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


Published in: Angewandte Chemie

DOI:
10.1002/ange.201806913
10.1002/anie.201806913

Citation for published version (APA):
**Abstract:** Inspired by the commercially available azoimidazolium dyes (e.g., Basic Red 51) that can be obtained from arylazidonium 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 arylazidonium 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.

The metal-free activation and functionalization of dinitrogen is one of the key challenges of modern main-group chemistry. The low-lying N_{2} orbital (HOMO) and high-lying π* orbital (LUMO) make dinitrogen a weak Lewis base and a weak Lewis acid, and, therefore, a relatively inert substrate. Inspired by the recently reported interaction of boranes with metal–N_{2} complexes enabling facile N protonation, borylation, and silylation, Stephan and co-workers demonstrated that diphenyldiazomethane, a formal diphenylcarbene–N_{2} adduct, can function as a Lewis base (HOMO: −7.31 eV; Figure 1), forming a labile adduct with B(C_{2}F_{6})_{3}. While the direct interaction of dinitrogen with boranes has only been observed spectroscopically under forcing conditions, the use of transient borylenes afforded as table 2eV; Figure 1), forming a labile adduct with B(C_{2}F_{6})_{3}. While the direct interaction of dinitrogen with boranes has only been observed spectroscopically under forcing conditions, the use of transient borylenes afforded as table 2.

**Figure 1.** Lewis acid (C_{2}H_{6}) and base (Ph,C) augmented activation of N_{2}, including the HOMO (bottom) and LUMO (top) energies (in eV) calculated at the ωB97X-D/6-311 + G(d,p) level of theory.

We were intrigued by the reaction of boranes with metal–N_{2} complexes enabling facile N protonation, borylation, and silylation, Stephan and co-workers demonstrated that diphenyldiazomethane, a formal diphenylcarbene–N_{2} adduct, can function as a Lewis base (HOMO: −7.31 eV; Figure 1), forming a labile adduct with B(C_{2}F_{6})_{3}. While the direct interaction of dinitrogen with boranes has only been observed spectroscopically under forcing conditions, the use of transient borylenes afforded as table 2.

**Figure 2.** Reported arylazidonium–phosphine adducts.
and co-workers characterized C only spectroscopically (R = Cl, CN, SO₂NH₂, C(O)OEt; Figure 2).[19] Herein, we report on the facile synthesis of readily tuneable azophosphonium salts simply from phosphines and aryl diazonium tetrafluoroborates in acetonitrile, and provide detailed mechanistic insight by experimental and computational means. Related reactions of phenyl diazonium tetrafluoroborate with tertiary amines have also been investigated.

We found that the treatment of the phenyl diazonium salt [PhN⁺][BF₄]⁻[18] with triphenylphosphine (1.0 equiv) in acetonitrile at 0°C afforded the red azophosphonium salt [PhN⁺(PPh₃)₂][BF₄]⁻ (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, ²JPP = 18.8 Hz).[10] which we tentatively ascribed to the bis-phosphine adduct [PhN(PPh₃)₂N(PPh₃)][BF₄]⁻.[19] 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 tri-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 phenyl diazonium tetrafluoroborate with Bu₃P (1.1 equiv) in acetonitrile resulted in an immediate colour change from colourless to pink and afforded azophosphonium salt [PhN⁺(PPh₃)₃][BF₄]⁻ (ΔE = 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 2 M 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 Na[BPh₄] in DCM),[20] displays an almost planar (P1-N1-N2-C1 173.4(7)°) trans azophosphonium 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 arylazimidazolium borates [ArN⁺(IMes)][BPh₄] (Ar = Mes, o/p-C₆H₄) 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)/1.24(2) Å, respectively),[21b] illustrating that in these cationic azo dyes, phosphines behave similar to carbenes.

As the colour of the azophosphonium salts can be readily tuned by changing the donor ligand (1 (L = PPh₃): red; 2a (L = tBu₃P): pink), we next investigated the influence of the para substituent on the aren ring on the photophysical properties of 2. Treatment of the 4-substituted phenyl diazonium salts [(p-R-C₆H₄)N⁺][BF₄] (R = NO₂ (b), Br (e), OMe (d), NMe₂ (e)) with tert-butylyphosphine (1.1 equiv) in acetonitrile afforded the intensely coloured (from purple to red/brown) azophosphonium salts [(p-R-C₆H₄)N⁺(PPh₃)₂][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 ¹³P 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 arylazophosphonium tetrafluoroborates 1 and 2a–e and molecular structure of [(C₆H₅)N⁺(PPh₃)₂][BF₄]⁻ (2a–BP₃).](image1)

![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).](image2)
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 \( (\Delta\lambda_{\text{max}} = 4-11 \text{ nm}) \), indicating a minor influence of the solvent.[10] Time-dependent DFT calculations at the CAM-B3LYP/TZ2P level of theory reveal two low-lying excitations for 2a–e with \( n \rightarrow \pi^* \) (E-S1) and \( \pi \rightarrow \pi^* \) (E-S2) 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 \( \pi \)-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–diazoimmonium 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 (ArN=N). \[ \text{Subsequent radical coupling with the concomitantly formed phosphine radical cation (R}_{\text{P}}^+ \] presents an alternative pathway to afford these readily tuneable azophosphonium salts. As N-based Lewis bases, such as amines, are known to undergo one-electron oxidation by Lewis acids to generate the corresponding radical cations,[24] we also included triphenylamine and triisopropylamine (\( \text{tBu}_3\text{N} \) is still elusive)[25] in our mechanistic study.

In contrast to the reaction with triphenylphosphine, treatment of phenyldiazonium tetrafluoroborate with triphenylamine yields azobenzene 3 (Scheme 2)[26] by electrophilic aromatic substitution of the arylamine.[27] Blocking the para position resulted in a different outcome. We discovered that treatment of \([\text{PhN}_2][\text{BF}_4]\) with \( \text{p-tolylamine} \) in \( \text{CH}_2\text{CN} \) afforded an immediate colour change to deep blue, characteristic of the formation of the radical cation \( [\text{p-tol,N}^+]_2 \), which was confirmed by EPR spectroscopy (Figure S6).[28] Compared to the cyclic voltammogram of triphenylamine \( (E_{\text{pa}} = 0.97 \text{ V vs. Fe/Fe}^+) \), the oxidation potential of the more electron-rich \( \text{p-tolylamine} \) is shifted to more negative potentials \( (E_{\text{pa}} = 0.78 \text{ V vs. Fe/Fe}^+) \), which supports the notion that \( \text{p-tolylamine} \) is more prone to one-electron oxidation than triphenylamine \( (\Delta G^\circ = 20.3 \text{ vs. 24.7 kcal mol}^{-1}) \), respectively; Table 2).

<table>
<thead>
<tr>
<th>( \lambda_{\text{max}} ) [nm]</th>
<th>( \lambda_{\text{abs}} ) [nm]</th>
<th>HOMO [eV]</th>
<th>HOMO-1 [eV]</th>
<th>LUMO [eV]</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>
</tr>
<tr>
<td>2b</td>
<td>73.8</td>
<td>303 (4.29)</td>
<td>453 (2.68)</td>
<td>–12.6</td>
</tr>
<tr>
<td>2c</td>
<td>70.3</td>
<td>336 (4.33)</td>
<td>517 (2.18)</td>
<td>–11.6</td>
</tr>
<tr>
<td>2d</td>
<td>65.8</td>
<td>373 (4.44)</td>
<td>500 (2.49)</td>
<td>–11.2</td>
</tr>
<tr>
<td>2e</td>
<td>59.6</td>
<td>464 (4.62)</td>
<td>–39</td>
<td>–10.3</td>
</tr>
</tbody>
</table>

[a] Absorption wavelength corresponding to the lowest-energy transition \( (\lambda_{\text{abs}}) \); molar extinction coefficients \( (e, \text{M}^{-1} \text{cm}^{-1}) \); solvent: \( \text{CH}_2\text{CN} \); HOMO, HOMO-1, and LUMO energies at \([\text{W2018}]_D/6-311+\text{G}(d,p)\). [b] \( n \rightarrow \pi^* \) transition. [c] \( \pi \rightarrow \pi^* \) 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.

Interestingly, the bulky triisopropylamine[31] provided a different reaction course. Treatment of phenyldiazonium tetrafluoroborate with \( \text{IPr}_2(\text{N}) \) in \( \text{CH}_2\text{CN} \) resulted in the formation of triazene \( [\text{PhN}_2][\text{BF}_4] \) (72%),[28] disso–

![Scheme 2. Reaction of \([\text{PhN}_2][\text{BF}_4]\) with tertiary amines.](image)

**Scheme 2.** Reaction of \([\text{PhN}_2][\text{BF}_4]\) with tertiary amines.

Table 1: Frontier molecular orbitals and oxidation potentials of selected Lewis bases (LB), including the free energy changes for radical cation formation.

<table>
<thead>
<tr>
<th>( E_{\text{pa}} ) (LB/( \text{LB}^- )) vs. ( \text{Fe/Fe}^+ )</th>
<th>( E_{\text{pa}} )</th>
<th>( \Delta G^\circ ) ( kcal mol(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{PhN}_2 )</td>
<td>–7.10</td>
<td>0.95</td>
</tr>
<tr>
<td>( \text{p-tol,N} )</td>
<td>–6.80</td>
<td>1.04</td>
</tr>
<tr>
<td>( \text{IPr}_2(\text{N}) )</td>
<td>–7.33</td>
<td>1.69</td>
</tr>
<tr>
<td>( \text{IPr}_2(\text{N}) )</td>
<td>–7.97</td>
<td>0.92</td>
</tr>
<tr>
<td>( \text{tBu}_3\text{N} )</td>
<td>–7.69</td>
<td>1.53</td>
</tr>
</tbody>
</table>

[a] Calculated at \([\text{W2018}]_D/6-311+\text{G}(d,p)\). [b] \( \text{CH}_2\text{CN} \), 0.1 \text{ M} \( \text{[Bu}_3\text{N}]^{-}[\text{PF}_6 \text{]} \), glassy carbon working electrode, \( v = 100 \text{ mVs}^{-1} \). [c] \( \Delta G^\circ = –nF E_\text{red} \), \( F \) is Faraday constant; \( E_\text{red}(\text{PhN}_2^+) \) \( = \) –0.10 V vs. \( \text{Fe/Fe}^+ \).

Table 2: Frontier molecular orbitals and oxidation potentials of selected Lewis bases (LB), including the free energy changes for radical cation formation.

<table>
<thead>
<tr>
<th>HOMO [eV]</th>
<th>LUMO [eV]</th>
<th>( E_{\text{pa}} ) (LB/( \text{LB}^- )) vs. ( \text{Fe/Fe}^+ )</th>
<th>( \Delta G^\circ ) ( kcal mol(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{PhN}_2 )</td>
<td>–7.10</td>
<td>0.95</td>
<td>0.97 V</td>
</tr>
<tr>
<td>( \text{p-tol,N} )</td>
<td>–6.80</td>
<td>1.04</td>
<td>0.78 V</td>
</tr>
<tr>
<td>( \text{IPr}_2(\text{N}) )</td>
<td>–7.33</td>
<td>1.69</td>
<td>1.20 V</td>
</tr>
<tr>
<td>( \text{IPr}_2(\text{N}) )</td>
<td>–7.97</td>
<td>0.92</td>
<td>1.23 V</td>
</tr>
<tr>
<td>( \text{tBu}_3\text{N} )</td>
<td>–7.69</td>
<td>1.53</td>
<td>0.90 V</td>
</tr>
</tbody>
</table>


Zuschriften
phenyldiazonium cation \(E_p^{\text{iso}}(\text{PhN}_2^2/\text{PhN}_2^-) = -0.10 \, \text{V} \) vs. Fe/Fc\(^{\ast}\).\(^{[35]}\) Based on the sizable free energy change for radical cation formation by one-electron oxidation of the phosphines \(\Delta G^\circ > 23 \, \text{kcalmol}^{-1}\); Table 2) and the facile formation of 1 and 2 at low temperatures (even at \(-20^\circ\text{C}\)),\(^{[10]}\) 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-butylyphosphine by single-electron transfer (SET) is feasible when using stronger oxidants. Treatment of \(\text{tBu}_2\text{P}\) with the nitrosonium salt \([\text{NO}][\text{BF}_3]\) \((E_p^{\text{iso}}(\text{NO}^\ast/\text{NO}) = 0.87 \, \text{V} \) vs. Fe/Fc\(^{\ast}\))\(^{[32]}\) in acetonitrile resulted in the formation of \([\text{tBu}_2\text{P}][\text{BF}_3]\) as the major product (31\(^{\text{P}} = 56.1 \, \text{ppm} ; \quad \delta_{\text{HH}} = 445.6 \, \text{Hz}; \quad \text{Scheme 3})\(^{[10,33]}\)

\[
\begin{align*}
[\text{NO}][\text{BF}_3] + \text{tBu}_2\text{P} & \rightleftharpoons \text{NO} + \text{tBu}_2\text{P} \overset{\text{NO}}{\rightarrow} \text{CH}_2\text{CN} + \text{BF}_3 \\
\text{tBu}_2\text{P-NO} & \rightarrow [\text{tBu}_2\text{P}][\text{BF}_3] \\
\end{align*}
\]

\textbf{Scheme 3.} Reaction of \(\text{tBu}_2\text{P}\) with \([\text{NO}][\text{BF}_3]\) together with the experimental (black) and simulated (red) EPR spectra of \(\text{tBu}_2\text{P-NO}\).

Simulated g value and hyperfine coupling constants (A): \(g_{\text{xx}} = 2.0071, \quad A_{\text{iso}}^{\text{HH}} = +29.55 \, \text{MHz}, \quad A_{\text{iso}}^{\text{HH}} = -34.10 \, \text{MHz}\).

which could be attributed to H atom abstraction from the solvent by the reactive \([\text{tBu}_2\text{P}^\ast]\) radical cation intermediate \(\Delta G^\circ = 0.7 \, \text{kcalmol}^{-1}\).\(^{[34]}\) In addition, we detected small amounts of a radical species by EPR spectroscopy (Scheme 3) that features a six-line pattern at \(g_{\text{xx}} = 2.0071\), which is consistent with an organic doublet with hyperfine coupling interactions (A) with nitrogen \(A_{\text{iso}}^{\text{HH}} = +29.55 \, \text{MHz}\) and an I = 1/2 nucleus, likely phosphorus \(A_{\text{iso}}^{\text{HH}} = -34.10 \, \text{MHz}; \quad \text{Scheme 3})\(^{[10]}\). We postulate this to be the nitrosyl–phosphine adduct \(\text{tBu}_2\text{P-NO}^\ast\) \((\Delta E = -0.5 \, \text{kcalmol}^{-1})\)\(^{[10]}\) which can be formed by the capture of the in situ generated NO by residual \(\text{tBu}_2\text{P}\).

In summary, in acetonitrile, aryldiazonium salts react as nitrogen-based Lewis acids with phosphines, enabling the facile synthesis of tuneable azophosphonium salts. The corresponding azosufoxonium salts \([\text{RN}_2(\text{NR})_3]^{\text{X}}\) 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 functionalization of dinitrogen with aryl cations\(^{[36]}\) and phosphines.

\section*{Acknowledgements}

This work was supported by the Council for Chemical Sciences of The Netherlands Organization for Scientific Research (NWO/CW) by a VIDI grant (J.C.S.). We gratefully acknowledge Ed Zuidinga for mass spectrometric analyses and Albert M. Brouwer and Joeri Hessels for fruitful discussions.

\section*{Conflict of interest}

The authors declare no conflict of interest.

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

\textbf{How to cite:} Angew. Chem. Int. Ed. \textbf{2018}, 57, 11929–11933

\textbf{Angew. Chem.} \textbf{2018}, \textbf{130}, 12105–12109


