

Murahashi Coupling Polymerization: Nickel(II)–N-Heterocyclic Carbene Complex-Catalyzed Polycondensation of Organolithium Species of (Hetero)arenes

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Supporting Information

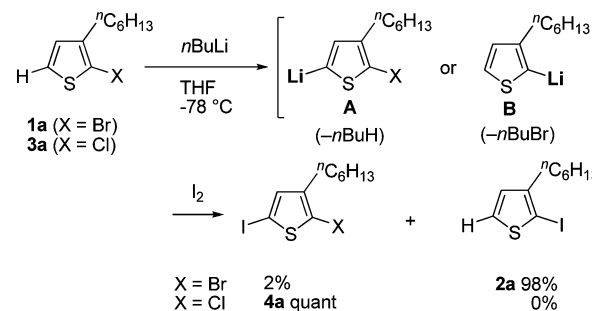
ABSTRACT: Revisiting Murahashi coupling, we found that it effectively allows polymerization of lithiated (hetero)arenes by nickel(II)-catalyzed polycondensation. Deprotonative polymerization of 2-chloro-3-substituted thiophene with *n*-butyllithium gave head-to-tail-type poly(3-substituted thiophene). Poly(1,4-arylene)s were obtained by the reaction of the corresponding dibromides through lithium–bromine exchange. A lithiated thiophene derivative obtained via deprotonative halogen dance also underwent polymerization to afford a bromo-substituted polythiophene.

Transition-metal-catalyzed cross-coupling has recently attracted considerable attention in organic synthesis, polymer synthesis, and materials science.¹ A number of named coupling reactions with various organometallic reagents are employed for C–C bond-forming reactions. In contrast with the explosive success in cross-coupling of several main-group metallic reagents, there has been less study of the Murahashi coupling with an organolithium reagent as an organometallic species, despite the fact that it appeared much earlier in the history of cross-coupling.² It has been considered to be difficult as a synthetic reaction because its high reactivity in the generation and reaction of organolithium reagents makes it hard to control the transition-metal-catalyzed coupling with organic electrophiles, which generally proceeds under more harsh conditions. Recently, Murahashi coupling has been shown to proceed under certain conditions in which rapid mixing of freshly formed organolithium with the substrate and catalyst in a flow system³ or slow addition into an extremely diluted mixture in a nonpolar solvent⁴ are the key for successful coupling to overcome the difficulty.

We envisaged that the cross-coupling of organolithium would also be realized in some polymerization reactions that would take place rapidly in a catalyst-transfer manner,⁵ in which immediate incorporation of the organolithium monomer into the polymer end may also compensate for the significant reactivity differences between main-group metals and transition metals. Herein we show that Murahashi coupling polymerization catalyzed by a nickel(II) complex bearing an N-heterocyclic carbene (NHC) ligand effectively gives poly[(hetero)arylene]s with extended π conjugation.

We first chose lithiated thiophene as a monomer of polythiophenes that have been prepared by the polymerization of the corresponding thiophene–magnesium species to proceed in a catalyst-transfer-type chain-growth polymerization despite

polycondensation.⁵ As there had been few studies on the deprotonation of halothiophenes with organolithium, the formation of the organolithium species of 2-bromo-3-hexylthiophene (**1a**) with *n*-butyllithium in a deprotonative manner was examined. However, lithiation at the 5-position hardly took place, and instead, lithium–bromine exchange resulted, as confirmed by treatment with I₂ to afford 3-hexyl-2-iodothiophene (**2a**) in 98% yield. On the other hand, it was found that a similar reaction with 2-chloro-3-hexylthiophene (**3a**) under similar conditions afforded **4a** in a quantitative yield (Scheme 1). Accordingly, formation of the lithiated monomer appeared to take place much more smoothly than that of the corresponding Grignard species.⁶

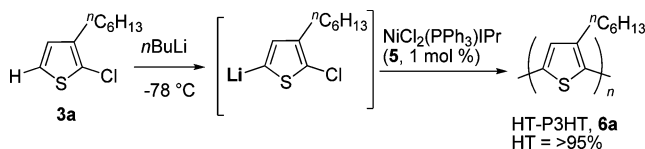
Scheme 1. Reactions of **1a** and **3a** with *n*-Butyllithium

As deprotonative formation of organolithium was achieved only with chlorothiophene **3a**, the attempted polymerization of bromothiophene **1a**⁶ was also unsuccessful, affording no polymerized product at all. However, the reaction of lithiated **3a** with a 1.0 mol % loading of the nickel catalyst NiCl₂(PPh₃)IPr (**5**) [IPr = 1,3-bis(2,6-diisopropylphenyl)imidazole-2-ylidene⁷], which was shown to be a highly effective catalyst for the polymerization of the corresponding thiophene–magnesium species,⁸ at 0 °C for 10 min in tetrahydrofuran (THF) resulted in complete consumption of **3a** to furnish poly(3-hexylthiophene) (P3HT) **6a** in 80% isolated yield with a number-average molecular weight (*M*_n) of 10 100 Da [polydispersity index (PDI) = 1.93]. Improved PDI was achieved when the reaction was carried out in cyclopentyl methyl ether (CPME) under similar conditions (*M*_n = 12 500 Da; PDI = 1.35), whereas toluene and 1,4-dioxane were found to be ineffective solvents. The reaction at

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a lower temperature ($-20\text{ }^{\circ}\text{C}$) proceeded sluggishly in 45% yield for 120 min. On the other hand, the reaction hardly proceeded at $-40\text{ }^{\circ}\text{C}$ after stirring for 180 min (Table 1). The head-to-tail

Table 1. Murahashi Coupling Polymerization of 3a^a



temp ($^{\circ}\text{C}$), time (min)	solvent	% yield of 6a ^b	M_n (Da)	PDI
0, 10	THF	80 ^c	10100	1.93
	CPME	66	12500	1.35
	toluene	0	—	—
	1,4-dioxane	20	5300	1.34
-20 , 120	CPME	45	8500	1.47
-40 , 180	CPME	0	—	—
-78 to 0 , 30 ^d	CPME	84 ^c	32000	2.25

^aUnless otherwise specified, the deprotonation reaction was carried out with 0.5 mmol of 3a, 1.0 equiv of *n*BuLi at $-78\text{ }^{\circ}\text{C}$. After further stirring at $0\text{ }^{\circ}\text{C}$ for 30 min, the polymerization was performed with 1 mol % 5 in 2 mL of the solvent. ^bIsolated yields. ^cConsumption of 3a was confirmed to be $>95\%$ by ^1H NMR analysis. ^dAddition of *n*BuLi to 3a and 5 (1 mol %) at $-78\text{ }^{\circ}\text{C}$ and stirring for 30 min while raising the reaction temperature to $0\text{ }^{\circ}\text{C}$.

(HT) regularity of the thus-obtained P3HT 6a was confirmed to be 97–98% by measurement of the ^1H NMR spectrum. Polymerization was also found to proceed when *n*-butyllithium was added to a mixture of 3a and nickel catalyst 5 at $-78\text{ }^{\circ}\text{C}$ and then the temperature was gradually raised to $0\text{ }^{\circ}\text{C}$ within 30 min. Although a lithiated thiophene derivative has been shown to polymerize by transition-metal catalysis after metal exchange to magnesium or zinc,^{6e} it should be pointed out that the use of chlorothiophene and the Ni–NHC complex allowed the successful polymerization of organolithium without additional metal exchange.

We next studied the reaction conditions of the Murahashi coupling polymerization of chlorothiophenes 3 (Table 2). When nickel catalyst 5 was used, 3a effectively underwent the polymerization (entry 1), while other catalysts such as Pd-PEPPSI-IPr⁹ were ineffective (entry 2). The reaction with nickel(II) catalysts bearing other bidentate phosphine ligands also resulted in no reaction.¹⁰ The molecular weight of the polymer 6a was dependent on the ratio of thiophene 3a and the nickel catalyst loading (entries 3–6) but was slightly smaller than the theoretical value.^{4,5} A linear increase in M_n was observed as the polymerization progressed (entries 7–10), which differs from the behavior that would be observed for step-growth polycondensation.⁵ These results suggest that Murahashi coupling polymerization also proceeds in a chain-growth manner. Poly(3-octylthiophene) was also obtained by the reaction of 2-chloro-3-octylthiophene (3b) under similar conditions (entry 11).

Worthy of note is the observation that unprecedented Murahashi cross-coupling polymerization of organolithium was achieved with chlorothiophene as a premonomer and a nickel catalyst bearing an NHC ligand.^{7c} This finding markedly contrasts with previous examples of Murahashi coupling, which have mainly been performed with palladium catalysts.^{2a} The key for success would also be the deprotonative generation of organolithium species with chlorothiophene 3a. The Murahashi

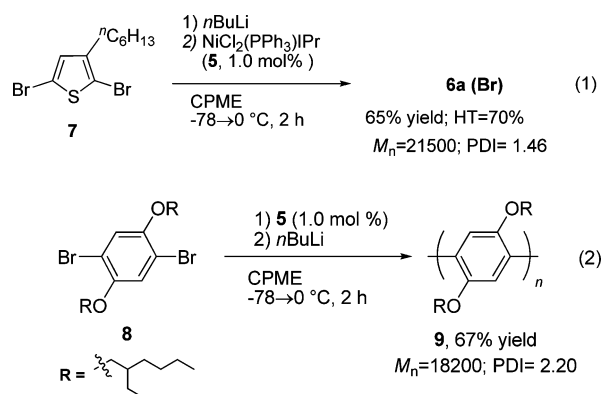
Table 2. Murahashi Coupling Polymerization of Thiophene Derivatives with a Nickel or Palladium Catalyst^a

entry	thiophene	catalyst (mol %)	solvent	%yield (%HT) ^b [time, min] ^c	M_n^d (PDI)
1		NiCl ₂ (PPh ₃)IPr (1.0)	CPME ^e	66 (>99) ^f	12500 (1.35)
2		Pd-PEPPSI-IPr (1.0)	THF	0	
3		NiCl ₂ (PPh ₃)IPr (1.5)	CPME	83	7900 (1.37)
4		NiCl ₂ (PPh ₃)IPr (2.0)	CPME	84	6600 (1.36)
5		NiCl ₂ (PPh ₃)IPr (2.5)	CPME	72	4900 (1.32)
6		NiCl ₂ (PPh ₃)IPr (3.0)	CPME	79	4400 (1.33)
7		NiCl ₂ (PPh ₃)IPr (1.0)	CPME	38 ^g [1]	3300 (1.26)
8				59 ^g [3]	7100 (1.35)
9				72 ^g [5]	8300 (1.33)
10				97 ^g [10]	11600 (1.36)
11		NiCl ₂ (PPh ₃)IPr (1.0)	CPME	91 (96)	14900 (1.89)

^aUnless otherwise specified, the reaction was carried out with 0.5 mmol of 3a, 1.0 equiv of *n*BuLi, deprotonation at $-78\text{ }^{\circ}\text{C}$, and polymerization at $0\text{ }^{\circ}\text{C}$ for 2 h. ^bThe head-to-tail regioselectivity was estimated by ^1H NMR analysis. ^cThe reaction period is shown. ^dEstimated by SEC using polystyrene standards. ^eCPME = cyclopentyl methyl ether. ^fThe reaction period was 1 h. ^gConversion of 3a was estimated by ^1H NMR analysis.

coupling polymerization was also examined with the related thienyllithium formed by bromine–lithium exchange of 2,5-dibromo-3-hexylthiophene (7). Although the polymerization of a dibromoarylene derived from fluorene with organolithium was shown to proceed,¹¹ the corresponding polyarylene was suggested to be obtained under competing homocoupling and cross-coupling reactions. By contrast, equimolar amounts of 7 and *n*BuLi resulted in monolithiation of 7, which induced cross-coupling polymerization with Ni–NHC catalyst 5 (eq 1 in Scheme 2). Although the corresponding polythiophene 6a(Br) was obtained with reasonable M_n , the HT regioselectivity of the obtained polymer was found to be inferior because of insufficient regioselectivity in lithiation of 7.¹² An analogous debrominative coupling was also found to take place with 1,4-dialkoxy-2,5-dibromobenzene 8, which does not involve the regiochemical issue, by the addition of *n*BuLi in the presence of Ni–NHC catalyst 5 to afford the corresponding polyarylene 9 (eq 2 in Scheme 2).¹³ Although further studies are necessary for the understanding of the detail of dehalogenative polycondensation,

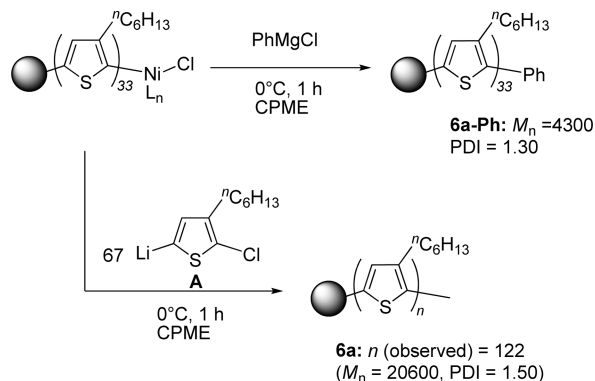
Scheme 2. Debrominative Polymerization of (Hetero)arylenes



it is remarkable that monolithiated species from **7** and **8** are indeed employed for the cross-coupling polycondensation.

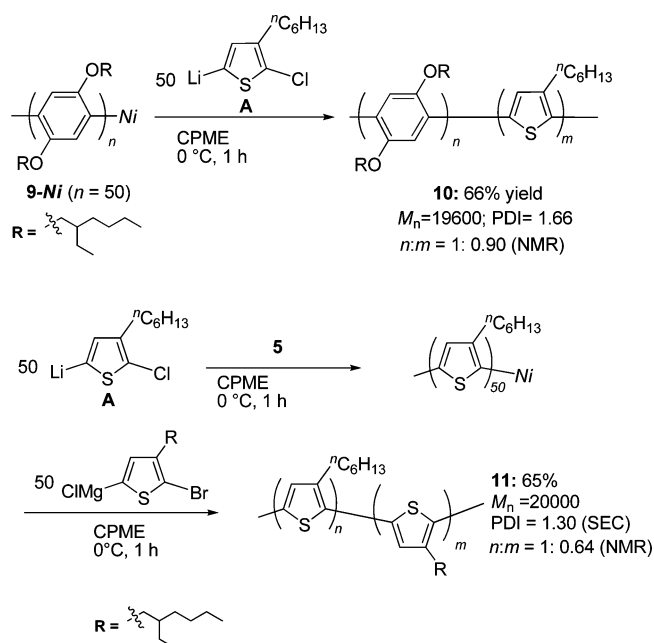
Since polymerization of thiophenes through organolithium species appeared to proceed via the catalyst-transfer mechanism,⁵ end functionalization of the polymer obtained by Murahashi coupling could be achieved using a Grignard reagent. Treatment of the polymerization solution containing 3 mol % **5** (Table 2, entry 6) with phenylmagnesium chloride at 0 °C for 1 h afforded the end-phenylated polymer **6a-Ph**.¹⁴ Size-exclusion chromatography (SEC) analysis of **6a-Ph** ($M_n = 4300$ Da, PDI = 1.30) showed that neither coupling of polymers nor fission of the polymer chain took place. Moreover, addition of further amounts of lithiated thiophene **A** to the polymerization solution increased the molecular weight ($M_n = 20600$ Da, PDI = 1.50). These results shown in Scheme 3 suggest that the reaction proceeds in a chain-growth manner at the polymer end, similar to the case of polythiophene syntheses with in situ-formed thienylmagnesium.^{4–7}

Scheme 3. Transformation of the Living Polythiophene End Formed by Murahashi Coupling Polymerization



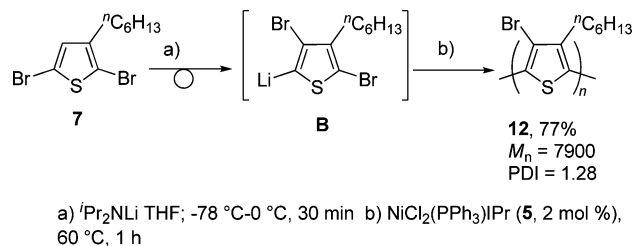
Block copolymerization of poly(hetero)arylenes obtained by Murahashi coupling was also intriguing on the basis of the above end functionalization (Scheme 4). Addition of lithiated thiophene monomer **A** to the reaction mixture of polyarylene **9** afforded the corresponding block copolymer **10**, in which the polyarylene/polythiophene ratio was confirmed to be 1:0.90 by ¹H NMR analysis. Polythiophene formed by Murahashi coupling polymerization was also found to incorporate thiophene–magnesium species, affording polythiophene block copolymer **11**.

Scheme 4. Block Copolymerization Including Murahashi Coupling Polycondensation



It was also found that organolithium species generated by halogen dance¹⁵ underwent Murahashi coupling polymerization to afford a new class of polythiophene (Scheme 5). Treatment of

Scheme 5. Murahashi Coupling Polycondensation via Halogen Dance



7 with lithium diisopropylamide (*i*Pr₂NLi) at –78 to 0 °C in THF induced halogen dance, leading to 5-lithiated intermediate **B**.¹⁶ Addition of nickel catalyst **5** to the reaction mixture afforded the corresponding polythiophene **12** in 77% yield ($M_n = 7900$ Da, PDI = 1.28) after stirring at 60 °C for 1 h. Although dibromothiophene **7** has been established to give P3HT **6a** by polymerization with a Grignard reagent and a transition-metal catalyst,⁵ it should be pointed out that polymerization via halogen dance gave completely different polymer **12** bearing a bromine substituent at the 4-position of the thiophene, which would allow further transformations with the C–Br bond.¹⁷

In summary, we have shown that Murahashi coupling polymerization is achieved in the polycondensation of (hetero)arylenes. The use of a nickel catalyst bearing an NHC ligand was shown to be highly effective. The results markedly contrast with previous reports on Murahashi coupling, in which palladium was an effective transition-metal catalyst whereas nickel was considered to be ineffective. Three classes of lithiations, including deprotonation, lithium–bromine exchange, and halogen dance, were shown to form lithiated monomers, and subsequent polymerization in the presence of the Ni–NHC

complex led to the corresponding polymers. Since the strategy based on lithiation instead of magnesiation significantly extends the available metalated organic substrates, Murahashi coupling can be a versatile preparative protocol for various π -conjugated polymers as a cross-coupling polycondensation.

■ ASSOCIATED CONTENT

● Supporting Information

Experimental details and characterization of new compounds and polymers. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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(10) Polymerization under similar conditions with nickel catalysts bearing the bidentate phosphines dppe, dppp, dppb, and dppf as ligands resulted in no reaction.

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(12) Polymerization of the lithiated monomer resulted in complete conversion with inferior HT selectivity, whereas the conversion of the related GRIM polymerization was ca. 80–90%, suggesting that the high HT regularity of the GRIM method involves a tradeoff, as the metalated thiophene obtained by bromine–metal exchange at the 2-position remained unreacted.

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(14) MALDI-TOF MS measurements suggested that phenylation occurred at the both polymer ends, as ca. 166 Da intervals between peaks of **6a-Ph** and a representative peak at 2314 Da [calcd 2312 Da = 77 (Ph) + 166 \times 13 (13 3-hexylthiophen-2,5-diyl) + 77 (Ph)] were observed. According to the reaction mechanism of initiation suggested by Kiri,^{5d} the end groups are considered to be chlorothiophene and thienylnickel(II)–Cl in the living polymerization mixture, and this was confirmed by MALDI-TOF MS (see the Supporting Information). Thus, addition of excess PhMgCl would induce phenylation by cross-coupling at both ends.

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(16) Halogen dance was confirmed by hydrolysis of **B** to give 2,4-dibromo-3-hexylthiophene exclusively (see the Supporting Information).

(17) Details of the halogen dance and the scope of the transformation of obtained polymers will be described in due course.