**Introduction**

Tris(pentafluorophenyl)borane has recently emerged as a powerful Lewis acid catalyst.\(^1\)–\(^3\) The strong Lewis acidity\(^4\)–\(^6\) at the boron center allows us to establish a wide range of organic transformations \(\text{via} \ C\text{-}B,\(^4\)–\(^6\) C\text{-}C,\(^7\)–\(^10\) C\text{-}N,\(^11,12\) C\text{-}O,\(^13,14\) and C\text{-}Si\(^15\)–\(^18\) bond formations.\(^5\)\) Pioneered by Stephan and Erker, \(\text{B}(\text{C}_6\text{F}_5)_3\) has gained popularity in frustrated Lewis pair (FLP) chemistry which encompasses widespread applications in organic reactions.\(^19\)–\(^22\) Indeed, numerous efforts have been devoted to the activation of alkenes and alkynes by FLPs for the formation of cyclic scaffolds.\(^23\)–\(^26\) However, in many cases, the highly desirable catalytic reaction is obstructed by the initially formed stable borate adduct.\(^26\)–\(^28\) Consequently, \(\text{B}(\text{C}_6\text{F}_5)_3\) catalyzed cyclization leading to important heterocyclic scaffolds is rare.\(^29\)–\(^33\)

In this context, 1,2,4-triazoles are omnipresent heterocyclic motifs in numerous biologically active compounds\(^33\)–\(^34\) and they also have widespread applications in organic light emitting diodes,\(^35,36\) organic photovoltaic cells, electroluminescent devices,\(^37,38\) bi-stable resistive memory devices,\(^39\) pesticides, and medicines.\(^40\) Given their applications, a number of strategies have been paid for by the Royal Society of Chemistry

This has shifted the gear for metal-free N\(_2\) activation closer to reality. Conversely, the direct interaction of N\(_2\)-tosylhydrazones with \(\text{B}(\text{C}_6\text{F}_5)_3\) and their application in catalytic transformations have not been reported yet.

On the other hand, environmentally benign acceptorless catalytic dehydrogenation which is highly challenging even for transition-metal complexes\(^31,33\) is rare under metal-free conditions.\(^33\)–\(^36\) Very recently, we have presented a manganese-

---

**Scheme 1** Applications of borane adducts in main group chemistry.
catalyzed acceptorless-dehydrogenative olefination of heteroarenes with primary alcohols. Herein, we report B(C$_6$F$_5$)$_3$ catalyzed acceptorless-dehydrogenative-cyclization of N-tosylhydrazones 1 and anilines 2 to triaryl-1,2,4-triazoles 3 via a borane adduct 4 followed by sequential C–N/N–N bond formation (Scheme 1b). Furthermore, extensive DFT calculations are performed not only to understand the mechanistic features of borane catalyzed triazole formation but also to assist future development of similar classes of reactions.

## Results and discussion

Initially, to check the reactivity of hydrazone 1$_a$ with B(C$_6$F$_5$)$_3$, a stoichiometric reaction in benzene at room temperature was carried out. It leads to the formation of a Lewis adduct 4$_a$ ($^1$B – 2.5 ppm) after 1 h in 82% yield (Scheme 2). When 4$_a$ was reacted with an aromatic amine 2$_a$ at 80 °C in benzene, 3,4,5-triaryl-1,2,4-triazole 3$_{aaa}$ was formed in 85% NMR yield along with an equimolar amount of TsNH$_2$ and B(C$_6$F$_5$)$_3$.

As B(C$_6$F$_5$)$_3$ was finally released from the adduct 4$_a$ after its reaction with the amine 2$_a$, it was posited that catalytic turnover should be possible under thermal conditions. Interestingly, when the reaction was implemented with 5 mol% B(C$_6$F$_5$)$_3$ at 80 °C 1,2,4-triazole 3$_{aaa}$ was obtained in 82% isolated yield along with 68% of TsNH$_2$ as a byproduct (Table 1, entry 1). While the increased catalyst loading did not significantly improve the yield (entry 2), a slight decrease in the product yield was observed with 3 mol% B(C$_6$F$_5$)$_3$ (entry 3). The use of less Lewis acidic boranes such as BPh$_3$ was unproductive (entry 4). In addition, less hindered boranes like BF$_3$·OEt$_2$ resulted in no detectable product formation (entry 5). Other Lewis acid catalysts like Sc(OTf)$_3$, FeCl$_3$ and ZnCl$_2$ were also not effective for this reaction (entry 6, Schemes S9 and S10 in the ESI†).

Next, the scope of this metal-free protocol was explored. A series of hydrazones 1 could be employed with various anilines 2 to afford symmetrical 3,4,5-triaryl-1,2,4-triazoles 3 in good to excellent yields (Table 2). The reaction of 1$_a$ and 1$_b$ with anilines 2$_{a-d}$ bearing OMe-, Me-, H-, Cl- and Br-substituents at the para- or meta-position of the aryl ring afforded the triazoles 3$_{aab}–3_{bbf}$ in 66–87% yields. Similarly, the hydrazones 1$_c$–g having substituents with different steric and electronic properties at the ortho-, meta-, and para-position on the aromatic rings could readily be cyclized with 2$_a$ to produce 3$_{cca}–3_{gga}$ in 71–86% yields. Electronically biased aryl rings could be installed smoothly to obtain 3$_{ech}$, 3$_{hbb}$, and 3$_{icg}$ in 56–78% yields. Likewise, thiophene- and fluorine-containing 1,2,4-triazoles 3$_{ech}$ and 3$_{jjk}$ could be synthesized in 79% and 84% yields,

**Table 1** Optimization of B(C$_6$F$_5$)$_3$ catalyzed cyclization of the hydrazone 1$_a$ with anilines 2$_a$.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Deviation from above</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>None</td>
<td>82 (n.r.)</td>
</tr>
<tr>
<td>2</td>
<td>10 mol% B(C$_6$F$_5$)$_3$</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>3 mol% B(C$_6$F$_5$)$_3$</td>
<td>74</td>
</tr>
<tr>
<td>4</td>
<td>5 mol% B(C$_6$F$_5$)$_3$</td>
<td>n.r.</td>
</tr>
<tr>
<td>5</td>
<td>5 mol% BF$_3$·OEt$_2$</td>
<td>n.r.</td>
</tr>
<tr>
<td>6</td>
<td>5 mol% Sc(OTf)$_3$ or FeCl$_3$ or ZnCl$_2$</td>
<td>n.r.</td>
</tr>
</tbody>
</table>

**Table 2** B(C$_6$F$_5$)$_3$ catalyzed synthesis of symmetrical 1,2,4-triazoles.

<table>
<thead>
<tr>
<th>R$_1$, R$_2$, R$_3$</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3$_{aab}$</td>
<td>84%</td>
</tr>
<tr>
<td>3$_{abb}$</td>
<td>77%</td>
</tr>
<tr>
<td>3$_{abc}$</td>
<td>65%</td>
</tr>
<tr>
<td>3$_{aad}$</td>
<td>55%</td>
</tr>
<tr>
<td>3$_{aae}$</td>
<td>79%</td>
</tr>
<tr>
<td>3$_{aaf}$</td>
<td>83%</td>
</tr>
<tr>
<td>3$_{aag}$</td>
<td>85%</td>
</tr>
<tr>
<td>3$_{aa}$</td>
<td>86%</td>
</tr>
<tr>
<td>3$_{aab}$</td>
<td>83%</td>
</tr>
<tr>
<td>3$_{aac}$</td>
<td>71%</td>
</tr>
<tr>
<td>3$_{aad}$</td>
<td>75%</td>
</tr>
<tr>
<td>3$_{aaf}$</td>
<td>78%</td>
</tr>
<tr>
<td>3$_{aa}$</td>
<td>85%</td>
</tr>
<tr>
<td>3$_{aac}$</td>
<td>77%</td>
</tr>
<tr>
<td>3$_{aad}$</td>
<td>75%</td>
</tr>
<tr>
<td>3$_{aaf}$</td>
<td>78%</td>
</tr>
<tr>
<td>3$_{aaa}$</td>
<td>84%</td>
</tr>
<tr>
<td>3$_{aab}$</td>
<td>83%</td>
</tr>
<tr>
<td>3$_{aac}$</td>
<td>71%</td>
</tr>
<tr>
<td>3$_{aad}$</td>
<td>75%</td>
</tr>
<tr>
<td>3$_{aaf}$</td>
<td>78%</td>
</tr>
<tr>
<td>3$_{aa}$</td>
<td>85%</td>
</tr>
<tr>
<td>3$_{aac}$</td>
<td>77%</td>
</tr>
<tr>
<td>3$_{aad}$</td>
<td>75%</td>
</tr>
<tr>
<td>3$_{aaf}$</td>
<td>78%</td>
</tr>
<tr>
<td>3$_{aaa}$</td>
<td>84%</td>
</tr>
</tbody>
</table>

*a Reaction conditions: 1$_a$ (0.5 mmol), 2$_a$ (0.25 mmol), and B(C$_6$F$_5$)$_3$ (5 mol%) in 2.0 mL benzene; isolated yield. b NMR yield using 1,3,5-trimethoxybenzene as the internal standard. n.r. = no reaction.

**Scheme 2** Borane adduct of N-tosylhydrazone 1$_a$ and its transformation.
respectively. Notably, an ester-group could also be tolerated under the reaction conditions to furnish 3aksi in 80% yield. On the other hand, substrates containing amides, nitro groups, olefins, primary alcohols, primary amino groups, N-tosylhydrazone of aliphatic aldehydes, and N-methanesulfonyl hydrazone were found to be unsuitable as either the starting materials remained intact or a complex mixture of products was formed (Schemes S1–S5 in the ESI†).

To further demonstrate the applicability of our protocol, we examined the possibility of obtaining unsymmetrical 1,2,4-triazoles by employing two different hydrazones (Table 3). In fact, the synthesis of unsymmetrically substituted 1,2,4-triazoles is considered to be highly challenging and to the best of our knowledge, their single step synthesis from readily accessible starting materials is less explored. Gratifyingly, when 2a was reacted with an equimolar mixture of 1a and 1c the unsymmetrical 1,2,4-triazole 3aca was obtained as a major product in 77% yield and symmetrical triazoles were only obtained in minor amounts. The products could be purified via column chromatography on silica-gel using an ethyl acetate/hexane mixture as the eluent. Similar reactivity and selectivity were also observed for the synthesis of 3ada and 3aca. Likewise, biphenyl-, haloaromatic- and heteroaromatic-rings could be installed without any difficulty to give the triazoles 3akc, 3aja, 3akc, 3bcb, and 3bdb in 61–80% yields. Colorless crystals of 3akc, grown from a saturated benzene solution stored at room temperature, were suitable for single-crystal X-ray analysis and clearly confirmed the structure of the product (Fig. S3 in the ESI†).

In order to obtain insight into the reaction mechanism, several equilibrium studies were performed initially with N-tosylhydrazones and anilines in the presence of Lewis acids (Scheme 3). At the onset, the relative Lewis basicity of aniline and N-tosylhydrazone towards B(C₆F₅)₃ was analyzed (Scheme 3a). Thus, in a stoichiometric reaction of 2a and B(C₆F₅)₃ at room temperature in C₆D₆, the ratio of 2a and 5a (B(C₆F₅)₃ adduct of 2a) was found to be 1 : 4 (2a : 5a = 1 : 4). Similarly, the stoichiometric mixture of 1a and B(C₆F₅)₃ in C₆D₆ at room temperature afforded quantitative formation of 4a (B(C₆F₅)₃ adduct 1a) where the ratio was 1a : 4a = 0 : 100. This confirms the tendency of N-tosylhydrazine 1 to form a stronger Lewis acid–base adduct with B(C₆F₅)₃ in comparison to aniline 2.

**Table 3** B(C₆F₅)₃ catalyzed synthesis of unsymmetrical 1,2,4-triazoles

| Reaction conditions: Table 1, entry 1 in the 0.5 mmol scale. Yields of the analytically pure product. Selectivities are given within parenthesis. | Thermal ellipsoids are shown at a 60% probability level. Ref. 58. | Scheme 3 Equilibrium and selectivity studies for 1,2,4-triazole formation. |

---

Chemical Science Edge Article
Open Access Article. Published on 05 July 2019. Downloaded on 9/7/2019 11:51:53 AM. This article is licensed under a Creative Commons Attribution-NonCommercial 3.0 Unported Licence.
Moreover, a competitive equilibrium study was performed with two electronically biased N-tosylhydrazones (1\textsubscript{a} vs. 1\textsubscript{b}) with B(C\textsubscript{6}F\textsubscript{5})\textsubscript{3} (Scheme 3b). Accordingly, a stoichiometric (1 : 1) mixture of 1\textsubscript{a} and 1\textsubscript{b} was treated with 1 equivalent of B(C\textsubscript{6}F\textsubscript{5})\textsubscript{3} in C\textsubscript{6}D\textsubscript{6} at room temperature. This selectively afforded the Lewis acid–base adduct 4\textsubscript{a} whereas 1\textsubscript{b} remained unreacted (4\textsubscript{a} : 1\textsubscript{b} = 1 : 1). Thus, N-tosylhydrazones having electron rich arenes will form strong Lewis acid–base adducts than hydrazones having electron deficient arenes. This is possibly a crucial factor for the selectivity observed during the synthesis of unsymmetrical 1,2,4-triazoles as shown in Table 3. Along this direction, in fact, the reaction of aniline 2\textsubscript{a} with a mixture of 1\textsubscript{a} and 1\textsubscript{c} having electronically similar substituents (Cl and Br) on arenes in the presence of the B(C\textsubscript{6}F\textsubscript{5})\textsubscript{3} catalyst provided a mixture of two symmetrical and unsymmetrical 1,2,4-triazoles (Scheme 3c) as both the hydrazones have similar probabilities for the formation of Lewis acid–base adducts with B(C\textsubscript{6}F\textsubscript{5})\textsubscript{3}. Thus, electronically biased hydrazones are good candidates for better selectivity of unsymmetrical triazoles.

In the case of competitive equilibrium studies of two different anilines with B(C\textsubscript{6}F\textsubscript{5})\textsubscript{3}, a stoichiometric (1 : 1 : 1) mixture of 2\textsubscript{a}, 2\textsubscript{c} and B(C\textsubscript{6}F\textsubscript{5})\textsubscript{3} in C\textsubscript{6}D\textsubscript{6} at room temperature gave their corresponding Lewis acid–base adduct 5\textsubscript{a} and 5\textsubscript{c}, respectively in an 8:1 ratio (Scheme S8 in the ESI\textsuperscript{†}). Thus, it is also noteworthy that other Lewis acids like Sc(O\textsubscript{f})\textsubscript{3} and BPH\textsubscript{3} did not form any Lewis acid–base adducts with N-tosylhydrazones or anilines under similar reaction conditions (Schemes S9 and S10 in the ESI\textsuperscript{†}).

In addition, the kinetic isotope effect (KIE) of 1.0 measured from a parallel reaction of 2\textsubscript{a} with 1\textsubscript{a} and its deuterated analogue 1\textsubscript{a}–D suggests that the breakage of the imine C–H bond of 1\textsubscript{a} is not involved in the rate-determining step (Scheme 4a). Kinetic monitoring of the reaction suggests an exponential decay of both the reactants 1\textsubscript{a} and 2\textsubscript{a}, whereas sigmoidal increase of 3\textsubscript{a,b,a} was observed (Fig. S1 in the ESI\textsuperscript{†}). The initial rate curve for triazole product formation possibly indicates that at the beginning, product formation is slower due to accumulation of reactive intermediates. Further kinetic studies revealed that the reaction is first order in the catalyst (Scheme S11 in the ESI\textsuperscript{†}) and aniline 2\textsubscript{a} (Scheme S12 in the ESI\textsuperscript{†}), and zero order in the N-tosylhydrazone 1\textsubscript{a} (Scheme S13 in the ESI\textsuperscript{†}). In addition, the electronic influence of the aryl-substituents on both the reactants was investigated by a Hammett correlation study (Scheme 4b). By varying different electronic groups on the aryl-ring of 2 a small \( \rho = -1.17 \) was obtained. This plausibly indicates a weak resonance interaction involving a positive-charge at the N center of aniline in the rate-determining step. On the other hand, a negligible substituent effect (\( \rho = -0.16 \)) was determined for N-tosylhydrazones. Meanwhile, the evolution of H\textsubscript{2} gas as a byproduct was confirmed by the transfer hydrogenation\textsuperscript{59,60} of styrene under the reaction conditions (Scheme 4c).

A 2 : 1 : 1 mixture of 1\textsubscript{a}, 2\textsubscript{a} and styrene in the presence of the B(C\textsubscript{6}F\textsubscript{5})\textsubscript{3} catalyst afforded 82% of 3\textsubscript{a,b,a} along with 68% of ethylbenzene (Scheme 4c). Moreover, we performed a number of control experiments using amidines, azines, and imines as possible reaction intermediates albeit none of them proceeded to give 1,2,4-triazoles (Schemes S14–S16 in the ESI\textsuperscript{†}).

A plausible mechanism is proposed on the basis of the above experimental observations and previous literature reports (Scheme 5).\textsuperscript{14,55} To the best of our knowledge DFT calculations of N–N cyclization leading to 1,2,4 triazole fragments are obscure. Based on the proposed mechanism of the B(C\textsubscript{6}F\textsubscript{5})\textsubscript{3}–catalyzed acceptorless-dehydrogenative-cyclization of N-tosylhydrazones with anilines (Scheme 5), we have performed DFT calculations to investigate the detailed reaction mechanism and to gain insight into the driving force for the formation of the 1,2,4-triazole moiety 3\textsubscript{a,b,a}. Additionally, the calculations seek to address some pertinent questions regarding the studied system: (a) the specific role of B(C\textsubscript{6}F\textsubscript{5})\textsubscript{3} in the reaction, (b) the rate-limiting-step in the reaction, and (c) product distribution for unsymmetrical coupling.

The reaction is initiated with the coordination of B(C\textsubscript{6}F\textsubscript{5})\textsubscript{3} to the sp\textsuperscript{2} nitrogen (N\textsuperscript{1}) in N-tosylhydrazone (1\textsubscript{b}) which results in

Scheme 4  Kinetic and mechanistic studies for the synthesis of 1,2,4-triazole.

Scheme 5  Plausible reaction mechanism.
the formation of an isoequivalent encounter complex 4b‡ (Scheme 6). The approach of the nucleophilic N1 center in 1b towards the electron-deficient B center in B[C6F5]3 furnishes the slightly more stable Lewis adduct 4b via a transition state [4P-4]‡ with an activation barrier of 10.9 kcal mol⁻¹. Despite the fact that the N2 center in 1a is significantly electron-rich (−0.646 e) compared to the N1 center (−0.242 e), as obtained by the natural population analysis (NPA), B[C6F5]3 gets coordinated to the N1 center. This is attributed to the fact that the lone pair orbital located on the N1 atom (HOMO-5) is significantly destabilized compared to the one on the N2 atom (HOMO-5) by 0.4 eV (Fig. S100 in the ESI†). Furthermore, coordination at the N2 center resulted in adduct 4b’, which is less stable than 4b‡ by 2.4 kcal mol⁻¹ (Scheme S17 in the ESI†).

To cast light on the origin of the activation barrier and the bonding scenario in [4P-4]‡, energy decomposition analysis-natural orbital for chemical valence (EDA) analysis was performed, considering 1b and B[C6F5]3 as interacting fragments (Table S4 in the ESI†). Examination of the individual energy terms of the EDA reveals that the B–N1 bond has a higher electrostatic character (ΔE_electr: 39.8%) than the covalent character (ΔE_orb: 33.5%). Importantly, the major contribution to the total covalent interaction (ΔE_orb) originates from the donation of the lone pair on the N1 center in 1b to the vacant 2p orbit of boron in the B[C6F5]3 fragment (Fig. S101 in the ESI†). We have calculated the associated eigenvalue of 0.49 e quantifying the amount of charge flow from donor → acceptor fragments. Additionally, the B[C6F5]3 fragment has the predominant contribution to the destabilizing distortion energy (ΔE_dist). The calculated electron density [ρ(r)] of 0.112 at the (3, −1) bond critical point (BCP) of the B–N1 bond in 4b‡ along with the respective Laplacian of +0.192 [∇²ρ(r)] suggests a donor–acceptor type interaction.⁶¹⁶² Thereafter, the coordination of the substituted aniline (2a) to 4b affords the intermediate 6ba which finally leads to a slightly more stable Zwitterionic complex 7ba accompanied by a moderately low energy barrier of 8.8 kcal mol⁻¹. The imaginary mode in [6-7]ba‡ portraits the formation of the C–N³ bond (1.849 Å) along with concomitant elongation of the C–N¹ bond (1.383 Å). It is worthwhile to mention that the HOMO in 7ba represents the lone pair orbital located on the N³ atom (Fig. S100 in the ESI†). The subsequent proton transfer from N³ to the N1 center in 7ba furnishes the significantly less stable intermediate 8ba via a four-membered transition state [7-8]ba‡ (Scheme 6, Fig. 1a). The step 7ba → 8ba involving proton migration requires an activation barrier of 32.0 kcal mol⁻¹ and thus becomes the rate-limiting step for the overall transformation.⁶³ Indeed, this is supported by the experimental rate curve with a slower rate at the beginning of the reaction (vide supra, Fig. S1 in the ESI†). The single imaginary mode in [7-8]ba‡ depicts the synchronous breaking of N³–H (1.296 Å) and formation of N¹–H (1.353 Å) bonds. In [7-8]ba¹, the B–N³ bond gets significantly elongated (1.602/1.676 Å in 7ba/[7-8]ba‡) and this weakening of the donor–acceptor bond is reflected in the reduced NPA charge on the B center (+0.467/ +0.488 e in 7ba/[7-8]ba‡). It should be noted that both aniline and TsNH₂ assisted alternative intermolecular proton transfer between the two nitrogen centers (N³ → N¹) are less favorable than the intramolecular path reported in Scheme 6 (Scheme S18a and b in the ESI†).

From here on, the coupling of a second N-tosylhydrazide unit is required for the progress of the reaction. This is accomplished through an initial proton transfer from the C center in 8ba to N¹ in 1b. Such a proton abstraction from the tertiary C atom is manifested with N⁰–N² bond elongation. This intermolecular proton transfer is clearly favorable (−17.5 kcal mol⁻¹), creating charged species 1b⁺ and 9ba respectively (Scheme 7), whereas the coordination of 1b instead of proton transfer is highly unfavorable (refer Scheme S18c in the ESI†). In accordance with the experimental findings, KIE measurements suggest the non-involvement of imine C–H bond cleavage in the rate-determining step (Scheme 4a). Though obvious, it is important to note that hydrogen abstraction from electronegative N centers in 8ba is undoubtedly difficult, leading to highly unstable intermediates (Scheme S18d in the ESI†). Close inspection of the structural parameters in 9ba indicates considerable elongation, rather than

Scheme 6 Part I: the reaction pathway for the formation of the intermediate 8ba. The energy values above the arrows denote the Gibbs free energy changes (ΔG°) of the individual steps. The values within parentheses are the relative ΔG° energies w.r.t the starting structures. All energy terms are in kcal mol⁻¹.
dissociation of the N¹–N² bond (1.450 Å/2.987 Å = 8ba/9ba) and generation of a partial double bond character in the C–N¹ bond (1.568 Å/1.323 Å = 8ba/9ba). The N¹ center of the -NHTS unit in 9ba shows significant hydrogen bonding interactions with the H² atom connected to the N³ center, as evidenced by the N¹–H² (1.088 Å) and N²–H² (1.622 Å) bond lengths. The dissociation of the TsNH₂ fragment is quite evident from 10ba with a shorter N²–H² distance (1.057 Å) and further elongated N¹–N² distance (3.634 Å). Complete removal of TsNH₂ will generate a highly nucleophilic N³ center in 11ba which will immediately coordinate with the preformed cationic intermediate 1b⁺ to generate substantially stable 12ba (Scheme 7). The coupling of two oppositely charged species is further facilitated by the exothermicity of C–N¹ bond formation.

From 12ba the cyclization step is necessary to generate the triazole product 3ba (Scheme 5). Under these circumstances, it might be conceivable that the liberation of a second TsNH₂ unit will facilitate N¹–N³ bond formation. Thus, protonation at the N³ center is necessary, similar to the preceding step 8ba → 1b⁺ + 9ba in Part II (Scheme 7). Unlike in 8ba, the possibility...
of C–H abstraction in 12ba either as a proton or hydride transfer is unfeasible (refer Scheme S18e in the ESI†). However, the formation of cationic species 13ba after protonation along with anionic 9ba generation is possible, but it is less exothermic than the previous transfer (8ba → 1b− + 9ba; Schemes 7 and 8). Unfortunately, the addition of protons to any other electronegative center resulted in either high energy intermediates or reaction dead ends (refer Scheme S18f in the ESI†). In order to enhance the nucleophilicity at the N1 center, B(C6F5)3 was uncoordinated in the presence of an aryl amine (2a) to generate notably unstable 14ba (Scheme 8). Subsequent rearrangement to isomeric 15ba provides adequate structural disposition for facile cyclization to proceed. We have explored numerous possibilities for N1–N4 bond formation. However, none of them gave promising alternatives; instead the activation barriers are too high or transition states could not be optimized after numerous attempts (Scheme S18g in the ESI†). The cyclization step involving the transition state [15-16]ba‡ requires an activation barrier of 15.8 kcal mol⁻¹ and it witnesses a progressive removal of the TsNH₂ unit.

As expected, the transition vector in [15-16]ba‡ depicts the breaking of the N4–N5 bond (1.794 Å) with the concomitant formation of the N1–N4 bond (2.192 Å). Complete removal of TsNH₂ affords the saturated triazole intermediate 17ba, which is 35.6 kcal mol⁻¹ more stable than 15ba. Subsequent deprotonation at the N1 center by 1b will generate the significantly less stable intermediate 18ba.1 This step is facile with an activation barrier of only 1.6 kcal mol⁻¹ (Scheme S19 in the ESI†). The protonated form 1b+ generated can have two fates: it may either participate in the preceding steps reported in Part II (Scheme 7) or can undergo an exothermic exchange of protons to a free amine (2a + 1b+ → 2a+ + 1b; 4.8 kcal mol⁻¹). Generally, the intermediates formed after coupling of the second N-tosylhydrazine moiety are highly stable compared to the starting structures and the driving force for the subsequent reactions is the increasing exergonicity towards product formation (refer Fig. 1b). This statement is supported by high-resolution-mass-spectrometry studies which clearly detect a similar skeleton to

Scheme 7 Part II: the reaction pathway for the formation of the intermediate 12ba. For other information refer the caption of Scheme 6.

Scheme 8 Part III: the reaction pathway for the formation of the intermediate 18ba. For other information refer the caption of Scheme 6.
18bba (Fig. S2 in the ESI†). In order to address the positional effect of B(C₆F₅)₃ in the cyclization step, we calculated two isomers in which it coordinates to other N centers (N⁴ and N⁷) in 12bba. The resulting intermediates 35bba and 36bba are unstable and did not provide a low energy route to the cyclization step (Scheme S18h in the ESI†). Furthermore, in the absence of B(C₆F₅)₃, the cyclization step leading to 18bba encounters a high transition barrier (38.2 kcal mol⁻¹; Scheme S18i in the ESI†) and thus underscores the significance of B(C₆F₅)₃ in this current transformation.

In the next step, 18bba undergoes dehydrogenative aromatization²⁴⁵ to furnish triazole 3bba and an ion pair 22a through B(C₆F₅)₃-mediated hydride abstraction [19bba → 20bba] followed by proton abstraction involving substituted anilines (21bba → 3bba + 22a; Scheme 9). We have calculated intrinsic activation barriers of 13.1 and 21.7 kcal mol⁻¹ for the hydride and proton abstraction steps, respectively. Thereafter, two hydrogen atoms in the ion pair 22a produce a H₂ molecule via the four-membered transition state [22-5] (Scheme 9, Fig. 1b). Liberation of H₂ along with the formation of the frustrated Lewis acid–base pair (FLP) adduct 5a is facile with a barrier of only 11.3 kcal mol⁻¹ (Scheme 9). The evolution of H₂ was also confirmed by the transfer hydrogenation of styrene (vide supra, Scheme 4c). Finally, maintaining an endoergic equilibrium, the FLP adduct regenerates B(C₆F₅)₃ and substrate 2a.⁶⁵ In sum, the computational results do have concurrence with the experimental findings, particularly in understanding the dual role of B(C₆F₅)₃ in activating the N-tosylhydrazone towards nucleophilic attack and acceptor-less liberation of H₂ with the formation of a FLP (Scheme 9). Additionally, the rate determining step involving intramolecular proton transfer ([7bba → 8bba]; Δ¹G_L^s = 32.0 kcal mol⁻¹) can be surmounted at a reaction temperature of 80 °C.⁶⁶ Optimized geometries of the transition states with selected geometrical parameters along with the energy profiles are shown in Fig. 1.

For unsymmetrical systems

An equimolar mixture of 1a and 1c in the presence of 2a afforded the unsymmetrical triazole 3aca as the major product (77%) compared to the symmetrical counterpart (vide supra; Table 3). To provide reasonable justification for this observation we decided to compare the relative propensity of Lewis acid–base adduct formation of N-tosylhydrazones 1a and 1c with B(C₆F₅)₃ (B(C₆F₅)₃ → 4a,cP → 4a,c). As expected, the formation of 4c is more facile than 4a by ca. 3.0 kcal mol⁻¹ (Fig. S102 in the ESI†). This is in accordance with the experimentally observed equilibrium ratio in Scheme 3b. Eventually the activation barrier for B(C₆F₅)₃ coordination is favorable for the –OMe substituent by 3.6 kcal mol⁻¹ (ΔDG_a,P ≈ 42.5 kcal mol⁻¹ vs. 33.3 kcal mol⁻¹), clearly indicating the preference for 1a to undergo B(C₆F₅)₃ assisted intra-molecular proton transfer in a facile manner. Therefore, when 8a/c couples with another hydrazone unit, the preferred choice will be the chloro-substituted analogue 1a as most of the 1a will be available in the adduct form 4a. The combination of 8a with 1c will lead directly to 12aca in a favorable fashion with an exothermicity of 5.6 kcal mol⁻¹ (Fig. S103 in the ESI†). From 12aca, the generation of 16aca requires a barrier of 20.4 kcal mol⁻¹ which is almost similar to the value obtained in the previous case (20.0 kcal mol⁻¹; 12bba → 16bba; Fig. 1b). This barrier is 1.1 kcal mol⁻¹ lower than the symmetrical case (Fig. S103 in the ESI†) further supporting the preference for unsymmetrical triazole (3aca) formation (Fig. S103 in the ESI†).

Scheme 9 Part IV: the reaction pathway for the formation of the desired product 1,2,4-triazole complex (3bba) and the hydrogen evolution step. For other information refer the caption of Scheme 6.
After the formation of the triazole ring in $^{16}_{\text{NOV}}$, which is 71.5 kcal mol$^{-1}$ more stable than the starting materials, the subsequent $^2\text{B(C}_{6}\text{F}_{5})_3$ assisted dehydrogenation follows an analogous mechanism as outlined before (Scheme 9; Fig. 1b).$^{37}$

Conclusions

In summary, we have demonstrated $^2\text{B(C}_{6}\text{F}_{5})_3$ catalyzed metal-free, one-pot, dehydrogenative-cyclization of hydrazones with anilines to furnish both symmetrical and unsymmetrical 3,4,5-triaryl-1,2,4-triazoles. The isolation of the $^2$-tosylhydrazone-borane adduct is also reported for the first time. Mechanistic experiments and DFT calculations suggest that the $^2\text{B(C}_{6}\text{F}_{5})_3$ catalyst serves a dual role: the activation of the hydrazone for the nucleophilic attack and the formation of an FLP for dehydrogenation. Calculations also reveal that the rate-determining step involves intra-molecular hydrogen transfer between the $^2$-centers after aniline gets bonded to the $^2$-Tosylhydrazone unit. The chemo-selective, step-economical, oxidant-free and mild reaction protocol could give a potential platform for the increasing focus on main-group catalyzed chemical transformation without using transition metal.

Computational methods

All computations are performed using Gaussian 09$^{48}$ and ADF 2018.103$^{49}$ quantum codes. Geometry optimizations of the saddle points without any symmetry constraints are carried out using the B3LYP hybrid functional$^{50}$ in conjunction with the SVP basis set$^{71}$ in the Gaussian 09 program package. Harmonic force constants are computed at the optimized geometries to characterize the nature of the stationary points as minima ($^2_{\text{min}}$ = 0) or transition states ($^2_{\text{trans}}$ = 1). Transition states are located by using the linear synchronous transit (LST)$^{72}$ scan method in which the reaction coordinate was kept fixed at different distances while all other degrees of freedom are relaxed. After the linear transit search, the transition states are optimized by using the default Berny algorithm implemented in the Gaussian 09 code. All transition states are validated by intrinsic reaction coordinate (IRC) calculations. In addition, single point calculations were performed on the B3LYP/SVP optimized structures using the dispersion corrected hybrid functional B3LYP-D3$^{73}$ in conjunction with a large basis set (triple-$\zeta$ quality split valence plus polarization, TZVP).$^{74}$ The effect of solvation (benzene, dielectric constant $\varepsilon = 2.27$) was assessed by a self-consistent reaction field (SCRF) approach, using the conductor-like polarizable continuum model (CPCM).$^{75}$ Tight wave function convergence criteria and an “ultrafine” (99 950 grid) were used for the single point calculations. Natural bond orbital (NBO)$^{76}$ analysis was performed at the B3LYP-D3/TZVP/B3LYP/SVP level using the NBO Version 3.1 program. QTAIM (quantum theory of atoms in molecules) calculations are also performed to characterize the electron distribution around some selected bonds in the chemical species applying Bader’s AIM (atoms-in-molecule) theory.$^{77}$ Furthermore, to gain insight into the bonding scenario in the transition state $^{1P-\delta}_{\text{a}}$, EDA (energy decomposition analysis) calculations in conjunction with the NOCV (natural orbital for chemical valence)$^{78}$ method are undertaken using the ADF 2018.103 package. Implementation and application of the EDA method, which was originally developed by Morokuma$^{79}$ and later modified by Ziegler and Rauk,$^{80}$ can be found elsewhere.$^{81-85}$ The figures provided in the manuscript are generated using ChemDraw Ultra 12.0 and CYLview$^{86}$ visualization software.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We thank the IISER Kolkata (Start-up grant) for financial support. M. M. G. thanks the SERB (PDF/2017/000028) for the NPDF fellowship. S. De and S. Dutta thank the UGC and CSIR, respectively for senior research fellowships. D. K. acknowledges the funding from the bilateral DST-DFG (INT/FRG/DFG/P-05/2017) scheme and the IISER Kolkata for computational facility. The authors thank Dr. S. Lakhdar (CNRS–ENSI Caen), and Prof. Dr. H. Mayr (LMU Munich) for helpful discussions. Dedicated to Professor Dr. Vinod K. Singh on the occasion of his 60th birthday.

Notes and references

Deprotonation from the N$_4$ center will afford highly unstable intermediates ($\Delta G^\circ_a = 37.6$ kcal mol$^{-1}$) compared to $^{17}$bba.


67 The energy span in Part IV ($^{18}_{\text{aca}} \rightarrow 20_{\text{aca}}$) is reduced by ca. 4.0 kcal mol$^{-1}$ when intermediates for the step $^{17}_{\text{aca}} \rightarrow 18_{\text{aca}}$ were optimized in benzene continuum (B3LYP/SVP(CPCM) level).


86 C. Y. Legault, CYLView, 1.0b, Université de Sherbrooke, 2009, see http://www.cylview.org.