Activation of Diazo Compounds by Fluorinated Triarylborane Catalysts

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Abstract The diverse applicability of diazo compounds as versatile reagents has enlarged the chemical toolbox in organic synthesis. Over the past few decades, transition-metal-catalyzed diazo compound activation has ignited the classical synthetic methodology via utilizing highly reactive metal carbene species. Many reviews have also appeared in the literature that show the advantages and disadvantages of metal-catalyzed activation of diazo compounds. Recently, tris(pentafluorophenyl)borane-mediated diazo activation reactions has remodeled this research area due to the potential for mild, environmentally friendly, metal-free, nontoxic reaction conditions, and the diverse reactivity patterns of boranes towards diazo compounds. In this review, we discuss the reactivity of the boron–diazo precursor adducts with compounds using catalytic and stoichiometric halogenated triarylboranes and, the mechanism of N2 release from the diazo reagent. This generates the reactive carbene species as a key intermediate which can further be exploited for O–H, N–H, S–H, and C–H insertions, azide insertion, group transfer, C–C/C=C coupling reactions, [2+2] or [2+4] cascade cyclization reactions, annihilation reactions, etc.

1 Introduction

Diazocompounds are useful synthons that have served as a carbene source for a variety of functionalization reactions via the carbene transfer strategy. In general, transition-metal-catalyzed carbeneoid species have attained enormous success due to the high reactivity of metal carbeneoids. Many reviews have also covered metal-catalyzed diazo activation reactions for the construction of nitrogen and non-nitrogen-based organic motifs. But the major disadvantages associated with these classical metal-catalyzed diazo activation reactions are the post-reaction contaminations.
tion due to the use of precious and toxic metals and selectivity issues due to the high reactivity of metal carbeneoid species that often affect the design and construction of drug molecules.\textsuperscript{5,6} To address these issues, in recent investigations, borane catalysis has been employed as a transition-metal-free and environmentally friendly approach.\textsuperscript{7,8} In particular, the continued effort to develop metal-free diazo activation reactions using tris(pentafluorophenyl)borane \([\text{B}(\text{C}_6\text{F}_5)_3]\) as a catalyst has partially resolved the selectivity and toxicity issues.\textsuperscript{3} Comparative studies between metal carbeneoid and metal-free carbene generation disclosed that synergic and metal–carbon (M–C) back-bonding interactions control the high reactivity of a metal carbeneoid, whereas the high Lewis acidity of \([\text{B}(\text{C}_6\text{F}_5)_3]\) and the vacant p-orbital in the boron center promotes boron coordination with the diazo compounds and thus activates the diazo compounds.\textsuperscript{9}

In this review, we have mainly emphasized the reactivity of diazo compounds in the presence of catalytic and stoichiometric tris(pentafluorophenyl)borane as well as related halogenated triarylboranes \([\text{B}(\text{Ar}^X)_3]\). The binding sites of the borane with the diazo compound and the mode of \(\text{N}_2\) release are also discussed. We have catalogued the reactions by reaction type including \(\text{O}–\text{H}^{10}\), \(\text{N}–\text{H}^{11,12}\), \(\text{S}–\text{H}^{13}\), and \(\text{C}–\text{H}\) insertions,\textsuperscript{14,15} azide insertion,\textsuperscript{16} carbonate transfer,\textsuperscript{17} C–C and C=C bond-forming reactions,\textsuperscript{18,19} cascade reactions,\textsuperscript{20,21} and annulation reactions,\textsuperscript{22,23} by utilizing diazo compounds as a carbene synthon in the presence of the borane \([\text{B}(\text{C}_6\text{F}_5)_3]\) as a metal-free catalyst.

## 2 Diazo Activation Using Stoichiometric Boranes

Although metal-catalyzed diazo activation has been well studied, the mechanism of activation of diazo compounds using Lewis acidic boranes has been less well explored. In this regard, the use of stoichiometric and catalytic reactions using boranes has shown a significant breakthrough in understanding their mode of activation. Although the reaction of diazo compounds with \(\text{BF}_3\)-\(\text{OEt}_2\) has been previously studied,\textsuperscript{24,25} many new contributions to the field have emerged using triarylboranes, which is the focus of this review. In 2017, Stephan and co-workers reported that the Lewis acid–base adduct of Lewis acidic \(\text{HB}(\text{C}_6\text{F}_5)_2\) and \([\text{B}(\text{C}_6\text{F}_5)_3]\) with the diazo compound diphenyl diazomethane \((\text{Ph}_2\text{CN}_2)\) is important in its activation. However, the stoichiometric addition of \([\text{B}(\text{C}_6\text{F}_5)_3]\) and \(\text{Ph}_2\text{CN}_2\) at \(-78\) °C led to the \(\text{N}_2\text{CN}_2\text{B}(\text{C}_6\text{F}_5)_3\) adduct \([\text{Ph}_2\text{CN}_2\text{B}(\text{C}_6\text{F}_5)_3]\) in 74% yield (Scheme 1).\textsuperscript{26} The \(\text{N}_2\text{B}\) adduct was confirmed through \(^{11}\text{B}\) and \(^{19}\text{F}\) NMR spectroscopic analysis. Evolution of \(\text{N}_2\) from \([\text{Ph}_2\text{CN}_2\text{B}(\text{C}_6\text{F}_5)_3]\) adduct at elevated temperature was also observed to furnish the proposed carbene \([\text{C}_3\text{B}(\text{C}_6\text{F}_5)_3]\). DFT analysis supported the formation of the \([\text{C}_3\text{B}(\text{C}_6\text{F}_5)_3]\) adduct; evolution of \(\text{N}_2\) from \([\text{Ph}_2\text{CN}_2\text{B}(\text{C}_6\text{F}_5)_3]\) was found to be exergonic by 53 kcal/mol. The calculated bond length for \([\text{C}_3\text{B}(\text{C}_6\text{F}_5)_3]\) was found to be 1.66 Å, which resembles the C–B bond length found in \([\text{B}(\text{C}_6\text{F}_5)_3]\), and the calculated bond order was 0.64 for the \([\text{C}_3\text{B}(\text{C}_6\text{F}_5)_3]\) single bond. It was hypothesized that the steric bulk of the arene rings on \(\text{Ph}_2\text{CN}_2\) prohibited the carbene insertion into C–B bonds. On the other hand, \(\text{HB}(\text{C}_6\text{F}_5)_3\) in the presence of diphenyl diazomethane showed an unusual 1,1-hydroboration reaction to produce the corresponding compound having an N–N bond in 83% yield (Scheme 1).

[Scheme 1](#) Activation of diphenyl diazomethane using stoichiometric boranes

Stephan and co-workers also extended their study of diphenyl diazomethane and \([\text{B}(\text{C}_6\text{F}_5)_3]\) in the presence of \(\text{Cp}^\text{‡}\text{Co}\). It was noted that diphenyl diazomethane, \([\text{B}(\text{C}_6\text{F}_5)_3]\), and \(\text{Cp}^\text{‡}\text{Co}\) produced a mixture of \([\text{Cp}^\text{‡}\text{Co}][\text{Ph}_2\text{CN}_2\text{NH}\text{B}(\text{C}_6\text{F}_5)_3]\) and \([\text{Cp}^\text{‡}\text{Co}][\text{Me}_3\text{SiCH}\text{B}(\text{C}_6\text{F}_5)_3]\). However, a single electron transfer (SET) process was assumed to be operative from \(\text{Cp}^\text{‡}\text{Co}\) to \(\text{Ph}_2\text{CN}_2\text{B}(\text{C}_6\text{F}_5)_3\) for the formation of \([\text{Cp}^\text{‡}\text{Co}][\text{Me}_3\text{SiCH}\text{B}(\text{C}_6\text{F}_5)_3]\) (Scheme 1).\textsuperscript{27}

In 2020, Stephan also found that frustrated Lewis pairs (FLPs) \(\text{R}_2\text{POBcat}\) \((\text{R} = \text{Bu}, \text{mesityl}, \text{cat} = \text{catechol})\) derived from phosphine oxides and \(\text{CIBcat}\) reacted with \(\text{Ph}_2\text{CN}_2\) to form the compound \(\text{Ph}_2\text{C}(\text{N}_2)\text{BcatOPR}_2\) \((\text{R} = \text{Bu})\) in 87% yield (Scheme 1).\textsuperscript{28} Unfortunately, a problem with isolation prevented the purification of the compound \(\text{Ph}_2\text{C}(\text{N}_2)\text{BcatOPR}_2\) \((\text{R} = \text{mesityl})\), nevertheless single crystal X-ray analysis helped to assign the structure of the compound.

As shown in Scheme 2, several electrophilic boranes have been reacted with electronically varied diazomethanes to provide sterically demanding borane derivatives in high yields.\textsuperscript{29} The new borane \((\text{Me}_3\text{SiCH}(\text{C}_6\text{F}_5))\text{B}(\text{C}_6\text{F}_5)_3\) was produced in 65% yield when a 2 M hexane solution of \(\text{Me}_3\text{SiCH}(\text{N}_2)\) interacted rapidly with stoichiometric amounts of \([\text{C}_6\text{F}_5)_3\text{B}\) in \(\text{CH}_2\text{Cl}_2\) at \(-78\) °C via insertion of \(\text{Me}_3\text{SiCH}(\text{N}_2)\) into a C–B bond. The product was purified by recrystallization. Again, the addition of 2 equivalents of \(\text{Me}_3\text{SiCH}(\text{N}_2)\) with \([\text{C}_6\text{F}_5)_3\text{B}\) at \(-78\) °C provided the double in-
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Stoichiometric reactions of boranes and diazo esters

Scheme 2 Stoichiometric reactions of boranes and diazo esters

Stephan and co-workers showed that the stoichiometric addition of \( B(C_6F_5)_3 \) in ethyl \( \alpha \)-diazo propanoate produced an \( E \) and \( Z \) mixture of boron enolates, which were subsequently converted into the double insertion product in 62% yield in the presence of another equivalent of ethyl \( \alpha \)-diazo propanoate (Scheme 3).\(^{30}\) The resulting enolate product reacted with pyridine leading to the corresponding adduct in 73% yield. This product is a potential intermediate in the O→B adduct formation rather than N→B formation as observed by Stephan and co-workers for \( \text{Ph}_2\text{CN}_2 \).\(^{26}\) Subsequently, at room temperature or higher, \( \text{N}_2 \) release rapidly occurred and the aryl group migrated from \( \text{BAr}_3 \) to the carbene carbon center yielding a similar boron enolate to that observed by Stephan and co-workers (Scheme 3).\(^{30}\) The aryl migration efficiency was found to be improved by increasing the Lewis acid strength in the order of \( \text{BPh}_3 < B(4-\text{FC}_6\text{H}_4)_3 \) < \( B(2,6-\text{F}_2\text{C}_6\text{H}_3)_3 \) < \( B(3,4,5-\text{F}_3\text{C}_6\text{H}_2)_3 \). We also found that the borane enolate generated from an \( \alpha \)-diazo ester and borane could participate in addition reactions to carbonyls, anhydrides, nitriles, esters isocyanates to offer a wide range of \( \alpha \)-aryl functionalized \( \beta \)-hydroxy and \( \beta \)-keto esters.\(^{32}\) Using the new borane \( B(3,4-\text{Cl}_2\text{C}_6\text{H}_3)_3 \) with \( (4-\text{MeOC}_6\text{H}_4)\text{C}(\text{N}_2)\text{CO}_2\text{Me} \), the aryl transfer \( (4-\text{MeOC}_6\text{H}_4)\text{C}(3,4-\text{Cl}_2\text{C}_6\text{H}_3)\text{CO}_2\text{Me} \) product was isolated in 92% yield following work up. This product is a potential intermediate in the
synthesis of diclofensine, an antidepressant developed by Hoffmann-LaRoche, and has been previously synthesized by a rhodium-catalyzed process. Alternatively, when 2-benzyloxy-substituted diazo ester derivatives were employed in the standard reaction conditions, unexpected reactivity was observed through the formation of 3,3-disubstituted benzofuran-2(3H)-ones (Scheme 4). It was proposed, by detailed NMR studies and crossover experiments, that an unpredicted intramolecular attack of boron enolate posed, by detailed NMR studies and crossover experiments, that an unpredicted intramolecular attack of boron enolate on the benzyl group followed by an aryl group transfer led to the desired product via intermediate II. Interestingly, this report disclosed the metal-free approach for the formation of sterically hindered C3 disubstituted lactones in a single-step process.

3 Diazo Activation Using Catalytic B(C6F5)3

Most of the reactions involving Lewis acidic B(C6F5)3 and diazo compounds have employed donor/acceptor-substituted diazo compounds, such as α-aryl-α-diazo esters, due to their higher stability. It is not surprising therefore that most studies involving diazo activation using B(C6F5)3 have focused on α-aryl-α-diazo ester compounds. In general two binding modes of α-aryl-α-diazo esters with catalytic B(C6F5)3, have been suggested in the literature including N\textsubscript{diazo}→B or O\textsubscript{carbonyl}→B adduct formation. However, the boranes were found to preferentially bind to the more Lewis basic oxygen of the carbonyl group to form the O→B adduct. This was found both experimentally and computationally (Figure 1). By DFT studies the C–N bond in the boron-coordinated diazo ester is longer and weaker (1.334 Å) than in the free uncoordinated diazo ester (1.318 Å). In addition, a shortening of the C–C bond length from 1.470 Å to 1.436 Å was also observed for the O→B adduct. As a result, release of nitrogen becomes easier. A subsequent study using DFT calculations with various donor/acceptor diazo compounds implied that the ease of N\textsubscript{2} release from the O→B adduct depended upon the electronic effect on the aryl ring (Ar) or the carbonyl group (e.g., ester, aldehyde, ketone, etc.) of the diazo ester (Figure 1b). The calculations showed that there is a strong correlation between the reaction free energy of carbene formation and the activation barrier to N\textsubscript{2} release. Thus, generally there was a lower activation barrier to N\textsubscript{2} release in the presence of water as a hydroxy source to yield a series of α-hydroxy esters (Scheme 5a). Various α-diazo esters bearing OMe, Cl, and COOMe substituents at the aryl group and a thiophene-based α-diazo ester effectively participated in the O–H insertion reaction producing the corresponding products in reasonable yields. It should be noted that the Lewis acidic borane B(C6F5)3 in the presence of water acts as Bronsted acid. As depicted in Scheme 5a, two different possible mechanisms are proposed. Either B(C6F5)3+nH\textsubscript{2}O assists in the protonation of the diazo ester to produce intermediate I, which is then attacked by water, or conversely, as demonstrated in intermediate II, the borane...
serves as a bifunctional catalyst that could help both protonation and nucleophilic attack by water to produce the desired hydroxylated product. It was assumed that noncovalent interactions including N–H, F–H hydrogen bonding interactions, and O–B interactions associated with the water molecules could promote the nucleophilic attack. In 2021, α-phosphoryloxy carbonyl compounds were also reported by Jiang and co-workers (Scheme 5b).36 They showed that various phosphinic acids including di(naphthalen-2-yl)phosphinic acid, and dibenzylphosphinic acid could be used as O–H insertion precursors in the presence of 10 mol% B(C6F5)3 as a catalyst to afford C–O bonded products (α-phosphoryloxy carbonyls) in good to excellent yields.

![Scheme 5](image)

Scheme 5 (a) Tang’s and (b) Jiang’s reports on B(C6F5)3-catalyzed O–H insertions of α-diazo esters

The borane-catalyzed S–H insertion reaction of thiols with α-aryl-α-diazo esters has also been demonstrated to form a new C–S bond. Li and co-workers have shown that the neat mixing of thiols with α-aryl-α-diazo esters produced the α-thio ester as a product (Scheme 6).37 Various thiols including thiophenol, thiophene-3-thiol, and propane-1-thiol effectively participated in the S–H insertion reaction to yield the desired α-thio ester derivatives as shown in Scheme 6. It is predicted that the formation of the reactive carbene intermediate is expected to be involved to promote the addition reaction with thiols followed by proton transfer to afford the final product.

![Scheme 6](image)

Scheme 6 Li’s work on B(C6F5)3-catalyzed α-aryl-α-diazo esters in S–H insertion for the synthesis of α-thio esters

Selective N-alkylation of benzotriazoles is challenging due to selectivity issues generating a mixture of N1 and N2-alkylated benzotriazoles.37 In 2021, Stephan and co-workers successfully resolved this selectivity issue with the help of a borane catalyst. They found that N–H insertion of benzotriazoles was assisted by a boron enolate (O→B adduct) from B(C6F5)3 and α-aryl-α-diazo esters which offered the site-selective N1-alkylation of various substituted benzotriazoles and triazoles (Scheme 7a).37

At the same time, Koenigs and co-workers developed a similar strategy for N–H insertion of carbazoles with α-aryl-α-diazo esters using the same borane as a metal-free catalyst (Scheme 7b).37 Phenothiazines and phenoxazines also took part in the N–H insertion reaction to give the corresponding products in good to excellent yields. As proposed by the authors, the coordination of the carbonyl oxygen atom in the α-diazo ester substrate with the borane made the carbene a hard electrophile, which was consequently attacked by the hard nucleophilic nitrogen atom of the carbazole, according to the HSAB (Hard Soft Acid Base) principle.38 These strategies demonstrate the development of a novel and metal-free borane-catalyzed C–N bond-forming reaction that could potentially substitute the more toxic and expensive transition-metal-catalyzed C–N coupling reactions in the area of N-heterocycle synthesis.

Activation of C–H bonds over the cross-coupling of C–X bonds has become attractive in synthetic transformations as it can be performed directly without using any prefunctionalized starting materials. However, while metal-catalyzed C–H activations are well-documented in the literature, the metal-free C–H bond functionalization using Lewis acids is not as extensively explored in the modern organic synthetic community. In this regard, C–H functionalization using the concept of O→B adduct formation between a diazo compound and a borane has been recently implemented. Indeed, Zhang and co-workers demonstrated that the borane-catalyzed ortho C–H functionalization of unprotected phenols could be accomplished with α-aryl-α-diazoacetates (Scheme 8a).35 They proposed that an intermolecular hydrogen bonding interaction between a fluorine atom of

![Synthesis](image)

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the B(C₆F₅)₃ catalyst and the phenolic O–H group is operative in attaining high chemoselectivity. In turn, control experiments including deuterium labeling on phenol (C₆H₅OD) confirmed that the phenolic O–H was the proton source in this reaction as a deuterium labelled product was found. The reaction with anisole instead of phenol gave the (13% and 9% yields, respectively), indicating the importance of a hydrogen-bonded assisted mechanism.

On the other hand, Koenigs and co-workers observed that N-protected carbazoles could exhibit C3–H functionalization with α-aryl-α-diazo esters to produce various C–C coupled products provided the corresponding C–H functionalized products in reasonable yields. Thus, these studies showed that the implementation of metal-free borane catalysts could potentially widen the synthetic scope of chemoselective reactions.

In 2020, we reported the chemoselective C3–H or C2–H insertions of indoles and pyrroles, respectively, with α-aryl-α-diazo esters achieved using B(C₆F₅)₃ as a metal-free catalyst (Scheme 9). Interestingly, protected and unprotected indoles smoothly reacted with the α-diazo esters to furnish C–C coupled products in excellent yields. No other N–H insertion product was observed for unprotected indoles.

We have mechanistically investigated the reaction between the reactive carbene–borane intermediate I and indoles that initially leads to the formation of the kinetically controlled C2 and C3 cyclopropanation species, which then furnishes a cationic intermediate II via cyclopropane ring opening. Finally, the desired C3-alkylated product is obtained by aromatization and proton transfer. In contrast, pyrrole governed electrophilic substitution at the C2 position yields the C2-alkylated product.

Organic azides are very useful synthons that are utilized as valuable building blocks for the synthesis of N-heterocycles. The development of catalytic protocols employing trisubstituted organic azides is highly desirable.
action has been well explored using metal catalysis via the formation of a metal carbene intermediate. In 2020, Mancinelli and Wilkerson-Hill introduced a complementary $\text{B(C}_6\text{F}_5)_3$-catalyzed approach for the cyclopropanation reaction of unactivated alkenes using diazo compounds as a reactive carbene synthon (Scheme 11).\(^{41}\)

The substrates having halogen functionalities were tolerated nicely to produce corresponding cyclopropanes with excellent yields using 10 mol\% catalyst in 1,2-dichloroethane at 50 °C for 14–16 h. However, the diazo compounds dimethyl diazomalonate, ethyl diazocyanoacetate, and ethyl diazoacetate were unsuccessful in producing the desired cyclopropanated product. At the same time, we also reported the cyclopropanation of alkenes using 10 mol\% catalyst in $\text{CH}_2\text{Cl}_2$ at 45 °C for one day.\(^{14}\) Subsequently we examined the cyclopropenation of alkynes (Scheme 11). A wide range of cyclopropene products could be afforded using 10 mol\% of freshly prepared $\text{B(C}_6\text{F}_5)_3$ in 1,2-dichloroethane solvent at 50–65 °C temperature.\(^{42}\) The mechanism was proposed to proceed in a similar manner to that described earlier through $\text{O} \rightarrow \text{B}$ adduct formation and subsequent loss of $\text{N}_2$ to form a borane-coordinated reactive carbene species \(\text{I}\) which can be better described by the resonance stabilized intermediate \(\text{II}\). Subsequently, nucleophilic attack from the acetylene onto \(\text{II}\) leads to another carbocation intermediate \(\text{III}\) having a new C–C bond. Finally, intramolecular attack from the boron enolate onto the car-
bocationic center in III delivers the cyclopropene with the regeneration of the boron catalyst. It was found that internal alkynes gave low yields compared to terminal alkynes. Interestingly, a competitive experiment using a substrate with both terminal alkene and alkyn functionalities revealed that only the alkene functionality participated in the cyclopropanation reaction without touching the alkyne.

In our continued effort towards developing Lewis acid catalysts for organic synthesis, we also examined the reactivity of benzo-fused furans and indenes using the same borane catalyst (Scheme 12). In all cases, the C=C bond in the 5-membered ring took part in a [2+1] cycloaddition reaction with the α-aryl-α-diazo esters to yield a range of substituted cyclopropanes.

As illustrated in Scheme 12, various benzo-furans and indenes reacted smoothly with α-aryl-α-diazo esters in the presence of 10 mol% B(C₆F₅)₃ under mild conditions to produce the functionalized cyclopropane derivatives in good to excellent yields and as a single diastereoisomer. A DFT study revealed that the cyclopropanation took place with a significantly lower energy barrier than C–H insertions for all the heterocycles, however this was found to be the kinetic product. For indoles and pyrroles, C–H insertion became thermodynamically feasible because the cyclopropanated product was less unstable and the energy barrier to the C–H insertion was low enough to be possible under the reaction conditions. It was calculated that a highly diastereoselective cyclopropanated product is preferred for benzofurans and indenes as the energy barrier (32.6 kcal/mol) is too high for the formation of the thermodynamic C–H insertion products rather than cyclopropanation.

In 2023, Stephan and co-workers extended the cyclopropanation reaction to 3-alkylidene-oxindoles in the presence of diazo esters and catalytic B(C₆F₅)₃ (Scheme 13). The spirocyclopropane-oxindole products were attained in excellent yields and high diastereoselectivities (up to d.r. 20:1). This newly developed protocol was also utilized for scale-up synthesis (up to 2.5 g, 96% yield).

4.3 Annulation Reactions

The annulation reaction strategy is a useful strategy commonly employed to synthesize cyclic organic architectures. The recent breakthroughs in annulation reactions have been spurred by using triphenylborane as a metal-free catalyst. In 2018, Brewer and Fang found that β-hydroxy-α-diazo ketones underwent intramolecular electrophilic vinylation in the presence of 0.25 mol% B(C₆F₅)₃ (Scheme 14). It was indicated that B(C₆F₅)₃ coordinates with N₂ of the diazo precursor assisting the formation of the vinyl diazonium ion I via a dihydroxylation process. Following the elimination of N₂ from intermediate I, the vinyl cation II is generated. Afterwards, the vinyl cation II (destabilized by the carbonyl group) exhibits ring expansion to give the tricyclic, seven-membered final products through loss of the proton. As shown in Scheme 14, OMe and ‘Bu substituted β-hydroxy-α-diazo ketones gave the corresponding indenones in reasonable yields.
In 2022, we reported a Lewis acid catalyzed cyclization reaction using conjugated diene and dienophiles to form pyrazoles (Scheme 15).20 By mixing two distinct diazo compounds (an α-aryl-α-diazo ester and an α-vinyl-α-diazo ester), N-substituted pyrazoles could be afforded as a major and minor regioisomer. Various conjugated diene and dienophiles were screened under the standard reaction conditions to provide a wide range of N-substituted pyrazoles in near quantitative yields. Mechanistically it was proposed that the α-aryl-α-diazo ester was activated by B(C6F5)3 through the O→B adduct I. Reactive carbene species II was then generated by the release of N2 from I. Next, reactive carbene species II reacted with the conjugated α-vinyl-α-diazo ester to form O→B hydrazine adduct III, which subsequently cyclizes to give the N-substituted pyrazoles as the minor isomer V via intermediate IV, and the catalyst is regenerated. The minor isomer could then be interconverted to give the major isomer by a second B(C6F5)3-catalyzed cycle. The minor isomer V formed an N→B adduct VI with B(C6F5)3 which then reacts with another molecule of minor isomer V to provide the more thermodynamically stable isomer (major) via the formation of VII and VIII.

So far, we have discussed that diazo esters could bind with the borane through the formation of either the B→O adduct or the B→N adduct, but, recent findings by Nemoto and co-workers proposed a third activation mode (Scheme 16).23 They suggested that the activation mode of the borane with the diazo compound could be switched to a B→C adduct I. Subsequently, the B→C adduct can lead to N2 evolution to generate active species II. As outlined in Scheme 16, various terminal α-diazo amides in the presence of the borane catalyst led to dearomative spiro cyclizations. Not only with phenols and naphthols, but also indoles gave the spirocyclic product via dearamatization.

It was rationalized that cooperative noncovalent interactions including π–π stacking between the pentafluoro-
benzene rings on the borane and the phenol, and F–C interactions between one of the fluorine atoms and the diazo carbon stabilized the B–C bond and facilitated neighboring group participation with the amide group to generate the active carbene species. The intermediate II could then go on to form various spirocyclic motifs, such as cyclohexadienones, tetraenones, and indolenines, through a dearomatization reaction under ambient conditions. It was observed that 2,6-di-tert-butylpyridine was acting here as a proton scavenger and thus enhanced the yield of the reaction.

In 2023, Stephan and co-workers reported [2+4] and [2+2] cascade cyclization reactions starting from N-protected imines and α-diazo ketones using B(C_6F_5)_3 as a catalyst (Scheme 17). Importantly, by altering the N-protecting group in the imine, different reactivity was observed. When N-tert-butoxycarbonyl imines were reacted with α-diazo ketones, a series of β-lactams were synthesized via a [2+2] cascade cyclization process. In contrast, the use of N-benzyl imines as imine partners with α-diazo ketones led to oxazinone derivatives via a [2+4] cycloaddition process. The reactions proceeded through a reactive ketene intermediate which is formed by a Wolff rearrangement. Subsequently, the ketene reacts with the imines to offer either β-lactams or oxazinone derivatives with good yields.

### 4.4 C–C Bond Scission and C=C Bond Forming Reactions

Carbon–carbon (C–C) bond-forming reactions are considered the backbone of synthetic organic chemistry. In 2019, Prabhu and co-workers demonstrated that the reaction of allylic alcohols with α-aryl-α-diazo esters in the presence of B(C_6F_5)_3 as a catalyst resulted in the formation of a new C–C bond (Scheme 18). Several cinnamyl alcohols reacted with α-diazo esters to give the desired products in moderate yields. The mechanism proposed by them to proceed through the B–N adduct I, which then gives borane-coordinated reactive carbene species II following N_2 release. The intermediate II is suggested to be stabilized by the extended conjugation with the adjacent aryl group as in II’. Following, nucleophilic attack by the allylic β-sp^2-carbon onto intermediate II, the borane-coordinated cation species III is formed. Cationic intermediate III is then converted into a four-membered cyclic intermediate IV, eventually giving the desired C–C coupled product via intermediate V with the regeneration of the borane catalyst.

In our previous work, we have investigated the B(C_6F_5)_3-catalyzed formation of C=C bonds from the reaction of benzyl aryl esters with α-diazo esters (Scheme 19). Not only did the benzyl diaryl esters show benzylic alkenylation, but also aryl-alkynyl and aryl-alkenyl esters were effectively used to afford the desired propargylic alkenylation product. Unfortunately, the E/Z-selectivity of the alkene product when using asymmetric esters and α-diazo esters was poor. Optimization of the reaction conditions suggested that the reaction did not proceed without a catalyst and B(C_6F_5)_3 was proven to be the best catalyst for this transformation. It became clear from DFT experiments that borane preferred to coordinate with the carbonyl oxygen of the aryl ester rather than the nitrogen or carbonyl oxygen of the diazo ester. The O_{aryl}→B adduct (intermediate I) helped in the generation of a carbenium species II as indicated in Scheme 19. Following, nucleophilic attack by the diazo ester, and an E2-type elimination reaction with the help of intermediate III, the C=C coupled product is generated with loss of N_2 and benzoic acid from intermediate IV.

### 4.5 Group Transfer Reactions

In 2019, Prabhu and co-workers envisioned a borane-catalyzed carbene transfer reaction using di-tert-butyl dicarbonate as a carbon donor and α-diazo esters as the carbene acceptor (Scheme 20). The authors proposed a similar mechanism to that proposed in their previous study (Scheme 18) in that the B(C_6F_5)_3 forms N→B adduct I with the diazo ester which subsequently is converted into resonance stabilized intermediate II/II’. The nucelphilic carbonate then interacts with intermediate II to give α-B(C_6F_5)_3 stabilized oxonium ylide III. In the next step, III is converted...
into intermediate IV containing the carbonate functionality, which reacts with another molecule of II to furnish inter-
mediate V. The desired product is then realized by the elim-
ination of a cation stabilizing R¹ group as depicted in
Scheme 20.

### 4.6 Ring-Opening Reactions

Following on from the above discussion in Section 4.2, our studies on C–H insertion of pyrroles and indoles and our cyclopropanation/cyclopropanation studies with various multiple bonded species (alkynes, alkynes, benzofu-
rans, and indenes) led us to also investigate the reactivity of furans. To our surprise, the reactions of furans with α-diazo esters catalyzed by B(C₆F₅)₃ led to a new reactivity pathway that resulted in the ring opening of the furan (Scheme 21).

Although the ring-opening reaction worked well with B(C₆F₅)₃, we observed that the slightly less Lewis acidic borane tris(2,4,6-trifluorophenyl)borane [B(2,4,6-F₃C₆H₂)₃] was a better catalyst for this transformation. Our DFT stud-
ies helped us to understand the difference in reactivity. The α-diazo ester O→B adduct led to loss of N₂, as described ear-
erlier, and reaction with the furan leads to the kinetically con-
trolled C2 and C3 cyclopropane intermediate I. The result-

### 4.7 Miscellaneous Reactions of Diazo Compounds with B(C₆F₅)₃

In 2023, we showed that α-vinyl-α-diazo esters showed divergent reactivity with borane catalysts in the presence of nitrones (Scheme 22). By switching the diazo precursor and the reaction conditions (B(C₆F₅)₃, loading and tempera-
ture), either isoxazolidines or Mukaiyama–Mannich addi-
tion products could be afforded in which the diazo func-
tionality was untouched. A range of isoxazolidine and
Mukaiyama–Mannich addition products were isolated in
moderate to good yields and good diastereoselectivities. In
these reactions the inability of the borane to activate the di-
azo functionality was proposed to be due to the preferential
binding of the borane to the nitrone. The highly functionalized diazo-containing products could be utilized in further reactivity using rhodium-based catalysts.

5 Conclusions

In conclusion, we have discussed recent literature on Lewis acidic triarylborane-mediated diazo compound activation. Most of these studies have employed B(C₆F₅)₃ as an alternative to the previously reported precious transition-metal-catalyzed diazo activation. Various modes of diazo activation by B(C₆F₅)₃ have been proposed for diazo esters through O→B/N→B/C→B adduct formation. Mechanistic insights from DFT studies have helped to interpret the mode of activation in these compounds and suggest that the O→B adduct is the most likely in the case of α-diazo esters to generate the borane stabilized carbene intermediate. DFT studies have also aided in understanding the catalytic reaction mechanism in the presence of the substrate as well as to understand the different reaction scopes and selectivities.

Stoichiometric and catalytic addition of B(C₆F₅)₃ and other fluorinated triarylboranes to diazo compounds has led to various boron-based organic complex molecules involving B–N, B–C bonds and valuable organic transformations including O–H, N–H, S–H, and C–H insertions, azide insertion, carbonate transfer, C–C and C=C bond forming reactions, cycloadditions, and annulation reactions. Recent findings also revealed that the diazo group in vinyl diazo esters could remain intact in the presence of B(C₆F₅)₃ when reacted with nitrone. We foresee that the utilization of borane catalysis involving diazo compounds will advance
main group inorganic chemistry towards highly selective organic reactions, and it will pave a new direction in the area of borane-catalyzed synthetic methodology. Overall, this review offers an excellent guideline for the synthesis of high-value-added molecules, such as natural products and biologically active drug compounds, using Lewis acidic boranes as a metal-free catalyst.

Conflict of Interest
The authors declare no conflict of interest.

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