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rsc.li/catalysisSynthesis of ene-yne-enes by nickel-catalyzed double S_N2' substitution of 1,6-dichlorohexa-2,4-diyne†Gongbao Wang, Erik-Jan Lindeboom,
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1,6-Dichlorohexa-2,4-diyne undergoes nickel-catalyzed double substitution with aryl and alkenyl Grignard reagents to provide substituted ene-yne-enes. The reaction is formally an extension of the well-described S_N2' -allylic and -propargylic substitution reactions but the mechanism is considerably more complex. The products might function as building blocks for conjugated polymers.

Introduction

Transition metal-catalyzed S_N2' -allylic and -propargylic substitution reactions with organometallic reagents as nucleophiles have been deeply studied in the last twenty years. In particular, copper-catalyzed allylic substitution of allylic halides and esters with organozinc, boron, aluminum and Grignard reagents is well understood and has developed into a powerful tool in organic synthesis as it provides a carbon–carbon single bond and a new carbon–carbon double bond.¹ As often a chiral center is formed in these reactions, both substrate control and catalyst control have been used to provide the products enantio-enriched.² The corresponding S_N2' -propargylic substitution reaction has received much less attention although in particular the groups of Alexakis, Lipshutz, and Krause have convincingly shown that this reaction provides a versatile entry into (enantio-enriched) allenes.³

Both reactions have now evolved to such an extent that more complex substrates with larger conjugated systems and alkenes and alkynes with two leaving groups have come within reach. Thus, on the one hand, dienes and ene-yne^{4,5} equipped with a leaving group at the allylic position have been studied and, on the other hand, alkenes and alkynes with leaving groups at the 1 and 4 positions,^{6,7} next to *gem*-disubstituted allylic systems,^{8,9} have been successfully used as substrates (Scheme 1).

In the case of 1,4-dichlorobut-2-ene,⁷ allylic substitution takes place once, providing a homo-allylic product suitable

for further functionalization. This has been cleverly used for desymmetrization as well.^{10–13} In the case of 1,4-disubstituted but-2-yne, the reaction takes place twice,^{14–21} as the initially formed 4-substituted 1,2-butadiene again acts as a substrate for the reaction, to provide disubstituted 1,3-butadienes. This reaction has been extensively exploited as the products, in turn, are starting materials for subsequent Diels–Alder reactions^{22–32} (Scheme 2).

After an initial report of Mkryan and co-workers,²² this double substitution reaction has been carried out mainly using organocuprates based on Grignard or organozinc reagents (Scheme 2).

Although less far developed than that catalyzed by copper, nickel-catalyzed allylic and propargylic substitution is also well known.³³ In addition, palladium catalysis has been employed in this double S_N2' substitution, in particular with less reactive organometallics such as organotin and organoboron compounds together with alkyne dicarbonates. Here, satisfactory yields of 1,3-dienes were obtained as well, although the advantages compared to the use of copper and “hard” organometallics seemed somewhat limited (Scheme 3).

Very recently, however, this reaction was extended to the direct use of readily available propargylic diols.³⁴ This adds

Scheme 1 Substrates for S_N2' -allylic and -propargylic substitution reactions.

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† Electronic supplementary information (ESI) available: NMR spectra of all the compounds and the complex, IR spectrum of the complex, GC-MS spectra of compound 3–9, and additional crystallographic data in CIF or other electronic format see DOI: 10.1039/c7cy00429j

Scheme 2 Double S_N2' reactions of 1,4-disubstituted 2-butyne.

Scheme 3 The application of organoboron and tin compounds to form 2,3-disubstituted 1,3-butadienes.

considerably to the applicability of the reaction as this procedure is essentially (pseudo) halogen-free (Scheme 4).

The reaction has been used in particular for the preparation of dendralenes. This was carried out by reacting vinyl Grignard reagents with 1,4-dichlorobut-2-yne using Ni as a catalyst (Scheme 2, RM = vinyl MgBr).³⁵ This methodology gives rapid access to novel substituted dendralenes and addressed the deficiency of the synthesis of these compounds. As an example of selective S_N2' substitution, instead of S_N2' substitution, the iron-catalyzed coupling of bulky Grignard reagents to propargylic and allylic halides is mentioned.³⁶

We were curious to determine whether the S_N2' -propargylic substitution reaction could be extended to a diyne as the substrate with leaving groups at the 1 and 6 positions. Surprisingly, this motif seems to have escaped attention although the starting material, 1,6-dichlorohexa-2,4-diyne, is readily prepared by chloro-substitution of 1,6-dihydroxyhexa-2,4-diyne, which in turn is prepared by Glaser coupling of propargyl alcohol. We report here that the nickel-catalyzed reaction of 1,6-dichlorohexa-2,4-diyne with aryl or alkenyl Grignard reagents leads to the formation of 2,5-disubstituted hexa-1,5-dien-3-yne *via* formal double S_N2' substitution (Scheme 5).

Results and discussion

Partly based on literature precedents in the double substitution of 1,4-dichlorobut-2-yne, we focused on the reaction of phenylmagnesium bromide with 1,6-dichlorohexa-2,4-diyne (2), prepared from hexa-2,4-diyne-1,6-diol (1), in the presence of nickel catalysts (Table 1). In the Kumada–Tamao–Corriu reaction, a cross-coupling reaction of Grignard reagents catalyzed by nickel, the catalysts Ni(dppp)Cl₂, Ni(dppe)Cl₂ and Ni(dppf)Cl₂ are often effective so these were initially selected. It turned out that although all catalysts led to full conversion

Scheme 4 Direct cross-coupling reactions of propargylic diols.

Scheme 5 Nickel-catalyzed formal double S_N2' substitution of 1,6-dichloro-hexa-2,4-diyne with Grignard reagents.

of the starting material, in particular Ni(dppp)Cl₂ provided an acceptable NMR yield of a product that turned out to be diphenyl ene-yne-ene 3 (Table 1, entry 1). In addition, an N-heterocyclic carbene Ni catalyst was investigated, but this did not lead to an identifiable product (Table 1, entry 5). The structure of diphenyl ene-yne-ene 3 was established by ¹H- and ¹³C-NMR, mass spectrometry, and comparison of these spectra with the literature, as 3 has been prepared once before *via* another route.³⁵ Apart from homo-coupling of the Grignard reagent, we were unsuccessful in the identification of other products in addition to 3. In addition to 3, NMR and GC indicated the formation of oligomers, likely because of subsequent reactions of the product (*vide infra*).

Upon selection of Ni(dppp)Cl₂ as the catalyst, we varied its loading (Table 1, entries 1 and 6–8). The results indicated that 0.5 mol% Ni(dppp)Cl₂ was sufficient to fully convert the starting material (Table 1, entry 8) but 1 mol% catalyst gave the highest NMR yield (Table 1, entry 7). The addition of PPh₃ to the reaction led to a slight decrease in yield (Table 1, entry 9), possibly due to decomposition of the product by nucleophilic attack of PPh₃. Without a catalyst, only a trace of product was detected with 53% conversion of 2 after 1 h (Table 1, entry 10), demonstrating the necessity of the catalyst in this reaction.

With a suitable catalyst system selected, our attention turned to the optimization of the amount of the Grignard reagent required (Table 2). It turned out that also with 2.5 equiv. of phenylmagnesium bromide the starting material was fully converted, but the NMR yield was higher when 3 equiv. was used. A further increase in the amount of the Grignard reagent lowered the yield to some extent.

Subsequently, several solvents commonly used for the Kumada–Tamao–Corriu reaction were evaluated for the reaction on hand (Table 3), and THF showed to be optimal (Table 3, entry 1). As 1,4-dioxane leads to a shift in the Schlenk equilibrium because it complexes to MgBr₂, thereby forming diphenylmagnesium,³⁶ the NMR yield probably decreased although the conversion was only slightly lower (Table 3, entries 1–4).

The yield of the reaction is surprisingly sensitive to the reaction temperature. Carrying out the reaction in a temperature range of –10 to –20 °C led to the highest NMR yields, whereas both lower and higher temperatures caused a significant drop in yield. Variation in the order and rate of addition showed that adding 2 slowly at an approximate rate of 10 mmol h^{–1} for a reaction on a 1 mmol scale led to acceptable isolated yields. At a considerably higher addition rate, the yields dropped. The reaction was complete in approximately 1 h, whereas prolonged reaction times led to significantly

Table 1 Defining a suitable Ni catalyst and catalyst loading for the double S_N2' -propargylic substitution^a

Entry	Catalyst ^c (mol%)	Yield ^b (%)	Conversion of 2 (%)
1	Ni(dppp)Cl ₂ (2.5)	52	100
2	Ni(dppe)Cl ₂ (2.5)	38	100
3	Ni(dppf)Cl ₂ (2.5)	30	100
4	Pd(PPh ₃) ₄ (2.5)	6	98
5	IPrNiCl ₂ (PPh ₃) (2.5)	n.d. ^d	74
6	Ni(dppp)Cl ₂ (5.0)	48	100
7	Ni(dppp)Cl ₂ (1.0)	73	100
8	Ni(dppp)Cl ₂ (0.5)	62	100
9	Ni(dppp)Cl ₂ (1.0) ^e	63	100
10	—	Trace	53

^a Reaction conditions: 2 (1.0 mmol), PhMgBr (3.0 mmol, 3.0 mL, 1.0 M in THF), the addition rate of 2 was 10 mmol h⁻¹, the reaction was performed at a final concentration of 0.1 M 2. ^b The yield of the desired product was determined by q⁻¹H-NMR. ^c dppp, 1,3-bis-(diphenylphosphino)propane; dppe, 1,2-bis-(diphenylphosphino)ethane; dppf, 1,1'-bis-(diphenylphosphino)ferrocene; PPh₃, triphenylphosphine; IPr, 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene. ^d n.d., not detected. ^e 2 mol% PPh₃ was added.

Table 2 Optimization of the stoichiometry of the Grignard reagent in the double S_N2' -propargylic substitution^a

Entry	Equiv. of PhMgBr	Yield ^b (%)	Conversion (%)
1	2.5	60	100
2	3.0	73	100
3	3.5	68	100
4	4.0	65	100

^a Reaction conditions: 2 (1.0 mmol), PhMgBr (1.0 M in THF), Ni(dppp)Cl₂ (0.01 mmol), the addition rate of 2 was 10 mmol h⁻¹, the reaction was performed at a final concentration of 0.1 M 2. ^b The yield of the desired product was determined by q⁻¹H-NMR.

Table 3 Defining the optimal solvent in the double S_N2' -propargylic substitution^a

Entry	Solvent	Yield ^b (%)	Conversion (%)
1	THF	73	100
2	Et ₂ O	49	100
3	MTBE	56	100
4	1,4-Dioxane	31	98

^a Reaction conditions: 2 (1.0 mmol), PhMgBr (3.0 mmol, 3.0 mL, 1.0 M in THF), Ni(dppp)Cl₂ (0.01 mmol), the addition rate of 2 was 10 mmol h⁻¹, the reaction was performed at a final concentration of 0.1 M 2. ^b The yield of the desired product was determined by q⁻¹H-NMR.

lower yields, most probably because the product decomposed under the influence of the remaining Grignard reagent.

With the reaction conditions optimized, our next efforts focused on the scope of applicable Grignard reagents (Fig. 1). For aryl Grignard reagents, modest to good crude yields are

obtained, more or less regardless of the presence of electron-donating or electron-withdrawing substituents and the substitution pattern (3, 4, 5, 6, 7). Nevertheless, the isolated yields after purification by column chromatography strongly varied due to the instability of the various products. It turned out

that, although decomposing in the reaction and upon column purification, the products could be stored as solutions in pentane at $-10\text{ }^{\circ}\text{C}$ for several weeks. Unfortunately, the crude yield in the reaction with *cis*-2-butenylmagnesium bromide was low, although the yield of **8** after purification nearly equaled the crude yield, indicating that this compound is stable. We assume that the oligomerization of **8** is slow because it is less prone to act as an activated alkene. When the more reactive benzyl Grignard reagent was used, only the double $\text{S}_{\text{N}}2$ product (**9**) was obtained. This corresponds to the reaction with methylmagnesium bromide that also produced solely the double $\text{S}_{\text{N}}2$ product as shown by the $^1\text{H-NMR}$ of the reaction mixture (the product was too volatile to isolate).

In order to obtain rigorous proof of the structure of these unstable ene-yne-ene, the diphenyl ene-yne-ene product **3** was treated with dicobalt octacarbonyl (see the Experimental section and Fig. 2). This led to a stable solid that was purified by column chromatography and subsequent crystallization. Crystals suitable for X-ray analysis were obtained in this way and this showed unambiguously the structure of the dicobalt complex **10** and thereby the structure of diphenyl ene-yne-ene **3**.

Proposed mechanism

The mechanism of the Kumada–Tamao–Corriu reaction, the Ni-catalyzed cross-coupling of Grignard reagents with aryl halides, is reasonably well understood.^{37–43} Based on this mechanism, we propose the following pathway for the formation of diphenyl ene-yne-ene **3** (Scheme 6). The precatalyst is re-

Fig. 2 Complex **10**, = $3\text{-Co}_2(\text{CO})_6$. CCDC deposition number: 1519007.

duced to $\text{Ni}(0)$ by the homo-coupling of the Grignard reagent leading to the formation of biphenyl. The $\text{Ni}(0)$ catalyst undergoes oxidative insertion into one of the C–Cl bonds of 1,6-dichlorohexa-2,4-diyne **2** to give propargylic nickel(II) intermediate In1. Rearrangement gives allenyl nickel(II) complex In3, either *via* intermediate In2 or directly. In3 undergoes transmetalation with the Grignard reagent to give phenyl-allenyl nickel(II) intermediate In4. Reductive elimination would then lead to the formation of **P1** (route a), although this compound was not observed.

Subsequent oxidative insertion of $\text{Ni}(0)$ into the C–Cl bond of **P1** would produce intermediate In5. A more likely hypothesis is that In4 undergoes intramolecular transfer of nickel(0) to the terminal C–Cl bond to yield In5 directly (route b). Similar rearrangements are well precedent in so-called catalyst-

Fig. 1 Scope of the double $\text{S}_{\text{N}}2'$ -propargylic substitution reaction in terms of the Grignard reagent. Reaction conditions: 1,6-dichlorohexa-2,4-diyne (2.0 mmol, 2.0 mL, 1 M in THF), Grignard reagent (6.0 mmol, 6.0 or 12.0 mL, 1.0 or 0.5 M in THF), $\text{Ni}(\text{dppp})\text{Cl}_2$ (0.02 mmol), THF (12 or 6 mL). ^a6.0 mL of a 1.0 M solution of 4-chlorophenylmagnesium bromide in 2-methyl-THF and 12.0 mL of THF were used. Crude yield is the yield as determined by q-NMR before column purification. ^bThe direct double $\text{S}_{\text{N}}2$ substitution product was obtained.

Scheme 6 Proposed mechanism for the double S_N2' reaction.

transfer (poly)condensations, also for $Ni(dppp)$. In those cases, association of $Ni(II)$ with the π -system of an aromatic ring, however, is mostly involved.⁴⁴ Rearrangement of In5 gives complex In7, either *via* intermediate In6 or directly. Subsequently, In7 undergoes transmetalation with the Grignard reagent, and final reductive elimination of In8 produces diphenyl ene-yne-ene 3.

It is clear that this complex pathway can derail at several places (Scheme 7). First of all, considerably more biphenyl (around 20%) is observed than can be accounted for by the initial reduction of the precatalyst (1 mol%). This can be explained by side reactions that lead to the regeneration of the $Ni(II)$ species. So In1, In2, In3 and in principle In4 can undergo elimination to provide cumulene 11 and $Ni(II)Cl_2$. Cumulene 11 is most probably so unstable that it escapes observation. This elimination is known and forms the basis for the synthesis of radialenes according to Iyoda *et al.*⁴⁵ We specu-

late that the elimination in the latter case is very fast because of the formation of a fully substituted double bond, whereas in the current reaction, a 1,1-disubstituted double bond is formed and the cross-coupling reaction can apparently compete. Magnesium halogen exchange with the substrate is also possible and leads to dimer and oligomer formation of the substrates. Within 0.5 h, half of the starting material was consumed also in the absence of catalyst, whereas biphenyl formation was observed. Finally, it is clear that the product 3 is unstable under the reaction conditions, and might be sensitive to nucleophilic attack by the Grignard reagent.

Conclusion

It has been shown that 1,6-dichlorohexa-2,4-diyne undergoes nickel-catalyzed disubstitution with Grignard reagents to provide diaryl- or dialkenyl-substituted ene-yne-enes. This is a

Scheme 7 Derailing pathway of the double S_N2' reaction.

new and significant contribution to the field of transition metal-catalyzed allylic and propargylic substitution reactions in which the mechanism is considerably more complex and involves extensive rearrangements of the intermediate nickel species. The products can be isolated, purified, and characterized either as such or as the corresponding dicobalt hexacarbonyl complex. Although the application of these ene-yne-ene systems might be hampered by their instability, it is definitely worthwhile to pursue. Prepared efficiently from low-cost starting materials and catalysts, these compounds might function as building blocks for conjugated polymers. Ene-yne-enes resemble the repeating unit in polydiacetylenes, which have important applications in organic films.^{45,46} Olefin metathesis of these ene-yne-enes could provide an alternative way to produce these polymers with better control over their chain length and processability.

Experimental section

General experimental details

All reactions were performed using oven-dried glassware and dry solvents unless otherwise specified. THF, Et₂O, MTBE and DCM were taken from an MBraun solvent purification system (SPS-800). All other reagents were purchased from Sigma-Aldrich, TCI Europe, Strem Chemicals or Acros Organics and were used without further purification unless noted otherwise. CuI was purified before use according to the literature procedure.⁴⁷ IR spectra were recorded on a Perkin-Elmer FTIR spectrometer. ¹H NMR, ¹³C NMR and ¹⁹F NMR spectra were recorded on a Varian AMX400 (400, 100.6 and 376 MHz, respectively). Chemical shift values are reported in ppm with the solvent resonance as the internal standard. Data are reported as follows: chemical shifts, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, dd = double doublet, dq = double quartet, qd = quarter doublet, m = multiplet), coupling constants (Hz), and integration. GC-MS measurements were performed with an HP 6890 series gas chromatography system with an HP1 or HP5 column (Agilent Technologies, Palo Alto, CA), equipped with an HP 5973 mass-sensitive detector. Flash chromatography: Merck silica gel type 9385, 230–400 mesh. TLC: Merck silica gel 60, 0.25 mm. Compounds were visualized using UV, Seebach's reagent (phosphomolybdic acid, 25 g; cerium sulfate, 7.5 g; H₂O, 500 mL; H₂SO₄, 25 mL) and potassium permanganate staining.

General procedure for quantitative NMR experiments

Exactly 0.50 mL of the reaction mixture was sampled using a syringe and added to a mixture of 1 mL of HPLC grade pentane and 2 mL of 0.1 M HCl_{aq}. The mixture was shaken, the organic layer was separated and the volatiles were removed *in vacuo*. To the residue was added 0.5 mL of 0.1 M mesitylene in CDCl₃ as an internal standard. Then, the solution was measured through a quantitative NMR experiment.⁴⁷ The spectra were obtained with a sufficiently long acquisition time (3 s) and processed using MestReNova version 10.2. The

crude yield of the desired product was determined based on the ratio between the signals of the double bond hydrogens of the product and the signals of the internal standard.

Synthesis of the starting material

Hexa-2,4-diyne-1,6-diol (1).⁴⁸ To a dried 500 mL three-necked flask with a stirring bar were added 1.43 g (7.5 mmol) of CuI, 1.78 g (7.5 mmol) of NiCl₂·6H₂O, 4.5 mL (30 mmol) of TMEDA and 62.8 mL (450 mmol) of Et₃N in 340 mL of dry THF at room temperature under air. The solution was stirred until the solution was bright dark green and 8.41 g (150 mmol) of propargyl alcohol was slowly added to the reaction mixture while bubbling O₂ through the solution *via* a glass inlet over 45 min. After 24 h, the THF and the remaining Et₃N were removed *in vacuo* and the residue was dissolved in 500 mL of EtOAc. This mixture was filtered and the filtrate was carefully washed with saturated NH₄Cl (3 × 100 mL). The aqueous phase was separated and further extracted with EtOAc (3 × 100 mL). Then, the combined organic layers were washed with brine (100 mL), dried over anhydrous Na₂SO₄, filtered, and concentrated under vacuum. The pure product was obtained as a white solid through flash precipitation of the residue with EtOAc and *n*-pentane (7.85 g, 95%). ¹H NMR (400 MHz, acetone-d₆) δ 4.27 (d, *J* = 6.0 Hz, 4H), 4.38 (t, *J* = 6.0 Hz, 2H). ¹³C NMR (101 MHz, acetone-d₆): δ 50.8, 69.0, 79.5. The spectroscopic data corresponded to the literature.⁴⁹

1,6-Dichlorohexa-2,4-diyne (2).⁵⁰ To a dry 250 mL three-necked flask were added 3.04 g (28 mmol) of hexa-2,4-diyne-1,6-diol, 5.6 mL (70 mmol) of pyridine and 100 mL of dry DCM at room temperature under a N₂ atmosphere. The flask was then cooled to 0 °C with an ice bath and a solution of 5.1 mL (70 mmol) of SOCl₂ in 20 mL of dry DCM was added dropwise to the reaction mixture. After the addition, the ice bath was removed and the reaction mixture was stirred overnight. Then, the reaction mixture was poured into 300 mL of crushed ice and extracted with Et₂O (3 × 100 mL). The organic layer was washed with saturated NaHCO₃ (3 × 100 mL) and brine (150 mL), and the organic layer was dried over Na₂SO₄ and decolorized using activated carbon. The solvent was removed *in vacuo* at 0 °C and the residue was purified by means of a short silica column using pentane as the eluent. The fractions containing the product were collected and evaporated *in vacuo* at 0 °C to give the pure product as a colorless liquid (2.91 g, 71%). As the product decomposed over time, it was stored as a 1 M solution in dry THF at –80 °C and used quickly. ¹H NMR (400 MHz, CDCl₃): δ 4.21 (s, 4H). ¹³C NMR (101 MHz, CDCl₃): δ 30.4, 70.0, 74.7. The spectroscopic data corresponded to the literature.⁵¹

General procedure for the double S_N2' reaction of 1,6-dichlorohexa-2,4-diyne

A 50 mL Schlenk flask, flame-dried three times and placed under a N₂ atmosphere, was charged with 10.8 mg (0.02 mmol) of Ni(dppp)Cl₂ and 6 or 12 mL of dry THF. The reaction mixture was subsequently cooled to –15 °C using a cold

acetone bath. A solution of 6.0 mmol of the Grignard reagent (0.5 or 1.0 M in dry THF) was added to the reaction mixture. After the addition, the solution was stirred for 10 min at $-15\text{ }^{\circ}\text{C}$. Then, a solution of 2 mL of 1,6-dichlorohexa-2,4-diyne (1.0 M in THF) was added over 12 min using a syringe pump. After the addition, the solution was left to stir at $-15\text{ }^{\circ}\text{C}$ for an additional 10 min. After this time, the acetone bath was removed and the reaction mixture was left to stir for another 1 h. Then, a quantitative NMR was taken to determine the crude yield of the desired product. The reaction mixture was subsequently poured into a mixture of 150 mL of H_2O , 10 mL of 2 M HCl and 150 mL of *n*-pentane. The organic layer was separated, washed with H_2O ($2 \times 100\text{ mL}$) and brine (150 mL), dried over anhydrous MgSO_4 , filtered, and concentrated under vacuum at $0\text{ }^{\circ}\text{C}$. The resulting residue was purified using flash silica column chromatography using *n*-pentane as the eluent. The fractions containing the product were collected and evaporated *in vacuo* at $0\text{ }^{\circ}\text{C}$ to give the pure product as a colorless oil or white solid. As the product polymerized quickly over time, yields were lower than expected based on q-NMR. The isolated product was stored at $-80\text{ }^{\circ}\text{C}$ in *n*-pentane.

Hexa-1,5-dien-3-yne-2,5-diyl dibenzene (3).

Phenylmagnesium bromide was used as the Grignard reagent (1.0 M in THF). Crude yield, 72%. The pure product was obtained as a colorless oil (0.20 g, isolated yield, 44%). ^1H NMR (400 MHz, CDCl_3): δ 5.78 (d, $J = 0.8\text{ Hz}$, 2H), 6.00 (d, $J = 0.8\text{ Hz}$, 2H), 7.41–7.31 (m, 6H), 7.72–7.69 (m, 4H). ^{13}C NMR (101 MHz, CDCl_3): δ 90.1, 121.2, 126.3, 128.5, 128.6, 130.7, 137.4. GC-MS: m/z (relative intensity, %) = 230 (100, M^+), 229 (54), 228 (44), 215 (36). The analytical data were in accordance with the literature.³⁵

4,4'-(Hexa-1,5-dien-3-yne-2,5-diyl)bis(methylbenzene) (4).

p-Tolylmagnesium bromide was used as the Grignard reagent (1.0 M in THF). Crude yield, 68%. The pure product was obtained as a white solid (0.11 g, isolated yield, 22%). ^1H NMR (400 MHz, CDCl_3): 2.37 (s, 6H), 5.71 (d, $J = 0.8\text{ Hz}$, 2H), 5.95 (d, $J = 0.8\text{ Hz}$, 2H), 7.18 (d, $J = 8.0\text{ Hz}$, 4H), 7.60 (d, $J = 8.0\text{ Hz}$, 4H). ^{13}C NMR (101 MHz, CDCl_3): δ 21.3, 90.0, 120.2, 126.1, 129.3, 130.5, 134.6, 138.4. GC-MS: m/z (relative intensity, %) = 258 (100, M^+), 228 (55), 243 (48), 129 (33).

4,4'-(Hexa-1,5-dien-3-yne-2,5-diyl)bis(chlorobenzene) (5). A 50 mL Schlenk flask, flame-dried three times and placed under a N_2 atmosphere, was added to 10.8 mg (0.02 mmol) of Ni(dppp)Cl_2 and 12 mL of dry THF. The reaction mixture was then cooled to $-15\text{ }^{\circ}\text{C}$ using a cold acetone bath. A solution of 6.0 mmol of (4-chlorophenyl)magnesium bromide (1.0 M in 2-methyltetrahydrofuran) was added to the reaction mixture. After the addition, the solution was stirred for 10 min at $-15\text{ }^{\circ}\text{C}$. Then, a solution of 2 mL of 1,6-dichlorohexa-2,4-diyne (1.0 M in THF) was added over 12 min using a syringe pump. After the addition, the solution was left to stir at $-15\text{ }^{\circ}\text{C}$ for an additional 10 min. After this, the acetone bath was removed and the reaction mixture was left to stir for another 1 h. Then, a quantitative NMR was taken to determine the crude yield of the desired product (50%). The reaction mixture was subsequently poured into a mixture of 150 mL of

H_2O , 10 mL of 2 M HCl and 150 mL of *n*-pentane. The organic layer was separated, washed with H_2O ($2 \times 100\text{ mL}$) and brine (150 mL), dried over anhydrous MgSO_4 , filtered, and concentrated under vacuum at $0\text{ }^{\circ}\text{C}$. The resulting residue was purified using flash silica column chromatography using *n*-pentane as the eluent. The fractions containing the product were collected and evaporated *in vacuo* at $0\text{ }^{\circ}\text{C}$ to give the pure product as a white solid (0.15 g, 26%). As the product polymerized quickly over time, some of the product was lost in the column and the isolated product was stored at $-80\text{ }^{\circ}\text{C}$ in *n*-pentane. ^1H NMR (400 MHz, CDCl_3): δ = 5.76 (s, 2H), 5.98 (s, 2H), 7.36–7.33 (m, 4H), 7.62–7.59 (m, 4H). ^{13}C NMR (101 MHz, CDCl_3): δ = 89.9, 121.8, 127.5, 128.8, 129.5, 134.5, 135.7. GC-MS: m/z (relative intensity, %) = 298 (52, M^+), 263 (41), 228 (100), 226 (40).

5,5'-(Hexa-1,5-dien-3-yne-2,5-diyl)bis(1,3-dimethylbenzene) (6). (3,5-Dimethylphenyl)magnesium bromide was used as the Grignard reagent (0.5 M in THF). Crude yield, 56%. The pure product was obtained as a white solid (0.17 g, isolated yield, 30%). ^1H NMR (400 MHz, CDCl_3): δ = 2.35 (s, 12H), 5.72 (d, $J = 0.8\text{ Hz}$, 2H), 5.96 (d, $J = 1.2\text{ Hz}$, 2H), 6.98 (s, 2H), 7.33 (s, 4H). ^{13}C NMR (101 MHz, CDCl_3): δ = 21.5, 90.2, 120.8, 124.2, 130.2, 130.9, 137.4, 138.0. GC-MS: m/z (relative intensity, %) = 287 (23), 286 (100, M^+), 271 (45), 256 (62).

4,4'-(Hexa-1,5-dien-3-yne-2,5-diyl)bis(fluorobenzene) (7). (4-Fluorophenyl)magnesium bromide was used as the Grignard reagent (1.0 M in THF). Crude yield, 60%. The pure product was obtained as a white solid (0.19 g, isolated yield, 36%). ^1H NMR (400 MHz, CDCl_3): 5.75 (s, 2H), 5.93 (s, 2H), 7.10–7.04 (m, 4H), 7.69–7.63 (m, 4H). ^{13}C NMR (101 MHz, CDCl_3): δ 90.0, 115.5 (d, $J = 21.7\text{ Hz}$), 121.1 (d, $J = 1.9\text{ Hz}$), 128.0 (d, $J = 8.0\text{ Hz}$), 129.6, 133.4 (d, $J = 3.4\text{ Hz}$), 163.0 (d, $J = 248.4\text{ Hz}$). ^{19}F NMR (376 MHz, CDCl_3): δ -113.51 to -113.58 (m, 2F). GC-MS: m/z (relative intensity, %) = 266 (100, M^+), 265 (35), 264 (30), 133 (48).

(2*E*,8*E*)-3,8-Dimethyl-4,7-dimethylenedeca-2,8-dien-5-yne (8). (*E*-But-2-en-2-yl)magnesium bromide was used as the Grignard reagent (0.5 M in THF). Crude yield, 25%. The pure product was obtained as a white solid (74.5 mg, isolated yield, 20%). ^1H NMR (400 MHz, CDCl_3): 1.75 (dq, $J = 7.2\text{ Hz}$, 1.5 Hz, 6H), 1.88–1.87 (m, 6H), 5.30 (d, $J = 2.0\text{ Hz}$, 2H), 5.43 (dq, $J = 7.0\text{ Hz}$, 1.4 Hz, 2H), 5.58 (d, $J = 2.0\text{ Hz}$, 2H). ^{13}C NMR (101 MHz, CDCl_3): δ 15.0, 23.5, 89.4, 123.4, 123.5, 130.7, 134.5. GC-MS: m/z (relative intensity, %) = 186 (18, M^+), 171 (92), 156 (100), 141 (86), 128 (80).

1,8-Diphenylocta-3,5-diyne (9). A 50 mL Schlenk flask, flame-dried three times and placed under a N_2 atmosphere, was added to 10.8 mg (0.02 mmol) of Ni(dppp)Cl_2 and 13.7 mL of dry THF. The reaction mixture was then cooled to $-15\text{ }^{\circ}\text{C}$ using a cold acetone bath. A solution of 6.0 mmol of benzylmagnesium chloride (1.4 M in dry THF) was added to the reaction mixture. After the addition, the solution was stirred for 10 min at $-15\text{ }^{\circ}\text{C}$. Then, a solution of 2 mL of 1,6-dichlorohexa-2,4-diyne (1.0 M in THF) was added over 12 min using a syringe pump. After the addition, the solution was left to stir at $-15\text{ }^{\circ}\text{C}$ for 10 min more. After the stirring, the

cold acetone bath was removed and the reaction mixture was left to stir for another 1 h. Then, a quantitative NMR was taken to determine the crude yield of the desired product (43%). The reaction mixture was poured into a mixture of 150 mL of H₂O, 10 mL of 2 M HCl and 150 mL of *n*-pentane. Then, the organic layer was separated, washed with H₂O (2 × 100 mL) and brine (150 mL), dried over anhydrous MgSO₄, filtered, and concentrated under vacuum at 0 °C. The resulting residue was purified using flash silica column chromatography using *n*-pentane as the eluent. The fractions containing the product were collected and evaporated *in vacuo* at 0 °C to give the pure product as a white solid (0.20 g, 38%). This product was relatively stable at room temperature. ¹H NMR (400 MHz, DMSO-*d*₆): 2.58 (t, *J* = 7.2 Hz, 4H), 2.75 (t, *J* = 7.2 Hz, 4H), 7.24–7.19 (m, 6H), 7.31–7.27 (m, 4H). ¹³C NMR (101 MHz, DMSO-*d*₆): δ 20.4, 33.7, 65.7, 77.6, 126.2, 128.3, 128.4, 140.0. GC-MS: *m/z* (relative intensity, %) = 258 (17, M⁺), 167 (33), 165 (26), 91 (100), 65 (24).

Hexa-1,5-dien-3-yne-2,5-diyl dibenzene(dicobaltoctacarbonyl complex) (10). A 50 mL Schlenk flask, flame-dried three times and placed under a N₂ atmosphere, was charged with 10.8 mg (0.02 mmol) of Ni(dppp)Cl₂ and 12 mL of dry THF. The reaction mixture was then cooled to –15 °C using a cold acetone bath. A solution of 6.0 mmol of phenylmagnesium bromide (1.0 M in THF) was added to the reaction mixture. After the addition, the solution was stirred for 10 min at –15 °C. Then, a solution of 2 mL of 1,6-dichlorohexa-2,4-diyne (1.0 M in THF) was added over 12 min using a syringe pump. After the addition, the solution was left to stir at –15 °C for an additional 10 min. After this, the acetone bath was removed and the reaction mixture was left to stir for another 1 h. Then, the reaction mixture was poured into a mixture of 150 mL of water, 10 mL of 2 M HCl and 150 mL of *n*-pentane. Afterwards, the organic layer was separated, washed with water (2 × 100 mL) and brine (150 mL), dried over anhydrous MgSO₄, filtered, and concentrated under vacuum at 0 °C. To a 50 mL round-bottom flask, a solution of the resulting residue in 12 mL of dry THF was added followed by 0.82 g of Co₂(CO)₈ (2.4 mmol). The reaction mixture was left to stir overnight. After this, the reaction mixture was concentrated under vacuum. The resulting residue was purified using flash silica column chromatography using *n*-pentane as the eluent. The fractions containing the product were collected and evaporated *in vacuo* at 0 °C to give the pure product as a red brown solid (0.18 g, 17%). ¹H NMR (400 MHz, CD₃CN): δ = 5.75 (d, *J* = 0.8 Hz, 2H), 5.84 (d, *J* = 1.2 Hz, 2H), 7.36–7.30 (m, 6H), 7.52–7.49 (m, 4H). ¹³C NMR (101 MHz, CD₂Cl₂): δ = 98.7, 118.9, 127.6, 128.8, 128.9, 141.4, 148.1, 199.7. IR (neat): ν_{max} 2924, 2854, 2091, 2025, 2009, 1995, 1975, 1958, 1617, 1595, 1572, 1493, 1444, 1399, 1383, 890, 843, 773, 740, 721, 699, 628 cm^{–1}.

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Notes and references

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