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Tetrahedron Letters 49 (2008) 586–588
Tetrahedron Letters

Synthesis of 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl derivatives for investigation of ionic liquids

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Received 15 October 2007; revised 22 November 2007; accepted 26 November 2007

Abstract

Direct sulfonation of 4-hydroxy-2,2,6,6-tetramethylpiperidine-1-yloxyl using chlorosulfuric acid trimethylsilylester results in 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl in 94% yield that is the basis for the synthesis of potassium 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl and sodium 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl. These nitroxides can be employed as spin probes to investigate properties of ionic liquids in the molecular domain.

Keywords: Spin probes; ESR spectroscopy; Nitroxides; Ionic liquids

Ionic liquids have become huge attention for extraction processes, in electrochemical devices, and as solvents for organic, inorganic, and polymerization reactions.[1–6] The ionic structure and the relative high viscosity distinguish ionic liquids from conventional organic solvents or water.[2–7] Ionic liquids are sometimes called 'designer solvents' because one can tune the solvent property just by changing either the nature of the cation or the anion. Until today, knowledge about the microscopic nature of ionic liquids obtained by molecular probes can be considered as rare. Spin probes are a versatile tool to explore the molecular properties of these new solvents.[8–15] Either neutral spin probes or spin probes bearing a trimethylammonium group have been investigated in ionic liquids. Previous publications of 2,2,6,6-tetramethylpiperidine-1-yloxyl bearing an ammonium group demonstrated a very sensitive answer of the spin probe upon change of the ionic liquid because ionic interactions between the cationic probe and the ionic solvent show a stronger answer of such charged probes compared to neutral spin probes.[12,13,15] Incorporation of a sulfate group into 2,2,6,6-tetramethylpiperidine-1-yloxyl opens the possibility to study interactions of the negatively charged probe with the cation of the solvent. In general, the 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl can be obtained by reaction of 4-hydroxy-2,2,6,6-tetramethylpiperidine-1-yloxyl either with sulfonyl chloride or with chlorosulfuric acid in a one-step reaction or from 4-hydroxy-2,2,6,6-tetramethylpiperidine and chlorosulfuric acid followed by oxidation of the 2,2,6,6-tetramethyl-4-piperidinyl hydrogensulfate with hydrogen peroxide that is a two-step synthesis.[16–18] No experimental details are available for the one-step synthesis of 2,2,6,6-tetramethylpiperidine-1-yloxyl from the literature.[16,17] The goal of this Letter is to show the feasibility of an efficient synthetic route to obtain the 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl in a one-step reaction. Reaction of the free radical 4-hydroxy-2,2,6,6-tetramethylpiperidine-1-yloxyl (**1**) with chlorosulfuric acid trimethylsilylester was found to be an efficient route to obtain 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl (**2**) in a good yield (94%) (Fig. 1).[19,20] Potassium 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl (**3**) and sodium 4-sulfonatooxy-2,2,6,6-tetramethylpiperidin-1-yloxyl (**4**) are formed by neutralization with the corresponding alkali hydroxide solutions.[21,22]

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0040-4039/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetlet.2007.11.150

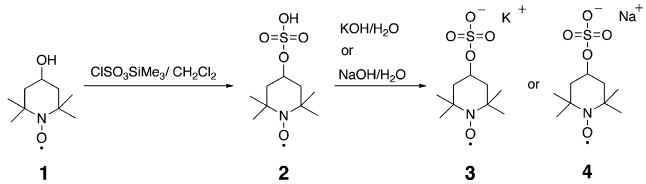

Fig. 1. Formation of 4-sulfonatooxy-2,2,6,6-tetramethyl (piperidine-1-yloxyl) (**2**) and its potassium (**3**) and sodium (**4**) salts.

ESR spectra of 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl and its salts are similar if they are dissolved in the same solvent, and they are characteristic for 2,2,6,6-tetramethylpiperidine-1-yloxyl derivatives. However, the solvent influences the habitus of the spectra as can be seen in Figure 2. The spectrum of **3** measured in DMSO is typical for a low viscous solvent. On the other side, the spectrum of **3** dissolved in 1-butyl-3-methylimidazolium tetrafluoroborate exhibits a broader linewidth.

The average rotational correlation times (τ) and the hyperfine coupling constants (A_{iso} (^{14}N)) of the spin probes (**2** (DMSO): $\tau = 0.4$ ns, A_{iso} (^{14}N) = 15.8 G; **3** (DMSO): $\tau = 0.4$ ns, A_{iso} (^{14}N) = 15.7 G; **4** (DMSO): $\tau = 0.3$ ns, A_{iso} (^{14}N) = 15.8 G; **2** (ionic liquid): $\tau = 7.4$ ns, A_{iso} (^{14}N) = 16.1 G; **3** (ionic liquid): $\tau = 5.4$ ns, A_{iso} (^{14}N) = 16.0 G; **4** (ionic liquid): $\tau = 6.9$ ns, A_{iso} (^{14}N) = 16.1 G) determined by the method of Budil et al. show a lower mobility in the ionic liquid than in dimethylsulfoxide and a distinct micropolarity.[23] This is caused by the strong interactions between the 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl derivatives and 1-butyl-3-methylimidazolium tetrafluoroborate and by the higher viscosity of this ionic liquid with respect to the solvent dimethylsulfoxide.[24,25]

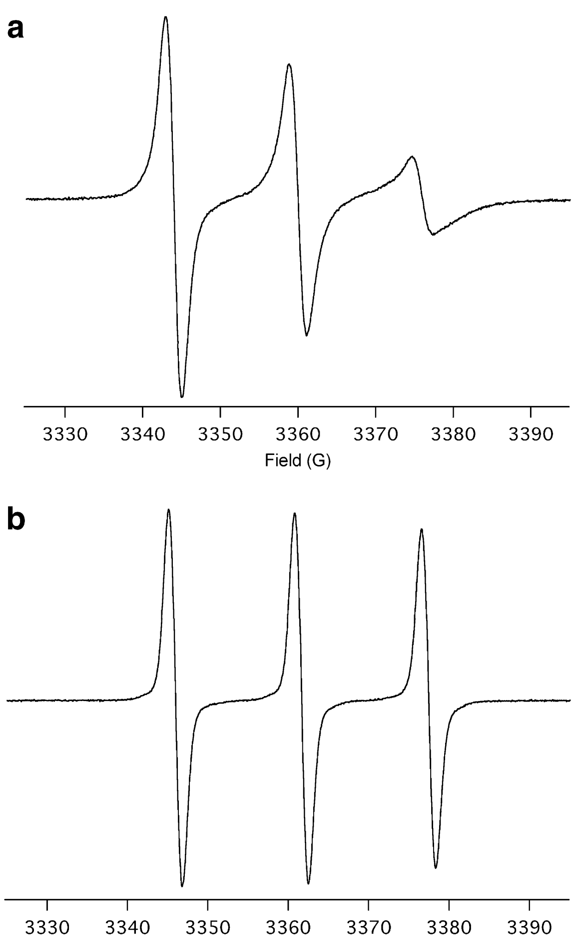

Fig. 2. ESR spectra of **3** dissolved in (a) 1-butyl-3-methylimidazolium tetrafluoroborate (A_{iso} (^{14}N) = 16.0 G; $\tau = 5.4$ ns) and in (b) dimethylsulfoxide (A_{iso} (^{14}N) = 15.7 G; $\tau = 0.4$ ns) at room temperature.

In conclusion, the one step synthesis of 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl results in a high yield on the basis of commercially available 4-hydroxy-2,2,6,6-tetramethylpiperidine-1-yloxyl using chlorosulfuric acid trimethylsilylester. This opens new possibilities for synthesis of 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl salts with various cations that are useful for investigation of ionic liquids. Moreover, selection of counter ions belonging to the ionic liquid should give more detailed information about the influence of structural effects of ionic liquids on micropolarity and microviscosity.

Acknowledgments

The authors gratefully acknowledge A. Laschewsky for the use of laboratory equipment, the group of E. Kleinpeter, especially I. Starke and S. Fürstenberg for mass spectrometric investigation, and the DFG for financial support within the priority program SPP 1191.

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19. Materials: 4-Hydroxy-2,2,6,6-tetramethylpiperidine-1-yloxyl (**1**) and chlorosulfuric acid trimethylsilylester from Aldrich were used as obtained.
20. For synthesis of 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl (**2**) 1 mmol 4-hydroxy-2,2,6,6-tetramethyl-piperidine-1-yloxyl (**1**) is dissolved in 5 mL methylenechloride at 0 °C under nitrogen. Then 3.08 mL of a solution of chlorosulfuric acid trimethylsilylester (1 mmol) in methylene chloride is added within 30 min. The chlorosulfuric acid trimethylsilylester methylene chloride solution is obtained by filling up of 0.5 mL chlorosulfuric acid trimethylsilylester with methylene chloride to a volume of 10 mL. Stirring the reaction mixture overnight and warming it up to room temperature results in a yellow precipitate, which is isolated and washed with 20 mL methylene chloride. After drying in vacuum 237 mg of 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl (**2**) are obtained (yield: 94%, mass spectrometry: 252 Dalton in the TOF MS ES^- mode that corresponds to the mass of **2**, IR: characteristic vibrations for the $R–O–SO_3^-$ group at 1208 cm^{-1} and 1248 cm^{-1}, mp 230–237 °C dec determined by thermogravimetric analysis and microscopic observation of **2** during heating).
21. Potassium 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl (**3**) and sodium 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl (**4**) are obtained by neutralization of 100 mg (0.397 mmol) 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl (**2**) with 4 mL of 0.1 N aqueous potassium hydroxide or sodium hydroxide solution at room temperature. The transparent solution obtained is evacuated to partially remove the solvent. The residue is transferred into methanol, kept into the refrigerator over night, and filtrated. The transparent solution is evacuated, and the residue is crystallized from a methanol tert. butylmethylether mixture (v/v = 1/10) resulting in crystals after three days storing in the refrigerator. These crystals are potassium 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl (yield: 79% after recrystallization; mass spectrometry: 251 Dalton in the TOF MS ES^- mode that corresponds to the mass of the anion; IR: characteristic vibrations for the $R–O–SO_3^-$ group at 1239 cm^{-1}; mp 216–219 °C dec) or sodium 4-sulfonatooxy-2,2,6,6-tetramethylpiperidine-1-yloxyl (yield: 90% after recrystallization; mass spectrometry: 251 Dalton in the TOF MS ES^- mode; IR: characteristic vibrations for the $R–O–SO_3^-$ group at 1221 cm^{-1} and 1257 cm^{-1}; mp 150–162 °C dec).
22. Methods: A Bruker IFS 66 FTIR spectrometer was used for FTIR measurements. Mass spectra were taken in the ES^- mode with an ESI Q-TOF instrument. ESR spectra of the spin probes were measured in X-band with a CW spectrometer E500 (Bruker). Thermogravimetric analysis was carried out using a Mettler-Toledo TGA/SDTA 851^e.
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