S_N^H Reactions of ferrocenyllithium and azine *N*-oxides

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Dedicated to Prof. Henk C. van der Plas on the occasion of his 80th birthday

Abstract
A non-catalytic C-C coupling of ferrocenyllithium and heterocyclic *N*-oxides **2** was carried out for the first time using the reaction of nucleophilic substitution of hydrogen (S_N^H) in azines.

Keywords: Azine *N*-oxides, ferrocenes, C-C coupling, nucleophilic substitution of hydrogen

Introduction

An interest in heterocyclic ferrocene derivatives is due first of all to their unique photophysical,[1] magnetic,[2] and redox[3] properties along with the possibility of their application in analytical[4] and medicinal[5] chemistry, and as efficient catalytic reagents in asymmetric synthesis.[6] Heteroarylferrocenes are often synthesized by means of a "building on" of a heterocyclic subunit on the ferrocene matrix using substituents introduced before in the ferrocene structure. The second method is a direct introduction of heterocycles in ferrocene. The applicability of the first method is limited by the necessity of obtaining the different starting ferrocene synthons. Various cross-couplings catalyzed with transition metals, such as Negishi,[7,8] Kumada,[9] Sonogashira[10] and Stille[11,12] reactions, have been examined as the second strategy. An aromatic halide is used as a substrate in the cross-couplings mentioned above. At the same time, the alternative C-C cross-couplings of azines and ferrocene are S_N^H reactions which do not require a preliminary introduction of either halogen or other nucleofuges in the azine structure. It is essential that these reactions proceed in the absence of transition metals as catalysts which usually contaminate the target product.

Recently the application of S_N^H reactions for the synthesis of a series of azinylferrocenes via the direct oxidative coupling of azine and ferrocenyllithium has been reported.[13] We succeeded in the development of the simple, efficient approach of direct introduction of ferrocene subunit in azine structure, which made it possible to obtain mono- and 1,1'-diazinyl ferrocenes in good yields.

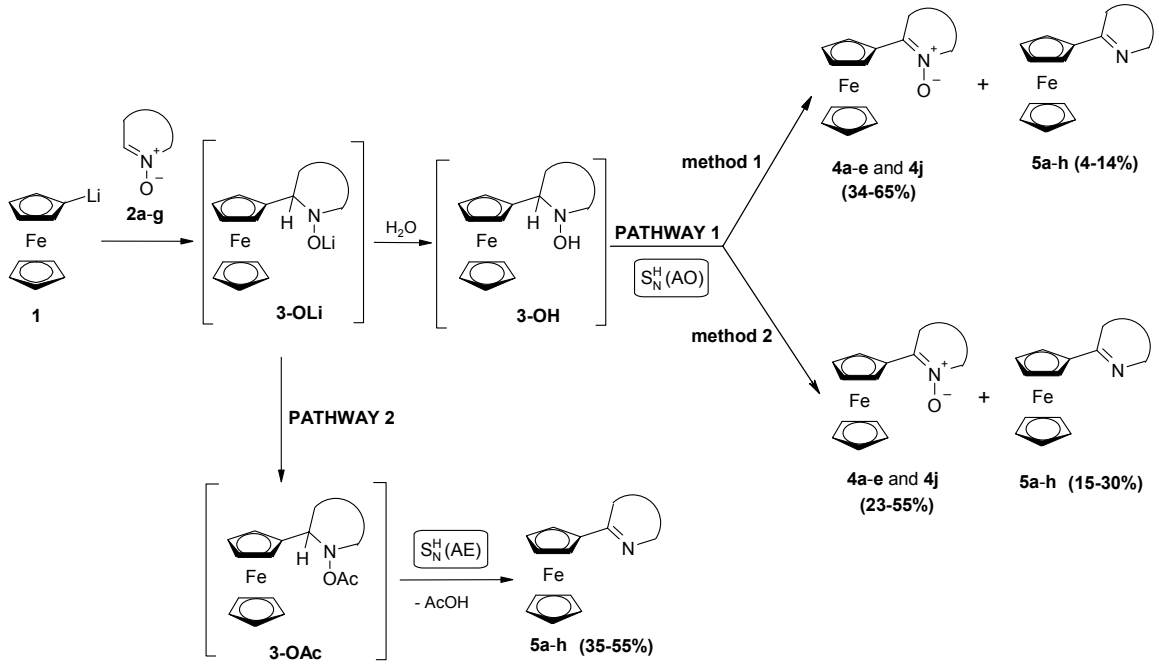
In this paper, we wish to report a new non-catalytic S_N^H C-C coupling of ferrocenyllithium and azines when *N*-oxide (an activated form of azine) is used as a substrate.

Results and Discussion

It has been found that ferrocenyllithium reacts with various *N*-oxides of mono-, di- and triazines, including both non-annelated and benz-annelated ones (quinoline oxide **2a**, isoquinoline oxide **2b**, pyrimidine oxide **2c**, quinoxaline oxide **2d**, phthalazine oxide **2e**, pyridine oxide **2f**, pyrazine oxide **2g**, 2,2'-bipyridyl oxide **2h**, 3,6-diphenyl-1,2,4-triazine-4-oxide **2j**), giving corresponding heterocyclic derivatives of ferrocene.

According to a generally accepted concept, the nucleophilic substitution of hydrogen in aza-arenes proceeds in two stages.[14] At the first step the nucleophilic reagent **1** forms a σ^H-adduct **3-OLi** with aza-heterocyclic *N*-oxide **2**, at the second stage the aromatization of intermediates **3-OH** or **3-OAc** to S_N^H products **4** or **5** takes place. There are two possible ways for the aromatization stage. The oxidation of S_N^H (AO) intermediate **3-OH** (Scheme 1) predominantly results in the reaction products **4** with the retention of *N*-oxide function during the aromatization process. We used DDQ (2,3-dichloro-5,6-dicyanobenzoquinone) (PATHWAY 1, method 1) or atmospheric oxygen (PATHWAY 1, method 2) as oxidants. In this case a mixture of products **4** and **5** is formed. Deoxygenative aromatization (PATHWAY 2) is realized according to the addition-elimination S_N^H (AE) scheme, and compounds **5** without *N*-oxide function can be obtained.

Interaction of ferrocenyllithium with azine *N*-oxides is accompanied with the formation of heterocyclic ferrocene-containing products. The lithium derivative **1** was synthesized in the reaction of bromoferrocene and *n*-butyllithium for 15 min at room temperature under an argon atmosphere.[15] Bright orange suspension of ferrocenyllithium was cooled to -78 °C, and a solution of the corresponding *N*-oxide in dry tetrahydrofuran was added. A reaction mixture was stirred for 10 min and then heated to room temperature. As the temperature increased, the color of the suspension changed to dark brown. In order to convert σ^H-adducts **3-OLi** into corresponding dihydro- compounds **3-OH**, 1 mmol of water was added to the reaction mixture.



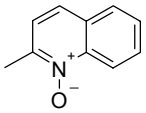
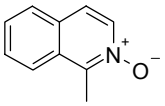
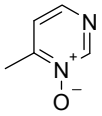
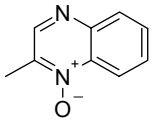
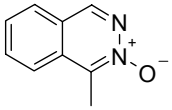
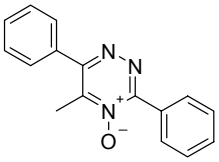
PATHWAY 1: **method 1**: DDQ, **method 2**: H_2O, O_2; **PATHWAY 2:** Ac_2O

Scheme 1

When DDQ was used as an oxidant (THF solution of 1 equivalent) the oxidative type of aromatization S_N^H(AO) took place (PATHWAY 1, method 1). DDQ was chosen as an external oxidant because of good results obtained when it was used in aromatization of σ^H-adducts of ferrocenyllithium and different azines. We succeeded in increasing the reaction yields up to 30-40% as compared with other oxidative reagents.[13] The oxidant was added to the reaction mixture at room temperature. The suspension formed was immediately filtered through a layer of neutral aluminum oxide and subjected to alumina column chromatography. As a result, new heteroarylferrocene structures **4a-e** and **4j** were synthesized in 34-65% yields (Table 1). Moreover, the concomitant azinyl ferrocenes **5a-h** were isolated from the reaction mixture in 4-14% yields by column chromatography.

It should be mentioned that in this case the *N*-oxide function remains in the structure of azaheterocyclic fragment. Compounds **4** cannot be obtained by other known methods, *e.g.,* by oxidation of corresponding azinylferrocenes. Hydrogen peroxide in acetic acid as an oxidant is not applied in such cases because of the instability of the ferrocene moiety in these conditions. It should also be noted that in the case of pyrazine oxide **2g** and 2,2'-bipyridyl oxide **2h** we failed to isolate the corresponding ferrocenyl- containing *N*-oxides. It requires additional studies to account for these results.

Table 1. Yields of compounds **4a-e** and **4j**

Compound	*N*-oxide azinyl residue		Yield, %	
			PATHWAY 1	
			method 1	method 2
4a	1-Oxido-quinolin-2-yl		65	55
4b	2-Oxido-isoquinolin-1-yl		34	44
4c	1-Oxido-pyrimidin-6-yl		35	24
4d	1-Oxido-quinoxalin-2-yl		60	51
4e	2-Oxido-phthalazin-1-yl		35	23
4j	3,6-Diphenyl-4-oxido-1,2,4-triazin-5-yl		36	24

The spectroscopic characteristics and elemental analysis data for the obtained heteroarylferrocenes agreed well with proposed structures **4a-e** and **4j**. The peaks of the molecular ions were registered in mass spectra. The absorption bands corresponding to stretching vibrations of *N*-oxide group at ν 1208-1275 cm^{-1} were observed in the IR spectra. The ^1H NMR spectra of compounds **4a-e** and **4j** showed the characteristic signals of monosubstituted ferrocene, *viz*. singlet (5H intensity) of unsubstituted cyclopentadienyl fragment of ferrocene at δ 4.02-4.24 ppm and two multiplets (2H intensity) of the monosubstituted cyclopentadienyl fragment at δ 4.50–5.58 ppm, as well as signals of the corresponding heteroaromatic fragments at δ 7.47–9.08 ppm.

Most of the compounds were obtained in the crystalline state. The spatial structure of compound **4a** was established by X-ray diffraction (Figure 1). Selected bond lengths and bond angles are listed in Table 2.

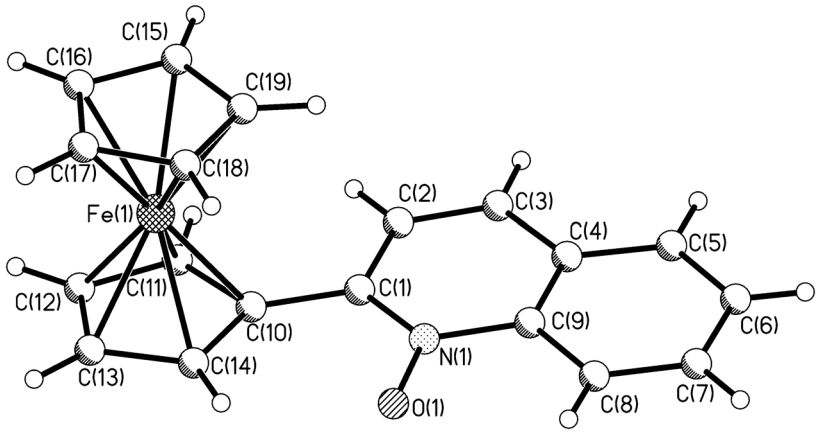


Figure 1. X-ray structure of compound **4a** with crystallographic numbering.

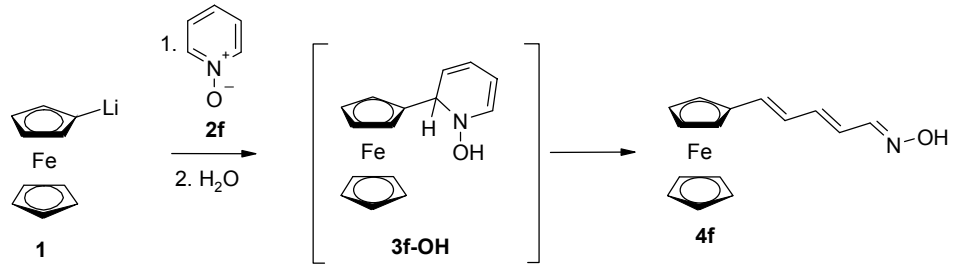
Table 2. Selected bond lengths (Å) and bond angles (deg) in molecule **4a**

Bond lengths			
Fe(1)-C(11)	2.028(3)	C(1)-C(2)	1.422(4)
Fe(1)-C(14)	2.026(3)	C(3)-C(2)	1.340(3)
Fe(1)-C(16)	2.035(4)	C(4)-C(3)	1.421(4)
Fe(1)-C(13)	2.024(3)	C(4)-C(5)	1.402(4)
Fe(1)-C(19)	2.028(3)	C(6)-C(5)	1.388(5)
Fe(1)-C(12)	2.044(3)	C(6)-C(7)	1.360(6)
Fe(1)-C(18)	2.034(4)	C(8)-C(7)	1.398(6)
Fe(1)-C(17)	2.040(3)	C(9)-C(8)	1.395(4)
Fe(1)-C(15)	2.048(4)	C(9)-C(4)	1.367(4)
Fe(1)-C(10)	2.044(2)	C(9)-N(1)	1.425(4)
C(1)-C(10)	1.455(3)	N(1)-O(1)	1.301(3)
Bond angles			
N(1)-C(1)-C(2)	118.5(3)	O(1)-N(1)-C(9)	117.6(3)
N(1)-C(1)-C(10)	121.3(3)	C(1)-N(1)-C(9)	120.9(3)
C(2)-C(1)-C(10)	120.2(3)	C(9)-C(4)-C(3)	118.8(3)
C(4)-C(9)-N(1)	120.2(3)	C(2)-C(3)-C(4)	119.5(3)
O(1)-N(1)-C(1)	121.5(3)	C(3)-C(2)-C(1)	122.1(3)

The unsubstituted Cp (C(15)–C(19) atoms) and monosubstituted Cp (C(10)–C(14) atoms) cyclopentadienyl rings are coplanar (the angle is 1.60°). The oxidoquinoline ring is rotated relative to the Cp" ring by 5.42°. The Ct-Fe-Ct" angle is 179.39°, where Ct and Ct" are centers of Cp and Cp" rings, respectively. The Fe(1)–Cp and Fe(1)–Cp" distances are 1.656 and 1.635 Å, respectively.

In the case of pyridine *N*-oxide, **2f,** the reaction product has acyclic structure **4f**. According to literature data, opening of pyridine ring took place at the stage of the σ^H-adduct formation when

phenyl-, alkyl-, alkenyl- and alkynyl-Grignard reagents had been used as nucleophiles.[16,17] Thus, intermediate **3f-OH** was converted to 5-ferrocenylpenta-2,4-dienal oxime **4f**. (Scheme 2). Derivative **4f** is quite unstable and decomposed after four days at room temperature.

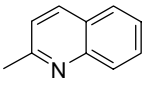
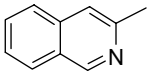
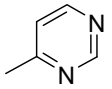
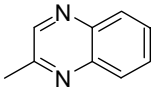
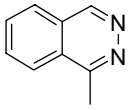
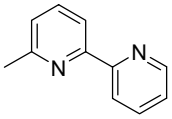


Scheme 2

A peak of **4f** molecular ion was registered in mass spectra. The absorption bands corresponding to stretching vibrations of C=N and O-H groups were observed at ν 1610 and 3264 cm^{-1}, respectively, in the IR spectrum. The ^{1}H NMR spectrum of oxime **4f** showed characteristic proton signals of the monosubstituted ferrocene fragment at δ 4.08-4.49 ppm, as well as the proton signals of polyene substituent at δ 5.91-8.27 ppm and O-H group at δ 10.81 ppm.

When acetic anhydride was added as dehydrating agent to intermediate **3-OLi** (Scheme 1), aromatization process proceeded according to the eliminative type (PATHWAY 2) and was accompanied by removal of an acetic acid molecule from **3-OAc**. The reaction mixture was heated to a room temperature, and then treated with acetic anhydride. The suspension obtained was stirred for 15 min, a solvent was evaporated, and the residue was subjected to alumina column chromatography. As a result, we obtained the known azinylferrocenes **5a-d, 5f** and **5h**. Characteristics of the obtained derivatives agreed to the literature data.[13] Moreover, we synthesized the previously unknown phthalazine and pyrazine derivatives, **5e** and **5g**. Yields of azinylferrocenes **5a**-**h** were 35-55% (Table 3).

Table 3. Yields of compounds **5a-h**

Compound	Azinyl residue		Yield, %		
			PATHWAY 1		PATHWAY 2
			method 1	method 2	
5a	Quinolin-2-yl		14	30	55
5b	Isoquinolin-3-yl		10	23	48
5c	Pyrimidin-4-yl		7	15	38
5d	Quinoxalin-2-yl		12	25	52
5e	Phthalazin-1-yl		4	15	35
5f	Pyridin-2-yl		6	18	38
5g	Pyrazin-2-yl		8	20	42
5h	2,2'-Bipyridyl-6		12	24	50

It has been found that the aromatization process of intermediate **3-OH** could proceed spontaneously in the presence of atmospheric oxygen (Scheme 1); however, the selectivity is essentially decreased in this case. The reaction products comprised a mixture of *N*-oxido-azinylferrocenes **4** (23-55% yield) and derivatives **5** (15-30% yield) without *N*-oxide fragment in the azine moiety (PATHWAY 1, method 2).

Conclusions

Thus, the use of S_N^H methodology makes it possible to obtain a series of heterocyclic ferrocene containing derivatives **4** and **5**, the reaction products' type depends on the starting heteroaryl *N*-oxides, and conditions of the aromatization stage of σ^H-adducts. For the first time, ferrocenyl-containing heterocyclic *N*-oxides **4** were synthesized. Such a type of compounds were not known

before. However, it should be recognized that for the synthesis of azinylferrocenes it is necessary to use coupling of ferrocenyllithium and heterocycles,[13] since we failed to increase yields of the compounds **5** previously synthesized, as we planned at the beginning of our research.

Experimental Section

General Procedures. Solvents were purified according to standard procedures. The course of the reactions was monitored and the purity of the reaction products was checked by TLC on Polygram Alox N/UV-254 plates. Column chromatography was performed on Sigma-Aldrich neutral aluminum oxide (activated, neutral, Brockmann I, STD grade, approx. 150 mesh, 58 Å). The ^{1}H NMR spectra were recorded on a Bruker DRX-250 Avance spectrometer in [$^2H_6$] DMSO with TMS as the internal standard. Chemical shifts (δ) were expressed in ppm relative to TMS at $\delta = 0$ and coupling constants (J) in Hz. The mass spectra were obtained on a Varian MAT-311A instrument, electron beam ionization, ionization energy 70 eV, direct inlet system, temperature of the ionization chamber 100–300 °C. The IR spectra were measured on a Perkin Elmer Spectrum One B FT-IR spectrometer in KBr pellets. Elemental analysis was performed on a Perkin Elmer 2400-II instrument. Melting points were determined on a Boethius apparatus and were uncorrected. Bromoferrocene,[15] quinoline oxide **2a**, isoquinoline oxide **2b**, pyrimidine oxide **2c**, quinoxaline oxide **2d**, phthalazine oxide **2e**, pyridine oxide **2f**, pyrazine oxide **2g**,[18] 2,2'-bipyridyl oxide **2h**,[19] and 3,6-diphenyl-1,2,4-triazine-4-oxide **2j** [20] were synthesized as described in the literature. The characteristics of the obtained quinolin-2-yl-ferrocene **5a**, isoquinoline-3-yl-ferrocene **5b**, pyrimidin-4-yl-ferrocene **5c**, quinoxalin-2-yl-ferrocene **5d**, pyridin-2-yl-ferrocene **5f**, 2,2'-bipyridyl-6-yl-ferrocene **5h** agree with literature data.[13]

General procedure for the synthesis of 4a-j and 5a-h
To 5 mL of a stirred Et_2O solution of bromoferrocene (264 mg, 1.0 mmol) *n*-BuLi (1.2 mmol, 0.75 mL of a 1.6 M solution in *n*-hexane) was added dropwise at room temperature under an argon atmosphere. The reaction mixture was stirred for 15 min at the same temperature then cooled to -78 °C and treated with *N*-oxide **2** (1.2 mmol) in minimum quantity of dry THF under argon. The resulting grayish brown suspension **3** was allowed to warm to room temperature and then stirred for 2 h.

Synthesis of *N*-oxido-azinylferrocenes 4a-e and **4j**. To the previously obtained suspension of **3,** a solution of DDQ (220 mg, 1.0 mmol) in THF (5 mL) was added, and the mixture was stirred for 15 min. Finally, the reaction mixture was filtered through neutral alumina and subjected to alumina column chromatography to give a mixture of bromoferrocene and ferrocene (hexane as the eluent), and the reaction product (Et_2O or EtOAc, or a mixture of *n*-hexane and EtOAc as the eluent) as a slowly eluting compound. The eluate was concentrated to dryness in vacuo and the residue was recrystallized from an appropriate solvent.

(1-Oxido-quinolin-2-yl)-ferrocene (4a). Yield 214 mg (65%), dark purple powder, mp 185 °C (*n*-hexane: benzene, 8: 2). R_f = 0.45 (eluent Et_2O). ^1H NMR: δ 4.09 (s, 5H, CpH); 4.50 (m, 2H, C_5H_4); 5.46 (m, 2H, C_5H_4); 7.58-7.75 (m, 4H, 5'H, 6'H, 7'H, 8'H); 7.91 (m, 1H, 3'H); 8.63 (m, 1H, 4'H). IR (KBr, cm^{-1}): ν = 3098, 1601, 1565, 1515, 1473, 1387, 1362, 1350, 1325, 1294, 1247, 1212 (N–O), 1119, 1106, 1084, 1024, 919, 813, 770, 732, 501. MS (70 eV) m/z (%): = 329 (M^+, 100). Anal. Calcd for $C_{19}H_{15}FeNO$ (329.18): C, 69.33; H, 4.59; N, 4.26. Found: C, 69.53; H, 4.32; N, 4.40%.

(2-Oxido-isoquinolin-1-yl)-ferrocene (4b). Yield 112 mg (34%), claret red powder, mp 105 °C (*n*-hexane: benzene, 8: 2). R_f = 0.20 (eluent *n*-hexane: EtOAc, 1: 1). ^1H NMR: δ 4.19 (s, 5H, CpH); 4.53 (m, 2H, C_5H_4); 5.04 (m, 2H, C_5H_4); 7.47-7.61 (m, 2H, 6'H, 7'H); 7.71 (m, 1H, 4'H), 7.85 (m, 1H, 5'H), 8.08 (m, 1H, 8'H), 8.46 (m, 1H, 3'H). IR (KBr, cm^{-1}): ν = 3412, 3092, 2923, 2851, 1558, 1471, 1384, 1329, 1246 (N–O), 1194, 1107, 1000, 960, 820, 761, 655, 499. MS (70 eV) m/z (%): = 329 (M^+, 100). Anal. Calcd for $C_{19}H_{15}FeNO$ (329.18): C, 69.33; H, 4.59; N, 4.26. Found: C, 69.64; H, 4.84; N, 4.43%.

(1-Oxido-pyrimidin-6-yl)-ferrocene (4c). Yield 98 mg (35%), dark purple powder, mp 145 °C (*n*-hexane: benzene, 7: 3). R_f = 0.15 (eluent EtOAc). ^1H NMR: δ 4.12 (s, 5H, CpH); 4.56 (m, 2H, C_5H_4); 5.43 (m, 2H, C_5H_4); 7.70 (d, 1H, 5'H, ^3J =5.2); 7.99 (d, 1H, 4'H, ^3J =5.2), 8.81 (c, 1H, 2'H). IR (KBr, cm^{-1}): ν = 3147, 3090, 3051, 3010, 1586, 1529, 1504, 1386, 1371, 1275 (N–O), 1245, 1226, 1105, 1014, 822, 674, 561, 496, 484. MS (70 eV) m/z (%): = 280 (M^+, 100). Anal. Calcd for $C_{14}H_{12}FeN_2O$ (280.11): C, 60.03; H, 4.32; N, 10.00. Found: C, 60.22; H, 4.38; N, 10.28%.

(1-Oxido-quinoxalin-2-yl)-ferrocene (4d). Yield 198 mg (60%), dark purple powder, mp 165 °C (*n*-hexane: benzene, 6: 4). R_f = 0.35 (eluent Et_2O). ^1H NMR: δ 4.14 (s, 5H, CpH); 4.58 (m, 2H, C_5H_4); 5.49 (m, 2H, C_5H_4); 7.73-7.83 (m, 2H, 6'H, 7'H); 8.03 (m, 1H, 5'H), 8.52 (m, 1H, 8'H), 9.08 (s, 1H, 3'H). IR (KBr, cm^{-1}): ν = 3132, 3083, 1578, 1561, 1495, 1477, 1384, 1362, 1329, 1303, 1221 (N–O), 1122, 1103, 1087, 1025, 998, 928, 884, 820, 768, 743, 637, 494, 481. MS (70 eV) m/z (%): = 330 (M^+, 100). Anal. Calcd for $C_{18}H_{14}FeN_2O$ (330.17): C, 65.48; H, 4.27; N, 8.48. Found: C, 65.25; H, 4.15; N, 8.60%.

(2-Oxido-phthalazin-1-yl)-ferrocene (4e). Yield 115 mg (35%), dark red powder, mp > 250 °C (*n*-hexane: benzene, 8: 2). R_f = 0.15 (eluent EtOAc). ^1H NMR: δ 4.24 (s, 5H, CpH); 4.68 (m, 2H, C_5H_4); 5.04 (m, 2H, C_5H_4); 7.81-7.89 (m, 3H, 5'H, 6'H, 7'H); 8.77-8.81 (m, 2H, 4'H, 8'H). IR (KBr, cm^{-1}): ν = 3129, 3065, 1610, 1555, 1488, 1439, 1389, 1342, 1326, 1274 (N–O), 1177, 1142, 1129, 1073, 840, 820, 762, 690, 645, 498, 486. MS (70 eV) m/z (%): = 330 (M^+, 92). Anal. Calcd for $C_{18}H_{14}FeN_2O$ (330.17): C, 65.48; H, 4.27; N, 8.48. Found: C, 66.32; H, 4.41; N, 8.43%.

(3,6-Diphenyl-4-oxido-1,2,4-triazin-5-yl)-ferrocene (4j). Yield 156 mg (36%), purple powder, mp > 250 °C (*n*-hexane). R_f = 0.60 (eluent *n*-hexane: EtOAc, 4: 6). ^1H NMR: δ 4.02 (s, 5H, CpH); 4.88 (m, 2H, C_5H_4); 5.58 (m, 2H, C_5H_4); 7.57-7.60 (m, 8H, Ph); 8.54-8.58 (m, 2H, Ph). IR (KBr, cm^{-1}): ν = 3091, 3061, 3035, 1483, 1445, 1395, 1385, 1345, 1308, 1208 (N–O), 1172, 1483, 1445, 1395, 1385, 1345, 1308, 1107, 1085, 1072, 1019, 1010, 823, 779, 766, 713, 699,

631, 518, 507, 482, 497, 474. MS (70 eV) m/z (%): = 433 (M^+, 96). Anal. Calcd for $C_{25}H_{19}FeN_3O$ (433.30): C, 69.30; H, 4.42; N, 9.70. Found: C, 66.32; H, 4.41; N, 9.43%.

Synthesis of 5-ferrocenylpenta-2,4-dienal oxime (4f). To the previously obtained suspension of **3f** 0.02 mL (1.0 mmol) of distilled water was added, and the mixture was stirred for 15 min. Then solvent was removed under reduced pressure, and the oily residue was subjected to alumina column chromatography to obtain a mixture of bromoferrocene and ferrocene (hexane as the eluent), and the reaction product (Et_2O as the eluent) as a slow eluting compound. The eluate was concentrated to dryness in vacuo and the residue was recrystallized from *n*-hexane. Yield 135 mg (48%), brown red powder, mp 115 °C (*n*-hexane). R_f = 0.75 (eluent Et_2O). ^{1}H NMR: δ 4.08 (s, 5H, CpH); 4.26 (m, 2H, C_5H_4); 4.49 (m, 2H, C_5H_4); 5.91 (m, 1H, CH); 6.27 (m, 1H, CH); 6.42 (m, 1H, CH); 6.90 (m, 1H, CH); 8.27 (d, 1H, N-CH, ^3J = 10.38), 10.81 (s, 1H, OH). IR (KBr, cm^{-1}): ν = 3264 (O-H), 3091, 3031, 1610 (C=N), 1106, 969, 945, 816, 788, 681, 501, 478. MS (70 eV) m/z (%): = 281 (M^+, 100). Anal. Calcd for $C_{15}H_{15}FeNO$ (281.14): C, 64.08; H, 5.38; N, 4.98. Found: C, 64.38; H, 5.34; N, 4.83%.

Synthesis of azinylferrocenes, 5a-h. To the previously obtained of **3** 0.08 mL (1.0 mmol) of acetic anhydride was added, and the mixture was stirred for 15 min. Then solvent was removed under reduced pressure and the oily residue subjected to alumina column chromatography to obtain a mixture of bromoferrocene and ferrocene (hexane as the eluent) and the reaction product (Et_2O or EtOAc, or a mixture of *n*-hexane and EtOAc as the eluent) as a slow eluting compound. The eluate was concentrated to dryness in vacuo and the residue was recrystallized from an appropriate solvent.

(Phthalazin-1-yl)-ferrocene (5e). Yield 110 mg (35%), orange powder, mp 135 °C (EtOAc). R_f = 0.60 (eluent *n*-hexane: EtOAc, 1: 1). ^{1}H NMR: δ 4.16 (s, 5H, CpH); 4.55-4.56 (s, 2H, C_5H_4); 5.02-5.03 (m, 2H, C_5H_4); 7.91-8.12 (m, 3H, 5'H, 6'H, 7'H); 8.78-8.82 (m, 1H, 8'H); 9.43 (s, 1H, 4'H). IR (KBr, cm^{-1}): ν = 2925, 2869, 1542, 1493, 1322, 1005, 827, 765. MS (70 eV) m/z (%): = 314 (M^+, 100). Anal. Calcd for $C_{18}H_{14}FeN_2$ (314.17): C, 68.82; H, 4.49; N, 8.92. Found: C, 68.72; H, 4.41; N, 8.87%.

(Pyrazin-2-yl)-ferrocene (5g). Yield 111 mg (42%), orange powder, mp 113 °C (*n*-hexane). R_f = 0.50 (eluent Et_2O). ^{1}H NMR: δ 4.03 (s, 5H, CpH); 4.44-4.46 (m, 2H, C_5H_4); 5.00-5.01 (m, 2H, C_5H_4); 8.31 (d, 1H, 3'H, ^4J = 2.4); 8.39-8.41 (m, 1H, 5'H); 8.75 (d, 1H, 6'H, ^3J = 1.5). IR (KBr, cm^{-1}): ν = 2968, 1519, 1497, 1384, 1104, 1014, 840, 811. MS (70 eV) m/z (%): = 264 (M^+, 100). Anal. Calcd for $C_{14}H_{12}FeN_2$ (264.11): C, 63.67; H, 4.58; N, 10.61. Found: C, 63.83; H, 4.56; N, 10.61%.

X-Ray analysis. The suitable crystals of compound **4a** were obtained by slow crystallization from benzene at room temperature. The crystallographic data were collected with an Xcalibur 3 CCD diffractometer. The relevant crystallographic data and structure refinement are given in Table 4. The structure was solved[21] by direct methods and refined[22] by anisotropic full-matrix least-squares technique. Perspective view and the numbering of the atoms are depicted in Figure

1. The hydrogen atoms were refined isotropically in idealized positions riding on the atom to which they are attached. Atomic coordinates, bond lengths, bond angles and thermal parameters were set at Cambridge Crystallographic Data Centre (CCDC), deposition number 720051. These data can be obtained free of charge on www.ccdc.cam.uk/conts/retrieving.html (or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, England; fax: +44 1223 335 033; or deposit@ccdc.cam.ac.uk). Any request to the CCDC should contain full literature quotation and CCDC reference numbers.

Table 4. Crystal and experimental data for compound **4a**

Empirical formula	$C_{19}H_{15}FeNO$
Formula weight	329.17
Temperature, T (K)	295(2)
Wavelength, λ (Å)	0.71073
Crystal system	Orthorhombic
Space group	$P2_12_12_1$.
Unit cell dimensions(Å)	a = 9.0712(11) α = β = γ = 90°
	b = 11.3863(11)
	c = 14.0340(9)
Unit-cell volume, V (Å^3)	1449.5(2)
Formula units per unit cell, Z	4
Calculated density, Dx (g cm^{-3})	1.508
Absorption coefficient, μ (mm^{-1})	1.040
F(000)	680
Crystal size (mm)	0.1878×0.1159×0.0669
Diffractometer	Xcalibur 3 CCD
Theta range for data collection, (°)	2.87 - 30.50
Index ranges	$-6 \le h \le 12$
	$-16 \le k \le 15$
	$-15 \le l \le 20$
Reflections collected	7531
Independent reflections [I>2σ(I)]	4187 (R_{int} = 0.0285)
Absorption correction	Analytical
Max. and min. transmission	0.880 and 0.771
Refinement method	Full-matrix least-squares on F^2
Data / parameters	4187 / 200
Goodness-of-fit (all)	1.005
Final R indices [I>2σ(I)]	R_1 = 0.0416, wR_2 = 0.0772
R indices (all data)	R_1 = 0.0958, wR_2 = 0.0828
Largest diff. peak and hole	0.975 and -0.194 eÅ^{-3}

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