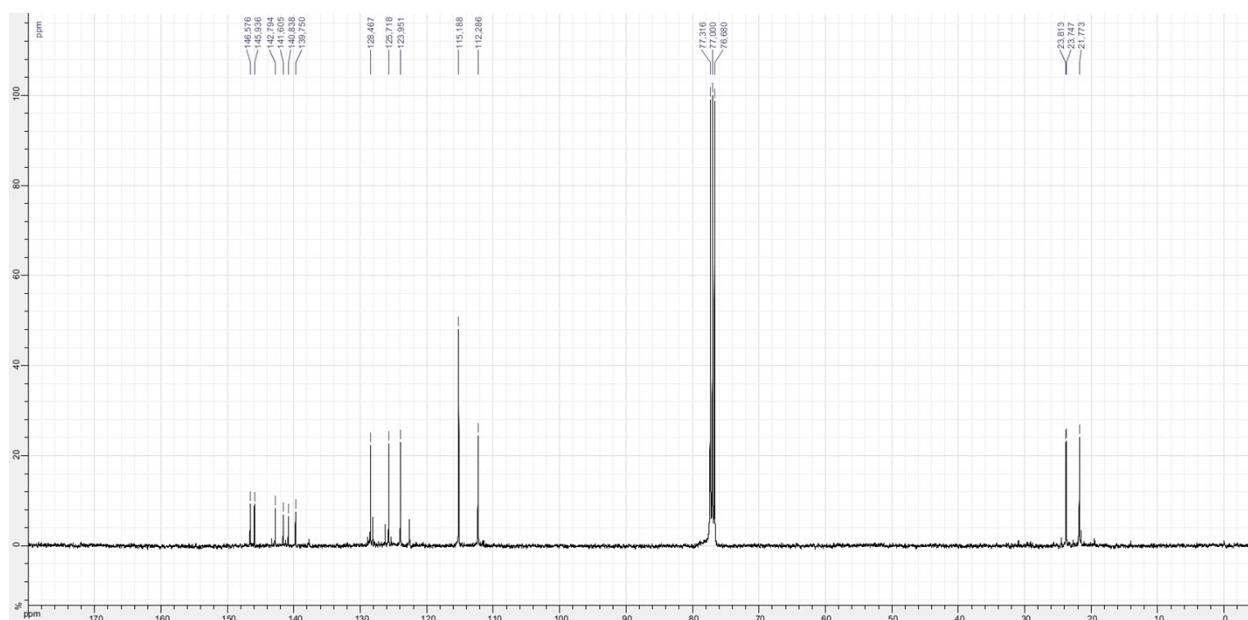
Yellowish oil. *Rf* 0.6 (petroleum ether, anisaldehyde, UV-active). ^1H NMR (CDCl_3 , 400 MHz): δ 2.04–2.08 (6 H, m, H10, H15), 2.15 (3 H, dd, J 1.5, 0.5, H5), 5.00–5.03 (2 H, m, C=CH₂), 5.07 (1 H, quint, H4a or H4b), 5.09–5.13 (2 H, m, C=CH₂), 5.38 (1 H, m, C=CH₂), 7.15 (1 H, d, J 8.0, H6), 7.28 (1 H, d, J 2.0, H11), 7.33 (1 H, dd, J 8.0, 2.0, H1). ^{13}C NMR (CDCl_3 , 100.6 MHz): δ 21.8 (C5), 23.7, 23.8 (C10, C15), 112.3 (C4), 115.2, 115.2 (C9, C14), 124.0, 125.7 (C1, C6), 128.5 (C11), 139.7 (C2), 140.8, 141.6 (C7, C12), 142.8 (C3), 145.9, 146.6 (C8, C13). HRMS (EI): m/z 198.1399 (M^+ C₁₅H₁₈⁺ requires 198.1403).

19– D. Brenna, M. Villa, T. N. Gieshoff, F. Fischer, M. Hapke, A. J. von Wangelin, *Angew. Chem. Int. Ed.* **2017**, *56*, 8451–8454 (supporting information).

20– G. Hilt, T. Vogler, W. Hess, F. Galbiati, *Chem. Commun.* **2005**, 1474–1475 (supporting information).

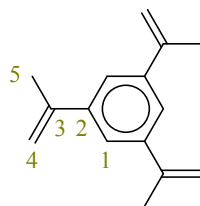


^1H NMR spectrum (CDCl_3 , 400 MHz).

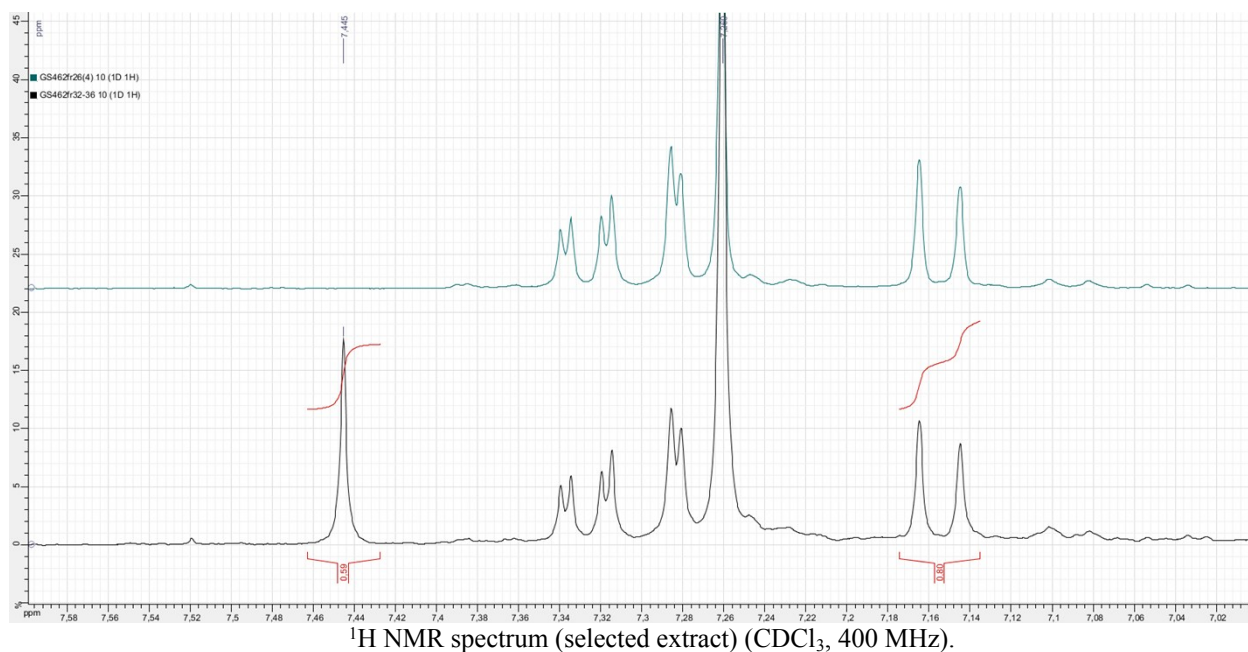


^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).

1,3,5-Triisopropenylbenzene **5'g**²⁰



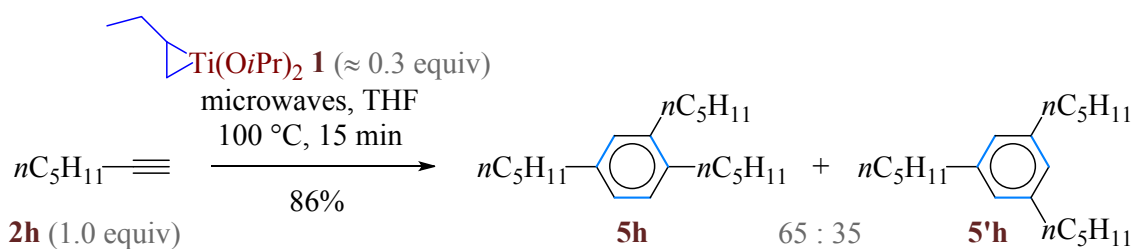
Yellowish oil. *R_f* 0.6 (petroleum ether, anisaldehyde, UV-active).²¹ ¹H NMR (CDCl₃, 400 MHz), characteristic signals: δ 2.18 (9 H, dd, *J* 1.5, 0.5, H5), 7.44 (3 H, s, H1).



¹H NMR spectrum (selected extract) (CDCl₃, 400 MHz).

Note: this analysis was recorded with a sample containing a ≈ 80 : 20 mixture of 1,2,4 and 1,3,5 isomers of triisopropenylbenzene **5g** and **5'g**. For comparison, a spectrum of pure **5g** is displayed (top, in green).

1,2,4-Tripentylbenzene **5h** and 1,3,5-tripentylbenzene **5'h**

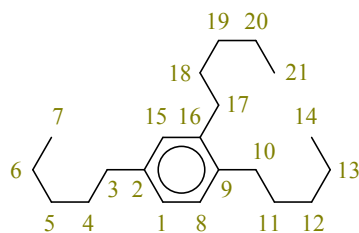


General procedure **G1** was applied with hept-1-yne **2h**. Work-up **W1** was carried out. Analysis of the crude product by ¹H NMR spectroscopy showed full conversion of the starting material and the production of 1,2,4- and 1,3,5-tripentylbenzene **5h** and **5'h** in an estimated 65 : 35 ratio. Minor diene by-products **4h** and **4'h** made purification difficult and they were therefore destroyed by the following treatment: concentrated H₂SO₄ (0.5 mL) was added dropwise to the crude product at 0 °C. After 15 min of stirring at r.t., H₂O (20 mL) was added dropwise at 0 °C and the mixture was extracted with Et₂O (3 × 20 mL). The combined organic phases were dried over MgSO₄, filtered

²¹– 1,3,5-Triisopropenylbenzene **5'g** is slightly more polar than the 1,2,4 isomer **5g**.

and concentrated under reduced pressure. Purification of the residue (351 mg, brown oil) by flash column chromatography on silica gel (petroleum ether) afforded a 62 : 38 mixture of **5h** and **5'h** (247 mg, 530 and 330 μmol respectively). The yields obtained for both compounds are thus 53% (**5h**) and 33% (**5'h**).

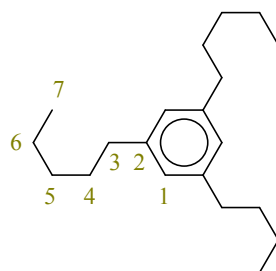
1,2,4-Tripentylbenzene **5h**^{4,22}



Yellow oil. R_f 0.8 (petroleum ether, anisaldehyde, UV-active). ^1H NMR (CDCl_3 , 400 MHz): δ 0.89 (3 H, t, J 6.5, H7), 0.90 (3 H, t, J 6.5, H14 or H21), 0.91 (3 H, t, J 6.5, H14 or H21), 1.20–1.42 (12 H, m, H5, H6, H12, H13, H19, H20), 1.50–1.65 (6 H, m, H4, H11, H18), 2.53 (2 H, t, J 7.5, H3), 2.56 (2 H, t, J 7.5, H10 or H17), 2.56 (2 H, t, J 7.5, H10 or H17), 6.95 (1 H, br d J 2.0, H15), 6.99 (2 H, AB part of an ABX system, δ_A 6.93, δ_B 7.04, J_{AB} 7.5, J_{AX} 2.0, J_{BX} 0.0, H1, H8).

^{13}C NMR (CDCl_3 , 100.6 MHz), characteristic signals: δ 14.1, 14.1, 14.1 (C7, C14, C21), 22.6, 22.6 (C13, C20), 22.7 (C6), 32.3, 32.8 (C10, C17), 35.6 (C3), 125.7 (C1), 128.9 (C8), 129.2 (C15), 137.7 (C2), 140.1, 140.3 (C9, C16). HRMS (EI):²³ m/z 288.2817 (M^+ $\text{C}_{21}\text{H}_{36}^+$ requires 288.2812).

1,3,5-Tripentylbenzene **5'h**^{4,22}

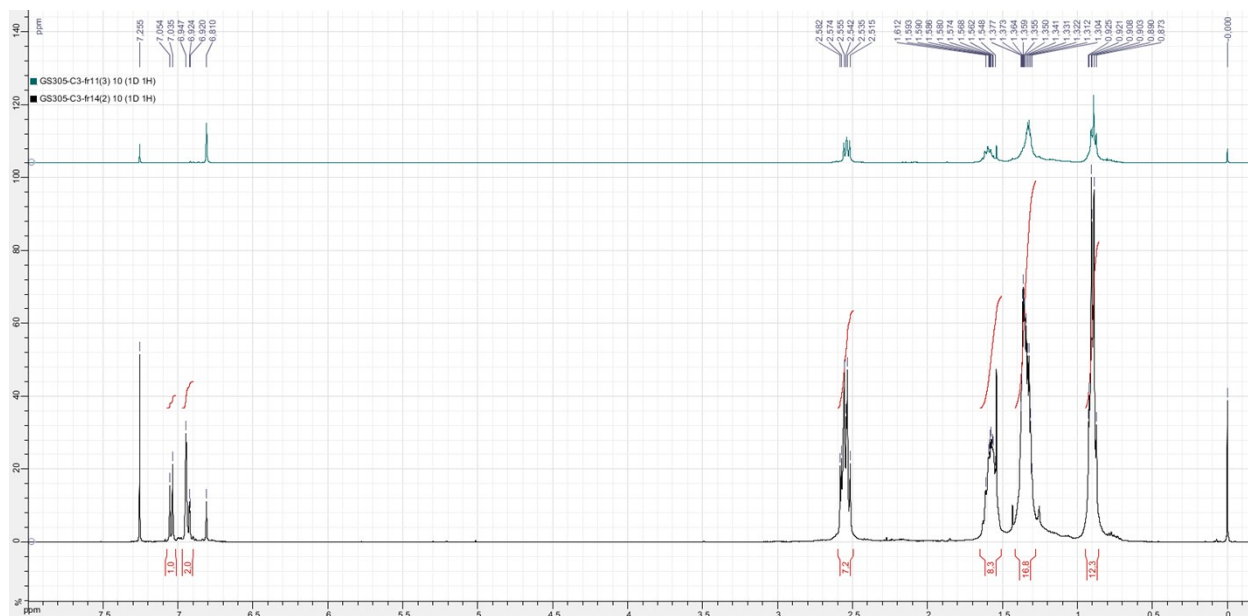


Yellow oil. R_f 0.8 (petroleum ether, anisaldehyde, UV-active).²⁴ ^1H NMR (CDCl_3 , 400 MHz): δ 0.89 (9 H, t, J 6.5, H7), 1.28–1.37 (12 H, m, H5, H6), 1.60 (6 H, tt, J 7.5, 7.0, H4), 2.54 (6 H, t, J 7.5, H3), 6.81 (3 H, s, H1). ^{13}C NMR (CDCl_3 , 100.6 MHz), characteristic signals: δ 14.1 (C7), 22.6 (C6), 36.0 (C3), 125.8 (C1), 142.7 (C2).

22– C. C. Eichman, J. P. Bragdon, J. P. Stambuli, *Synlett* **2011**, 1109–1112 (supporting information).

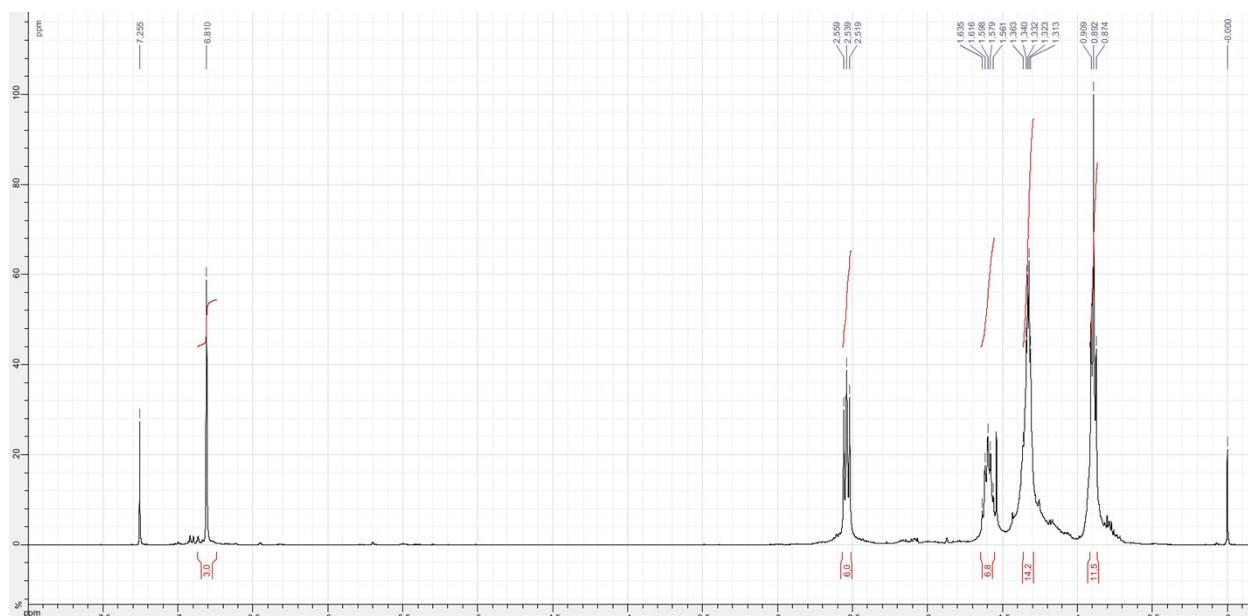
23– Analysis performed on a 62 : 38 mixture of **5h** and **5'h**.

24– 1,3,5-Tripentylbenzene **5'h** is slightly less polar than 1,2,4-tripentylbenzene **5h**.



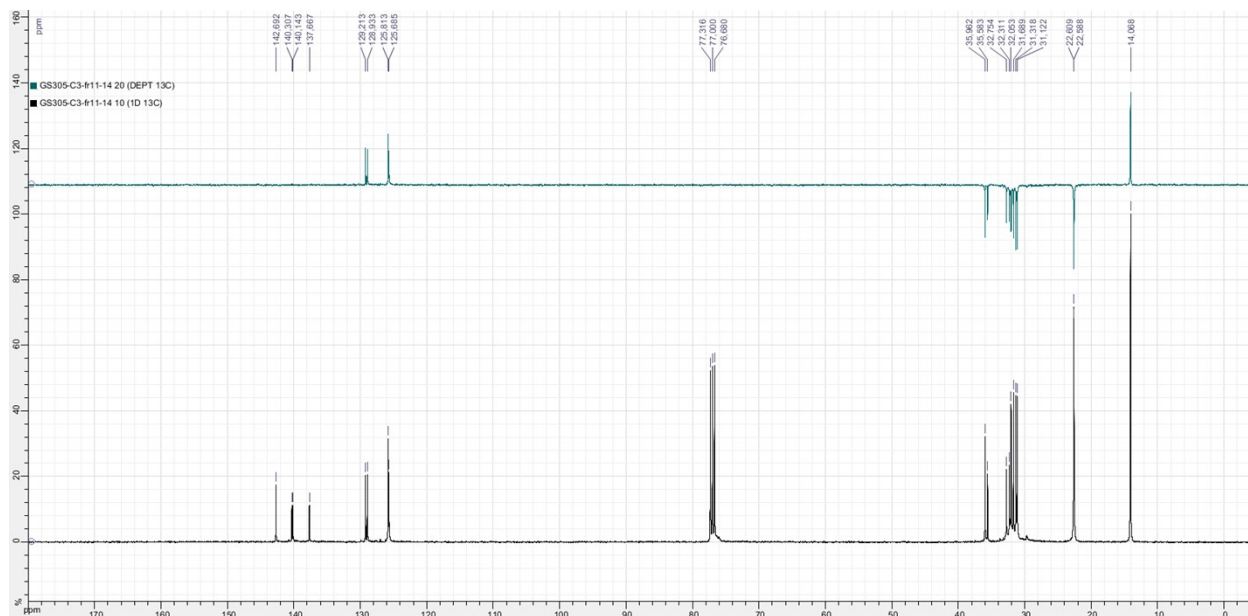
^1H NMR spectrum (CDCl_3 , 400 MHz).

Note: this analysis was recorded with a $\approx 90 : 10$ mixture of 1,2,4 and 1,3,5 isomers **5h** and **5'h**.
 For comparison, a spectrum of pure **5'h** is displayed (top, in green).



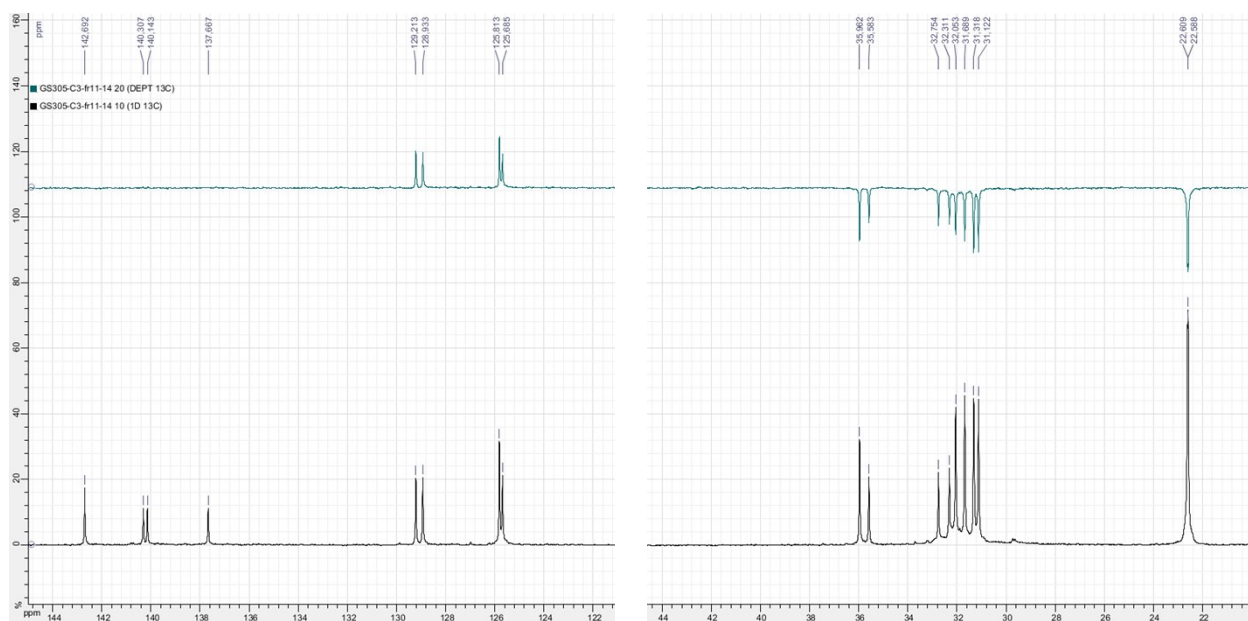
^1H NMR spectrum (CDCl_3 , 400 MHz).

Note: this analysis was recorded with essentially pure 1,3,5 isomer **5'h**.



^{13}C and DEPT135 NMR spectra (CDCl_3 , 100.6 MHz).

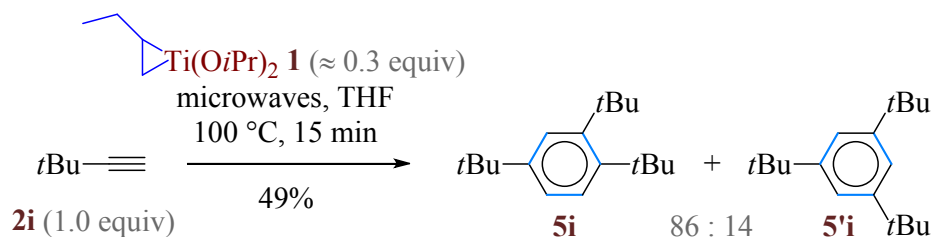
Note: this analysis was recorded with a $\approx 66 : 34$ mixture of 1,2,4 and 1,3,5 isomers **5h** and **5'h**.



^{13}C NMR and DEPT-135 spectra (selected extracts) (CDCl_3 , 100.6 MHz).

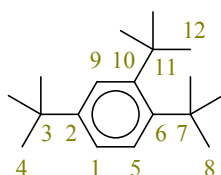
Note: this analysis was recorded with a $\approx 66 : 34$ mixture of 1,2,4 and 1,3,5 isomers **5h** and **5'h**.

1,2,4-Tri(*tert*-butyl)benzene **5i** and 1,3,5-tri(*tert*-butyl)benzene **5'i**



General procedure **G1** was applied with *tert*-butylacetylene **2i**. Work-up **W1** was carried out. ^{13}C NMR analysis of the crude product (360 mg, orange oil) showed full conversion of the starting material and the production of 1,2,4-tri(*tert*-butyl)benzene **5i** and 1,3,5-tri(*tert*-butyl)benzene **5'i** in 86 : 14 ratio. Purification by flash column chromatography on silica gel (petroleum ether) afforded a 90 : 10 mixture of **5i** and **5'i** (121 mg, 491 μmol , 49%). Further purification by trituration in MeOH afforded a highly pure **5i** / **5'i** mixture (ratio 97 : 3).

1,2,4-Tri(*tert*-butyl)benzene **5i**²⁵



White solid. R_f 0.8 (petroleum ether, anisaldehyde, UV-active). ^1H NMR (CDCl_3 , 400 MHz): δ 1.31 (9 H, s, H4), 1.54 (9 H, s, H8 or H12), 1.56 (9 H, s, H8 or H12), 7.13 (1 H, dd, J 8.5, 2.5, H1), 7.51 (1 H, d, J 8.5, H5), 7.62 (1 H, d, J 2.5, H9). ^{13}C NMR (CDCl_3 , 100.6 MHz): δ 31.3 (C4), 34.3 (C3), 34.80, 34.84 (C8, C12), 37.2, 38.0 (C7, C11), 122.2 (C1), 126.8 (C5), 129.1 (C9), 145.6 (C2), 147.3, 148.1 (C6, C10). HRMS (EI): m/z 246.2342 (M^+ $\text{C}_{18}\text{H}_{30}^+$ requires 246.2342).²⁶

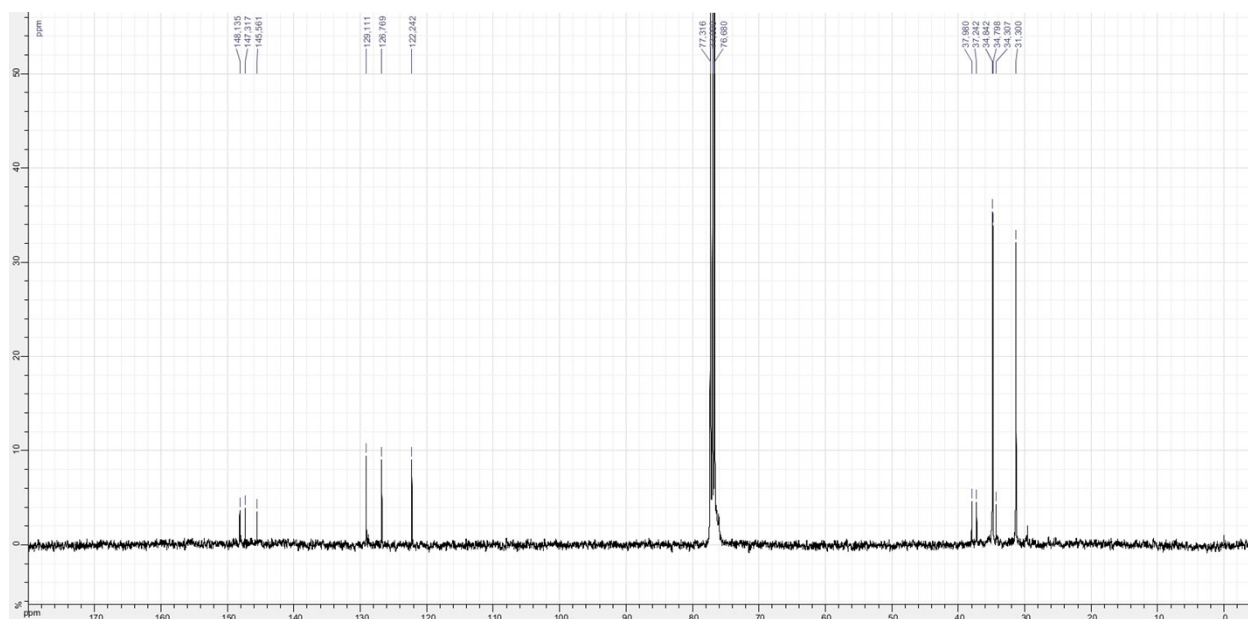


^1H NMR spectrum (CDCl_3 , 400 MHz).

Note: this analysis was recorded with a \approx 97 : 3 mixture of **5i** and **5'i**.

25– H. Künzer, S. Berger, *J. Org. Chem.* **1985**, *50*, 3222–3223.

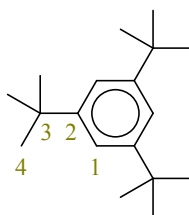
26– Analysis performed on a \approx 86 : 14 mixture of 1,2,4 and 1,3,5 isomers of tri(*tert*-butyl)benzene **5i** and **5'i**.



^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).

Note: this analysis was recorded with a $\approx 97 : 3$ mixture of **5i** and **5'i**.

1,3,5-Tri(*tert*-butyl)benzene **5'i**⁸

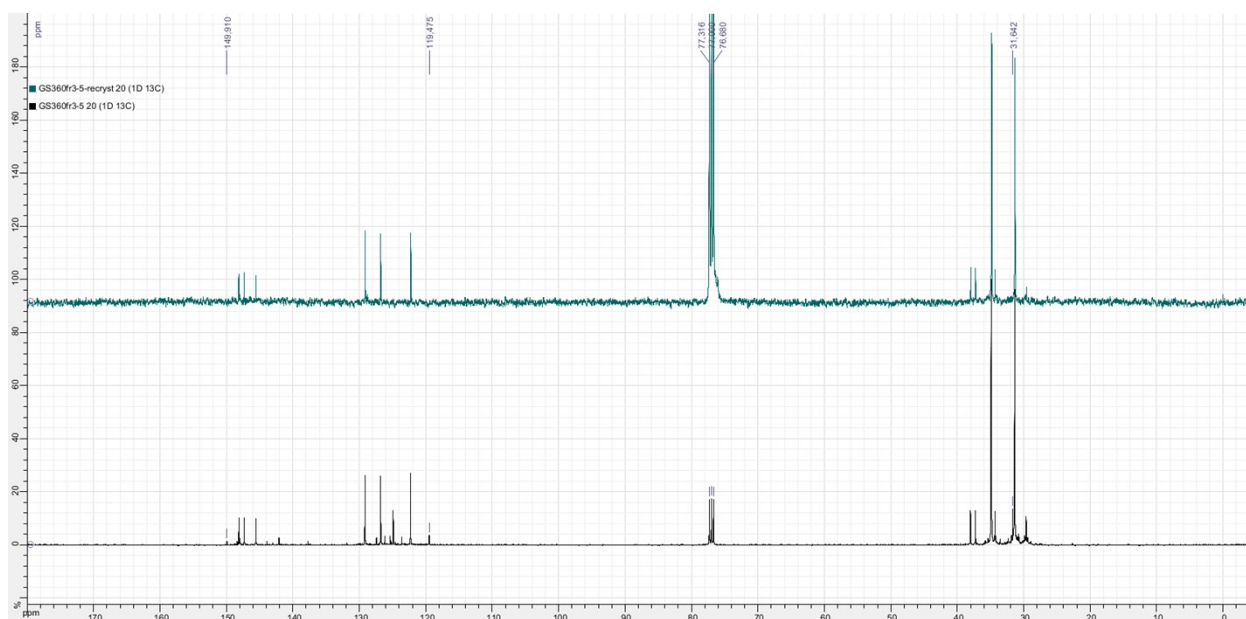


R_f 0.8 (petroleum ether, anisaldehyde, UV-active). ^1H NMR (CDCl_3 , 400 MHz), characteristic signal: δ 7.32 (3 H, s, H1). ^{13}C NMR (CDCl_3 , 100.6 MHz), characteristic signals: δ 31.6 (C4), 119.5 (C1), 149.9 (C2).



^1H NMR spectrum (CDCl_3 , 400 MHz).

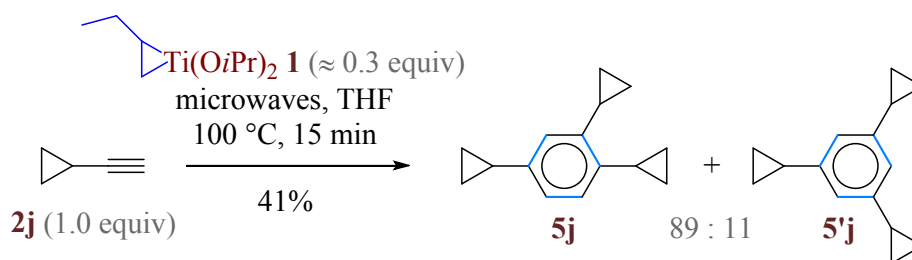
Note: in black (bottom), spectrum of a $\approx 90 : 10$ mixture of mixture of **5i** and **5'i**; in green (top), spectrum of **5i** alone.



^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).

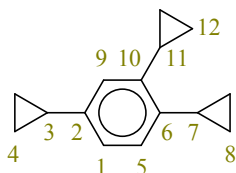
Note: in black (bottom), spectrum of a $\approx 86 : 14$ mixture of mixture of **5j** and **5'j**; in green (top), spectrum of **5j** alone.

1,2,4-Tricyclopropylbenzene **5j** and 1,3,5-tricyclopropylbenzene **5'j**



General procedure **G1** was applied with cyclopropylacetylene **2j**. Work-up **W1** was carried out. ^1H NMR analysis of the crude product showed the production of 1,2,4-tricyclopropylbenzene **5j** and 1,3,5-tricyclopropylbenzene **5'j** in 89 : 11 ratio. Conversion of the starting material was not determined. Purification by flash column chromatography on silica gel (pentane) afforded pure **5j** (28.1 mg, 142 μmol , 14%) and a 86 : 14 mixture of **5j** and **5'j** (52.7 mg, 229 and 37, μmol respectively). The yields obtained for both compounds are thus 37% (**5j**) and 4% (**5'j**).

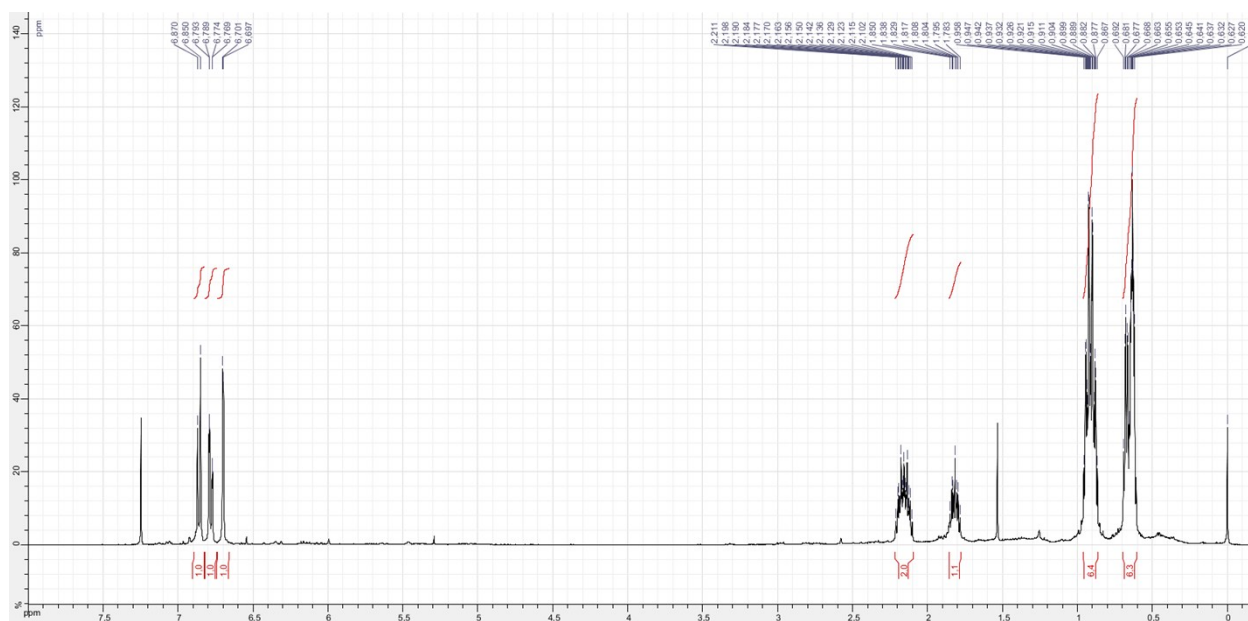
1,2,4-Tricyclopropylbenzene **5j**²⁷



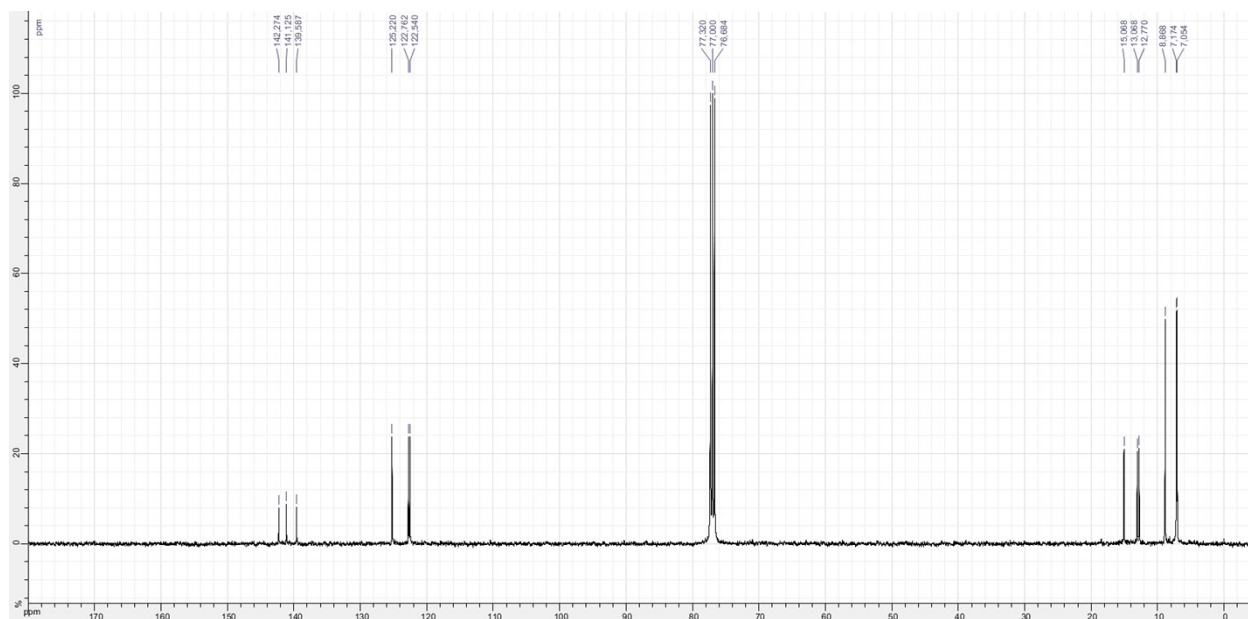
Colourless oil. R_f 0.5 (pentane, anisaldehyde, UV-active). ^1H NMR (CDCl_3 , 400 MHz): δ 0.60–0.66 (4 H, m, H8a, H12a), 0.67 (2 H, ddd, J 6.0, 5.0, 4.0, H4b), 0.86–0.97 (6 H, m, H4b, H8b, H12b), 1.82 (1 H, tt, J 8.5, 5.0, H3), 2.14 (1 H, tt, J 8.5, 5.5, H7 or H11), 2.18 (1 H, tt, J 8.5, 5.5, H7 or H11), 6.70 (1 H, d, J 2.0, H9), 6.82 (2 H, AB part of an ABX system, δ_A 6.78, δ_B 6.86, J_{AB} 8.0, J_{AX} 2.0, J_{BX} 0.0, H5, H1). ^{13}C NMR (CDCl_3 , 100.6 MHz): δ 7.1, 7.2 (C8, C12), 8.9 (C4),

27– S. K. Rodrigo, I. V. Powell, M. G. Coleman, J. A. Krause, H. Guan, *Org. Biomol. Chem.* **2013**, *11*, 7653–7657 (supporting information).

12.8, 13.1 (C7, C11), 15.1 (C3), 122.5, 122.8 (C5, C9), 125.2 (C1), 139.6 (C2), 141.1, 142.3 (C6, C10). HRMS (EI): m/z 198.1406 (M^+ $C_{15}H_{18}^{+}$ requires 198.1403).

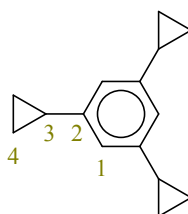


1H NMR spectrum (CDCl₃, 400 MHz).



^{13}C NMR spectrum (CDCl₃, 100.6 MHz).

1,3,5-Tricyclopropylbenzene **5j'**²⁷

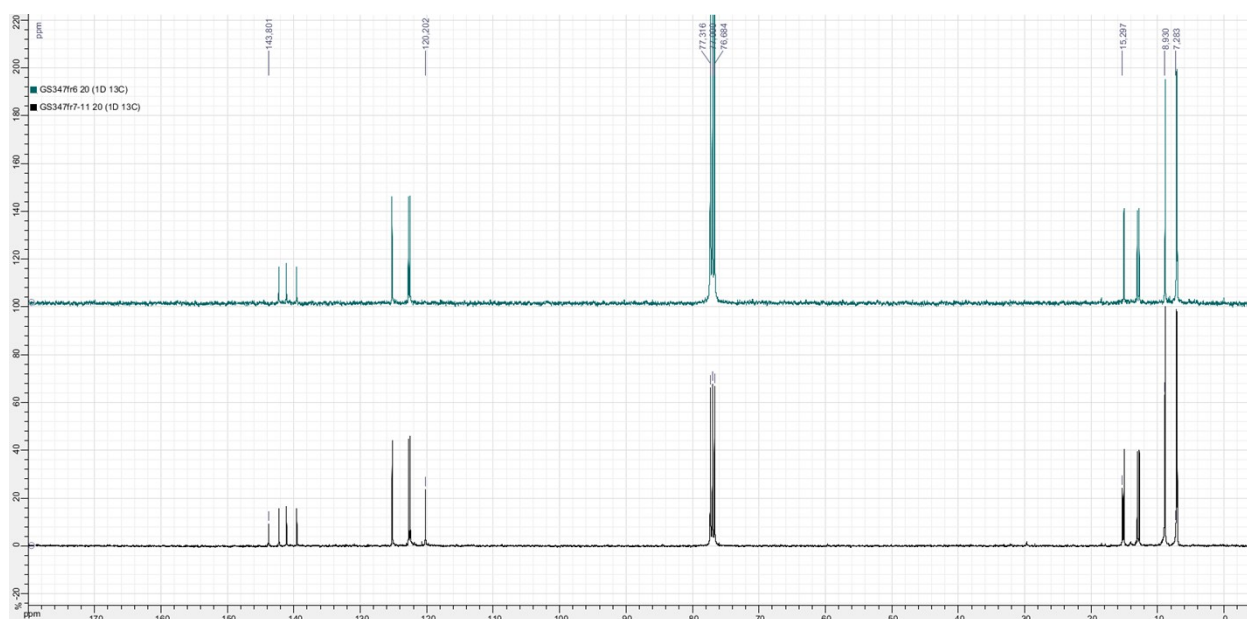


Rf 0.5 (pentane, anisaldehyde, UV-active).²⁸ ¹H NMR (CDCl₃, 400 MHz): δ 0.65 (6 H, m, H4a), 0.90 (6 H, m, H4b), 1.81 (3 H, tt, *J* 8.0, 5.0, H3), 6.56 (3 H, s, H1). ¹³C NMR (CDCl₃, 100.6 MHz): δ 8.9 (C4), 15.3 (C3), 120.2 (C1), 143.8 (C2).



¹H NMR spectrum (CDCl₃, 400 MHz).

Note: this analysis was recorded with a ≈ 86 : 14 mixture of 1,2,4 and 1,3,5 isomers **5j** and **5j'**.
For comparison, a spectrum of pure **5j** is displayed (top, in green).

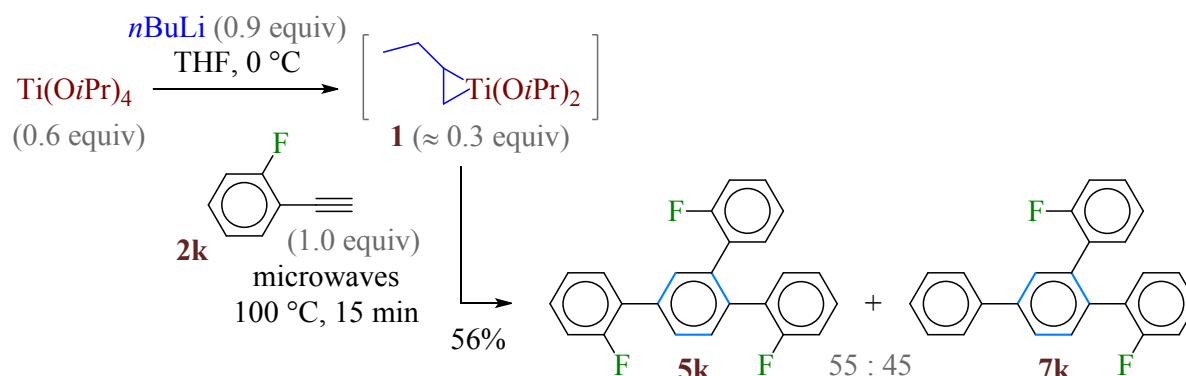


¹³C NMR spectrum (CDCl₃, 100.6 MHz).

Note: this analysis was recorded with a ≈ 86 : 14 mixture of 1,2,4 and 1,3,5 isomers **5j** and **5j'**.
For comparison, a spectrum of pure **5j** is displayed (top, in green).

28– 1,3,5-Tricyclopropylbenzene **5j'** is slightly more polar than the 1,2,4 isomer **5j**.

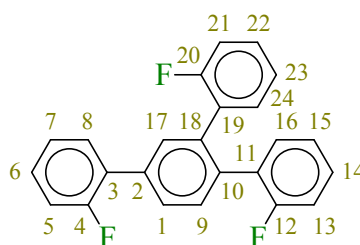
1,2,4-Tris(2-fluorophenyl)benzene **5k** and 1,2-bis(2-fluorophenyl)-4-phenyl-benzene **7k**



General procedure **G1** was applied with 2-fluorophenylacetylene. Work-up **W1** was carried out. Analysis of the crude product by ^{13}C NMR spectroscopy showed full conversion of the starting material and the production of **5k** and **7k** in an estimated 55 : 45 ratio. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 2%) afforded pure 1,2,4-tris(2-fluorophenyl)benzene **5k** (4.2 mg, 11.7 μmol , 1%) and a 52 : 48 mixture of **5k** and 1,2-bis(2-fluorophenyl)-4-phenyl-benzene **7k** (as determined by ^{13}C NMR spectroscopy, 198 mg, 286 and 264 μmol respectively). The yields obtained for both compounds are thus 30% (**5k**) and 26% (**7k**).

Note: for the estimation of the **5k/7k** ratio by ^{13}C NMR spectroscopy, the intensities of the following peaks were used: δ 124.4 (d, J 3.5, 1C of **5k**), 131.3 (d, J 2.5, 1C of **5k**), 126.5 (1C of **7k**), 127.2 (2C of **7k**) and 127.5 (1C of **7k**).

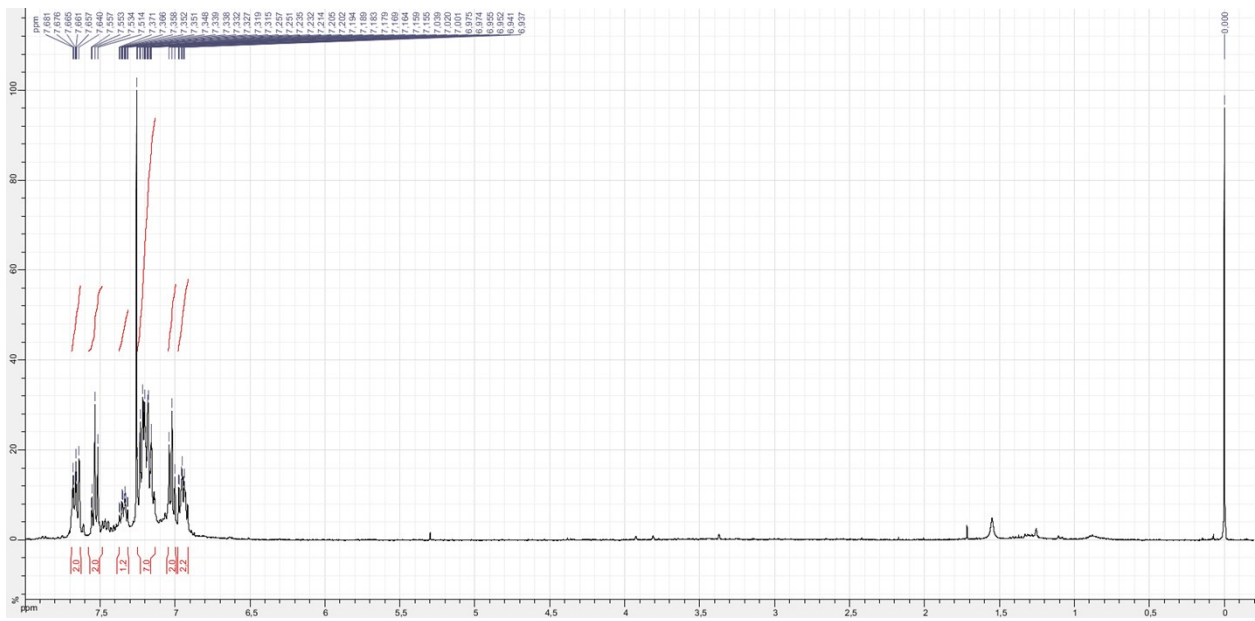
1,2,4-Tris(2-fluorophenyl)benzene **5k**



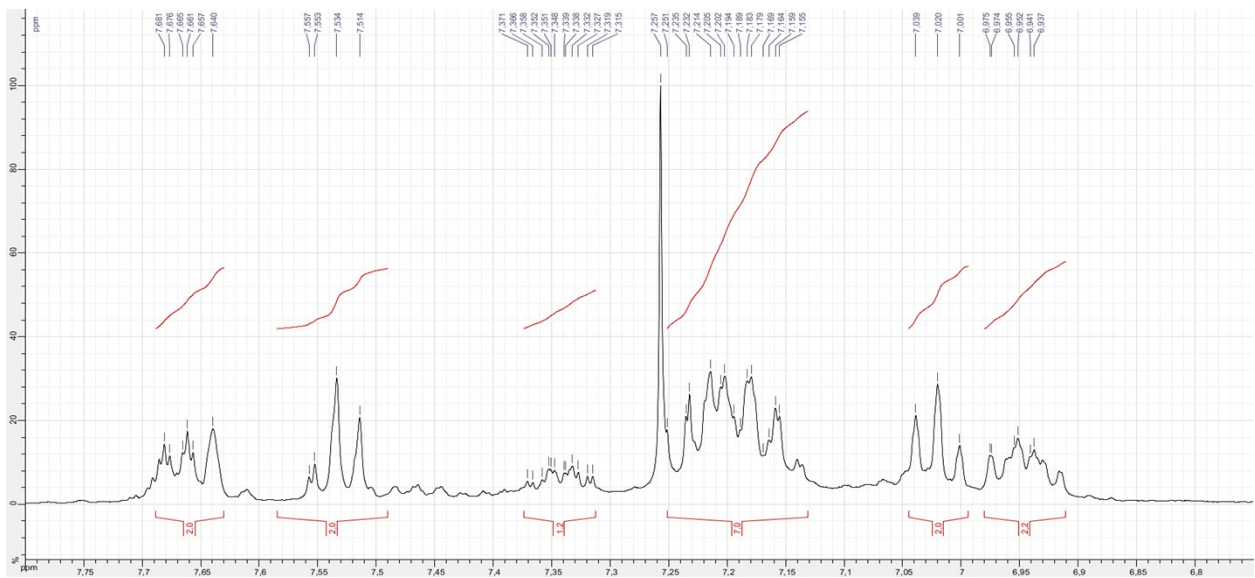
Colourless oil. R_f 0.3 (EtOAc/petroleum ether 2%, UV-active). ^1H NMR (CDCl_3 , 400 MHz): δ 6.94 (1 H, ddd, J 10.0, 8.0, 1.0, H13 or H21), 6.95 (1 H, ddd, J 10.0, 8.0, 1.0, H13 or H21), 7.02 (2 H, br d, J 7.5, H15, H23), 7.13–7.24 (5 H, m, H5, H14, H16, H22, H24), 7.23 (1 H, br t, J 7.5, H7), 7.34 (1 H, tdd, J 8.0, 5.0, 2.0, H6), 7.52 (1 H, d, J 8.0, H9), 7.54 (1 H, dd, J 8.0, 2.0, H1), 7.64 (1 H, br s, H17), 7.67 (1 H, ddd, J 8.0, 2.0, 1.5, H8). ^{13}C NMR (CDCl_3 , 100.6 MHz): δ 115.3 (2 C, d, J 22.5, C13, C21), 116.2 (d, J 22.5, C5), 123.6 (d, J 3.0, C15 or C23), 123.6 (d, J 3.0, C15 or C23), 124.4 (d, J 3.5, C7), 128.5 (C17), 129.02 (d, J 8.0, C14 or C22), 129.03 (d, J 8.0, C14 or C22), 129.2 (d, J 8.0, C6), 130.8, 130.8 (C1, C9), 131.3 (d, J 2.5, C8), 131.8 (2 C, br s, C16, C24), 135.0, 135.4, 135.8 (C2, C10, C18), 159.4 (d, J 247.0, C12 or C20), 159.5 (d, J 246.5, C12 or C20), 159.8 (d, J 248.0, C4). The signals of carbons C3, C11 and C19 could not be identified with certainty.

^{19}F NMR (CDCl_3 , 282.4 MHz): δ -117.76 (1 F, br m, F4), -115.32 (2 F, br m, F12, F20).

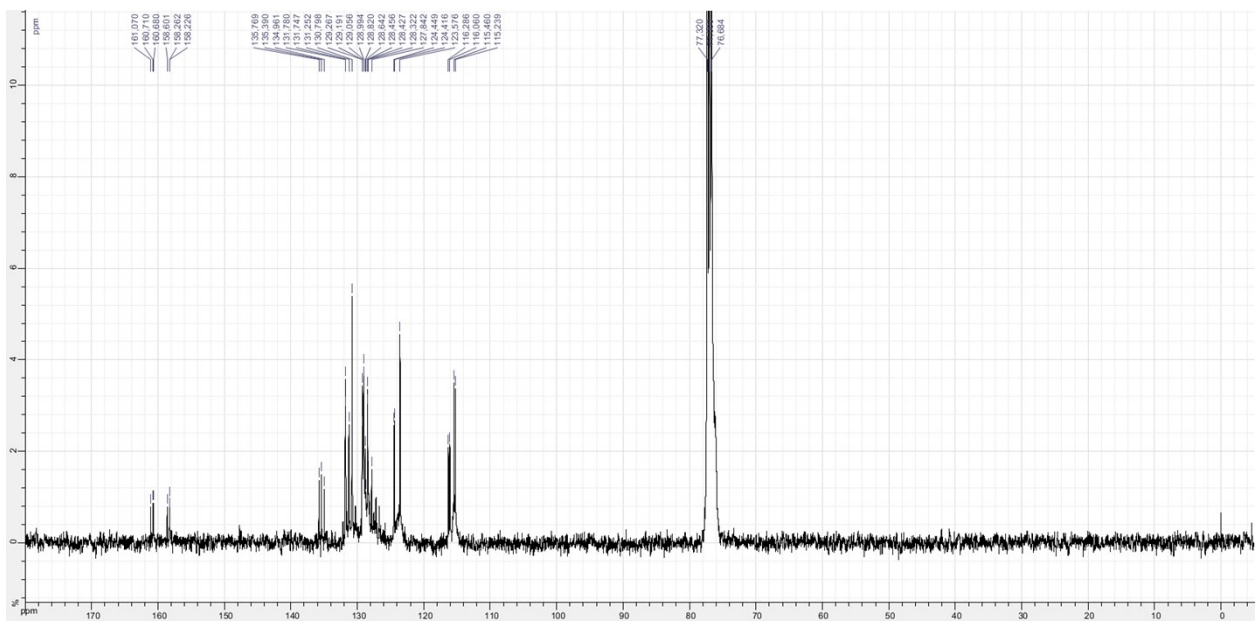
HRMS (EI): m/z 360.1130 (M^+ $\text{C}_{24}\text{H}_{15}\text{F}_3^+$ requires 360.1120).



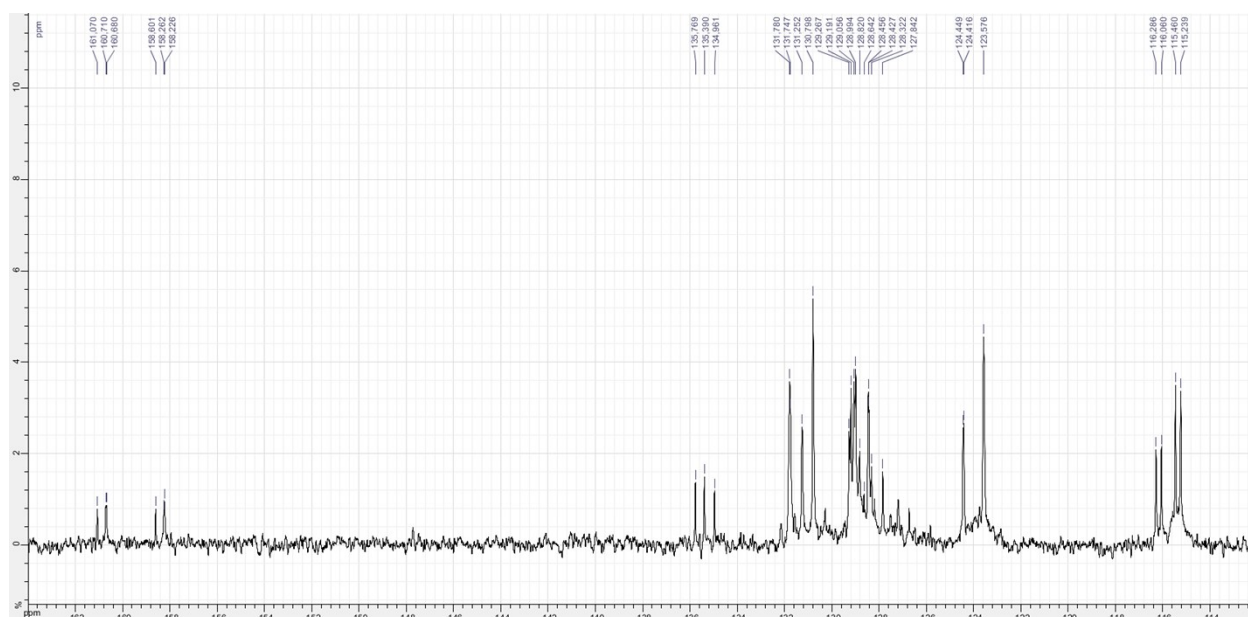
^1H NMR spectrum (CDCl_3 , 400 MHz).



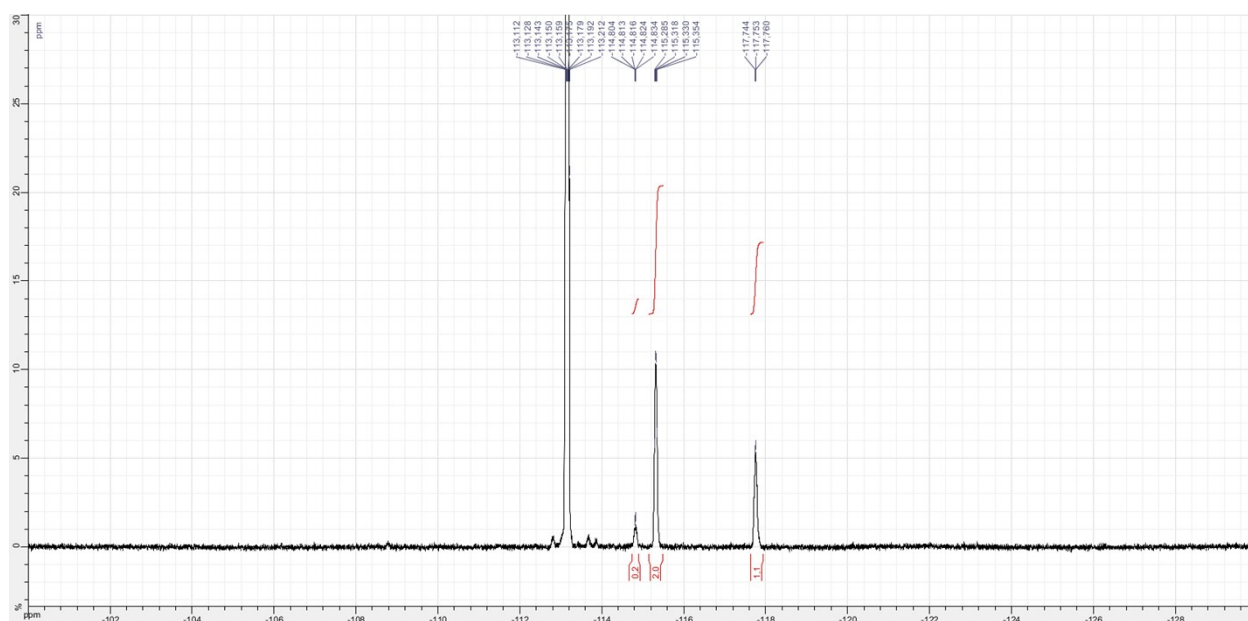
^1H NMR spectrum (selected extract) (CDCl_3 , 400 MHz).



^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).



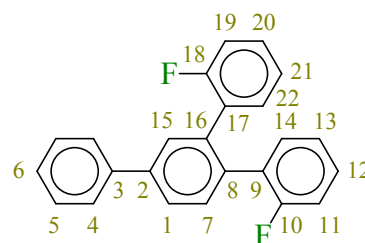
^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).



^{19}F NMR spectrum (CDCl_3 , 282.4 MHz).

Fluorobenzene was added to the sample, as an internal reference.

1,2-Bis(2-fluorophenyl)-4-phenyl-benzene **7k**

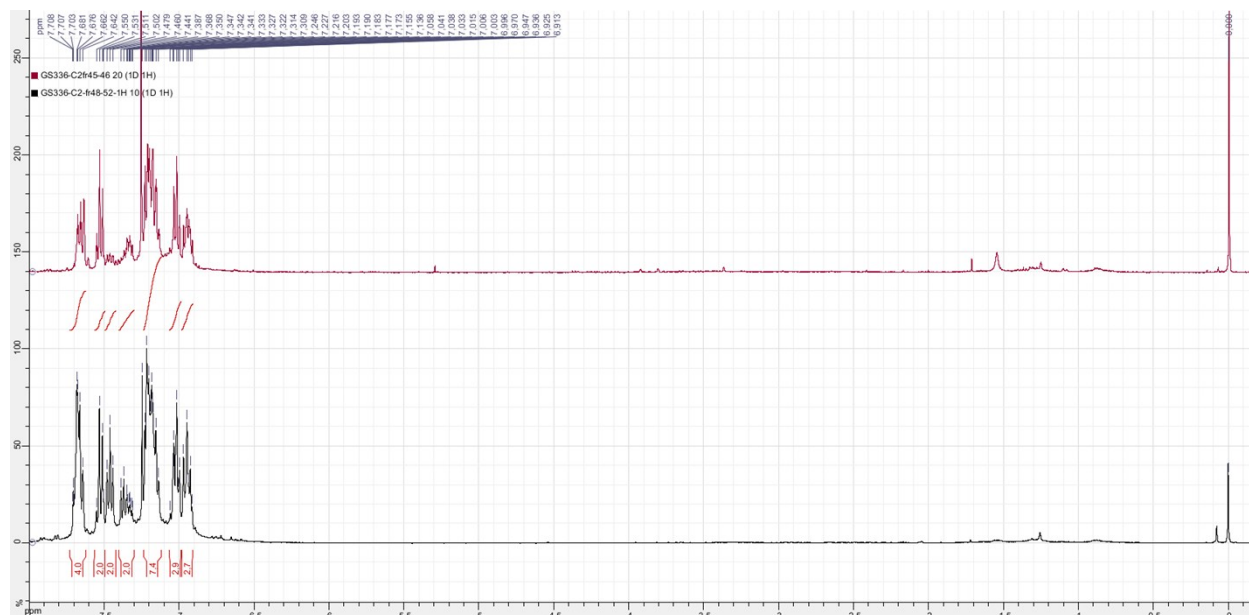


Colourless oil. R_f 0.3 (EtOAc/petroleum ether 2%, UV-active).²⁹ ^1H NMR (CDCl_3 , 400 MHz): δ 6.91–6.97 (2 H, m, H11, H19), 6.98–7.04 (2 H, m, H13, H21), 7.36 (1 H, br t, J 7.5, H6), 7.45 (2 H, br t, J 7.5, H5), 7.52 (1 H, d, J 8.0, H7), 7.12–7.24 (4 H, m, H12, H14, H20, H22), 7.63–7.70 (2 H, m, H1, H15), 7.66 (2 H, br d, J 8.0, H4). ^{13}C NMR (CDCl_3 , 100.6 MHz): δ 115.3 (2 C, d, J 22.5, C11, C19), 123.5 (d, J 3.0, C13 or C21), 123.6 (d, J 3.0, C13 or C21), 126.5 (C15), 127.2

29– 1,2-Bis(2-fluorophenyl)-4-phenyl-benzene is slightly more polar than 1,2,4-tris(2-fluorophenyl)benzene.

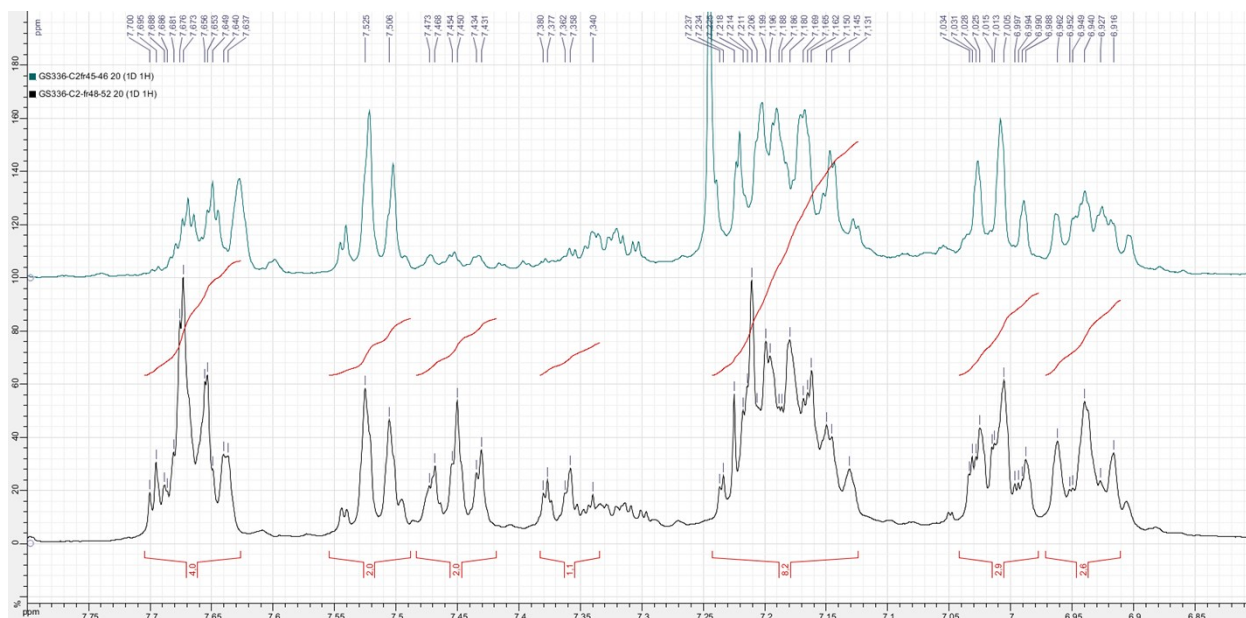
(C4), 127.5 (C6), 128.8 (C5), 129.4 (C1), 128.9 (d, J 7.5, C12 or C20), 129.0 (d, J 7.5, C12 or C20), 131.1 (C7), 131.7 (2 C, br s, C14, C22), 134.5 (C8 or C16), 136.0 (C8 or C16), 140.3 (C2 or C3), 140.8 (C2 or C3), 159.4 (d, J 247.0, C10 or C18), 159.4 (d, J 247.0, C10 or C18). The signals of carbons C9 and C17 could not be identified with certainty. ^{19}F NMR (CDCl_3 , 282.4 MHz): δ -115.38 (2 F, br m, F10, F18). HRMS (EI): m/z 342.1221 (M^+ $\text{C}_{24}\text{H}_{16}\text{F}_2^+$ requires 342.1215).

Note: this compound was not obtained in pure form but as a mixture with other reduction compounds, in minor amounts, and with 1,2,4-tris(2-fluorophenyl)benzene **5k**.



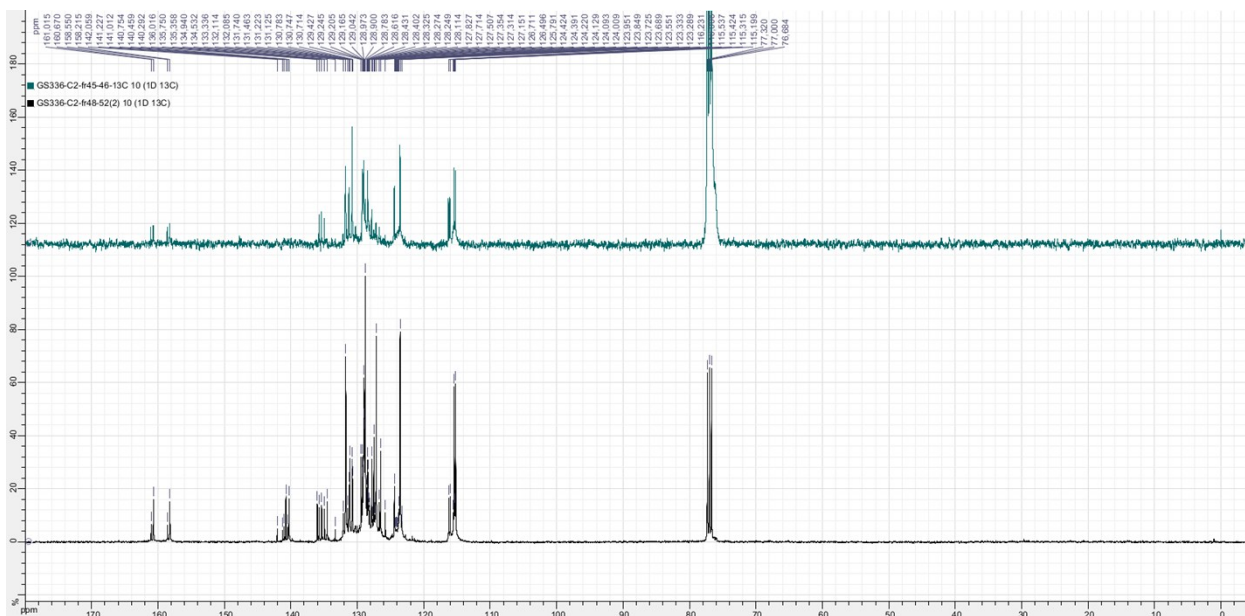
^1H NMR spectrum (CDCl_3 , 400 MHz).

Note: in black (bottom), spectrum of a \approx 50:50 mixture of **5k** and **7k**; in red (top), spectrum of **5k** alone.



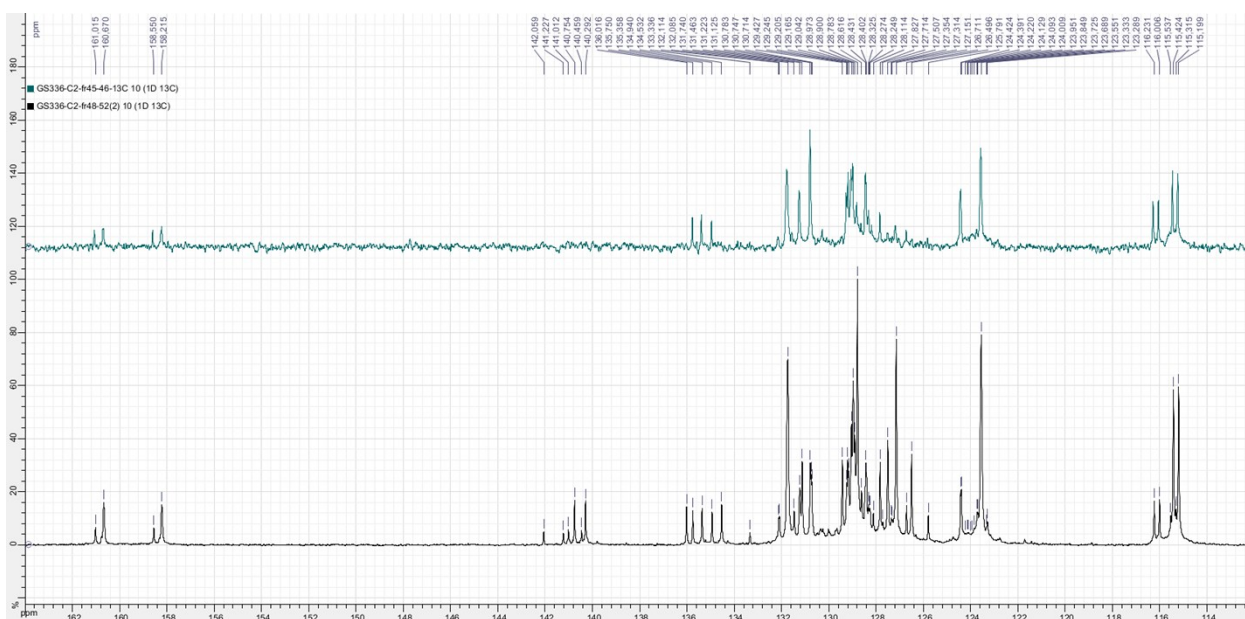
^1H NMR spectrum (selected extract) (CDCl_3 , 400 MHz).

Note: in black (bottom), spectrum of a \approx 50:50 mixture of **5k** and **7k**; in green (top), spectrum of **5k** alone.



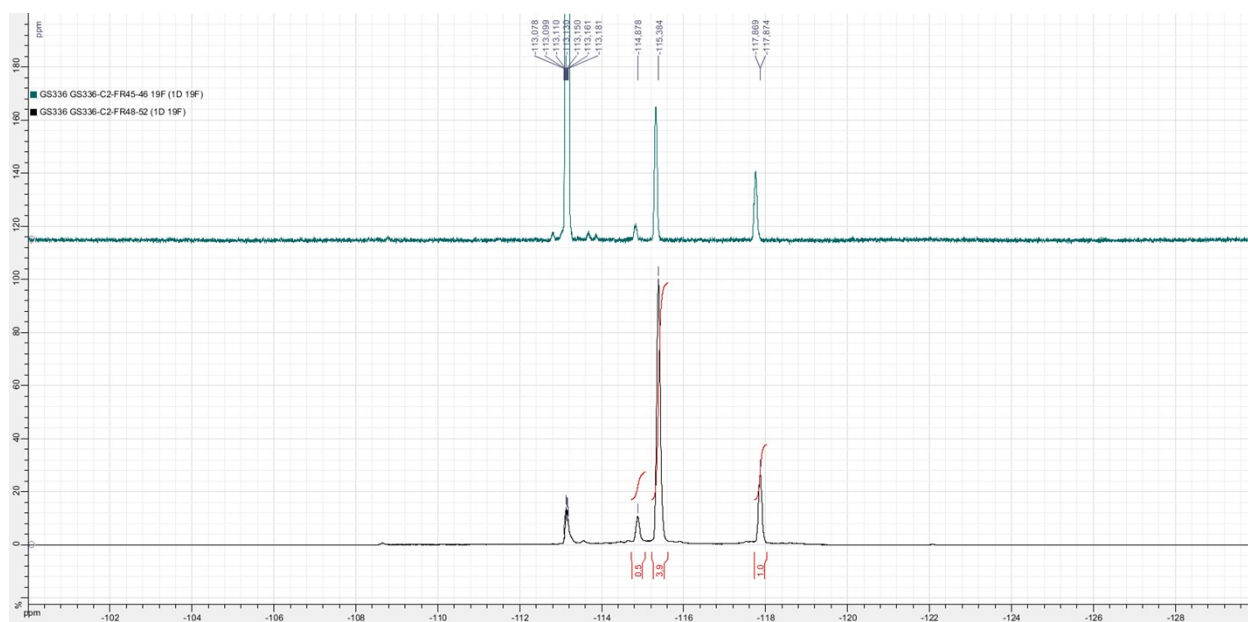
^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).

Note: in black (bottom), spectrum of a $\approx 50:50$ mixture of **5k** and **7k**; in green (top), spectrum of **5k** alone.



^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).

Note: in black (bottom), spectrum of a $\approx 50:50$ mixture of **5k** and **7k**; in green (top), spectrum of **5k** alone.



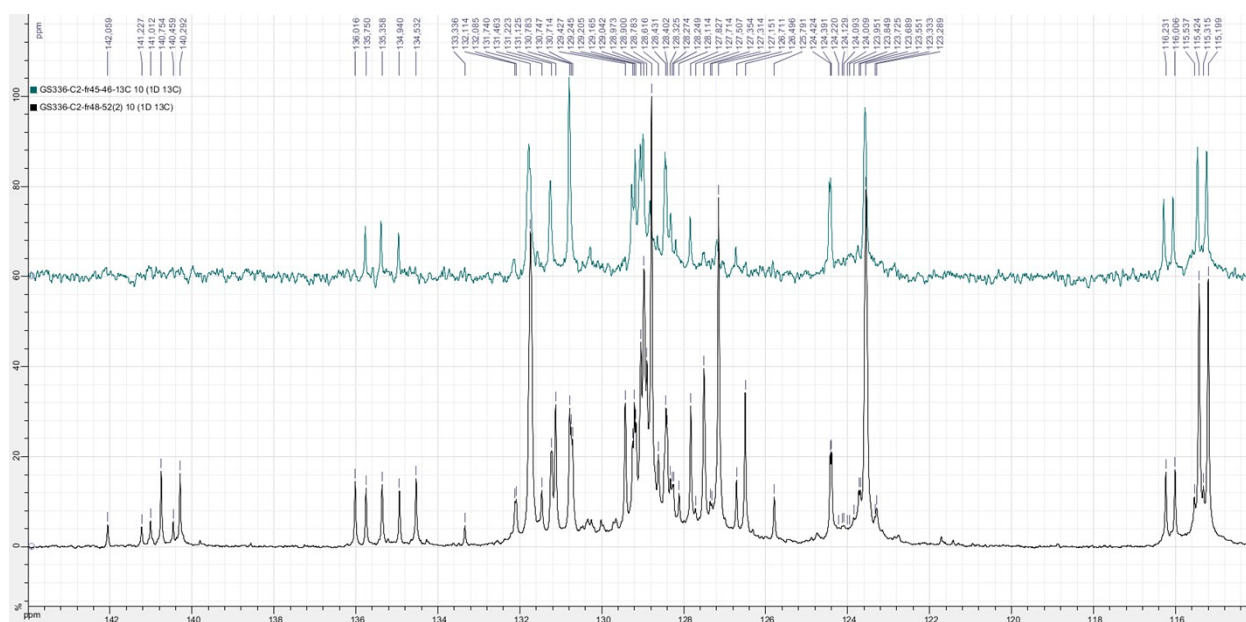
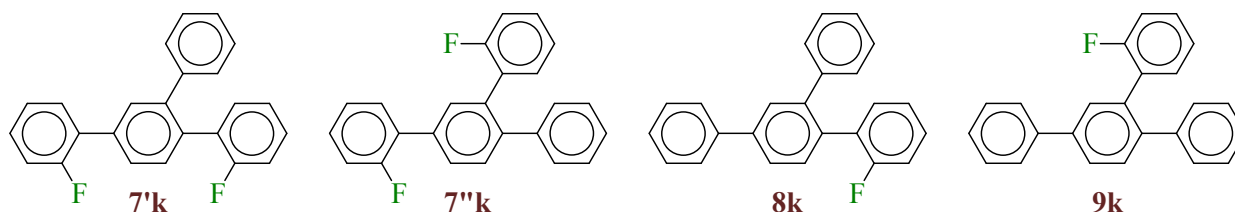
^{19}F NMR spectrum (CDCl_3 , 282.4 MHz).

Note: this is a spectrum of a $\approx 50:50$ mixture of **5k** and **7k**; in green (top), spectrum of **5k** alone. Fluorobenzene was added to the sample, as an internal reference.

Evidence for the formation of other hydro-dehalo substitution products

■ ^{13}C NMR spectroscopy.

In the ^{13}C NMR spectra of several samples obtained after purification by flash column chromatography, smaller peaks at δ 115.43 (2 C, d, J 22.5), 125.8, 126.7, 128.1, 129.4, 131.5, 132.1 (d, J 3.0), 140.5, 141.0, 141.2, 142.1, 159.5 (d, J 247.0) were observed, revealing the presence of (a) minor by-product(s). In retrospect, these peaks were also found in the ^{13}C NMR spectrum of the crude product. The doublet at δ 115.43 is consistent with 1,2,4-triarylbenzene structures having a 2-fluorophenyl substituent at position 1 or at position 2, i.e. with the following possible structures **7'k**, **7''k**, **8k** and **9k**:



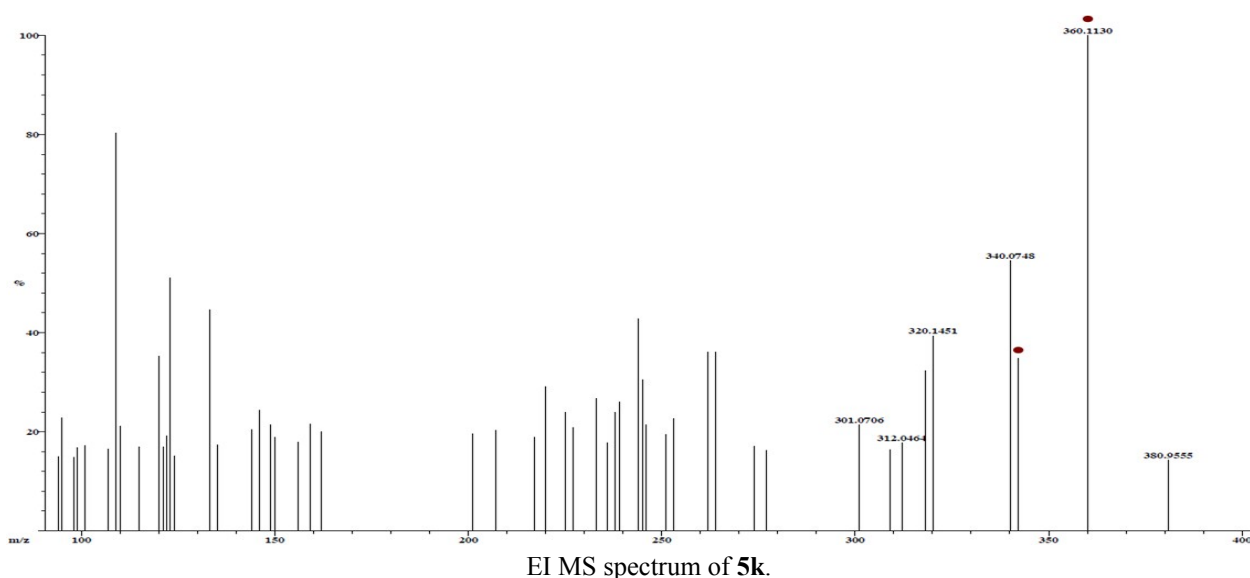
^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).

Note: in black (bottom), spectrum of a \approx 50:50 mixture of **5k** and **7k**; in green (top), spectrum of **5k** alone.

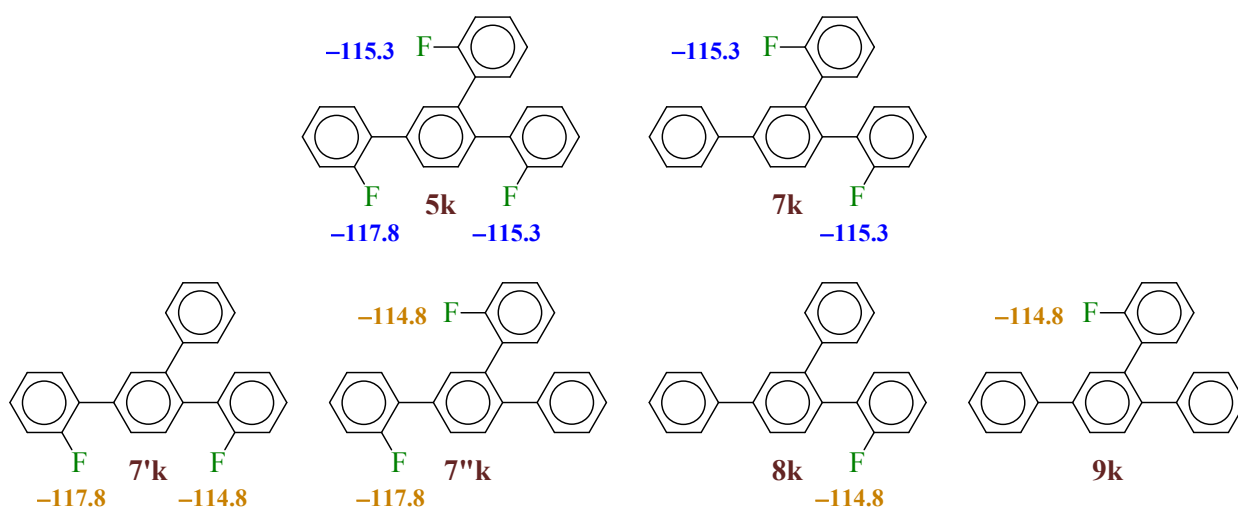
Small peaks at 115.43 (2 C, d, J 22.5), 125.8, 126.7, 128.1, 129.4, 131.5, 132.1 (d, J 3.0), 140.5, 141.0, 141.2 and 142.1 are clearly visible, revealing the presence of (a) minor by-product(s).

■ Mass spectrometry and ^{19}F NMR spectroscopy.

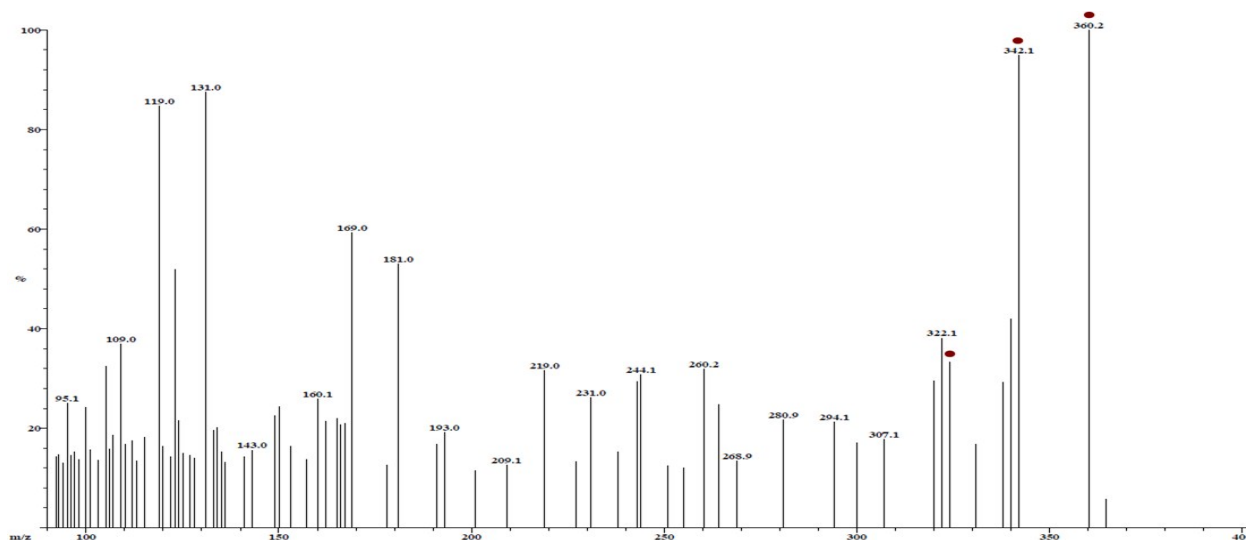
a) The electronic impact MS spectrum of a sample of partially purified trifluoro compound **5k** is displayed below. The molecular peak is clearly visible at m/z 360 (100%, **5k** $^{+}$ $\text{C}_{24}\text{H}_{15}\text{F}_3^{+}$). A smaller peak is visible at m/z 342 (36%), suggesting the presence of minor amounts of (a) difluoro product(s). Importantly, no peak at m/z 324 is observed, which indicates the absence of any monofluoro compound in this sample.



Analysis of the corresponding ^{19}F NMR spectrum is not consistent with the presence of **7k** as a significant difluoro contaminant. Indeed, the integral ratio for the broad signals at δ -115.32 and -117.76 ppm has an expected value of 2 in the case of pure **5k**. Addition of minor amounts of **7k** would increase this number, since its fluorine atoms resonate at δ -115.38 ppm. However, the measured ratio on this sample is 1.8 (see the spectrum displayed further above, recorded with the **5k** sample) and a minor peak is observed at δ -114.82 ppm. With the tentative chemical shift assignment displayed below, all these observations are consistent with the minor difluoro compound(s) being **7'k** and/or **7''k**.

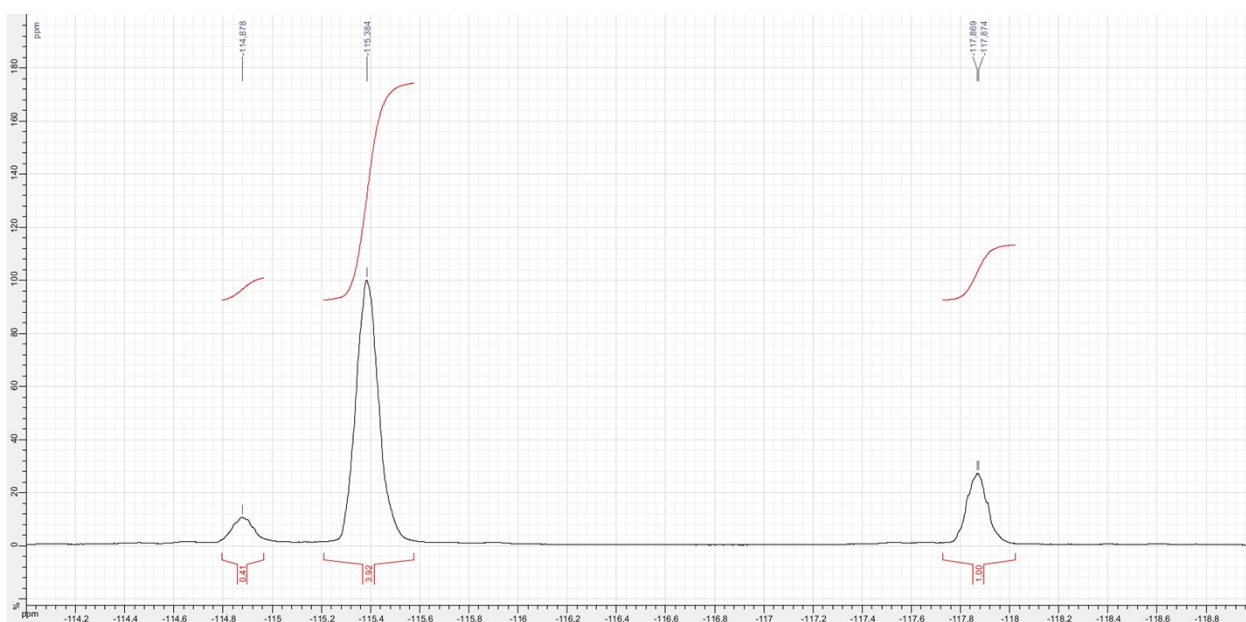


b) The other electronic impact MS spectrum shown below was recorded with another sample containing a nearly equimolar mixture of **5k** and **7k**, which was also employed to record a ^{13}C NMR spectrum, displayed further above. The molecular peaks are clearly visible at m/z 360 (100%, **5k** $^{+\bullet}$ $\text{C}_{24}\text{H}_{15}\text{F}_3^{+\bullet}$) and 342 (95%, **7k** $^{+\bullet}$ $\text{C}_{24}\text{H}_{16}\text{F}_2^{+\bullet}$). A peak at m/z 324 is observed (34%), which is in agreement with the presence of (a) monofluoro compound(s) in this sample.



EI MS spectrum of a $\approx 50:50$ mixture of **5k** and **7k**.

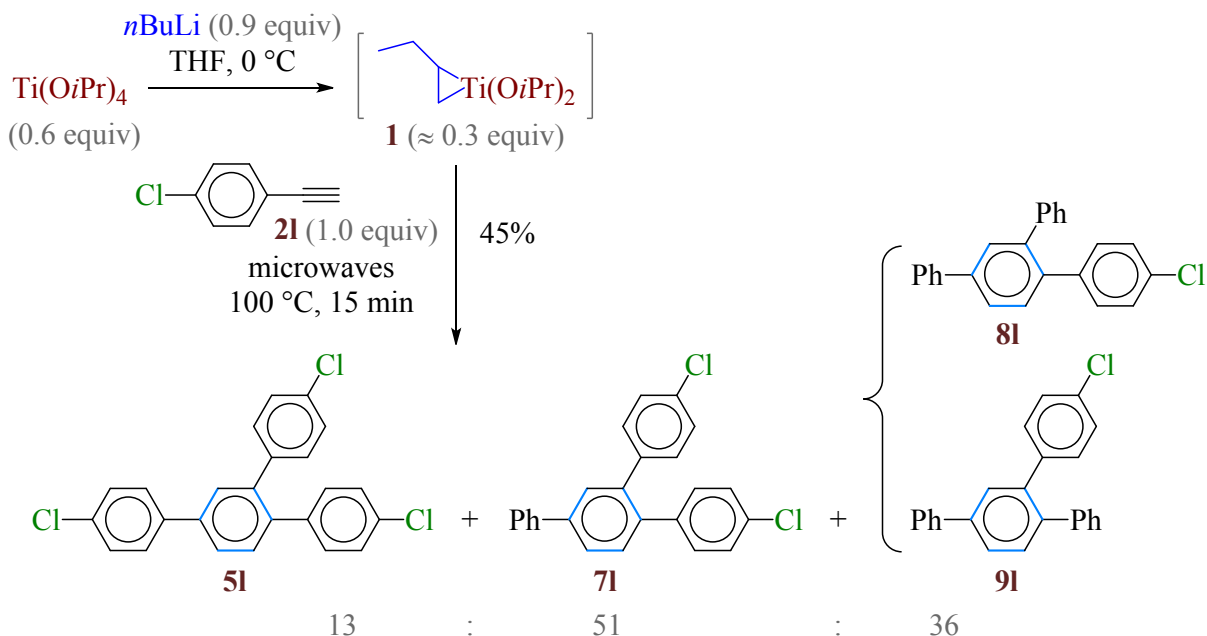
Moreover, the intensity ratio for the peaks at m/z 342 (**7k**) and m/z 324 [putative monofluoro compound(s)] is 74 : 26, while the intensity ratio of the ^{13}C NMR peaks at 140.8 (**7k**) and 142.1 (unidentified minor compound in the same sample), both corresponding to non-hydrogen-substituted aromatic carbon nuclei, is 77 : 23. These values are close and the results are consistent with the presence of a monofluoro product as a minor contaminant, which would then be one of the two molecules, **8k** or **9k**. This picture is also in agreement with the corresponding ^{19}F NMR spectrum (displayed again below). Indeed, still considering our tentative chemical shift assignment shown above, the integral values indicate a distribution, for compounds **5k**, **7k** and **8k/9k**, of 1.00 : 0.96 : 0.41 (to be compared with 1.00 : 0.95 : 0.34 on the MS spectrum).



^{19}F NMR spectrum spectrum of a $\approx 50:50$ mixture of **5k** and **7k** (selected extract) (CDCl_3 , 282.4 MHz).

1,2,4-Tris(4-chlorophenyl)benzene 5I, 1,2-bis(4-chlorophenyl)-4-phenyl-benzene 7I, 1-(4-chlorophenyl)-2,4-diphenyl-benzene 8I and 1-(4-chlorophenyl)-2,5-diphenyl-benzene 9I

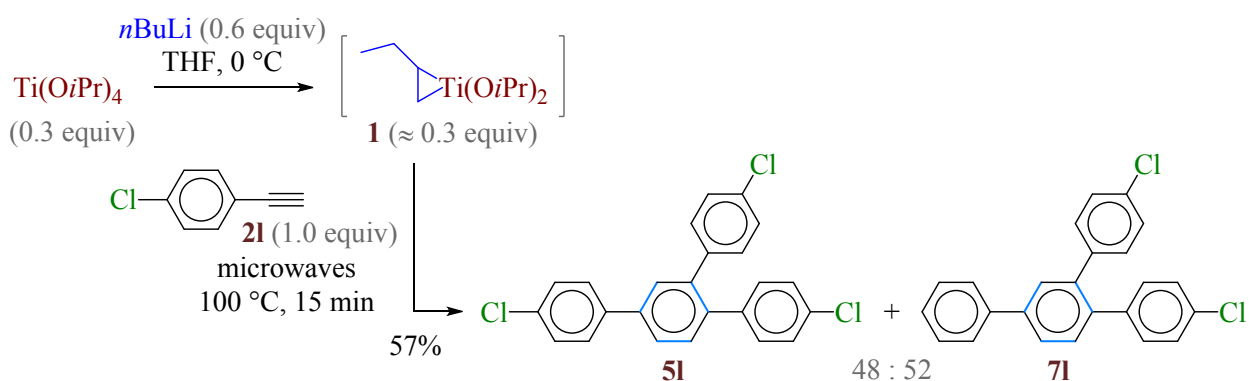
a) Using $\text{Ti}(\text{O}i\text{Pr})_4/n\text{BuLi}$ in 2 : 3 ratio



General procedure **G1s** was applied with 4-chlorophenylacetylene **2I**. Work-up **W1** was carried out. Analysis of the crude product (422 mg, orange oil) by ^{13}C NMR spectroscopy showed full conversion of the starting material and the presence of 1,2-bis(4-fluorophenyl)-4-phenyl-benzene **7I** as the major product of the reaction. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 2%) afforded a 27 : 73 mixture of **5I** and **7I** (as determined by ^{13}C NMR spectroscopy, 78.7 mg, 55.3 and 149 μmol respectively), pure **7I** (6 mg, 16.0 μmol , 2%) and a mixture of **7I** with other reduced compounds (ratio dichloro/monochloro compounds 28 : 72 as determined by MS; 75.5 mg, 60.3 and 155 μmol respectively). Assuming **7I** is the sole dichloro product, the yields obtained are thus 6% (**5I**), 23% (**7I**) and 16% (**9I** and isomers).

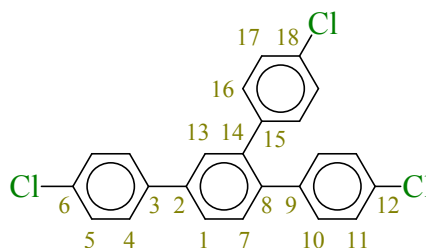
Note: for the estimation of the **5I/7I** ratio by ^{13}C NMR spectroscopy, the intensities of the following peaks were used: δ 126.3 (1C of **5I**) and 126.6 (1C of **7I**).

b) Using $\text{Ti}(\text{O}i\text{Pr})_4/n\text{BuLi}$ in 1 : 2 ratio



General procedure **G2s** was applied with 4-chlorophenylacetylene **21**. Work-up **W1** was carried out. Analysis of the crude product (388 mg, orange oil) by ^{13}C NMR spectroscopy showed full conversion of the starting material and the production of 1,2,4-tris(4-chlorophenyl)benzene **51** and 1,2-bis(4-chlorophenyl)-4-phenyl-benzene **71** in an estimated 48 : 52 ratio. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 2%) afforded pure **51** (26.9 mg, 65.7 μmol , 7%), a 41 : 59 mixture of **51** and **71** (as determined by ^{13}C NMR spectroscopy as described above, 62.5 mg, 65.8 and 94.7 μmol respectively) and relatively pure **71** (129 mg, 344 μmol , 34%). The yields obtained for both compounds are thus 13% (**51**) and 44% (**71**).

1,2,4-Tris(4-chlorophenyl)benzene **51**¹³



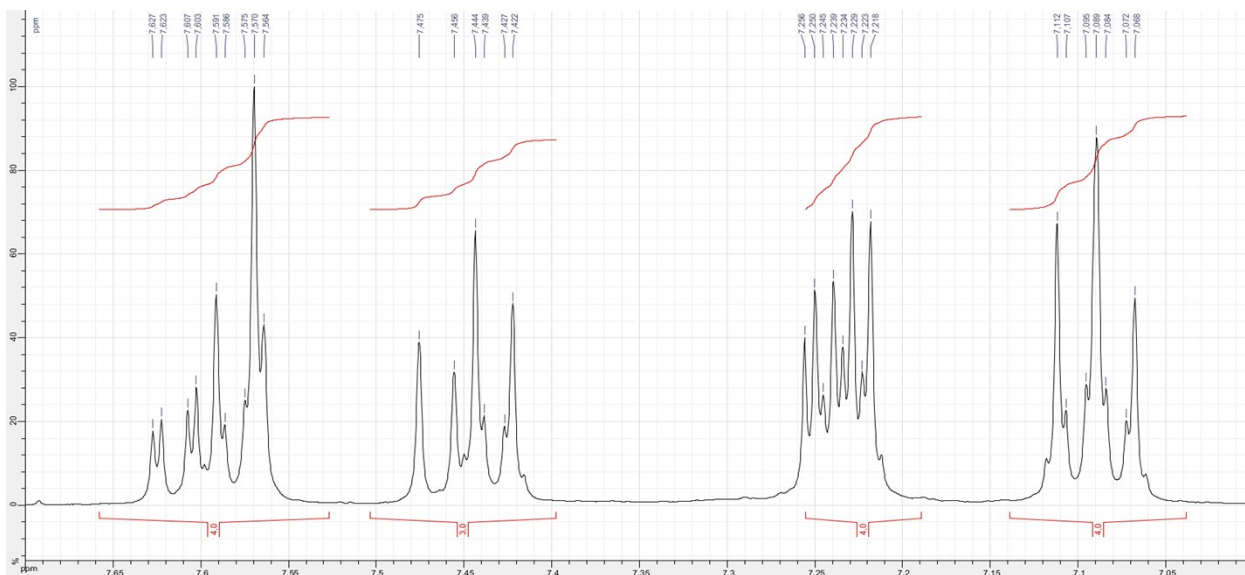
White solid. M.p. 147–150 °C (lit. 150–151 °C¹¹; 159–161 °C¹⁰; 190–191 °C¹²).

R_f 0.4 (EtOAc/petroleum ether 2%, PMA, UV-active). ^1H NMR (CDCl_3 , 400 MHz): δ 7.08 (2 H, br d, J 8.5, H11 or H17), 7.10 (2 H, br d, J 8.5, H11 or H17), 7.23 (2 H, br d, J 8.5, H10 or H16), 7.24 (2 H, br d, J 8.5, H10 or H16), 7.43 (2 H, br d, J 8.5, H5), 7.47 (1 H, d, J 8.0, H7), 7.57 (1 H, d, J 2.0, H13), 7.58 (2 H, br d, J 8.5, H4), 7.61 (1 H, dd, J 8.0, 2.0, H1).

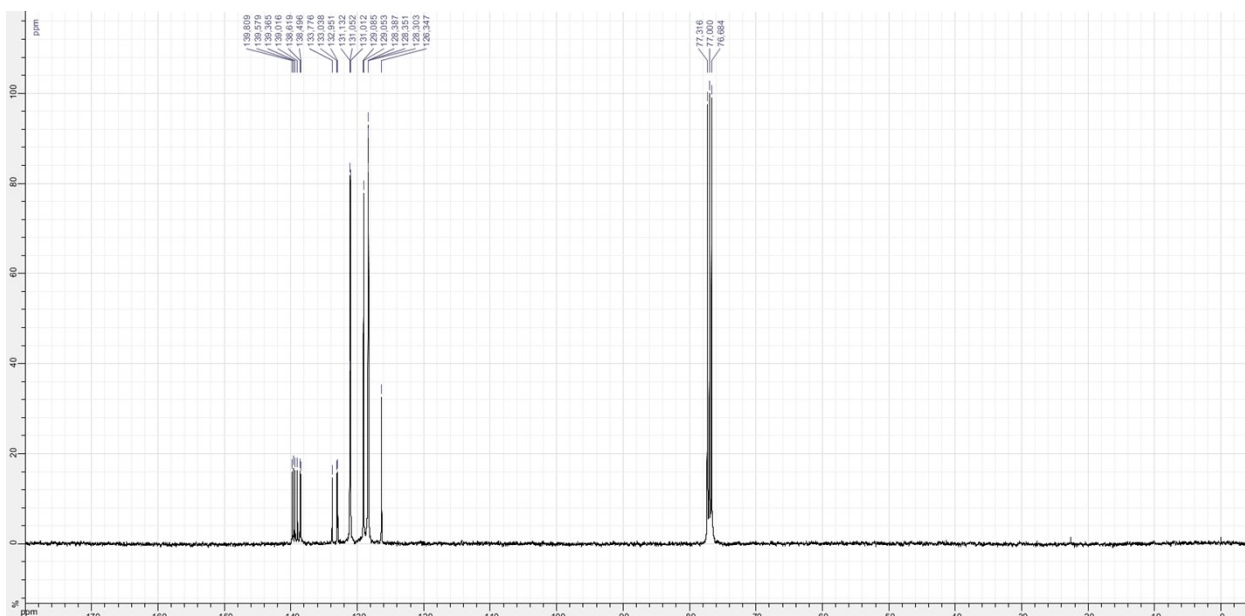
^{13}C NMR (CDCl_3 , 100.6 MHz): δ 126.3 (C13), 128.30, 128.35, 128.39 (C4, C10, C16), 129.05 (C5), 129.08 (C1), 131.01, 131.05 (C11, C17), 131.1 (C7), 132.95, 133.04 (C12, C18), 133.8 (C6), 138.5, 138.6 (C9, C15), 139.0 (C3), 139.4, 139.6, 139.8 (C2, C8, C14). HRMS (EI): m/z 408.0228 (M^+ $\text{C}_{24}\text{H}_{15}^{35}\text{Cl}_3^+$ requires 408.0234).



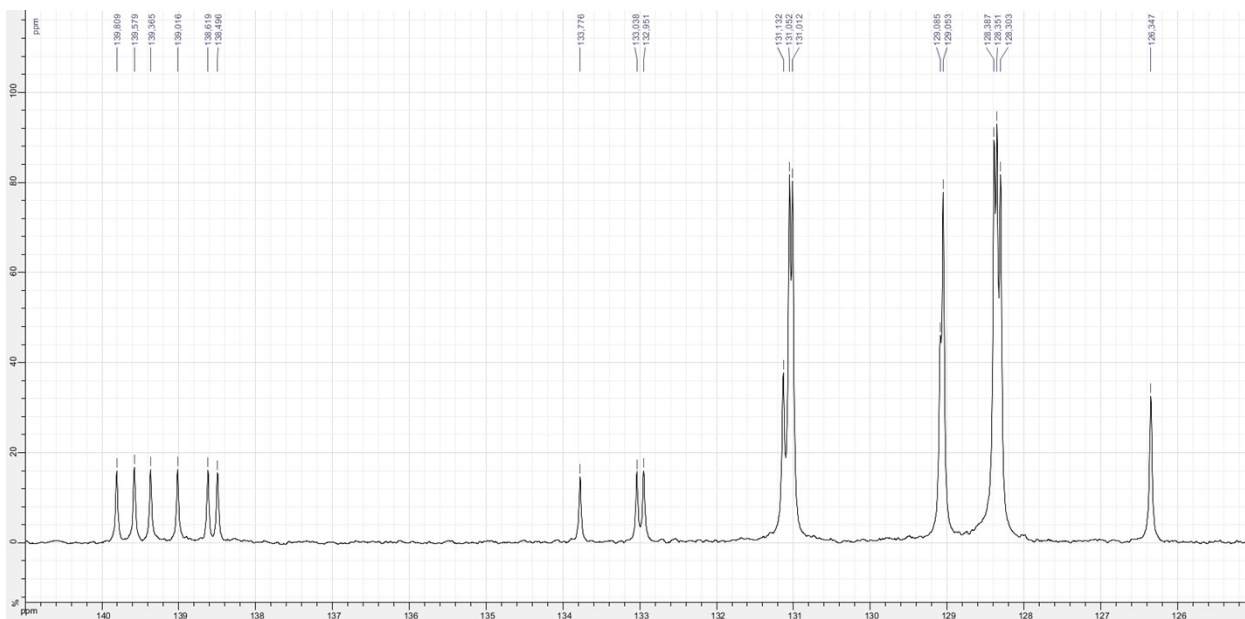
^1H NMR spectrum (CDCl_3 , 400 MHz).



^1H NMR spectrum (selected extract) (CDCl_3 , 400 MHz).

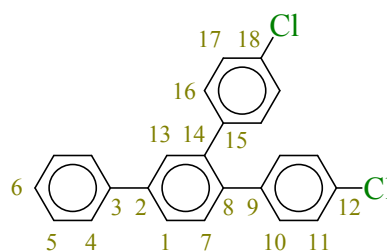


^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).

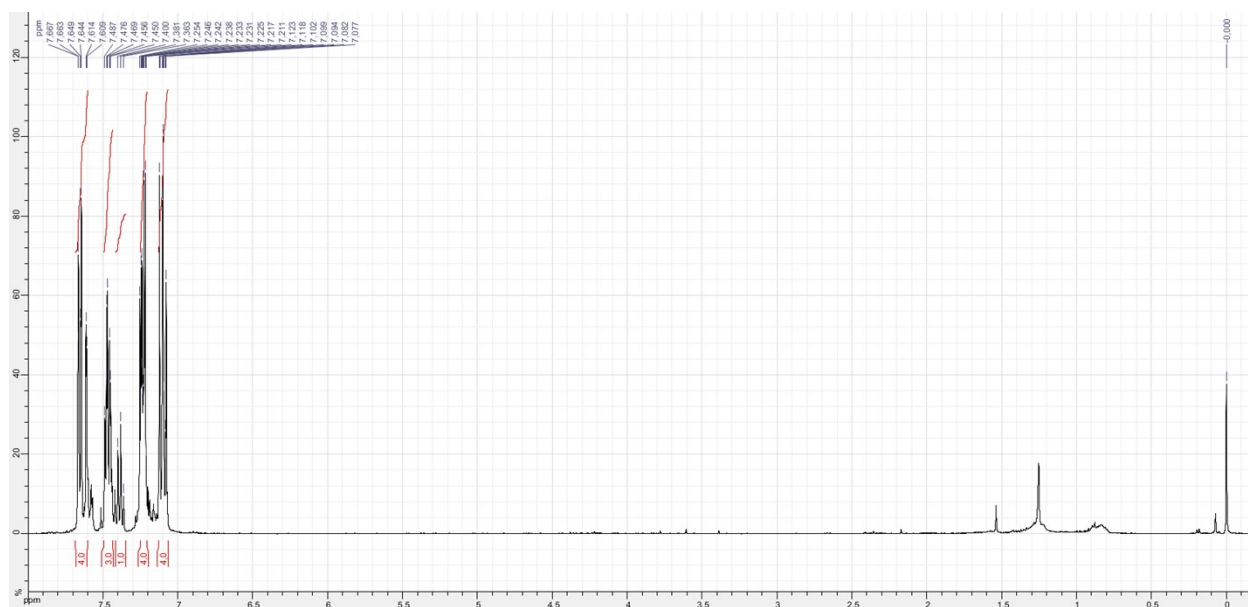


^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).

1,2-Bis(4-chlorophenyl)-4-phenyl-benzene **71**

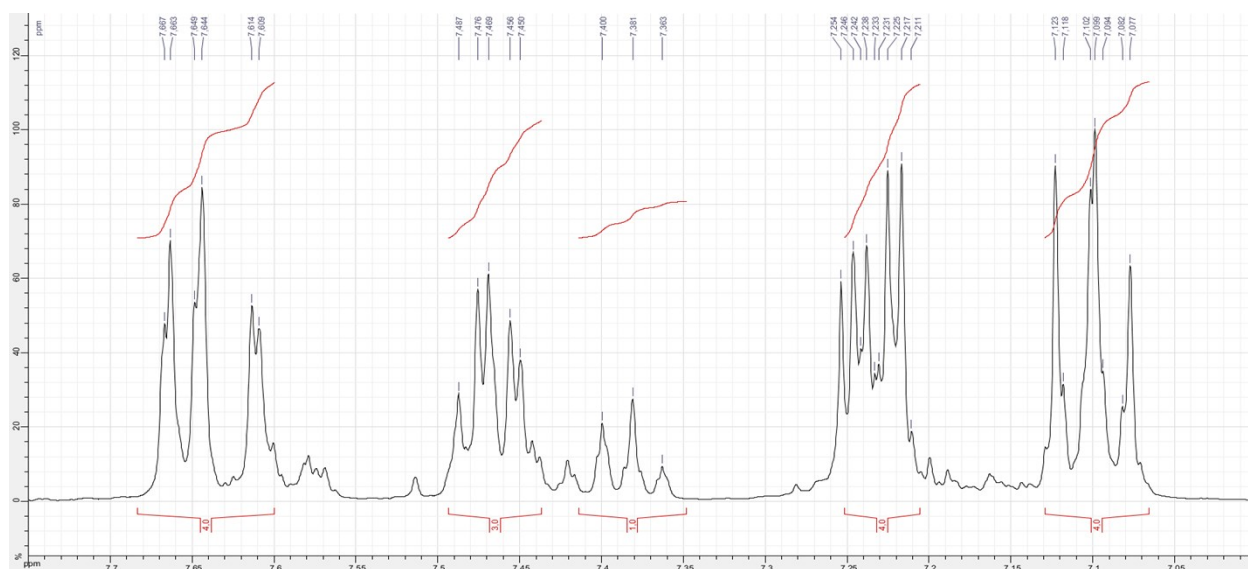


Colourless oil. R_f 0.4 (EtOAc/petroleum ether 2%, PMA, UV-active).³⁰ ^1H NMR (CDCl_3 , 400 MHz): δ 7.09 (2 H, br d, J 8.5, H11 or H17), 7.11 (2 H, br d, J 8.5, H11 or H17), 7.23 (2 H, br d, J 8.5, H10 or H16), 7.24 (2 H, br d, J 8.5, H10 or H16), 7.38 (1 H, br t, J 7.5, H6), 7.47 (1 H, d, J 8.0, H7), 7.47 (2 H, br dd, J 8.0, 7.5, H5), 7.61 (1 H, br d, J 2.0, H13), 7.66 (2 H, br d, J 8.0, H4), 7.66 (1 H, br dd, J 8.0, 2.0, H1). ^{13}C NMR (CDCl_3 , 100.6 MHz): δ 126.6 (C13), 127.1 (C4), 127.6 (C6), 128.32, 128.34 (C10, C16), 128.9 (C5), 129.3 (C1), 131.03 (C7), 131.06, 131.10 (C11, C17), 132.84, 132.92 (C12, C18), 138.1 (C9), 139.2 (C15), 139.56, 139.64 (C8, C14), 140.2 (C2), 140.9 (C3). HRMS (EI):³¹ m/z 374.0639 (M^+ $\text{C}_{24}\text{H}_{16}^{35}\text{Cl}_2^{+}$ requires 374.0624).

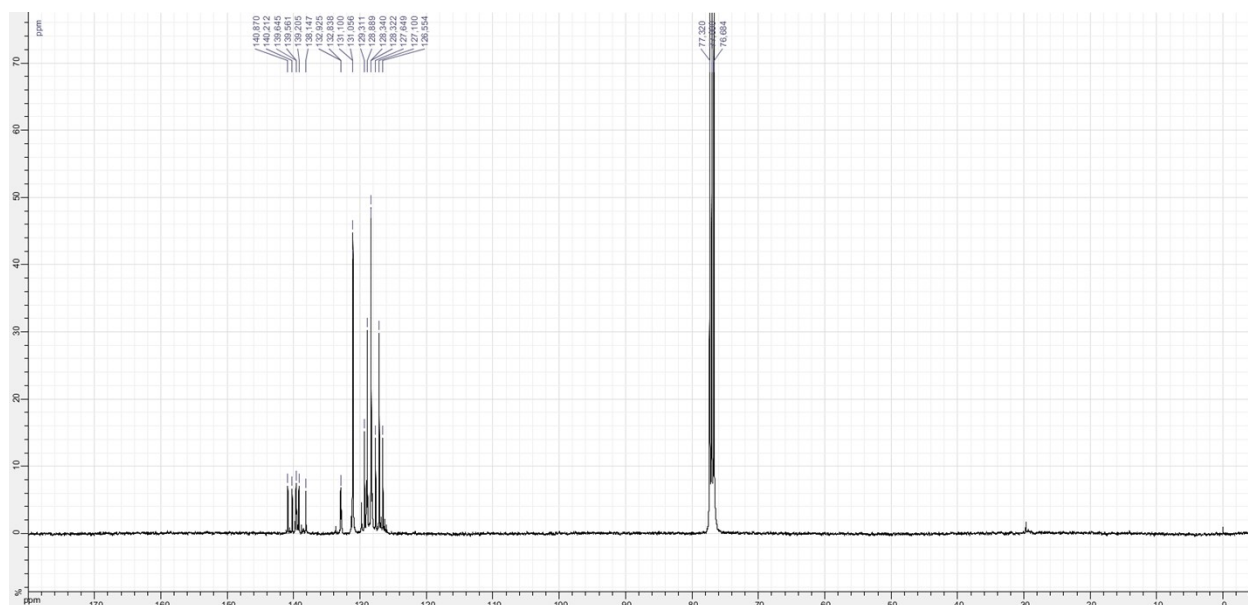


^1H NMR spectrum (CDCl_3 , 400 MHz).

30– 1,2-Bis(4-chlorophenyl)-4-phenylbenzene **71** is slightly more polar than 1,2,4-tris(4-chlorophenyl)benzene **51**.
31– Analysis performed on a 73 : 27 mixture of **71** and **51**.

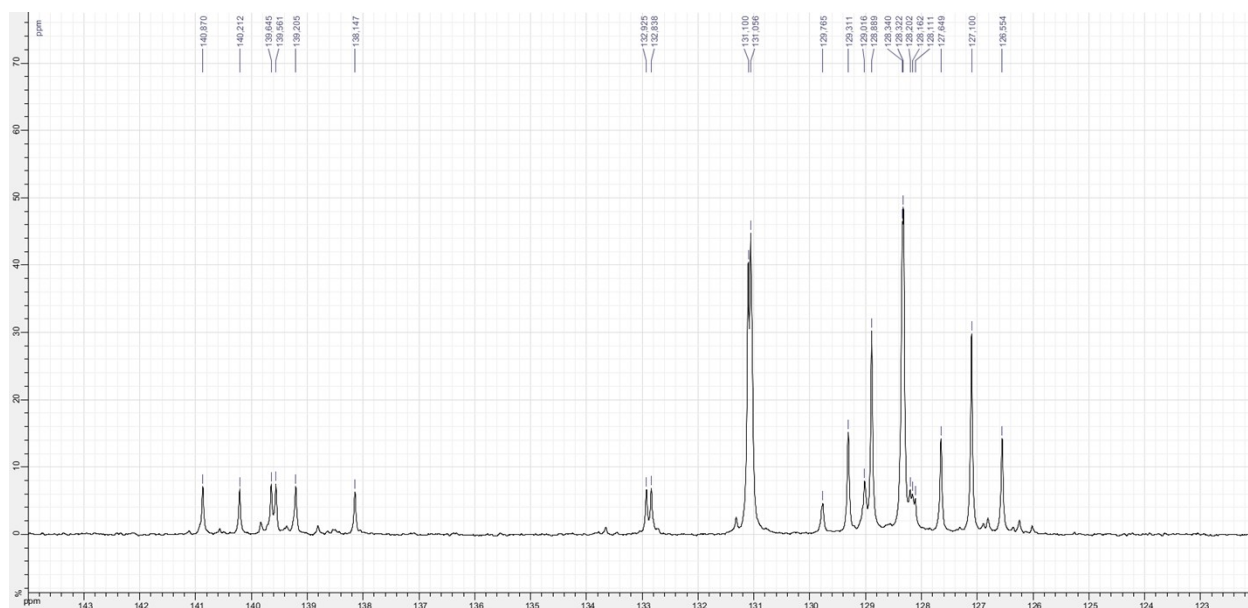


^1H NMR spectrum (selected extract) (CDCl_3 , 400 MHz).



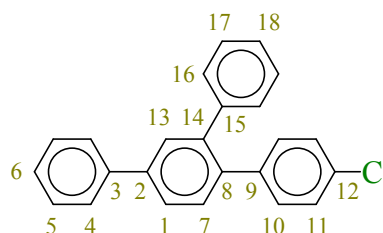
^{13}C NMR spectrum (CDCl_3 , 100.6 MHz).

Note: The signals at 22.6, 76.3, 120.2 and 148.2 ppm do not belong to 1,2-bis(4-chlorophenyl)-4-phenyl-benzene.



^{13}C NMR spectrum (selected extract) (CDCl_3 , 100.6 MHz).

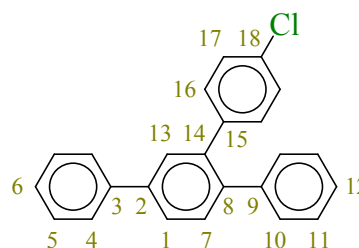
1-(4-Chlorophenyl)-2,4-diphenyl-benzene **8I**



R_f 0.4 (EtOAc/petroleum ether 2%, PMA, UV-active).³² ^{13}C NMR (CDCl_3 , 100.6 MHz), characteristic signals (tentative proposal): δ 126.2 (C13), 126.8 (C18), 129.5 (C1), 138.1 (C9), 140.9, 141.1 (C3, C15).

Note: this compound was not obtained in pure form. It is proposed that as one of the contaminants observed in a mixture containing **7I** and **9I**. See the detailed discussion presented further below.

1-(4-Chlorophenyl)-2,5-diphenyl-benzene **9I**¹¹



R_f 0.4 (EtOAc/petroleum ether 2%, PMA, UV-active).³² ^{13}C NMR (CDCl_3 , 100.6 MHz), characteristic signals: δ 126.4 (C12), 126.7 (C13), 127.1 (C4), 127.5 (C6), 128.1, 128.1 (C10, C16), 128.9 (C5), 129.2 (C1), 129.8 (C11), 131.1 (C7), 131.1 (C17), 132.6 (C18), 139.4, 139.9, 140.3, 140.5, 140.7 (C2, C3, C8, C9, C14, C15). HRMS (EI):³³ m/z 340.1019 ($\text{M}^{+\bullet}$ $\text{C}_{24}\text{H}_{17}^{35}\text{Cl}^{+\bullet}$ requires 340.1013).

Note: this compound was not obtained in pure form but as a mixture with **7I** and minor amounts of contaminants, which most likely include other isomers of **7I** and **9I**. See the next paragraph for the presentation of a ^{13}C spectrum of this mixture.

Analysis of the mixture of dichloro / monochloro products obtained after purification of the crude product of the reaction performed with $\text{Ti}(\text{O}i\text{Pr})_4/n\text{BuLi}$ in 1 : 2 ratio.

As reported further above, a fraction (75.5 mg) was obtained, containing a mixture of dichloro and monochloro compounds. Some analytical detail is presented hereafter.

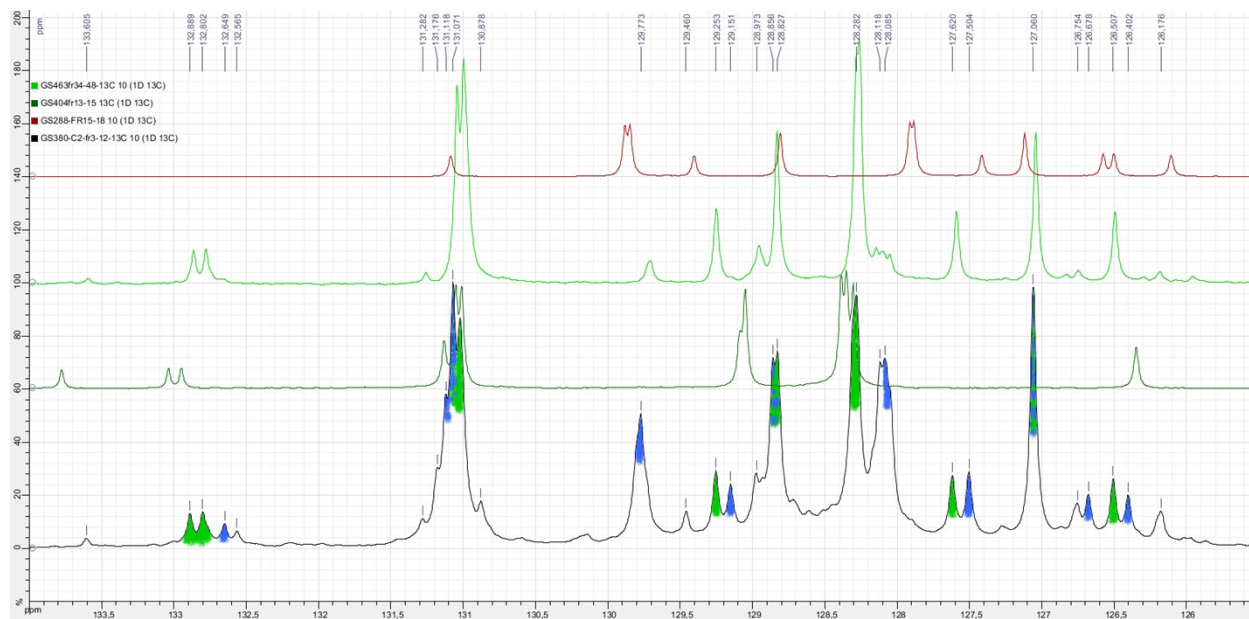
■ ^{13}C NMR spectroscopy.

Analysis of the mixture by ^{13}C NMR spectroscopy showed very clearly the presence of the dichloro compound **7I** as a major constituent (see the following extracts of the ^{13}C NMR spectrum, displayed at the bottom, in black, and the comparison with a spectrum of **7I**, shown in light green). The corresponding peaks are marked in light green as well. Conversely, the trichloro compound **5I** was not observed in this sample, as is especially visible in the ^{13}C NMR spectrum extract number 2, shown further below (a spectrum of **5I** is displayed in dark green, for comparison). MS spectrometry confirmed the absence of this derivative but provided evidence for the presence of (a)

32– Monochloro compounds **8I** and **9I** are slightly more polar than 1,2-bis(4-chlorophenyl)-4-phenyl-benzene **7I**.

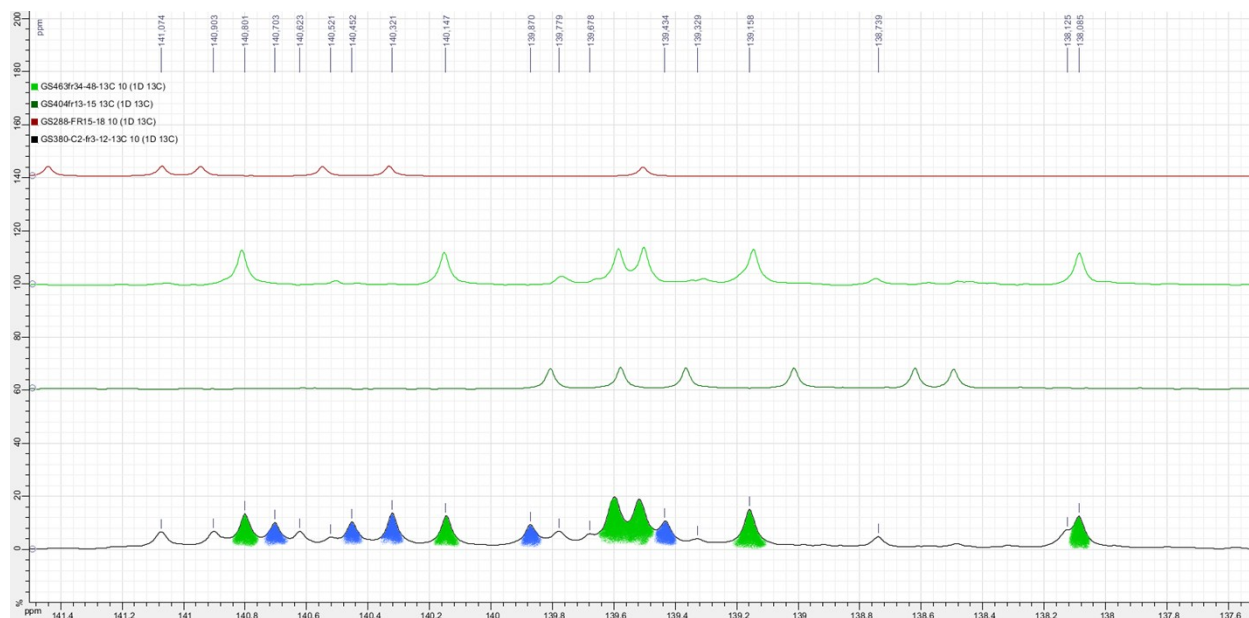
33– Analysis performed on a mixture of dichloro and monochloro compounds, including **7I** and **9I**.

monochloro compound(s) (see further below). The reported ^{13}C NMR signals of **9I**, a known compound,¹¹ were therefore compared with our spectrum. A perfect match was found, strongly supporting the presence of **9I** in the mixture. The corresponding peaks are marked in blue.



Note: in black (bottom), spectrum of a mixture of chlorinated compounds, with peaks marked in light green (compound **7I**) and in blue (signals assigned to the known monochloro molecule **9I**).

Above are shown: in dark green, a spectrum of the trichloro molecule **5I**; in light green, a spectrum of the dichloro compound **7I**; in red, a spectrum of 1,2,4-triphenylbenzene **5a**.



Note: in black (bottom), spectrum of a mixture of chlorinated compounds, with peaks marked in light green (compound **7I**) and in blue (signals assigned to the known monochloro molecule **9I**).

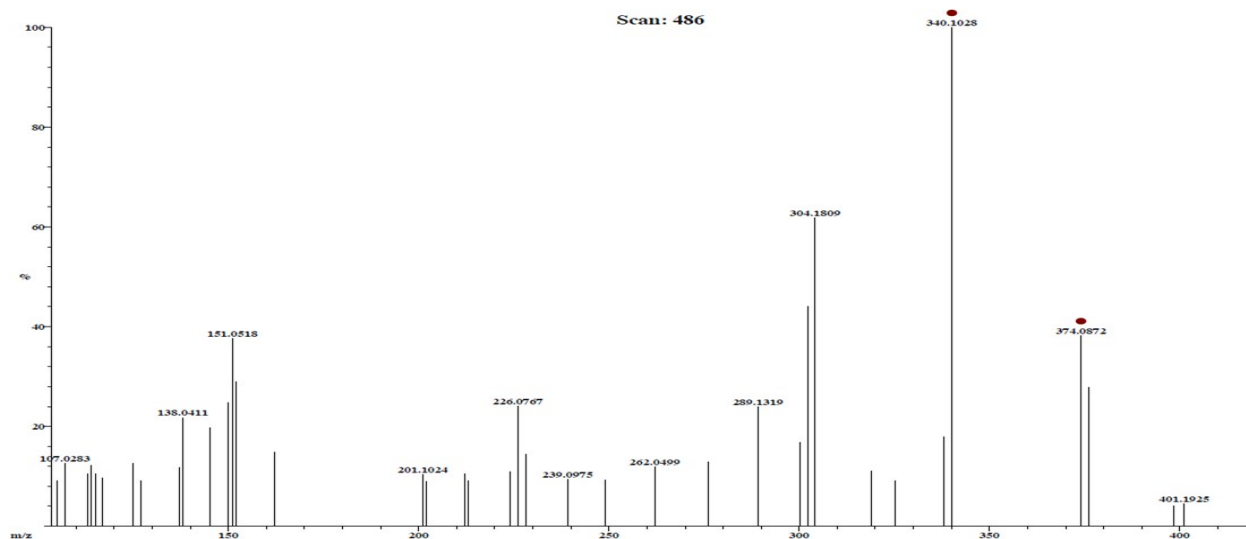
Above are shown: in dark green, a spectrum of the trichloro molecule **5I**; in light green, a spectrum of the dichloro compound **7I**; in red, a spectrum of 1,2,4-triphenylbenzene **5a**.

It is apparent that, apart from **7I** and **9I**, at least two other molecules are present in the mixture. This is particularly visible on the extract number 2, with 9 unassigned peaks in the 138-142 ppm region,

at δ 138.1, 138.7, 139.3, 139.7, 139.8, 140.5, 140.6, 140.9 and 141.1 ppm. Possible candidate structures for monochloro derivatives are 1-(4-chlorophenyl)-2,4-diphenyl-benzene **8I** and the known molecule 1-(4-chlorophenyl)-3,4-diphenyl-benzene. However, several ^{13}C NMR chemical shifts that are reported for the latter compound are not visible on our spectrum, e.g. at δ 128.5, 130.0, 131.4, 141.3 and 141.5 ppm.¹¹ Moreover, hydro-de-chloro substitution of the dichloro derivative **7I** is perhaps not likely to be very selective. The resulting formation of **8I**, along with **9I**, appears reasonable. Finally, one can notice a small peak at δ 133.6 ppm. This is consistent with the chemical shift of the $\underline{\text{C}}\text{-Cl}$ carbon atom of a compound of the type 1-(4-chlorophenyl)-3,4-diaryl-benzene. With some possibilities having been ruled out, the remaining candidate structures for this minor component of the mixture are the dichloro compounds 1,3-bis(4-chlorophenyl)-4-phenyl-benzene and 1,4-bis(4-chlorophenyl)-3-phenyl-benzene, so far undescribed, to the best of our knowledge.

■ Mass spectrometry.

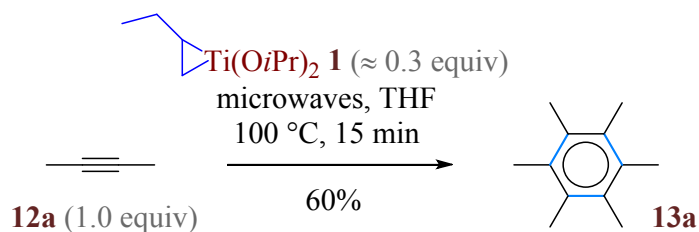
The spectrum shown below was recorded with the same sample. The molecular peaks are clearly visible at m/z 340 (100%, [**9I** and, most likely, isomers such as **8I**] $^+ \cdot \text{C}_{24}\text{H}_{17}^{35}\text{Cl}^+$) and 374 (38%, [**7I** and, possibly, isomers in minor amounts] $^+ \cdot \text{C}_{24}\text{H}_{16}^{35}\text{Cl}_2^+$). Assuming the relative intensities of these peaks directly relate to the compound ratio, the dichloro (mainly **7I** as mentioned in the preceding paragraph) and monochloro derivatives are thus estimated to be in a 28:72 ratio. No peak is observed at m/z 408 (trichloro compound **5I**) or at m/z 306 (fully dechlorinated product **5a**), supporting the absence of these molecules in the sample.



EI MS spectrum of the mixture of dichloro and monochloro products.

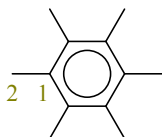
Note: because of a known malfunction of our spectrometer, molecular peaks of compounds having ^{37}Cl atoms tend to be poorly visible (or not visible at all).

Hexamethylbenzene **13a**



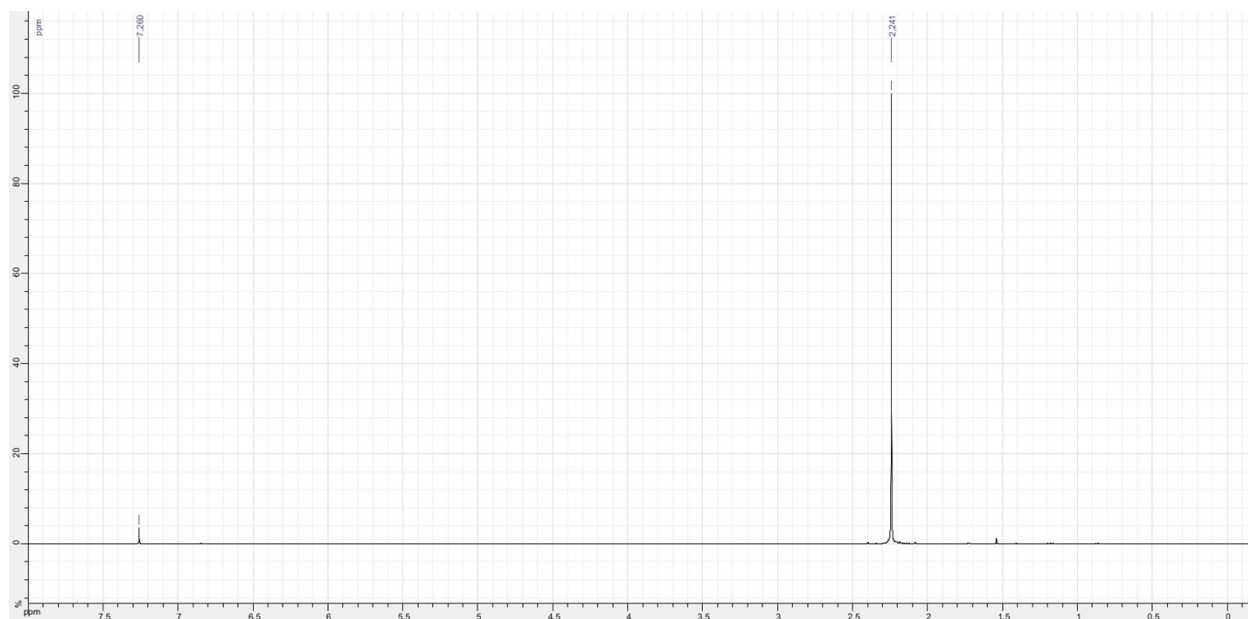
General procedure **G1** was applied with but-2-yne **12a**. Work-up **W1** was carried out. ^1H and ^{13}C NMR analyses of the crude product (177 mg, yellow solid) showed that it contained mainly hexamethylbenzene **13a**. The presence of the starting material, an extremely volatile compound (b.p. $27\text{ }^\circ\text{C}$), was not observed. Purification by flash column chromatography on silica gel (petroleum ether) afforded pure **13a** (97.8 mg, $603\text{ }\mu\text{mol}$, 60%).

Hexamethylbenzene **13a**⁸

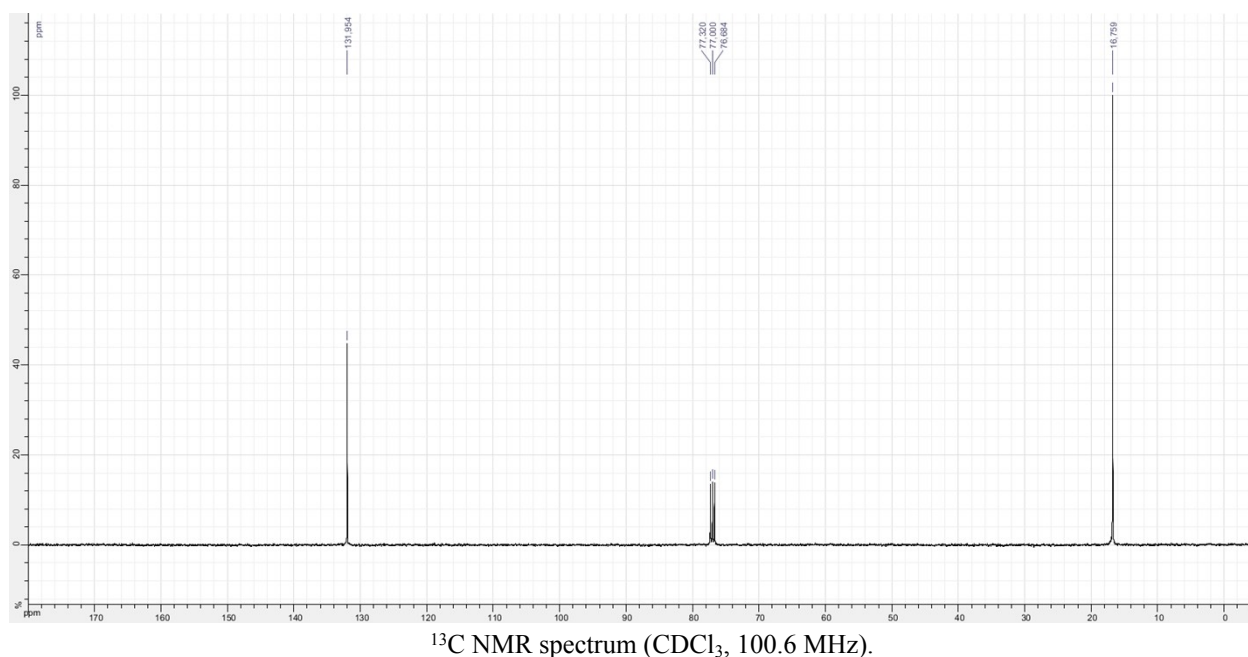


White solid. R_f 0.6 (petroleum ether, anisaldehyde, UV-active).

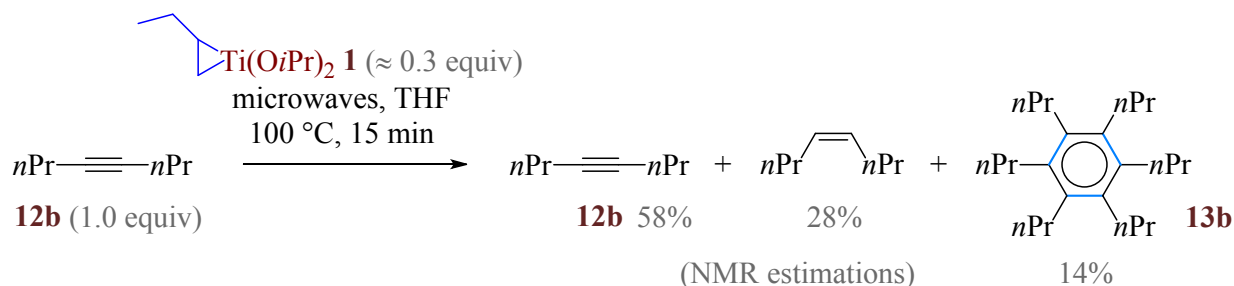
^1H NMR (CDCl_3 , 400 MHz): δ 2.24 (18 H, s, H2). ^{13}C NMR (CDCl_3 , 100.6 MHz): δ 16.8 (C2), 132.0 (C1). HRMS (EI): m/z 162.1402 (M^+ $\text{C}_{12}\text{H}_{18}^+$ requires 162.1403).



^1H NMR spectrum (CDCl_3 , 400 MHz).

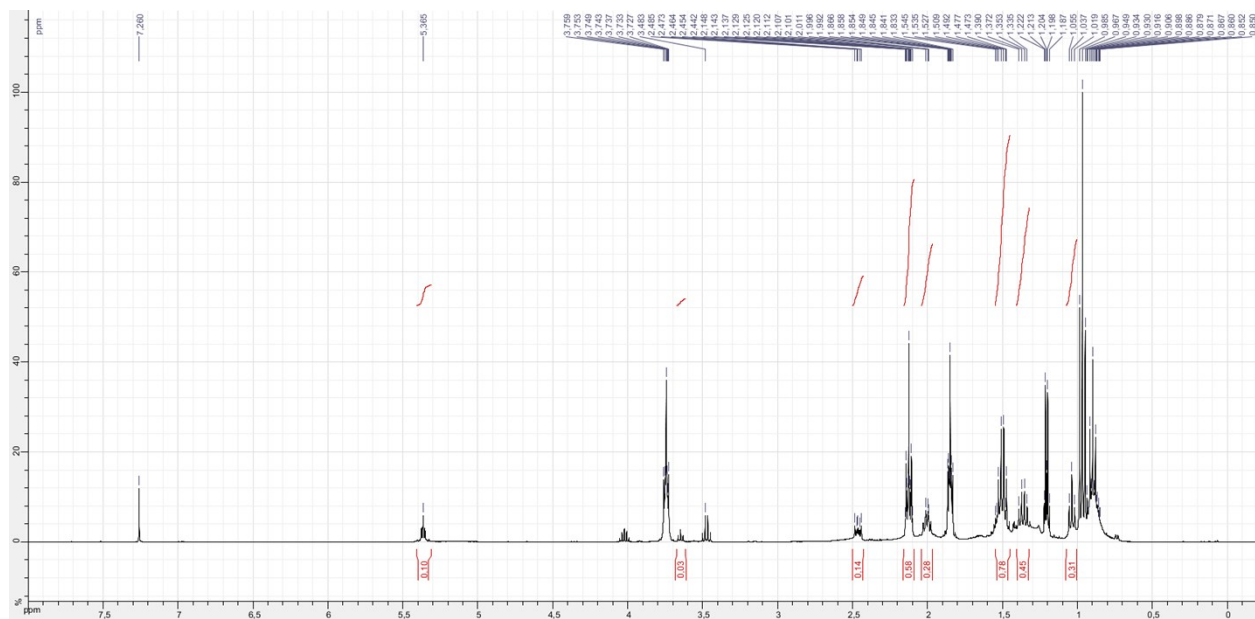


Hexapropylbenzene **13b**

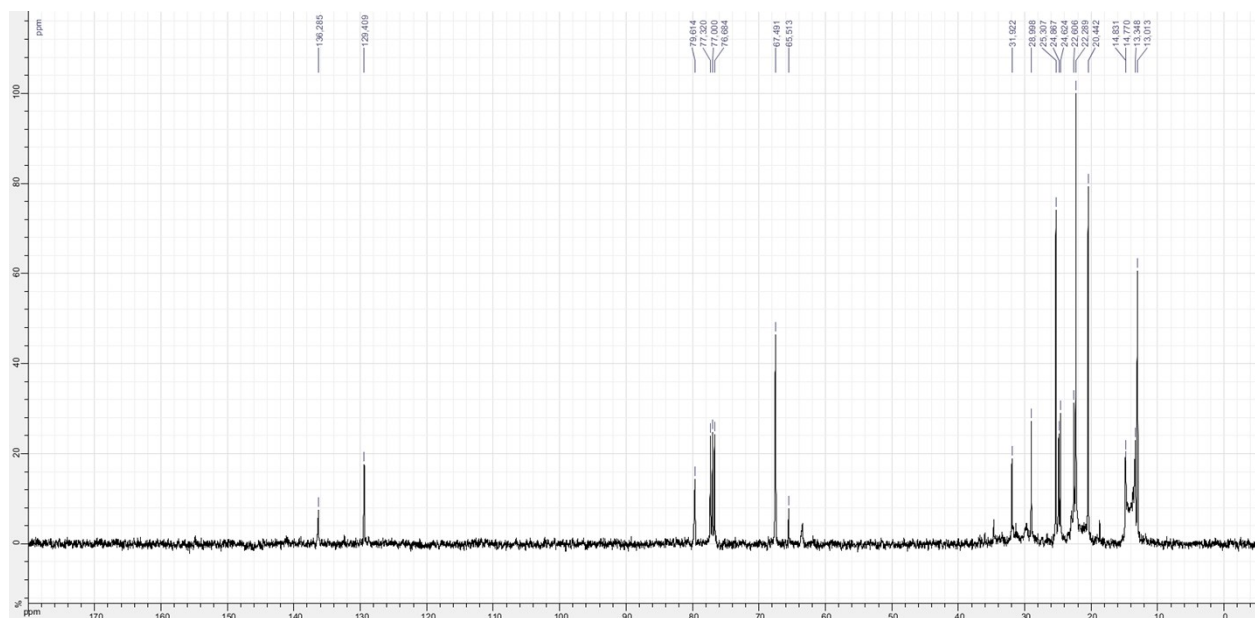


General procedure **G1** was applied with oct-4-yne **12b**. Work-up **W1** was carried out. ^1H and ^{13}C NMR analyses of the crude product (orange oil) showed the presence of starting material **12b** as the main component (58%), (*Z*)-oct-4-ene (28%) and hexapropylbenzene **13b** (14%), these yields being estimated by integration of the ^1H NMR signals at δ 2.12 (**12b**),⁸ 2.00 [(*Z*)-oct-4-ene]⁸ and 2.46 ppm (**13b**). The absence of any signal on the ^{13}C NMR spectrum at δ 126.4 ppm indicated that (4*E*,6*E*)-5,6-dipropyldeca-4,6-diene was not part of the mixture.³⁴

34– C. Denhez, S. Médécan, F. Hélicon, J.-L. Namy, J.-L. Vasse, J. Szymoniak, *Org. Lett.* **2006**, *8*, 2945–2947 (supporting information).

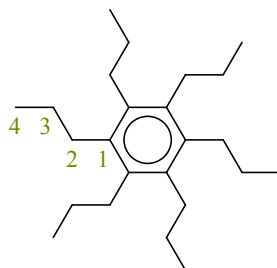


^1H NMR spectrum of the crude product (CDCl_3 , 400 MHz).



^{13}C NMR spectrum of the crude product (CDCl_3 , 100.6 MHz).

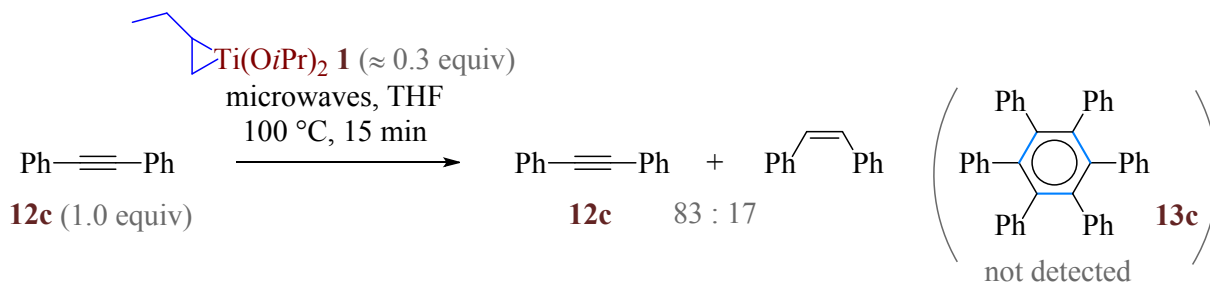
Hexapropylbenzene **13b**³⁵



¹H NMR (CDCl₃, 400 MHz): δ 1.04 (18 H, t J 7.5, H4), 1.52 (12 H, tt J 8.5, 7.5, H3), 2.46 (12 H, distorted t, J 8.5, H2). ¹³C NMR (CDCl₃, 100.6 MHz): δ 14.8 (C4), 24.9 (C3), 31.9 (C2), 136.3 (C1). HRMS (EI): m/z 330.3268 (M^+ C₂₄H₄₂⁺ requires 330.3281).

Note: this compound was observed in the crude product of the reaction of oct-4-yne **12b**. No attempt was made to isolate it.

Hexaphenylbenzene **13c**

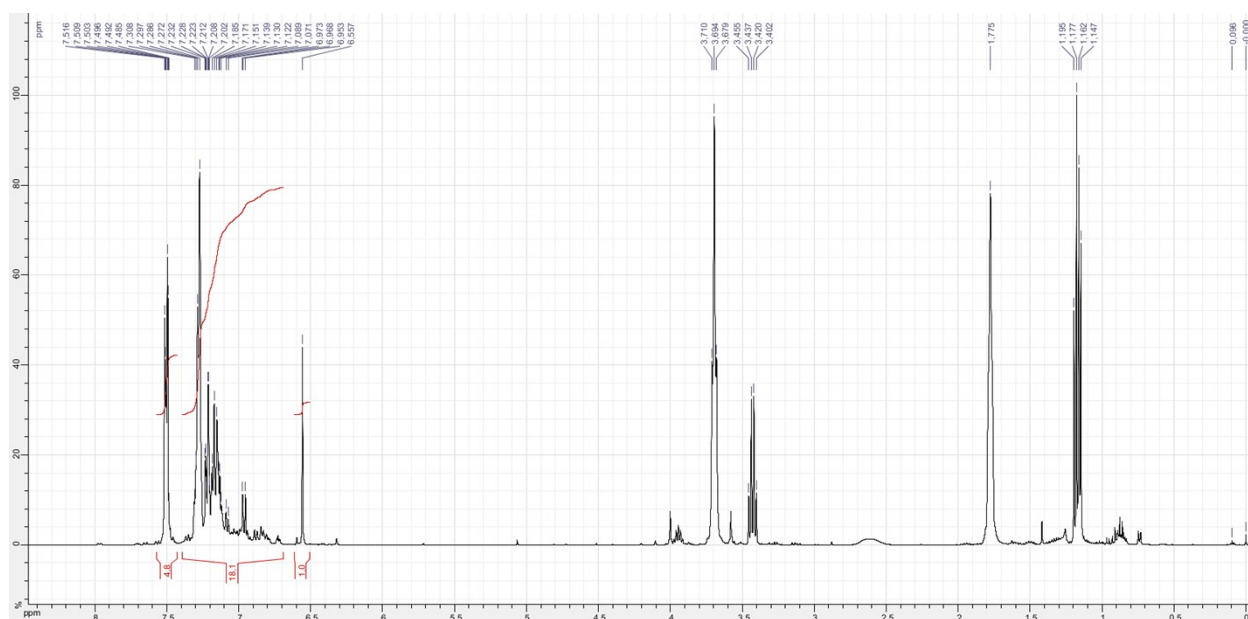


General procedure **G1** was applied with diphenylacetylene **12c**. Work-up **W1** was carried out. ¹H and ¹³C NMR analyses of the crude product showed that it contained essentially only starting material **12c** and *cis*-stilbene in 83:17 ratio, as estimated by measuring the intensities of characteristic ¹³C NMR signals at δ 131.3 (**12c**)⁸ and 130.0 ppm (*cis*-stilbene).⁸ Hexaphenylbenzene **13c**³⁶ and (1*E*,3*E*)-1,2,3,4-tetraphenylbuta-1,3-diene³⁷ were not detected.

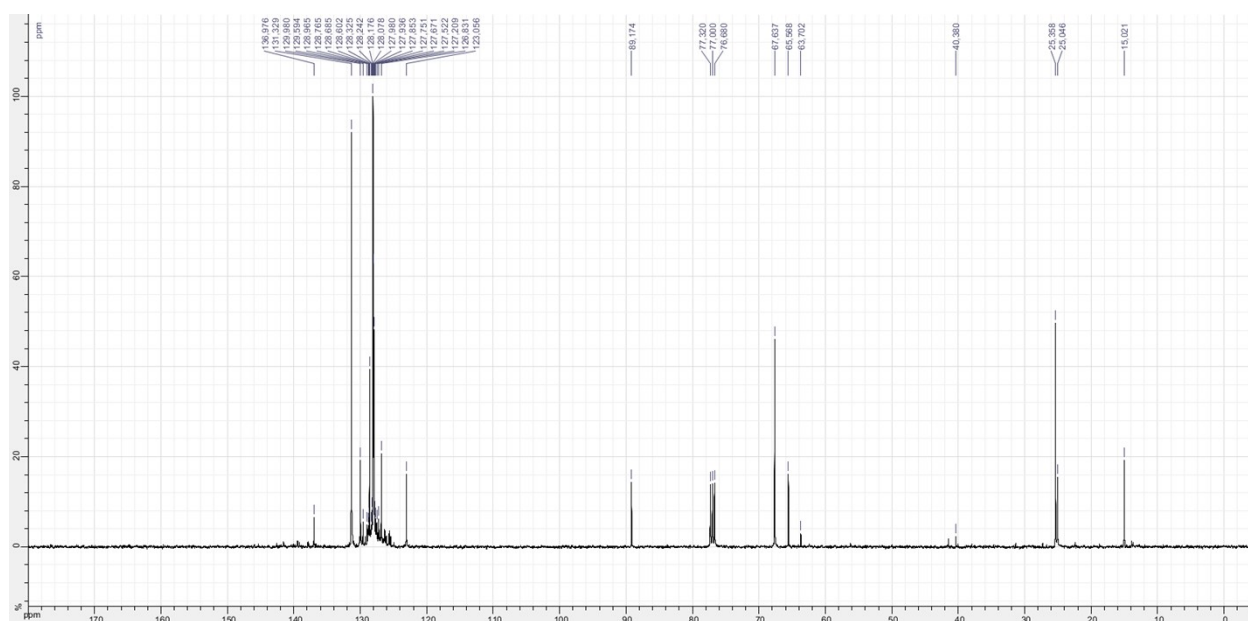
35– B. R. Steele, C. G. Screttas, *J. Am. Chem. Soc.* **2000**, *122*, 2391–2392 (supporting information).

36– M. F. N. N. Carvalho, F. M. T. Almeida, A. M. Galvão, A. J. L. Pombeiro, *J. Organomet. Chem.* **2003**, *679*, 143–147.

37– E. Negishi, S. J. Holmes, J. M. Tour, J. A. Miller, F. E. Cederbaum, D. R. Swanson, T. Takahashi, *J. Am. Chem. Soc.* **1989**, *111*, 3336–3346.

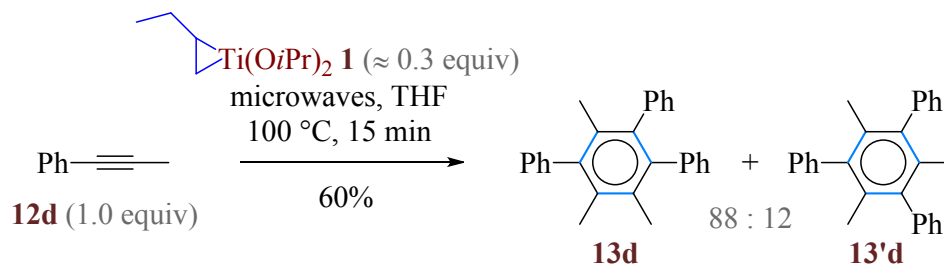


^1H NMR spectrum of the crude product (CDCl_3 , 400 MHz).



^{13}C NMR spectrum of the crude product (CDCl_3 , 100.6 MHz).

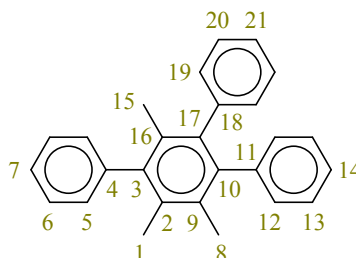
1,2,4-Trimethyl-3,5,6-triphenyl-benzene **13d** and 1,3,5-trimethyl-2,4,6-triphenyl-benzene **13'd**



General procedure **G1** was applied with 1-phenyl-prop-1-yne **12d**. Work-up **W1** was carried out. ^1H and ^{13}C NMR analyses of the crude product (412 mg, brown oil) showed the presence of trimethyl-triphenyl-benzene isomers **13d** and **13'd** (ratio 88 : 12, 60%), (*Z*)-1-phenyl-prop-1-ene (23%) and starting material **12d** (17%), these yields being estimated by measuring the intensities of

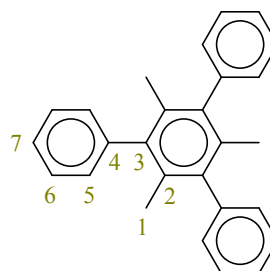
characteristic ^{13}C NMR signals at δ 18.1 and 18.3 (**13d**), 19.4 (**13'd**), 14.2 [(*Z*)-1-phenyl-prop-1-ene]³⁸ and 3.9 ppm (**12d**).⁸ The absence of any characteristic signal on the ^1H and ^{13}C NMR spectra, except for a very small peak at δ 6.79 ppm (^1H NMR), indicated that only traces, at most, of (*1E,3E*)-2,3-dimethyl-1,4-diphenyl-but-1,3-diene³⁹ were present in the mixture. Purification by flash column chromatography on silica gel (EtOAc/petroleum ether, gradient from 0 to 5%) afforded a 82 : 18 mixture of pure trimethyl-triphenyl-benzene isomers **13d** and **13'd** (208 mg, 597 μmol , 60%). Purity was further increased by trituration in MeOH.

1,2,4-Trimethyl-3,5,6-triphenyl-benzene **13d**^{40,41}



White solid. R_f 0.5 (EtOAc/petroleum ether 2%, PMA, UV-active). ^1H NMR (CDCl_3 , 400 MHz): δ 1.72 (3 H, s, H15), 2.04 (3 H, s, H1 or H8), 2.05 (3 H, s, H1 or H8), 6.94–7.16 (10 H, m, H12–H14, H19–H21), 7.25 (6 H, br d, J 8.0, H5), 7.35 (3 H, br t, J 7.5, H7), 7.45 (6 H, br tt, J 8.0, 7.5, H6). ^{13}C NMR (CDCl_3 , 100.6 MHz), characteristic signals: δ 18.1, 18.3 (C1, C8), 19.4 (C15), 125.64, 125.69 (C14, C21), 126.4 (C7), 127.27, 127.30 (C12, C18), 128.4 (C5), 129.3 (C6), 130.3 (4 C, C13, C20), 131.2, 131.9 (C2, C9), 133.9 (C16), 139.2 (C3), 140.6, 141.4 (C10, C17), 141.56, 141.58 (C11, C18), 142.4 (C4). HRMS (EI): m/z 348.1865 (M^+ $\text{C}_{27}\text{H}_{24}^+$ requires 348.1873).⁴²

1,3,5-Trimethyl-2,4,6-triphenyl-benzene **13'd**⁴⁰



R_f 0.5 (EtOAc/petroleum ether 2%, PMA, UV-active).⁴³ ^1H NMR (CDCl_3 , 400 MHz): δ 1.72 (9 H, s, H1), 7.23 (2 H, br d, J 8.0, H5), 7.32 (1 H, br t, J 7.5, H7), 7.43 (2 H, br tt, J 8.0, 7.5, H6). ^{13}C NMR (CDCl_3 , 100.6 MHz), characteristic signals: δ 19.4 (C1), 126.4 (C7), 128.4 (C5), 129.3 (C6), 133.2 (C2), 139.8 (C3), 142.1 (C4).

38– C. Belger, N. M. Neisius, B. Plietker, *Chem. Eur. J.* **2010**, *16*, 12214–12220 (supporting information).

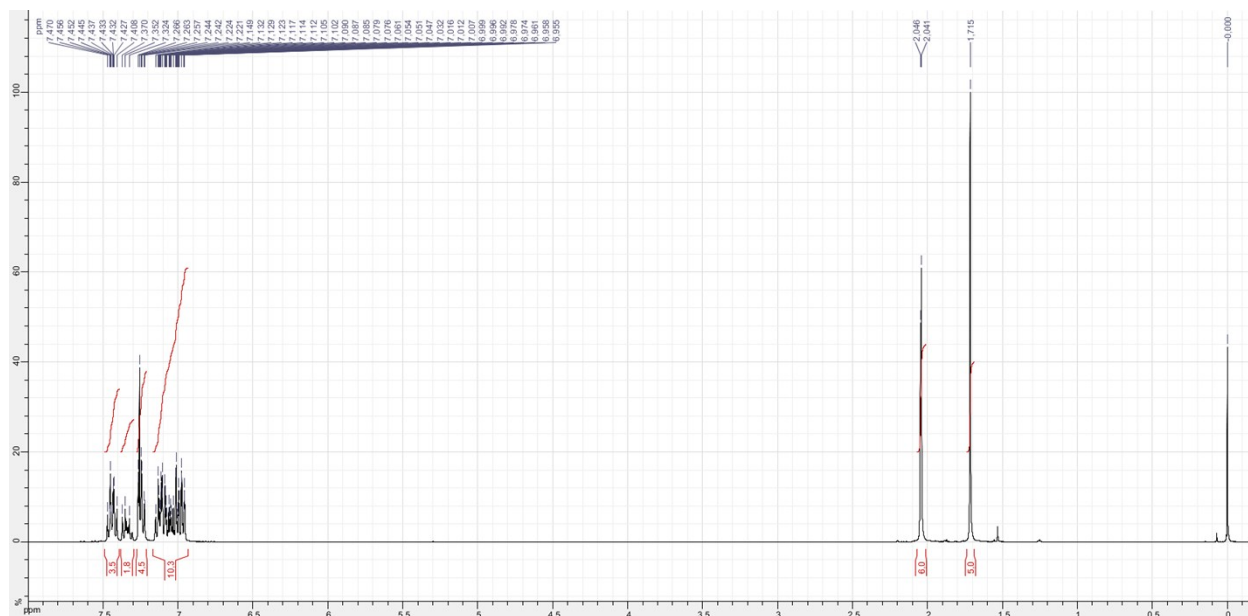
39– L. Yang, R. S. H. Liu, N. L. Wendt, J. Liu, *J. Am. Chem. Soc.* **2005**, *127*, 9378–9379 (supporting information).

40– A. K. Jhingan, W. F. Maier, *J. Org. Chem.* **1987**, *52*, 1161–1165.

41– K. Yoshida, I. Morimoto, K. Mitsudo, H. Tanaka *Tetrahedron* **2008**, *64*, 5800–5807.

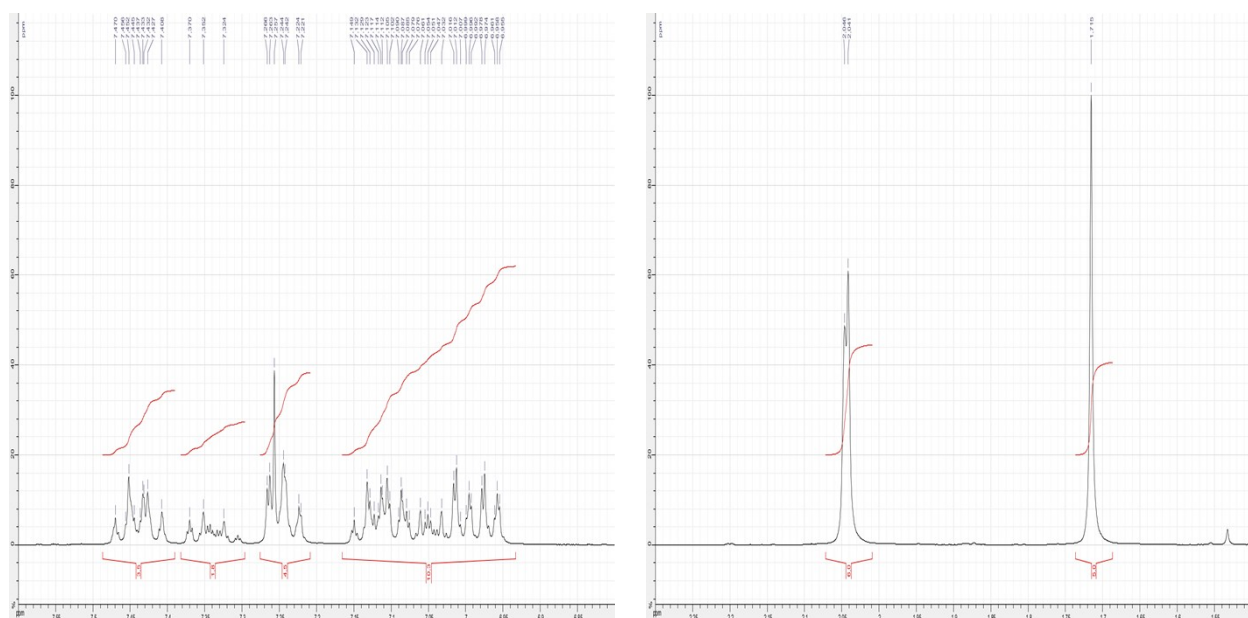
42– Analysis performed on a \approx 82 : 18 mixture of **13d** and **13'd**.

43– 1,3,5-Trimethyl-2,4,6-triphenyl-benzene **13'd** is slightly less polar than **13d**.



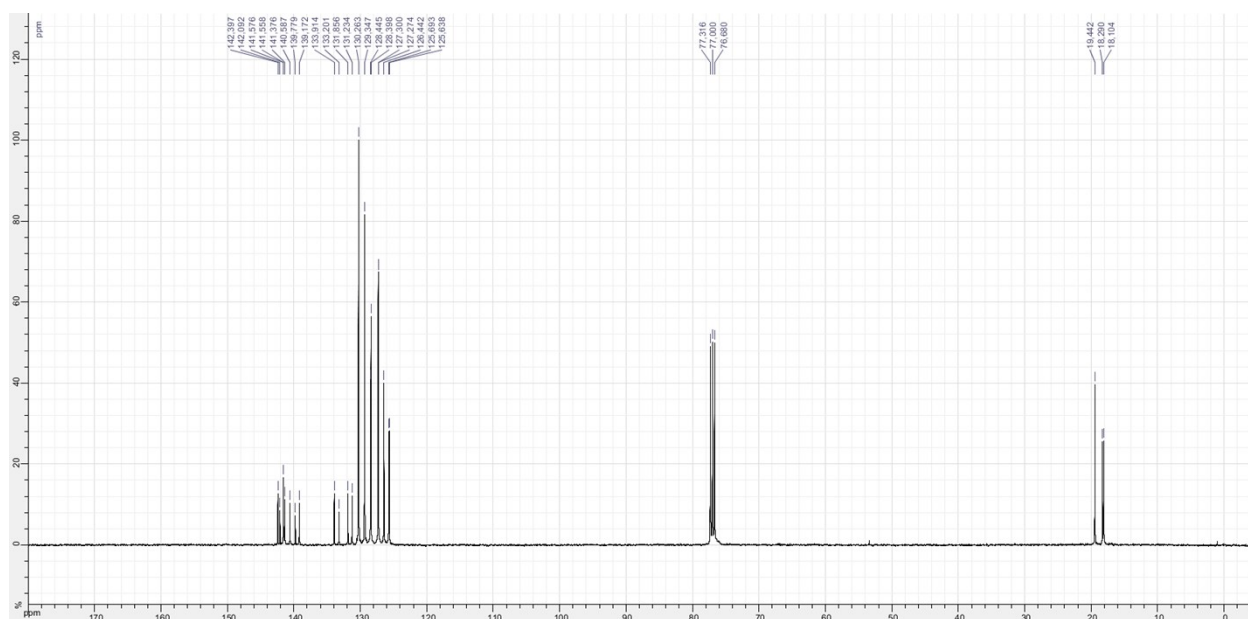
¹H NMR spectrum (CDCl₃, 400 MHz).

Note: this analysis was recorded with a $\approx 82 : 18$ mixture of **13d** and **13'd**.

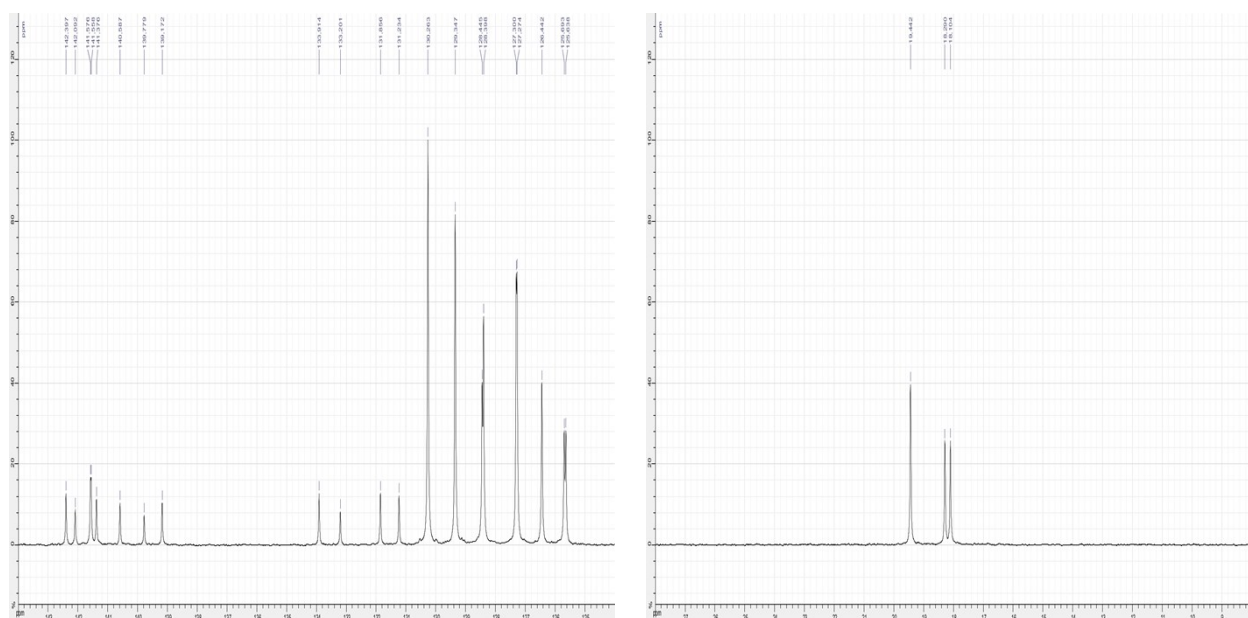


¹H NMR spectrum (selected extracts) (CDCl₃, 100.6 MHz).

Note: this analysis was recorded with a $\approx 82 : 18$ mixture of **13d** and **13'd**.

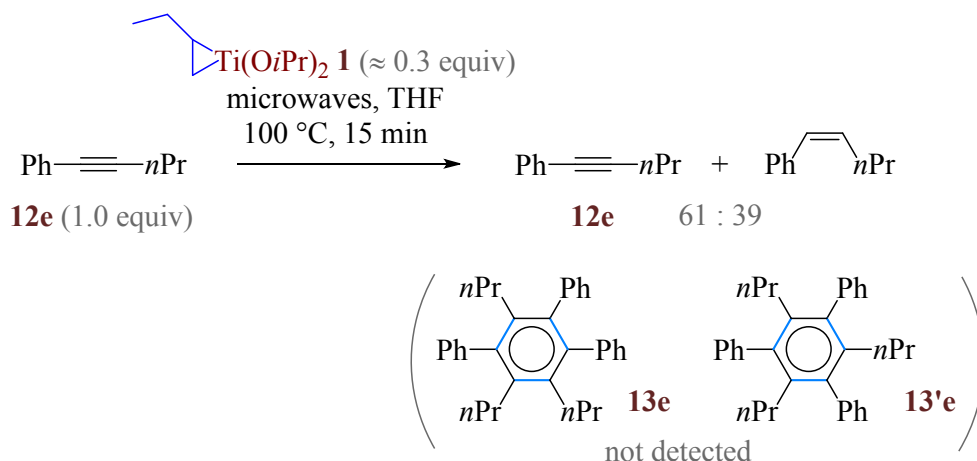


13C NMR spectrum (CDCl₃, 100.6 MHz).
*Note: this analysis was recorded with a $\approx 82 : 18$ mixture of **13d** and **13'd**.*

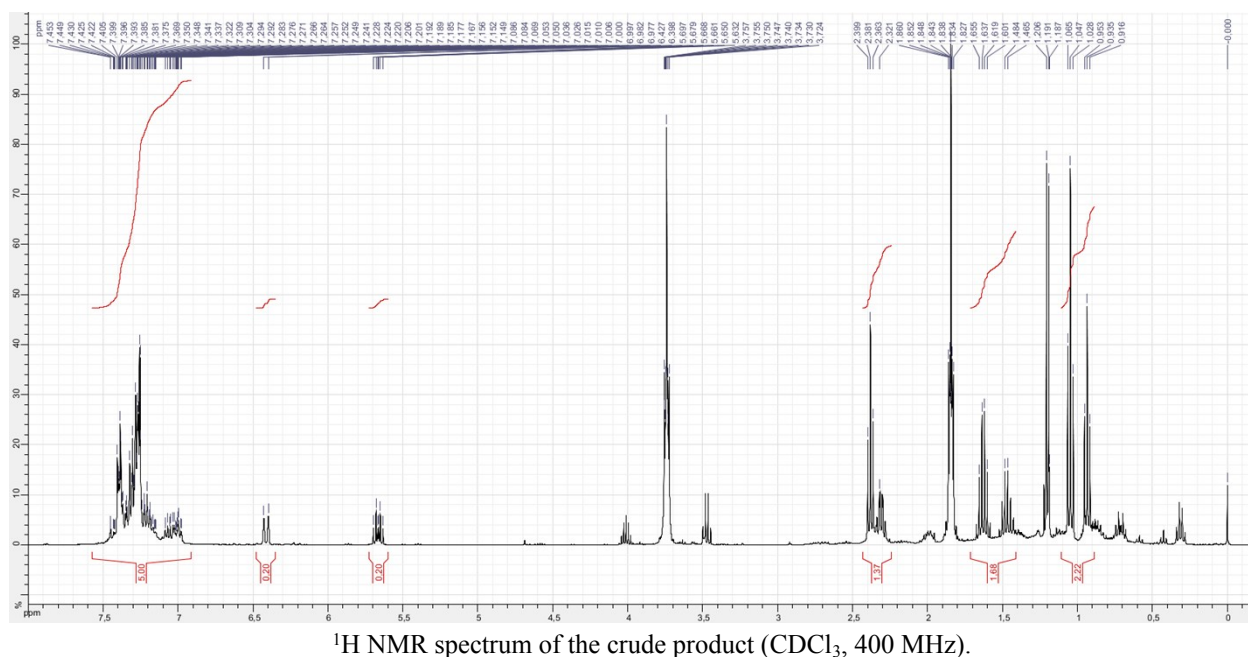


13C NMR spectrum (selected extracts) (CDCl₃, 100.6 MHz).
*Note: this analysis was recorded with a $\approx 82 : 18$ mixture of **13d** and **13'd**.*

1,2,4-Triphenyl-3,5,6-tripropyl-benzene **13e** and 1,3,5-triphenyl-2,4,6-tripropyl-benzene **13'e**

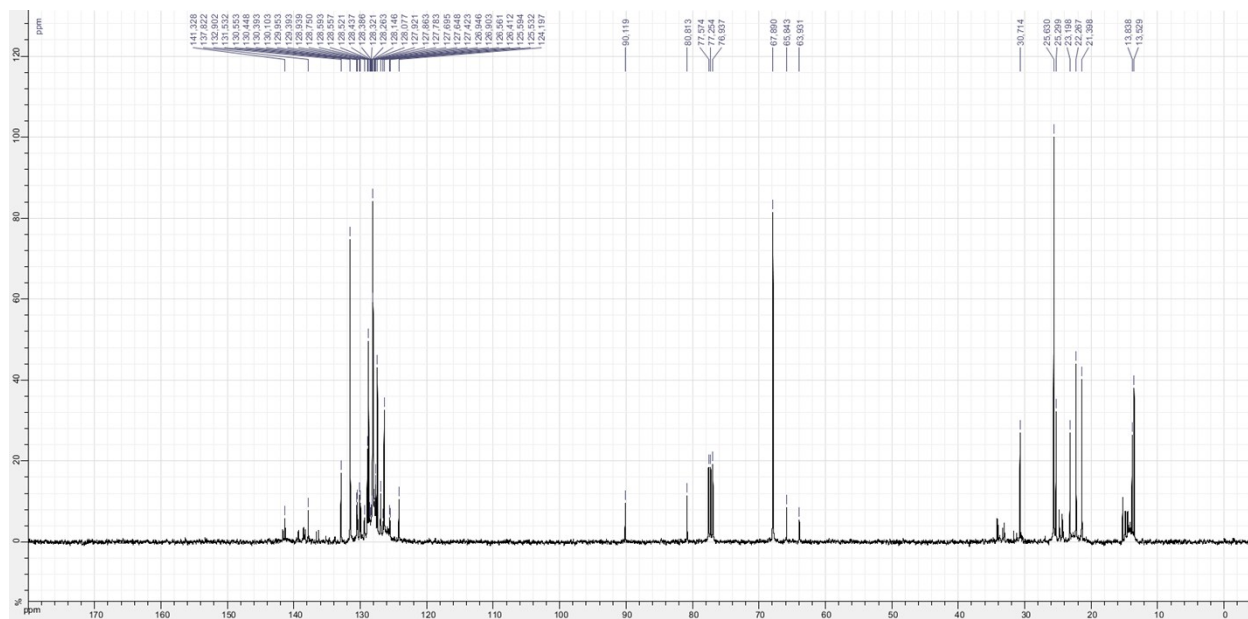


General procedure **G1** was applied with 1-phenylpent-1-yne **12e**. Work-up **W1** was carried out. ^1H and ^{13}C NMR analyses of the crude product showed that it contained essentially only starting material **12e** and (*Z*)-1-phenyl-pent-1-ene in 61:39 ratio, as estimated by measuring the intensities of characteristic ^{13}C NMR signals at δ 21.4, 22.3 (**12e**)⁴⁴, 23.2 and 30.7 ppm [(*Z*)-1-phenyl-pent-1-ene].⁴⁵ No significantly intense signals, that could correspond to triphenyl-tripropyl-benzene isomers **13e** or **13'e**, nor to (*1E,3E*)-1,4-diphenyl-2,3-dipropyl-buta-1,3-diene, were detected.



44– S. Xu, N. L. Truex, S. Mohan, E. Negishi, *Arkivoc* **2012**, vii, 242–252.

45– V. A. Rassadin, Y. Six, *Tetrahedron* **2014**, 70, 787–794 (supporting information).



^{13}C NMR spectrum of the crude product (CDCl_3 , 100.6 MHz).