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Bis-β-sulfanylethylester and cyclic disulfide-*S*-oxides as precursors of bifunctionalized anionic derivatives with two oxidized sulfurs

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Abstract

The cyclic disulfide and the bis-β-sulfanyl ethyl ester derived from dithiol, *N*,*N*′-1,2-phenylenebis(3-methyl-3-sulfanylbutanamide) were used as precursors to prepare upon oxidation the cyclic disulfide-*S*-oxides and the thioether sulfur oxidized species including thioether/sulfoxide, bis-sulfoxide, sulfoxide/sulfone, and bis-sulfone. Ring cleavage with KOH/EtOH of the cyclic disulfide-*S*-monooxide followed by reaction of the opened intermediate with ethyl acrylate afforded the sulfinate/β-sulfanyl ethyl ester derivative. Selective oxidation with 1 and 2 equiv of (3*S*)-3-*tert*-butyl-3-methyl-2-(phenylsulfonyl)oxaziridine or with 3 equiv of DMD led to the isolation of a series of compounds containing a sulfonate and a β-sulfanyl, a β-sulfinyl, and a β-sulfonyl ethyl ester. Retro-Michaël reaction applied to the β-sulfonyl/β-sulfinyl and bis-β-sulfonyl derivatives enabled to produce compounds containing a sulfinate and a β-sulfinyl or a β-sulfonyl ethyl ester as well as the bis-sulfinate dianion. DMD oxidation of the latter afforded the bis-sulfonate dianion. All these anionic species were characterized by ^{1}H NMR, mass spectrometry, HRMS or elemental analysis. Sulfenates in such pseudopeptidic structures could not be isolated from the ring cleavage of the cyclic disulfide-*S*-dioxide or from a retro-Michaël reaction applied to the β-sulfinyl ethyl ester. A cyclization reaction leading to an isothiazolidin-3-one is likely to occur as observed from the ring cleavage of the cyclic disulfide-*S*-dioxide. Finally, Ni(II) and Co(III) have been inserted into the disulfinate dianion leading to the corresponding diamidato/disulfinato complexes *S*-bonded to Ni(II) or Co(III) centers.

Keywords: Disulfide-*S*-oxides; *N*-Sulfonyloxaziridine; Sulfinate; Sulfonate; Sulfur; Complex

1. Introduction

Sulfur can occur in many different redox states in proteins or in low molecular weight compounds used in biology or in medicine. This includes sulfoxides, sulfones and sulfenic, sulfinic and sulfonic acids, and the lesser known disulfide-*S*-oxides.[1] Usually, proteins or small molecules carry only one type of sulfur modification at a time. For instance, peroxyredoxins are involved in the reduction of hydrogen peroxide through the conversion of their active cysteine to sulfenic acid, and it is only when the level of H_2O_2 becomes very high that the sulfenic acid is over-oxidized to sulfinic acid.[2] As far as small molecules are concerned, the natural antibiotics, allicin[3] and leinamycin,[4] contain a unique disulfide-*S*-monooxide. In contrast, nitrile hydratase (NHase)[5] and thiocyanate hydrolase (SCNase)[6] are the only proteins which retain at their active site three sulfurs in three different oxidation states, thiolate, sulfenate, and sulfinate. These three sulfur oxidized species can only coexist since they are stabilized by coordination to a metal center. In our ongoing research on the synthesis of sulfur oxidized species and the study of their reactivity toward metal cations, our present objective was to find proper conditions to produce small molecules with two sulfurs in two different states, one of the sulfurs being oxidized at the level of sulfinate or sulfonate. The ultimate aim was to prepare mixed thiolate/sulfinate or sulfonate and mixed sulfinate/sulfenate and to trap all these species with a metal cation, such as Ni(II) or Co(III).

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As starting dithiol, we have selected *N*,*N*′-1,2-phenylenebis(3-methyl-3-sulfanylbutanamide), **1**, which is a 12-atom tetradentate chelate providing a N_2S_2 donor set to a metal cation. Recently, Caupene et al.[7] and Sivaramakrishnan et al.[8] have described an efficient method to prepare sulfenates using a retro-Michaël reaction initiated by a base from a β-sulfinyl ester obtained by selective oxidation of the corresponding β-sulfanyl ester with a *N*-sulfonyloxaziridine or with dimethyldioxirane. We applied this method to a β-sulfonyl ester to prepare sulfinate. The acyclic bis-thiol was converted to a bis-β-sulfanyl ethyl ester, which was further oxidized to a series of mixed species containing thioether, sulfoxide, and sulfone. In a second approach, the bis-thiol was oxidized to a cyclic disulfide, and then to the cyclic disulfide-*S*-monooxide (thiosulfinate) and disulfide-*S*-dioxide (thiosulfonate). Recently, we have studied in detail the cleavage of the cyclic pseudopeptidic thiosulfinate under basic conditions[9] and we have shown that it selectively promoted, as previously described by Kice and Liu, [10] the intermediate formation of a mixed thiolate/sulfinate species. In this paper, we show that the cleavage of a β-sulfonyl ester by a retro-Michaël reaction or the cleavage of the S(O)–S bond of a thiosulfinate followed by reaction with ethyl acrylate are two convenient procedures to access to a series of bis-functionalized compounds containing two sulfur oxidized species with at least either one sulfinate or one sulfonate.

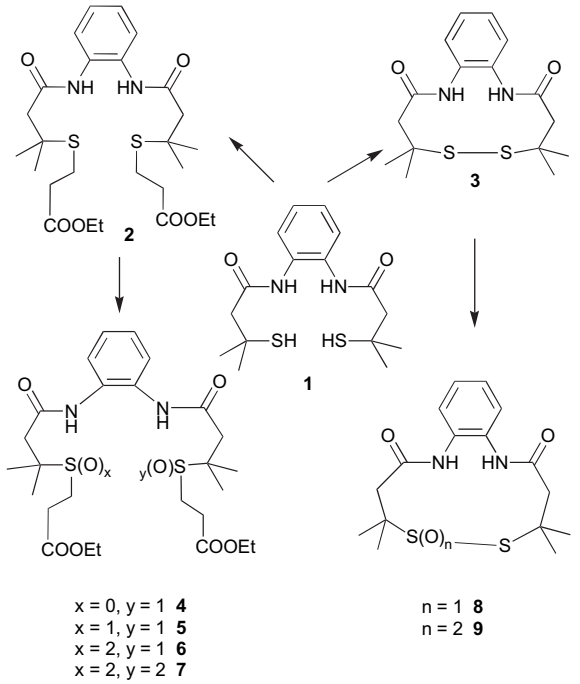
2. Results and discussion

2.1. Synthesis of the neutral sulfur oxidized species

Addition of *N*,*N*′-1,2-phenylenebis(3-methyl-3-sulfanylbutanamide), **1** (Scheme 1), on ethyl acrylate in the presence of a catalytic amount of NaOMe provided the bis-β-sulfanyl ethyl ester, **2**. Oxidation with 1 to 4 equiv of dimethyl dioxirane (DMD) is not selective and provided a mixture of thioether oxidized species. However, using 1 and 3 equiv of DMD, the monosulfoxide, **4**, and the sulfoxide/sulfone, **6**, were isolated, after purification, in 32% and 46% yield, respectively. Oxidation with an excess of DMD afforded the bis-sulfone, **7**, as a unique product. The bis-sulfoxide, **5**, can be prepared by oxidation of **1** either with 2 equiv of DMD or more conveniently, since the oxidation is selective, with 2 equiv of the *N*-sulfonyloxaziridine derived from pinacolone, (3*S*)-3-*tert*-butyl-3-methyl-2-(phenylsulfonyl)oxaziridine. This oxaziridine has been previously described by Perio et al. to selectively oxidize thiolate to sulfenate at low temperature.[11]

The cyclic thiosulfinate, **8** (Scheme 1), was prepared, as recently described,[12] in two steps from the corresponding dithiol, **1**. Oxidation with iodine in the presence of triethylamine under high dilution conditions afforded the cyclic monodisulfide, **3**, which was further oxidized to thiosulfinate, **8**, with 1 equiv of DMD at −20 °C. This thiosulfinate was converted to thiosulfonate, **9**, under phase transfer conditions using Oxone® as an oxidant and tricaprylmethylammonium chloride as a catalyst.[13]

Compounds **4**–**7**, and **8** and **9** have been characterized by ^{1}H NMR, IR (Table 1) as well as elemental analysis. The sulfoxides display in IR a ν_{SO} stretching mode at 1022 cm^{-1} and the sulfones display two $\nu_{(SO_2)}$ modes around 1100 and 1300 cm^{-1}. When the IR spectra are calibrated relative to the $\nu_{(CO)}$ stretching frequency at 1732 cm^{-1}, it appears that the $\nu_{(SO)}$ vibration is twice more intense in the bis-sulfoxide, **5**, than in the monosulfoxide, **4**, whereas the intensities of the $\nu_{(SO_2)}$ vibrations are not modified when going from the sulfoxide/sulfone, **6**, to the bis-sulfone, **7**. The ν_{SO} and $\nu_{(SO_2)}$ vibrations of the thiosulfinate and of the thiosulfonate are located at 1070 cm^{-1}, and 1093, 1125, and 1292 cm^{-1}, respectively. In ^{1}H NMR, oxidation of the thioether to sulfoxide induces a lowfield shift of the amide NH, but this effect is lower upon oxidation to the sulfone. This result suggests a strong hydrogen bond between the NH and the SO groups. The same trend is observed upon oxidation of the cyclic disulfide to thiosulfinate and thiosulfonate. However, in both series, the methyl groups are more deshielded as the thioether is converted to sulfoxide and sulfone, and as the disulfide is oxidized



Scheme 1. Structures of the neutral sulfur compounds.

Table 1
Selected chemical shifts in ^{1}H NMR and selected stretching modes in IR of neutral sulfur oxidized species as depicted in Scheme 1

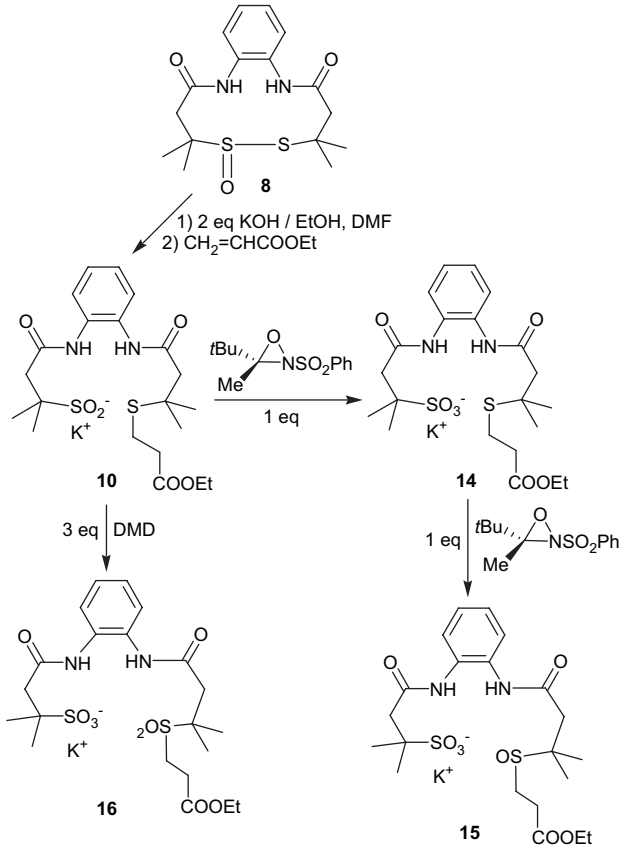
Compound	^{1}H NMR (δ ppm, $CDCl_3$)		IR (ATR, cm^{-1})	
	NH	CH_3	SO	SO_2
2	8.73	1.51		
4	8.75; 8.71	1.47; 1.51	1022	
5	9.28; 9.25	1.69; 1.71	1022	
6	8.90; 8.92	1.56; 1.75; 1.59; 1.76	1022	1105; 1297
7	8.51	1.82		1103; 1307
3	8.06	1.52		
8	8.02; 8.33	1.49; 1.63	1070	
9	7.69; 8.10	1.71; 1.84		1093; 1125; 1292

to disulfide *S*-monooxide and disulfide *S*-dioxide. These characteristics can help to discriminate between all these compounds.

2.2. Synthesis of the anionic derivatives

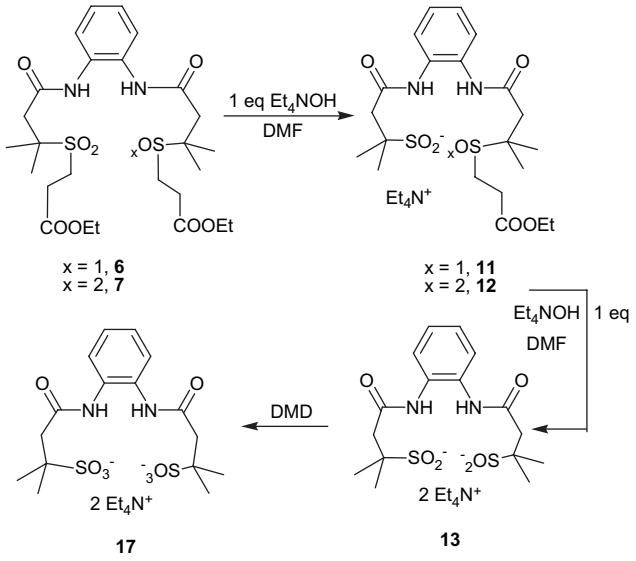
2.2.1. Synthesis of the bis-sulfinate and of the mixed oxidized species containing one sulfinate

Reaction of the thiosulfinate, **8**, with 2 equiv of KOH/EtOH, followed by the trapping of the opened species with ethyl acrylate selectively provided the mixed sulfinate/thioether, **10**, without any trace of the mixed thioether/sulfone (Scheme 2). This result shows that (i) the cleavage of the S(O)–S bond of the thiosulfinate results formally, as previously described,[9,10] from the selective attack of HO^- at the sulfinyl sulfur leading to the formation of a mixed thiolate/sulfinate and (ii) the sulfinate is not nucleophilic enough to react with ethyl acrylate. In another study, the mixed thiolate/sulfinate has been trapped with metal cations such as Zn(II),[9] Ni(II),[9] and Co(III)[14] providing the corresponding mixed thiolate/sulfinate complexes.



Scheme 2. Synthesis of the sulfinate/thioether and of mixed sulfonates/thioether, sulfoxide, and sulfone via a combination of ring-opening of the thiosulfinate and selective oxidations.

The retro-Michaël reaction initiated with 1 equiv of Et_4NOH as a base, produces the selective formations of sulfinate/sulfoxide, **11**, from **6**, and of sulfinate/sulfone, **12**, from **7**

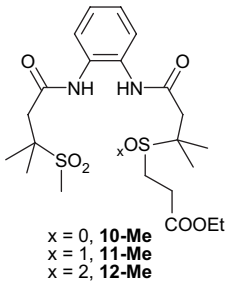


Scheme 3. Synthesis of mixed sulfinates/sulfoxide and sulfone, bis-sulfinate, and bis-sulfonate via a combination of retro-Michaël reactions and DMD oxidation.

(Scheme 3). In these reactions Et_4NOH cannot be replaced by Et_3N. Addition of a second equivalent of Et_4NOH to **12** yields the bis-sulfinate, **13**, showing that the two sulfinates masked as sulfones in **12** can be sequentially deprotected. However, because the thiolate is not a good leaving group, addition of 1 equiv of Et_4NOH to **10** did not allow to revert back to the mixed thiolate/sulfinate. Some of the sulfinate salts could not be characterized by elemental analysis, consequently all the sulfinates **10**–**13** were converted to the corresponding methyl sulfones (**10-Me** to **12-Me** and **13-Me$_2$**) (Schemes 4 and 5) by reaction with CH_3I and they were thoroughly characterized. All the methyl sulfones exhibited in IR the typical $\nu_{(SO_2)}$ stretching modes around 1110 and 1290 cm^{-1}, and in ^1H NMR a singlet around 3 ppm assigned to the methyl.

2.2.2. Synthesis of the bis-sulfonate and of the mixed oxidized species with one sulfonate

Oxidation of the sulfinate/thioether, **10**, with 1 and 2 equiv of the *N*-sulfonyloxaziridine promoted the selective formation of the mixed sulfonate/thioether, **14**, and the mixed sulfonate/sulfoxide, **15**, respectively (Scheme 2). DMD is too a strong oxidant to selectively prepare these intermediates, but with 3 equiv of DMD, **10** was directly converted to the mixed sulfonate/sulfone, **16** (Scheme 2). Similarly, the bis-sulfinate, **13**,

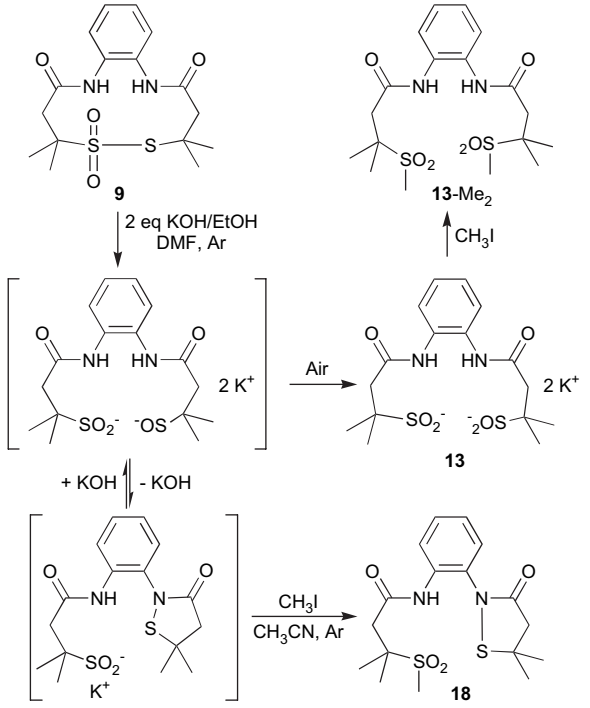


Scheme 4. Structures of the sulfones.

was converted to the bis-sulfonate, **17** (Scheme 3), which has been previously obtained by DMD oxidation of the zinc complex derived from the dithiol, **1**, $(Et_4N)_2[Zn(N_2S_2)]$.[15] The sulfonate derivatives **14**–**17** were characterized by IR, ^1H NMR, and HRMS. In contrast to sulfinates, as previously reported,[16] they did not react with CH_3I to yield the expected sulfonyl methyl ester.

2.3. Reactivity of the cyclic thiosulfonate *9*

The cleavage of the $S(O_2)$–S bond of a thiosulfonate with HO^- has been described to occur by selective attack of HO^- at the sulfenyl sulfur resulting in the formation of a sulfinate and a sulfenate.[17] Upon reaction with ethyl acrylate we expected the direct formation of the mixed sulfinate/sulfoxide, **11**, but we did not get this compound. We tried to trap the opened intermediates with CH_3I. When the reaction was conducted under air after treatment of **9** with 2 equiv of KOH/EtOH under argon, we isolated in a 50% yield after purification by TLC the bis-methyl sulfone **13-Me$_2$** (Scheme 5). When the opened species was trapped with CH_3I under anaerobic conditions, the characteristics of the final product corresponded to those of the mixed methylsulfone/isothiazolidin-3-one, **18**. The ESI^+ mass spectrum exhibits a molecular peak at m/z=385.2, $[M+H^+]$. In ^1H NMR, there is only one NH signal at 8.38 ppm. The methylsulfone is characterized in ^1H NMR by a methyl resonance at 2.87 ppm in $CDCl_3$, and in IR by the two expected $\nu_{(SO_2)}$ vibrations at 1102 and 1260 cm^{-1}. The formation of these two products can be explained as follows: after cleavage of the $S(O_2)$–S bond, the sulfenate in this pseudopeptidic structure would be in equilibrium with the isothiazolidin-3-one as depicted in Scheme 5, leading after alkylation of the sulfinate to the formation of **18**. Air oxidation of the sulfenate promotes the formation of the bis-sulfinate and, after alkylation, the formation of the bis-methylsulfone, **13-Me$_2$**. Recently, such isothiazolidin-3-one derivatives have been prepared as mimics of the inactivation of protein tyrosine phosphatase 1B following the oxidation with H_2O_2 of its active cysteine to a sulfenic acid.[8] This inactivation was explained by a nucleophilic reaction between the peptide amide nitrogen and the sulfenic acid providing the formation of such a cyclic compound that has been identified by X-ray crystallography.[18] This means that the pseudopeptidic structure of **1** precludes any isolation or trapping of sulfenate species, either from compounds containing a β-sulfinyl ethyl ester, such as **4**, **5** or **6** or from the cyclic thiosulfonate **9** (Scheme 1).

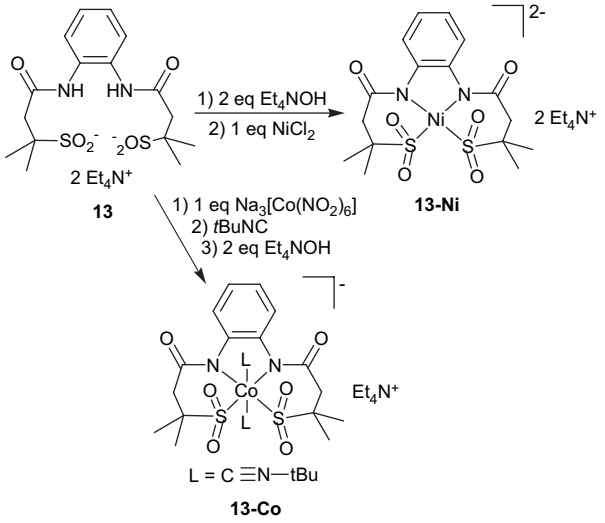


Scheme 5. Products derived from the ring-opening of the thiosulfonate.

2.4. Metalation of the bis-sulfinate *13*

The bis-sulfinate, **13**, is a potential tetradentate ligand for metal cations. After deprotonation of the two amides in DMF by 2 equiv of Et_4NOH at 0 °C, addition of 1 equiv of $NiCl_2$, leads to the formation of the bis-amidate/bis-sulfinate complex $(Et_4N)[Ni(N_2(SO_2)_2)]$, **13-Ni** (Scheme 6), which shows ^1H NMR and IR characteristics similar to those of an authentic sample previously prepared by another route.[12] Insertion of Co(III) as the sodium hexanitritocobalt(III) salt in the presence of *t*-BuNC in excess to stabilize the six-coordinated species leads, as a major product, to the diamagnetic six-coordinated complex $(Et_4N)[Co(N_2(SO_2)_2)(t\text{-BuNC})_2]$, **13-Co** (Scheme 6), which was previously selectively prepared upon DMD oxidation of the dithiolate cobalt complex derived from the dithiol, **1**, $(Et_4N)[Co(N_2S_2)]$.[19] The IR spectra of **13-Co** and **13-Ni** display $\nu_{(SO_2)}$ vibrations around 1000 and 1200 cm^{-1} typically observed in *S*-bonded metal sulfinates.

It is worth noting that no metal cations could be inserted into compounds **10** and **11** containing in addition to the sulfinate a β-sulfanyl ethyl ester and a β-sulfinyl ethyl ester,

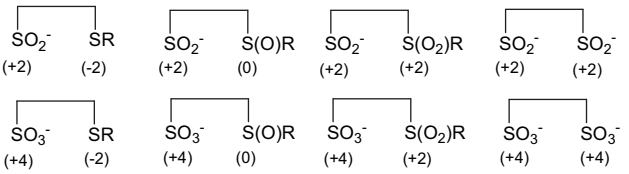


Scheme 6. Metalation of the bis-sulfinate with Ni(II) and Co(III).

respectively, after addition of 2 equiv of Et_4NOH to deprotonate the amides. Moreover compounds **10** and **11** are not the precursors of mixed thiolate/sulfinate and mixed sulfinate/sulfenate ligands, respectively. The retro-Michaël reaction is not possible from the β-sulfanyl ethyl ester, **10**, since the thiolate is not a good leaving group and when performed from the β-sulfinyl ethyl ester, **11**, the sulfenate is not stable in such pseudopeptidic structure, as discussed above.

3. Conclusion

Using a cyclic thiosulfinate and a bis-β-sulfonyl ethyl ester, and a mixed β-sulfinyl/β-sulfonyl ethyl ester derived from an acyclic pseudopeptidic dithiol, we thoroughly describe the synthesis, in high yields, of a series of sulfinate and sulfonate compounds associated with another sulfur oxidized function. They are summarized with their formal oxidation states in Scheme 7. These syntheses use a combination of cleavage of the S(O)–S bond or controled retro-Michaël reactions and selective oxidations with either *N*-sulfonyloxaziridine or DMD. The oxaziridine, described to selectively oxidize thiolate to sulfenate, appears also to be a mild oxidant, which successively converts, sulfinate to sulfonate then thioether to sulfoxide and sulfoxide to sulfone. DMD as a stronger oxidant is very convenient to completely oxidize a β-sulfanyl ester to a β-sulfonyl ester or a disulfinate to a disulfonate. The presence of a peptide amide, NH, in close proximity of a β-sulfinyl ethyl ester or of the sulfenyl sulfur of the thiosulfonate prevents the isolation of the sulfenate by a retro-Michaël reaction or by opening of the cyclic thiosulfonate with potassium hydroxide, respectively, probably because a cyclization reaction leads to the formation of a more stable isothiazolidin-3-one derivative. Finally, among all these anionic derivatives, the disulfinate is the only one which behaves as a potential tetradentate ligand for metal cations after deprotonation of the amides.



Scheme 7. Formal oxidation states of the different sulfinates and sulfonates synthesized.

4. Experimental

4.1. Physical measurements

IR spectra were obtained with a Perkin–Elmer Spectrum One FTIR spectrometer equipped with a MIRacleTM single reflection horizontal ATR unit (zirconium–selenium crystal). ESI-MS mass spectra were performed on a Thermo Finnigan LCD Advantage spectrometer. HRMS and elemental analyses were carried out by the mass spectrometry and microanalysis services at Gif-sur-Yvette CNRS. ^{1}H NMR spectra were recorded at 300 K on a Bruker ARX-250 spectrometer and chemical shifts are reported in parts per million downfield from tetramethylsilane.

4.2. Materials

All chemicals were purchased from Acros and Aldrich. The solvents were reagent grade (SDS) and were dried and distilled before use following standard procedures. Dried diethyl ether was purchased from Riedel-deHaën. All reactions were performed under argon. Products were purified by Flash Master chromatography using a BPSUP (AIT) column or by preparative TLC (silica gel F_{254} MERCK, 1 mm). The oxaziridine, (3*S*)-3-*tert*-butyl-3-methyl-2-(phenylsulfonyl)oxaziridine, was synthesized as previously described.[11] Stock solutions of DMD prepared in acetone were titrated by oxidation of thioanisole into the corresponding sulfoxide as previously reported.[20]

4.2.1. 4,4,7,7-Tetramethyl-1,3,4,7,8,10-hexahydro-5,6,1,10-benzodithiadiazacyclododecine-2,9-dione 5,5-dioxide **9**

To a CH_2Cl_2 solution (15 mL) of thiosulfinate **8**[12] (50 mg, 0.14 mmol) containing a catalytic amount of tricaprylmethylammonium chloride (TOMAC), a solution of oxone® ($2KHSO_5$; $KHSO_4$; K_2SO_4) (112.8 mg, 0.18 mmol) in water (5 mL) was added dropwise. The solution was stirred for 48 h at room temperature. After the usual workup, the mixture was purified by column chromatography over silica gel (5 g) using AcOEt as eluent to give a white solid: 35 mg, yield 67%. ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.71 (s, 6H), 1.84 (s, 6H), 2.81 (s, 2H), 3.08 (s, 2H), 7.32 (m, 2H), 7.41 (m, 1H), 7.53 (m, 1H), 7.69 (s, 1H), 8.1 (s, 1H). ^{13}C NMR (500 MHz, $CDCl_3$) δ 22.9, 31.8, 45.7, 48.4, 58.6, 71.9, 126.1, 127, 127.9, 128.2, 130.7, 132.3, 167, 169.1. IR (ATR, cm^{-1}): 3252, 3238, 1691, 1677, 1093, 1125, 1292. Anal. Calcd for $C_{16}H_{22}N_2O_4S_2$: C, 51.87; H, 5.99; N, 7.56. Found: C, 52.29; H, 5.97; N, 7.12.

4.2.2. Diethyl 3,3′-{1,2-phenylenebis[imino(2-methyl-4-oxobutane-4,2-diyl) thio]}dipropanoate **2**

Ethyl acrylate (63 μL, 0.59 mmol) in 2 mL of EtOH was added dropwise to an EtOH solution (10 mL) of the dithiol **1** (100 mg, 0.29 mmol, 1 equiv) containing a catalytic amount of NaOMe in MeOH (1 M, 30 μL, 0.03 mmol, 0.1 equiv). After stirring the reaction mixture at room temperature for 5 h, and evaporating the solvents in vacuo the slurry was directly purified by flash chromatography using CH_2Cl_2/AcOEt 9:1 as eluent to give a colorless oil: 150 mg, yield 94%. TLC: CH_2Cl_2/AcOEt 9:1, R_f 0.46. ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.26 (t, J=6.9 Hz, 6H), 1.51 (s, 12H), 2.63 (t, J=7.3 Hz, 4H), 2.67 (s, 4H), 2.89 (t, J=7.3 Hz, 4H), 4.14 (q, J=6.9 Hz, 4H), 7.21 (m, 2H), 7.59 (m, 2H), 8.73 (s, 2H). IR (ATR, cm^{-1}): 3288, 1732, 1660. Mass (ESI$^+$/MeOH) *m/z* 563.3 [M+Na$^+$]. Anal. Calcd for $C_{26}H_{40}N_2O_6S_2$: C, 57.75; H, 7.46; N, 5.18. Found: C, 58.08; H, 7.48; N, 5.11.

4.3. General procedure for the oxidation with DMD

A 0.12 M solution of DMD in acetone (1 to 5 equiv) was added dropwise at −20 °C to a dry acetone solution (10 mL) of the bis-thioether (1 equiv). The reaction mixture was allowed to reach 0 °C, then stirred for 1 h. The yellow slurry obtained after concentration in vacuo was directly purified by flash chromatography.

4.3.1. Ethyl 3-[(3-{[2-({3-[(3-ethoxy-3-oxopropyl)sulfinyl]-3-methylbutanoyl}amino)phenyl]amino}-1,1-dimethyl-3-oxopropyl)thio]propanoate **4**

Compound **4** was obtained as a colorless oil upon oxidation of **2** (150 mg, 0.27 mmol) with 1 equiv of DMD (2.3 mL, 0.27 mmol). Chromatography: eluent CH_2Cl_2/MeOH 95:5; 50 mg, yield 32%. TLC: CH_2Cl_2/EtOH 95:5, R_f 0.5. ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.28 (t, J=6.9 Hz, 3H), 1.30 (t, J=6.9 Hz, 3H), 1.47 (s, 3H), 1.51 (s, 9H), 2.61−3.02 (m, 12H), 4.12 (q, J=6.9 Hz, 2H), 4.21 (q, J=6.9 Hz, 2H), 7.2 (m, 2H), 7.58 (m, 1H), 7.73 (s, 1H), 8.71 (s, 1H), 8.75 (s, 1H). IR (ATR, cm^{-1}): 3256, 1733, 1687, 1663, 1022. Mass HRMS (TOF MS ESI$^+$/MeOH) Calcd for $C_{26}H_{40}N_2O_7NaS_2$ [**4**+Na$^+$]: 579.2175. Found: 579.2169.

4.3.2. Diethyl 3,3′-{1,2-phenylenebis[imino(2-methyl-4-oxobutane-4,2-diyl)sulfinyl]}dipropanoate **5**

Compound **5** was obtained as a colorless oil upon oxidation of **2** (290 mg, 0.53 mmol) with 2 equiv of DMD (8.92 mL, 1.07 mmol). Chromatography: eluent CH_2Cl_2/EtOH 96:4; 280 mg, yield 90%. Another procedure can be used to synthesize **5**: (3*S*)-3-*tert*-butyl-3-methyl-2-(phenylsulfonyl)oxaziridine (547 mg, 2.14 mmol) in 10 mL of dry THF was added dropwise to a THF solution (50 mL) of **2** (580 mg, 1.07 mmol). The reaction mixture was stirred at room temperature for 12 h and was concentrated in vacuo. Purification by flash chromatography using CH_2Cl_2/EtOH 96:4 as eluent gave **5** as a colorless oil: 600 mg, yield 97%. TLC: CH_2Cl_2/EtOH 96:4, R_f 0.2. ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.52 (t, J=6.9 Hz, 6H), 1.69 (s, 6H), 1.71 (s, 6H), 2.8−3.24 (m, 12H), 4.43 (q, J=6.9 Hz, 4H), 7.41 (m, 2H), 7.92 (m, 2H), 9.25 (s, 1H), 9.28 (s, 1H). ^{13}C NMR (250 MHz, $CDCl_3$) δ 14.53, 20.25, 22.20, 28.56, 41.14, 44.05, 56.45, 56.55, 61.62, 124.92, 126.09, 129.97, 168.49, 171.7. IR (ATR, cm^{-1}): 3245, 1732, 1684, 1022. Mass (ESI$^+$/MeOH) *m/z* 573.2 [M+H$^+$], 595.1 [M+Na$^+$]. Anal. Calcd for $C_{26}H_{40}N_2O_8S_2$: C, 54.52; H, 7.04; N, 4.89. Found: C, 54.56; H, 7.12; N, 4.83.

4.3.3. Ethyl 3-[(3-{[2-({3-[(3-ethoxy-3-oxopropyl)sulfinyl]-3-methylbutanoyl}amino)phenyl]amino}-1,1-dimethyl-3-oxopropyl)sulfonyl]propanoate **6**

Compound **6** was prepared as a colorless oil upon oxidation of **2** (300 mg, 0.55 mmol) with 3 equiv of DMD (13.75 mL, 1.65 mmol). Chromatography: eluent CH_2Cl_2/EtOH 98:2; 150 mg, yield 46%. TLC: CH_2Cl_2/EtOH 98:2, R_f 0.16. ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.40 (t, J=6.9 Hz, 3H), 1.41 (t, J=7.3 Hz, 3H), 1.56 (s, 3H), 1.59 (s, 3H), 1.75 (s, 3H), 1.76 (s, 3H), 2.79−3.07 (m, 10H), 3.49 (t, J=7.7 Hz, 2H), 4.29 (q, J=6.9 Hz, 2H), 4.32 (q, J=7.3 Hz, 2H), 7.29 (m, 2H), 7.7 (m, 1H), 7.84 (s, 1H), 8.90 (s, 1H), 8.92 (s, 1H). ^{13}C NMR (250 MHz, $CDCl_3$) δ 14.51, 20.13, 21.66, 22.53, 26.2, 28.45, 41.2, 41.77, 42.37, 44.37, 56.47, 61.84, 62.44, 125.06, 126.19, 126.76, 130.31, 167.91, 168.59, 171.06, 171.75. IR (ATR, cm^{-1}) 3251, 1733, 1686, 1664, 1297, 1105, 1022. Mass HRMS (TOF MS ESI$^+$/MeOH) *m/z* Calcd for $C_{26}H_{40}N_2O_9NaS_2$ [**6**+Na$^+$]: 611.2073. Found: 611.2059.

4.3.4. Diethyl 3,3′-{1,2-phenylenebis[imino(2-methyl-4-oxobutane-4,2-diyl)sulfonyl]}dipropanoate **7**

Compound **7** was prepared upon oxidation of **2** (290 mg, 0.536 mmol) with 5 equiv of DMD (22.3 mL, 2.68 mmol). Precipitation with diethyl ether yielded a white powder: 320 mg, yield 99%. TLC: CH_2Cl_2/EtOH 98:2, R_f 0.26. ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.49 (t, J=7.2 Hz, 6H), 1.82 (s, 12H), 3.02 (s, 4H), 3.11 (t, J=7.5 Hz, 4H), 3.58 (t, J=7.5 Hz, 4H), 4.4 (q, J=7.2 Hz, 4H), 7.37 (m, 2H), 7.81 (m, 2H), 8.51 (s, 2H). ^{13}C NMR (250 MHz, $CDCl_3$) δ 14.48, 21.91, 26.13, 41.77, 42.4, 61.86, 62.52, 125.39, 126.6, 130.23, 168.04, 171.12. IR (ATR, cm^{-1}) 3203, 1732, 1641, 1308, 1104. Mass (ESI$^+$/MeOH) *m/z* 627.3 [M+Na$^+$]. Anal. Calcd for $C_{26}H_{40}N_2O_{10}S_2$: C, 51.64; H, 6.67; N, 4.63. Found: C, 52.26; H, 6.64; N, 4.31.

4.3.5. Bis(N,N,N-triethylethanaminium) 4,4′-[1,2-phenylene di(imino)]bis(2-methyl-4-oxobutane-2-sulfonate) **17**

Compound **17** was obtained upon oxidation of **13** (20 mg, 0.03 mmol) with 3 equiv of DMD (750 μL, 0.09 mmol). Precipitation with diethyl ether gave a very hygroscopic yellow powder: 20.5 mg, yield 99%. Its Physical properties were similar to those previously described.[15]

4.3.6. Potassium 4-{[2-({3-[(3-ethoxy-3-oxopropyl)thio]-3-methylbutanoyl}amino)phenyl]amino}-2-methyl-4-oxobutane-2-sulfinate **10**

A 0.58 M solution of KOH in EtOH (prepared from melted KOH) (953 μL, 0.553 mmol) was added dropwise at −40 °C to the thiosulfinate, **8** (98 mg, 0.276 mmol) dissolved in 4 mL of DMF. After 1 h at −40 °C, ethyl acrylate (300 μL, 2.76 mmol) was added. The reaction mixture was stirred for 2 h and was allowed to warm to room temperature and was concentrated in vacuo. Diethyl ether was then added and a pale yellow powder was precipitated and filtered: 126 mg, yield 90%. ^{1}H NMR (250 MHz, acetone-d_6) δ 1.08 (s, 6H), 1.24 (t, J=6.9 Hz, 3H), 1.50 (s, 6H), 2.59 (s, 2H), 2.63 (t, J=7.3 Hz, 2H), 2.88 (s, 2H), 3.03 (t, J=7.3 Hz, 2H), 4.12 (q, J=6.9 Hz, 2H), 6.94−7 (m, 2H), 7.8−7.82 (m, 1H), 8.16−8.2 (m, 1H), 10.29 (s, 1H), 11.17 (s, 1H). IR (ATR, cm^{-1}) 3248, 1727, 1663, 1031, 969. Mass (ESI$^-$/MeOH) *m/z* 471.4 [M−K$^+$]. Anal. Calcd for $C_{21}H_{31}KN_2O_6S_2 \cdot 0.6$ KCl: C, 45.40; H, 5.62; N, 5.04. Found: C, 45.67; H, 5.69; N, 4.92.

4.4. General procedure for the deprotection with Et_4NOH

A 1.4 M solution of Et_4NOH in MeOH (1 or 2 equiv) was added dropwise to a dry CH_3CN solution (1 mL) of the

β-sulfanyl ester (1 equiv). The reaction mixture was stirred for 10 min and concentrated in vacuo. After precipitation with diethyl ether, the yellow powder was filtered and dried under argon. Because residual salts are difficult to eliminate, the mass of the isolated sulfinates, **11**–**13**, is higher than the mass expected for a quantitative yield, and so it is not reported.

*4.4.1. N,N,N-Triethylethanaminium 4-{[2-({3-[(3-ethoxy-3-oxopropyl)sulfinyl]-3-methylbutanoyl}amino)phenyl]amino}-2-methyl-4-oxobutane-2-sulfinate **11***

Compound **11** was obtained by treatment of **6** (4.6 mg, 0.078 mmol) with 1 equiv of Et_4NOH (5.6 μL, 0.078 mmol): quantitative yield. ^1H NMR (250 MHz, $CDCl_3$) δ 1.23 (t, J=7.3 Hz, 12H), 1.26 (s, 6H), 1.29 (t, J=6.9 Hz, 3H), 1.6 (s, 6H), 1.94 (s, 2H), 2.24 (s, 2H), 2.87 (m, 4H), 3.17 (q, J=7.3 Hz, 8H), 4.21 (q, J=6.9 Hz, 2H), 7.1 (m, 2H), 7.58 (m, 1H), 8.01 (m, 1H), 9.48 (s, 0.5H), 10.32 (s, 0.5H), 11.23 (s, 0.5H), 12.26 (s, 0.5H). The NH protons appear as a set of 4 singlets accounting for 0.5H each. This is probably because the sulfur of the sulfoxide is chiral. IR (ATR, cm^{-1}) 3245, 2925, 1731, 1675, 1026, 966. Mass HRMS (TOF MS ESI^-/MeOH) Calcd for $C_{21}H_{31}N_2O_7S_2$ [**11**$-Et_4N^+$]: 487.1573. Found: 487.1572.

*4.4.2. N,N,N-Triethylethanaminium 4-{[2-({3-[(3-ethoxy-3-oxopropyl)sulfonyl]-3-methylbutanoyl}amino)phenyl]amino}-2-methyl-4-oxobutane-2-sulfinate **12***

Compound **12** was obtained by treatment of **7** (14 mg, 0.023 mmol) with 1 equiv of Et_4NOH (16.5 μL, 0.023 mmol): quantitative yield. ^1H NMR ($CDCl_3$) δ 1.19 (s, 6H), 1.22 (t, J=7.3 Hz, 12H), 1.30 (t, J=6.9 Hz, 3H), 1.66 (s, 6H), 2.67 (d, J=13.7 Hz, 2H), 2.91 (t, J=7.3 Hz, 2H), 3.06 (s, 2H), 3.14 (q, J=7.3 Hz, 8H), 3.65 (t, J=7.3 Hz, 2H), 4.2 (q, J=6.9 Hz, 2H), 7.07 (m, 2H), 7.65 (m, 1H), 8.08 (m, 1H), 10.51 (s, 1H), 10.69 (s, 1H). IR (cm^{-1}) 3240, 1734, 1677, 1290, 1105, 1026, 966, 919. Mass HRMS (TOF MS ESI^-/MeOH) Calcd for $C_{21}H_{31}N_3O_8S_2$ [**12**$-Et_4N^+$]: 503.1522. Found: 503.1547.

*4.4.3. Bis(N,N,N-triethylethanaminium) 4,4′-[1,2-phenylene di(imino)]bis(2-methyl-4-oxobutane-2-sulfinate) **13***

Compound **13** was obtained by treatment of **7** (20 mg, 0.033 mmol) with 2 equiv of Et_4NOH (48 μL, 0.067 mmol): quantitative yield. ^1H NMR (250 MHz, DMSO-d_6) δ 0.92 (s, 12H), 1.17 (t, J=7.2 Hz, 24H), 2.32 (s, 4H), 3.22 (q, J=7.2 Hz, 16H), 7.02 (m, 2H), 7.6 (m, 2H), 10.6 (s, 2H). IR (ATR, cm^{-1}) 3363, 3249, 1670, 1173, 1031, 1003, 967, 919. Mass HRMS (TOF MS ESI^-/MeOH) Calcd for $C_{24}H_{42}N_3O_6S_2$ [**13**$-Et_4N^+$]: 532.2515. Found: 532.2539.

*4.4.4. Potassium 4-{[2-({3-[(3-ethoxy-3-oxopropyl)thio]-3-methylbutanoyl}amino)phenyl]amino}-2-methyl-4-oxobutane-2-sulfonate **14***

(3*S*)-3-*tert*-Butyl-3-methyl-2-(phenylsulfonyl)oxaziridine (10 mg, 0.0391 mmol) was added to a THF solution (2 mL) of **10** (20 mg, 0.039 mmol) placed at −40 °C. The reaction mixture was stirred for 2 h and was allowed to warm to room temperature and concentrated in vacuo. Precipitation with diethyl ether afforded a pale yellow powder: 30 mg, quantitative yield. ^1H NMR (250 MHz, acetone-d_6) δ 1.23 (t, J=6.9 Hz, 3H), 1.38 (s, 6H), 1.51 (s, 6H), 2.65 (s, 2H), 2.66 (t, J=6.9 Hz, 2H), 2.88 (s, 2H), 3.06 (t, J=6.9 Hz, 2H), 4.12 (q, J=6.9 Hz, 2H), 7.04 (m, 2H), 7.56 (m, 1H), 8.05 (m, 1H), 9.15 (s, 1H), 9.93 (s, 1H). IR (ATR, cm^{-1}): 3261, 2973.5, 1730, 1663, 1186, 1033. Mass (ESI^+/MeOH) *m/z* 548.9 [M+Na^+]. Mass HRMS (TOF MS ESI^+/MeOH)) Calcd for $C_{21}H_{31}N_2O_7NaS_2K$ [**14**+Na^+]: 549.1107. Found: 549.1087.

*4.4.5. Potassium 4-{[2-({3-[(3-ethoxy-3-oxopropyl)sulfinyl]-3-methylbutanoyl}amino)phenyl]amino}-2-methyl-4-oxobutane-2-sulfonate **15***

(3*S*)-3-*tert*-Butyl-3-methyl-2(phenylsulfonyl)-1,2-oxaziridine (7.6 mg, 0.03 mmol) was added to a THF solution (2 mL) of **14** (10.5 mg, 0.02 mmol) placed at −40 °C. Following the same procedure as described for **14**, compound **15** was isolated as a yellow powder: 11 mg, quantitative yield. ^1H NMR (250 MHz, acetone-d_6) δ 1.26 (t, J=6.9 Hz, 3H), 1.38 (s, 6H), 1.44 (s, 3H), 1.48 (s, 3H), 2.61 (s, 2H), 2.83(m, 4H), 2.86 (s, 2H), 4.16 (q, J=6.9 Hz, 2H), 7.06 (m, 2H), 7.54 (m, 1H), 8.03 (m, 1H), 8.84 (s, 1H), 10.11 (s, 1H). IR (ATR, cm^{-1}): 3430, 3262, 2979, 1727, 1662, 1184, 1031, 1031. Mass (ESI^-/MeOH) *m/z* 503 [M−K^+]. HRMS (TOF MS ESI^-/MeOH) Calcd for $C_{21}H_{31}N_2O_8S_2$ [**15**−K^+]: 503.1522. Found: 503.1542.

*4.4.6. Potassium 4-{[2-({3-[(3-ethoxy-3-oxopropyl)sulfonyl]-3-methylbutanoyl}amino)phenyl]amino}-2-methyl-4-oxobutane-2-sulfonate **16***

A 0.12 M solution of DMD in acetone (915 μL, 0.11 mmol) was added dropwise at −20 °C to a dry acetone solution (3 mL) of **10** (19 mg, 0.036 mmol). The reaction mixture was allowed to warm to 0 °C and was stirred for 1 h and then concentrated in vacuo. Precipitation with Et_2O gave a white powder: 12 mg, yield 60%. ^1H NMR (250 MHz, acetone-d_6) δ 1.26 (t, J=6.9 Hz, 3H), 1.41 (s, 6H), 1.59 (s, 6H), 2.68 (s, 2H), 2.88 (t, J=6.9 Hz, 2H), 3.02 (s, 2H), 3.67 (t, J=6.9 Hz, 2H), 4.17 (q, J=6.9 Hz, 2H), 7.08 (m, 2H), 7.5 (m, 1H), 8.06 (m, 1H), 8.92 (s, 1H), 10.03 (s, 1H). IR (ATR, cm^{-1}) 3445, 3266, 2980, 2938, 1730, 1664, 1293, 1120, 1183, 1031. Mass HRMS (TOF MS ESI^-/MeOH) Calcd for $C_{21}H_{31}N_2O_9S_2$ [**16**−K^+]: 519.1471. Found: 519.1446.

4.5. General procedure for trapping the sulfinates with MeI

MeI (10 or 20 equiv) was added dropwise to a dry CH_3CN solution (3 mL) of the sulfinate prepared by deprotection of the β-sulfinyl ester (1 equiv). The reaction mixture was stirred for 2 h and was concentrated in vacuo. Precipitation with Et_2O afforded a powder, which was purified by preparative TLC.

*4.5.1. Ethyl 3-({1,1-dimethyl-3-[(2-{[3-methyl-3-(methylsulfonyl)butanoyl]amino}phenyl)amino]-3-oxopropyl}thio)-propanoate (**10-Me**)*

Compound **10-Me** was obtained from **10** (10 mg, 0.0195 mmol) with MeI (12 μL, 0.195 mmol) and isolated as

a yellow powder, which was purified with CH_2Cl_2/AcOEt 6:4; 8.5 mg, yield 90%. TLC: CH_2Cl_2/AcOEt 6:4, R_f 0.45. ^{1}H NMR (250 MHz, acetone-d_6) δ 1.23 (t, J=6.9 Hz, 3H), 1.52 (s, 6H), 1.60 (s, 6H), 2.60 (t, J=6.9 Hz, 2H), 2.79 (s, 2H), 2.83 (s, 2H), 2.95 (t, J=6.9 Hz, 2H), 3.02 (s, 3H), 4.12 (q, J=6.9 Hz, 2H), 7.14–7.18 (m, 2H), 7.67–7.74 (m, 2H), 9.32 (s, 1H), 9.52 (s, 1H). IR (ATR, cm^{-1}) 3235, 1725, 1666, 1290, 1108. Mass (ESI$^+$/MeOH) *m/z* 509.3 [M+Na$^+$], 525.2 [M+K$^+$]. Anal. Calcd for $C_{22}H_{34}N_2O_6S_2$: C, 54.30; H, 7.04; N, 5.76. Found: C, 53.95; H, 6.98; N, 5.71.

4.5.2. Ethyl 3-({1,1-dimethyl-3-[(2-{[3-methyl-3-(methyl sulfonyl)butanoyl]amino}phenyl)amino]-3-oxopropyl}-sulfinyl)propanoate (**11-Me**)

Compound **11-Me** was obtained from **11** (22.9 mg, 0.037 mmol) with MeI (23 μL, 0.37 mmol) and was isolated as a white oil: 6 mg, yield 33%. TLC: CH_2Cl_2/MeOH 95:5, R_f 0.22. ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.30 (t, J=6.9 Hz, 3H), 1.46 (s, 3H), 1.50 (s, 3H), 1.64 (s, 6H), 2.86 (s, 2H), 2.89 (m, 6H), 2.94 (s, 3H), 4.2 (q, J=6.9 Hz, 2H), 7.2 (m, 2H), 7.68 (m, 2H), 8.55 (s, 1H), 8.72 (s, 1H). IR (ATR, cm^{-1}): 3252, 2981, 2934, 1731, 1684, 1664, 1291, 1107, 1022. Mass HRMS (TOF MS ESI$^+$/MeOH) Calcd for $C_{22}H_{34}N_2O_7NaS_2$ [**11-Me**+Na$^+$]: 525.1705. Found: 525.1728.

4.5.3. Ethyl 3-({1,1-dimethyl-3-[(2-{[3-methyl-3-(methyl sulfonyl)butanoyl]amino}phenyl)amino]-3-oxopropyl}-sulfonyl)propanoate (**12-Me**)

Compound **12-Me** was prepared upon alkylation of **12** (15 mg, 0.019 mmol) with MeI (15 μL, 0.24 mmol) and was isolated as a white solid: 11 mg, yield 92%. TLC: CH_2Cl_2/MeOH 95:5, R_f 0.27. ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.28 (t, J=6.9 Hz, 3H), 1.64 (s, 6H), 1.66 (s, 6H), 2.93 (d, J=8.2 Hz, 4H), 2.93 (t, J=7.3 Hz, 2H), 3.02 (s, 3H), 3.39 (t, J=7.3 Hz, 2H), 4.21 (q, J=6.9 Hz, 2H), 7.21 (m, 2H), 7.68 (m, 2H), 8.43 (s, 1H), 8.61 (s, 1H). IR (ATR, cm^{-1}): 3328, 1734, 1656, 1665, 1289, 1104, 950. Mass HRMS (TOF MS ESI$^+$/MeOH) Calcd for $C_{22}H_{34}N_2O_8NaS_2$ [**12-Me**+Na$^+$]: 541.1654. Found: 541.1667.

4.5.4. N,N′-1,2-Phenylenebis[3-methyl-3-(methylsulfonyl)-butanamide (**13-Me$_2$**)

Compound **13-Me$_2$** was prepared from **13** (12.6 mg, 0.019 mmol) with MeI (24 μL, 0.38 mmol) and isolated as a white solid: 8 mg, yield 98%. TLC: CH_2Cl_2/MeOH 9:1, R_f 0.25. ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.64 (s, 12H), 2.87 (s, 4H), 2.95 (s, 6H), 7.2 (m, 2H), 7.7 (m, 2H), 8.17 (s, 2H). IR (ATR, cm^{-1}) 3271, 1656, 1284, 1106, 909. Anal. Calcd for $C_{18}H_{28}N_2O_6S_2$: C, 49.98; H, 6.52; N, 6.48. Found: C, 49.62; H, 6.41; N, 6.62.

4.5.5. N-[2-(5,5-Dimethyl-3-oxoisothiazolidin-2-yl)phenyl]-3-methyl-3-(methylsulfonyl)butanamide **18**

An aqueous solution of KOH (1 M, 170 μL, 0.170 mmol) was added dropwise at −30 °C to the thiosulfonate, **9** (30 mg, 0.085 mmol) dissolved in dry DMF (1 mL), then 2 equiv MeI (11 μL, 0.170 mmol) was quickly added. The reaction mixture was concentrated in vacuo. Precipitation with diethyl ether afforded a white product, which was filtered and washed with diethyl ether. ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.63 (s, 6H), 1.71 (s, 6H), 2.78 (s, 2H), 2.87 (s, 3H), 2.98 (s, 2H), 7.19–7.29 (m, 2H), 7.41 (d, 2H), 7.87 (d, 2H), 8.38 (s, 1H). IR (ATR, cm^{-1}): 1660, 1289, 1101, 755. Mass (ESI$^+$/MeOH) *m/z* 385.2 [100%, M+H$^+$], 423 [M+K$^+$].

4.5.6. (Et$_4$N)[Co(N$_2$(SO$_2$)$_2$)(*t*-BuNC)$_2$] complex (**13-Co**)

A DMF solution of $Na_3[Co^{III}(NO_2)_6]$ (0.041 mmol) prepared in the presence of the minimum amount of water as previously described[14] was added dropwise at −40 °C to the bis-sulfinate, **13** (25 mg, 0.041 mmol) dissolved in DMF (1 mL). A large excess of *t*-BuNC (200 μL) and 2 equiv of Et_4NOH (59 μL, 0.083 mmol) were then added to the mixture, which turned orange to brown. The solution was then allowed to warm to room temperature. After evaporation to dryness in vacuo, the slurry was dissolved in CH_3CN, filtered and precipitated with diethyl ether at 0 °C. The powder was redissolved in acetone and was slowly poured into diethyl ether to yield a brown powder: 20 mg, yield 65%. Its ^{1}H NMR (250 MHz) in CD_3CN was similar to that of an authentic sample.[19] IR (ATR, cm^{-1}): 3407, 1659, 1221, 1068. Mass (ESI$^-$/MeOH) *m/z* 624.9 [55%, M−Et$_4$N$^+$].

4.5.7. (Et$_4$N)$_2$[Ni(N$_2$(SO$_2$)$_2$)] complex (**13-Ni**)

$NiCl_2 \cdot 6H_2O$ (20 mg, 0.083 mmol) in 1 mL of DMF was added at −40 °C to a DMF solution (2 mL) of the bis-sulfinate, **13** (50 mg, 0.083 mmol). Et_4NOH (2 equiv) was then added and the mixture was allowed to warm to room temperature. After evaporation to dryness in vacuo, the orange slurry was dissolved in CH_3CN and precipitated with diethyl ether. The solid was washed with acetone and dried to give an orange powder: 41 mg, yield 70%. The ^{1}H NMR was similar to that previously described.[12] IR (ATR, cm^{-1}): 3371, 1599, 1160, 1054. Mass (ESI$^+$/MeOH) *m/z* 848.3 [M+Et$_4$N$^+$].

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