Photodegradation of 2-Mercaptobenzothiazole Disulfide and Related Benzothiazoles

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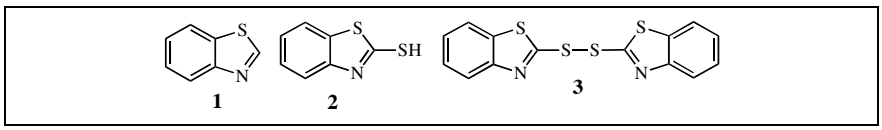
Dedicated to the memory of Dr. Benoît Célariès



The photodegradation of 2-mercaptobenzothiazole disulfide, 2-mercaptobenzothiazole and benzothiazole was investigated. Benzothiazole was found to undergo photodimerization into 2,2'-bibenzothiazole, and in the presence of oxygen to give two additional photoproducts – 2-hydroxybenzothiazole and 2-methylbenzothiazole. The major degradation products of 2-mercaptobenzothiazole are benzothiazole and 2-benzothiazolesulfonic acid, with 2,2'-thiobisbenzothiazole and 2-mercaptobenzothiazole disulfide as the minor degradation products. Direct photolysis of 2-mercaptobenzothiazole disulfide gave 2-mercaptobenzothiazole and in acetonitrile 2-thiocyanatobenzothiazole was also detected. A mechanism is proposed to rationalize the formation of photodegradation products.

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INTRODUCTION

Benzothiazoles are heterocyclic compounds used predominantly as rubber vulcanization accelerators [1]. Their photolysis has been studied by several researchers. Photodegradation studies of benzothiazole (**1**) were reported by Grellmann and Tauer [2] and had shown that 2,2'-bibenzothiazole (**4**) (30% after 2 hours) is a photoproduct of benzothiazole (**1**) upon irradiation in air-saturated acetonitrile. The dimer formation does not take place in methanol, ethanol, 2-propanol, water or methylcyclohexane, but other reactions take place which were left for further investigation.

Photodegradation of 2-mercaptobenzothiazole (**2**) was studied by three groups of researchers. Párkányi and Abdelhamid [3] followed the reaction in air-saturated ethanol, methanol or acetonitrile at $\lambda > 290$ nm and positively identified one intermediate - bis-(2-benzothiazolyl) disulfone - and the final product benzothiazole sulfate. 2-Mercaptobenzothiazole disulfide (**3**) was identified upon irradiation in benzene or toluene, and no reaction was observed in nitrogen-purged ethanol.

Two years later Abdou *et al*. [4] reported sulfur (9.7%), 2-mercaptobenzothiazole disulfide (**3**, 32%), 2-hydroxybenzothiazole (**5**, 20.5%) and benzothiazole (**1**, 5.6%) as the photodegradation products after 120 hours of irradiation. The presence of unchanged starting material (20.8%) was detected as well.

The most recent report on the decomposition of 2-mercaptobenzothiazole (**2**) was published by Malouki *et al*. [5] in 2004. A sample was irradiated at $\lambda > 290$ nm in aerated water medium producing benzothiazole (**1**) and 2-hydroxybenzothiazole (**5**) as the photodegradation products as well as an unidentified product. The irradiation in the deoxygenated medium led to the formation of 90% of benzothiazole (**1**).

The kinetics and mechanism of the photolysis of 2-mercaptobenzothiazole disulfide (**3**) were studied by Shizuka *et al*. [6] in 1972. 2-Mercaptobenzothiazole (**2**) was identified as a reaction product upon irradiation at 253.4 nm in the presence of oxygen or nitrogen in the ethanol-glycerol system. It was reported as well that upon irradiation in benzene and cyclohexane at 290 nm other so far not identified products were formed. Abdou *et al*. [4] detected the following products in ethanol or acetonitrile for irradiations at $\lambda > 290$ nm: sulfur (14.2%), **2** (29.2%), **5** (30%) and **1** (6.8%). Unchanged 2-mercaptobenzothiazole disulfide (**3**) (17%) was present as well.

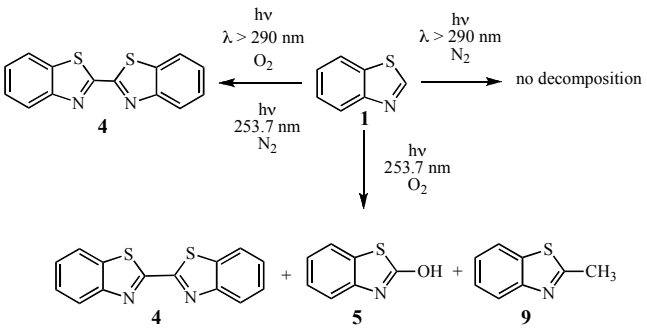
The specific research objectives of our study were to identify the photodegradation products of 2-mercaptobenzothiazole disulfide (**3**), 2-mercaptobenzothiazole (**2**) and benzothiazole (**1**) and to propose an overall photodegradation pathway. The irradiation process was followed by high performance liquid chromatography and ultraviolet spectroscopy.

RESULTS AND DISCUSSION

Photodegradation of Benzothiazole. Photodegradation of benzothiazole (**1**) in methanol was performed at 253.7 nm and $\lambda > 290$ nm, in the presence or absence of oxygen. There was no decomposition observed in nitrogen-purged methanol after 24 hours of irradiation at $\lambda > 290$ nm. In aerated methanol benzothiazole undergoes symmetric

photodehydrodimerization into its dimer 2,2'-bibenzothiazole (**4**) as observed by Grellmann and Tauer [2]. At 253.7 nm, besides the dimer **4**, which is also formed in the nitrogen-purged solution, 2-hydroxybenzothiazole (**5**) and 2-methylbenzothiazole (**9**) are obtained. The dark study had shown no further decomposition of benzothiazole (**1**). The observed formation of photodegradation products of benzothiazole is summarized in Scheme 1.

Scheme 1

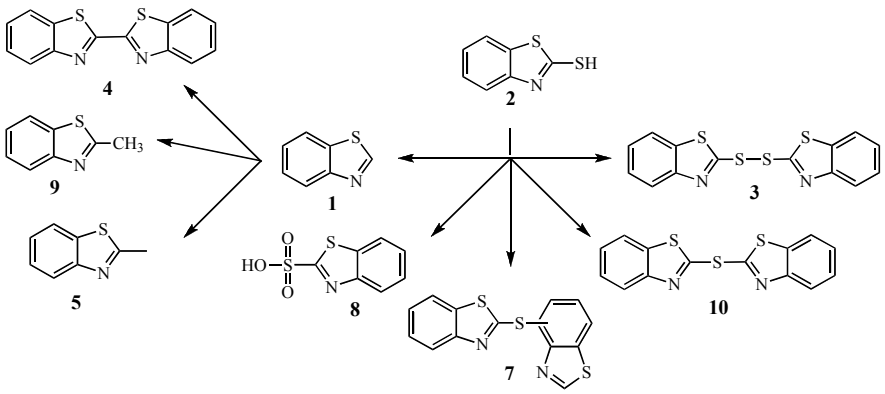


Photodegradation of 2-Mercaptobenzothiazole. In nitrogen-purged methanol benzothiazole (**1**) is the only degradation product of 2-mercaptobenzothiazole (**2**) at 253.7 nm or at $\lambda > 290$ nm. From performed analysis we can confirm that benzothiazole (**1**) is the principal photoproduct together with an oxygenated photoproduct 2-benzothiazolesulfonic acid (**8**), and its monomer 2,2'-thiobisbenzothiazole (**10**) which is formed in small amounts. Additional degradation products were detected as well, such as 2-methylbenzothiazole (**9**), 2-hydroxybenzothiazole (**5**) and 2,2'-bibenzothiazole (**4**) which are further degradation products of benzothiazole (**1**). The presence of the dimer 2-mercaptobenzothiazole disulfide (**3**) was detected at higher concentration of 2-mercapto-benzothiazole (1×10^{-2} *M*) in methanol upon irradiation in a Pyrex vessel or in acetonitrile as the irradiation medium. The formation of photoproducts is summarized in Scheme 2.

Photodegradation of 2-Mercaptobenzothiazole Disulfide. Photodegradation of 2-mercaptobenzothiazole disulfide (**3**) was explored in four solvents at two irradiation wavelengths in the presence or absence of oxygen. 2-Mercaptobenzothiazole (**2**) and a postulated 2,x'-thiobisbenzothiazole (**7**) are the principal degradation products, which are further decomposed into benzothiazole (**1**) and 2-benzothiazolesulfonic acid (**8**). In the case of the assignment of an unsymmetrical 2,x'-thiobisbenzothiazole (**7**) (where x = 4, 5, 6, 7 and refers to the position on the benzothiazole ring) an authentic standard or the starting material for its synthesis was not available, nor was there a spectrum in the computer databases or the literature. Although the high resolution mass spectra and the fragmentation pattern together with ^{1}H NMR support the proposed structure, the ^{13}C NMR spectrum lacks carbons in the positions 2 and 2'. Both carbons are quaternary and are part of the thiazole ring. This makes them more difficult to acquire. Higher amount of sample is required for the positive detection of these carbons and for the performance of 2D NMR experiments. The uncontrollable degradation of this compound during the collection step by liquid chromatography unavoidably limits the collected amount. Therefore the identification of the compound **7** is tentative. There are documented cases in which certain ^{13}C signals are not directly observable and are undetectable [7,8]. Further supporting information for the existence of a 2,x'-thiobisbenzothiazole are the publications by Cole *et al.* [9] and Crank and Mursyidi [10]. It was found that benzimidazole and 2-aminobenzimidazole give unsymmetrical dehydro dimers. The structural similarity of benzothiazoles and benzimidazoles leads us to believe that this type of product formation is also possible with benzothiazoles.

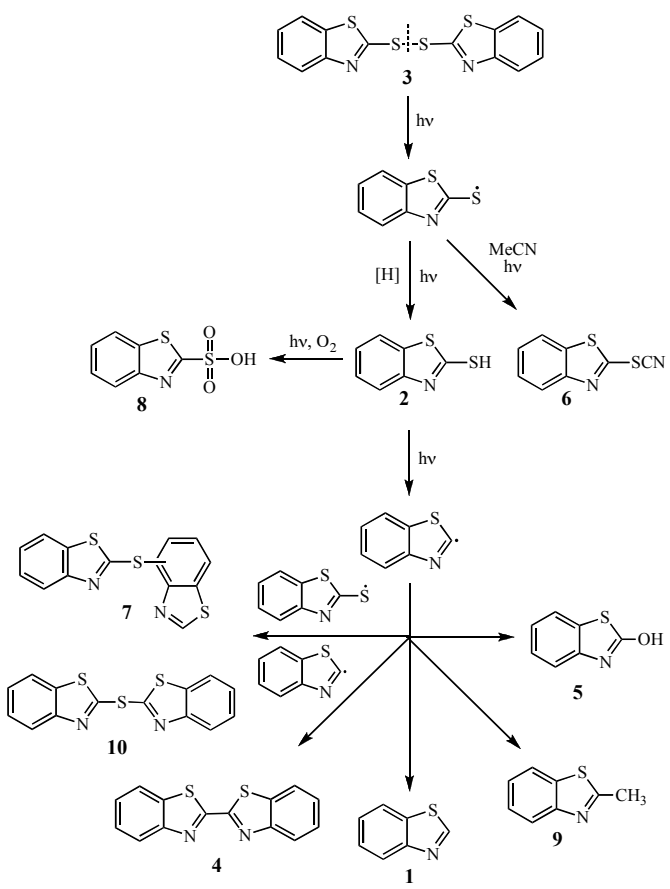
Proposed Photolytic Pathway. The proposed overall photodegradation pathway for 2-mercaptobenzothiazole disulfide (**3**) and related benzothiazoles is shown in Scheme 3. Homolytic cleavage of the S-S bond leads to the formation of 2-mercaptobenzothiazolyl radical. The

Scheme 2



homolytic cleavage of disulfides and formation of thiols is a well-known process [6,11]. After hydrogen abstraction from the solvent, 2-mercaptobenzothiazole (**2**) is formed which is further oxidized into 2-benzothiazolesulfonic acid (**8**) [5]. 2-Thiocyanatobenzothiazole (**6**) is detected only in acetonitrile. A benzothiazolyl radical is formed after cleavage of the sulfur-benzothiazole bond and after hydrogen abstraction benzothiazole (**1**) is obtained. Another pathway for the benzothiazole formation in oxygenated media was proposed by Malouki *et al*. [5]. After oxidation of 2-mercaptobenzothiazole (**2**) and further desulfurization of 2-benzothiazolesulfinic acid or benzothiazolesulfonic acid (**8**) benzothiazole (**1**) or 2-hydroxybenzothiazole (**5**) are formed. In a deoxygenated medium, desulfurization of 2-mercaptobenzothiazole can take place with the formation of an episulfide [11]. Further recombination of the benzothiazolyl radical with a 2-mercaptobenzothiazolyl radical or another benzothiazolyl radical leads to an unsymmetrical 2,x'- (**7**) or symmetrical 2,2'-thiobisbenzothiazole (**10**) and 2,2'-bibenzothiazole (**4**). A mechanism for the formation of 2,4'- and 2,5'-bibenzothiazole upon irradiation of benzimidazole was described by Cole *et al*. [12]. Further oxygenation or methylation of benzothiazole leads to 2-hydroxybenzothiazole (**5**) and 2-methylbenzothiazole (**9**).

Scheme 3



Effect of Irradiation Conditions. The choice of irradiation wavelength and media, duration of time exposure, concentration of starting material and presence or absence of oxygen can influence the speed of reaction and product formation.

Our results show that with both the quartz and Pyrex flasks irradiation causes the formation of the same photoproducts. The major difference is in how fast the compounds are decomposing and in what ratios the individual products are being formed. A quartz vessel allows for much faster occurring degradation since light of higher frequency passes through. Absorption of the light of higher frequency provides higher energy necessary to break a bond in a molecule.

A less concentrated solution undergoes faster degradation as expected. The presence or absence of oxygen can affect the speed of the reaction and can dictate the product formation as well. Benzothiazolesulfonic acid (**8**) and 2-hydroxybenzothiazole (**5**) are oxygenated products of **2** and **1** and are formed only under aerobic conditions. For the decomposition of 2-mercaptobenzothiazole disulfide (**3**) in methanol at 253.7 nm it was observed that irradiation in nitrogen is faster than in the presence of oxygen, in agreement with Shizuka [6].

In this work we have investigated direct photolysis of benzothiazole (**1**), 2-mercaptobenzothiazole (**2**) and 2-mercaptobenzothiazole disulfide (**3**) and the photolytic pathway was proposed on the basis of the identified photodegradation products. A chromatographic method was developed for the separation of photoproducts in the irradiated mixture. The products were identified by a comparison of retention times, ultraviolet spectra and mass spectra with the available standards. Additionally a 2,x'-thiobisbenzothiazole (**7**) (x = 4, 5, 6, 7) was tentatively postulated as a photodegradation product.

EXPERIMENTAL

Benzothiazoles. The following data were obtained for commercially purchased individual standards: benzothiazole **(1)** t_R 13.32 min, UV [methanol] (log ε): 201 nm (0.802), 217 nm (0.851), 251 nm (0.277), 284 nm (0.104), 294 nm (0.094); ms (ESI) $[M+H]^+$ 138.88; 2-mercaptobenzothiazole **(2)** t_R 12.86 min, UV [methanol] (log ε): 208 nm (0.503), 230 nm (0.462), 237 nm (0.466), 325 nm (0.974); ms (ESI) $[M+H]^+$ 167.88, $[M-H]^-$ 166.24; 2-mercaptobenzothiazole disulfide **(3)** t_R 29.15 min, UV [methanol] (log ε): 221 nm (0.778), 272 nm (0.408); ms (ESI) $[M+H]^+$ 333.15, $[M-H]^-$ 331.24; 2,2'-bibenzothiazole **(4)** t_R 27.75 min, UV [methanol] (log ε): 215 nm (1.023), 253 nm (0.200), 327 nm (0.485), 343 nm (0.558), 362 nm (0.406); ms (ESI) $[M+H]^+$ 269.05; 2-hydroxybenzothiazole **(5)** t_R 9.75 min, UV [methanol] (log ε): 213 nm (0.923), 237 nm (0.150), 281 nm (0.080), 289 nm (0.079); ms (ESI) $[M-H]^-$ 150.31; 2-methylbenzothiazole **(9)** t_R 17.71 min, UV [methanol] (log ε): 201 nm (0.802), 217 nm (0.851), 251 nm (0.277), 283 nm (0.068), 293 nm (0.056); ms (ESI) $[M+H]^+$ 149.95; 2,2'-thiobisbenzothiazole **(10)** t_R 27.37 min, UV

[methanol] (log ε): 203 nm (0.978), 219 nm (0.939), 278 nm (0.436), 300 nm (0.386); ms (ESI) $[M+H]^+$ 301.24.

2-Thiocyanatobenzothiazole (6) was prepared by synthetic procedure by Miyashita *et al*. [13]. t_R 19.53 min, UV [methanol] (log ε) : 202 nm (4.408), 219 nm (4.376), 241 nm (4.045), 269 nm (4.138); GC-MS: 192/166/134; ^{1}H NMR (DMSO-d_6): δ 7.52 (td, CH), 7.58 (td, CH), 8.30 (dd, CH), 8.16 (dd, CH); ^{13}C NMR (DMSO-d_6) δ 110.2, 123.2, 126.9, 127.9, 137.2, 153.0, 156.2 ppm.

2,x'-Thiobisbenzothiazole (7) was collected by performing multiple injections using liquid chromatography. t_R 23.68 min, UV [methanol] (log ε): 224 nm (0.729), 268 nm (0.341), 288 nm (0.279), 299 nm (0.257), 336 (0.806); HRMS $[M+H]^+$ calc 300.9927 for $C_{14}H_9S_3N_2$ found, 300.9924; GC-MS (300/273/242/166/134/76) reflects the loss of CHN· (-27), S· (-32), C_6H_5· (-77), S· (-32) and CHNS· (-59); ^{1}H-NMR (CD_3CN-d_6) 7.96 ppm (d, 1H), 7.84 ppm (dd, 2H), 7.76 ppm (dd, 1H), 7.46 ppm (m, 2H), 7.36 ppm (m, 2H); ^{13}C-NMR (DMSO-d_6) 121.4, 121.8, 123.7, 124.5, 126.5, 128.8, 134.4, 134.8, 153.4, 153.5.

Potassium salt of benzothiazolesulfonic acid was synthesized following the procedure described by Brown *et al*. [14] and further acidified into benzothiazolesulfonic acid (**8**). t_R 1.73 min, UV [methanol] (log ε) : 202 nm (4.058), 219 nm (4.004), 262 nm (3.677), 292 nm (3.157); HRMS [M-H]$^-$ calc 213.9633 for $C_7H_4S_2NO_3$, found 213.9598; ^{1}H NMR (DMSO-d_6): δ 7.46 (td, CH), 7.51 (td, CH), 7.98 (dd, CH), 8.06 (dd, CH); ^{13}C NMR (DMSO-d_6) δ 123.1, 124.1, 126.5, 127.0, 135.9, 153.3, 174.8 ppm.

For irradiations at λ > 290 nm a Rayonet photochemical reactor (The Southern N.E. Ultraviolet Co.) was used. It was equipped with 16 high pressure mercury lamps RPR-2537A. An 18 mL Pyrex vessel Rayonet-RPV-8 was used for irradiations with the Rayonet type reactor. The dark studies were done as well in this type of reactor. A sample wrapped in the aluminum foil was irradiated simultaneously with unwrapped solution and the temperature inside of the reactor was monitored.

For irradiations at 253.7 nm an ACE Glass (ACE Glass Inc., Vineland, NJ) microscale photochemical reactor was used equipped with Pen-Ray 5.5 watt low pressure mercury lamp (TM UVP, Inc., San Gabriel, CA). Cooling of the system was obtained by circulating water through the water jacket of the immersion well.

Chromatographic analyses were performed using an LC pump, series 410 (PerkinElmer) coupled to a diode array detector, series 235 C (PerkinElmer), and PeakSimple chromatography data system, model 203 (SRI Instruments).

Hypersil ODS 5 μm column (250 x 4.6 mm) (Thermo Electron Corporation) was used as the stationary phase and 0.1% formic acid and acetonitrile as the mobile phase at flow 1 mL/min. Elution started with a 5 minute isocratic period of 30% of MeCN followed by linear gradient to 100% MeCN in 25 minutes and isocratic period of 100% of MeCN for 10 minutes. The detector wavelength was set to 255 nm and sample was injected into 20 μL loop.

The changes in the UV spectra were measured using Cary 3 UV-Vis spectrophotometer (Varian Inc.) using 1 cm quartz cells. ^{1}H and ^{13}C NMR data were recorded on a Varian MercuryPlus-400 spectrometer (Varian Inc., Palo Alto, CA).

Absorption spectra of individually eluted peaks were observed using liquid chromatography coupled to a photodiode array detector (LC-PDA) all components of Series 1100 (Hewlett Packard/Agilent Inc.). Chromatograms were detected at three wavelengths: 220 nm, 255 nm and 280 nm.

Mass spectrometer M-8000 from Hitachi was equipped with an electron spray ionization (ESI) source and ion trap mass analyzer. ESI parameters were as follows: source temperature 150 ºC, assistant gas temperature 120 ºC, aperture 1 and 2 temperature 180 ºC, detector 400 V, focus 30 V drift 60 V, and the capillary voltage was set to 3.5 kV in positive and 4.0 kV in negative mode. Formic acid (0.1%) or 10 mM ammonium acetate were used as additives to water mobile phase in positive or negative mode to help ion formation. Direct injections of standards were performed using syringe pump model 355 (Sage Instruments) with mobile phase 70:30% of MeCN:H_2O (water with added additives) and flow 0.2 mL/min.

TurboMass Gold, mass spectrometer (PerkinElmer Instruments, Wellesley, MA) together with AutoSystem XL, gas chromatograph (PerkinElmer Instruments, Wellesley, MA) were used for GC-MS analysis, using helium as mobile phase at flow 1.3 mL/min and split ratio 15:1. The injector temperature was 260 °C and the column was maintained at 150 °C for an initial 1 min, followed by heating to 250 °C at 10 °C/min. The column used was EC^{TM}5 (Alltech, Deerfield, IL) 30 m x 0.25 mm ID and 0.25 μm film thickness.

Stock solutions of 2-mercaptobenzothiazole disulfide were prepared in methanol, ethanol, acetonitrile, and cyclohexane, of 2-mercaptobenzothiazole in methanol and acetonitrile and of benzothiazole in methanol, with the precautions that the solutions were never heated above 45°C and were always kept in total darkness. The solution was purged with nitrogen or air for 10 minutes before and during the time of irradiation. At given time intervals analytical samples were taken from the irradiated solution, and analyzed by HPLC and UV. Finally the irradiated solution was concentrated under a stream of nitrogen.

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