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Radicals derived from Lewis acid/base pairs

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While conventional approaches to stabilizing main group radicals have involved the use of Lewis acids or bases, this tutorial review focuses on new avenues to main group radicals derived from combinations of donor and acceptor molecules. Reactions involving the use of both classical Lewis acid–base adducts and frustrated Lewis pair systems are discussed and the subsequent reactivity is considered.

Key learning points

1. The development of Lewis pair chemistry has contributed to advancements in generation of persistent or transient radicals.
2. Frustrated radical pairs have been shown to cleave chemical bonds in a homolytic fashion.
3. Single electron delivery to Lewis pairs leads to transient radical anions that split a variety of chemical bonds.
4. A variety of stable radicals have been achieved *via* reactions involving frustrated Lewis pairs or classical Lewis adducts.

Introduction

In 1923, Gilbert N. Lewis classified electron-pair donors and electron-pair acceptors as Lewis bases (LBs) and Lewis acids (LAs) respectively.¹ Since then, classical Lewis acid–base adducts (CLAs) derived from the two electron donation from a Lewis base (LB) to a Lewis acid (LA) were thought to be thermodynamically stable and generally unreactive. This paradigm changed in 2006 with the discovery that a reversible activation of H₂ could be mediated by *p*-(Mes₂P)C₆F₄(B(C₆F₅)₂) (Mes = mesityl).² In this case, the Lewis basic phosphorus and acidic boron centres are sterically encumbered and this precludes the dative bond formation permitting the reaction with H₂. Subsequently this observation was generalized to combinations of LAs and LBs with appropriate steric hindrance to deter dative bonding. Indeed, access to dissociative equilibria has proved sufficient to such frustrated Lewis pairs (FLPs) to react with a wide variety of substrates,^{3–6} as well as to effect metal-free hydrogenation catalysis.

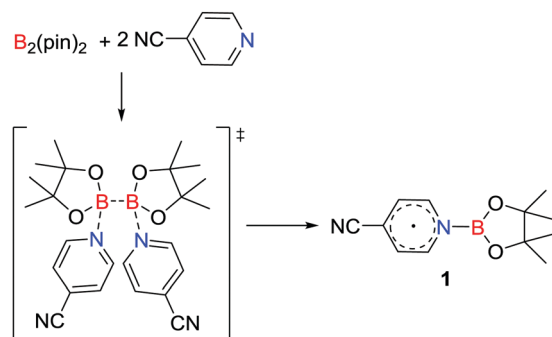
Over the last decade the above development of FLP chemistry has been predicated on the notion that the chemistry results from two-electron processes in which the Lewis bases and acids act as two electron donors and acceptors respectively. However, a number of recent studies have either inferred or demonstrated

the role of radical pathways in reactions involving Lewis acids and bases, both in FLP chemistry and beyond. At the same time, carbon-based radicals have an extended history dating from the landmark work of Gomberg more than one century ago.⁷ In contrast, main group radicals have received much less attention. The conventional approaches to stabilizing main group radicals has involved the use of LAs or LBs. For example, LA-complexation of a radical donor has been known for some time⁸ and the reactivity of such species has been exploited more recently.^{9,10} The complementary approach in which LBs are used to stabilize radicals has also been employed. For example, several recent studies have used singlet carbenes to stabilize main group radicals^{11–14} In this tutorial review, we focus on new avenues to main group radicals derived from combinations of donor and acceptor molecules. Reactions involving the use of both CLA and FLP systems are discussed and the subsequent reactivity of the derived radicals is considered.

Donor–acceptor induced homolysis

A unique approach to the generation of a main group radical involves base induced homolysis of an element–element bond. In 2016, Li, Zhu and co-workers¹⁵ described such a strategy involving the transient formation of a donor–acceptor adduct derived from the addition of two equivalents of 4-cyanopyridine to B₂(pin)₂. This prompted homolytic cleavage of the B–B bond affording the pyridine-ligated boryl radical [NCC₅H₄NBpin][•] **1** (Scheme 1).

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Scheme 1 Synthesis of a pyridine-ligated neutral boryl radical **1** via a homolytic cleavage of the B–B bond in $B_2(\text{pin})_2$.

The donor 4-cyanopyridine behaves as a one-electron acceptor, reminiscent of homolytic cleavage reactions of a base stabilized diborane (**4**).¹⁶

In extending this approach Jiao and Zhang showed that the combination of $B_2(\text{pin})_2$, MeOK and 4-phenylpyridine afforded the novel pyridine-boryl species $[\text{PhC}_5\text{H}_4\text{NBpin}(\text{OMe})^\bullet][\text{K}]$ **2** and $[(\text{PhC}_5\text{H}_4\text{N})_2\text{Bpin}][\text{K}]$ **3** (Scheme 2).¹⁷ In the absence of MeOK, no radical was observed, inferring that the pyridine-boryl adduct reacts with MeOK to prompt the homolytic B–B bond cleavage to produce **2** and **3**. These species behave as super electron donors, and can be used in catalytic radical borylation reactions and reductive cleavage reactions.^{17,18}



Scheme 2 Synthesis of **2** and **3**.

Radical capture by FLPs

Recently, Erker, Grimme, Warren *et al.* prepared a novel type of aminoxyl radical **4** via the reaction of an intramolecular FLP $\text{Mes}_2\text{PCH}_2\text{CH}_2\text{B}(\text{C}_6\text{F}_5)_2$ with NO (Scheme 3).^{19,20} Compound **4** was fully characterized including single crystal X-ray diffraction. The Mulliken spin densities of O and N atoms in **4** are 0.54 and 0.34 a.u., respectively. Shortly thereafter, Erker and co-workers reported analogous reactions leading to a variety of related aminoxyl radicals **5–10** (Scheme 3).^{20–22}



Scheme 3 Examples of aminoxyl radicals derived from reactions of FLPs with NO.



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Ministry of Education. He has published over 50 peer-reviewed papers, and his research spans synthetic and computational chemistry with the focus of unusual main group compounds.



Douglas W. Stephan

Douglas W. Stephan began independent career at the University of Windsor (1982). In 2008 he moved to the University of Toronto as a Professor and Canada Research Chair. A highly successful researcher in inorganic chemistry/catalysis, he is best known for articulating the concept of “frustrated Lewis pairs”. Stephan has received a number of awards. He was named a Fellow of the Royal Society of Canada (2005), a Fellow of the Royal Society (2013, London), a Corresponding Member of North-Rhein-Westfaelia Academy (2014, Germany), and an Einstein Visiting Professor at the Technical University of Berlin (2016–2019) and made the Thomson Reuters Highly Cited List (2014–2018).



Scheme 4 Examples of hydrogen atom abstraction reactions of aminoxy radicals.

These aminoxy radicals were shown to engage readily in H-atom abstraction reactions (Scheme 4). For example, compounds 4 and 8 rapidly reacted with 1,4-cyclohexadiene to afford the corresponding diamagnetic products 11 and 12, respectively, along with the formation of benzene. Compound 7 underwent abstraction of H-atoms with cyclohexene to give 13 and a pair of diastereoisomers of 14 and 15.

Frustrated radical pairs

A triarylamine radical cation

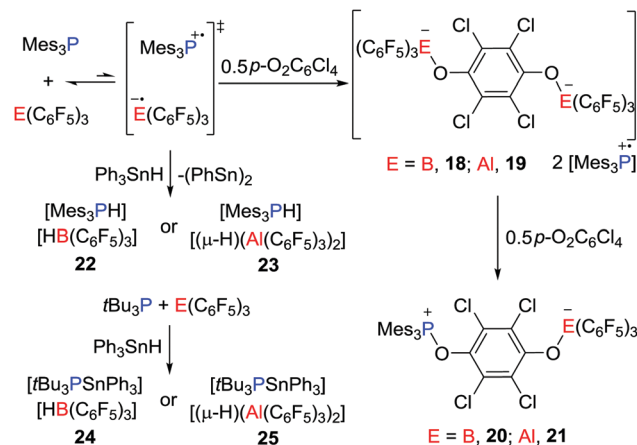
Although the one-electron oxidation of transition-metal complexes by $\text{B}(\text{C}_6\text{F}_5)_3$ has been described,^{23,24} Wang *et al.* reported the first example of a one-electron oxidation of a triarylamine $(\text{C}_6\text{H}_3\text{CMe}_2)_3\text{N}$ 16 by $\text{B}(\text{C}_6\text{F}_5)_3$ in 2013 (Scheme 5),²⁵ affording the deep blue triarylamine radical cation 17. Although the salt of the weakly coordinating alanate $17[\text{Al}(\text{OR}_\text{F})_4]$ ($\text{OR}_\text{F} = \text{OC}(\text{CF}_3)_3$) was isolated, the formation of the boron centred radical anion in the reaction with $\text{B}(\text{C}_6\text{F}_5)_3$ was not confirmed as this species decomposes rapidly (*vide infra*).²⁶

Phosphine/Lewis acid frustrated radical pairs (FRPs)

Stephan and co-workers have recently reported evidence for a mechanism for FLP reactivity that involves a radical pathway.²⁷ Upon dissolving Mes_3P and $\text{E}(\text{C}_6\text{F}_5)_3$ ($\text{E} = \text{B}$ or Al) in very dry toluene or chlorobenzene, the formation of a trace amount of the purple-colored $[\text{Mes}_3\text{P}^\bullet]^+$ was observed. Although the EPR



Scheme 5 Synthesis of 17 via a one-electron oxidation by $\text{B}(\text{C}_6\text{F}_5)_3$.



Scheme 6 Reactivity of $\text{R}_3\text{P}/\text{E}(\text{C}_6\text{F}_5)_3$ toward $p\text{-O}_2\text{C}_6\text{Cl}_4$ and Ph_3SnH .

spectrum of the purple solution generated from $\text{Mes}_3\text{P}/\text{B}(\text{C}_6\text{F}_5)_3$ displayed a weak signal, the solution generated from the corresponding Al reaction revealed a room-temperature doublet EPR resonance with a g value of 2.0089 and a hyperfine coupling constant of 238 G. This confirmed the presence of $[\text{Mes}_3\text{P}^\bullet]^+$, however, the presumed radical anion $[\text{E}(\text{C}_6\text{F}_5)_3]^-$ was not observed as it was rapidly quenched by reactions with solvent.^{25,26} Nonetheless, these data support the notion of single-electron transfer (SET) equilibria between the FLP and FRP of the form $[\text{Mes}_3\text{P}^\bullet][\text{E}(\text{C}_6\text{F}_5)_3]$. Generation of these FRPs in the presence of tetrachloro-1,4-benzoquinone ($p\text{-O}_2\text{C}_6\text{Cl}_4$) prompts the formation of the radical salt $[\text{Mes}_3\text{P}^\bullet]_2[(\text{C}_6\text{F}_5)_3\text{EOC}_6\text{Cl}_4\text{OE}(\text{C}_6\text{F}_5)_3]$ ($\text{E} = \text{B}$, 18; Al , 19) (Scheme 6).

These species react further with $p\text{-O}_2\text{C}_6\text{Cl}_4$ to give the 1,6-addition products $[\text{Mes}_3\text{POC}_6\text{Cl}_4\text{OE}(\text{C}_6\text{F}_5)_3]$ ($\text{E} = \text{B}$, 20; Al , 21) (Scheme 6). Alternatively, the FRPs homolytically split the Sn-H bond in Ph_3SnH to give $[\text{Mes}_3\text{PH}][\text{HB}(\text{C}_6\text{F}_5)_3]$ 22 or $[\text{Mes}_3\text{PH}][(\mu\text{-H})(\text{Al}(\text{C}_6\text{F}_5)_3)_2]$ 23, respectively (Scheme 6), along with $(\text{Ph}_3\text{Sn})_2$. In sharp contrast, the combination of $t\text{Bu}_3\text{P}/\text{E}(\text{C}_6\text{F}_5)_3$ shows no evidence of radical formation. Indeed, addition of Sn-H to these FLPs prompts heterolytic Sn-H cleavage affording $[t\text{Bu}_3\text{P}^+\text{SnPh}_3][\text{HB}(\text{C}_6\text{F}_5)_3]$ 24 and $[t\text{Bu}_3\text{P}^+\text{SnPh}_3][(\mu\text{-H})(\text{Al}(\text{C}_6\text{F}_5)_3)_2]$ 25, respectively (Scheme 6). This contrasting behaviour demonstrates that FLPs can react either *via* consecutive one-electron steps or *via* a classic two electron process.

In a recent and related study, the reactivity of the $\text{Mes}_3\text{P}/\text{B}(\text{C}_6\text{F}_5)_3$ pair with benzyl peroxide derivatives was shown to proceed to efficiently split the O-O bond in a homolytic fashion, giving radical salts $[\text{Mes}_3\text{P}^\bullet][\text{PhCOOB}(\text{C}_6\text{F}_5)_3]$ 26, $[\text{Mes}_3\text{P}^\bullet][p\text{-BrC}_6\text{H}_4\text{COOB}(\text{C}_6\text{F}_5)_3]$ 27 and $[\text{Mes}_3\text{P}^\bullet][p\text{-MeC}_6\text{H}_4\text{COOB}(\text{C}_6\text{F}_5)_3]$ 28 (Scheme 7).²⁸ Control experiments showed that the combination of $\text{B}(\text{C}_6\text{F}_5)_3$ with the peroxides gave an adduct mixture. These reactions represent the first examples where FLPs react *via* a SET process affording the homolytic cleavage of a homodiatom bond. It is also noteworthy that related phosphoniumyl radical cations $[\text{Tipp}_3\text{P}^\bullet]^+$ ($\text{Tipp} = 2,4,6\text{-triisopropylphenyl}$) and $[\text{Tipp}_2\text{MesP}^\bullet]^+$ were prepared and structurally characterized by Wang *et al.*²⁹ employing the weakly coordinating anions such as $[\text{Al}(\text{OR}_\text{F})_4]^-$ ($\text{OR}_\text{F} = \text{OC}(\text{CF}_3)_3$) and $[\text{Al}(\text{OR}_\text{Me})_4]^-$ ($\text{OR}_\text{Me} = \text{OC}(\text{CF}_3)_2\text{Me}$).

Scheme 7 Reactivity of Mes₃P/B(C₆F₅)₃ toward benzyl peroxide derivatives.

Scheme 8 One-electron oxidation of phosphines in silylium ion/phosphine Lewis pairs.

In 2018, Müller, Klare *et al.* demonstrated that a SET as a viable reaction pathway for silylium ion/phosphine Lewis pairs (Scheme 8). For example, in solution, both FLPs consisting of R₃P/[(Me₅C₆)₃Si][B(C₆F₅)₄] (R = Tipp or Mes) and CLAs derived from the combination of R₃P/[iPr₃Si(odcb)][B(C₆F₅)₄] (odcb = 1,2-dichlorobenzene) promote the establishment of a SET equilibrium mixture with the corresponding radical pairs **29–31**, indicating that complete frustration of the Lewis pairs is not necessarily a prerequisite for such SET processes.

Single electron transfer in a Lewis acid–base reaction

More recently, the group of Müller disclosed that a Lewis acid–base reaction between the nucleophilic hafnocene-based germylene **32** and B(C₆F₅)₃ leading to a Ge-B CLA **33** is initiated by a SET process (Scheme 9).³⁰ The radical salt **34** generated by a SET from the germylene to B(C₆F₅)₃ was identified by EPR and UV-vis spectroscopy. In addition, the nature of the radical cation was confirmed *via* independent synthesis of the [B(C₆F₅)₄][−] salt *via* the reaction of **32** with [Ph₃C][B(C₆F₅)₄]. This work provided evidence for a SET in CLA formation reactions.

Scheme 9 Synthesis of **33** via a radical complex **34**.

Electron transfer in FLP-reactions

C–H activation by FRPs

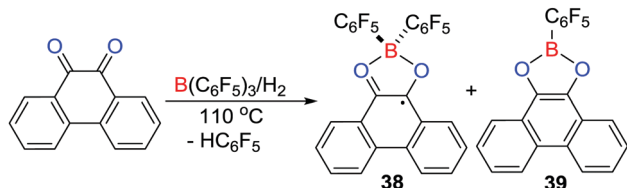
Prior to the recognition of the possibility of a radical pathway for FLP reactivity, it was noted that combination of B(C₆F₅)₃ and PMes₃ generated a faintly purple solution. While early efforts to support a radical pathway were unsuccessful, in 2013, unequivocal evidence of highly reactive transient FRPs of the form [R₃P[•]][[•]O(Al(C₆F₅)₃)₂] (R = *t*Bu or Nap, Nap = naphthyl) was obtained.³¹ Generated from the reactions of R₃P and Al(C₆F₅)₃ in a molar ratio of 1 : 2 with N₂O (1 atm) (Scheme 10), these FRPs were shown to effect C–H bond activation. In the case of R = *t*Bu, a C–H bond of the *t*Bu group was readily activated to form [tBu₂PMe(C(CH₂)Me)][(μ-OH)(Al(C₆F₅)₃)₂] **35**, whereas for R = Nap, the intermolecular activation of toluene or bromobenzene afforded [Nap₃PCH₂Ph][[(μ-OH)(Al(C₆F₅)₃)₂] **36** or [Nap₃PC₆H₄Br][[(μ-HO)(Al(C₆F₅)₃)₂] **37**, respectively (Scheme 10). These reactions proceeded *via* the corresponding FLP-N₂O adducts, as supported by isolation of the species tBu₃P(N₂O)Al(C₆F₅)₃ using the equal molar portion of *t*Bu₃P and Al(C₆F₅)₃. The H atom in the anion [(μ-HO)(Al(C₆F₅)₃)₂][−] was derived from hydrogen atom abstraction from the toluene solvent by the transient radical anion [(μ-O[•])(Al(C₆F₅)₃)₂][−].

Borocyclic radicals *via* H₂ activation

It is well known that carbonyl–oxygen atoms form adducts with Lewis acids.³² Nonetheless, the equilibrium access to Lewis pairs provides a pathway to reaction with H₂ resulting in carbonyl hydrogenation.³³ In a similar sense, Stephan *et al.* in 2016 reported that the reaction of phenanthrene-9,10-dione with B(C₆F₅)₃ in toluene led to formation of a Lewis acid–base adduct (C₆F₅)₃B(O₂C₁₄H₈) featuring a tetracoordinated boron centre.³⁴ Remarkably, treating the above reaction mixture with H₂ (4 atm) at 110 °C resulted in the formation of two products, the major one being [(C₆F₅)₂B(O₂C₁₄H₈)][•] **38** together with the minor product (C₆F₅)B(O₂C₁₄H₈) **39** (Scheme 11). The paramagnetic nature of **38** was confirmed by EPR spectroscopy which revealed hyperfine coupling to the ¹¹B atom (*a*_B = 2.58 G) and to hydrogen atoms with *a*_H = 3.39, 0.00, 2.43, and 1.01 G. These data were



Scheme 10 C–H bond activation by transient FRPs.

Scheme 11 Synthesis of a borocyclic radical **38** via an FLP hydrogenation.

Scheme 12 Stable borocyclic radicals prepared via FLP hydrogenations.

consistent with DFT calculations of the spin density showing the delocalization of the unpaired electron over the phenanthrene backbone.

A mechanistic study showed that initially the FLP-hydrogenation of the dione proceeds giving phenanthrene-9,10-diol. This diol reacts with the dione to afford 9,10-phenanthrenequinhydrone radical that readily coordinates $B(C_6F_5)_3$ to form a paramagnetic Lewis acid–base adduct, followed by protonation of one of the C_6F_5 rings affording **38** and HC_6F_5 . Alternatively, if the reduced diol reacts with $B(C_6F_5)_3$, double protodeborylation affords the minor product **39**.

The analogous reactions of $B(C_6F_5)_3$ with pyrene-4,5-dione,³⁴ *N*-(2,6-dimethylphenyl)-phenanthreno-iminoquinone³⁵ or *N,N*-di-*p*-tolylphenanthrene-9,10-diimine³⁵ under the atmosphere of H_2 (4 atm) at 110 °C led to the formation of the related stable borocyclic radical **40–42**, respectively (Scheme 12). Notably, the borocyclic radicals **38** and **40–42** are stable towards moisture and oxygen, presumably due to the delocalization of the unpaired electron over the aromatic backbone. Nevertheless, the one-electron chemical reduction of **38** or **40** with cobaltocene generated the corresponding cobaltocenium borate salts.³⁴

In an ensuing work, the reactivity of **38** with a variety of nucleophiles was probed (Scheme 13).³⁶ The LUMO of **38** primarily involves π^* -antibonding orbitals over the phenanthrene backbone, prompting a reaction with Ph_3P to give two regioisomeric zwitterions, 1-(Ph_3P) $C_{14}H_7O_2B(C_6F_5)_2$ **43** and 3-(Ph_3P) $C_{14}H_7O_2B(C_6F_5)_2$ **44**, coupled with the related boronic ester **39** and HC_6F_5 . Similarly, the reaction of **38** with tBu_3P afforded the zwitterion 3-(tBu_3P) $C_{14}H_7O_2B(C_6F_5)_2$ **45** and the salt [tBu_3PH][$C_{14}H_8O_2B(C_6F_5)_2$] **46**, while reaction with *N*-heterocyclic carbene IMes or quinuclidine gave 3-(IMes) $C_{14}H_7O_2B(C_6F_5)_2$ **47** and [IMesH][$C_{14}H_8O_2B(C_6F_5)_2$] **48** or 3-($C_7H_{13}N$) $C_{14}H_7O_2B(C_6F_5)_2$ **45** and [H(NC_7H_{13})][$C_{14}H_8O_2B(C_6F_5)_2$] **50**, respectively (Scheme 13). In contrast, treatment of **38** with DMAP led to attack at the carbonyl carbon atoms, affording [9,10-(DMAP) $_2C_{14}H_8O_2B(C_6F_5)_2$][$C_{14}H_8O_2B(C_6F_5)_2$] **51** (Scheme 13).

A neutral aminyl radical from disulfide activation

The FLP system consisting of the nitrogen based Lewis acidic nitrenium cation **52** with tBu_3P has been shown to react $(PhS)_2$

Scheme 13 Reactivity of **38** toward nucleophiles.Scheme 14 Synthesis of an aminyl radical **53** via FLP activation of diphenyl disulfide.

to afford the persistent neutral aminyl radical, [(*p*-ClC₆H₄)N₂-(PtBu₃)]• **53** and the salt [PhSPtBu₃][BF₄] **54** (Scheme 14).³⁷ This is reminiscent of the dione/borane reaction with H_2 described above, suggesting that the concerted FLP action on the disulphide prompts electron transfer. It is noteworthy that the radical **53** was also accessible *via* a more conventional reduction of **52** with cobaltocene or PhSNa.

Transient donor–acceptor radicals

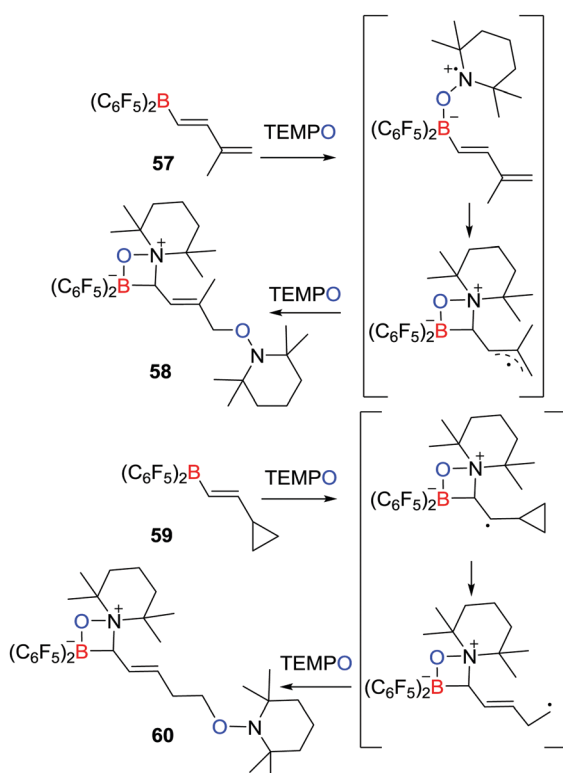
In 2016, the Erker group described the selective oxidation of the intramolecular amine/borane FLP, [$C_4H_6Me_4N(CH_2)_3B(C_6F_5)_2$],



Scheme 15 Oxidation of an intramolecular amine/borane FLP with dioxygen. Free energies are given in kcal mol⁻¹.

with dioxygen (Scheme 15).³⁸ In this case, the resulting tetrahydroisoxazolium borate salt $[\text{C}_5\text{H}_6\text{Me}_4\text{N}(\text{CH}_2)_3\text{O}][\text{C}_5\text{H}_6\text{Me}_4\text{N}(\text{CH}_2)_3\text{B}(\text{C}_6\text{F}_5)_2\text{OB}(\text{C}_6\text{F}_5)_3]$ **56** was formed *via* a series of transient radical intermediates. Initially an endergonic generation of alkyl radicals prompts the propagation step generating a borylperoxide intermediate, leading to the formation of **56** in an overall thermodynamically favourable process (-59.5 kcal mol⁻¹) (Scheme 15).

A related work described by Erker, Studer *et al.* described that the reaction of the boryldiene $\text{CH}_2=\text{C}(\text{Me})\text{CH}=\text{CHB}(\text{C}_6\text{F}_5)_2$ **57**



Scheme 16 Synthesis of **58** and **60** *via* transient radicals.



Scheme 17 FLP reactivity of $t\text{Bu}_3\text{P}/\mathbf{61}$ with $(\text{PrS})_2$ leading to a spontaneous radical chain degradation.

with two equivalents of TEMPO yielded species **58** featuring a zwitterionic four-membered ring, in which two TEMPO radicals added to the boryldiene starting material (Scheme 16).³⁹ The authors proposed that the initial coordination of TEMPO to the Lewis acidic boron centre affords a transient radical that undergoes cyclization and then couples a second TEMPO to give the product **58**. Trapping of TEMPO at the terminal position is presumably sterically driven. Similarly, the cyclopropyl-substituted alkenyl borane, $\text{C}_3\text{H}_5\text{CH}=\text{CHB}(\text{C}_6\text{F}_5)_2$ **59** was shown to react with two equivalents of TEMPO affording the ring-opening product **60** (Scheme 16). This observation supported the generation of the analogous radical intermediates. Indeed the scope of analogous reaction with TEMPO radical was extended in 2017.⁴⁰

In a recent work, the FLP derived from a nitrogen-centered LA, namely a cyclic (alkyl)(amino)nitrenium cation, $[\text{C}_6\text{H}_4\text{CPh}_2\text{N}_2t\text{Bu}][\text{BF}_4]$ **61**, and $t\text{Bu}_3\text{P}$ was shown to react with dipropyl disulfide $(\text{PrS})_2$.⁴¹ One product is the salt $[t\text{Bu}_3\text{PSPr}][\text{BF}_4]$. The other product derived from the heterolytic S-S cleavage, $[(\text{C}_6\text{H}_4)(\text{N}t\text{Bu})\text{N}(\text{SPr})\text{CPh}_2]$, was not observed but instead, the reaction affords a mixture of $(t\text{BuS})_2$, $(t\text{BuSSPr})$, Pr_2S , $[\text{C}_6\text{H}_4\text{CPh}_2\text{N}_2]$ **62** and $[\text{C}_6\text{H}_4\text{CPh}_2\text{NPh}]$ **63**, consistent with a radical chain pathway (Scheme 17).

Electron transfer to an acid/base adduct

Ferrocene/Lewis pair systems

Another approach to reactive radicals is derived from the addition of a one-electron donor with a Lewis donor/acceptor combination. This concept was first demonstrated by Agapie and Henthorn who reported reactions of ferrocene/ $\text{B}(\text{C}_6\text{F}_5)_3$ pairs with dioxygen which afforded $[\text{Cp}'_2\text{Fe}]_2[(\text{C}_6\text{F}_5)_3\text{BOOB}(\text{C}_6\text{F}_5)_3]$ ($\text{Cp}' = \text{Cp}$ **64** or Cp^* **65**); the first examples of dianionic boron peroxide salts (Scheme 18).⁴² Although $\text{B}(\text{C}_6\text{F}_5)_3$ is inert to $^3\text{O}_2$ over 24 h, the presence of $\text{B}(\text{C}_6\text{F}_5)_3$ appeared to facilitate the reduction of $^3\text{O}_2$ by ferrocenes. A cyclic voltammetry (CV) study suggested the reaction proceeded *via* the transient B_2O_2 superoxide intermediate although attempts to access this intermediate were unsuccessful.

Exploiting a related strategy, Stephan and co-workers exploited such single electron delivery from Cp^*_2Fe in the presence of a Lewis acid ($\text{E}(\text{C}_6\text{F}_5)_3$, $\text{E} = \text{B}$ or Al) for small

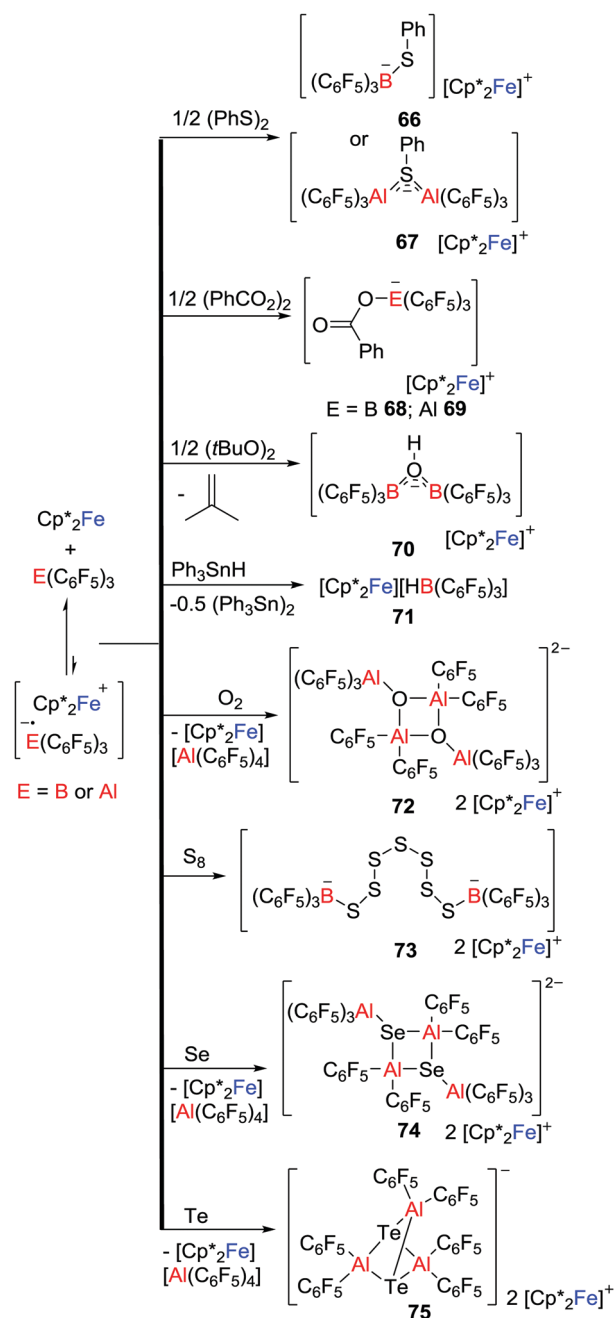
Scheme 18 Reactivity of ferrocene/B(C₆F₅)₃ toward dioxygen.

molecule activation.⁴³ In this fashion, O–O, S–S, Se–Se, Te–Te, C–H, C–O and Sn–H bonds were cleaved in a homolytic fashion, affording a variety of ferrocenium salts **66**–**75** featuring novel B- and Al-containing anions (Scheme 19). For example, exposure of a solution of Cp^{*}₂Fe/Al(C₆F₅)₃ to dry ³O₂ immediately resulted in the O–O bond cleavage, giving the salt [Cp^{*}₂Fe]⁺[[C(C₆F₅)₃–AlOAl(C₆F₅)₂]^{2–} **72** with a dianionic Al₂O₂ core. This stands in contrast to the corresponding reaction of Cp^{*}₂Fe/B(C₆F₅)₃ that yields **65** in which the O–O bond remains intact (Scheme 18). The corresponding reactions of Cp^{*}₂Fe/E(C₆F₅)₃ with elemental Te and S₈ afford a unique tricyclic Al₃Te₂ anion and a dianion in which two boron centers are linked by seven sulfur atoms, respectively (Scheme 19).

Control reactions showed the slow generation of ferrocenium cation in the absence of substrate molecules, consistent with SET from Cp^{*}₂Fe to E(C₆F₅)₃, suggesting that the generated [Cp^{*}₂Fe]⁺ reacts with substrate. Alternatively, SET to the Lewis acid-substrate adduct is also possible. It is noteworthy that Chen also proposed the generation of the fleeting [Al(C₆F₅)₃][–] that was followed by decomposition during thermolysis of a C₆D₅Br solution of Al(C₆F₅)₃ with Cp₂Fe at 100 °C for 3 days,⁴⁴ although the radical anion [Al(C₆F₅)₃][–] was not observed.

In a recent work, this concept of SET was extended to systems based on the transition-metal-based LA; Zn(C₆F₅)₂ (Scheme 20).⁴⁵ In this case, the combination of Zn(C₆F₅)₂ and [(PhC(S)S)₂] gave a weak CLA, while the cleavage of the S–S bond of [(PhC(S)S)₂] was achieved immediately upon mixing the substrate with Zn(C₆F₅)₂ and Cp^{*}₂Fe, leading to a salt [Cp^{*}₂Fe][PhCS₂Zn(C₆F₅)₂] **76**. No SET reaction from Cp^{*}₂Fe to Zn(C₆F₅)₂ was observed in the absence of [(PhC(S)S)₂], inferring that single electron delivery from Cp^{*}₂Fe to the CLA prompts the rapid cleavage of the S–S bond.

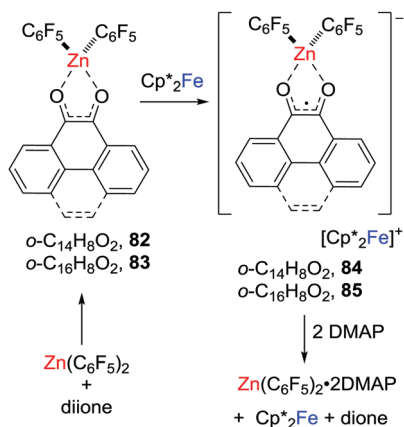
More recently, the group of Severin reacted Cp[′]₂Fe/Al(C₆F₅)₃ (Cp[′] = Cp^{*} or Cp) with N₂O (Scheme 21), affording salts [Cp[′]₂Fe][[(μ-HO)(Al(C₆F₅)₃)₂] (Cp[′] = Cp^{*}, **77**; Cp, **79**).⁴⁶ At the same time, neutral species **78** and **80** involving the C–H activation of the metallocenes were isolated. These observations indicated the formation of the transient oxyl radical anion [OAl(C₆F₅)₃][–] that spontaneously abstracts hydrogen atoms from the metallocenes. The ensuing metallocene-based radicals underwent radical/radical coupling reactions leading to **78** and

Scheme 19 Reactivity of Cp^{*}₂Fe/E(C₆F₅)₃ toward small molecule substrates.

80. This is further evidenced by the reaction of Ph₃C[•]/Al(C₆F₅)₃ with N₂O, wherein [OAl(C₆F₅)₃][–] was trapped by the excess Ph₃C[•] to give the salt [Ph₃C][Ph₃COAl(C₆F₅)₃] **81**.

Zinc-containing radical anions

In 2018, related zinc-dione-containing radical anions were prepared *via* a single electron transfer to donor–acceptor system consisting of dione/Zn(C₆F₅)₂ (Scheme 22).⁴⁵ Specifically, the phenanthrene-9,10-dione or pyrene-4,5-dione donor–acceptor adduct [(C₁₄H₈O₂)Zn(C₆F₅)₂] **82** or [(C₁₆H₈O₂)Zn(C₆F₅)₂] **83** was shown to feature low-lying LUMOs relative to those of the corresponding free diones. One-electron reduction of these

Scheme 20 Reaction of $\text{Cp}^*_2\text{Fe}/\text{Zn}(\text{C}_6\text{F}_5)_2$ with $[(\text{PhC}(\text{S})\text{S})_2]$.Scheme 21 Reaction of $\text{Cp}'_2\text{Fe}/\text{Al}(\text{C}_6\text{F}_5)_3$ or $\text{Ph}_3\text{C}^\bullet/\text{Al}(\text{C}_6\text{F}_5)_3$ with N_2O .

Scheme 22 Synthesis and reactivity of zinc-containing radicals.



Scheme 23 Synthesis of semiquinone radical anions.

adducts with Cp^*_2Fe gave the persistent zinc-cyclic radical anions **84** and **85** with counterions of the ferrocenium cation.

These salts proved labile undergoing reaction with DMAP to give $[\text{Zn}(\text{C}_6\text{F}_5)_2(\text{DMAP})_2]$ with the regeneration of Cp^*Fe and the free corresponding dione (Scheme 22).

Semiquinone radical anions

In a recent and related work, Erker *et al.* reported that, in the presence of two molar equivalents of $\text{B}(\text{C}_6\text{F}_5)_3$, *p*-benzoquinone, 9,10-anthraquinone, acenaphthenequinone or 9,10-phenanthrenequinone reacted with a one-electron donor such as TEMPO, Gomberg dimer and Cp^*_2Fe , leading to the formation of a series of isolable doubly *O*-borylated semiquinone radical anion salts **86–93** (Scheme 23).⁴⁷ In the absence of $\text{B}(\text{C}_6\text{F}_5)_3$, the corresponding reaction of the studied quinones with TEMPO, Gomberg dimer or Cp^*_2Fe did not react. The presence of $\text{B}(\text{C}_6\text{F}_5)_3$ appeared to facilitate the reduction of the quinones.

Bis(borane)superoxide radicals

In 2017, the group of Erker demonstrated that electron transfer can be effected from TEMPO to boranes in the presence of O_2 (Scheme 24),⁴⁸ affording the salts of the bis(borane)superoxide radical anion $[\text{C}_5\text{H}_6\text{Me}_4\text{N}=\text{O}][^\bullet\text{O}_2[\text{B}(\text{C}_6\text{F}_5)_3]_2]$ **94** and $[\text{C}_5\text{H}_6\text{Me}_4\text{N}=\text{O}][^\bullet\text{O}_2[\text{B}(p\text{-C}_6\text{F}_4\text{H})_3]_2]$ **95** respectively. These species are analogous to the $[\text{Cp}^*_2\text{Fe}]^+$ salts reported by Agapie and Henthorn (Scheme 18) (*vide supra*).⁴² Interestingly, the Gomberg dimer of the trityl radical reacted in a similar fashion to give the salt $[\text{Ph}_3\text{C}][^\bullet\text{O}_2[\text{B}(p\text{-C}_6\text{F}_4\text{H})_3]_2]$ **96** (Scheme 24). These results showcase the advantage of application of TEMPO or the trityl radical for the isolation of these bis(borane)superoxide radical



Scheme 24 Synthesis and reactivity of a bis(borane)superoxide radical anion.

anions. Interestingly, THF or DMSO reacted with **94** prompted the regeneration of TEMPO and O_2 and formation of $(\text{THF})\text{B}(\text{C}_6\text{F}_5)_3$ or $(\text{DMSO})\text{B}(\text{C}_6\text{F}_5)_3$, respectively. This observation indicates that displacement of $\text{B}(\text{C}_6\text{F}_5)_3$ moiety from the anion alters the redox potential of the transient superoxide radical prompting electron transfer to the oxoammonium cation to generate TEMPO and liberating O_2 .

Conclusion and perspectives

The generation and characterization of radical species in main group chemistry has become more prevalent in the literature recently. Indeed, this tutorial has described a number of strategies involving the combinations of Lewis acids and bases that result in radical reactants or products. These include the induction of element–element bond homolysis, electron transfer between donor and acceptor molecules, the use of FLPs to stabilize or generate reactive radicals, and electron transfer to donor–acceptor adducts. The systems presented herein, also serve to highlight the notion that donor–acceptor interactions are not be limited to classical dative two-electron adduct formation. Thus, while many combinations of Lewis acids and bases form either CLA and FLP combinations and react *via* a diamagnetic, two-electron pathway, judicious choice of donor–acceptor combinations can afford radical pathways, offering new routes and strategies for the exploitation of main group chemistry in reactivity and synthesis.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- G. N. Lewis, *Valence and the Structure of Atoms and Molecules*, Chemical Catalog Com., New York, 1923.
- G. C. Welch, R. R. S. Juan, J. D. Masuda and D. W. Stephan, *Science*, 2006, **314**, 1124–1126.
- J. S. J. McCahill, G. C. Welch and D. W. Stephan, *Angew. Chem., Int. Ed.*, 2007, **46**, 4968–4971.
- D. W. Stephan, *Science*, 2016, **354**, aaf7229.
- D. W. Stephan and G. Erker, *Angew. Chem., Int. Ed.*, 2015, **54**, 6400–6441.
- D. W. Stephan, *J. Am. Chem. Soc.*, 2015, **137**, 10018–10032.
- M. Gomberg, *J. Am. Chem. Soc.*, 1900, **22**, 757–771.
- B. M. Hoffman and T. B. Eames, *J. Am. Chem. Soc.*, 1969, **91**, 5168–5170.
- J. J. Scepaniak, A. M. Wright, R. A. Lewis, G. Wu and T. W. Hayton, *J. Am. Chem. Soc.*, 2012, **134**, 19350–19353.
- B. M. Hoffman and T. B. Eames, *J. Am. Chem. Soc.*, 1971, **93**, 3141–3146.
- M. Melaimi, R. Jazzar, M. Soleilhavoup and G. Bertrand, *Angew. Chem., Int. Ed.*, 2017, **56**, 10046–10068.
- C. D. Martin, M. Soleilhavoup and G. Bertrand, *Chem. Sci.*, 2013, **4**, 3020–3030.
- V. Nesterov, D. Reiter, P. Bag, P. Frisch, R. Holzner, A. Porzelt and S. Inoue, *Chem. Rev.*, 2018, **118**, 9678–9842.
- Y. Su and R. Kinjo, *Coord. Chem. Rev.*, 2017, **352**, 346–378.
- G. Wang, H. Zhang, J. Zhao, W. Li, J. Cao, C. Zhu and S. Li, *Angew. Chem., Int. Ed.*, 2016, **55**, 5985–5989.
- L. L. Cao and D. W. Stephan, *Organometallics*, 2017, **36**, 3163–3170.
- L. Zhang and L. Jiao, *Chem. Sci.*, 2018, **9**, 2711–2722.
- L. Zhang and L. Jiao, *J. Am. Chem. Soc.*, 2017, **139**, 607–610.
- A. J. P. Cardenas, B. J. Culotta, T. H. Warren, S. Grimme, A. Stute, R. Fröhlich, G. Kehr and G. Erker, *Angew. Chem., Int. Ed.*, 2011, **50**, 7567–7571.
- M. Sajid, A. Stute, A. J. P. Cardenas, B. J. Culotta, J. A. M. Hepperle, T. H. Warren, B. Schirmer, S. Grimme, A. Studer, C. G. Daniliuc, R. Fröhlich, J. L. Petersen, G. Kehr and G. Erker, *J. Am. Chem. Soc.*, 2012, **134**, 10156–10168.
- M. Sajid, G. Kehr, T. Wiegand, H. Eckert, C. Schwickert, R. Pöttgen, A. J. P. Cardenas, T. H. Warren, R. Fröhlich, C. G. Daniliuc and G. Erker, *J. Am. Chem. Soc.*, 2013, **135**, 8882–8895.
- R. Liedtke, F. Scheidt, J. Ren, B. Schirmer, A. J. P. Cardenas, C. G. Daniliuc, H. Eckert, T. H. Warren, S. Grimme, G. Kehr and G. Erker, *J. Am. Chem. Soc.*, 2014, **136**, 9014–9027.
- C. J. Harlan, T. Hascall, E. Fujita and J. R. Norton, *J. Am. Chem. Soc.*, 1999, **121**, 7274–7275.
- C. J. Beddows, A. D. Burrows, N. G. Connelly, M. Green, J. M. Lynam and T. J. Paget, *Organometallics*, 2001, **20**, 231–233.
- X. Zheng, X. Wang, Y. Qiu, Y. Li, C. Zhou, Y. Sui, Y. Li, J. Ma and X. Wang, *J. Am. Chem. Soc.*, 2013, **135**, 14912–14915.
- E. J. Lawrence, V. S. Oganessian, G. G. Wildgoose and A. E. Ashley, *Dalton Trans.*, 2013, **42**, 782–789.
- L. Liu, L. L. Cao, Y. Shao, G. Ménard and D. W. Stephan, *Chem*, 2017, **3**, 259–267.

- 28 L. L. Liu, L. L. Cao, D. Zhu, J. Zhou and D. W. Stephan, *Chem. Commun.*, 2018, **54**, 7431–7434.
- 29 X. Pan, X. Chen, T. Li, Y. Li and X. Wang, *J. Am. Chem. Soc.*, 2013, **135**, 3414–3417.
- 30 Z. Dong, H. H. Cramer, M. Schmidtman, L. A. Paul, I. Siewert and T. Muller, *J. Am. Chem. Soc.*, 2018, **140**, 15419–15424.
- 31 G. Ménard, J. A. Hatnean, H. J. Cowley, A. J. Lough, J. M. Rawson and D. W. Stephan, *J. Am. Chem. Soc.*, 2013, **135**, 6446–6449.
- 32 J. R. Lawson and R. L. Melen, *Inorg. Chem.*, 2017, **56**, 8627–8643.
- 33 L. J. Hounjet, C. Bannwarth, C. N. Garon, C. B. Caputo, S. Grimme and D. W. Stephan, *Angew. Chem., Int. Ed.*, 2013, **52**, 7492–7495.
- 34 L. E. Longobardi, L. Liu, S. Grimme and D. W. Stephan, *J. Am. Chem. Soc.*, 2016, **138**, 2500–2503.
- 35 K. L. Bamford, L. E. Longobardi, L. Liu, S. Grimme and D. W. Stephan, *Dalton Trans.*, 2017, **46**, 5308–5319.
- 36 L. E. Longobardi, P. Zatspein, R. Korol, L. Liu, S. Grimme and D. W. Stephan, *J. Am. Chem. Soc.*, 2017, **139**, 426–435.
- 37 A. Waked, R. O. Memar and D. W. Stephan, *Angew. Chem., Int. Ed.*, 2018, **57**, 11934–11938.
- 38 T. Wang, G. Kehr, L. Liu, S. Grimme, C. G. Daniliuc and G. Erker, *J. Am. Chem. Soc.*, 2016, **138**, 4302–4305.
- 39 F. Türkyilmaz, G. Kehr, J. Li, C. G. Daniliuc, M. Tesch, A. Studer and G. Erker, *Angew. Chem., Int. Ed.*, 2016, **55**, 1470–1473.
- 40 X. Tao, F. Türkyilmaz, C. G. Daniliuc, G. Kehr and G. Erker, *J. Organomet. Chem.*, 2017, **847**, 167–172.
- 41 J. Zhou, L. L. Liu, L. L. Cao and D. W. Stephan, *Angew. Chem., Int. Ed.*, 2018, **57**, 3322–3326.
- 42 J. T. Henthorn and T. Agapie, *Angew. Chem., Int. Ed.*, 2014, **53**, 12893–12896.
- 43 L. L. Liu, L. L. Cao, Y. Shao and D. W. Stephan, *J. Am. Chem. Soc.*, 2017, **139**, 10062–10071.
- 44 J. Chen and E. Y. X. Chen, *Dalton Trans.*, 2016, **45**, 6105–6110.
- 45 L. L. Cao, K. L. Bamford, L. L. Liu and D. W. Stephan, *Chem. – Eur. J.*, 2018, **24**, 3980–3983.
- 46 Y. Liu, E. Solari, R. Scopelliti, F. Fadaei Tirani and K. Severin, *Chem. – Eur. J.*, 2018, **24**, 1–8.
- 47 X. Tao, C. G. Daniliuc, R. Knitsch, M. R. Hansen, H. Eckert, M. Lubbessmeyer, A. Studer, G. Kehr and G. Erker, *Chem. Sci.*, 2018, **9**, 8011–8018.
- 48 X. Tao, C. G. Daniliuc, O. Janka, R. Pöttgen, R. Knitsch, M. R. Hansen, H. Eckert, M. Lubbessmeyer, A. Studer, G. Kehr and G. Erker, *Angew. Chem., Int. Ed.*, 2017, **56**, 16641–16644.