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Mendeleev Commun., 2020, **30**, 577–579

Mendeleev Communications

Rearrangements of diferrocenylcyclopropenium ions in the reactions with bis-1,4-O,S-nucleophiles

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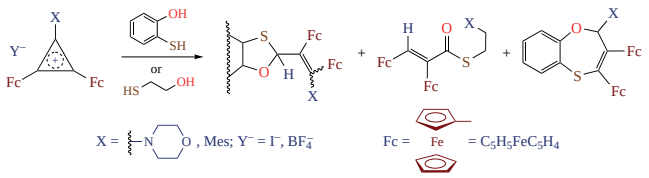
DOI: 10.1016/j.mencom.2020.09.008

Reactions of 3-R-1,2-diferrocenylcyclopropenium ions (R is 4-morpholino or SMe) with 2-mercaptophenol or 2-mercaptoethanol proceed *via* a ring opening and result in three types of products, namely, diferrocenyl-substituted 1,3-oxathiolanes, 1,4-oxathiepines and alkyl prop-2-enethioates.

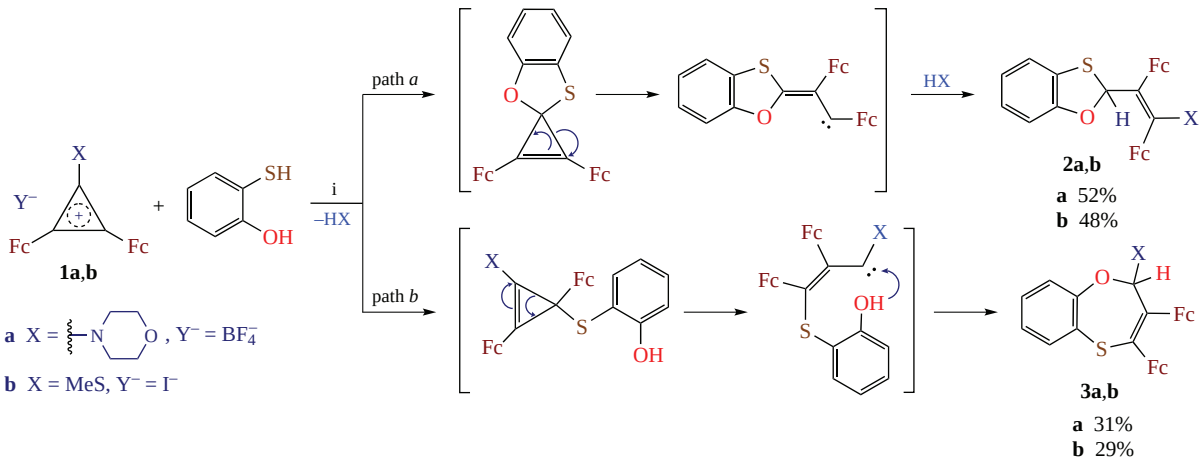


Keywords: ferrocene, cyclopropenium salts, bis-1,4-O,S-nucleophiles, 1,3-oxathiolanes, oxathiepines, prop-2-enethioates.

The chemistry of hetero- and carbocycles with two ferrocenyl substituents is based on a sufficient accessibility of 2,3-diferrocenylcyclopropenone and diferrocenyl-cyclopropenium salts[1] with heteroatomic substituents. In practice compounds with a three-membered ring represent both the target products and intermediates in various carbon skeleton transformations.[2,3] Diferrocenylcyclopropene derivatives can react with mono C- and N-,[1] bis-1,3-N,N-,[4,5] bis-1,4-N,N-[6,7] and bis-1,4-N,O-nucleophiles[7,8] both with retention and opening of cyclopropene fragment. Thus, reactions of 2,3-diferrocenyl-1-morpholino- and 1-methylthiocyclopropenium salts **1a**,**b** with aromatic and aliphatic bis-1,4-N,N-nucleophiles and aliphatic bis-1,4-N,O-nucleophiles result in five-membered heterocycles (benzoimidazoles, imidazolines, oxazolines) exclusively upon the double attack of the bis-nucleophiles on the C^1 atom of the three-membered ring with the elimination of morpholine or methylmercaptane molecule and with subsequent intramolecular transformations of the 1,2-diferrocenyl-4,7-diaza- and 4-aza-7-oxaspiro[2.4]hept-1-ene intermediates[6,7] into vinylcarbenes, which are stabilized by intramolecular transformation or by addition of proton and intermolecular transformation of allylic cations in the final 2-(1,2-diferrocenyl-vinyl)benzimidazoles, imidazolines or 4,5-dihydrooxazoles.

The nucleophilic attacks of aromatic bis-1,4-N,O-nucleophiles on the cyclopropenium salt **1b**, contrary to the bis-1,4-N,N-nucleophiles and aliphatic bis-1,4-N,O-nucleophiles, would take place on both the C^1 and C^2 atoms. In the former case, benzooxazoles are also formed due to nucleophilic attacks on the C^1 atom. In the case of attack on the C^2 atom linked to a ferrocenyl substituent, the tetra-substituted three-membered ring undergoes spontaneous opening to form lineal vinylcarbenes. The transformations of the intermediates with the migration or addition of the 'intermolecular' proton, or with intramolecular cyclizations yield the final compounds such as linear 3-aza-1,3-diferrocenylalka-1,3-dienes, oxazepines and oxazines.[7,8] This work presents a comparative study of the effects of the sulfur atoms of bis-1,4-O,S-nucleophiles in contrast to the nitrogen atoms of bis-1,4-O,N-nucleophiles on the reaction course. These effects may provide formation of interesting compounds potent of having fungicidal, bactericidal, anti-inflammatory, herbicidal, phytocidal as well as anti-HIV activities.[9–14]

In this work, reactions of bis-1,4-O,S-nucleophiles, 2-mercaptophenol and 2-mercaptoethanol, with 2,3-diferrocenylcyclopropenium salts **1a**,**b** were studied. The starting diferrocenyl-1-morpholinocyclopropenium tetrafluoroborate **1a** was obtained



Scheme 1 *Reagents and conditions*: i, Et_3N, PhH, reflux, 6–8 h.

from ethoxy(diferrocenyl)cyclopropenium tetrafluoroborate and morpholine.[1] 2,3-Diferrocenyl-1-methylthiocyclopropenium iodide **1b**[15] was synthesized by reaction of 2,3-diferrocenylcyclopropenethione[16] and methyl iodide in benzene. In fact, reaction of 2,3-diferrocenylcyclopropenium salts **1a**,**b** with 2-mercaptophenol proceeded in two parallel pathways *a* and *b* (Scheme 1) forming 1,3-benzoxathioles **2a**,**b** and 1,5-benzoxathiepines **3a**,**b**, respectively, in comparable yields.

The ^{1}H NMR spectra of compounds **2a**,**b** contained characteristic resonances for morpholino and methylthio protons at 2.72–3.55 and 2.38 ppm, respectively, while their ^{13}C NMR contained signals at 50.77, 67.63 ppm and 19.20 ppm, respectively. These spectra also contained signals for the protons of the C_5H_5 and C_5H_4 moieties for the two ferrocene substituents, multiplets for the aromatic protons. Thioacetal fragment O–CH–S manifested proton (1H) singlets at 6.17 (**2a**) or 6.60 (**2b**) and the corresponding carbon signals at ~110 ppm. However, the data obtained from these ^{1}H and ^{13}C NMR spectra do not allow one to identify the positions of the morpholino- and methylthio-substituents and protons of the CH groups.

The structure of compound **2b** was verified by single crystal X-ray diffraction (Figure 1)† and was in accordance with the ^{1}H and ^{13}C NMR spectroscopic characterization. The main geometrical parameters are given in Table S1 (see Online Supplementary Materials).[17–21] Data from the X-ray analysis showed that compound **2b** is 2-(*E*-1,2-diferrocenyl-2-methylthiovinyl)-1,3-benzoxathiolane with *E*-configuration of the double bond. Presumably, compound **2a** would possess similar structure.

An important feature of the ^{1}H NMR spectra of compounds **3a**,**b** is the presence of the singlets for the protons of the methine groups (CH-morpholino and CH–SMe), which shifted upfield (5.48 and 5.45 ppm, respectively) compared to isomers **2a**,**b**, which is similar to data reported for the synthesis for diferrocenyl(hydroxy)oxazepines.[15] We have assigned the seven-membered heterocyclic structures of 3,4-diferrocenyl-2*H*-1,5-benzoxathiepines for compounds **3a**,**b**, based on these criteria. The number of signals for the Fc, CH_2, CH_3, Ar, CH, C and C_{ipso}Fc in the ^{13}C NMR spectra of compounds **3a**,**b** is also consistent with their structures.

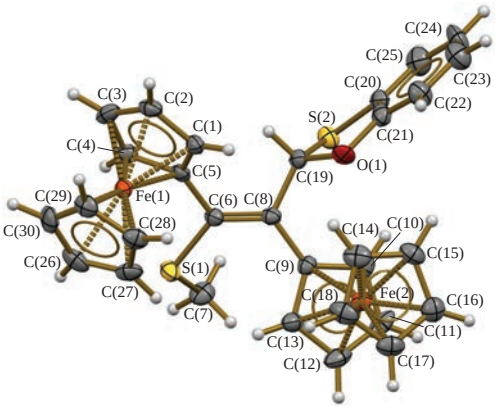
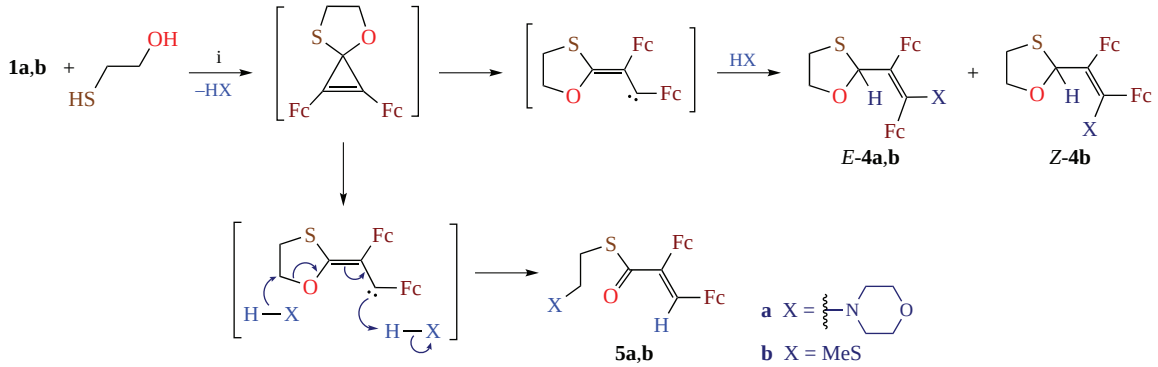


Figure 1 Molecular structure of compound **2b** according to XRD data. The ellipsoids are drawn at the 50% probability level.

The reaction of 2-mercaptoethanol with 2,3-diferrocenylcyclopropenium salts **1a**,**b** affords several products, the major of them being 1,3-oxathiolanes *E*-**4a** (49%), *E*-**4b** (31%), and *Z*-**4b** (23%), ethyl 2-propenethioates *Z*-**5a** (25%) and *Z*-**5b** (18%) (Scheme 2). These compounds were separated by column chromatography. The structures of compounds **4**, **5** were established by IR, ^{1}H and ^{13}C NMR spectroscopy, mass spectrometry, as well as elemental analysis (for details, see Online Supplementary Materials).

The assignment of the isomeric 4,5-dihydrooxathiolanes *E*-**4a**,**b** and *Z*-**4b** to the *E* and *Z* isomeric series has been carried out based on their ^{1}H NMR spectroscopic data, while taking into account the previously established NMR criteria for the assignment of *E* and *Z* isomers for diferrocenylvinyloxazolines.[5(a),15] Thus, the ^{1}H NMR spectra of the oxathiolanes *E*-**4a** and *E*-**4b** contain two singlets at 4.22/4.24, 4.23/4.28 ppm belonging to the protons for the two ferrocene C_5H_5 groups, respectively. In the ^{1}H NMR spectrum of isomer *Z*-**4b** analogous signals were located at 4.10/4.26 ppm. The fact that the difference in the chemical shifts for the ferrocene protons in isomer *Z*-**4b** ($\Delta\delta$ = 0.16 ppm) is larger than that in isomer *E*-**4a** ($\Delta\delta$ = 0.02 ppm) and *E*-**4b** ($\Delta\delta$ = 0.05 ppm) is the evidence for the *cis*-arrangement of Fc substituents at the double bond of compound *Z*-**4b**.



Scheme 2 *Reagents and conditions*: i, Et_3N, PhH, reflux, 6–8 h.

† *Crystal data for* **2b**. $C_{30}H_{26}Fe_2OS_2$ (M = 578.33), triclinic, space group $P\bar{1}$ at 130(2) K: a = 7.6795(6), b = 8.5130(4) and c = 19.7792(14) Å, α = 88.655(4)°, β = 87.639(6)°, γ = 71.950(5)°, Z = 2, d_{calc} = 1.564 g cm^{-3}, V = 1228.32(15) Å^3, μ(MoKα) = 1.374 mm^{-1}, F(000) = 596. A total of 16637 reflections were collected (5923 independent reflections, R_{int} = 0.0485), GOOF 1.043, final R indices [$I > 2\sigma(I)$]: R_1 = 0.0500 and wR_2 = 0.0978, R indices (all data): R_1 = 0.0788 and wR_2 = 0.1109, 317 refined parameters. Crystallographic data were collected on an Oxford Diffraction Gemini 'A' diffractometer with a CCD area detector with λ(CuKα) = 1.54184 Å at 130 K. Structure solution and refinement were carried out using the programs SHELXS-2014[19] and SHELXL-2014,[19] respectively, WinGX v2018.3[20] and Mercury CSD 4.1.0[21] were used to prepare the material for publication. Full-matrix least-squares refinement was carried out by minimizing $(Fo^2 - Fc^2)^2$. All nonhydrogen atoms were refined anisotropically. Hydrogen atoms attached to carbon toms were placed in geometrically idealized positions and refined as riding on their parent atoms, with C–H = 0.95–1.00 Å with U_{iso}(H) = 1.2 U_{eq}(C) for aromatic and methyne groups, and U_{iso}(H) = 1.5 U_{eq}(C) for methyl group.

CCDC 1980452 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre *via* http://www.ccdc.cam.ac.uk.

In summary, the observed difference in regioselectivity of the nucleophilic attacks and in the formation of products **2**–**5** is related, most probably, to the structures of the nucleophiles (the steric factor) and to the nature of the heteroatoms (O and S) in the nucleophiles, and hence to a different electron-density distribution in the aromatic cyclopropenium ring (electronic factors).

The work was supported by DGAPA–UNAM (Mexico, grant IN 217318 and PASPA-UNAM-2020-1) and CONACyT (Mexico, grant CB-2015/251437).

Online Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.mencom.2020.09.008.

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Received: 7th May 2020; Com. 20/6215