



Article Palladium-Catalyzed Cross-Coupling Reaction of Bis(cyclopentadienyl)diaryltitaniums with Terminal Alkynes

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Abstract: Organotitanium compounds find application in diverse reactions, including carbon–carbon bond formation and oxidation. While titanium (IV) compounds have been used in various applications, the potential of bis(cyclopentadienyl)diaryltitanium in cross-coupling reactions remains unexplored. This study focuses on Sonogashira-type cross-coupling reactions involving terminal alkynes and organotitanium compounds. Diaryltitanocenes were synthesized using titanocene dichloride with lithium intermediates derived from aryl iodide. Under open-flask conditions, reactions of diphenyltitanocenes with ethynylbenzene in the presence of 20 mol% Pd(OAc)₂ in DMF produced coupling products in a remarkable 99% yield. Various diaryltitanocenes and alkynes under standard conditions yielded corresponding cross-coupling products with moderate to good yields. Notably, the Sonogashira-type alkynylation proceeds under mild conditions, including open-flask conditions, and without the need for a base. Furthermore, this cross-coupling is atom-economical and involves the active participation of both aryl groups of the diaryltitanocene. Remarkably, this study presents the first example of a Sonogashira-type cross-coupling using titanium compounds as pseudo-halides.

Keywords: palladium-catalyzed cross-coupling reaction; titanium; terminal alkyne; Sonogashira-type reaction; open-flask conditions

e, S. ross-Coupling **1. Introduction**

The chemical reactivity of organotitanium compounds has received considerable attention. Organotitanium compounds are used in various applications, including carbon-carbon bond formation and oxidation reactions [1–4]. Among these, aryltitanium (IV) alkoxides [ArTi(OR)₃] have been shown to act as transmetallating agents, that is, nucleophiles, in cross-coupling reactions with halides using Pd and Ni catalysts [5–10]. For example, Hayashi et al. reported that the cross-coupling reaction of 2-naphthyl triflate and ArTi(*i*-PrO)₃ using catalyst systems of [Pd(C₃H₅)Cl]₂ and phosphine ligands affords biaryls [5]. Gau et al. developed a reaction in which a benzyl halide was reacted with PhTi(*i*-PrO)₃ using a Pd(OAc)₂/P(*p*-Tol)₃ system to produce the corresponding 1-benzyl-4-arylbenzenes [8]. However, the application of bis(cyclopentadienyl)diaryltitanium (Ar₂TiCp₂: diaryltitanocene) in cross-coupling reactions has not yet been reported.

The Sonogashira reaction is an important cross-coupling reaction used in the synthesis of natural products, biologically active compounds, and pharmaceutical intermediates [11–14]. The conventional protocol for this reaction involves the reaction of a terminal alkyne with an aryl halide or triflate as an electrophile in the presence of a Pd-phosphine complex as a catalyst and Cu salt as a co-catalyst, with a high quantity of amine as the solvent and base under an inert atmosphere. Over the past four decades, various modifications of the Sonogashira reaction have been developed. Among these, aryl donors containing typical elements, such as boron, silicon, phosphorus, antimony, bismuth, sulfur, tellurium, and iodine, have been reported to behave as alternative aryl halides and triflates as electrophilic partners in Sonogashira-type reactions [15–26].



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). In 2003, Zou et al. conducted a procedure for constructing internal alkynes via the crosscoupling reaction of terminal alkynes and arylboronic acids catalyzed by a Pd(dppf)Cl₂-AgO system in the presence of excess K_2CO_3 as the base [15]. Since then, this type of reaction, with arylboronic acids and silver reagents as oxidants, has attracted considerable attention, and several groups reported improved methods [16–19]. Recently, Zhu et al. developed the reaction of terminal alkynes with hypervalent aryl iodonium salts using a PdCl₂-AgI system and triethylamine [20]. Cheng et al. conducted aryl trimethoxysilanes as useful arylating agents using the Pd(dppf)Cl₂-AgF system in the presence of NaHCO₃ [21]. Moreover, triarylbismuthines act as arylating agents in systems comprising Pd(OAc)₂-AgF and K_3PO_4 systems [22]. However, the Sonogashira-type reactions of terminal alkynes with organotitanium compounds under open-flask conditions have not yet been examined. Inspired by this knowledge and our continuing studies regarding this novel Sonogashiratype reaction, we present a Pd-catalyzed C(Ar)–C(sp) bond formation using silver salt and terminal alkynes, with Ar₂TiCp₂ as pseudo-halides, that is, electrophiles, without a base.

2. Results and Discussion

2.1. Synthesis of Bis(cyclopentadienyl)diaryltitanium

Bis(cyclopentadienyl)diaryltitanium **2** was synthesized according to the procedures specified in previous reports [27,28]. Aryl iodide **1** was treated with 1.0 equivalents of *n*-butyllithium in dry ether under an argon atmosphere at -30 °C, followed by dichlorobis(cyclopentadienyl)titanium (Cp₂TiCl₂), thus resulting in the formation of **2a–e** in good-to-excellent yields (Scheme 1). Unfortunately, the use of the methoxy derivative, with a stronger electron-donating group on its benzene ring compared to the methyl group, yielded only a complex mixture, not **2b**. The resulting products, whose color ranged from yellowish to dark red, were crystalline compounds that were stable at room temperature in air.



Scheme 1. Synthesis of bis(cyclopentadienyl)diaryltitanium.

2.2. *Molecular Structures of* 2*c*

Figure 1 shows the crystal structure of **2c**, and Table 1 lists the selected bond lengths and angles. The two cyclopentadienyl rings were π -bonded to titanium with an average Ti– C distance of 2.392 Å, which corresponds to the length reported for Ph₂TiCp₂ (2.31 Å) [29]. The C–C bond lengths in the cyclopentadienyl rings were also approximately the same as those of Ph₂TiCp₂, which varied from 1.397 to 1.411 Å with an average C–C bond length of 1.402 Å. The two aryl rings were σ -bonded to a titanium atom, with an average Ti–C distance of 2.21 Å. These lengths were similar to the distance of Ph₂TiCp₂ (2.27 Å). The arrangement of the four ligands on titanium was pseudotetrahedral, with C (1) –Ti–C (1'), C (1)–Ti–Cp (1) (center), and C (1') –Ti–Cp (1) (center) bond angles of 98.66°, 102.44°, and 108.18°, respectively.



Figure 1. Molecular structures of 2c with 50% probability thermal ellipsoids.

Fable 1. Selected bond lengths	(À	Í)) and bond angles (°	')	for 2c.
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Bond Lengths (Å)		
Ti-Cp (1) (average)	2.392	
Ti-Cp $(1')$ (average)	2.392	
Ti-C (1)	2.2107(15)	
Ti-C (1')	2.2107(15)	
Bond angles (°)		
C (1)-Ti-C (1')	98.66(8)	
C (1)-Ti-Cp (1) (left)	102.44	
C (1')-Ti-Cp (1) (left)	108.18	

2.3. Cross-Coupling Reactions of Diaryltitanocenes with Terminal Alkynes

First, the optimal experimental conditions were determined for cross-coupling using diphenyltitanocene (2a) and phenylacetylene (3a) as model substrates. Table 2 lists the results of the screening of suitable catalysts, additives, and solvents. We first reacted 2a (0.25 mmol) with 3a (0.5 mmol) using various Pd catalysts (20 mol%) and AgF (4.0 eq.) in DMF at room temperature under open-flask conditions for 24 h (entries 1–5). This reaction could be performed with any of the Pd(II) and Pd(0) catalysts, among which $Pd(OAc)_2$ provided the best yield of diphenylethyne **4a** (entry 1). In the screening of additives, such as silver reagents and CsF, only AgF exhibited high reactivity (entries 1 and 7–10). Pd(OAc)₂ and AgF were essential for this reaction, and the reaction did not proceed without their additions (entries 6 and 11). Solvent screening revealed that the reaction proceeded in DMF, DMA, DMSO, NMP, CH₃CN, and CH₃OH (entries 1 and 12–16), with DMF offering the best yield (entry 1). By contrast, THF, CH_2Cl_2 , and toluene were inefficient reaction solvents (entries 17-19). When the reactions were performed under argon and oxygen atmospheres, the yield of the coupling product 4a was lower than that obtained under open-flask conditions (entries 1, 20, and 21). Decreasing the loading of Pd(OAc)₂ from 20 to 10 mol% resulted in a significantly lower yield of 4a (20% yield, entry 22), thus suggesting that the reaction was sensitive to catalyst loading. Consequently, the optimal result was obtained when 2a was treated with 2.0 equivalents of alkyne 3a and 4.0 equivalents of AgF under open-flask conditions at room temperature (entry 1). The results obtained under these optimum conditions indicate that the two phenyl groups on the titanium atom of **2a** are utilized in the reaction.

C	Cp Ti Ph Ph Pd ca 2a Solve	t. (20 mol%) kdditive ent, rt, 24 h	4a	+	
Entry	Pd cat.	Additive	Solvent	4a (%) ^{b,c}	5 (%) ^{b,d}
1	Pd(OAc) ₂	AgF	DMF	99 (98) ^e	
2	PdCl ₂	AgF	DMF	67	
3	$PdCl_2(PPh_3)_2$	AgF	DMF	93	1
4	Pd(PPh ₃) ₄	AgF	DMF	77	
5	Pd(dba) ₂	AgF	DMF	80	1
6		AgF	DMF	3	1
7	Pd(OAc) ₂	AgOAc	DMF	4	
8	Pd(OAc) ₂	AgNO ₃	DMF	19	1
9	Pd(OAc) ₂	Ag ₂ O	DMF		
10	$Pd(OAc)_2$	CsF	DMF		
11	Pd(OAc) ₂		DMF		3
12	Pd(OAc) ₂	AgF	DMA	86	
13	Pd(OAc) ₂	AgF	DMSO	84	
14	$Pd(OAc)_2$	AgF	NMP	80	
15	Pd(OAc) ₂	AgF	CH ₃ CN	74	
16	Pd(OAc) ₂	AgF	CH ₃ OH	71	
17	Pd(OAc) ₂	AgF	THF	17	3
18	Pd(OAc) ₂	AgF	CH_2Cl_2	2	
19	Pd(OAc) ₂	AgF	Toluene		
20 ^f	$Pd(OAc)_2$	AgF	DMF	87	2
21 ^g	$Pd(OAc)_2$	AgF	DMF	65	2
22 ^h	$Pd(OAc)_2$	AgF	DMF	20	

Table 2. Reaction screening of diphenyltitanocene 2a with phenylacetylene 3a^a.

^a Reaction conditions: **2a** (0.25 mmol), **3a** (0.5 mmol), Pd catalyst (0.05 mmol), additive (1.0 mmol), solvent (3.0 mL). ^b GC yield. ^c The yield 100% corresponds to the formation of 0.5 mmol of **4a**. ^d The yield 100% corresponds to the formation of 0.25 mmol of **5**. ^e Isolated yield. ^f Under O₂. ^g Under Ar. ^h Pd(OAc)₂ (10 mol%).

Under the optimal identified reaction conditions for this Sonogashira-type reaction, we examined the scope with respect to diaryltitanocene **2** (0.25 mmol) and terminal alkyne **3** (0.5 mmol). The results of these coupling reactions are listed in Table **3**. The reaction of diaryltitanocene **2c**–**e** with both electron-donating and electron-withdrawing groups on the aromatic ring with phenylacetylene **3a** afforded the corresponding adducts **4b-d** in good to moderate yields (55–76%). Then, diphenyltitanocene **2a** was reacted with various terminal alkynes **3b**–**f** to produce coupling products **4b**–**d** and **4f**, which were substituted with electron-donating or electron-withdrawing groups at the 4-position of the benzene ring, in 61–88% yields. However, contrary to the expectations, the corresponding **4e** was not obtained using 4-ethynylanisole **3b**. Sterically hindered acetylene compounds **3g** and **3h** with substituents at the *ortho* position of the benzene ring afforded products **4g** and **4h** without any difficulty. Terminal alkynes bearing vinyl **3i** and alkyl **3j** afforded products **4i** and **4j**, respectively, in fair yields. By contrast, the reaction of terminal alkyne **3k** with a heteroaryl group, such as thiophene, produced the corresponding coupling product **4k** in a low yield (34%), which did not confirm the effectiveness of this system.

Cp			Pd(OAc) ₂ (20 mol% AgF (4.0 eq.))			
Cp		+ H	DMF, rt, 24 h	→ ×-	E —R		
2	×						
Diaryltitanocene (2)	x	Acetylene (3)	R	Isolated Yiel	d (%)		
2c	Me	3a	C_6H_5	Me-	4b : 76		
2d	Cl	3a	C_6H_5		4c : 55		
2e	CF ₃	3a	C_6H_5	F ₃ C-	4d : 73		
2a	Н	3b	$4-MeOC_6H_4$	OMe	4e:		
2a	Н	3c	$4-MeC_6H_4$	✓————————————————————————————————————	4b : 88		
2a	Н	3d	$4-ClC_6H_4$	CI	4c : 61		
2a	Н	3e	$4\text{-BrC}_6\text{H}_4$	── Br	4f : 68		
2a	Н	3f	$4\text{-}CF_3C_6H_4$	CF3	4d : 63		
2a	Н	3g	2-MeC ₆ H ₄		4g : 94		
2a	Н	3h	2,4,6- MeC ₆ H ₂	Me Me Me	4h : 65		
2a	Н	3i	Cyclohexenyl		4i : 55		
2a	Н	3ј	<i>n</i> -Butyl	√nBu	4j : 48		
2a	Н	3k	2-Thienyl		4k : 34		

Table 3. Substrate scope of coupling reactions between 2 and 3 ^{a,b}.

x

^a Reaction conditions: 2 (0.25 mmol), 3 (0.5 mmol), Pd(OAc)₂ (0.05 mmol), AgF (1.0 mmol), DMF (3.0 mL).
 ^b Isolated yield.

The mechanism of the Sonogashira-type reaction with diaryltitanocenes **2** is currently unclear. We considered mechanisms similar to those described in our previous study [22]. Plausible mechanisms for the reaction between terminal alkynes and diaryltitanocenes in the formation of internal alkynes are shown in Scheme 2. The first step of the reaction was the transmetallation between diaryltitanocene (**2**) and the $Pd^{II}X_2$ catalyst to form intermediates **A** and **B**. Silver acetylide **C** and HF were formed from terminal alkyne **3** and AgF. A second transmetallation of **B** with silver acetylide **C** afforded intermediate **D**, which underwent a reductive elimination to form coupling product **4** and a Pd^0 species. The Pd^0 species was oxidized by the silver cation or AgX to regenerate Pd^{II} (Scheme 2, first cycle). Subsequently, the ligand-exchange reaction of intermediate **A** with the $Pd^{II}X_2$ catalyst generated intermediate **B**, followed by the reaction of **B** with **C** to afford **D**. Intermediate **D** was converted to **4** via a reductive elimination (Scheme 2, second cycle). Another route in the second cycle is possible, in which the oxidative addition of **A** to Pd^0 affords Pd^{II} intermediate **F**.



Scheme 2. Plausible reaction mechanism.

3. Conclusions

In conclusion, diaryltitanocenes are a new class of arylating reagents for Sonogashiratype coupling reactions under open-flask conditions. This is the first example of the use of bis(cyclopentadienyl)diaryltitanium as a pseudo-halide in a cross-coupling reaction. The reaction proceeded without a base and all aryl groups on the titanium reagent participated in the reaction. The reaction afforded the corresponding cross-coupling products in satisfactory yields, even with diaryltitanocenes and terminal alkynes. On the other hand, the synthesis of diaryltitanocenes with strong electron-donating groups, such as methoxy groups, on the phenyl rings is challenging, leaving room for improvement as a general synthetic method. The Sonogashira-type reactions using diaryltitanocenes were also more electronically sensitive than the reported reactions of compounds containing typical elements, such as arylboronic acids and triarylbismuthines, with various acetylene derivatives. The studies on the mechanism of this reaction and the reactions of diaryltitanocenes with other coupling partners are ongoing.

4. Materials and Methods

4.1. General Information

All reagents and solvents were purchased from commercial suppliers and used without further purification. ¹H nuclear magnetic resonance (NMR, trimethylsilane: δ 0.00 ppm or CHCl₃: δ 7.26 ppm as an internal standard) and ¹³C NMR (CDCl₃: δ 77.0 ppm as an internal standard) spectroscopy were conducted using an ECZ-400S (400 and 100 MHz, respectively) spectrometer (JEOL, Zhubei, China). Melting points, which were uncorrected, were measured using a micro-melting-point hot stage apparatus (Yanagimoto, Yokohama, Japan). Gas chromatography-mass spectrometry (GC-MS) (electron ionization (EI)) was performed using a 5977E Diff-SST MSD-230V spectrometer (Agilent Technologies, Santa Clara, CA, USA), and elemental analyses were performed on an MT-5 elemental analyzer (Yanagimoto, Yokohama, Japan). Infrared (IR) spectroscopy was conducted using an FTIR-8400S (Shimadzu, Kyoto, Japan), and the spectra were reported in the frequency of absorption (cm⁻¹) with only selected IR absorbencies reported. All chromatographic separations were performed using Silica Gel 60N (Kanto Chemical Co., Inc., Tokyo, Japan), and thin-layer chromatography (TLC) was performed using Sil G25 UV₂₅₄ pre-coated TLC plates (Macherey-Nagel, Hoerdt, France).

4.2. Synthesis of Bis(cyclopentadienyl)diaryltitanium

To a solution of aryl iodide (20 mmol, 2.0 eq.) in anhydrous Et₂O (10 mL), added *n*-BuLi (22 mmol, 1.56 M solution in hexane) at -30 °C. Stir the mixture for 1 h at room temperature. Add the resulting solution of ArLi dropwise to a solution of Cp₂TiCl₂ (10 mmol) in anhydrous Et₂O (10 mL) at -30 °C. Warm the resulting solution -30 °C to room temperature before stirring for 16 h. The reaction mixture was slowly added to methanol (4.0 mL) at -30 °C. Filter the resulting solution and volatiles removed under a high vacuum to obtain bis(cyclopentadienyl)diaryltitanium. (Copies of ¹H and ¹³C NMR see Supplementary Materials).

Diphenyltitanocene (2a) [27]. Light-yellow prisms (2.77 g, 84%), mp 146–148 °C (from CH₂Cl₂-Hexane), $R_f = 0.4$ (Hexane: AcOEt = 20:1). ¹H NMR (400 MHz, CDCl₃) δ : 6.20 (10H, s, Cp-H), 6.88 (6H, d, *J* = 6.8 Hz, Ar-H), 6.97 (4H, t, *J* = 6.8 Hz, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ : 115.9 (CH), 123.7 (CH), 126.5 (CH), 134.9 (CH), 191.1 (C). IR (KBr/cm⁻¹) 1639, 1411, 1356, 1236, 1049, 1016, 815, 732, 702, 669. Anal. Calcd. for C₂₂H₂₀Ti: C, 79.5; H, 6.07, found: C, 79.4; H, 6.17.

Di-*p*-tolyltitanocene (2c) [27]. Dark-red prisms (2.66 g, 74%), mp 137–139 °C (from CH₂Cl₂-Hexane), $R_f = 0.3$ (Hexane: AcOEt = 20:1). ¹H NMR (400 MHz, CDCl₃) δ : 2.22 (6H, s, CH₃), 6.18 (10H, s, Cp-H), 6.78–6.79 (8H, m, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ : 21.1 (CH₃), 115.8 (CH), 127.2 (CH), 133.0 (C), 135.0 (CH), 187.7 (C). IR (KBr/cm⁻¹) 1629, 1438, 1265, 1182, 1070, 1016, 810, 721, 669, 623. Anal. Calcd. for C₂₄H₂₄Ti: C, 80.0; H, 6.71, found: C, 80.2; H, 6.82.

Bis-4-chlorophenyltitanocene (2d) [30]. Orange powder (3.17 g, 79%), mp 59–61 °C (from CH₂Cl₂-Hexane), $R_f = 0.4$ (Hexane: AcOEt = 8:2). ¹H NMR (400 MHz, CDCl₃) δ: 6.18 (10H, s, Cp-H), 6.76 (4H, d, *J* = 8.4 Hz, Ar-H), 6.92 (4H, d, *J* = 8.8 Hz, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ: 116.2 (CH), 126.3 (CH), 129.9 (C), 136.2 (CH), 187.9 (C). IR (KBr/cm⁻¹) 1654, 1585, 1483, 1089, 815, 717, 669. Anal. Calcd. for C₂₂H₁₈Cl₂Ti: C, 65.9; H, 4.52, found: C, 65.6; H, 4.61.

Bis-4-(trifluoromethyl)phenyltitanocene (2e) [30]. Brown powder (4.31 g, 92%), mp 141–143 °C (from CH₂Cl₂-Hexane), $R_f = 0.3$ (Hexane: AcOEt = 8:2). ¹H NMR (400 MHz, CDCl₃) δ: 6.22 (10H, s, Cp-H), 6.96 (4H, d, *J* = 7.6 Hz, Ar-H), 7.19 (4H, d, *J* = 7.9 Hz, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ: 116.3 (CH), 122.6 (q, ³*J*_{C,F} = 3.9 Hz, CH), 124.8 (q, ¹*J*_{C,F} = 269 Hz, C), 126.2 (q, ²*J*_{C,F} = 31.6 Hz, C), 134.8 (CH), 195.6 (C). IR (KBr/cm⁻¹) 1587, 1381, 1246, 1153, 1074, 1024, 1006, 827, 725, 667. Anal. Calcd. for C₂₄H₁₈F₆Ti: C, 61.6; H, 3.87, found: C, 61.7; H, 3.99.

4.3. Single-Crystal X-ray Diffraction Experiment of 2c

Single crystals of **2c** were obtained from ethanol, and a suitable crystal was selected and analyzed using an XtaLAB Synergy Dualflex, HyPix diffractometer (Rigaku, Auburn Hills, MI, USA). The crystal was maintained at 100 K during the data collection. Using Olex2 (OlexSys) [31], the structure was solved with the ShelXT [32] structure solution program using intrinsic phasing. The structure of **2c** was refined with the ShelXL [33] refinement package using a least squares minimization.

Crystal Data for 2c

 $C_{24}H_{24}Ti \ (M = 360.33 \text{ g/mol}): \text{ orthorhombic, space group Pbcn (No. 60), } a = 8.25760(10) \text{ Å},$ $b = 12.4042(2) \text{ Å}, c = 17.9027(3) \text{ Å}, V = 1833.75(5) \text{ Å}^3, Z = 4, T = 100 \text{ K}, \mu(\text{CuK}\alpha) = 3.942 \text{ mm}^{-1},$ $D_{calc} = 1.305 \text{ g/cm}^3, 16514 \text{ reflections measured (} 9.882^\circ \le 2\Theta \le 154.368^\circ), 1923 \text{ unique}$ $(R_{int} = 0.0467, R_{sigma} = 0.0250), which were used in all the calculations. The final R₁ was 0.0330$ $(I > 2\sigma(I)) and wR₂ was 0.0906 (all data). CCDC 2287849.$

4.4. General Procedure for the Synthesis of 1,2-Disubtituted Alkyne

 Cp_2TiAr_2 (0.25 mmol), arylacetylene (0.5 mmol), Pd(OAc)₂ (11.2 mg, 0.05 mmol), and AgF (126 mg, 1.0 mmol) were added to 3.0 mL of anhydrous DMF. Then, the mixture was

stirred at room temperature for 24 h. The conversions were confirmed by TLC and isolated yields were obtained after silica gel chromatography (eluting with hexane).

1,2-Diphenylacetylene (4a) [34]. Colorless prisms (87.5 mg, 98%), mp 62–63 °C (from ethanol), $R_f = 0.5$ (hexane). ¹H NMR (400 MHz, CDCl₃) δ : 7.33–7.38 (6H, m, Ar-H), 7.52–7.55 (4H, m, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ : 89.5 (C), 123.3 (C), 128.36 (CH), 128.44 (CH), 131.7 (CH). MS (EI) *m*/*z* (%): 178 (100, M⁺), 152 (11), 89 (6), 76 (7). IR (KBr) ν : 2247 (C \equiv C), 1599, 918 cm⁻¹.

1-Methyl-4-(phenylethynyl)benzene (4b) [34]. Colorless plates (70.1 mg, 76% from **2c** with **3a**; 84.5 mg, 88% from **2a** with **3c**), mp 71–72 °C (from ethanol), $R_f = 0.3$ (hexane). ¹H NMR (400 MHz, CDCl₃) δ : 2.37 (3H, s, CH₃), 7.15 (2H, d, *J* = 8.0 Hz, Ar-H), 7.31–7.33 (3H, m, Ar-H), 7.41 (2H, d, *J* = 8.4 Hz, Ar-H), 7.51 (2H, dd, *J* = 8.0, 2.4 Hz, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ : 21.7 (CH₃), 88.8 (C), 89.7 (C), 120.3 (C), 123.6 (C), 128.2 (CH), 128.4 (CH), 129.2 (CH), 131.6 (CH), 131.7 (CH), 138.5 (C). MS (EI) *m*/*z* (%): 192 (100, M⁺), 165 (14), 115 (9), 95 (10). IR (KBr) ν : 2216 (C=C), 1595, 916 cm⁻¹.

1-Chloro-4-(phenylethynyl)benzene (4c) [35]. Colorless prisms (58.5 mg, 55% from 2d with 3a; 64.7 mg, 61% from 2a with 3d), mp 82–83 °C (from CH₂Cl₂-hexane), $R_f = 0.5$ (Hexane). ¹H NMR (400 MHz, CDCl₃) δ: 7.31–7.36 (5H, m, Ar-H), 7.49 (2H, dt, J = 8.8, 2.4 Hz, Ar-H), 7.50–7.53 (2H, m, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ: 88.4 (C), 90.4 (C), 121.9 (C), 123.0 (C), 128.5 (CH), 128.6 (CH), 128.8 (CH), 131.7 (CH), 132.9 (CH), 134.4 (C). MS (EI) m/z (%): 212 (100, M⁺), 176 (33), 151 (11), 88 (6). IR (KBr) ν: 2214 (C≡C), 1587, 910 cm⁻¹.

1-(Phenylethynyl)-4-(trifluoromethyl)benzene (4d) [35]. Colorless prisms (89.5 mg, 73% from **2e** with **3a**; 77.5 mg, 63% from **2a** with **3f**), mp 95–98 °C (from ethanol), $R_f = 0.5$ (hexane). ¹H NMR (400 MHz, CDCl₃) δ: 7.36–7.38 (3H, m, Ar-H), 7.52–7.56 (2H, m, Ar-H), 7.58–7.64 (4H, m, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ: 88.1 (C), 91.9 (C), 122.6 (C), 124.0 (q, ¹*J*_{C,F} = 285 Hz, C), 125.4 (q, ³*J*_{C,F} = 3.8 Hz, CH), 127.2 (C), 128.5 (CH), 128.9 (CH), 130.0 (q, ²*J*_{C,F} = 32.6 Hz, C), 131.9 (CH), 132.9 (CH). MS (EI) m/z (%): 246 (100, M⁺), 227 (4), 176 (4), 98 (4). IR (KBr) ν: 2220 (C≡C), 1609, 845 cm⁻¹.

1-Bromo-4-(phenylethynyl)benzene (4f) [35]. Colorless prisms (87.0 mg, 68%), mp 82–83 °C (from CH₂Cl₂-hexane), $R_f = 0.5$ (hexane). ¹H NMR (400 MHz, CDCl₃) δ : 7.34–7.39 (5H, m, Ar-H), 7.46–7.53 (4H, m, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ : 88.4 (C), 90.6 (C), 122.4 (C), 122.6 (C), 123.0 (C), 128.5 (CH), 128.6 (CH), 131.71 (CH), 131.74 (CH), 133.2 (CH). MS (EI) m/z (%): 256 (100, M⁺), 176 (61), 151 (22), 88 (17). IR (KBr) ν : 2214 (C=C), 1597, 833 cm⁻¹.

1-Methyl-2-(phenylethynyl)benzene (4g) [34]. Colorless oil (91.0 mg, 94%), $R_f = 0.5$ (hexane). ¹H NMR (400 MHz, CDCl₃) δ: 2.52 (3H, s, CH₃), 7.16–7.19 (1H, m, Ar-H), 7.23–7.26 (2H, m, Ar-H), 7.32–7.37 (3H, m, Ar-H), 7.50 (1H, d, *J* = 7.2 Hz, Ar-H), 7.53–7.56 (2H, m, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ: 20.9 (CH₃), 88.5 (C), 93.5 (C), 123.1 (C), 123.7 (C), 125.7 (CH), 128.3 (CH), 128.4 (CH), 128.5 (CH), 129.6 (CH), 131.6 (CH), 132.0 (CH), 140.3 (C). MS (EI) *m*/*z* (%): 192 (100, M⁺), 165 (33), 115 (19), 95 (15). IR (KBr) ν: 2214 (C≡C), 1601, 912 cm⁻¹.

1,3,5-Trimethyl-2-(phenylethynyl)benzene (4h) [36]. Colorless needles (71.5 mg, 65%), mp 35–36 °C (from ethanol), $R_f = 0.4$ (hexane). ¹H NMR (400 MHz, CDCl₃) δ : 2.30 (3H, s, CH₃), 2.48 (6H, s, CH₃), 6.89 (2H, s, Ar-H), 7.31–7.36 (3H, m, Ar-H), 7.52 (2H, dd, J = 8.4, 1.6 Hz, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ : 21.2 (CH₃), 21.5 (CH₃), 87.5 (C), 97.2 (C), 120.1 (C), 124.2 (C), 127.7 (CH), 128.0 (CH), 128.5 (CH), 131.5 (CH), 137.9 (C), 140.3 (C). MS (EI) m/z (%): 220 (100, M⁺), 202 (76), 178 (5). IR (KBr) v: 2211 (C≡C), 1595, 912 cm⁻¹.

(Cyclohex-1-en-1-ylethynyl)benzene (4i) [34]. Colorless oil (50.0 mg, 55%), $R_f = 0.4$ (hexane). ¹H NMR (400 MHz, CDCl₃) δ : 1.61–1.69 (3H, m, CH₂), 2.11–2.16 (3H, m, CH₂), 2.19–2.23 (2H, m, CH₂), 6.19–6.22 (1H, m, CH), 7.24–7.31 (3H, m, Ar-H), 7.39–7.43 (2H, m, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ : 21.7 (CH₂), 22.5 (CH₂), 25.9 (CH₂), 29.4 (CH₂), 86.9 (C), 91.4 (C), 120.8 (C), 123.9 (C), 127.8 (CH), 128.3 (CH), 131.6 (CH), 135.3 (CH). MS (EI) m/z (%): 182 (100, M⁺), 167 (61), 153 (60), 115 (43). IR (KBr) v: 2201 (C=C), 1597, 918 cm⁻¹.

Hex-1-yn-1-ylbenzene (4j) [37] Colorless oil (38.4 mg, 48%), $R_f = 0.5$ (hexane). ¹H NMR (400 MHz, CDCl₃) δ: 0.95 (3H, t, J = 7.2 Hz, CH₃), 1.46–1.63 (4H, m, CH₂ × 2), 2.41 (2H, t, J = 6.8 Hz, CH₂), 7.26–7.29 (3H, m, Ar-H), 7.38–7.40 (2H, m, Ar-H). ¹³C NMR

(100 MHz, CDCl₃) δ : 13.8 (CH₃), 19.3 (CH₂), 22.2 (CH₂), 31.0 (CH₂), 80.7 (C), 90.5 (C), 124.2 (C), 127.6 (CH), 128.3 (CH), 131.7 (CH). MS (EI) *m*/*z* (%): 158 (34, M⁺), 143 (56), 115 (100), 89 (13). IR (KBr) v: 2232 (C=C), 1599, 912 cm⁻¹.

2-(Phenylethynyl)thiophene (4k) [34]. Colorless needles (31.3 mg, 34%), mp 48–50 °C (from ethanol), $R_f = 0.4$ (hexane). ¹H NMR (400 MHz, CDCl₃) δ : 7.01 (1H, dd, J = 5.2, 3.6 Hz, Ar-H), 7.27–7.29 (2H, m, Ar-H), 7.33–7.35 (3H, m, Ar-H), 7.49–7.52 (2H, m, Ar-H). ¹³C NMR (100 MHz, CDCl₃) δ : 82.7 (C), 93.1 (C), 123.0 (C), 123.4 (C), 127.2 (CH), 127.4 (CH), 128.50 (CH), 128.54 (CH), 131.5 (CH), 132.0 (CH). MS (EI) m/z (%): 184 (100, M⁺), 152 (12), 139 (18), 126 (4). IR (KBr) ν : 2201 (C≡C), 1595, 853 cm⁻¹.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/reactions4040037/s1. The crystal structures have been deposited into the CCDC with the number 2287849 and CIF files are also provided as Supplementary Materials.

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