

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-pyridylimido-2-pyridylamidine with S₂Cl₂ 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**, Chart 1)⁴ and dithiadiazolyls (**2**).⁵ In principle, the 1,2,4,6-thiatriazinyl (**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,

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 imidoamidine 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-pyridylimido-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.

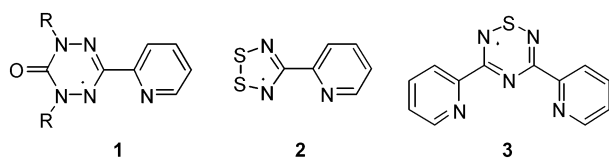


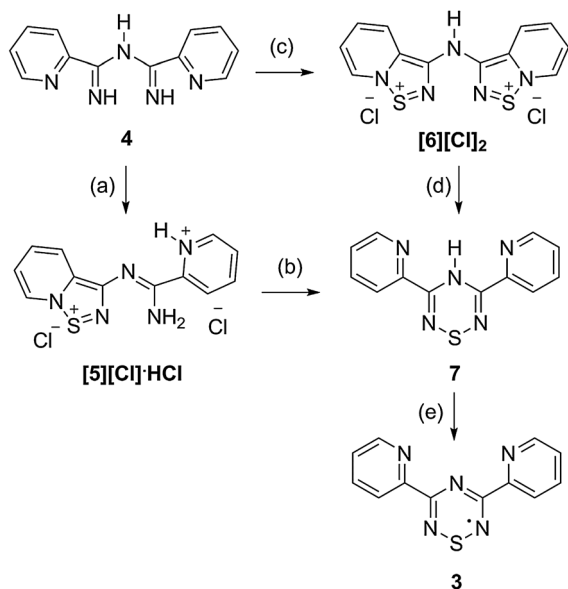
Chart 1

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Scheme 1 Synthesis of bis(2-pyridyl)-1,2,4,6-thiatriaziny radical. *Reagents and conditions:* (a) S_2Cl_2 , MeCN, RT; (ii) $100\text{ }^\circ\text{C}$, 10^{-2} mmHg ; (b) $140\text{ }^\circ\text{C}$, 10^{-2} mmHg ; (c) S_2Cl_2 , MeCN, reflux; (d) Ph_3Sb , MeCN, reflux; (e) DMAP, I_2 , DCM.

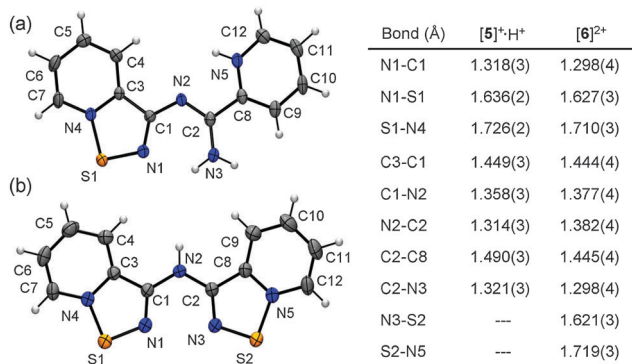


Fig. 1 ORTEP drawings (50% thermal ellipsoids) of (a) $[\text{5}][\text{OTf}]\cdot\text{HOTf}$ and (b) $[\text{6}][\text{OTf}]_2$. Anions have been removed for clarity.

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 $[\text{6}]^{2+}$ was considered. To that end, *N*-2-pyridylimidoyl-2-pyridylamide (**4**) was treated with excess S_2Cl_2 at reflux, affording $[\text{6}]^{2+}$ as an insoluble chloride salt that gave a distinctly different IR spectrum compared to $[\text{5}][\text{Cl}]\cdot\text{HCl}$. To confirm the identity of $[\text{6}]^{2+}$, it was converted into the corresponding triflate salt, $[\text{6}][\text{OTf}]_2$, by treatment with trimethylsilyl triflate. Colourless needles suitable for structural analysis were obtained by crystallization from MeCN (Fig. 1b), demonstrating that $[\text{6}]^{2+}$ is comprised of two nearly identical

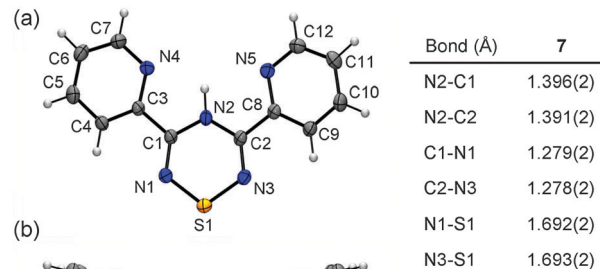


Fig. 2 ORTEP drawings (50% thermal ellipsoids) of **7** viewed from (a) above and (b) side of the molecular framework.

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 $[\text{6}]^{2+}$ 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 $[\text{6}][\text{Cl}]_2$ with Ph_3Sb 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 $153.83(3)^\circ$ 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 $[\text{5}][\text{Cl}]\cdot\text{HCl}$ at $140\text{ }^\circ\text{C}$ *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.*, $\text{HCl}_{(\text{g})}$) regenerates $[\text{5}][\text{Cl}]\cdot\text{HCl}$. Thus, thermal treatment of $[\text{5}][\text{Cl}]\cdot\text{HCl}$ causes rearrangement to the thiatriazine, whereas the presence of acid favours **TTAH** ring opening and generation of $[\text{5}][\text{Cl}]\cdot\text{HCl}$. This unprecedented interconversion of the *N*-bridgehead-1,2,5-thiadiazolium and **TTAH** may be monitored visually, as $[\text{5}][\text{Cl}]\cdot\text{HCl}$ 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-thiatriaziny (**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-thiatriaziny (*cf.* $g = 2.0055$; $a_{\text{N}} = 0.372\text{ mT}$; $a_{\text{N}} = 0.427\text{ mT}$).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 ^{14}N nuclei (experimentally derived



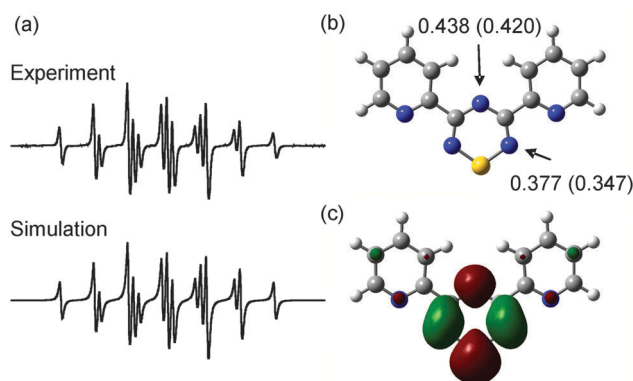


Fig. 3 (a) Experimental and simulated EPR spectrum of **3** in DCM ($g = 2.0068$; SW = 3.5 mT; LW = 0.024 mT). (b) Experimentally derived and UB3LYP/EPR-II/6-31G(d)//UB3LYP/6-311G(d,p) calculated (in parenthesis) coupling constants a_N (in mT). (c) UB3LYP/6-311G(d,p) singly occupied molecular orbital.

constants: $a_N = 0.377$ mT; $a_N = 0.438$ mT; calculated coupling constants: $a_N = 0.347$ mT; $a_N = 0.420$ 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 $[5][OTf]\cdot HOTf$: $C_{14}H_{11}F_6N_5O_6S_3$, $M = 555.46$, triclinic, $a = 9.1987(3)$ Å, $b = 9.8364(3)$ Å, $c = 11.7652(4)$ Å, $\alpha = 94.5844(16)^\circ$, $\beta = 102.6573(17)^\circ$, $\gamma = 92.0173(17)^\circ$, $V = 1033.82(6)$ Å³, space group $P\bar{1}$, $Z = 2$, 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 $[6][OTf]_2$: $C_{14}H_9F_6N_5O_6S_4$, $M = 585.50$, triclinic, $a = 8.4770(3)$ Å, $b = 10.1380(3)$ Å, $c = 12.6490(4)$ Å, $\alpha = 88.7192(17)^\circ$, $\beta = 78.5886(16)^\circ$, $\gamma = 83.6975(17)^\circ$, $V = 1059.12(6)$ Å³, space group $P\bar{1}$, $Z = 2$, 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**: $C_{12}H_9N_3S$, $M = 255.30$, monoclinic, $a = 13.6633(4)$ Å, $b = 3.84480(10)$ Å, $c = 22.7022(7)$ Å, $\beta = 106.326(2)^\circ$, $V = 1144.52(6)$ Å³, space group $P2_1/c$, $Z = 4$, 2799 reflections measured, 2174 unique ($R_{int} = 0.0377$). The final $wR(F_2)$ was 0.1183 (all data).

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