Aryldiazonium Salts as Nitrogen-Based Lewis Acids: Facile Synthesis of Tuneable Azophosphonium Salts


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Abstract: Inspired by the commercially available azoimidazolium dyes (e.g., Basic Red 51) that can be obtained from aryldiazonium salts and N-heterocyclic carbenes, we developed the synthesis of a unique set of arylazophosphonium salts. A range of colours were obtained by applying readily tuneable phosphine donor ligands and para-substituted aryldiazonium salts as nitrogen-based Lewis acids. With cyclic voltammetry, a general procedure was designed to establish whether the reaction between a Lewis acid and a Lewis base occurs by single-electron transfer or electron-pair transfer.

Figure 1. Lewis acid (C₅H₅N) and base (Ph₂C) augmented activation of N₂. According to the HOMO (bottom) and LUMO (top) energies (in eV) calculated at the ωB97X-D/6-311 + G(d,p) level of theory,[24] its π⁺ acceptor orbital (LUMO: from +1.30 (N₂) to −6.24 eV; see Figure 1). This makes aryldiazonium salts suitable nitrogen-based Lewis acids,[9] which we were keen on investigating.

Figure 2. Reported aryldiazonium–phosphine adducts.
and co-workers characterized C only spectroscopically (R = Cl, CN, SO₂NH₂, C(O)OEt; Figure 2). Herein, we report on the facile synthesis of readily tuneable azophosphonium salts simply from phosphines and arylazidation tetrafluoroborates in anecotitile, and provide detailed mechanistic insight by experimental and computational means. Related reactions of phenylazidation tetrafluoroborate with tertiary amines have also been investigated.

We found that treatment of the phenyldiazonium salt [PhN=][BF₄] [29] with triphenylphosphine (1.0 equiv) in acetonitrile at 0°C afforded the red azophosphonium salt [PhN=-(PPh₃)][BF₄] 1 (δ¹³P[H] = 39.4 ppm; Scheme 1; ΔE = −43.5 kcal mol⁻¹ at the oB97X-D/6-311 + G(d,p) level of theory) [10] in near-quantitative yield after work-up; only a minor side product could be detected by ³¹P NMR spectroscopy (ca. 2%; δ¹³P[H] = 43.9 and 52.5 ppm, JPP = 18.8 Hz) [10], which we tentatively ascribed to the bis-phosphine adduct [PhN(PPh₃)N(PPh₃)][BF₄]. [20] As Horner and Stöhr had indicated [10] that compound 1 is unstable both in solution and in the solid state, [10] we resorted to the stronger and sterically more encumbered donor tert-butylphosphine, which, according to DFT calculations at the oB97X-D/6-311 + G(d,p) level of theory, should provide a more stable product (ΔE = −53.2 kcal mol⁻¹). [10] The reaction of phenyldiazonium tetrafluoroborate with Bu₄P (1.1 equiv) in acetonitrile resulted in an immediate colour change from colourless to pink and afforded azophosphonium salt ([PhN=][BF₄] 2a (δ¹³P[H] = 69.4 ppm; Scheme 1) as the sole product in 95% yield upon isolation. Gratifyingly, this cationic Lewis adduct is stable towards air, moisture, and even an aqueous 2M HCl solution (only the tetrafluoroborate anion hydrolysed over time). [21] The molecular structure of 2a (Scheme 1), [22,23] determined by X-ray crystal-structure analysis of suitable crystals of its tetraphenylborate analogue (obtained after anion exchange with NaBPh₄ in DCM) [20] displays an almost planar (P1-N1-N2-C1 173.4(7)) trans azarylazophosphonium moiety with a disordered azo group. The C–N and N–N bond lengths (1.437(7) and 1.245(6) Å, respectively) are comparable to those of the related arylazodiadzolium borates [ArN=-(IMes)][BPh₄] (Ar = Mes, o/p-CIC₆H₄) reported by Severin and co-workers (C–N: 1.411(2)/1.395(4)/1.455(13); N–N: 1.265(2)/1.266(9)/1.242(2) Å, respectively), [11] illustrating that in these cationic azo dyes, phosphines behave similar to carbenes.

As the colour of the azarylazophosphonium salts can be readily tuned by changing the donor ligand (1 (L = PPh₃): red; 2a (L = Bu₄P: pink), we next investigated the influence of the para substituent on the arenic ring on the photophysical properties of 2. Treatment of the 4-substituted phenyldiazonium salts [(p-R-C₆H₄)N=][BF₄] (R = NO₂ (b), Br (e), OMe (d), NMe₂ (e)) [19] with tert-butylphosphine (1.1 equiv) in acetonitrile afforded the intensely coloured (from purple to red/brown) aryarylazophosphonium salts [(p-R-C₆H₄)N=-(PBu₄)][BF₄] 2b–e in 87–96% yield upon isolation (Scheme 1 and Figure 3). [10] Evidently, the para substituent has a direct influence on the ³¹P NMR chemical shift as well as the colour (see Table 1 and Figure 3), which we further substantiated by UV/Vis spectroscopy. Compounds 2a–

![Scheme 1. Synthesis of azarylazophosphonium tetrafluoroborates 1 and 2a–e and molecular structure of [(C₆H₄)N=-(PBu₄)][BF₄] (2a–BP₄₄; displacement ellipsoids are set at 30% probability, hydrogen atoms and the noncoordinating BPh₄ anion are omitted for clarity, one disorder component is shown). Selected bond lengths [Å] and torsion angles [°] (values for the second disorder component in square brackets): P1–N1A 1.742(5) [1.766(7)], N1A–N2A 1.245(6) [1.245(8)], N2A–C1A 1.437(7) [1.439(8)], P1–N1A–N2A–C1A 173.4(7) [167.3(11)].](Image 18x803 to 58x825)

![Figure 3. UV/Vis spectra and colours of azophosphonium salts 2a–e in solution (0.006 M in CH₃CN) and in the solid state (from left to right: 2a, 2b, 2c, 2d, and 2e).](Image 52x193 to 291x389)
show an intense absorption maximum ranging from $\lambda_{\text{max}} = 303$ to $464$ nm along with a weak absorption in the visible region at $\lambda_{\text{max}} = 453$–523 nm that displays a gradual bathochromic shift from electron-withdrawing to electron-donating para substituents (Table 1). Changing the solvent from acetonitrile to DCM led to a small bathochromic shift ($\Delta \lambda_{\text{max}} = 4$–11 nm), indicating a minor influence of the solvent.\(^{[10]}\)

Time-dependent DFT calculations at the CAM-B3LYP/6–311 G* level of theory\(^{[20,24]}\) reveal two low-lying excitations for 2a–e with $\pi \rightarrow \pi^*$ (E-$S_1$) and $n \rightarrow \pi^*$ (E-$S_2$) character. The first excitation corresponds to the HOMO–LUMO transition (with 89–95 % weight contribution) from the n orbital, which is an out-of-phase combination of lone pairs on the two azo nitrogen atoms (Figure S10). As the azophosphonium dyes are not perfectly planar, this excitation has non-zero oscillator due to the admixture of n-orbitals from the aromatic ring (TD-DFT: 508 nm, $f = 0.0005$ for 2a).

The change in colour is determined by the para substituents, which have a stabilizing effect on HOMO and HOMO-1 and to a lesser extent on the LUMO (Table 1). The second excitation ($\pi \rightarrow \pi^*$ transition) is allowed (295 nm, $f = 0.5749$ for 2a), but outside the visible range (except for 2e, $R = \text{NMe}_2$). The $\pi$ and $\pi^*$ orbitals involved in these two excitations are bonding/antibonding orbitals centred mostly on the N–N moiety (Figure S10).

Intuitively, the phosphine–diazonium Lewis adducts 1 and 2 are the result of classical donor–acceptor reactivity. Yet, aryldiazonium salts are also known to undergo one-electron reduction in the presence of organic electron donors, generating aryldiazido radicals ($\text{ArN}_3^-$).\(^{[25]}\) Subsequent radical coupling with the concomitantly formed phosphine radical cation ($\text{R}^+$)\(^{[26]}\) presents an alternative pathway to afford these readily tuneable azophosphonium salts. As N-based Lewis bases, such as arylamines, are known to undergo one-electron oxidation by Lewis acids to generate the corresponding radical cations,\(^{[26]}\) we also included triphenylamine and triisopropylamine ($\text{Bu}_3\text{N}$ is still elusive)\(^{[27]}\) in our mechanistic study.

In contrast to the reaction with triphenylphosphine, treatment of phenyldiazonium tetrafluoroborate with triphenylphosphine yields azobenzene 3 (Scheme 2)\(^{[28]}\) by electrophilic aromatic substitution of the arylamine.\(^{[29]}\) Blocking the para position resulted in a different outcome. We discovered that treatment of [PhN$_3$][BF$_4$] with tri-$p$-tolylamine in CH$_2$CN afforded an immediate colour change to deep blue, characteristic of the formation of the radical cation [$p$-$\text{tol}$,$N^+$], which was confirmed by EPR spectroscopy (Figure S6).\(^{[30]}\) Compared to the cyclic voltammogram of triphenylamine ($E^\text{o}_p = 0.97$ V vs. Fe/Fe$^\text{II}$), the oxidation potential of the more electron-rich $p$-tolylamine is shifted to more negative potentials ($E^\text{o}_p = 0.78$ V vs. Fe/Fe$^\text{II}$; Table 2), which supports the notion that tri-$p$-tolylamine is more prone to one-electron oxidation than triphenylamine ($\Delta G^\circ = 20.3$ vs. 24.7 kcal mol$^{-1}$, respectively; Table 2).

Interestingly, the bulky triisopropylamine\(^{[31]}\) provided a different reaction course. Treatment of phenyldiazonium tetrafluoroborate with $\text{Pr}_3\text{N}$ (2 equivs) in CH$_2$CN resulted in the formation of triazene PhN$_3$-$\text{NiPr}_3$ (72 %,\(^{[26]}\) dissoziation of the azolinium cation (H$_2$N$\text{NiPr}_3$)$_2$BF$_4$)\(^{[30]}\) (Scheme 2).\(^{[30]}\) Cyclic voltammetry shows that the reaction of triisopropylamine with [PhN$_3$][BF$_4$] is, for thermodynamic reasons, unlikely to be initiated by single-electron transfer ($E^\text{o}_p$(PhN$_3$-$\text{NiPr}_3$/[BF$_4$]) = −0.10 V vs. Fe/Fe$^\text{II}$).

Table 1: $^{31}$P{H} NMR chemical shifts, optical properties, and energies of the frontier orbitals for azophosphonium salts 2a–e.$^{[10]}$

<table>
<thead>
<tr>
<th></th>
<th>$\Delta\nu_0$ [ppm]$^{[10]}$</th>
<th>$\lambda_{\text{max}}$ [nm]$^{[10]}$</th>
<th>HOMO</th>
<th>HOMO-1</th>
<th>LUMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>2a</td>
<td>69.4</td>
<td>316 (4.21)</td>
<td>515 (2.16)</td>
<td>$-12.1$</td>
<td>$-12.2$</td>
</tr>
<tr>
<td>2b</td>
<td>73.0</td>
<td>303 (4.29)</td>
<td>453 (2.68)</td>
<td>$-12.6$</td>
<td>$-12.8$</td>
</tr>
<tr>
<td>2c</td>
<td>70.3</td>
<td>336 (4.33)</td>
<td>517 (2.18)</td>
<td>$-11.6$</td>
<td>$-12.2$</td>
</tr>
<tr>
<td>2d</td>
<td>65.8</td>
<td>373 (4.44)</td>
<td>500 (2.49)</td>
<td>$-11.9$</td>
<td>$-11.9$</td>
</tr>
<tr>
<td>2e</td>
<td>59.6</td>
<td>464 (4.62)</td>
<td>$-30$ (0.56)</td>
<td>$-10.3$</td>
<td>$-10.5$</td>
</tr>
</tbody>
</table>

[a] Absorption wavelength corresponding to the lowest-energy transition ($\lambda_{\text{max}}$); molar extinction coefficients ($\epsilon$, M$^{-1}$ cm$^{-1}$); solvent: CH$_2$CN; HOMO, HOMO-1, and LUMO energies at $\omega$B97X-D/6–311 + G(d,p).

[b] $\pi \rightarrow \pi^*$ transition. [c] $n \rightarrow \pi^*$ transition. [d] The initially yellow solution becomes pink after a few hours and purple after a few days, indicating secondary interactions, [e] $n \rightarrow \pi^*$ transition not visible.

Scheme 2. Reaction of [PhN$_3$][BF$_4$] with tertiary amines.

Table 2: Frontier molecular orbitals and oxidation potentials of selected Lewis bases (LB), including the free energy changes for radical cation formation.$^{[10]}$

<table>
<thead>
<tr>
<th></th>
<th>HOMO</th>
<th>LUMO</th>
<th>$E^\text{o}_p$(LB/ LB$^\text{II}$) vs. Fe/Fe$^\text{II}$</th>
<th>$\Delta G^\circ$</th>
<th>$\Delta E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhN$_3$</td>
<td>$-7.10$</td>
<td>0.95</td>
<td>0.97 V vs. Fe/Fe$^\text{II}$</td>
<td>20.7</td>
<td>$-24.9$ kcal mol$^{-1}$</td>
</tr>
<tr>
<td>$p$-$\text{tol}$N</td>
<td>$-6.80$</td>
<td>1.04</td>
<td>0.78 V vs. Fe/Fe$^\text{II}$</td>
<td>20.3</td>
<td>$-24.9$ kcal mol$^{-1}$</td>
</tr>
<tr>
<td>$\text{Pr}_3\text{N}$</td>
<td>$-7.33$</td>
<td>1.69</td>
<td>1.20 V vs. Fe/Fe$^\text{II}$</td>
<td>30.0</td>
<td>$-24.9$ kcal mol$^{-1}$</td>
</tr>
<tr>
<td>$\text{Bu}_3\text{N}$</td>
<td>$-7.97$</td>
<td>0.92</td>
<td>1.23 V vs. Fe/Fe$^\text{II}$</td>
<td>30.7</td>
<td>$-24.9$ kcal mol$^{-1}$</td>
</tr>
<tr>
<td>$\text{Pr}_3\text{P}$</td>
<td>$-7.69$</td>
<td>1.53</td>
<td>0.90 V vs. Fe/Fe$^\text{II}$</td>
<td>23.3</td>
<td>$-24.9$ kcal mol$^{-1}$</td>
</tr>
</tbody>
</table>

[a] Calculated at $\omega$B97X-D/6–311 + G(d,p). [b] CH$_2$CN, 0.1 M $n$Bu$_3$N$^-$[PF$_6$]$^-$, glassy carbon working electrode, $\nu = 100$ mVs$^{-1}$. [c] $\Delta G^\circ = -nF E^\text{o}_\text{red} = -nRT \ln K_{\text{eq}}$, F = Faraday constant; $E^\text{o}_\text{red}(\text{PhN}_3^+)$ | $\text{H}^\circ$ = $-0.10$ V vs. Fe/Fe$^\text{II}$.
We postulate this to be the nitrosyl–phosphine 1978 100 57 Angew. Chem. Int. Ed. Based on the sizable free energy change for radical cation formation by one-electron oxidation of the phosphines (ΔG° > 23 kcal mol⁻¹; Table 2) and the facile formation of 1 and 2 at low temperatures (even at ~20°C),[10] we conclude that these azophosphonium salts are most likely formed by a two-electron Lewis acid–base coupling rather than single-electron transfer followed by radical coupling.

Oxidation of tri-tert-butylphosphine by single-electron transfer (SET) is feasible when using stronger oxidants. Treatment of tBu₃P with the nitrosonium salt [NO][BF₄] (E°ₚ(NO⁺/NO) = 0.87 V vs. Fe/Fe⁺)[32] in acetonitrile resulted in the formation of [tBu₃PH][BF₄] as the major product (δ¹³P = 56.1 ppm, Δν∥H = 445.6 Hz; Scheme 3).[10,33]

Scheme 3. Reaction of tBu₃P with [NO][BF₄] together with the experimental (black) and simulated (red) EPR spectra of tBu₃P·NO·.[10]

which could be attributed to H atom abstraction from the solvent by the reactive [tBu₃P⁺] radical cation intermediate (ΔG° = 0.7 kcal mol⁻¹).[14] In addition, we detected small amounts of a radical species by EPR spectroscopy (Scheme 3) that features a six-line pattern at gₑ,ₚ = 2.0071, Aₚ = +29.55 MHz, Aₑ = −34.10 MHz.

In summary, in acetonitrile, aryldiazonium salts react as nitrogen-based Lewis acids with phosphines, enabling the facile synthesis of tuneable azophosphonium salts. The corresponding azosubstituted cations (RS₂(NR₃)₂)⁺[X] are still elusive, but should be accessible with strongly donating tertiary amines that lack β-hydrogen atoms. We have shown that in addition to the established donor–acceptor reactivity, Lewis acids and bases can undergo one-electron processes, which will have profound impact on (frustrated) Lewis acid/ base chemistry and catalysis.[9] Currently, we are exploring the synthesis of azophosphonium salts by the direct func-

tionalization of dinitrogen with aryl cations[36] and phosphines.

Acknowledgements

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Conflict of interest

The authors declare no conflict of interest.

Keywords: diazonium salts · donor–acceptor adducts · N-based Lewis acids · phosphines · single-electron transfer

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[7] 1,2-azaborine also reacts with dinitrogen; see: c) K. Edel, S. A.
[12] Fort the reaction of diazonium salts with tertiary amines, see:
[22] CCDC 1846991 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre. For experimental details of the X-ray crystal structure determination, see the Supporting Information.