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Non-innocent pyridyl nitrogens: unprecedented interconversion of *N*-bridgehead-thiadiazolium salts and thiatriazine in the generation of thiatriazinyl[†]

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Condensation of *N*-2-pyridylimidoyl-2-pyridylamidine with S_2Cl_2 affords fused *N*-bridgehead-1,2,5-thiadiazolium salts, which can be converted to 3,5-bis(2-pyridyl)-4-hydro-1,2,4,6-thiatriazine (Py₂TTAH). Oxidation of Py₂TTAH with iodine yields the corresponding 1,2,4,6-thiatriazinyl radical, identified by EPR spectroscopy.

Over the past decade, much research has focused on the use of stable neutral radicals as building blocks for molecular conductors and magnetic materials.^{1,2} Their application as spin bearing ligands in coordination complexes has also been actively pursued.^{1,3} Within this context, the use of chelating heterocyclic neutral radicals is an attractive design strategy, as has been demonstrated by pyridyl functionalized verdazyls $(1, \text{Chart } 1)^4$ and dithiadiazolyls (2).⁵ In principle, the 1,2,4,6thiatriazinyl (TTA) framework,⁶ a neutral seven π -electron ring system, represents an ideal building block in the rational design of chelating spin bearing ligands.⁷ In particular, 3,5-bis(2-pyridyl)-1,2,4,6-thiatriazinyl (3; Py2TTA) would possess a chelating environment similar to that of 2,2';6',2"-terpyridine (terpy); a tridentate ligand that has received a great deal of attention (e.g., close to 3000 publications in the last five years) due to its potential in a wide range of research areas (e.g., biomedical applications, catalysis,



^a Department of Chemistry and Centre for Catalysis Research and Innovation, University of Ottawa, 10 Marie Curie, Ottawa, ON K1N 6N5, Canada. E-mail: jbrusso@uottawa.ca gas adsorption, magnetic materials, organic electronics, *etc.*).⁸ Given the immense interest in coordination complexes based on terpy, the generation of a structural mimic in which one of the pyridine rings is replaced by a **TTA** radical is appealing. Although phenyl functionalized **TTA** radicals are known, the reactivity of the pyridyl derivatives described here is profoundly different due to the presence of non-innocent pyridyl nitrogens, which can coordinate to sulphur and generate *N*-bridgehead-heterocycles.⁹ In that regard, the unprecedented but necessary interconversion of an *N*-bridgehead-1,2,5-thiadiazolium salt to a 1,2,4,6-thiatriazine (**TTAH**) precedes the generation of **3**. Herein, the synthetic sequence and molecular structures of the intermediates will be presented along with EPR characterization of the 3,5-bis(2-pyridyl)-1,2,4,6-thiatriazinyl radical (**3**).

The first report of a TTA radical was described by Markovskii et al. using EPR spectroscopy.¹⁰ Since then, both symmetrically and asymmetrically substituted TTA radicals have been prepared, most of which are, at least partly, functionalized with aryl groups.6,11-13 Known preparative routes include the reaction of amidines with S₃N₃Cl₃^{6,11} or condensation of imidoylamidine hydrochlorides with excess SCl₂,^{13,14} followed by reduction with Ph₃Sb. Our synthetic sequence followed a similar route, as outline in Scheme 1, in which N-2-pyridylimidoyl-2-pyridylamidine (4), prepared from reaction of 2-cyanopyridine with NH₃(g), was treated with S₂Cl₂. This reaction did not, however, generate the anticipated 3,5-bis(2-pyridyl)-1-chloro-1,2,4,6-thiatriazine. Instead, the condensation afforded [5][Cl]HCl, a dication containing N-bridgehead-1,2,5-thiadiazolium and pyridinium moieties. This material was isolated as an insoluble chloride salt, which was metathesized using trimethylsilyl triflate to a soluble triflate salt ([5][OTf] HOTf). Crystallization from acetonitrile (MeCN) afforded colourless needles suitable for X-ray analysis, the results of which are shown in Fig. 1a.[‡] The planarity of [5][OTf]·HOTf (mean deviation of 0.0746 Å from the 18 atom framework), coupled with its short C-N bond lengths, suggests some degree of resonance delocalization along the central N-C-N-C-N backbone.

Initially, isolation of [5][Cl]·HCl was surprising as we were expecting to generate 3,5-bis(2-pyridyl)-1-chloro-1,2,4,6-thiatriazine.

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(a) C5 C12	Bond (Å)	[5]⁺∙H⁺	[6] ²⁺
C6 C4 N2 N5 C10 C10	N1-C1	1.318(3)	1.298(4)
	N1-S1	1.636(2)	1.627(3)
N4 C1 C2 C8 C9	S1-N4	1.726(2)	1.710(3)
(b) \$1 N1 N3	C3-C1	1.449(3)	1.444(4)
	C1-N2	1.358(3)	1.377(4)
C5 C10	N2-C2	1.314(3)	1.382(4)
C6 C7 N4 C1 C2 C2 C2 C2 C2 C2 C2 C2 C2 C2 C2 C2 C2	C2-C8	1.490(3)	1.445(4)
	C2-N3	1.321(3)	1.298(4)
	N3-S2		1.621(3)
	S2-N5		1.719(3)

Fig. 1 ORTEP drawings (50% thermal ellipsoids) of (a) [5][OTf]·HOTf and (b) $[6][OTf]_2$. Anions have been removed for clarity.

Clearly the reactivity of the pyridyl derivatives described here is in marked contrast to the previously reported phenyl functionalized TTA analogues. This is attributed to the ability of the pyridyl nitrogen atoms to coordinate to sulphur. To our knowledge, the only other example of such an interaction was reported by Rawson et al.9 Given the availability of two pyridyl substituents, the possibility of generating a bis(N-bridgehead-1,2,5-thiadiazolium) dication $[6]^{2+}$ was considered. To that end, N-2-pyridylimidoyl-2-pyridylamidine (4) was treated with excess S_2Cl_2 at reflux, affording $[6]^{2+}$ as an insoluble chloride salt that gave a distinctly different IR spectrum compared to [5][Cl]·HCl. To confirm the identity of $[6]^{2+}$, it was converted into the corresponding triflate salt, [6][OTf]₂, by treatment with trimethylsilyl triflate. Colourless needles suitable for structural analysis were obtained by crystallization from MeCN (Fig. 1b), demonstrating that $[6]^{2+}$ is comprised of two nearly identical



Fig. 2 ORTEP drawings (50% thermal ellipsoids) of **7** viewed from (a) above and (b) side of the molecular framework.

N-bridgehead-1,2,5-thiadiazolium moieties linked together by a central nitrogen atom, which are twisted with respect to one another by an angle of $33.26(4)^\circ$.

With $[6]^{2+}$ in hand, a two-electron reduction could afford a diradical or lead to ring opening, as proposed by Rawson.⁹ In our hands, treatment of $[6][Cl]_2$ with Ph₃Sb at reflux generated a deep burgundy solution which, upon cooling, afforded deep red needles of 3,5-bis(2-pyridyl)-4-hydro-1,2,4,6-thiatriazine (7); the structural identity of which was confirmed by X-ray analysis (Fig. 2). This closed-shell molecule is bent along the N2–S1 axis with an angle of 153.83(3)° between the two halves of the framework. This, coupled with the short C1–N1 and C2–N3 bond lengths, indicates an antiaromatic structure, as is expected for **TTAH**.¹⁵

Alternatively, 7 can also be prepared *via* thermolysis of [5][Cl]·HCl at 140 °C *in vacuo* or at reflux in chlorobenzene. It is therefore apparent that the key intermediates in the formation of pyridine functionalized **TTA** heterocycles are the *N*-bridgehead-1,2,5-thiadiazolium cations. Furthermore, treatment of 7 with a proton source (*e.g.*, HCl_(g)) regenerates [5][Cl]·HCl. Thus, thermal treatment of [5][Cl]·HCl causes rearrangement to the thiatriazine, whereas the presence of acid favours **TTAH** ring opening and generation of [5][Cl]·HCl. This unprecedented interconversion of the *N*-bridgehead-1,2,5-thiadiazolium and **TTAH** may be monitored visually, as [5][Cl]·HCl is a colourless solid and 7 is deep red. Accordingly, this system may have potential in thermo/acidochromic applications.

Regardless of how pyridine functionalized **TTAH** is prepared, its conversion to the corresponding radical, 3,5-bis-(2-pyridyl)-1,2,4,6-thiatriazinyl (3), can be effected by oxidation. To that end, treatment of 7 with half an equivalent of iodine in the presence of base (*e.g.*, 4-dimethylaminopyridine) yields a dark red solution that exhibits a strong and persistent EPR signal (Fig. 3) whose appearance is consistent with **TTA** radicals bearing electron-withdrawing substituents that polarize spin density away from the N–S–N region of the **TTA** core.^{12,16} Indeed the EPR spectrum of **3** is virtually identical to that reported for 3,5-bis(*p*-nitrophenyl)-1,2,4,6-thiatriazinyl (*cf. g* = 2.0055; $a_N = 0.372$ mT; $a_N = 0.427$ mT).¹² Accordingly, the observed signal consists of a complex multiplet that can be simulated using a model based on hyperfine coupling to two equivalent and one unique ¹⁴N nuclei (experimentally derived



Fig. 3 (a) Experimental and simulated EPR spectrum of 3 in DCM (g = 2.0068; SW = 3.5 mT; LW = 0.024 mT). (b) Experimentally derived and UB3LYP/EPR-II/6-31G(d)//UB3LYP/6-311G(d,p) calculated (in parenthesis) coupling constants a_N (in mT). (c) UB3LYP/6-311G(d,p) singly occupied molecular orbital.

constants: $a_{\rm N}$ = 0.377 mT; $a_{\rm N}$ = 0.438 mT; calculated coupling constants: $a_{\rm N}$ = 0.347 mT; $a_{\rm N}$ = 0.420 mT).

Based on this study, it is clear the presence of pyridyl substituents in the development of sulphur/nitrogen heterocycles has a significant impact on reaction pathways. In particular, the coordinating ability of the pyridine nitrogen atoms, and the apparent proclivity of pyridyl ligands to form *N*-bridgehead-heterocycles, is an important finding and holds potential in the design of novel open and closed shell heterocyclic compounds. The synthetic challenges associated with non-innocent pyridyl nitrogens can be overcome, as demonstrated here in the preparation of the 3,5-bis(2-pyridyl)-1,2,4,6-thiatriazinyl radical (3). In conclusion, not only do we anticipate rich coordination chemistry for this radical acting as a multidentate chelating ligand, we also foresee the possibility of developing new radical ion and biradical systems from controlled reduction of $[6]^{2+}$ and related compounds.

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Notes and references

‡ Crystal data at 200(2) K for [5][OTf]-HOTf: C₁₄H₁₁F₆N₅O₆S₃, *M* = 555.46, triclinic, *a* = 9.1987(3) Å, *b* = 9.8364(3) Å, *c* = 11.7652(4) Å, *α* = 94.5844(16)°, β = 102.6573(17)°, γ = 92.0173(17)°, *V* = 1033.82(6) Å³, space group *P*I, *Z* = 2, 5084 reflections measured, 3959 unique (*R*_{int} = 0.0288). The final

wR(*F*₂) was 0.1220 (all data). Crystal data at 296(2) K for [6][OTF]₂: C₁₄H₉F₆N₅O₆S₄, *M* = 585.50, triclinic, *a* = 8.4770(3) Å, *b* = 10.1380(3) Å, *c* = 12.6490(4) Å, *α* = 88.7192(17)°, *β* = 78.5886(16)°, *γ* = 83.6975(17)°, *V* = 1059.12(6) Å³, space group *P*₁, *Z* = 2, 4339 reflections measured, 3639 unique (*R*_{int} = 0.0188). The final wR(*F*₂) was 0.1195 (all data). Crystal data at 200(2) K for 7: C₁₂H₉N₅S, *M* = 255.30, monoclinic, *a* = 13.6633(4) Å, *b* = 3.84480(10) Å, *c* = 22.7022(7) Å, *β* = 106.326(2)°, *V* = 1144.52(6) Å³, space group *P*₂₁/*c*, *Z* = 4, 2799 reflections measured, 2174 unique (*R*_{int} = 0.0377). The final wR(*F*₂) was 0.1183 (all data).

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