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LETTERS TO THE EDITOR

Reaction of Styrene with Chlorine Dioxide

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Abstract—Reaction of styrene with chlorine dioxide under various conditions selectively produces 1-phenyl-2-chloroethanone, with 1-phenyl-2-chloroethanol, 2-hydroxy-1-phenylethanone, (1,2-dichloroethyl)benzene, (2-chloro-1-phenyl)ethene, and (1,2,2-trichloroethyl)benzene isolated as reaction byproducts.

Keywords: 1-phenyl-2-chloroethanone, 1-phenyl-2-chloroethanol, 2-hydroxy-1-phenylethanone, (1,2-dichloroethyl)benzene, (2-chloro-1-phenyl)ethene, (1,2,2-trichloroethyl)benzene

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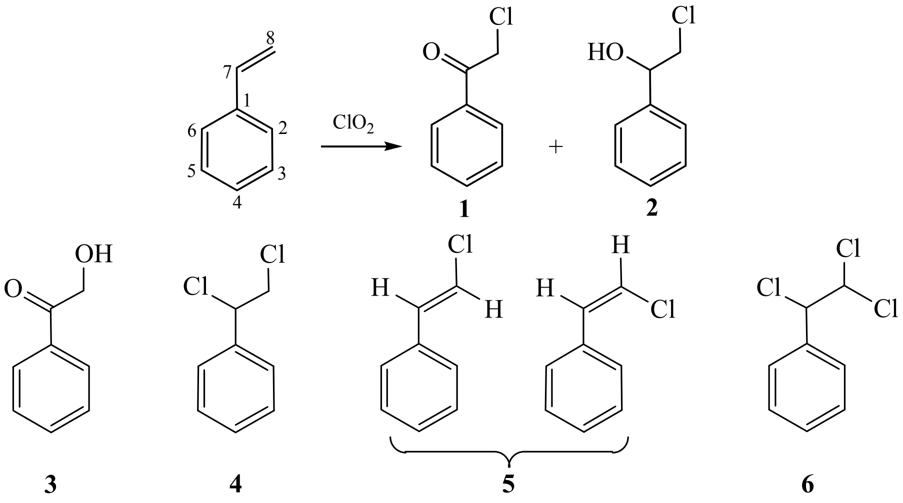
Chloroketones and chlorohydrins are versatile intermediate products in synthesis of bioactive compounds [1]. Hydroxyketones are used for the synthesis of pharmaceuticals and fragrances and also are employed as fungicides, wood disinfectants, stabilizers of proteins and polyhydroxy compounds, reagents in analytical chemistry, etc. [2]. Similar styrene derivatives also have found extensive application. Chloroacetophenone is a toxic lacrimator which is synthesized either by chlorination of acetophenone or by the reaction of benzene with chloroacetyl chloride in the presence of anhydrous aluminum chloride [3]. Styrene chlorohydrin, a semiproduct in industrial synthesis of a synthomycin, is obtained by hydroxychlorination of styrene with calcium hypochlorite or by passing gaseous chlorine through an emulsion of styrene and water, whereby a part of styrene is converted to 1-phenyl-1,2-dichloroethane, difficultly separable from chlorohydrin [4]. The formation of 1-phenyl-1,2-dichloroethane can be avoided by carrying out the reaction of bromobenzene with anhydrous chloroacetaldehyde in the presence of magnesium metal, followed by hydrolysis of magnesium bromoalkoxide [5].

Here we studied the reaction of styrene with chlorine dioxide under various conditions. Chlorine dioxide is used for oxidation of alcohols [6, 7], sulfur-containing amino acids [8], and thiols and disulfides [9, 10], as well as for the preparation of variously structured sulfoxides [11–13] and quinones [14–16]. There are examples of using chlorine dioxide for oxidation of unsaturated compounds, giving a complex mixture of chlorination products [17, 18]. Chlorine dioxide was found to epoxidize styrene in aqueous solutions [19]. The monochlorine monoxide thereby formed then oxidized chlorine dioxide to chlorate and was reduced to hypochlorous acid. The end products included styrene oxide resulting from the reaction of hypochlorous acid with styrene and compounds formed via epoxide ring opening. Considerable amounts of styrene oxide were obtained when the oxidation was carried out at pH 6. Upon adding sulfamic acid the yields of the chlorinated products decreased substantially.

When carrying out the reaction of styrene with ClO_2 we varied the technique of supplying ClO_2, the styrene-ClO_2 molar ratio (1 : 1, 1 : 2), and the catalyst [$VO(acac)_2$, FIBAN K-1 sulfonic cation-exchange resin, KSF clay]. A ClO_2-air mixture was bubbled through styrene or a solution of styrene in an organic solvent (CH_2Cl_2 or DMF), or, alternatively, a solution of ClO_2 in H_2O or in CH_2Cl_2 was added dropwise to styrene. The reaction was run at 20°C until complete conversion of styrene was achieved; the reaction products were separated by column chromatography.

Our results showed that, under the actual conditions, the reaction of styrene with ClO_2 gave a mixture of compounds, chief among which are chloroketone **1** and chlorohydrin **2** (Scheme 1).

Scheme 1.



The reaction run with the use of an aqueous solution of ClO_2 at an equimolar ratio of the reactants gave 1-phenyl-2-chloroethanone **1** in a maximum yield of 69%, with up to 25% of 1-phenyl-2-chloroethanol **2** and up to 6% of 2-hydroxy-1-phenylethanone **3** formed as well. As the molar ratio of the reactants increased, the yield of **1** increased (81%), probably, due to oxidation of the hydroxy group in **2** to ketone with an excess of ClO_2.

On changing the solvent from water to CH_2Cl_2 the yield of **1** did not exceed 55%, and that of **2**, 5%. The presence in the reaction mixture of (1,2-dichloroethyl)-benzene **4** (23%) and of (2-chloro-1-phenyl)ethene **5** (17%) is explained by the formation of chlorine molecules from ClO_2 decomposition in an aprotic solvent. Bubbling ClO_2-air mixture through a solution of styrene in CH_2Cl_2 led to a similar set of reaction products. In a DMF medium styrene was oxidized with ClO_2 predominantly to **1** with no formation of other chlorination products. As the consumption of the oxidant increased the yield of **1** increased to 75%. Bubbling ClO_2 directly through styrene led to the formation of **1–3** in approximately equal amounts (20–24%).

The catalysts tested in the reaction of styrene with chlorine dioxide included $VO(acac)_2$, FIBAN K-1, and KSF clay. FIBAN K-1 is a fibrous strongly acidic cation-exchange resin with SO_3H^+ functional group, whose polymer base is formed by polypropylene fiber with graft styrene-divinylbenzene copolymer. This is an effective catalyst for olefin isomerization, alcohol dehydration, and redox reactions [20, 21]. Montmorillonite KSF is a solid Lewis acid; H_2SO_4 may occur on its surface. $VO(acac)_2$ is employed as a catalyst for epoxidation of allyl alcohols [22].

The use of the catalysts tested did not lead to selective oxidation of styrene; in all cases the amounts of chlorination products **4** and **5** increased. Also, (1,2,2-trichloroethyl)benzene **6** (1%) was isolated from the reaction catalyzed by $VO(acac)_2$, unlike the reaction run under other conditions.

The structures of **1–6** were confirmed by IR and NMR spectroscopy; the characteristics of the compounds synthesized corresponded to the published data [23–27].

(2-Chloro-1-phenyl)ethene **5** is a mixture of *trans*-(**5a**) and *cis*-isomers (**5b**) which we could not separate chromatographically. The ratio and yield of the isomers formed were estimated from the integrated intensities of the signals from methine protons at C^7 and C^8 atoms in the ^1H NMR spectrum at 6.68 and 6.88 ppm for (*trans*-2-chloro-1-phenyl)ethene **5a** and at 6.33 and 6.73 ppm for (*cis*-2-chloro-1-phenyl)ethene **5b**. According to the NMR data, the *cis*- and *trans*-isomers were in a 1 : (4–8) ratio.

The ^1H NMR spectrum of (1,2,2-trichloroethyl)-benzene **6** exhibited signals from protons of two methine groups appearing as doublets at 5.28 and 6.07 ppm, as well as signals from phenyl protons (multiplet, δ 7.35–7.48 ppm).

Thus, the reaction of styrene with chlorine dioxide allows selectively producing α-chloroacetophenone by using an aqueous solution of ClO_2 or by bubbling ClO_2 through a solution of styrene in DMF.

Oxidation of styrene with chlorine dioxide *(general procedure).* A mixture of air and ClO_2 (dichloromethane extract from 263 mL of an aqueous solution, *c* = 7–8 g/L) was bubbled through 2.920 g (28.1 mmol) of styrene or a styrene solution in DMF or CH_2Cl_2, or, alternatively, 280 mL of a ClO_2 solution in H_2O or in CH_2Cl_2 (*c* = 7–8 g/L) was added under stirring. The reaction was run at 20°C until complete conversion of styrene was achieved. The course of the reaction was monitored by TLC on Sorbfil plates (eluent 1 : 1 benzene–petroleum ether). The reaction products were extracted from the aqueous solution with chloroform and separated by column chromatography on Alfa Aesar 70/230μ silica gel (eluent chloroform, benzene-petroleum ether). In a similar way the reaction was carried out in the presence of a catalyst or with a ClO_2 excess.

1-Phenyl-2-chloroethanone 1. Yield 14–69%, colorless oily liquid. IR spectrum, ν, cm^{-1}: 1732 (C=O), 692 (C–Cl). ^{1}H NMR, δ, ppm: 4.74 s (2H, C^8H_2), 7.52 t (2H, $C^3H + C^5H$, *J* = 9.0 Hz), 7.62 t (1H, C^4H, *J* = 6.0 Hz), 7.99 d (2H, $C^2H + C^6H$, *J* = 9.0 Hz).

1-Phenyl-2-chloroethanol 2. Yield 5–25%, light yellow oily liquid. IR spectrum, ν, cm^{-1}: 3448 (O–H), 3030 (C–H_{ar}), 698 (C–Cl).

2-Hydroxy-1-phenylethanone 3. Yield 6–22%, white paste-like mass, mp 87°C (mp 88°C [26]). IR spectrum, ν, cm^{-1}: 3433 (O–H), 3030 (C–H_{ar}), 1747 (C=O).

(1,2-Dichloroethyl)benzene 4. Yield 2–23%, colorless oily liquid. IR spectrum, ν, cm^{-1}: 3028 (C–H_{ar}), 696 (C–Cl).

(2-Chloro-1-phenyl)ethene 5. Yield 12–21%, colorless oily liquid. IR spectrum, ν, cm^{-1}: 1608 (C=C), 697 (C–Cl). ^{13}C NMR spectrum (*cis*-isomer **5b**), δ_C, ppm: 118.75 (C^8), 126.17 (C^2, C^6), 128.20 (C^4), 128.83 (C^3, C^5), 133.34 (C^7), 134.93 (C^1).

(1,2,2-Trichloroethyl)benzene 6. Yield 1%, colorless oily liquid. ^{1}H spectrum, δ, ppm: 5.28 (1H, C^8H, *J* = 5.8 Hz), 6.07 d (1H, C^7H, *J* = 5.8 Hz), 7.35–7.48 m (5H, C_6H_5).

IR spectra were measured on a Prestige 21 spectrometer (KBr pellets). ^{1}H and ^{13}C NMR spectra were recorded in a DMSO solution on a Bruker Avance-II-300 spectrometer (300 and 75 MHz, respectively). The content of the components in the reaction mixture was determined on a Kristall 2000M chromatograph with a flame ionization detector using a 2×1000 mm column packed with 10% Carbowax 20M deposited on Chromaton N-AW-DMCS; carrier gas argon; oven temperature 50– 230°C at a rate of 6°C/min.

Melting points were determined on a Sanyo Gallenkamp apparatus with a digital thermometer. The reaction products were separated by column chromatography ("wet" packing method) on Alfa Aesar 70/230μ silica gel. Thin-layer chromatography was performed on Sorbfil plates, with *tert*-butyl methyl ether as eluent and 5% potassium permanganate solution as developing agent.

Solution of ClO_2 in dichloromethane was prepared by extraction of ClO_2 from an aqueous solution (*c* = 7–8 g/L), followed by drying over $MgSO_4$. Montmorillonite KSF [Acros Organics, surface area 15± 10 m^2/g; chemical composition: SiO_2 (54.0%), Al_2O_3 (17.0%), Fe_2O_3 (5.2%), CaO (1.5%), MgO (2.5%), Na_2O (0.4%), K_2O (1.5%); 8–12% free H_2SO_4] was used without pretreatment. FIBAN K-1 catalyst was made available by the Institute of Physical Organic Chemistry, National Academy of Sciences of Belarus.

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