JOC The Journal of Organic Chemistry

Note

pubs.acs.org/joc

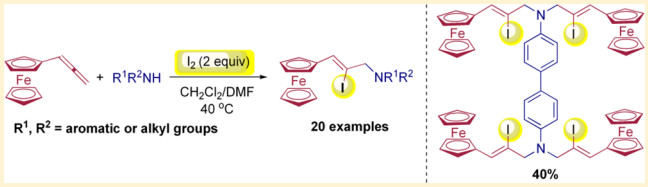
Iodine-Mediated Highly Regio- and Stereoselective Iodoamination of Ferrocenyl Allene: An Approach for the Synthesis of Ferrocene-Containing Allylic Amines

Shufeng Chen,* Qing Yan, Haiying Zhao, and Baoguo Li*

College of Chemistry and Chemical Engineering, Inner Mongolia University, Hohhot 010021, People's Republic of China

Supporting Information

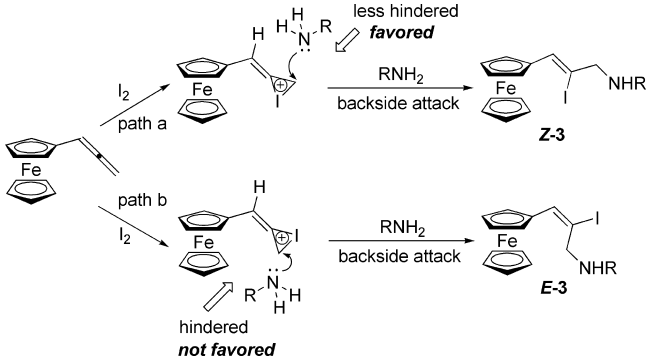
ABSTRACT: A straightforward and efficient protocol for the highly regio- and stereoselective synthesis of ferrocene-containing allylic amine derivatives via an iodine-mediated iodoamination of ferrocenyl allene was developed. The regio- and stereoselectivity of this reaction may be controlled by the steric effect of the bulky ferrocene group.



Allylic amines and related derivatives are versatile building blocks in materials science as well as in organic synthesis and are also broadly found in many natural products and pharmaceutically active molecules.[1] On the other hand, ferrocenes are an important group of organometallic compounds which display interesting biological properties,[2] and also some specifically designed ferrocene-containing compounds are valuable candidates for antimalarial or anticancer therapies.[3] Consequently, integration of a ferrocenyl moiety into allylic amine derivatives may increase their biological activities or create new medicinal properties. However, as far as our knowledge is concerned, there is no efficient method for the synthesis of these novel ferrocene-containing allylic amines. Herein, we report a highly regio- and stereoselective iodoamination reaction for the convenient syntheses of ferrocene-containing allylic amine derivatives from ferrocenyl allene.

Recently, allenes have attracted great attention from organic chemists due to their unique structures and diverse reactivities.[4] Various synthetic methodologies have been developed on the basis of allene chemistry. Among these, the electrophilic additions of allenes are synthetically attractive, because two functionalities are constructed in one step.[5] However, due to the presence of two C=C bonds, control of the regioselectivity as well as steroselectivity with the reaction is still challenging. Ma and co-workers have demonstrated that introducing a functional group, such as sulfoxide,[6] sulfone,[7] phosphine oxide,[8] or sulfide or selenide,[9] to the allene moiety can control the regio- and stereochemistry of the halo-/seleno-hydroxylation or amidation and thiiranation reactions of allenes. Moreover, the same group has also developed a highly regio- and stereoselective iodohydroxylation reaction of non-heteroatom-substituted allenes, where the furanone group is believed to serve as a stereochemistry-determining functionality.[10] Inspired by this report, and also as an extension of our interest in ferrocene and allene chemistry, we have conceived that highly regio- and stereoselective electrophilic addition may be achieved simply through installation of a bulky ferrocene group onto the allene moiety,[11] where the ferrocene group can act as a stereochemistry-determining functionality as shown in Scheme 1.

Scheme 1. Highly Regio- and Stereoselective Iodoamination of Ferrocenyl Allene

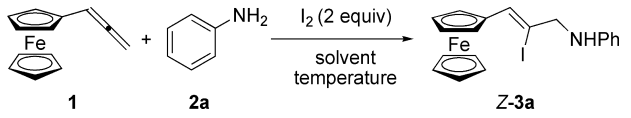


With this idea in mind, the iodoamination of ferrocenyl allene **1** with aniline **2a** and I_2 was chosen as the model reaction. To our delight, when the reaction was carried out in dichloromethane at 40 °C for 1 h using 2.0 equiv of I_2 in an air atmosphere, the corresponding ferrocene-containing β-iodoallylic amine product *Z*-**3a** was obtained in 45% yield as the only stereoisomer, as expected (Table 1, entry 1). Other solvents, such as THF, toluene, and CH_3CN, were inferior and generated the desired product in 18, 25, and 33% yields, respectively (entries 2−4). Similarly, DMF was also confirmed to be suitable for this iodoamination reaction, furnishing *Z*-**3a** in 43% yield (entry 5). Encouraged by these results, we next carefully examined the effect of the component solvent on this transformation (entries 6−8). The results indicated that 60/1 CH_2Cl_2/DMF is the most effective solvent, with the yield of *Z*-

Received: March 25, 2013
Published: May 2, 2013

dx.doi.org/10.1021/jo4006206 | J. Org. Chem. 2013, 78, 5085−5089

Table 1. Optimization of Reaction Conditions[a]



1 2a Z-3a

entry	solvent	T (°C)	time (h)	yield (%)[b]
1	CH_2Cl_2	40	1	45
2	THF	60	1	18
3	$PhCH_3$	60	1	25
4	CH_3CN	60	2	33
5	DMF	60	1	43
6	100/1 CH_2Cl_2/DMF	40	1	39
7	45/1 CH_2Cl_2:/DMF	40	1	61
8	**60/1 CH_2Cl_2/DMF**	**40**	**1**	**77**
9[c]	60/1 CH_2Cl_2/DMF	40	1	65

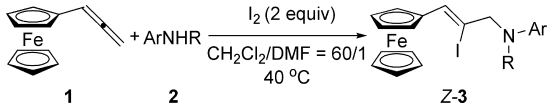
[a]The reaction was carried out using 0.5 mmol of ferrocenyl allene **1**, 1.0 mmol of aniline **2a**, and 1.0 mmol of iodine in 2.0 mL of solvent. [b]Yield of isolated product after chromatography. [c]4.0 equiv of I_2 was used.

3a being improved to 77%. No better result was achieved by increasing the loading of iodine (entry 9).

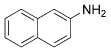
With optimized conditions in hand, we then examined the scope and limitation of the current iodoamination reaction using various aromatic amines as the substrates (Table 2). As shown in Table 2, a wide range of subsituted anilines worked well in the reaction and were complete within 1.5 h, giving 42−78% isolated yields. It was found that substrates with a phenyl ring bearing an electron-donating group generally gave slightly higher yields (Table 2, entries 2 and 3), while substrates with a halogen or strong electron-withdrawing substituent on the phenyl ring, such as a nitro group, gave slightly lower yields (entries 5−12). Unfortunately, a complex mixture was observed when *p*-aminophenol (**2d**) was employed in this transformation (entry 4). It should be noted that the reaction proceeded readily and gave the highest yield of the corresponding product when *N*-methylbenzenamine was used as the substrate (entry 13). However, when naphthalen-2-amine (**2n**) was used in this reaction, only a moderate yield of the product *Z*-**3n** was obtained after workup (entry 14). In addition, substrates with an *ortho*-substituted aromatic ring needed longer reaction times and gave lower yields of the products, probably due to the steric hindrance effect (entries 8, 9, and 12). Further investigation revealed that this approach was not suitable for a substrate bearing a heteroaromatic ring substituent (entry 15).

Subsequently, optimized conditions for the iodoamination were employed in the reaction of several aliphatic amines (Scheme 2). We were surprised to find that the electrophilic addition of aliphatic amine nucleophiles to ferrocenyl allene gave the bis(allyl) adducts, in which two ferrocene-containing allylic moieties are bonded through the nitrogen atom to the aliphatic amines. For example, propan-1-amine and butan-1-amine reacted with 2.0 equiv of ferrocenyl allene in the presence of 2.0 equiv of I_2 to give the corresponding bis(allyl) adducts **3p** and **3q** in 62 and 48% isolated yields, respectively. Moreover, it was noted that this approach was also applicable to the substrate bearing a heteroaromatic ring substituent and gave a satisfactory yield of the product **3r**. These results can be explained by the higher nucleophilicities of the aliphatic amines. However, when 2-aminoethanol was used in this reaction, only a 17% yield of the desired product **3s** was obtained. This may be attributed to the nucleophilic competition of the amino

Table 2. Synthesis of Ferrocene-Containing Allylic Amines Using Ferrocenyl Allene and Various Aromatic Amines[a]



1 2 Z-3

Entry	2, Ar, R	Reaction time (h)	Z-3, Yield (%)[b]
1	**2a**, C_6H_5, H	1	*Z*-**3a**, 77
2	**2b**, *p*-$CH_3C_6H_4$, H	0.5	*Z*-**3b**, 69
3	**2c**, *p*-$CH_3OC_6H_4$, H	0.5	*Z*-**3c**, 68
4	**2d**, *p*-HOC_6H_4, H	1	*Z*-**3d**, 0[c]
5	**2e**, *p*-ClC_6H_4, H	1	*Z*-**3e**, 59
6	**2f**, *p*-BrC_6H_4, H	1	*Z*-**3f**, 57
7	**2g**, *m*-ClC_6H_4, H	1	*Z*-**3g**, 55
8	**2h**, *o*-ClC_6H_4, H	1.5	*Z*-**3h**, 42
9	**2i**, *o*-FC_6H_4, H	1.5	*Z*-**3i**, 45
10	**2j**, *p*-$NO_2C_6H_4$, H	1	*Z*-**3j**, 64
11	**2k**, *m*-$NO_2C_6H_4$, H	1	*Z*-**3k**, 60
12	**2l**, *o*-$NO_2C_6H_4$, H	1.5	*Z*-**3l**, 54
13	**2m**, C_6H_5, CH_3	1	*Z*-**3m**, 78
14	**2n**, 	1	*Z*-**3n**, 47
15	**2o**, 	2	*Z*-**3o**, 0

[a]Reactions were carried out with ferrocenyl allene **1** (0.5 mmol), aromatic amines (1.0 mmol), and iodine (1.0 mmol) in 2.0 mL of solvent. [b]Yield of isolated product after chromatography. [c]The reaction gave a complex mixture.

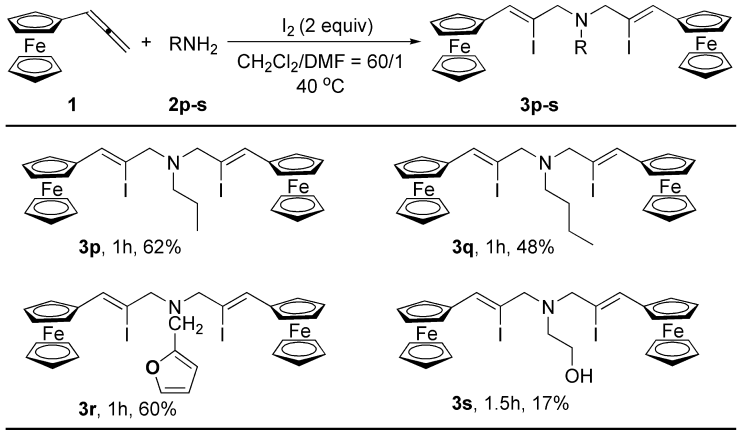
group with the hydroxyl group. Unfortunately, no reaction occurred when secondary aliphatic amines, such as diethylamine and diisopropylamine, were employed in this transformation. The configuration of the C=C bond of the products *Z*-**3** was further established by the NOE study of *Z*-**3f**.[12]

More interestingly, when benzidine **2t** was employed in this iodoamination reaction, we were surprised to find that the symmetrical tetraferrocenyl-substituted allylic amine derivative **3t** with four ferrocene units linked by a biphenyl core, which is difficult to synthesize using traditional methods, was successfully obtained under the above reaction conditions, although the yield was not good. We attributed the result of low yield to the steric effect of benzidine (Scheme 3).

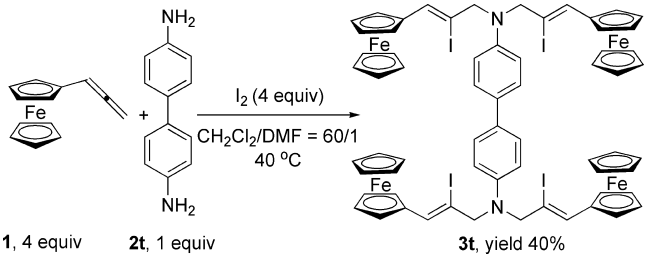
The ferrocene-containing *β*-iodoallylic amines are attractive and can be further converted in organic synthesis due to the presence of the C−I bond, the C=C bond, and the allylic amine group. The synthetic potential of this methodology was demonstrated by the reactions of *Z*-**3m**. The alkene and alkyne groups can be easily introduced into the *β*-position through the Heck and Sonogashira coupling protocols to afford the

dx.doi.org/10.1021/jo4006206 | J. Org. Chem. 2013, 78, 5085−5089

Scheme 2. Synthesis of Ferrocene-Containing Allylic Amines Using Aliphatic Amines as Nucleophiles

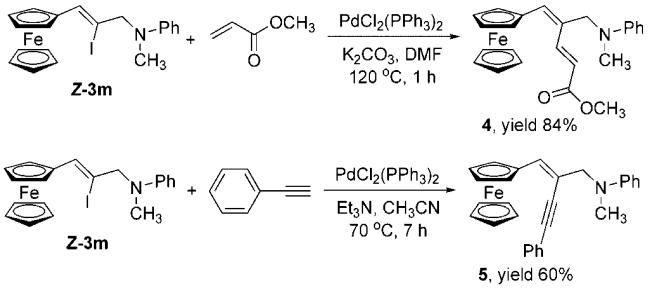


Scheme 3. Iodoamination of Ferrocenyl Allene with Benzidine



ferrocene-containing conjugated molecules ferrocenyl butadiene **4** and ferrocenyl enyne **5**, respectively (Scheme 4).

Scheme 4. Synthetic Application of *Z*-3m



In conclusion, an iodine-mediated iodoamination of ferrocenyl allene has been developed, providing a series of ferrocene-containing allylic amine derivatives with high regio- and stereoselectivities in moderate to excellent yields. It is believed that the regio- and stereoselectivity may be controlled by the steric effect of the bulky ferrocene group. Due to the increasing importance of allylic amines and ferrocenes in the bioorganic and pharmaceutical fields, this method will be a valuable choice for organic synthesis and it may open up new possibilities for incorporating allylic amines with ferrocene chemistry.

EXPERIMENTAL SECTION

General Information. All reagents were used as received from commercial sources, unless specified otherwise, or prepared as described in the literature. All solvents were purified following standard literature procedures. For chromatography, 200−300 mesh silica gel (Qingdao, China) was employed. ^{1}H and ^{13}C NMR spectra were recorded with 500 and 125 MHz FT-NMR spectrometers. Chemical shifts are reported in ppm using tetramethylsilane as internal standard when $CDCl_3$ was used as solvent. IR spectra were recorded on a FT-IR instrument. The HRMS analysis was obtained on a GCTOF mass spectrometer. Melting points were determined with a melting point apparatus and are uncorrected.

General Procedure for the Iodine-Mediated Iodoamination of Ferrocenyl Allene and Amines. The amine (1.0 mmol), ferrocenyl allene (0.5 mmol), I_2 (1.0 mmol), and 60/1 CH_2Cl_2/DMF (2.0 mL) were added sequentially into a dried reaction tube in an air atmosphere. The resulting mixture was heated to 40 °C for the indicated time. The mixture was cooled to room temperature. The solvent was removed under vacuum, and the resulting residue was purified on a silica gel column (EtOAc/petroleum ether) to provide the desired ferrocene-containing allylic amine product *Z*-**3**.

(Z)-N-(3-Ferrocenyl-2-iodoallyl)benzenamine (***Z-3a***)*:* yellow oil; 170 mg, 77% yield; R_f = 0.5 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3414, 3089, 3021, 1600, 1503, 1442, 1104, 998, 867, 749, 692 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.04 (s, 5H), 4.06 (d, J = 1.0 Hz, 2H), 4.25 (t, J = 1.5 Hz, 2H), 4.30 (s, 1H), 4.74 (t, J = 2.0 Hz, 2H), 6.68 (d, J = 8.0 Hz, 2H), 6.74 (t, J = 7.5 Hz, 1H), 6.85 (s, 1H) 7.19−7.24 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 57.9, 68.9, 69.3, 69.4, 80.7, 99.6, 113.7, 118.4, 129.4, 132.8, 147.0; HRMS (ESI) calcd for $C_{19}H_{18}FeINK$ $[M + K]^+$ 481.9470, found 481.9474.

(Z)-N-(3-Ferrocenyl-2-iodoallyl)-4-methylbenzenamine (***Z-3b***)*:* yellow oil; 157 mg, 69% yield; R_f = 0.6 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3416, 3085, 1445, 1105, 1000, 811 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.22 (s, 3H), 4.04 (s, 7H), 4.18 (s, 1H), 4.24 (s, 2H), 4.74 (s, 2H), 6.61 (d, J = 8.0 Hz, 2H), 6.83(s, 1H), 7.01 (d, J = 8.0 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 20.6, 58.3, 68.8, 69.3, 69.4, 80.8, 100.1, 113.9, 127.6, 129.8, 132.8, 144.7; HRMS (ESI) calcd for $C_{20}H_{20}FeINK$ $[M + K]^+$ 495.9627, found 495.9630.

(Z)-N-(3-Ferrocenyl-2-iodoallyl)-4-methoxyaniline (***Z-3c***)*:* yellow oil; 161 mg, 68% yield; R_f = 0.4 (5/1 petroleum ether/ethyl acetate); IR (KBr) 3411, 3089, 1633, 1513, 1239, 1104, 819 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.70 (s, 3H), 4.00 (s, 2H), 4.03 (s, 5H), 4.24 (s, 2H), 4.73 (s, 2H), 6.65 (d, J = 9.0 Hz, 2H), 6.79 (d, J = 8.5 Hz, 2H), 6.82 (s, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 55.9, 58.8, 68.8, 69.3, 69.4, 80.6, 100.2, 114.9, 115.2, 133.0, 140.9, 152.7; HRMS (ESI) calcd for $C_{20}H_{20}FeINOK$ $[M + K]^+$ 511.9576, found 511.9579.

(Z)-4-Chloro-N-(3-ferrocenyl-2-iodoallyl)benzenamine (***Z-3e***)*:* yellow oil; 140 mg, 59% yield; R_f = 0.5 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3419, 3085, 1666, 1443, 1099, 1000, 816 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.03 (s, 2H), 4.06 (s, 5H), 4.26 (s, 2H), 4.31 (s, 1H), 4.75 (s, 2H), 6.59 (d, J = 7.0 Hz, 2H), 6.83 (s, 1H), 7.15 (d, J = 8.5 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 57.8, 68.9, 69.3, 69.4, 80.5, 98.8, 114.6, 122.8, 129.1, 133.1, 145.5; HRMS (ESI) calcd for $C_{19}H_{17}ClFeINK$ $[M + K]^+$ 515.9081, found 515.9082.

(Z)-4-Bromo-N-(3-ferrocenyl-2-iodoallyl)benzenamine (***Z-3f***)*:* yellow oil; 148 mg, 57% yield; R_f = 0.5 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3418, 3089, 1666, 1444, 1000, 815 cm^{-1}; ^{1}H NMR

dx.doi.org/10.1021/jo4006206 | J. Org. Chem. 2013, 78, 5085−5089

(500 MHz, $CDCl_3$) δ 4.02 (d, J = 4.0 Hz, 2H), 4.06 (s, 5H), 4.26 (t, J = 1.5 Hz, 2H), 4.30 (s, 1H), 4.74 (t, J = 1.5 Hz, 2H), 6.54 (d, J = 8.5 Hz, 2H), 6.82 (s, 1H),7.28−7.24 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 57.8, 69.0, 69.3, 69.4, 80.5, 98.7, 110.0, 115.2, 132.1, 133.2, 146.0; HRMS (ESI) calcd for $C_{19}H_{17}BrFeINK$ [M + K]$^+$ 561.8555, found 561.8563.

(Z)-3-Chloro-N-(3-ferrocenyl-2-iodoallyl)benzenamine (***Z-3g***): yellow oil; 130 mg, 55% yield; R_f = 0.6 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3415, 3090, 1640, 1443, 1103, 1043, 871, 823, 682 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.04 (d, J = 5.5 Hz, 2H), 4.06 (s, 5H), 4.27 (s, 2H), 4.39 (s, 1H), 4.76 (s, 2H), 6.56−6.54 (m, 1H), 6.65 (s, 1H), 6.71 (d, J = 8.0 Hz, 1H), 6.85 (s, 1H), 7.11 (t, J = 8.0 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 57.5, 68.9, 69.3, 69.4, 80.4, 98.4, 111.9, 113.1, 118.1, 130.3, 133.2, 135.0, 148.0; HRMS (ESI) calcd for $C_{19}H_{17}ClFeINK$ [M + K]$^+$ 515.9081, found 515.9082.

(Z)-2-Chloro-N-(3-ferrocenyl-2-iodoallyl)benzenamine (***Z-3h***): yellow oil; 100 mg, 42% yield; R_f = 0.6 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3410, 3197, 3147, 1647, 1461, 1106, 818 cm^{-1}; ^{1}HNMR (500 MHz, $CDCl_3$) δ 4.05 (s, 5H), 4.15 (s, 2H), 4.26 (s, 2H), 4.76 (s, 2H), 5.01 (s, 1H), 6.68 (t, J = 8.5 Hz, 2H), 6.83 (s, 1H), 7.15 (t, J = 8.0 Hz, 1H), 7.30 (d, J = 8.0 Hz, 1H); ^{13}CNMR (125 MHz, $CDCl_3$) δ 57.4, 68.8, 69.2, 69.4, 80.5, 98.1, 112.3, 114.1, 127.8, 129.3, 132.6, 139.3, 142.8; HRMS (ESI) calcd for $C_{19}H_{17}ClFeINK$ [M + K]$^+$ 515.9081, found 515.9075.

(Z)-N-(3-Ferrocenyl-2-iodoallyl)-2-fluorobenzenamine (***Z-3i***): yellow oil; 102 mg, 45% yield; R_f = 0.7 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3416, 1445, 1116, 1000, 826, 744 cm^{-1}; ^{1}HNMR (500 MHz, $CDCl_3$) δ 4.03 (s, 5H), 4.09 (s, 2H), 4.25 (s, 2H), 4.57 (s, 1H), 4.74 (s, 2H), 6.73−6.64 (m, 2H), 6.84 (s, 1H), 7.03−6.98 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 57.4, 68.9, 69.3, 69.4, 80.5, 98.7, 113.3, 113.4, 114.7, 114.8, 117.7, 117.8, 124.6, 124.6, 132.8, 150.6, 152.5; HRMS (ESI) calcd for $C_{19}H_{17}FFeINK$ [M + K]$^+$ 499.9376, found 499.9379.

(Z)-N-(3-Ferrocenyl-2-iodoallyl)-4-nitrobenzenamine (***Z-3j***): yellow solid; 155 mg, 64% yield; mp 160−162 °C (recrystallized from petroleum ether and dichloromethane at room temperature); R_f = 0.3 (5/1 petroleum ether/ethyl acetate); IR (KBr) 3388, 1666, 1458, 1112, 993, 820 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.09 (s, 5H), 4.16 (d, J = 5.5 Hz, 2H), 4.29 (s, 2H), 4.76 (s, 2H), 5.10 (s, 1H), 6.62 (d, J = 8.5 Hz, 2H), 6.87 (s, 1H), 8.11 (d, J = 8.5 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 57.0, 69.2, 69.4, 69.5, 80.1, 95.9, 112.0, 126.4, 134.2, 138.8, 152.4; HRMS (ESI) calcd for $C_{19}H_{17}FeIN_2O_2Na$ [M + Na]$^+$ 510.9582, found 510.9586.

(Z)-N-(3-Ferrocenyl-2-iodoallyl)-3-nitrobenzenamine (***Z-3k***): yellow oil; 145 mg, 60% yield; R_f = 0.3 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3410, 3105, 1621, 1412, 1185, 865, 834, 738 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.05 (s, 5H), 4.13 (d, J = 6.0 Hz, 2H), 4.28 (s, 2H), 4.65 (s, 1H), 4.77 (s, 2H), 6.92 (s, 1H), 6.94−6.96(m, 1H), 7.26 (s, 1H), 7.32 (t, J = 8.5 Hz, 1H), 7.49 (s, 1H), 7.58 (d, J = 8.0 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 57.2, 69.0, 69.3, 69.4, 80.1, 97.4, 107.3, 112.8, 119.4, 129.8, 134.2, 147.7, 149.3; HRMS (ESI) calcd for $C_{19}H_{17}FeIN_2O_2Na$ [M + Na]$^+$ 510.9582, found 510.9586.

(Z)-N-(3-Ferrocenyl-2-iodoallyl)-2-nitrobenzenamine (***Z-3l***): yellow solid; 130 mg, 54% yield; mp 104−106 °C (recrystallized from petroleum ether and dichloromethane at room temperature); R_f = 0.5 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3385, 2923, 1666, 1616, 1508, 1445, 1129, 998, 822, 743 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.07 (s, 5H), 4.28 (s, 4H), 4.77 (s, 2H), 6.73 (t, J = 7.5 Hz, 1H), 6.84 (s, 2H),7.46 (t, J = 7.5 Hz, 1H), 8.22 (d, J = 8.5 Hz, 1H), 8.47 (s, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 56.7, 69.1, 69.3, 69.5, 80.3, 95.2, 114.6, 116.6, 127.0, 132.6, 133.3, 136.3, 144.6; HRMS (ESI) calcd for $C_{19}H_{17}FeIN_2O_2Na$ [M + Na]$^+$ 510.9582, found 510.9586.

(Z)-N-(3-Ferrocenyl-2-iodoallyl)-N-methylbenzenamine (***Z-3m***): yellow oil; 177 mg, 78% yield; R_f = 0.3 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3420, 3093, 1666, 1599, 1444, 1111, 997, 819 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.07 (s, 3H), 4.06 (s, 5H), 4.20 (s, 2H), 4.25 (s, 2H), 4.74 (s, 2H), 6.62 (s, 1H), 6.77 (d, J = 8.0 Hz, 3H), 7.24−7.29 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 38.6, 66.8, 68.7, 69.2, 69.3, 80.8, 97.5, 112.2, 117.1, 129.2, 130.9, 148.6; HRMS (ESI) calcd for $C_{20}H_{20}FeINK$ [M + K]$^+$ 495.9627, found 495.9630.

(Z)-N-(3-Ferrocenyl-2-iodoallyl)naphthalen-2-amine (***Z-3n***): yellow oil; 114 mg, 47% yield; R_f = 0.3 (5/1 petroleum ether/ethyl acetate); IR (KBr) 3375, 3087, 3010, 1665, 1616, 1584, 1398, 1103, 999, 819 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.99 (s, 5H), 4.09−4.14 (m, 1H), 4.19 (s, 2H), 4.24 (s, 2H), 4.66 (s, 2H), 6.32 (s, 1H), 6.77 (d, J = 7.5 Hz, 1H), 7.24−7.21 (m, 1H), 7.46 (t, J = 7.5 Hz, 1H), 7.52 (t, J = 7.5 Hz, 1H), 7.87 (d, J = 8.0 Hz, 1H), 7.97 (d, J = 8.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 51.2, 68.5, 69.1, 69.2, 81.8, 99.9, 109.4, 121.5, 124.2, 124.9, 125.1, 126.1, 126.1, 128.5, 132.8, 133.2, 141.8; HRMS (ESI) calcd for $C_{23}H_{21}FeIN$ [M + H]$^+$ 494.0068, found 494.0073.

(Z)-3-Ferrocenyl-N-[(Z)-3-ferrocenyl-2-iodoallyl]-2-iodo-N-propylprop-2-en-1-amine (***3p***): yellow solid; 234 mg, 62% yield; mp 108−110 °C (recrystallized from petroleum ether and dichloromethane at room temperature); R_f = 0.8 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3083, 2953, 2859, 1631, 1437, 1102, 997, 875, 817, 816 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.99 (t, J = 7.5 Hz, 3H), 1.54−1.61 (m, 2H), 2.57 (t, J = 7.0 Hz, 2H), 3.44 (s, 4H), 4.17 (s, 10H), 4.28 (s, 4H), 4.84 (s, 4H), 7.03 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 12.2, 20.4, 54.8, 67.5, 68.7, 69.3, 69.4, 81.2, 99.7, 133.8; HRMS (ESI) calcd for $C_{29}H_{31}Fe_2I_2N$ 758.9245, found 758.9249.

N,N-Bis[(Z)-3-ferrocenyl-2-iodoallyl]butan-1-amine (***3q***): yellow oil; 185 mg, 48% yield; R_f = 0.8 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3083, 2953, 2859, 1631, 1437, 1102, 997, 875, 817, 816 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.96 (t, J = 7.0 Hz, 3H), 1.40−1.44 (m, 2H), 1.51−1.56 (m, 2H), 2.59 (t, J = 7.5 Hz, 2H), 3.43 (s, 4H), 4.16 (s, 10H), 4.28 (s, 4H), 4.84 (s, 4H), 7.02 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 14.3, 20.8, 29.4, 52.6, 67.5, 68.7, 69.3, 69.4, 81.2, 99.7, 133.8; HRMS (ESI) calcd for $C_{30}H_{33}Fe_2I_2N$ 772.9401, found 772.9406.

(Z)-3-Ferrocenyl-N-[(Z)-3-ferrocenyl-2-iodoallyl]-2-iodo-N-methylenefuran-2-amine (***3r***): yellow oil; 238 mg, 60% yield; R_f = 0.7 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3083, 2953, 2859, 1631, 1437, 1171, 1102, 997, 875, 817 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.47 (s, 4H), 3.82 (s, 2H), 4.16 (s, 10H), 4.28 (s, 4H), 4.84 (s, 4H), 6.27 (d, J = 3.0 Hz, 1H), 6.37 (s, 1H), 7.05 (s, 2H), 7.43 (s, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 47.9, 66.2, 68.7, 69.2, 69.4, 81.0, 98.7, 108.9, 110.1, 134.5, 142.0, 152.0; HRMS (ESI) calcd for $C_{31}H_{29}Fe_2I_2NO$ 796.9037, found 796.9034.

2-{Bis[(Z)-3-ferrocenyl-2-iodoallyl]amino}ethanol (***3s***): yellow oil; 64 mg, 17% yield; R_f = 0.2 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3412, 3083, 2953, 2858, 1631, 1437, 1102, 997, 875, 817 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.79 (t, J = 4.5 Hz, 2H), 2.90 (t, J = 5.5 Hz, 1H), 3.51 (s, 4H), 3.68 (d, J = 4.5 Hz, 2H), 4.18 (s, 10H), 4.30 (t, J = 2.0 Hz, 4H), 4.84 (t, J = 2.0 Hz, 4H), 6.87 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 54.0, 58.7, 67.0, 68.9, 69.3, 69.5, 80.6, 98.5, 135.7; HRMS (ESI) calcd for $C_{28}H_{29}Fe_2I_2NO$ 760.9037, found 760.9045.

N,N,N,N-Tetrakis[(Z)-3-ferrocenyl-2-iodoallyl]benzidine (***3t***): yellow solid; 158 mg, 40% yield; mp 168−170 °C (recrystallized from petroleum ether and dichloromethane at room temperature); R_f = 0.5 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3083, 2953, 1631, 1437, 1102, 997, 875, 817, 742 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.07 (s, 20H), 4.26 (t, J = 1.5 Hz, 8H), 4.33 (s, 8H), 4.76 (t, J = 1.5 Hz, 8H), 6.67 (s, 4H), 6.85 (d, J = 9.0 Hz, 4H), 7.47 (d, J = 8.5 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 64.5, 68.8, 69.2, 69.4, 80.7, 96.3, 113.3, 127.2, 131.0, 131.4, 146.0. Anal. Calcd for $C_{64}H_{56}Fe_4I_4N_2$: C, 48.52; H, 3.56; N, 1.77. Found: C, 48.71; H, 3.59; N, 1.76.

(2E,4E)-Methyl 5-ferrocenyl-4-{[methyl(phenyl)amino]methyl}-penta-2,4-dienoate (***4***): red oil; 174 mg, 84% yield; R_f = 0.3 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3093, 1713, 1602, 1434, 1110, 1034, 988, 816 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.04 (s, 3H), 3.78 (s, 3H), 4.06−4.04 (m, 7H), 4.33 (d, J = 1.5 Hz, 2H), 4.40 (s, 2H), 5.96 (d, J = 16.0 Hz, 1H), 6.42 (s, 1H), 6.72 (t, J = 9.0 Hz, 3H) 7.24−7.27 (m, 2H), 8.10 (d, J = 16.0 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 38.7, 51.7, 55.4, 69.4, 70.2, 70.4, 80.2, 112.2, 116.6, 116.8, 127.3, 129.2, 134.8, 141.6, 149.5, 168.0; HRMS (ESI) calcd for $C_{24}H_{25}FeNO_2$ 415.1235, found 415.1234.

dx.doi.org/10.1021/jo4006206 | J. Org. Chem. 2013, 78, 5085−5089

*(E)-N-[2-(Ferrocenylmethylene)-4-phenylbut-3-ynyl]-N-methylbenzenamine (**5**):* orange oil; 128 mg, 60% yield; R_f = 0.5 (10/1 petroleum ether/ethyl acetate); IR (KBr) 3090, 2368, 1598, 1443, 1111, 817 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 3.09 (s, 3H), 4.08 (s, 7H), 4.28 (s, 2H), 4.80 (s, 2H), 6.38 (s, 1H), 6.73 (t, J = 7.0 Hz, 1H), 6.83 (d, J = 8.5 Hz, 2H), 7.28−7.23 (m, 2H) 7.36−7.32 (m, 3H), 7.46−7.44 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 38.5, 59.0, 69.2, 69.3, 69.4, 80.7, 89.4, 95.6, 112.4, 114.6, 116.6, 123.8, 128.1, 128.5, 129.2, 131.3, 133.0, 149.4; HRMS (ESI) calcd for $C_{28}H_{25}FeN$ 431.1336, found 431.1325.

■ ASSOCIATED CONTENT

Supporting Information

Figures giving ^1H and ^{13}C NMR spectra for all products. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: shufengchen@imu.edu.cn (S.C.); baoguol@sohu.com (B.L.)

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This project was generously supported by the National Natural Science Foundation of China (Nos. 21262023 and 20902044) and the Program for Young Talents of Science and Technology in Universities of Inner Mongolia Autonomous Region (NJYT-12-B03).

■ REFERENCES

(1) (a) Wei, Z.; Knaus, E. E. *Synthesis* **1994**, 1463. (b) Johannsen, M.; Jørgensen, K. A. *Chem. Rev.* **1998**, *98*, 1689. (c) Trost, B. M.; Crawley, M. L. *Chem. Rev.* **2003**, *103*, 2921. (d) Basavaiah, D.; Rao, A. J.; Satyanarayana, T. *Chem. Rev.* **2003**, *103*, 811. (e) Nicolaou, K. C.; Bulger, P. G.; Sarlar, D. *Angew. Chem., Int. Ed.* **2005**, *44*, 4490.

(2) van Staveren, D. R.; Metzler-Nolte, N. *Chem. Rev.* **2004**, *104*, 5931.

(3) (a) Biot, C.; Dive, D. *Top. Organomet. Chem.* **2010**, *32*, 155. (b) Hillard, E.; Vessières, A.; Jaouen, G. *Top. Organomet. Chem.* **2010**, *32*, 81. (c) Ornelas, C. *New J. Chem.* **2011**, *35*, 1973.

(4) For recent reviews, see: (a) Krause, N.; Hashmi, A. S. K. *Modern Allene Chemistry*; Wiley-VCH: Weinheim, Germany, 2004. (b) Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2000**, *39*, 3590. (c) Marshall, J. A. *Chem. Rev.* **2000**, *100*, 3163. (d) Lu, X.; Zhang, C.; Xu, Z. *Acc. Chem. Res.* **2001**, *34*, 535. (e) Bates, R.; Satcharoen, V. *Chem. Soc. Rev.* **2002**, *31*, 12. (f) Sydnes, L. *Chem. Rev.* **2003**, *103*, 1133. (g) Wei, L. L.; Xiong, H.; Hsung, R. P. *Acc. Chem. Res.* **2003**, *36*, 773. (h) Ma, S. *Acc. Chem. Res.* **2003**, *36*, 701. (i) Ma, S. *Chem. Rev.* **2005**, *105*, 2829. (j) Brasholz, M.; Reissig, H.-U.; Zimmer, R. *Acc. Chem. Res.* **2009**, *42*, 45.

(5) Ma, S. *Acc. Chem. Res.* **2009**, *42*, 1679.

(6) (a) Ma, S.; Wei, Q.; Wang, H. *Org. Lett.* **2000**, *2*, 3893. (b) Ma, S.; Ren, H.; Wei, Q. *J. Am. Chem. Soc.* **2003**, *125*, 4817. (c) Fu, C.; Huang, X.; Ma, S. *Tetrahedron Lett.* **2004**, *45*, 6063. (d) He, G.; Zhou, C.; Fu, C.; Ma, S. *Tetrahedron* **2007**, *63*, 3800. (e) Wang, M.; Fu, C.; Ma, S. *Chem. Sci.* **2013**, *4*, 1016.

(7) (a) Zhou, C.; Fu, C.; Ma, S. *Tetrahedron* **2007**, *63*, 7612. (b) Zhou, C.; Fu, C.; Ma, S. *Angew. Chem., Int. Ed.* **2007**, *46*, 4379.

(8) Guo, H.; Qian, R.; Guo, Y.; Ma, S. *J. Org. Chem.* **2008**, *73*, 7934.

(9) (a) Ma, S.; Hao, X.; Huang, X. *Chem. Commun.* **2003**, 1082. (b) Ma, S.; Hao, X.; Huang, X. *Org. Lett.* **2003**, *5*, 1217. (c) Ma, S.; Hao, X.; Meng, X.; Huang, X. *J. Org. Chem.* **2004**, *69*, 5720. (d) Fu, C.; Chen, G.; Liu, X.; Ma, S. *Tetrahedron* **2005**, *61*, 7768.

(10) Gu, Z.; Deng, Y.; Shu, W.; Ma, S. *Adv. Synth. Catal.* **2007**, *349*, 1653.

(11) (a) Chen, S.; Shi, J.; Wang, B.; Zhao, H.; Li, B. *Appl. Organomet. Chem.* **2012**, *26*, 284. (b) Chen, S.; Wang, B.; Yan, Q.; Shi, J.; Zhao, H.; Li, B. *RSC Adv.* **2013**, *3*, 1758.

(12) For the details of the NOE experiment, see the Supporting Information.