

## A Simple and Efficient Synthesis of Di-, Tri-, and Tetraferrocenylarenes

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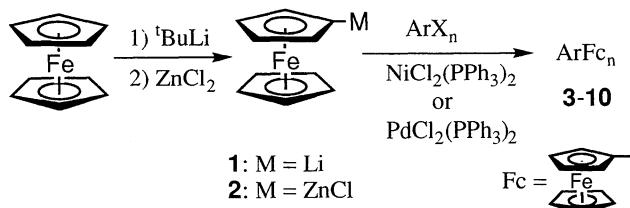
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A series of di-, tri-, and tetraferrocenylarenes were synthesized by using the nickel- and palladium-catalyzed cross coupling reactions of ferrocenylzinc chloride with the corresponding di-, tri-, and tetrahalogenoarenes. Redox properties of these ferrocenylarenes were studied by cyclic voltammetry in order to examine the intramolecular interaction between the ferrocenyl substituents.

There is considerable current interest in the intramolecular interaction between two or three ferrocenyl groups, because of the mixed-valence behavior in the partially oxidized species,<sup>1</sup> and because of the potential magnetic exchange interaction.<sup>2</sup> However, a limited number of methods were hitherto known for the synthesis of di-, tri-, and tetraferrocenylarenes.<sup>3,4</sup>

We now report here a new methodology for the one-pot synthesis of the title compounds using transition-metal catalyzed cross-coupling reaction.

Ferrocene can be easily converted into its lithio derivative **1** by treatment with *t*-butyllithium.<sup>5</sup> The reaction of ferrocenyl-lithium **1** with zinc chloride can be expected to produce ferrocenylzinc chloride **2**. Therefore, the cross-coupling reactions of **2** with halogenobenzene and its derivatives in the presence of nickel or palladium catalysts were carried out.



A typical procedure for the nickel-catalyzed cross-coupling reaction of **2** with 1,3-dibromobenzene is as follows. A solution of ferrocene (3 mmol) in THF (2.5 ml) was treated with a pentane solution of *t*-butyllithium (1.64 M, 2.1 ml, 3.44 mmol) at 0 °C for 30 min. To the solution was added a suspension of anhydrous zinc chloride (3.56 mmol) in THF (5 ml). The mixture was warmed to room temperature and stirred for 1 h to give **2**. To the mixture was added a suspension of  $\text{NiCl}_2(\text{PPh}_3)_2$  (0.1 mmol) in THF (2 ml) and then a solution of 1,3-dibromobenzene (1 mmol) in THF (5 ml). After being stirred at room temperature for 1 h, the mixture was treated with 2 M hydrochloric acid (2 ml). After usual work-up, the products were separated by column chromatography on silica gel to give **3** in 67% yield. The reactions of **2** with bromoarenes in the presence of  $\text{NiCl}_2(\text{PPh}_3)_2$  are summarized in Table 1.<sup>6</sup>

As shown in Table 1, the nickel-catalyzed cross-coupling of bromoarenes with ferrocenylzinc chloride **2** proceeds smoothly to give the corresponding products in good yields except for 1,2,4,5-tetrabromobenzene which has a steric hindrance between two neighboring bromines.

In order to develop another synthetic method for the construction of the ferrocenylarene system, we examined the

**Table 1.** Nickel-catalyzed coupling reaction of **2** with bromoarenes

Bromoarene	Product	Conditions <sup>a</sup>	Yield (%) <sup>b</sup>
		A	67
		A	66
		B	51
		C	16
		A	64

<sup>a</sup>Reaction conditions. A: ferrocene (3 mmol), bromoarene (1 mmol),  $\text{NiCl}_2(\text{PPh}_3)_2$  (0.1 mmol); B: ferrocene (4.5 mmol), bromoarene (1 mmol),  $\text{NiCl}_2(\text{PPh}_3)_2$  (0.1 mmol); C: ferrocene (6 mmol), bromoarene (1 mmol),  $\text{NiCl}_2(\text{PPh}_3)_2$  (0.2 mmol). <sup>b</sup>Isolated yields.

palladium-catalyzed cross-coupling reactions of halogenoarenes with ferrocenylzinc chloride **2**. To a solution of **2** in THF, which was prepared from ferrocene (3 mmol), *t*-BuLi, and  $\text{ZnCl}_2$  (4 mmol), were added successively a suspension of  $\text{PdCl}_2(\text{PPh}_3)_2$  (0.1 mmol) in THF (3 ml) and a solution of 1,3-dibromobenzene (1 mmol) in THF (5 ml). The mixture was stirred at room temperature for 1 h and then quenched with 2 M hydrochloric acid (2 ml). After usual work-up and purification, **3** was obtained in 80% yield. The results of the palladium-catalyzed reactions are summarized in Table 2.

The palladium-catalyzed cross-coupling reactions of dibromo-, diiodo- and tribromoarenes with **2** produce the corresponding di- and trifluorocenylarenes in good yields except for 3,4-dibromothiophene and 1,3-dibromoazulene. In the case of 3,4-dibromothiophene, steric interaction between two bromines decreases the yield of the product **11**. Similarly, the palladium-catalyzed reaction of 1,2-dibromobenzene with **2** gives the cross-coupling product **9** only in 23% yield, whereas the reaction of 1,2-diiodobenzene with **2** produces **9** in 70% yield. It is worth noting that the nickel-catalyzed reaction of 1,3-dibromoazulene gives better yield of the product than the palladium-catalyzed reaction does.

In order to investigate the intramolecular interaction of the two or three ferrocenyl groups in the oxidation states, the redox potentials of **3-10** were determined by cyclic voltammetry. As summarized in Table 3, all compounds show reversible redox

**Table 2.** Palladium-catalyzed coupling of **2** with halides

Halocarene	Product	Conditions <sup>a</sup>	Yield (%) <sup>b</sup>
		A	80
		A	60
		B	56
		A	37
		A	63
		A	70
		A	69
		A	27

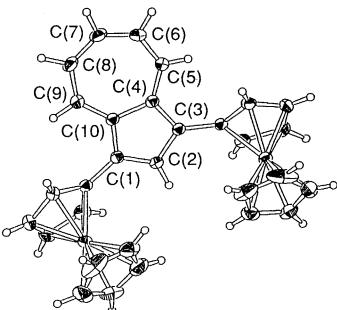
<sup>a</sup>Reaction conditions: A, FcH (3 mmol), haloarene (1 mmol), PdCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> (0.1 mmol); B, FcH (4.5 mmol), haloarene (1 mmol), PdCl<sub>2</sub>(PPh<sub>3</sub>)<sub>2</sub> (0.1 mmol). <sup>b</sup>Isolated yields.

waves corresponding to the interconversion between ferrocene and ferricinium ion. In the case of **3**, **4** and **5**, only one redox wave was observed, reflecting an almost negligible interaction between the *meta*-substituents. The redox peaks of **6** and **8** were also one strong redox wave with a pair of very small shoulders which might show a weak *para*-interaction. In contrast, **9**, **10**, and **11** show some interaction ( $\Delta E = 0.14$ -0.17) between two ferrocenyl groups under redox conditions. The *ortho*-interaction can be estimated to be rather strong because of potential through-bond and through-space interactions, and the thiophene system can retain the conjugation effect of its substituents.<sup>7</sup> Interestingly, **7** shows a marked interaction ( $\Delta E = 0.12$ ), although two ferrocenyl groups are located at the 1,3-position of the azulene ring. In addition, **7** has relatively low oxidation potentials, corresponding to a good  $\pi$ -donor.

**Table 3.** Redox potentials of polyferrocenylarenes<sup>a</sup>

Compound	$E^1_{1/2}$	$E^2_{1/2}$	$\Delta E$
<b>3</b>	+0.02	—	—
<b>4</b>	+0.02	—	—
<b>5</b>	-0.02	—	—
<b>6</b>	-0.05	—	—
<b>7</b>	-0.10	+0.02	0.12
<b>8</b>	—	+0.06	—
<b>9</b>	-0.01	+0.16	0.17
<b>10</b>	-0.02	+0.13	0.15
<b>11</b>	+0.01	+0.15	0.14

<sup>a</sup>All potentials in V vs ferrocene/ferricinium, benzonitrile, *n*-Bu<sub>4</sub>NClO<sub>4</sub> (0.1 mol dm<sup>-3</sup>); 0.1 Vs<sup>-1</sup>.



**Figure 1.** Molecular structure of **7**. The selected bond distances (Å): C1-C2 1.392(4), C2-C3 1.411(4), C3-C4 1.418(4), C4-C10 1.491(4), C1-C10 1.415(4).

The structure of **7** has been determined by X-ray analysis.<sup>8</sup> As shown in Figure 1, the azulene framework in **7** closely resembles the structure of unsubstituted azulene.<sup>9</sup> The two ferrocenyl substituents are situated parallel in the same direction, and the dihedral angles between the azulene ring and the cyclopentadienyl moiety of ferrocenes are ca 40°. Since the distance of the C4-C10 bond is long (1.49 Å), only a small 1-4  $\pi$ - $\pi$  interaction via C1-C10-C4-C3 carbons may contribute in **7**.

The synthesis of the mono- and dications derived from **7** is now under investigation.

#### References and Notes

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- 8 Crystal data for **7**: C<sub>30</sub>H<sub>24</sub>Fe<sub>2</sub>, FW = 496.21, orthorhombic, space group *Pbca* (#61); *a* = 21.89(4) Å, *b* = 27.02(4) Å, *c* = 7.42(3) Å, *V* = 4388(17) Å<sup>3</sup>, *Z* = 8, *D<sub>c</sub>* = 1.502 g cm<sup>-3</sup>. The structure was solved by a direct method using SAPI91. Full matrix least-squares refinement yielded the final *R* value of 0.037 (*R<sub>W</sub>* = 0.036) for 4014 independent reflections [ $2\theta \leq 55.0^\circ$ , *I* > 3.00 $\sigma(I)$ ] measured on a Rigaku AFC7R diffractometer using Mo-K $\alpha$  radiation ( $\lambda$  = 0.71069 Å) and  $\omega$ -2 $\theta$  scan.
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