

New π -Delocalized Persistent Radicals

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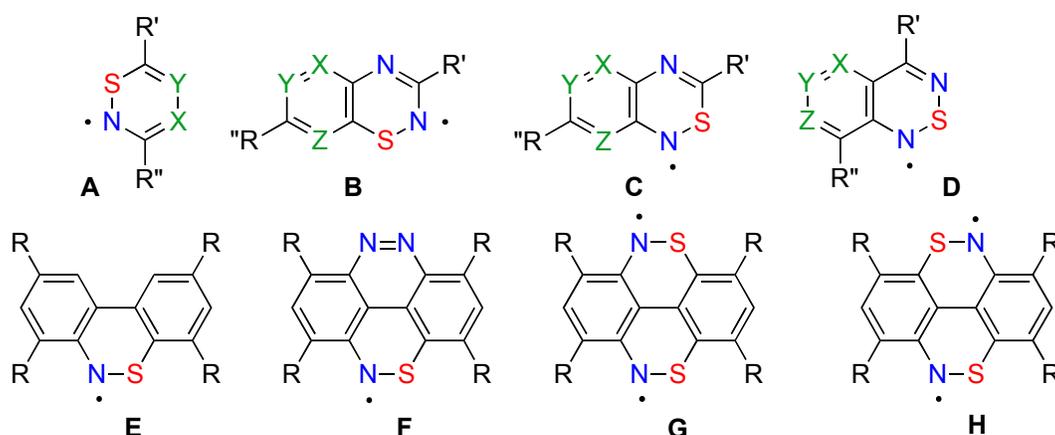
Abstract: Progress in the theoretical and experimental investigation of heterocyclic radicals suitable for incorporation into the structure of a liquid crystalline molecule is described. Five classes of heterocyclic systems are discussed, including their methods of preparation, stability and further functionalization to form potentially mesogenic materials.

Introduction

Over the past decade, we have been developing liquid crystalline radicals in order to study the magnetic behavior of stable radicals in organized media [1]. In this context, we have focused on electrically neutral π -delocalized heteroaromatic radicals containing the thioaminyll fragment [2]. Some of the possible heteroaromatic radicals are shown in Figure 1. The one- and two-ring radicals **A-D** are designed to be structural elements of calamitic (or rod-like) mesogens, while the three- and four-ring systems (**E-H**) are intended for construction of disk-like molecules expected to exhibit columnar phases [3].

Included among the synthetic targets are biradicals **G** and **H**. The former, a distant cousin of *m*-xylylene, is predicted to have a triplet ground state more stable than the singlet by at least 2.5 kcal/mol [4]. The availability of such a system makes it possible, in principle, to design a binary liquid crystalline mixture (e.g. **F** and **G**) with potential ferrimagnetic behaviour in the solid state.

Figure 1. Potential structural elements for liquid crystalline radicals. X, Y, Z = N, CH, C-F, C-Cl; R = poly[alkyl(oxy)]phenyl; R', R'' = alkyl(oxy), cycloalkyl, aryl.



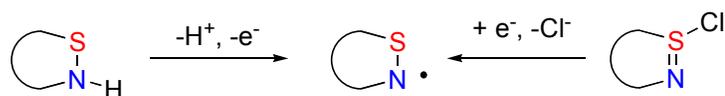
Most the heterocycles shown in Figure 1 are derived from previously unknown ring systems. Thus, in the first phase of the project, we focused on the development of synthetic methodologies for the construction of selected heterocyclic skeletons [5-8]. In parallel, we have developed a computational protocol to evaluate spin distribution, hyperfine coupling constants (hfcc), and redox properties of the heteroaromatic radicals [9]. Here we summarize our recent progress in the area of persistent free radicals.

Results and Discussion

Generation of Radicals.

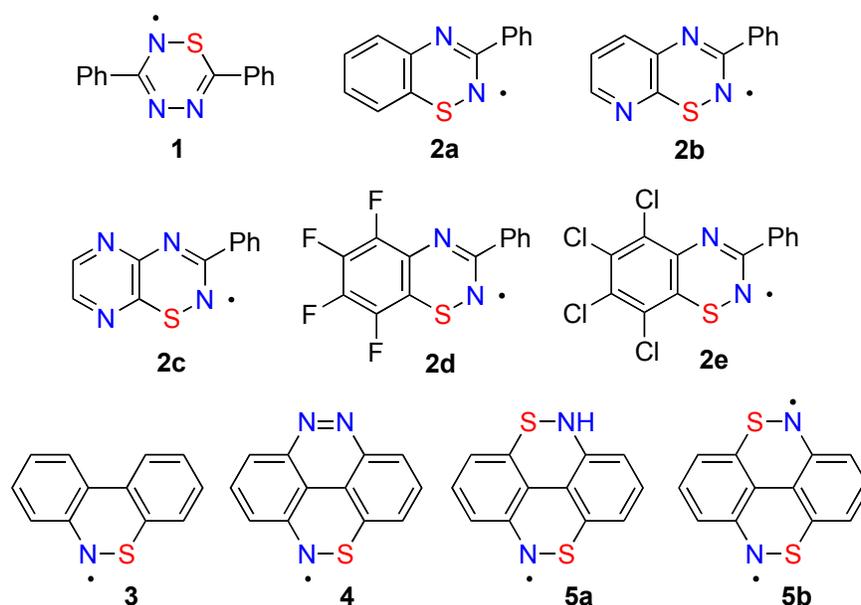
Considering the structural complexity and chemical sensitivity of the potential liquid crystalline molecules, we focused on oxidation of 1,2-thiazines as precursors for radical generation, rather than reduction of the appropriate sulfiminyl chlorides (Figure 2). The 1,2-thiazines are generally stable, they can be prepared in a regiospecific manner and their purification is straightforward [6,8,10]. In contrast, the sulfiminyl chlorides and salts are known to be reactive, highly moisture sensitive and many are strong oxidizing reagents, which may be incompatible with some functional groups [11,12]

Figure 2. Two general methods to generate the thioaminyl radicals.



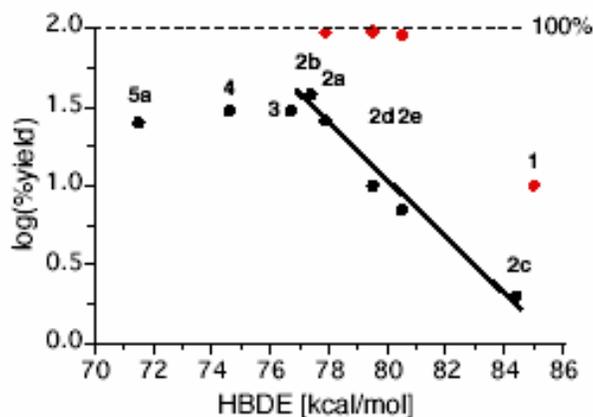
Thus far, we have synthesized nine 1,2-thiazines as precursors to five classes heterocyclic radicals (A, B, E, F, and H) shown in Chart I [6,8,10,13].

Chart I



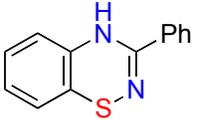
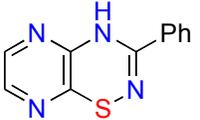
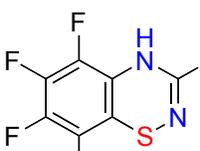
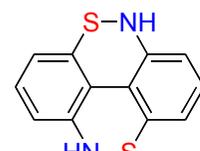
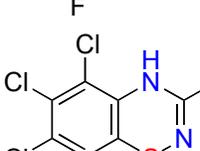
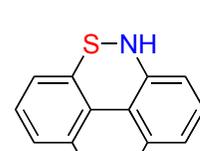
Initially, we used rigorously dried $\text{PbO}_2/\text{K}_2\text{CO}_3$ in benzene [14] to generate radicals from the corresponding sulfenamides. Under these conditions, several radicals were formed in respectable yields of about 30-40% (Table 1). However, the reactions were incomplete, which complicated attempts to isolate and purify the radicals. The pyrazino derivative **2c** and halogenated radicals **2d** and **2e** were formed only in low yields, impractical for preparative work. Attempts to generate **1** or **5b** by this method were frustratingly unsuccessful [6,13].

Figure 3. A plot of $\log(\% \text{ yield})$ vs Homolytic Bond Dissociation Energy (HBDE) for selected radicals generated with $\text{PbO}_2/\text{K}_2\text{CO}_3$ in benzene (circles) and $\text{AgO}/\text{K}_2\text{CO}_3$ in MeCN/toluene (red diamonds). The best fit line for **2** (circles): $\log(\% \text{ yield}) = 15.3 - 0.18 \times \text{HBDE}$ ($R^2 = 0.97$).



The efficiency of radical generation under these conditions would appear to depend upon the N-H homolytic bond dissociation energy (HBDE) of the precursor (Table 1 and Figure 3). The highest yields of about 30% were obtained for **2b-H**, **3-H**, **4-H** and **5a-H**, which have calculated HBDE's <78 kcal/mol. For compounds with higher HBDE values, the yield of radicals diminishes to 0 at about 85 kcal/mol (see Table 1).

Table 1. Calculated N-H Homolytic Bond Dissociation Energies (HBDE) and yields of radicals for selected compounds relative to methanol.

Compound	HBDE ^a [kcal/mol]	Yield ^b %	Compound	HBDE ^a [kcal/mol]	Yield ^b %
 2a-H^c	77.9	26	 1-H^d	85.0	0
 2b-H^c	77.4	38	 3-H^e	76.7	~30
 2c-H^c	84.4	2	 4-H^e	74.6	~30
 2d-H^c	79.5	10	 5a-H^f	71.5	~25
 2e-H^c	80.5	7	 5a^f	77.3	0

^a Homolytic Bond Dissociation Enthalpy was calculated with B3LYP/6-31G(d) using a general hypothetical reaction $RR'N-H + MeO\cdot \rightarrow RR'N\cdot + MeOH$ and the experimental value for HBDE for MeOH (Berkowitz, J.; Ellison, G. B.; Gutman, D. *J. Phys. Chem.* **1994**, *98*, 2744-2765).

^b Approximate spin yield in oxidation with PbO_2/K_2CO_3 in benzene.

^c Ref.15.

^d Ref.6.

^e Ref.10.

^f Ref. 13.

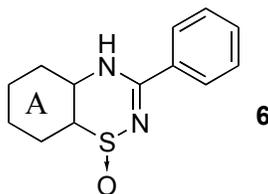
An analysis of the data for a series of systematically investigated radicals **2** [15], shows a strong correlation between HBDE and log (%yield) (Figure 3). The formation of biradical **5b** by oxidation of **5a-H** could not be detected spectroscopically. The biradical **5b** is predicted to have a singlet ground state, and therefore is ESR silent [1]. Since the concentration of the monoradical **5a** remained approximately constant regardless of the amount of PbO₂, the formation of **5b** could not be inferred. The results for **3-5** suggest that the yields of radicals generated using the PbO₂ method may have an upper limit of about 40%. This is consistent with results for acyclic sulfenamides, which typically give radicals in about 30-40% yield [16]. Thus, it appears that the HBDE can serve as an indicator of the efficiency for generation of radicals under these conditions.

Our recent systematic studies on the thiadiazine series **2** demonstrated that the strength of the oxidizing reagent and the polarity of the solvent play important roles in the efficiency of radical generation [15]. The results show that AgO/K₂CO₃ in either MeCN or a MeCN/toluene mixture is the most effective method for radical generation [17]. Under these conditions, radicals **2a**, **2d** and **2e** were generated in yields > 90% in less than 2 min (Figure 3). Also, the thiatriazinyl radical **1** was generated in about 10% spin yield [18]. This method holds much promise for the preparation of other radicals such as **3-5** in high yields and perhaps isolation as pure solids.

Stability of Radicals.

Thioaminyl radicals **1-4** are persistent and exhibit moderate to low sensitivity to oxygen. Solutions of **3** and **4** show significant stability to manipulation in air and quick filtration through Florisil. This is remarkable, considering that Ph-N-S-Ph, the acyclic analog of **3**, decomposes completely within 1 hr, [19] and requires additional substituents to enhance stability [20].

Detailed studies of thiadiazinyls **2** showed that their stability increases in the order **2c** < **2a** < **2b** < **2e** < **2d** [15]. Remarkable is the fact that the tetrafluoro derivative **2d** is more stable than the tetrachloro analog **2e**, which demonstrates the strong stabilizing effect of fluorine atoms on π -delocalized radicals. The kinetic data shows that **2d** has a half-life in solution of about 4 months in the absence of air, while in the presence of oxygen **2e** quickly decomposes with a half-life of about 40 min. The main decomposition product for **2** has been identified as the *S*-oxide **6**.

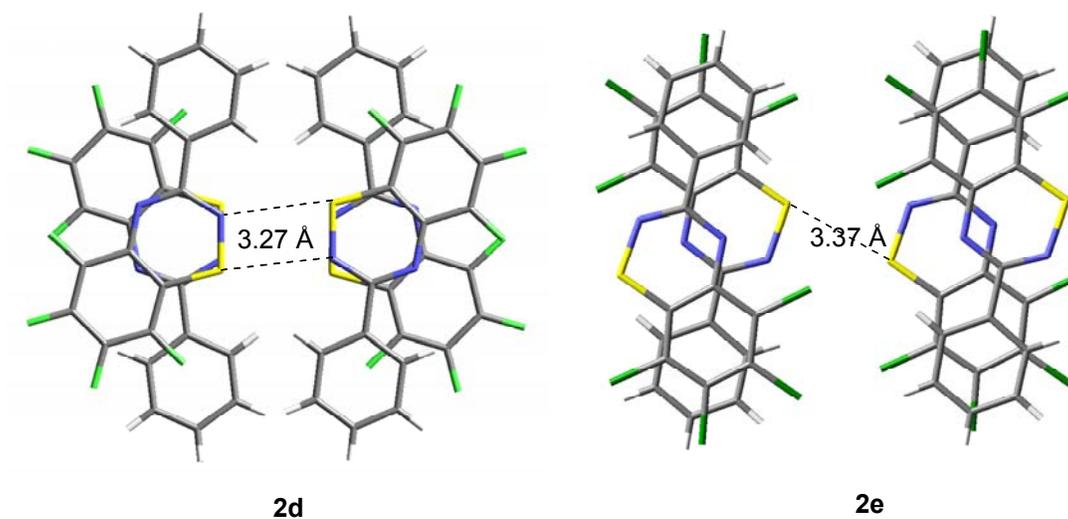


Among the three radicals that were generated in high yields, only **2d** and **2e** were sufficiently stable for chromatographic isolation and vacuum sublimation. This allowed a detailed investigation of their structural, spectroscopic, and electrochemical properties [15].

Solid State Structures.

So far only two radicals have isolated in the solid form suitable for X-ray crystallographic studies. Single crystal analysis revealed that **2d** and **2e** are nearly planar molecules, which is in agreement with DFT results for all radicals **2** [15]. The molecules of the tetrafluoro derivative **2d** are arranged in ideally parallel interpenetrating mirror-imaged stacks rotated by 166° (Figure 4). The stacking appears to be driven by SOMO-SOMO interactions largely localized on the thiadiazinyl rings. Surprisingly, the crystal structure shows little Peierls-type distortion or strong dimeric interactions typically observed for dithiadiazolyls [12]. Within each column, the S-N bonds form an infinite ladder-type structure with the ladder “rungs” slipped by 0.37 \AA . The intra-column $\text{S}\cdots\text{N}$ distance alternates between 3.193 \AA and 3.212 \AA , and the inter-column non-bonding $\text{S}\cdots\text{N}$ distance is about 3.27 \AA . These separations correspond to 93% - 95% of the van der Waals separation for the S and N atoms.

Figure 4. Partial packing diagrams for **2d** and **2e** viewed along the *c* axis (**2d**) and along the *a* axis (**2e**).



The packing of the tetrachloro analog **2e** within the crystal structure appears to be governed by quadrupolar interactions between the chlorinated and non-chlorinated benzene rings at the expense of the overlap between the thiadiazinyls (Figure 4). This is presumably due to the relatively large size of chlorine atoms, which do not allow for close face-to-face contact. The intermolecular separation within a column is about 3.45 \AA , which is about 0.25 \AA greater than that in **2d**. The $\text{S}\cdots\text{S}$ nonbonding distance for molecules in neighboring columns is about 3.4 \AA , which corresponds to 94% of the sum of the van der Waals radii.

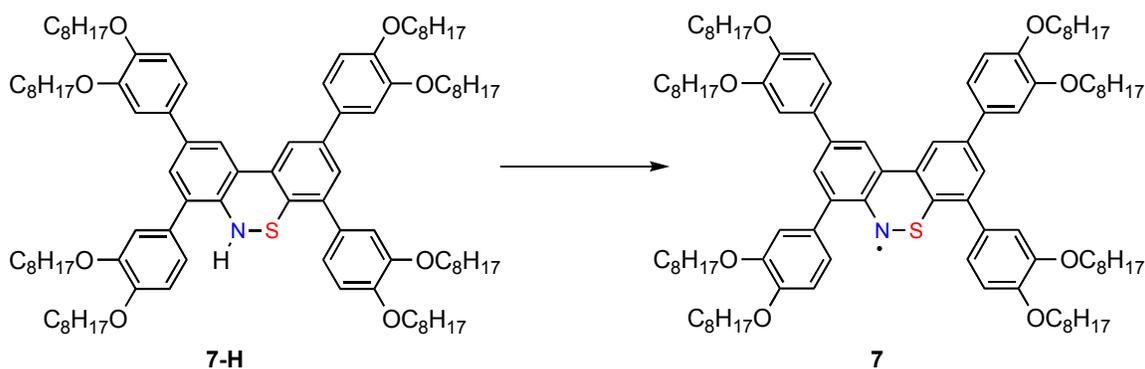
ESR analysis of the sublimed solid sample of **2d** revealed less than 1% of spin concentration at ambient temperature. This presumably results from the dominant antiferromagnetic spin alignment in the solid structure, which is consistent with theoretical analysis. Single point calculations at the

B3LYP/6-31+G(d) level for a pair of radicals (overlapping radicals **2d** in Figure 4) at their experimental atomic coordinates show a 5.2 kcal/mol preference for the singlet state over the triplet. Detailed temperature dependence studies will be necessary to better understand the solid state magnetic properties of this radical.

Towards Liquid Crystalline Radicals.

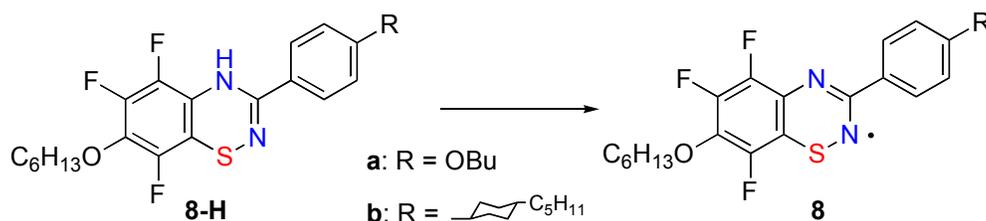
Results obtained for the parent radicals were encouraging and indicated that **2d**, **3** and **4** are sufficiently stable to be used as structural elements for liquid crystals. So far we have attempted the preparation of two such derivatives: the potentially discotic radical **7** and potentially calamitic radical **8**. The cyclic sulfenamide **7-H** exhibits columnar properties with a clearing temperature of 105 °C. This suggests that the radical **7** will also exhibit the desired mesogenic properties. Oxidation of **7-H** with the PbO₂/K₂CO₃ method in benzene gave moderate yields of the corresponding persistent radical **7** [21]. The use of the SO₂Cl₂/pyridine method [15] allowed the generation of **7** in high yield and isolation in the pure form. The dark-green material appeared to exhibit liquid crystalline behavior at ambient temperature. Unfortunately, detailed studies were hampered by its relatively fast decomposition in the presence of air, presumably accelerated by the presence of pyridinium salt impurities.

Scheme 1.



More recently, we prepared thiadiazines **8a-H** and **8b-H** and found that the latter exhibits smectic behavior [22]. Thiadiazine **8a-H** was oxidized to the corresponding radical **8a** using the SO₂Cl₂/pyridine method [15]. The crude radical was isolated as an 80% pure dark-green solid by passing the reaction mixture through Florisil and removing the solvent. The solid melted in air with rapid decomposition at about 78 °C. Again, the presumed presence of pyridinium salt impurities in the crude solid could lower the stability of the radical.

Scheme 2.



We are currently reinvestigating the preparation of **7** and **8** using the more effective AgO/K₂CO₃/MeCN method.

Summary and Prospects

We have made significant progress in experimental and theoretical investigations of persistent heterocyclic 1,2-thiazinyl radicals. Through systematic studies, we have found an efficient method for generation and isolation of such radicals from the corresponding cyclic 1,2-thiazines. Thus far two radicals have been isolated in the pure form, and others are being investigated.

Our results indicate that fluorination of the heteroaromatic nucleus provides an effective way to stabilize the radicals. The radicals are still moderately sensitive to molecular oxygen and require an anaerobic atmosphere for characterization in the liquid state (molten or solutions). Nevertheless, they are suitable for structural elements of liquid crystals, and such studies are already underway.

One such potentially mesogenic radical is **8b**, based on the parent **2d**. Its structure lends itself to further structural modification. Our synthetic methodology allows for facile incorporation of a number of substituents in the 7 position and modification of the phenyl group.

The availability of crystalline samples of **2d** and **2e** also provides opportunities for studies of crystalline molecular magnetic materials. It is conceivable that the judicious choice of substituents in benzo-1,2,4-thiadiazinyl can be used to engineer desired crystal structures and consequently to tune spin-spin interactions in the solid state.

Acknowledgments

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References and Notes

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17. Typical experimental procedure: precursor (1 mmol) was dissolved in dry toluene (7 mL) and dry MeCN (7 mL) was added. The solution was vigorously stirred over dry powdered AgO (1.23 g, 10 mmol) and K₂CO₃ (1.38 g, 10 mmol) at ambient temperature for 90 sec. The resulting black-green reaction mixture was diluted with toluene (10 mL), the solution was decanted from inorganic solids and filtered through a short jacketed column (5 cm of Florisil and 0.5 cm of silica) at -78 °C. Solvents were removed under reduced pressure (~1 Torr) at temperatures below 0 °C leaving a black-green solid of the radical.
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Sample Availability: Available from the authors.