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Cinnolino[5,4,3][*c,d,e*][1,2]benzothiazin-4-yl: A New Persistent Radical

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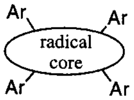
Introduction

Cyclic thioaminyl radicals have been investigated as molecular magnetic and conductive materials.[1,2] Their structural versatility allows for the design of a variety of new heterocyclic radicals including those suitable for structural elements of liquid crystals.[3] In this context, we focused on two radicals, **1a** and **2a**, as potential components for paramagnetic discogens **I**.[4] Here we report the preparation and properties of both radicals with an emphasis on the new persistent heterocyclic radical **2a**.



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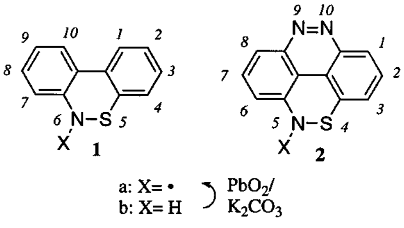


Results and Discussion

Synthesis. Dibenzo[*c*,*e*][1,2]thiazin-5-yl (**1a**) and cinnolino[5,4,3][*c*,*d*,*e*][1,2]benzothiazin-4-yl (**2a**) were generated in about 30% yield by PbO_2/K_2CO_3 oxidation of cyclic sulfenamides **1b**[5,6] and **2b**, respectively. This method[7] gave much higher yields of the radicals than the thianthrenium perchlorate/pyridine method previously described for generation of **1a**.[3]

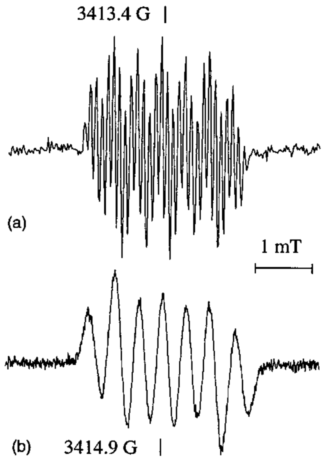
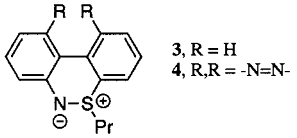


Figure 1. ESR spectra of **1a** (a) and **2a** (b) recorded in CH_2Cl_2 at 298 K.

Precursors **1b** and **2b** were obtained from the corresponding *S*-propyl sulfilimines **3**[5,6] and **4**,[8] by thermal elimination of propene according to the general procedure.[5]



The sulfenamides exhibit markedly different solubility and chromatographic properties despite similarities in their structures. The addition of the azo bridge to **1b** makes **2b** much less mobile on silica gel and only sparingly soluble in common solvents other than acetone and DMSO. Tetracycle **2b** crystallizes with half a molecule of water, as evident from elemental analysis and the ^{1}H NMR spectrum.

Sulfenamides **1b** and **2b** both undergo slow decomposition upon prolonged storage, which presumably is related to the hydrolysis of the amide bond and the oxidation of the NH group. ESR analysis of one of the less mobile fractions obtained from purification of **2b**, which was stored for 1 week in a refrigerator, showed the presence of radical **2a**.

ESR Spectra. Radicals **1a** and **2a** exhibit seven groups of multiplets, as shown in Figure 1. Each multiplet in the spectrum of **1a** (Figure 1a) consists of four lines (28 lines total), while in the spectrum of **2a** the multiplets are unresolved (Figure 1b).

Both spectra were numerically simulated using initial hyperfine coupling constant (hfcc) values obtained from B3LYP/6-31G* calculations. After a least-squares fit to nine parameters, the correlation between the simulated and the experimental spectra was >0.98, and the resulting hfcc's are shown in Figure 2. The same comparison of the experimental spectrum of **1a** with that simulated using the previously published hfcc's (obtained by visual comparison of the spectra),[3] shows a correlation of only 0.50.

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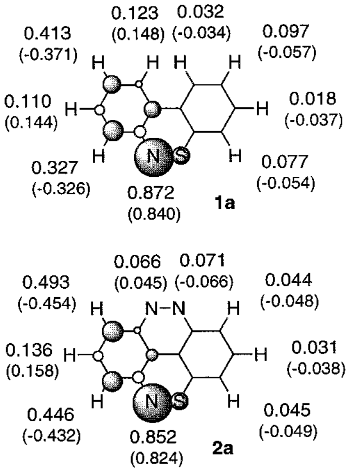

Figure 2. Experimental and calculated (in parentheses) hyperfine coupling constants (mT) and DFT-derived spin distribution maps for **1a** and **2a**. Circles represent relative total positive (full circles) and negative (open circles) spin densities greater than 0.05.

Both radicals have a similar principal coupling of about 0.85 mT to the thioaminyl nitrogen atom and about 0.4 mT to the hydrogen atoms in the positions ortho and para to the nitrogen. Additional splittings are due to coupling constants of 0.05−0.14 mT to hydrogen atoms meta to the thioaminyl bridge and the azo bridge nitrogen atoms in **2a**. The largest differences between **1a** and **2a** are observed for the hfcc's of hydrogen atoms and spin densities in the positions ortho and para to the nitrogen atoms, which are presumably affected by the electronegativity of the azo substituent.

The observed hfcc's and splitting patterns are consistent with the scaled[9] hfcc's values and spin densities derived from DFT calculations (Figure 2). The mean difference between the calculated and experimental data is 0.007 mT and the estimated standard deviation is 0.024 mT, which is close to the accuracy of the computational protocol.[9]

The g value measured for **1a** (2.0052) is slightly larger than that for **2a** (2.0049), which is consistent with the calculated larger spin concentration on the sulfur atom in the former (0.22) as compared with that in **2a** (0.21).

Both radicals **1a** and **2a** have the electronic state $^2A''$ and the unpaired electron resides on the π MO (−4.62 eV and −5.12 eV, respectively). The dipole moment μ calculated for **1a** (2.82 D) is larger than that for **2a** (1.82 D), which reflects the contribution of the azo bridge to the total dipole moment of the latter. The vertical ionization potential calculated for **2a** and scaled[9] by 0.984 is $I_p = 6.68$ eV and is higher by 0.47 eV than that for **1a**.

Stability of Radicals. When the radicals were generated with the PbO_2/K_2CO_3 system, both **1a** and **2a** showed similar stability. After 3 days, the intensity of the ESR signal of sealed samples decreased by 50%, and the radicals were still detected in the solution after 1 week. The decomposition rate was little affected by the presence of atmospheric oxygen in accordance with the general low oxygen sensitivity of thioaminyl radicals.[7,10] When thianthrenium perchlorate/pyridine was used as the oxidant, however, **1a** decayed rapidly within several hours,[3] while the relatively strong ESR signal of **2a** was still detected after 3 days. This significant difference in stability can be attributed to hydrolytic cleavage of the N−S bond catalyzed by pyridinium salts and accelerated by torsional strain of the two hydrogen atoms in 1 and 10 positions in **1a**. Replacement of these two hydrogen atoms with an azo bridge in **2a** stabilizes the heterocycle against hydrolysis.

To quantify stability, the toluene solutions were worked up in air and chromatographed. Evaporation of the original mixture to dryness and then redissolving the solid in toluene reduced the spin yield to 1/3 of the original 30%. When the resulting solution was passed through a short Florisil plug, only about 40% of the original amount of material was recovered, with about 10% spin concentration.

The stability of radicals **1a** and **2a** is remarkable, considering that their acyclic analogue PhṄSPh decomposes completely within 1 h[11] and requires substituents protecting the high spin density sites (positions ortho and para to nitrogen) for increased stability.[7] Further substitution of these persistent heterocyclic radicals will certainly increase their stability and perhaps enable their isolation and purification. Judicious choice of substituents will provide new opportunities for controlling bulk structures of solids and liquid crystals.

Experimental Section

Melting points are uncorrected. ^1H NMR spectra were referenced to the solvent. Elemental analysis was provided by Atlantic Microlab, Norcross, GA.

X-band ESR spectra were taken on a Bruker 300E instrument in distilled toluene which was degassed by three freeze/pump/thaw cycles. Spin concentration and yields were calculated by double integration of the ESR signal of the sample versus the integral intensity of a measured amount of 4-hydroxy-TEMPO radical purchased from Aldrich and assumed to be 100%. Samples were referenced using strong pitch with $g = 2.0028$. Lead dioxide and K_2CO_3 were dried in a vacuum at 100 °C for 24 h, in the presence of P_2O_5.

DFT calculations were carried out at the B3LYP/6-31G* level of theory using the Gaussian 94 package[12] on an SGI R8000 workstation. The calculated Fermi constants were converted to hfcc's and scaled by 0.937 for ^{14}N and 0.746 for ^1H, according to a general protocol.[9] Simulation of the ESR spectra was done with the PEST program (version 0.96 for Windows; available: http//epr.niehs.nih.gov/pest1.html) using the DFT results for the input. The resulting hfcc were perturbed until the global minimum for the fit was achieved.

Generation of Radicals. Method A. Precursor **1b** or **2b** (0.03 mmol) was dissolved in degassed dry toluene (10 mL, 3 mM solution) and stirred over PbO_2 (70 mg, 0.30 mmol) and K_2CO_3 (70 mg, 0.30 mmol) for 15 min. The solution acquired a dark color. A sample of 0.5 mL was transferred to an ESR tube and carefully degassed before the measurement.

Method B. Precursor **1b** or **2b** (0.03 mmol) was dissolved in degassed CH_2Cl_2 (10 mL, 3 mM solution), and pyridine (2 μL) was added. Thianthrenium perchlorate (20 mg, 0.06 mmol) was dissolved in degassed CH_2Cl_2 (10 mL, 6 mM solution), and 0.35 mL of this solution was mixed with 0.35 mL of solution of the

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precursor in an ESR tube with a vacuum adapter. The resulting solution acquired a darker color. It was carefully degassed before the measurement.

6*H*-Dibenzo[*d*,*e*][1,2]thiazine (1b).[5] The compound was prepared from 5-propyldibenzo[*d*,*e*][1,2]thiazine[5] (**3**) in 36% yield as described for **2b**. The crude product was purified on a silica gel column (hexane−CH_2Cl_2, 3:1 ratio) to give a pale yellow oil, which solidified upon standing: mp 44−45 °C; ^{1}H NMR (C_6D_6) δ 3.05 (bs, 1H), 6.90−7.00 (m, 6H), 7.43−7.47 (m, 2H).

5*H*-Cinnolino[5,4,3][*c*,*d*,*e*][1,2]benzothiazine (2b). 4-Propylcinnolino[5,4,3][*c*,*d*,*e*][1,2]benzothiazine[8] (**4**, 62 mg, 0.23 mmol) was dissolved in dry benzene (5 mL). The resulting solution was stirred at reflux for 18 h. The solvent was removed and the residue was separated on a silica gel column (hexane−EtOAc, 1:1 ratio, followed by pure EtOAc) to give 35 mg (67% yield) of reddish-brown powder: mp 207−208 °C; ^{1}H NMR (acetone-d_6) δ 5.93 (bs, 1H), 7.52 (d, $J = 7.4$ Hz, 1H), 7.60 (dd, $J_1 = 7.9$ Hz, $J_2 = 0.9$ Hz, 1H), 7.89 (td, $J_1 = 8.1$ Hz, $J_2 = 0.9$ Hz, 2H), 8.39 (td, $J_1 = 7.4$ Hz, $J_2 = 0.8$ Hz, 2H); IR (neat) ν_{max} 3165, 1577, 1430, 1262, 789 cm^{-1}; MS *m*/*e* 225 (M^+, 100), 196 (40). Anal. Calcd for $C_{12}H_7N_3S{\cdot}0.5H_2O$: C, 61.52; H, 3.44; N, 17.94. Found: C, 61.52; H, 3.17; N, 17.65.

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Supporting Information Available: Experimental, simulated, and difference spectra for **1a** and **2a** and simulation parameters. This material is available free of charge via the Internet at http:/pubs.acs.org.

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