Investigation of the Origins of Regiochemical Control in [4+2] Cycloadditions of 2-Pyrones and Alkynylboronates

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Abstract: The [4+2] cycloaddition of 2-pyrones with substituted alkynylboronates has been studied. In general, the highest yielding cycloadditions were obtained in reactions that employed a trimethylsilyl-substituted alkynylboronate. The highest regioselectivities were obtained using the corresponding phenyl-substituted alkyne, which provided a single regioisomer irrespective of the 2-pyrone used. Mechanistic studies suggest that the high regioselectivity observed is due to stabilization of a zwitterionic transition state.

Key words: cycloaddition, Diels–Alder reaction, alkynes, boron, regioselectivity

Introduction

Aromatic boronic acids and their derivatives have become some of the most heavily utilized intermediates in modern synthetic organic chemistry. The versatility of these compounds makes them attractive for many applications; the carbon–boron bond can easily be broken allowing the formation of a wide variety of species via various cross-coupling and functional group interconversion processes.[1] Synthetic methods towards these substrates classically involve use of organometallic intermediates, but transition-metal-catalyzed borylation techniques have emerged as very effective alternatives.[2] A complimentary approach to benzene-based boronic acid derivatives exploit alkynylboronates in cycloaddition processes, and both thermal- and metal-promoted variants have been documented.[3] In this context, we have recently reported an inverse-electron-demand [4+2] cycloaddition of alkynylboronates with 2-pyrones.[4] This strategy has proved to be of good general utility, allowing the formation of highly functionalized benzene boronic esters in a single step with good overall yield.

2-Pyrone substrates have been widely used in the literature as the diene partner in [4+2]-cycloaddition reactions.[5] Due to the electron-withdrawing nature of the carbonyl moiety in the ring, 2-pyrones tend to undergo inverse-electron-demand cycloadditions, usually reacting with relatively electron-rich dienophiles. However, studies by Afarinkia have shown that halo-substituted 2-pyrones can react with both electron-poor and -rich dienophiles,[6] whilst Kočevar employed 3-aminopyranones in reactions with alkynes bearing a range of electronically and sterically distinct groups.[7] The latter report also proposed that the reaction regioselectivity may be based on the formation of zwitterionic intermediates.

In the context of alkynylboronate cycloadditions, DFT-led studies have suggested that these dienophiles perform as modestly electron-rich substrates in reactions with tetrazines and sydnones.[8] We wished to further understand the reactivity of these compounds by exploring their reactions with 2-pyrones, and report our experimental and theoretical results towards this end herein.

Results and Discussion

Previous studies within our group have shown that 2-pyrones bearing a methyl ester at C4 or C5 undergo efficient cycloaddition reactions.[4a,b] This was presumed to be due to the LUMO lowering effect of this group, thereby promoting the inverse-electron-demand [4+2] reaction. Interestingly, while the position of the ester group had little effect on the overall reaction yields, it was found to have a significant impact on the cycloaddition regioselectivities (Scheme 1).[4b,c]

In order to better understand the effect of 2-pyrone substituents on the reaction efficiency and regioselectivity, we undertook an extensive study on the cycloaddition reactions of a number of functionalized 2-pyrones with alkynylboronates. Initially, the synthesis and reactivities of the readily accessible halo-2-pyrones was investigated (Table 1). Specifically, we were interested in examining the reactivities of the isomeric compounds 5-chloro-2-pyrone (**1a**) and 4-chloro-2-pyrone (**1b**), as these would provide us with a useful insight into the effect of altering the halogen substitution pattern on reaction regiocontrol. In the event, both 2-pyrones provided high yields of cycloadducts **3b** and **4b** when reacted with silyl-substituted ethynylboronate **2b**, but the products were formed with very poor regioselectivity (entries 2, 4). In contrast, only one regioisomer was formed when both **1a**,**b** were reacted with phenylethynylboronate **2a**, although low yields of cycloadduct were obtained in each case (entries 1, 3).[9]

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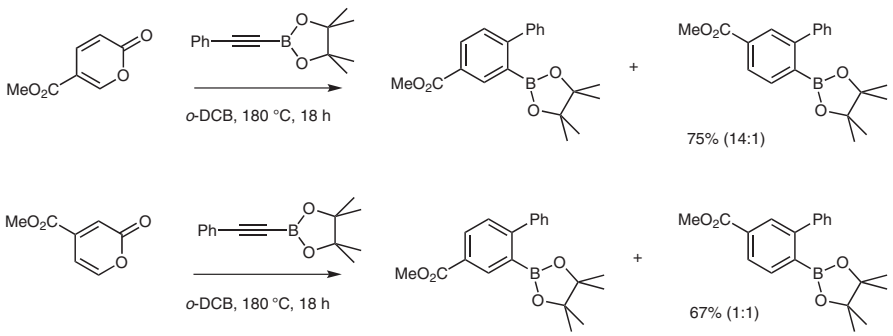


Scheme 1 Regiochemical dependence of ester-substituted 2-pyrone cycloadditions of alkynylboronates

Biographical Sketches

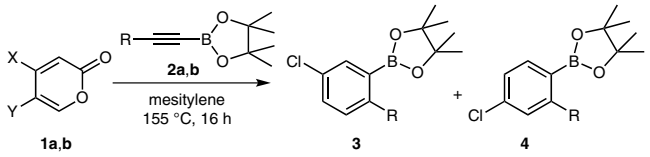
James Kirkham was born in Nottingham, UK, in 1986. He gained his undergraduate degree from the University of Sheffield in 2008. He remained in Sheffield to undertake his Ph.D. studies under the guidance of Prof. J. P. A. Harrity, which he completed in 2011. He is currently undertaking an independent research programme under the EPSRC/University of Sheffield Prize Doctoral Fellowship scheme.

Andrew Leach grew up in Chester, UK and gained his undergraduate and Ph.D. degrees from the University of Cambridge where he worked with Prof. S. V. Ley. Subsequently, he attained an AstraZeneca-Fulbright Award to work with Prof. K. N. Houk at the University of California, Los Angeles studying pericyclic reactions and the magnitude of protein–ligand interaction energies. Since 2003 he has been a computational chemist with AstraZeneca where he has worked in both the Cancer and Cardiovascular research areas.

Eleanor Row was born in Sheffield, and gained her undergraduate degree from the University of Hull in 1999 whilst working for Corus. In 2003 she completed her Ph.D. at the University of Sheffield in collaboration with SAFC pharma in the design and synthesis of CPY3A4 inhibitors. Her subsequent postdoctoral studies were carried out at the University of Liverpool into anti-parasitic agents under the supervision of Dr A. Stachulski followed by the development of antimalarial agents under the supervision of Professor P. M. O'Neill. In 2006 Eleanor moved to sanofi–aventis and is currently working as a Senior Research Investigator in Isotope Chemistry for Covance Ltd.

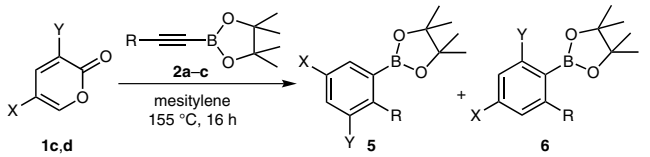
Joseph Harrity is Professor in Organic Chemistry at the University of Sheffield. He received his B.Sc. degree from the University of Strathclyde in 1991 where he remained to undertake his Ph.D. studies (1991–1994) under the guidance of Professor W. J. Kerr. He carried out postdoctoral studies in Boston College, USA (1994–1997) with Professor Amir Hoveyda before returning to take up a lectureship in 1997 at the University of Sheffield. Here he was promoted to Senior Lecturer and Reader, followed by a promotion to Professor in 2009. His recent research interests have focused on developing new strategies towards carbon–carbon bond forming processes for which he was awarded the Pfizer Discovery Academic Award in 2004.

Table 1 Cycloadditions of 4-Chloro- and 5-Chloro-2-pyrones



Entry	2-Pyrone	X	Y	R	Yield (%)	Ratio **3**/**4**
1	**1a**	H	Cl	Ph; **2a**	**3a**; 21	>98:2
2	**1a**	H	Cl	$SiMe_3$; **2b**	**3b**/**4b**; 70	4:3
3	**1b**	Cl	H	Ph; **2a**	**4a**; 25	< 2:98
4	**1b**	Cl	H	$SiMe_3$; **2b**	**3b**/**4b**; 70	3:5

Table 2 Cycloadditions of Chloro- and Bromo-Substituted 2-Pyrones

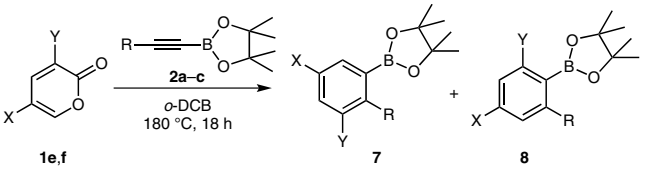


Entry	2-Pyrone	X	Y	R	Yield (%)	Ratio **5**/**6**
1	**1c**	Cl	Cl	Ph; **2a**	**5a**; 32	>98:2
2	**1c**	Cl	Cl	$SiMe_3$; **2b**	**5b**/**6b**; 71	1:1
3	**1d**	Br	H	Ph; **2a**	**5c**; 46	>98:2
4	**1d**	Br	H	$SiMe_3$; **2b**	**5d**/**6d**; 80	3:2
5	**1d**	Br	H	Bu; **2c**	**5e**/**6e**; 44	3:2

Having established the reactivity patterns of 2-pyrones **1a**,**b** towards alkynylboronate cycloadditions, the reactions of the readily available 3,5-dichloro-2-pyrone (**1c**) and 5-bromo-2-pyrone (**1d**) were studied next (Table 2). Pleasingly, both dienes provided silyl-substituted cycloadducts **5b**/**6b** and **5d**/**6d** in good yields (entries 2, 4). Once again, however, poor levels of regioselectivity were observed. Phenyl-substituted aromatics **5a** and **5c** were obtained regioselectively, but in poor yield (entries 1, 3). 2-Pyrone **1d** was also reacted with an alkyl-substituted ethynylboronate **2c**, which provided products **5e**/**6e** in reasonable yield, but with low levels of regiocontrol (entry 5).[10]

The poor yields observed in many of the cycloadditions of halo-2-pyrones prompted us to explore dienes with electron-withdrawing groups as these had previously been found to undergo more efficient reactions (see earlier in Scheme 1). Therefore, we prepared 5-cyano-2-pyrone (**1e**) and explored its reactions with alkynylboronates **2a**–**c** (Table 3). We were delighted to find that this diene reacted with alkynylboronates with far higher efficiency than simpler halo-2-pyrones. Similar to the previous examples, phenylethynylboronate **2a** provided cycloaddition product **7a** regioselectively (entry 1), whereas the silylethynylboronate **2b** afforded **7b**/**7b** with no regioselectivity (entry 2). The butyl-substituted ethynylboronate provided products in moderate yield, but with good regioselectivity (entry 3). Bromination of 5-cyano-2-pyrone was also achieved successfully, and the resulting 2-bromo-substituted 2-pyrone **1f** reacted with the alkynylboronates **2a**–**c** to afford the corresponding products in excellent yields. Interestingly, the extra steric bulk provided by bromide appeared to have little effect on the reaction regioselectivities, with products **7d**, **7e**/**8e**, and **7f**/**8f** forming in similar selectivities to those generated from pyrone **1e** (entries 4–6).[11]

Table 3 Cycloadditions of 5-Cyano-2-pyrones



Entry	2-Pyrone	X	Y	R	Yield (%)	Ratio **7**/**8**
1	**1e**	CN	H	Ph; **2a**	**7a**; 76	>98:2
2	**1e**	CN	H	$SiMe_3$; **2b**	**7b**/**8b**; 99	1:1
3	**1e**	CN	H	Bu; **2c**	**7c**/**8c**; 53	5:1
4	**1f**	CN	Br	Ph; **2a**	**7d**; 94	>98:2
5	**1f**	CN	Br	$SiMe_3$; **2b**	**7e**/**8e**; 96	1:1
6	**1f**	CN	Br	Bu; **2c**	**7f**/**8f**; 65	11:1

From these studies two trends in the reactivities of alkynylboronates have been observed, allowing us to form the following general conclusions:

Aryl-substituted ethynylboronates undergo highly selective cycloaddition reactions with 2-pyrones, but with varying yields.

Silyl-substituted ethynylboronates undergo high-yielding cycloaddition reactions with 2-pyrones, but with little to no regioselectivity.

In an effort to further understand these trends, quantum mechanical studies were performed to map the full reaction profile and to provide insight into the factors governing regioselectivity. The cycloaddition is assumed to proceed through a Diels–Alder reaction to form a bicyclic adduct and then a retro-Diels–Alder reaction extruding carbon dioxide. The calculations employed three different levels of theory. B3LYP is known to perform reasonably well in studies of pericyclic reactions,[12] whereas although RHF is expected to over predict barrier heights it often performs well (given the computational cost) at determining reaction energies.[13] Meanwhile, M06-2X has been claimed to be effective at computing barrier heights and transition state geometries.[14] All three levels were combined with the 6-31+G** basis set and the results are sum-

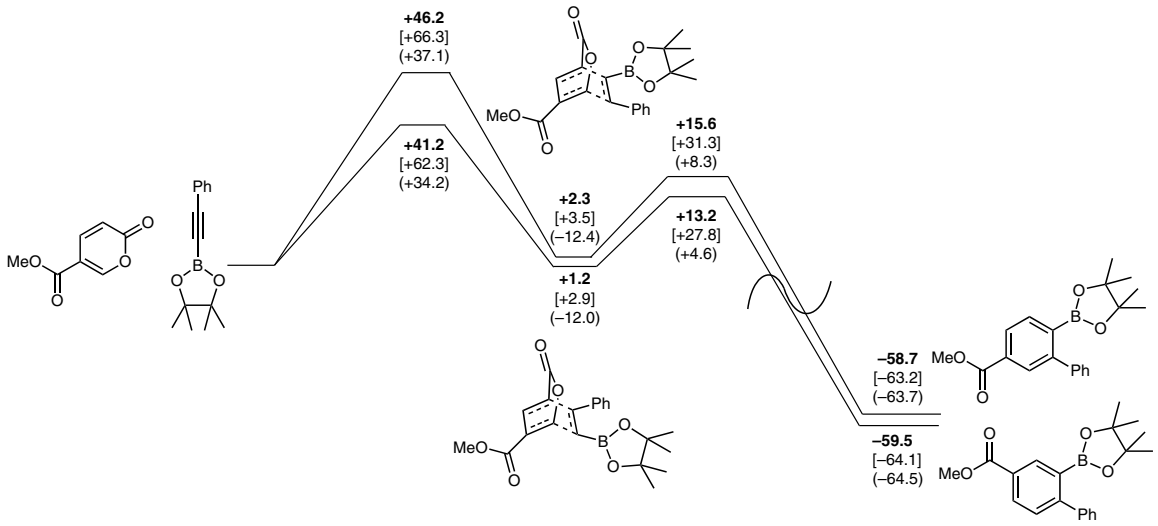


Figure 1 The free energy profile for the reaction between diene **1g** and dienophile **2a**. The first step is a Diels–Alder cycloaddition and the second a retro-Diels–Alder reaction in which carbon dioxide leaves. The energies reported are in kcal/mol relative to reactants and include vibrational corrections to free energies in the gas phase at 298 K. They are calculated at the B3LYP/6-31+G** [RHF/6-31+G**] (M062X/6-31+G**) levels of theory.

marized in Figure 1 for the reaction between diene **1g** and dienophile **2a**.

It can be seen in Figure 1 that all levels of theory agree that the reaction proceeds through a rate-limiting transition state for Diels–Alder addition to yield an adduct that is within a few kcal/mol of the reactants. This is followed by a retro-Diels–Alder reaction with a lower barrier than the first step and this yields an aromatic product that is significantly lower in energy than the reactants or intermediates. This same pattern is found for all reactions studied with all three levels of theory. This reaction profile would have the first step as rate and selectivity determining and so although all the cycloadditions described have been studied across the whole profile and these values and structures are reported in the supporting information, the focus here will be on the transition states for the first step.

It is seen in Figure 1 that although the barrier heights vary significantly depending upon the level of theory that is employed, the difference between the barriers leading to the two regioisomeric adducts are relatively consistent. B3LYP predicts that the proximal adduct (here denoting that the boronic ester adds adjacent to the oxygen in the pyran ring, see Figure 2) is favoured over the distal adduct (where the boronic ester adds away from the pyran ring oxygen) by 5 kcal/mol, RHF by 4 kcal/mol, and M06-2X by 2.9 kcal/mol. All levels of theory are consistent with the observed regiochemical outcome, although the experimentally observed selectivity (14:1) is lower than would be expected for any of the differences in free energy computed here.

To ascertain if any of the levels of theory are consistent with the observed outcomes, the differences in free energy barrier for the two regioisomers has been computed for a set of the dienes and dienophiles described above. These are summarized in Table 4 and show that all levels of theory predict that the proximal regioisomer is preferred, but

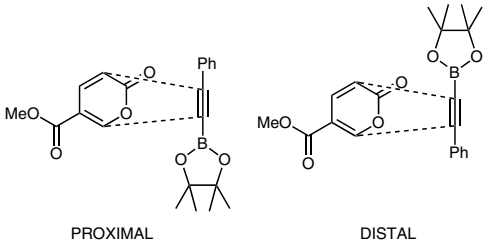
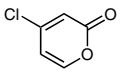
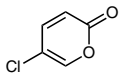
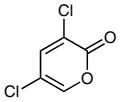
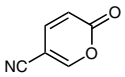
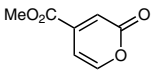
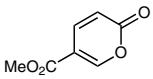


Figure 2 The regioisomeric structures and transition states as described by the relative positioning of the boronic ester group and the oxygen of the pyran ring

that the degree of preference changes by several kcal/mol. The experimentally observed preference can be transformed into an estimate of the energy difference between the processes assuming the two regioisomers are formed in processes obeying Arrhenius behaviour and with similar pre-exponential factors such that $\Delta\Delta G^{\ddagger} = RT \ln(\%\text{proximal}/\%\text{distal})$. These values are shown in Table 4 for the reactions that have been studied experimentally. The computed differences can be compared to those obtained from the experimental regioselectivities and show that the B3LYP calculations are able to provide a good correlation between the two (Figure 3).[15] RHF also provides a reasonable correspondence, but M06-2X does not. RHF however predicts barriers that are higher than is likely realistic and so the B3LYP description of the reaction appears to be the one that is most realistic and, hence, it is the structures computed at this level of theory that have been studied to provide insight into the origins of the regioselectivity. The plot in Figure 3 suggests that the experimental regioselectivity is not perfectly predicted by the B3LYP gas phase calculations, but that the experimental $\Delta\Delta G^{\ddagger}$ is approximately that computed by B3LYP multiplied by a factor of 0.54, with a small correction of 0.1 kcal/mol added. Predictions can be made of the preference for the proximal regioisomer using this cor-

Table 4 Calculated and Experimental Free Energy of Activation Values for Proximal and Distal Regioisomer Formation[a]

Diene	R	$\Delta\Delta G^{\ddagger}$ RHF	$\Delta\Delta G^{\ddagger}$ B3LYP	$\Delta\Delta G^{\ddagger}$ M06-2X	Experimental proximal/distal	$\Delta\Delta G^{\ddagger}$	Predicted proximal/distal
	Ph	1.9	2.7	0.9	>49:1	>3.3	7.0:1
	TMS	0.9	0.4	0.6	1.3:1	0.2	1.5:1
	Bu	1.9	2.3	2.6			5.2:1
	Ph	1.9	3.4	2.3	>49:1	>3.3	10.5:1
	TMS	0.6	0.9	0.2	1.7:1	0.4	2.1:1
	Bu	1.8	3.2	1.2			9.3:1
	Ph	4.9	6.6	5.7	>49:1	>3.3	87.3:1
	TMS	0.6	0.8	2.4	1:1	0.0	2.0:1
	Bu	5.3	2.4	5.9			5.6:1
	Ph	4.5	5.8	3.6	>49:1	>3.5	42.1:1
	TMS	0.6	0.7	1.5	1:1	0.0	1.8:1
	Bu	1.6	3.0	1.3	5:1	1.4	7.3:1
	Ph	0.5	0.9	0.2	1:1	0.0	2.1:1
	TMS	0.4	0.3	1.5	3:1	1.0	1.4:1
	Bu	1.0	1.7	0.2	10:1	2.1	3.2:1
	Ph	4.0	5.0	2.9	14:1	2.4	26.1:1
	TMS	0.5	0.7	0.3	1:1	0.0	1.7:1
	Bu	2.7	3.0	0.6	3:1	1.0	7.6:1

[a] The ratios are based on a reaction temperature of 155 °C.

rection and these are included in the final column in Table 4. These predictions show that in general the phenylethynylboronate is expected to be the most regioselective of the dienophiles examined and that electron-withdrawing groups at the 5-position of the diene enhance selectivity, but that electron-withdrawing groups at the 4-position diminish the regioselectivity.

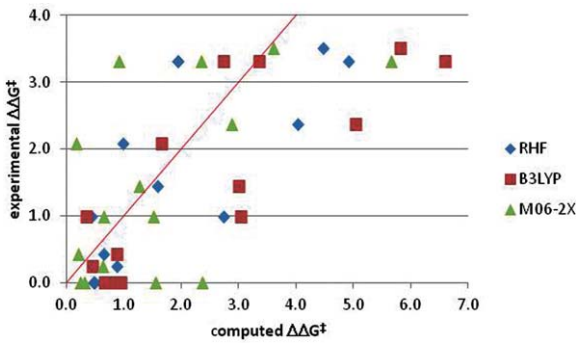


Figure 3 The experimentally observed preference for the proximal regioisomer (transformed to an effective $\Delta\Delta G^{\ddagger}$) is plotted against the difference in free energies of activation computed at three different levels of theory (RHF/6-31+G**, B3LYP/6-31+G**, and M06-2X/6-31+G**). The red line is the y = x line. All energies are in kcal/mol.

To investigate the origin of the effects that are manifest in both the experimental outcomes and the computed differences in free energy of activation, the geometries of the various computed structures have been examined. In Figure 4, the structures of the reactants, intermediates, products, and transition states for the profile shown in Figure 1 are presented. Of particular interest is that the two transition states for the initial Diels–Alder reaction differ markedly in the lengths of the two forming bonds. It can be seen that the lower energy structure is considerably more asynchronous than that of the higher energy one. An asynchronous transition state might be part of a stepwise process, but even when solvation was included (using the default parameters for mesitylene in Gaussian09) no intermediate could be located. The two structures are shown in more detail in Figure 5.

The forming bonds have lengths of 1.867 Å and 2.865 Å for the proximal regioisomer and 2.160 Å and 2.305 Å for the distal regioisomer. The same heightened asynchronicity is also observed with the RHF and M06-2X structures, but it is less pronounced and this may lie at the origin of why they are less well able to predict the regioselectivity. DFT studies on 2-pyrone Diels–Alder reactions reported by Štefane et al. also highlighted a polar and asynchro-

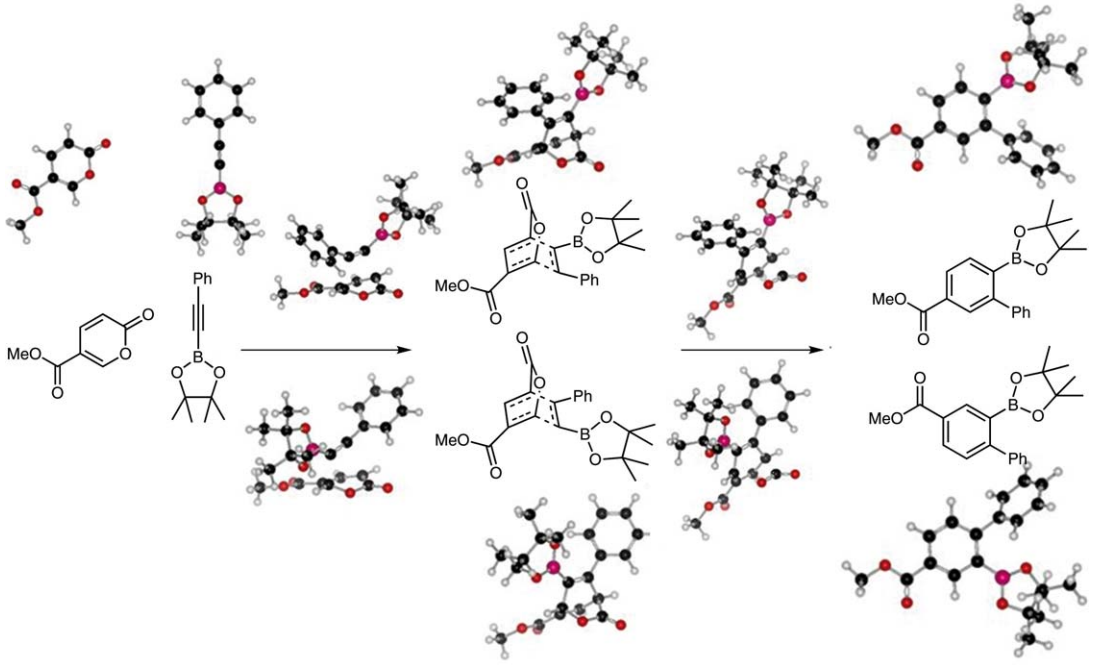


Figure 4 The structures corresponding to the reaction of methyl coumalate (**1g**) and **2a** and the energetic profile shown in Figure 1

nous transition state in reactions with electron-rich dienophiles.[16] Taken together with the results of our earlier studies suggesting the electron-rich nature of alkynylboronates,[8] the transition states uncovered in this work are consistent with a mechanism that involves a concerted reaction with significant polar character, and can be viewed as an addition of a nucleophilic alkyne with the 2-pyrone acting as an electrophile emphasizing the inverse-electron-demand nature of this reaction. The differences in other bond lengths, including that of the carbonyl, shown in Figure 5, support this view of the transition state.

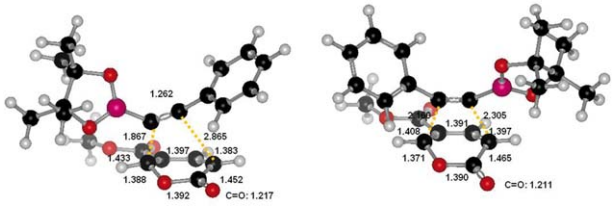


Figure 5 The rate-limiting transition state structures for the reaction of methyl coumalate (**1g**) and **2a** leading to proximal (left) and distal (right) regioisomers; bond distances are shown in Å

When the trimethylsilyl-substituted alkyne transition states are examined (as shown in Figure 6), it is seen that both are less asynchronous than the proximal transition state shown in Figure 5, suggesting that in this case both ends of the alkyne are approximately equal in terms of nucleophilicity.

The electronic similarity of the acetylenic carbon atoms in **2b** can be rationalized by inspection of the field effect values for Si- and B-based substituents in the Swain–Lupton equation [Me_3Si; +0.01 and $(HO)_2B$; –0.03].[17]

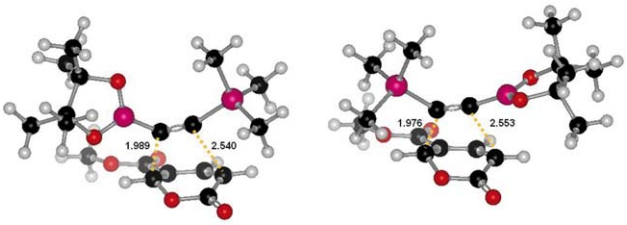
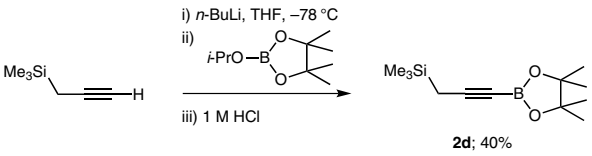


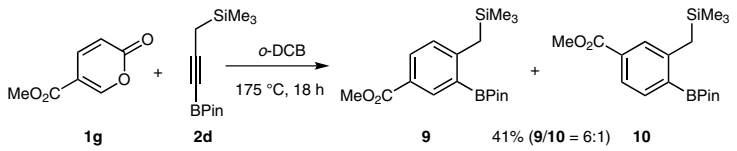
Figure 6 The transition states computed at the B3LYP/6-31+G** level leading to the two regioisomers for the reaction between **1g** and **2b**; bond distances are shown in Å

It was believed that a regioselective reaction could be affected by using an alternative group that could stabilize β-carbocations. As such, the 3-silylprop-1-ynylboronate **2d** was synthesized (Scheme 2), and reacted with methyl coumalate (**1g**).



Scheme 2 Synthesis of 3-(trimethylsilyl)prop-1-ynylboronate **2d**

In the event, the cycloaddition occurred regioselectively with the preferred isomer being consistent with the one predicted by theoretical studies (Scheme 3). Although regiocontrol was not as high as that noted with the corresponding phenylacetylene-derived substrate **2a** (see earlier in Scheme 1), an enhanced selectivity over the related butyl-substituted acetylene cycloadditions is observed.[18,19]

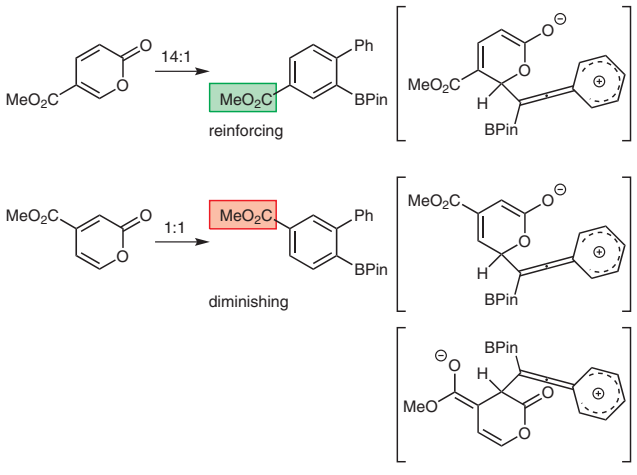


Scheme 3 Cycloaddition of 3-(trimethylsilyl)prop-1-ynylboronate **2d**

Conclusion

In conclusion, we have found that higher yields for the reactions of 2-pyrones with alkynylboronates can be obtained when the silyl-substituted ethynylboronate is used. The highest regioselectivities can be obtained with the phenyl-substituted dienophile, where typically only one regioisomer is formed. 2-Pyrones that have electron-withdrawing groups incorporated provide cycloadducts in generally higher yields. Halogens were shown to be essentially electron-neutral functional groups on 2-pyrone rings, as no enhancement or deterioration of either yields or regioselectivities were observed for these substrates.

Through theoretical studies of the cycloaddition transition states, we have discovered that 2-pyrone reactions with alkynylboronates proceed via asynchronous transition states. This accounts for the differences in regiochemical outcomes for phenyl- and silyl-substituted ethynylboronates. Moreover, the significance of zwitterionic transition states, as proposed by Stefané,[16] and implicated here, may provide a rationale for the different regiochemical outcomes observed in cycloadditions of phenyl-substituted acetylene **2a** with isomeric ester substituted pyrones (see earlier in Scheme 1). Specifically, the ester group in methyl coumalate reinforces stabilization of the zwitterionic transition state, whereas the 4-ester isomer would provide a pathway for stabilizing both proximal and distal addition modes and therefore diminishes cycloaddition regioselectivity (Scheme 4).



Scheme 4 Regiochemistry reinforcing and diminishing effects of ester substitution

Flash chromatography was performed on silica gel (BDH Silica Gel 60 43-60, or Fluorochem Davisil silica gel 43–60); petroleum ether = PE. TLC was performed on aluminum-backed plates pre-coated with silica (0.2 mm, Merck DC-alufolien Kieselgel 60 F254), which were developed using standard visualizing agents: UV light or $KMnO_4$. $^1H/^{13}C$ NMR spectra were recorded on Bruker AC-250 or Av1-250 instruments or AMX-400 or AV1-400 instruments. ^1H: solvent resonance as the internal standard ($CHCl_3$:δ = 7.27). ^{13}C NMR spectra were with complete proton decoupling; solvent resonance as the internal standard ($CDCl_3$: δ = 77.0). FTIR spectra were recorded on a Perkin Elmer Paragon 100 FTIR spectrophotometer. Samples were recorded as thin films using NaCl plates, as a CH_2Cl_2 soln or as a KBr disc. LR-MS were recorded on Micromass Autospec, operating in EI, CI, or FAB mode; or a Perkin-Elmer Turbomass Bench top GC-MS operating in either EI or CI mode. HRMS recorded for accurate mass analysis, were performed on either a MicroMass LCT operating in Electrospray mode (ES^+) or a MicroMass Prospec operating in either FAB (FAB^+), EI (EI^+) or CI (CI^+) mode. Melting points were performed on recrystallized solids and recorded on a Gallenkamp melting point apparatus and are uncorrected. Compounds **1a**–**f**[5,6,20] and **2a**–**c**[21] were prepared according to literature procedures.

Cycloaddition of Halo-2-pyrones with Alkynylboronic Esters; General Procedure 1

A mixture of the 2-pyrone (0.2 mmol) and alkynylboronate (0.4 mmol) in mesitylene (0.2 mL) was heated at 155 °C and stirred for 16 h under N_2. The product was purified by flash column chromatography (PE to 10% EtOAc–PE).[22]

2-(4-Chlorobiphenyl-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3a)

Using general procedure 1, with 2-pyrone **1a** (25 mg, 0.19 mmol) and alkyne **2a** (87 mg, 0.38 mmol), gave **3a** (13 mg, 21%) as a yellow oil.

FTIR (CH_2Cl_2, thin film): 2977 (s), 1544 (m), 1315 (s), 1141 cm^{-1} (s).

^1H NMR (250 MHz, $CDCl_3$): δ = 1.23 (s, 12 H, CH_3), 7.26 (d, J = 8.0 Hz, 1 H, H_{Ar}), 7.37–7.39 (m, 5 H, H_{Ar}), 7.59 (dd, J = 8.0, 2.5 Hz, 1 H, H_{Ar}), 7.85 (d, J = 2.5 Hz, 1 H, H_{Ar}).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 24.6, 84.1, 121.1, 127.2, 127.9, 129.0, 130.8, 133.0, 137.0, 142.0, 146.4.

HRMS (EI^+): m/z $[M]^+$ calcd for $C_{18}H_{20}{}^{11}B^{35}ClO_2$: 314.1245; found: 314.1238.

2-[5-Chloro-2-(trimethylsilyl)phenyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3b) and 2-[4-Chloro-2-(trimethylsilyl)phenyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (4b)

Using general procedure 1, with 2-pyrone **1a** (25 mg, 0.19 mmol) and alkyne **2b** (85 mg, 0.38 mmol), gave the product (41 mg, 70%) as a clear oil; inseparable mixture of **3b**/**4b** (4:3).

FTIR (CH_2Cl_2, thin film): 2980 (s), 1570 (m), 1388 (s), 1340 (s), 1145 (s), 845 cm^{-1} (s).

^1H NMR (250 MHz, $CDCl_3$): δ (**3b**) = 0.35 (s, 9 H, $SiCH_3$), 1.38 (s, 12 H, CH_3), 7.38 (dd, J = 8.0, 2.0 Hz, 1 H, H_{Ar}), 7.55 (d, J = 8.0 Hz, 1 H, H_{Ar}), 7.89 (d, J = 2.0 Hz, 1 H, H_{Ar}); δ (**4b**) = 0.37 (s, 9 H, $SiCH_3$), 1.38 (s, 12 H, CH_3), 7.34 (dd, J = 8.0, 2.0 Hz, 1 H, H_{Ar}), 7.57 (d, J = 2.0 Hz, 1 H, H_{Ar}), 7.87 (d, J = 8.0 Hz, 1 H, H_{Ar}).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ (**3b**/**4b**) = 0.0, 0.1, 24.6 (2 ×), 83.6, 86.9, 127.4, 129.2, 130.7, 132.3, 133.8, 135.0, 135.4, 135.5, 136.3, 137.3.

HRMS (EI$^+$): *m*/*z* [M]$^+$ calcd for $C_{15}H_{24}{}^{11}B^{35}ClO_2Si$: 310.1327; found: 310.1335.

2-(5-Chlorobiphenyl-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (4a)

Using general procedure 1, with 2-pyrone **1b** (25 mg, 0.19 mmol) and alkyne **2a** (87 mg, 0.38 mmol), gave **3a** (15 mg, 25%) as a yellow oil.

FTIR (CH_2Cl_2, thin film): 2977 (s), 1544 (m), 1315 (s), 1141 cm^{-1} (s).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.21 (s, 12 H, CH_3), 7.30–7.45 (m, 7 H, H_{Ar}), 7.67 (d, *J* = 8.0 Hz, 1 H, H_{Ar}).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ = 24.6, 83.9, 126.4, 127.2, 127.4, 127.9, 129.0, 129.1, 130.0, 134.2, 135.9.

HRMS (EI$^+$): *m*/*z* [M]$^+$ calcd for $C_{18}H_{20}{}^{11}B^{35}ClO_2$: 314.1245; found: 314.1238.

2-[5-Chloro-2-(trimethylsilyl)phenyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3b) and 2-[4-Chloro-2-(trimethylsilyl)phenyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (4b)

Using general procedure 1, with 2-pyrone **1b** (25 mg, 0.19 mmol) and alkyne **2b** (85 mg, 0.38 mmol), gave the product (40 mg, 70%) as a clear oil; inseparable mixture of **3b**/**4b** (3:5).

The mixture provided the same analytical data as for **3b** and **4b** above.

2-(4,6-Dichlorobiphenyl-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (5a)

Using general procedure 1, with 2-pyrone **1c** (25 mg, 0.15 mmol) and alkyne **2a** (68 mg, 0.30 mmol), gave **5a** (17 mg, 32%) as a yellow oil.

FTIR (CH_2Cl_2, thin film): 2979 (s), 1547 (m), 1328 (s), 1144 cm^{-1} (s).

^{1}H NMR (250 MHz, $CDCl_3$): δ (**5a**) = 1.10 (s, 12 H, CH_3), 7.24–7.28 (m, 2 H, H_{Ar}), 7.36–7.42 (m, 3 H, H_{Ar}), 7.53 (d, *J* = 2.0 Hz, 1 H, H_{Ar}), 7.56 (d, *J* = 2.0 Hz, 1 H, H_{Ar}).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ (**5a**) = 24.5, 84.1, 127.5, 127.6, 129.7, 130.7, 132.0, 132.9, 133.3, 134.0, 139.2.

HRMS (EI$^+$): *m*/*z* [M]$^+$ calcd for $C_{18}H_{19}{}^{11}B^{35}Cl_2O_2$: 348.0855; found: 348.0869.

2-[3,5-Dichloro-2-(trimethylsilyl)phenyl]-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (5b) and 2-[2,4-Dichloro-6-(trimethylsilyl)phenyl]-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6b)

Using general procedure 1, with 2-pyrone **1c** (25 mg, 0.15 mmol) and alkyne **2b** (67 mg, 0.30 mmol), gave the product (37 mg, 71%) as a clear oil; inseparable mixture of **5b**/**6b** (1:1).

FTIR (CH_2Cl_2, thin film): 2981 (s), 1562 (m), 1318 (s), 1142 (s), 1050 (m), 846 cm^{-1} (s).

^{1}H NMR (250 MHz, $CDCl_3$): δ (**5b**/**6b**) = 0.36 (s, 9 H, $SiCH_3$), 0.43 (s, 9 H, $SiCH_3$), 1.39 (s, 12 H, CH_3), 1.45 (s, 12 H, CH_3), 7.34–7.44 (m, 4 H, H_{Ar}).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ (**5b**/**6b**) = 0.0, 1.7, 25.3, 25.8, 84.6, 84.9, 113.2, 115.6, 119.1, 128.7, 130.3, 131.9 (2 ×), 135.0, 135.3, 138.7.

HRMS (EI$^+$): *m*/*z* [M]$^+$ calcd for $C_{15}H_{23}{}^{11}B^{35}Cl_2O_2Si$: 344.0937; found: 344.0932.

2-(4-Bromobiphenyl-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (5c)

Using general procedure 1, with 2-pyrone **1d** (50 mg, 0.29 mmol) and alkyne **2a** (132 mg, 0.58 mmol), gave **5c** (47 mg, 46%) as a yellow oil.

FTIR (CH_2Cl_2, thin film): 2981 (w), 1459 cm^{-1} (w).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.23 (s, 12 H, CH_3), 7.26 (d, *J* = 8.0 Hz, 1 H, H_{Ar}), 7.37–7.39 (m, 5 H, H_{Ar}), 7.59 (dd, *J* = 8.0, 2.5 Hz, 1 H, H_{Ar}), 7.85 (d, *J* = 2.5 Hz, 1 H, H_{Ar}).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = 24.6, 84.1, 121.1, 127.2, 127.9, 129.0, 130.8, 133.0, 137.0, 142.0, 146.4.

HRMS (EI$^+$): *m*/*z* [M]$^+$ calcd for $C_{18}H_{20}{}^{11}B^{79}BrO_2$: 359.0652; found: 359.0650.

2-[5-Bromo-2-(trimethylsilyl)phenyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (5d) and 2-[4-Bromo-2-(trimethylsilyl)phenyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6d)

Using general procedure 1, with 2-pyrone **1d** (50 mg, 0.29 mmol) and alkyne **2b** (130 mg, 0.58 mmol), gave the product (82 mg, 80%) as a clear oil; inseparable mixture of **5d**/**6d** (3:2).

FTIR (CH_2Cl_2, thin film): 2980 (s), 2977 (w), 1454 cm^{-1} (w).

^{1}H NMR (400 MHz, $CDCl_3$): δ (**5d** or **6d**) = 0.36 (s, 9 H, $SiCH_3$), 1.38 (s, 12 H, CH_3), 7.49–7.51 (m, 1 H, H_{Ar}), 7.53–7.56 (m, 1 H, H_{Ar}), 8.06 (d, *J* = 2.0 Hz, 1 H, H_{Ar}); δ (**5d** or **6d**) = 0.38 (s, 9 H, $SiCH_3$), 1.38 (s, 12 H, CH_3), 7.46–7.48 (m, 1 H, H_{Ar}), 7.74 (d, *J* = 2.0 Hz, 1 H, H_{Ar}), 7.80 (d, *J* = 8.0 Hz, 1 H, H_{Ar}).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ (**5d**/**6d**) = 0.5 (2 ×), 25.0 (2 ×), 84.0, 84.2, 123.4, 125.9, 130.8, 132.6, 136.0, 137.0, 137.9, 138.7, 145.6, 150.3.

HRMS (EI$^+$): *m*/*z* [M]$^+$ calcd for $C_{15}H_{24}{}^{11}B^{79}BrO_2Si$: 355.1504; found: 355.1507.

2-(5-Bromo-2-butylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (5e) and 2-(4-Bromo-2-butylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6e)

Using general procedure 1, with 2-pyrone **1d** (50 mg, 0.29 mmol) and alkyne **2c** (121 mg, 0.58 mmol), gave the product (43 mg, 44%) as a brown oil; inseparable mixture of **5e**/**6e** (3:2).

FTIR (CH_2Cl_2, thin film): 2958 (s), 2871 (m), 1715 (m), 1584 (m), 1345 (s), 1145 (s), 865 cm^{-1} (m).

^{1}H NMR (250 MHz, $CDCl_3$): δ (**5e**) = 0.94 (t, *J* = 7.0 Hz, 3 H, CH_3), 1.23–1.60 (m, 4 H, CH_2), 1.36 (s, 12 H, CH_3), 2.80–2.88 (m, 2 H, CH_2), 7.05 (d, *J* = 8.0 Hz, 1 H, H_{Ar}), 7.45 (dd, *J* = 8.0, 2.5 Hz, 1 H, H_{Ar}), 7.88 (d, *J* = 2.5 Hz, 1 H, H_{Ar}); δ (**6e**) = 0.94 (t, *J* = 7.0 Hz, 3 H, CH_3), 1.23–1.60 (m, 4 H, CH_2), 1.35 (s, 12 H, CH_3), 2.80–2.88 (m, 2 H, CH_2), 7.28–7.34 (m, 2 H, H_{Ar}), 7.63 (d, *J* = 8.0, 1 H, H_{Ar}).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ (**5e**/**6e**) = 13.9 (2 ×), 22.7 (2 ×), 24.8 (2 ×), 34.9, 35.3, 35.4 (2 ×), 83.6, 83.7, 119.1, 125.6, 128.0, 131.0, 132.1, 133.5, 137.6, 138.4, 148.9, 152.4.

HRMS (EI$^+$): *m*/*z* [M]$^+$ calcd for $C_{16}H_{24}{}^{11}B^{79}BrO_2$: 338.1053; found: 338.1066.

Cycloaddition of Nitrile-2-pyrones with Alkynylboronic Esters; General Procedure 2

A mixture of the 2-pyrone (0.2 mmol) and the alkynylboronate (0.4 mmol) in *o*-dichlorobenzene (0.2 mL) was heated at 175 °C and stirred for 18 h under N_2. The product was purified by flash column chromatography (PE to 10% EtOAc–PE).[22]

2-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)biphenyl-4-carbonitrile (7a)

Using general procedure 2, with 2-pyrone **1e** (25 mg, 0.21 mmol) and alkyne **2a** (96 mg, 0.42 mmol), gave **7a** (48 mg, 76%) as a clear oil.

FTIR (CH_2Cl_2, thin film): 2979 (m), 2228 (m), 1598 (m), 1346 cm^{-1} (s).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.24 (s, 12 H, CH_3), 7.36–7.44 (m, 5 H, H_{Ar}), 7.49 (d, *J* = 8.0 Hz, 1 H, H_{Ar}), 7.74 (dd, *J* = 8.0, 2.0 Hz, 1 H, H_{Ar}), 8.02 (d, *J* = 2.0 Hz, 1 H, H_{Ar}).

^{13}C NMR (100.6 MHz, $CDCl_3$): 24.6, 84.5, 109.9, 119.0, 128.0, 128.1, 128.9, 129.6, 133.4, 138.3, 141.4, 151.9.

HRMS (ES^+): *m/z* $[M]^+$ calcd for $C_{19}H_{20}{}^{11}BNO_2$: 306.1665; found: 306.1664.

3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)-4-(trimethylsilyl)benzonitrile (7b) and 4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)-3-(trimethylsilyl)benzonitrile (8b)

Using general procedure 2, with 2-pyrone **1e** (25 mg, 0.21 mmol) and alkyne **2b** (94 mg, 0.42 mmol), gave the product (62 mg, 99%) as a clear oil; inseparable mixture of **7b**/**8b** (1:1).

FTIR (CH_2Cl_2, thin film): 2980 (s), 2229 (s), 1342 (s), 1143 cm^{-1} (s).

^{1}H NMR (250 MHz, $CDCl_3$): δ (**7b**/**8b**) = 0.37 (s, 18 H, $SiCH_3$), 1.38 (s, 24 H, CH_3), 7.60–7.73 (m, 3 H, H_{Ar}), 7.85 (d, *J* = 1.0 Hz, 1 H, H_{Ar}), 7.98 (d, *J* = 7.5 Hz, 1 H, H_{Ar}), 8.17 (d, *J* = 1.0 Hz, 1 H, H_{Ar}).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ (**7b**/**8b**) = 0.0, 0.1, 24.7 (2 ×), 84.3 (2 ×), 111.6, 113.1, 118.8, 119.1, 130.6, 132.1, 134.3, 135.8, 137.0, 138.7, 148.4, 153.4.

HRMS (EI^+): *m/z* $[M]^+$ calcd for $C_{16}H_{24}{}^{11}BNO_2Si$: 302.1748; found: 302.1735.

4-Butyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzonitrile (7c) and 3-Butyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzonitrile (8c)

Using general procedure 2, with 2-pyrone **1e** (25 mg, 0.21 mmol) and alkyne **2c** (87 mg, 0.42 mmol), gave the product (32 mg, 53%) as a yellow oil; inseparable mixture of **7c**/**8c** (5:1).

FTIR (CH_2Cl_2, thin film): 2959 (s), 2228 (s), 1600 (s), 1347 (s), 1144 cm^{-1} (s).

^{1}H NMR (250 MHz, $CDCl_3$): δ (**7c**) = 0.94 (t, *J* = 7.0 Hz, 3 H, CH_3), 1.23–1.60 (m, 4 H, CH_2), 1.36 (s, 12 H, CH_3), 2.80–2.88 (m, 2 H, CH_2), 7.27 (d, *J* = 8.0 Hz, 1 H, H_{Ar}), 7.61 (dd, *J* = 8.0, 2.0 Hz, 1 H, H_{Ar}), 8.07 (d, *J* = 2.0 Hz, 1 H, H_{Ar}); δ (**8c**) = 0.94 (t, *J* = 7.0 Hz, 3 H, CH_3), 1.23–1.60 (m, 4 H, CH_2), 1.35 (s, 12 H, CH_3), 2.80–2.88 (m, 2 H, CH_2), 7.41–7.48 (m, 2 H, H_{Ar}), 7.84 (d, *J* = 8.0 Hz, 1 H, H_{Ar}).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ (**7c**/**8c**) = 13.9 (2 ×), 22.6, 22.7, 24.9 (2 ×), 35.1, 35.2, 35.8 (2 ×), 84.1 (2 ×), 109.0 (2 ×), 119.1, 119.2, 128.1, 129.8, 132.2, 133.8, 136.3, 139.9, 155.5 (2 ×).

HRMS (ES^+): *m/z* $[M]^+$ calcd for $C_{17}H_{24}{}^{11}BNO_2$: 286.1978; found: 286.1965.

2-Bromo-6-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)biphenyl-4-carbonitrile (7d)

Using general procedure 2, with 2-pyrone **1f** (25 mg, 0.13 mmol) and alkyne **2a** (59 mg, 0.26 mmol), gave **7d** (45 mg, 94%) as a yellow oil.

FTIR (CH_2Cl_2, thin film): 2979 (s), 2229 (w), 1590 (m), 1339 (s), 1142 cm^{-1} (s).

^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.10 (s, 12 H, CH_3), 7.19–7.26 (m, 2 H, H_{Ar}), 7.39–7.45 (m, 3 H, H_{Ar}), 7.91 (d, *J* = 1.5 Hz, 1 H, H_{Ar}), 7.99 (d, *J* = 1.5 Hz, 1 H, H_{Ar}).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ = 24.5, 84.5, 112.4, 117.4, 124.3, 127.7, 128.1, 129.1, 136.2, 137.0, 140.6, 151.9.

HRMS (EI^+): *m/z* $[M]^+$ calcd for $C_{19}H_{19}{}^{11}B^{79}BrNO_2$: 383.0692; found: 383.0680.

3-Bromo-5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-4-(trimethylsilyl)benzonitrile (7e) and 3-Bromo-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-5-(trimethylsilyl)benzonitrile (8e)

Using general procedure 2, with 2-pyrone **1f** (25 mg, 0.13 mmol) and alkyne **2b** (58 mg, 0.26 mmol), gave the product (46 mg, 96%) as a clear oil; inseparable mixture of **7e**/**8e** (1:1).

FTIR (CH_2Cl_2, thin film): 2981 (s), 2232 (m), 1332 (s), 1140 (s), 1048 (m), 847 cm^{-1} (s).

^{1}H NMR (250 MHz, $CDCl_3$): δ (**7e**/**8e**) = 0.38 (s, 9 H, $SiCH_3$), 0.48 (s, 9 H, $SiCH_3$), 1.39 (s, 12 H, CH_3), 1.48 (s, 12 H, CH_3), 7.71 (d, *J* = 1.5 Hz, 1 H, H_{Ar}), 7.75 (d, *J* = 1.5 Hz, 1 H, H_{Ar}), 7.77 (d, *J* = 1.5 Hz, 1 H, H_{Ar}), 7.81 (d, *J* = 1.5 Hz, 1 H, H_{Ar}).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ (**7e**/**8e**) = 0.0, 1.9, 25.5, 26.1, 85.1, 85.6, 113.5, 113.8, 117.6, 117.9, 127.9, 131.3, 131.5, 134.8, 135.2, 135.3, 136.5, 149.0.

HRMS (EI^+): *m/z* $[M]^+$ calcd for $C_{16}H_{23}{}^{11}B^{79}BrNO_2Si$: 379.0774; found: 379.0777.

3-Bromo-4-butyl-5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzonitrile (7f) and 3-Bromo-5-butyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzonitrile (8f)

Using general procedure 2, with 2-pyrone **1f** (25 mg, 0.13 mmol) and alkyne **2c** (54 mg, 0.26 mmol), gave the product (31 mg, 65%) as a yellow oil; inseparable mixture of **7f**/**8f** (11:1).

FTIR (CH_2Cl_2, thin film): 2977 (s), 2232 (m), 1337 (s), 1140 (s), 849 cm^{-1} (s).

^{1}H NMR (250 MHz, $CDCl_3$): δ (**7f**) = 0.97 (t, *J* = 7.0 Hz, 3 H, CH_2CH_3), 1.28–1.30 (m, 2 H, CH_2), 1.37 (s, 12 H, CH_3), 1.45–1.49 (m, 4 H, $CH_2CH_2CH_3$), 7.87 (d, *J* = 1.5 Hz, 1 H, H_{Ar}), 8.00 (d, *J* = 1.5 Hz, 1 H, H_{Ar}).

^{13}C NMR (62.9 MHz, $CDCl_3$): δ (**7f**) = 13.8, 22.9, 24.8, 33.1, 35.2, 84.4, 110.6, 117.5, 125.5, 137.8, 138.6, 154.2.

HRMS (EI^+): *m/z* $[M]^+$ calcd for $C_{17}H_{23}{}^{11}B^{79}BrNO_2$: 363.1005; found: 363.1003.

Trimethyl[3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)prop-2-ynyl]silane (2d)

A 2.5 M soln of BuLi in hexanes (4.25 mL, 8.93 mmol), was added dropwise to trimethylpropargylsilane (1.00 g, 8.93 mmol) in Et_2O, at –78 °C under N_2. The resulting mixture was stirred at this temperature for 1 h, then warmed to r.t. and stirred for 30 min. 2-Isopropoxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (1.83 mL, 8.93 mmol), was added dropwise, and the resulting suspension stirred for 3 h. 1 M HCl in Et_2O (11.61 mL, 11.61 mmol) was added dropwise, and the reaction stirred for 1 h. Lithium salts were removed via filtration through Celite under N_2, and the product purified via recrystallization (PE, bp 40–60 °C), affording **2d** (840 mg, 40%) as a colourless solid; mp 43–45 °C.

FTIR (CH_2Cl_2, thin film): 2982 (s), 2955 (s), 2197 (s), 1381 (s), 1312 cm^{-1} (s).

^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.14 (s, 9 H, $SiCH_3$), 1.28 (s, 12 H, CCH_3), 1.62 (s, 2 H, $SiCH_2$).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ = –2.0, 8.6, 24.7, 83.8, 103.7.

HRMS (AP^+): *m/z* $[M]^+$ calcd for $C_{12}H_{23}BO_2Si$: 239.1639; found: 239.1644.

Methyl 3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)-4-[(trimethylsilyl)methyl]benzoate (9) and Methyl 4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)-3-[(trimethylsilyl)methyl]benzoate (10)

Using general procedure 2, with 2-pyrone **1g** (25 mg, 0.16 mmol) and alkyne **2d** (77 mg, 0.32 mmol), gave the product (22 mg, 41%) as a yellow oil; inseparable mixture of **9**/**10** (6:1).

FTIR (CH_2Cl_2, thin film): 2976 (m), 2903 (w), 1722 (s), 1591 cm^{-1} (w).

^{1}H NMR (250 MHz, $CDCl_3$): δ (**9**) = 0.03 (s, 9 H, CH_3), 1.36 (s, 12 H, $SiCH_3$), 2.65 (s, 2 H, CH_2SiCH_3), 3.91 (s, 3 H, OCH_3), 7.05 (d, *J* = 8.0 Hz, 1 H, H_{Ar}), 7.95 (dd, *J* = 8.0, 2.0 Hz, 1 H, H_{Ar}), 8.44 (d, *J* = 2.0 Hz, 1 H, H_{Ar}).

^{13}C NMR (100.6 MHz, $CDCl_3$): δ (**9**) = –1.6, 25.0, 27.5, 51.8, 83.6, 125.1, 128.6, 131.6, 137.8, 154.3, 164.6.

HRMS (ES$^+$): *m*/*z* [M]$^+$ calcd for $C_{18}H_{29}{}^{11}BO_4Si$: 349.2002; found: 349.2006.

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Supporting Information for this article is available online at http://www.thieme-connect.com/ejournals/toc/synthesis.

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(10) The regiochemistry of **5a** was assigned by inference in comparison to the analogous cycloaddition reaction of 3,5-dibromopyran-2-one.[4a] The regiochemistry of compound **5c** was elucidated by NOE NMR spectroscopy, but that of compounds **5b**/**6b**, **5d**/**6d**, and **5e**/**6e** was not established due to the low levels of selectivity observed in these cases.
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