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Investigation of Substituent Effects on the Selectivity of 4π-Electrocyclization of 1,3-Diarylallylic Cations for the Formation of Highly Substituted Indenes

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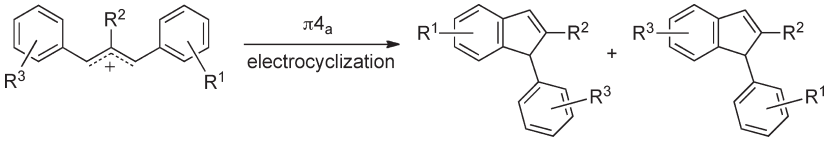

Differentially substituted 1,3-diaryl-substituted allylic cations generated by ionization of the corresponding allylic alcohols in the presence of a Lewis acid undergo chemoselective and regioselective electrocyclization reactions to generate 1-aryl-1*H*-indenes. Electrocyclization only occurs for allylic cations bearing a 2-substituent, with 2-ester and 2-alkyl substituents both tolerated. In general, the presence of electron-withdrawing substituents deactivates the ring and disfavors cyclization. In contrast, the selectivity of cyclization of systems containing electron-donating substituents depends on the nature and position of the electron-donating group. Electron-donating substituents at the meta position particularly favor cyclization. There was no obvious correlation of cyclization selectivity with calculated electron densities as has been suggested for electrophilic aromatic substitution reactions. However, the calculated selectivities determined by a gas-phase (B3LYP/6-31G* + ZPVE) comparison of the relative rates of cyclization were in remarkably good agreement with the observed selectivities. Calculated transition-state structures for cyclization are consistent with a cationic $\pi 4_a$ conrotatory electrocyclization mechanism. In some cases involving more electron-deficient systems, the initially formed 1*H*-indene underwent subsequent alkene isomerization to the 3*H*-indene. In one example, an unusual dimerization reaction occurred to give a cyclopenta[*a*]indene via an unusual formal cationic $2\pi+2\pi$ cycloaddition of the allylic cation with the intermediate indene.

Introduction

The cyclization of phenyl-substituted allylic cations is a well-established method for the synthesis of indenes.[1] Typically phenyl-substituted allylic alcohols **1**[2] react in strongly acidic media (i.e., FSO_3H, $FSO_3H-SbF_5-SO_2ClF$, H_2SO_4, etc.) via phenyl-substituted allylic cations **2**[3] to give indenes **5** (eq 1). The allylic cations **2** can be generated and observed (by ^1H NMR) at low temperatures (−70 °C) in super acid media and upon warming cyclize to give indenes **5**.[3a,4,5] Conventional Lewis acids have also been used for the cyclizations of **1** into **5**, such as boron trifluoride etherate, aluminum trichloride, etc.[6−8] The allylic alcohol precursors utilized have typically been 1-phenylallyl alcohols, 1-arylallyl alcohols, 1,3-diphenylallyl alcohols, 1,1,3-triphenylallyl alcohols, and tetra- or pentaphenyl-substituted allylic alcohols.

(1) (a) For review on indene formation, see: Ivchenko, N. B.; Ivchenko, P. V.; Nifant'ev, I. E. *Russ. J. Org. Chem.* **2000**, *36*, 609–637. For reviews on the synthesis of indenes and their use in transition metal chemistry, see: (b) Enders, M.; Baker, R. W. *Curr. Org. Chem.* **2006**, *10*, 937–953. (c) Halterman, R. L. *Chem. Rev.* **1992**, *92*, 965–994.

(2) Phenyl-substituted allylic alcohols are believed to be intermediates in the cyclodehydration of phenyl-substituted diols: (a) Blum-Bergmann, O. *Ber.* **1932**, *65*, 109–122. (b) Blum-Bergmann, O. *J. Chem. Soc.* **1935**, 1020–1022.

(3) (a) Olah, G. A.; Asensio, G.; Mayr, H. *J. Org. Chem.* **1978**, *43*, 1518–1520. (b) Pittman, C. U., Jr.; Miller, W. G. *J. Org. Chem.* **1974**, *39*, 1955–1956. (c) Bergmann, F. *J. Org. Chem.* **1941**, *6*, 543–549. (d) Koelsch, C. F. *J. Am. Chem. Soc.* **1932**, *54*, 3384–3389.

(4) (a) Pittman, C. U., Jr.; Miller, W. G. *J. Am. Chem. Soc.* **1973**, *95*, 2947–2956. (b) Dytnerski, D.; Ranganayakulu, K.; Singh, B. P.; Sorensen, T. S. *J. Org. Chem.* **1983**, *48*, 309–315. (c) Dytnerski, D.; Ranganayakulu, K.; Singh, B. P.; Sorensen, T. S. *Can. J. Chem.* **1982**, *60*, 2993–3004. (d) Deno, N. C.; Pittman, C. U., Jr.; Turner, J. O. *J. Am. Chem. Soc.* **1965**, *87*, 2153–2157.

(5) For the isolation of the 1,3-diphenylallyl cation as a stable tetrafluoroborate salt, see: Hafner, K.; Pelster, H. *Angew. Chem.* **1961**, *73*, 342.

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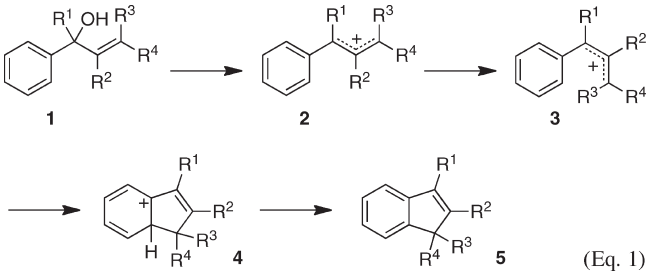
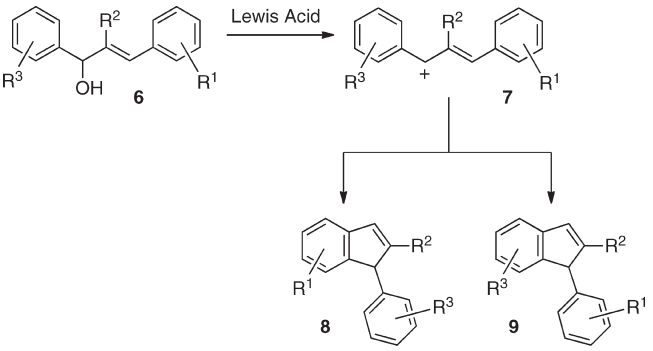


(Eq. 1)

The cyclization of **3** can be described as a 4π-conrotatory electrocyclization to give indanyl cation **4**, which is followed by elimination of a proton to give **5**.[2b,3a,b,4a,6c,8,9] This mechanism is reminiscent of the Nazarov reaction, which occurs via cationic conrotatory 4π-electrocyclization and proton loss to give cyclopentenones.[10,11] The cyclization of **3** into **4** can also be envisaged as an intramolecular electrophilic aromatic substitution (Friedel−Crafts alkylation) reaction. The allylic cation must first rearrange from the unreactive extended conformation **2** to adopt the conformation **3** suitable for cyclization. To promote reaction via this conformation it is necessary for the precursor alcohols **1** to contain at least one other substituent in addition to the phenyl group onto which cyclization occurs.[7]

While the electrocyclization of 1,3-diphenylallylic cations **2**/**3** (R^3 or R^4 = Ph) is known, examples of cyclization of differentially substituted 1,3-diarylallylic cations **7** have not been rigorously explored (Scheme 1).[12] Such reactions pose an interesting chemoselectivity issue[11,13] since cyclization of the unsymmetrical cation **7** can occur from either of the aromatic rings, leading to differentially substituted indenes **8** and **9**. We were particularly interested in discovering the factors that govern the chemoselectivity of electrocyclization of **6** to either **8** or **9** and whether they could be rationalized in terms of the well-known substituent effects for electrophilic aromatic substitution or whether other factors would play a role given the electrocyclic nature of the cyclization. We now describe experimental and computational studies on the conversion of **6** into functionalized indenes **8** and **9** and show how the chemoselectivity of electrocyclization of the intermediate cations **7** is dependent upon both the position and electronic nature of the substituents.

SCHEME 1. Selectivity of Cyclization of 1,3-Diarylallylic Cations 7 into Indenes 8 and 9



Results and Discussion

Synthesis of 1,3-diarylallylic alcohol precursors **6** (R^2 = Me or COOEt) was achieved using either Knoevenagel or aldol−based approaches from commercially available substituted benzaldehydes **10** (Scheme 2). Knoevenagel condensation[14] of **10** with ethyl benzoylacetate **11** (Ar = Ph, R^2 = COOEt) stereoselectively provided ethyl 3-aryl-2-benzoylpropenoates **12** (Ar = Ph, R^2 = COOEt) as the (*E*)-isomers.[15] This method was also extended to aldol reactions of propiophenone **11** (Ar = Ph, R^2 = Me) to stereoselectively prepare (*E*)-3-aryl-2-methyl-1-phenylpropenones **12** (Ar = Ph, R^2 = Me). For the synthesis of 1,3-diaryl-2-methylpropenones **12** (Ar ≠ Ph, R^2 = Me) a three-step aldol protocol was required. $TiCl_4$-mediated aldol reaction[16] between **10** and an appropriately substituted propiophenone **11** (Ar ≠ Ph, R^2 = Me) afforded *syn*-β-hydroxy ketones with high stereoselectivity. These were then immediately converted to the corresponding mesylates, which underwent elimination[17] to give (*E*)-2-propenones **12** (Ar ≠ Ph, R^2 = Me). Selective 1,2-reduction

(6) See, for example: (a) Zhou, X.; Zhang, H.; Xie, X.; Li, Y. *J. Org. Chem.* **2008**, *73*, 3958–3960. (b) Jeong, I. H.; Park, Y. S.; Kim, M. S.; Oh, S. T. *Bull. Korean Chem. Soc.* **2001**, *22*, 1173–1174. (c) Jeong, I. H.; Park, Y. S.; Kim, M. S.; Song, Y. S. *J. Fluorine Chem.* **2003**, *120*, 195–209.

(7) Solid-state thermolysis of magnesium alkoxides has also been reported to lead to efficient and regioselective indene formation; see: Tolbert, L. M. *J. Org. Chem.* **1979**, *44*, 4584–4588.

(8) (a) For $BF_3 \cdot OEt_2$-promoted cyclodehydration reactions of vinyl sulfide benzyl alcohols, see: Singh, G.; Ila, H.; Junjappa, H. *Synthesis* **1986**, 744–747. (b) For $BF_3 \cdot OEt_2$-catalyzed cyclizations of iodinated allylic alcohols, see: Zhou, X.; Zhang, H.; Xie, X.; Li, Y. *J. Org. Chem.* **2008**, *73*, 3958–3960.

(9) For mild acid-promoted cyclization of dienostrol and related dienes to the corresponding indenes, see: Hausmann, W.; Smith, A. E. W. *J. Chem. Soc.* **1949**, 1030–1032.

(10) For reviews of the Nazarov reaction, see: (a) Tius, M. A. *Eur. J. Org. Chem.* **2005**, *11*, 2193–2206. (b) Frontier, A. J.; Collison, C. *Tetrahedron* **2005**, *61*, 7577–7606. (c) Pellissier, H. *Tetrahedron* **2005**, *61*, 6479–6517. (d) Habermas, K. L.; Denmark, S. E.; Jones, T. K. *Org. React.* (*N.Y.*) **1994**, *45*, 1–158.

(11) The Nazarov reaction has also been used for the synthesis of indenes. See, for example: Liang, G.; Xu, Y.; Seiple, I. B.; Trauner, D. *J. Am. Chem. Soc.* **2006**, *128*, 11022–11023.

(12) (a) Wang, J.; Zhang, L.; Jing, Y.; Huang, W.; Zhou, X. *Tetrahedron Lett.* **2009**, *50*, 4978–4982. (b) There is a single reported example of a cyclization of methyl (2*Z*)-2-[hydroxy(4-chlorophenyl)methyl]-3-phenylacrylate into methyl 6-chloro-1-phenyl-1*H*-indene-2-carboxylate using Montmorillonite K10 clay under microwave conditions. However, no data were reported for the product; see: Shanmugam, P.; Rajasingh, P. *Chem. Lett.* **2005**, *34*, 1494–1495.

(13) In general, there have been relatively few studies of substituent effects for electrocyclic reactions. See, for example: (a) He, W.; Herrick, I. R.; Atesin, T. A.; Caruana, P. A.; Kellenberger, C. A.; Frontier, A. J. *J. Am. Chem. Soc.* **2008**, *130*, 1003–1011. (b) He, W.; Sun, X.; Frontier, A. J. *J. Am. Chem. Soc.* **2003**, *125*, 14278–14279. (c) Marcus, A. P.; Lee, A. S.; Davis, R. L.; Tantillo, D. J.; Sarpong, R. *Angew. Chem., Int. Ed.* **2008**, *47*, 6379–6383. (d) For substituent effects on the selectivity of Nazarov-type cyclizations of α-hydroxyallenes for the synthesis of benzofulvenes, see: Cordier, P.; Aubert, C.; Malacria, M.; Lacote, E.; Gandon, V. *Angew. Chem., Int. Ed.* **2009**, *48*, 8757–8760.

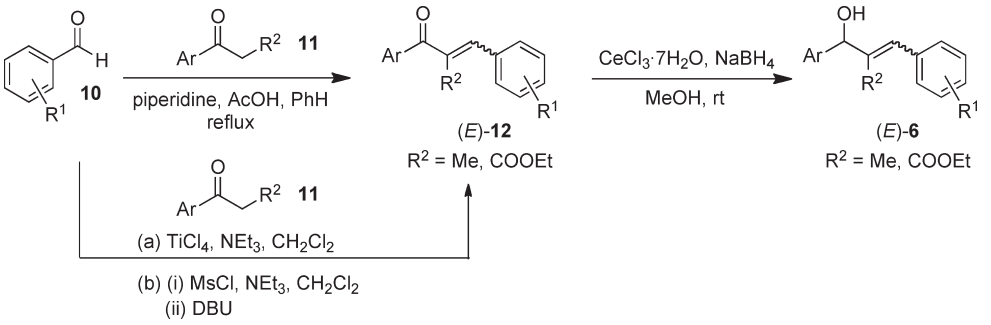
(14) (a) Antonioletti, R.; Bovicelli, P.; Malancona, S. *Tetrahedron* **2002**, *58*, 589–596. (b) Horning, E. C.; Koo, J.; Fish, M. S.; Walker, G. N. *Organic Synthesis*; Wiley: New York, 1963; Collect. Vol. IV, pp 408−409. (c) Allen, C. F. H.; Spangler, F. W.; Shriner, R. L.; Neumann, F. W. *Organic Synthesis*; Wiley: New York, 1955; Collect. Vol. III, pp 377−379.

(15) The stereochemistry of **12** was confirmed by the chemical shift of the vinylic proton (see: Li, Z.; Li, H.; Guo, X.; Cao, L.; Yu, R.; Li, H.; Pan, S. *Org. Lett.* **2008**, *10*, 803–805.). The vinylic proton of (*E*)-2-benzoyl-3-arylpropenonates resonate further downfield (δ 7.8−8.2 ppm) in comparison to the corresponding (*Z*)-isomers (δ 6.8−7.2 ppm).

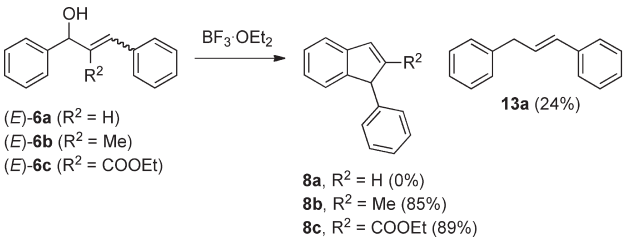
(16) Harrison, C. R. *Tetrahedron Lett.* **1987**, *28*, 4135–4138.

(17) Modified from the original procedure by: Degraw, J. I.; Christie, P. H.; Kisliuk, R. L.; Gaumont, Y.; Sirotnak, F. M. *J. Med. Chem.* **1990**, *33*, 212–215. Our attempts to eliminate the *syn*-β-hydroxy ketones directly using $POCl_3$ were unsuccessful.

SCHEME 2. Synthesis of 1,3-Diarylallylic Alcohols 6 Using Knoevenagel or Aldol-Based Approaches



SCHEME 3. Effect of Substitution at the 2-Position for the Cyclization of Alcohols 6



of the enones **12** using Luche conditions[18] generally afforded alcohols **6** in high yields. However, the reduction of the enones **12** (R^2 = COOEt) was often problematic because of incomplete conversion to the corresponding alcohols **6** and the presence of over-reduced byproducts.

Initial studies focused upon the effect of substituents at the 2-position through the reaction of alcohols **6a**−**c** in the presence of a Lewis acid ($BF_3 \cdot OEt_2$, 1.0 equiv) in dichloromethane at room temperature (Scheme 3).[19] Reaction of the unsubstituted precursor **6a** (R^2 = H) did not result in the formation of indene **8a**, with only the reduced species 1,3-diphenylpropene **13a** isolated in low yield. Similar formation of reduced products such as **13a** from allylic alcohols has been observed to occur via a disproportionation process.[20] Conversely, reaction of 2-methyl-substituted precursor **6b** (R^2 = Me) afforded indene **8b** in 85% yield. Interestingly, the presence of an electron-withdrawing group at the 2-position did not interfere with allylic cation formation or cyclization, with substrate **6c** (R^2 = COOEt) reacting to give the corresponding indene **8c** isolated in 89% yield.[21]

Reactions of the isomeric allylic alcohols **6d** or **14** with $BF_3 \cdot OEt_2$ (1.0 equiv) in dichloromethane at room temperature afforded an inseparable mixture of 1*H*-indenes **8d** and **9d** in combined 84% and 84% yield, respectively (Scheme 4). As anticipated, an identical 3:7 ratio of the indenes **8d**/**9d** was obtained for both reactions, demonstrating that the product ratio of the isomeric indenes is independent of the initial position of the allylic alcohol in the precursor, which is consistent with a mechanism involving the intermediacy of a common allylic cation.[22] The ratio of the products indicates that cyclization is favored through the unsubstituted phenyl ring over the *p*-methoxyphenyl ring. DIBAL-H reduction of the mixture of isomeric esters **8d**/**9d** gave the corresponding mixture of allylic alcohols **15a**/**b** in 73% yield.

The results can be rationalized in terms of cyclization via a common allyl cation intermediate, where cyclization requires the presence of a substituent at the C-2 allylic position (i.e., $R^2 \neq$ H) (Figure 1). For the symmetrical case (i.e., where both of the C-1 and C-3 substituents are phenyl groups), the allylic cation generated on ionization can exist in three forms, 7-***EE***, 7-***ZE*** (in this case identical to 7-***EZ***), and 7-***ZZ***. The low energy form 7-***EE*** exists in an extended "W" conformation and cannot directly undergo electrocyclization. Isomerization of 7-***EE*** through bond rotation to give 7-***ZE*** (or 7-***EZ***), which exists in an "S" conformation, is necessary before cyclization can occur. 7-***ZZ*** is also capable of undergoing cyclization, but it is even higher in energy due to the unfavorable $A_{1,3}$ strain between the two aromatic groups. Electrocyclization of 7-***ZE*** in a $\pi 4_a$ conrotatory fashion leads to intermediate indanyl cation **16**-***trans***, which on proton loss gives indene **8**. Similarly, $\pi 4_a$ conrotatory electrocyclization of 7-***ZZ*** leads to the indanyl cation **16**-***cis***, which on proton loss also gives **8**. The failure of **6a** to undergo cyclization to indene **8a** can be attributed to the difficulty of isomerization of cation 7-***EE*** (R^2 = H) into the reactive conformations 7-***ZE***, 7-***EZ***, or 7-***ZZ*** (R^2 = H) necessary for cyclization. Introduction of a substituent at the 2-position promotes cyclization as for the reactions of **6b** or **6c**. In these cases, $A_{1,2}$ strain between the central 2-substituent and the two

(18) (a) Gemal, A.; Luche, J. *J. Am. Chem. Soc.* **1981**, *103*, 5454–5459. (b) Barluenga, J.; Fañanás, F.; Sanz, R.; García, F.; García, N. *Tetrahedron Lett.* **1999**, *40*, 4735–4736.

(19) Following addition of $BF_3 \cdot OEt_2$ to **6a**−**c** at room temperature, an immediate color change from colorless to red or dark purple occurred, which we assume is due to the presence of the corresponding cations. In the case of **6b**/**c**, the color dissipated to a pale yellow solution (within 5 min), indicating that the allylic cation had been trapped and that indene formation was complete. In order to determine the influence of temperature on allylic cation formation, the reaction of **6b** was performed at −78 °C and slowly warmed to 0 °C. Addition of $BF_3 \cdot OEt_2$ to the pale yellow solution of **6b** at −78 °C did not result in any change in color. Slow warming of the solution over several minutes resulted in the solution darkening to an orange color at −55 °C, red at −45 °C, and finally a deep purple color at −30 °C. On further warming, the color started to dissipate at −20 °C, turning yellow at −10 °C, and finally pale yellow at 0 °C, at which point the reaction was quenched with water. Quenching the reaction at lower temperature (−78 °C) did not lead to indene formation. Similar color change observations were noted in the reaction of **6a**, except that the dark red color did not dissipate even after warming to room temperature.

(20) For an example of an $FeCl_3$-catalyzed disproportionation of allylic alcohols, see: Wang, J.; Huang, W.; Zhang, Z.; Xiang, X.; Liu, R.; Zhou, X. *J. Org. Chem.* **2009**, *74*, 3299–3304.

(21) Indene formation was also observed with trifluoromethyl-substituted phenylallyl cations. See: Gassman, P. G.; Ray, J. A.; Wenthold, P. G.; Mickelson, J. W. *J. Org. Chem.* **1991**, *56*, 5143–5146.

(22) (a) For a review of reactions with allylic cations, see: DeWolfe, R. H.; Young, W. G. *Chem. Rev.* **1956**, *56*, 753–901. (b) For a kinetic study of the acid-catalyzed equilibration of differentially substituted 1,3-diarylallylic alcohols via allylic cations, see: Bernstein, S. C. *J. Org. Chem.* **1968**, *33*, 3486–3488.

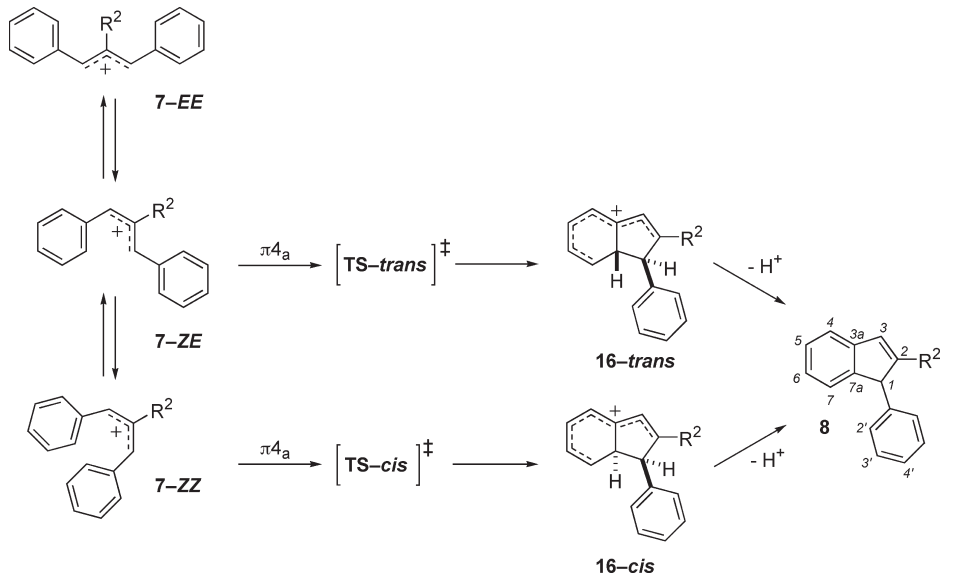
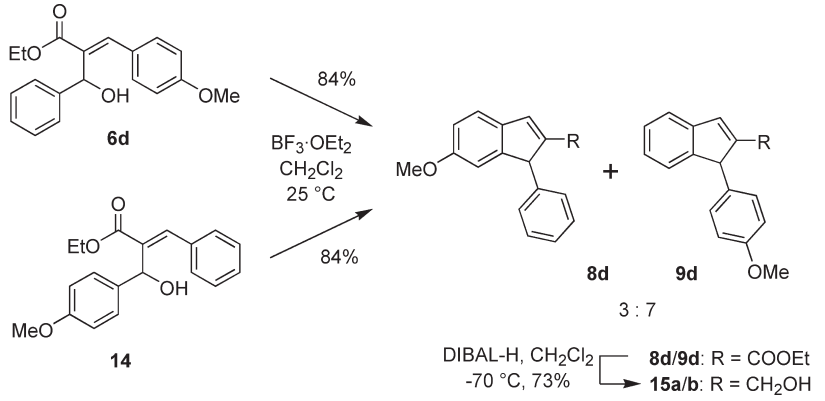


FIGURE 1. Mechanistic scheme for the cyclization of allylic cations **7** into 2-substituted 1-phenylindenes **8**.

SCHEME 4. Cyclization of Isomeric Alcohols 6d and 14 into Indenes 8d and 9d



flanking aromatic groups would be expected to result in destabilization of **7-*EE*** ($R^2 \neq H$), and facilitate isomerization. This $A_{1,2}$ strain would not occur for the unsubstituted case **7-*EE*** ($R^2 = H$). These experimental results support the hypothesis that a central substituent promotes indene formation by facilitating reaction through the "S" conformation of the arylallyl cation.[7]

A DFT computational study (B3LYP/6-31G*) on this cationic system **7**/**16** (R^2 = H, Me, and COOH) was consistent with this model (Tables 1 and 2).[23] The calculations were conducted in the gas phase and therefore do not take into account solvation effects. However, since all of the species are cationic, solvation effects could be anticipated to be roughly similar within each series. Relative energies were calculated both as ZPVE-corrected B3LYP/6-31G* energies and as thermally corrected B3LYP/6-31G* free energies (including ZPVE) at standard temperature and pressure. In general, there was only a minor variance between these relative energy values. **7-*ZE*** ($R^2 = H$) is calculated to be +6.1 kcal/mol higher in energy than **7-*EE*** ($R^2 = H$).

On the other hand, for the methyl-substituted case the energy difference of +1.8 kcal/mol between **7-*ZE*** and **7-*EE*** (R^2 = Me) is much lower, reflecting the ground-state destabilization of **7-*EE***. The relative energy of the intermediate indanyl cation is slightly lower for the **16-*trans*** form over the **16-*cis*** form in both the unsubstituted and 2-Me-substituted cases. However, the 2-Me substituted cation **16-*trans*** (R^2 = Me) is more stable than the unsubstituted cation **16-*trans*** ($R^2 = H$), with energy values relative to the corresponding allylic cations **7-*EE*** of +23.3 and +10.2 kcal/mol, respectively. The greater relative stabilization of the 2-Me-substituted intermediate indanyl cation is consistent with the electron-donating ability of the methyl group, which can directly stabilize the $\delta+$ charge at C-2. The electron-donating ability of the 2-methyl group would have a lesser effect on the precursor cations **7**, since the $\delta+$ charge is principally localized at C-1 and C-3. Analysis of the calculated transition states **TS-*trans*** and **TS-*cis*** (for R^2 = H and Me) show considerable C7a−C1 bond development consistent with late product-like transition states. The calculated bond lengths (C7a−C1) in **TS-*trans*** and **TS-*cis*** decrease along the series R^2 = Me > H > COOH, revealing that bond formation is more well developed (i.e., a later transition state) for the 2-COOH over the

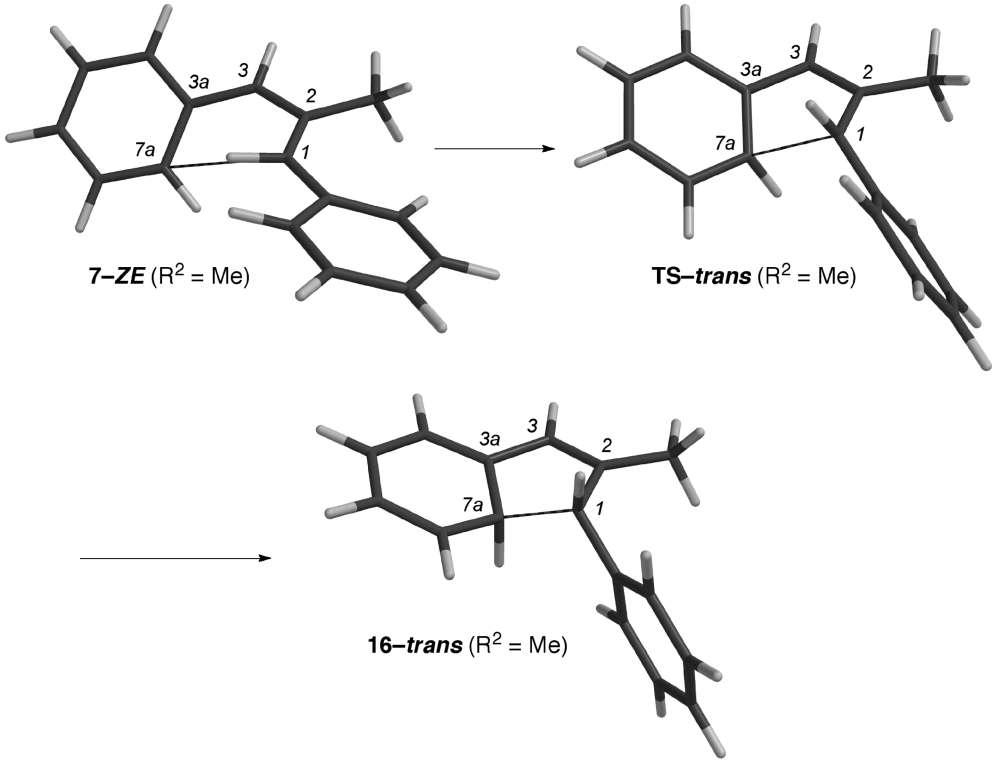
(23) For calculations on the cyclization of phenylallyl cation (B3LYP/6-31G*), see: Suzuki, T.; Ohwada, T.; Shudo, K. *J. Am. Chem. Soc.* **1997**, *119*, 6774–6780.

TABLE 1. Relative DFT Energies [B3LYP/6-31G* + ZPVE (B3LYP/6-31G* + G)][a] and Internuclear Distances (C7a−C1) for 7, 16, and TS-*trans*/*cis* (R^2 = H, Me, COOH)[b]

	R^2 = H (kcal mol^{-1})	R^2 = Me (kcal mol^{-1})	R^2 = COOH (kcal mol^{-1})
7-*EE*	0.0	0.0	0.0
7-*ZE*	+6.1 (+6.2) (C_{7a}−C_1 = 3.202 Å)	+1.8 (+1.8) (C_{7a}−C_1 = 3.111 Å)	+0.5 (+0.3) (C_{7a}−C_1 = 3.071 Å)
7-*ZZ*	+15.5 (+15.6)	+9.6 (+8.8)	+4.2 (+3.9)
16-*trans*	+23.3 (+24.3) (C_{7a}−C_1 = 1.601 Å)	+10.2 (+10.8) (C_{7a}−C_1 = 1.580 Å)	+14.2 (+14.5) (C_{7a}−C_1 = 1.594 Å)
16-*cis*	+24.9 (+26.0) (C_{7a}−C_1 = 1.562 Å)	+11.0 (+11.5) (C_{7a}−C_1 = 1.563 Å)	+13.8 (+14.4) (C_{7a}−C_1 = 1.562 Å)
TS-*trans*	+27.1 (+28.4) (C_{7a}−C_1 = 1.970 Å)	+17.8 (+18.6) (C_{7a}−C_1 = 2.035 Å)	+28.0 (+28.9) (C_{7a}−C_1 = 1.939 Å)
TS-*cis*	+34.1 (+35.3) (C_{7a}−C_1 = 2.046 Å)	+22.7 (+23.3) (C_{7a}−C_1 = 2.101 Å)	+31.7 (+32.2) (C_{7a}−C_1 = 2.023 Å)

[a]Relative energies are given as B3LYP/6-31G* + ZPVE and in parentheses as B3LYP/6-31G* + G (where G = free energy including ZPVE). [b]True minima on the potential energy hypersurface were identified by the presence of no imaginary frequencies, and transition structures were confirmed by identifying only one imaginary frequency.

TABLE 2. Calculated Geometries of 7-*ZE*, TS-*trans*, and 16-*trans* (R^2 = Me) (B3LYP/6-31G*)

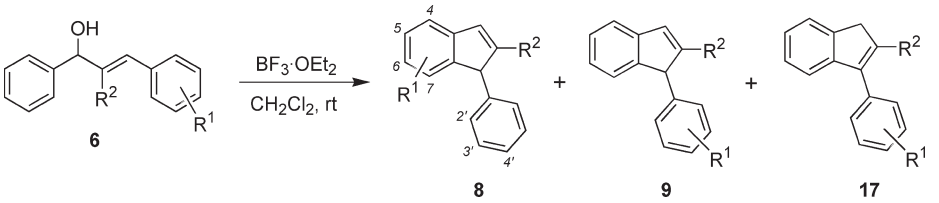


bond distance or dihedral angle	**7-*ZE*** (R^2 = Me)	**TS-*trans*** (R^2 = Me)	**16-*trans*** (R^2 = Me)
C_1−C_2	1.404 Å	1.478 Å	1.522 Å
C_2−C_3	1.403 Å	1.370 Å	1.373 Å
C_3−C_{3a}	1.431 Å	1.429 Å	1.419 Å
C_{3a}−C_{7a}	1.421 Å	1.449 Å	1.489 Å
C_{7a}−C_1	3.111 Å	2.035 Å	1.580 Å
Ph−C_1−C_2−C_3	179.2°	151.0°	141.2°

2-H- and 2-Me-substituted transition states. The negative vibrational mode for the transition states was animated to ensure that the imaginary frequency correctly represented the appropriate bond formation process, and revealed a conrotatory motion consistent with $\pi 4_a$ electrocyclization for both **TS-*trans*** and **TS-*cis***, with the latter being significantly higher in energy. The calculated transition barrier for the conversion of **7** into **16-*trans*** via **TS-*trans*** is considerably lower for the 2-Me-substituted case than for the unsubstituted case (17.8 and 27.1 kcal/mol, respectively) (Table 1). This can be attributed to both the greater ground-state destabilization of **7-*EE*** (R^2 = H), and the additional stabilization of **TS-*trans*** (R^2 = Me) that occurs as a result of the electron-donating 2-Me substituent.

At this stage, we set out to study the chemo- and regioselectivity of electrocyclization of differentially substituted 1,3-diarylallylic cations **7** (Scheme 1 and Table 3). The electrocyclizations of such unsymmetrical systems have not been investigated but are of interest, since it is not known whether substituent effects for cationic electrocyclization reactions would mirror those of electrophilic aromatic substitution.[4a,8,24] Accordingly, we set about investigating the reactions of monosubstituted substrates **6**, containing either a COOEt or methyl substituent at the 2-position of the allyllic

TABLE 3. Chemo- and Regioselectivity Study of the Cyclization of Differentially Substituted Allylic Alcohols 6



entry	allylic alcohol 6			isolated indenes 8, 9, or 17	crude ratio[a]	yield[b] (%)
		R^1	R^2			
1	**6e**	*p*-NO_2	COOEt	**17** (4′-NO_2)	*c*	70
2	**6f**	*m*-NO_2	COOEt	**17** (3′-NO_2)	*c*	67
3	**6g**	*o*-NO_2	COOEt	**17** (2′-NO_2)	*c*	69
4	**6h**	*p*-Cl	COOEt	**9** (4′-Cl)/**17** (4′-Cl)[d]	1:2.2[d]	61
5	**6i**	*m*-Cl	COOEt	**8** (5-Cl)/**8** (7-Cl)/**9** (3′-Cl)	1:1:1.5	56
6	**6j**	*o*-Cl	COOEt	**8** (4-Cl)/**9** (2′-Cl)	≤1:10	64
7	**6k**	*p*-Me	COOEt	**8** (6-Me)/**9** (4′-Me)	1:1	77
8	**6l**	*m*-Me	COOEt	**8** (5-Me)/**8** (7-Me)/**9** (3′-Me)	11:10:1	77
9	**6m**	*o*-Me	COOEt	**8** (4-Me)/**9** (2′-Me)	9:1	79
10	**6d**	*p*-OMe	COOEt	**8** (6-MeO)/**9** (4′-OMe)	3:7	84
11	**6n**	*m*-OMe	COOEt	**8** (5-OMe)/**8** (7-OMe)/**9** (3′-OMe)	15:1:−	96
12	**6o**	*o*-OMe	COOEt	**8** (4-OMe)/**9** (2′-OMe)	≤1:25	69
13	**6p**	*m*-CN	COOEt	**8** (5-CN)/**8** (7-CN)/**9** (3′-CN)	≤1:≤1:20	54
14	**6q**	*p*-CN	COOEt	**8** (6-CN)/**9** (4′-CN)	≤1:15:−[e]	57[e]
15	**6r**	*p*-NO_2	Me	**8** (6-NO_2)/**9** (4′-NO_2)	≤1:25	71
16	**6s**	*m*-CN	Me	**8** (5-CN)/**8** (7-CN)/**9** (3′-CN)	≤1:≤1:20	64
17	**6t**	*m*,*m*-di-OMe	Me	**8** (5,7-OMe)/**9** (3′,5′-OMe)	≥25:1	81
18	**6u**	*m*-Cl	Me	**8** (5-Cl)/**8** (7-Cl)/**9** (3′-Cl)	1: 1:5	75

[a]Crude ratio calculated by ^{1}H NMR analysis. [b]Isolated product yields are reported for the products after silica gel chromatographic purification. [c]Compounds **8**/**9** were not detected by ^{1}H NMR analysis, and only the isomerized product **17** was obtained (≥25:1). [d]^{1}H NMR analysis of the crude product, prior to purification on silica gel, revealed a 1: 2.2 ratio of **9** and **17** (R^1 = 4′-Cl), with none of compound **8** detectable. However, only compound **17** was isolated following silica gel column chromatographic purification. [e]The 1*H*-indene **9** was isolated prior to purification on silica gel. Purification resulted in a 1:1 mixture of **9**/**17**.

framework (i.e., R^2). A systematic examination of methyl, methoxy, chloro, and nitro groups at the *ortho*, *meta*, and *para* positions of **6** (R^2 = COOEt) was first undertaken (Table 3, entries 1−12). The indene products incorporated the substituents either in the indene ring as for **8**, or in the exocyclic aryl ring for **9** and **17**, with **17** resulting through alkene isomerization of **9**. Formation of **17** rather than **9** generally occurred for the more electron-deficient cases.

For the *para*-substituted cases, cyclization occurred preferentially through the unsubstituted ring for the nitro-, chloro-, and cyano-substituted compounds to give the 4′-substituted products **9** and/or **17** (Table 3, entries 1, 4, and 14). Isomerized product **17** (R^1 = NO_2) was obtained in the case of the more electron-deficient nitro-substituted system, while a 1:1 mixture of **9**/**17** (R^2 = COOMe, R^1 = 4′-CN) was obtained in the cyano-substituted case. In the latter case, only the unisomerized product **9** was observed by ^{1}H NMR analysis of the crude reaction mixture prior to chromatographic purification. Reaction of the *p*-methyl-substituted substrate **6** was unselective, leading to a 1:1 mixture of the 6-substituted indene **8** and the 4′-substituted indene **9** (Table 3, entry 7). Interestingly the more electron-donating *p*-methoxy-substituted substrate **6** underwent cyclization with a modest preference for formation of the 4′-substituted over the 6-substituted indenes (Table 3, entry 10). For the *o*-nitro-, chloro-, and methoxy-substituted cases, cyclization occurred preferentially through the unsubstituted phenyl ring, leading to the 2′-substituted compounds **17**/**9** (R^1 = 2′-NO_2, Cl, OMe) (Table 3, entries 3, 6, and 12). However, reaction of *o*-methyl-substituted **6** led to the selective formation of **8** (R^1 = 4-Me) over **9** (R^1 = 2′-Me) (Table 3, entry 9).

For the *meta*-substituted cases, three possible cyclization modes are possible. Cyclization onto the substituted aryl ring leads to either the 5- or 7-substituted indenes **8**, whereas cyclization through the unsubstituted phenyl ring leads to the 3′-substituted indene **9**. Once again, the presence of the strongly electron-withdrawing nitro or cyano groups resulted in selective cyclization to **17**/**9** (R^1 = 3′-NO_2 or CN) (Table 3, entries 2 and 13). Reaction of **6** (R^1 = *m*-Cl) was unselective, leading to a mixture of the 5-, 7-, and 3′-substituted indenes (Table 3, entry 5). Reaction of **6** (R^1 = *m*-Me) showed poor selectivity between **8** (R^1 = 5-Me or 7-Me) and **9** (R^1 = 3′-Me), although in this case the selectivity for the 7- over the 5-substituted indenes **8** was high (Table 3, entry 8). In contrast, reaction of **6** (R^1 = *m*-OMe) was highly selective, leading to a 15:1 ratio of the 5- and 7-substituted indenes **8**, with none of **9** (R^1 = 3′-OMe) being detected (Table 3, entry 11).

Similar trends were observed in the cyclizations of 2-Me-substituted precursors **6** (R^2 = Me) (Table 3, entries 15−18). Once again, the presence of strongly electron-withdrawing nitro or cyano groups led to preferential cyclization through the unsubstituted phenyl ring (Table 3, entries 15 and 16). Reaction of the di-*m*-OMe substituted **6** (R^2 = Me) led to exclusive formation of 5,7-di-OMe-substituted

(24) For unsymmetrical substituted 1-phenylallyl and 1,3-diphenylallyl systems containing alkyl and aryl substitutions along the allyl backbones that undergo regioselective cyclizations via an allyl cation, see: (a) Guo, S.; Liu, Y. *Org. Biomol. Chem.* **2008**, *6*, 2064–2070. (b) Xi, Z.; Guo, R.; Mito, S.; Yan, H.; Kanno, K.; Nakajima, K.; Takahashi, T. *J. Org. Chem.* **2003**, *68*, 1252–1257.

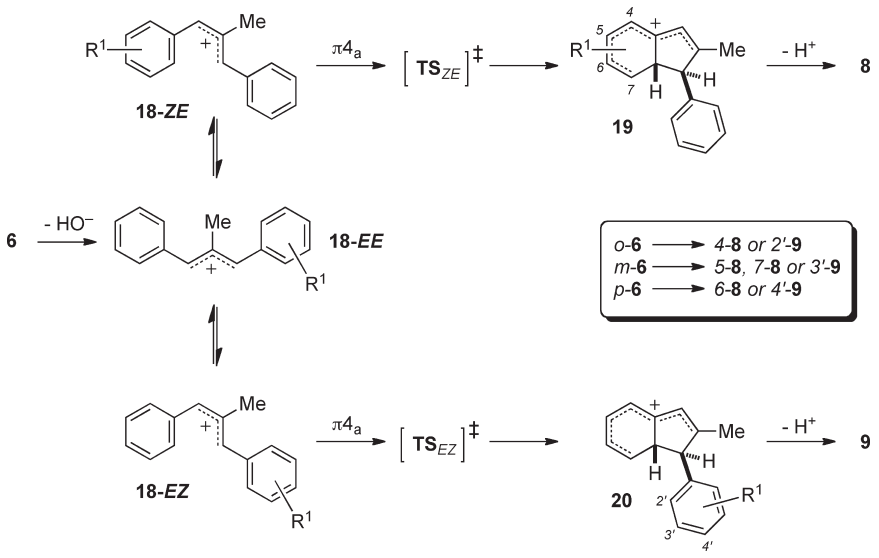


FIGURE 2. Mechanistic scheme for the formation of monosubstituted arylindenes **8/9**.

8 (R^2 = Me) (Table 3, entry 17). The cyclization of *m*-chloro-substituted **6** (R^2 = Me, R^1 = *m*-Cl) led to a mixture of the 5-Cl- and 7-Cl-substituted isomers of **8** and the 3′-Cl-substituted **9** (Table 3, entry 18). The selectivity for this reaction, favoring the *exo*-substituted product **9** (R^2 = Me, R^1 = 3′-Cl) over **8** (R^2 = Me, R^1 = 5-Cl or 7-Cl), is higher than that obtained for the corresponding *m*-Cl-2-COOEt-substituted compound **6** (i.e., Table 3, entry 5).

Isomerization of the double bond in the indene ring of **8**/**9** to give **17** was observed only for those substrates containing a central 2-COOEt ester substituent (Table 3, entries 1−4 and 14). One known mechanism for indene isomerization involves consecutive 1,5-hydrogen shifts, although this usually occurs at higher temperatures (> 100 °C).[25] However, since isomerization only occurs for more electron-deficient substrates, a more plausible alternative is that for the initially formed indene products bearing a 2-COOEt ester substituent group and an electron-deficient exocyclic aryl ring at the 1-position (i.e., **9**, R^2 = NO_2 or CN), the increased acidity of the dibenzylic C(1)−H proton facilitates a base catalyzed isomerization via an indenyl anion to give the more thermodynamically stable isomerized adducts **17**.[26] This is supported by the observation that in unsuccessful attempts to achieve conjugate addition reactions with the α,β-unsaturated ester moiety of **8/9** (R^1 = COOEt) using several traditional nucleophiles of varying basicity, only isomerization products **17** were isolated.[27]

One of the main goals of this study was to establish whether the selectivity of cyclization of substituted **6** would parallel those anticipated based on substituent effects for electrophilic aromatic substitution, in this case an intramolecular reaction, or whether other effects would be important because of the electrocyclic nature of the cyclization. The chemoselectivity of cyclization is presumably controlled by the respective transition-state barriers for cyclization, since subsequent proton loss to the product indenes should be rapid and irreversible. A cursory examination of reaction selectivity for formation of **8** versus **9** reveals that the presence of electron-withdrawing nitro or cyano substituents on **6** strongly disfavors cyclization onto the substituted ring, resulting in formation of **9**. This observation is perhaps not unexpected, and is consistent with what would be expected for an electrophilic aromatic substitution reaction. However, the presence of electron donating groups such as methyl or methoxy results in cyclization to either the substituted or unsubstituted ring of **6**, depending upon whether the substituent is at the *ortho, meta*, or *para* position. Overall, the results obtained for the chloro-, methyl-, and methoxy-substituted substrates **6** cannot be readily correlated with trends in reactivity that would be expected from a comparison with the substituent group effects on intermolecular electrophilic aromatic substitution or through the use of linear free energy relationships (using σ or σ^+ values).

An understanding of the chemoselectivity of cyclization was established through consideration of a DFT (B3LYP/6-31G*) computational study of the gas-phase transition state barrier for electrocyclization of the substituted cation **18** (R^2 = Me, R^1 = *o*-, *m*-, and *p*-NO_2, -Cl, -OMe, and -Me) into **19** via $\mathbf{TS_{ZE}}$ and for the cyclization of **18** into **20** via $\mathbf{TS_{EZ}}$ (Figure 2). Again, for this study it was assumed that since all of the species are cationic the effects of solvation would be anticipated to be roughly similar within each series. Therefore, calculations were conducted in the gas phase and do not explicitly include solvation effects. The transition-state barriers leading to the formation of **19** and **20** are calculated as the difference in energy (corrected for ZPVE or free energy/ZPVE) in kcal mol^{-1} between $\mathbf{TS_{ZE}}$ and **18-*EE*** and $\mathbf{TS_{EZ}}$ and **18-*EE***, respectively (Table 4). The difference in energy between the calculated transition states $\mathbf{TS_{ZE}}$ and $\mathbf{TS_{EZ}}$

(25) (a) Roth, W. R. *Tetrahedron Lett.* **1964**, *5*, 1009–1013. (b) Jones, D. W.; Marmon, R. J. *J. Chem. Soc., Perkin Trans. 1* **1993**, *6*, 681–690. (c) 1,5-Hydrogen shifts were observed with verbenindene derivatives at 115 °C in pyridine. See: Rupert, K. C.; Liu, C. C.; Nguyen, T. T.; Whitener, M. A.; Sowa, J. R. *Organometallics* **2002**, *21*, 144–149.

(26) (a) Friedrich, E. C.; Taggart, D. B. *J. Org. Chem.* **1975**, *40*, 720–723. (b) Bergson, G. *Acta Chem. Scand.* **1963**, *17*, 2691–2700. (c) Bergson, G.; Weidler, A.-M. *Acta Chem. Scand.* **1963**, *17*, 1798–1799. (d) Bergson, G.; Weidler, A.-M. *Acta Chem. Scand.* **1963**, *17*, 862–864.

(27) Attempted conjugate addition of indene **8c** with thiophenol (in the presence of 12 mol % of NEt_3) and sodium dimethylmalonate and indene **8d**/**9d** (*p*-OMe) with morpholine (in the presence of 150 mol % of *i*-Pr_2NEt) resulted in complete isomerization of the double bond. See the Supporting Information for details.

TABLE 4. Transition-State Barrier (in kcal mol^{-1}) Calculated [B3LYP/6-31G* + ZPVE (B3LYP/6-31G* + G)][a] for the Difference in Energy between TS[b,c] and the Respective 18-*EE* and Internuclear Distances (C7a−C1) for TS

transition state barrier[a,c]	R = H	R = NO_2	R = Cl	R = Me	R = OH
$\mathbf{TS}_{ZE}$ (*p*-6)	17.8 (18.6) (2.035 Å)	18.6 (19.7) (2.016 Å)	20.2 (21.1) (2.009 Å)	18.8 (19.6) (2.030 Å)	22.6 (23.3) (1.961 Å)
$\mathbf{TS}_{EZ}$ (*p*-4′)	17.8 (18.6) (2.035 Å)	16.9 (17.7) (2.076 Å)	18.5 (19.3) (2.037 Å)	18.8 (19.1) (2.018 Å)	20.4 (21.3) (1.983 Å)
$\mathbf{TS}_{ZE}$ (*m*-5)	17.8 (18.6) (2.035 Å)	21.2 (22.1) (1.990 Å)	16.7 (17.6) (2.074 Å)	16.0 (16.9) (2.087 Å)	13.5 (14.4) (2.159 Å)
$\mathbf{TS}_{ZE}$ (*m*-7)	17.8 (18.6) (2.035 Å)	18.8 (20.1) (1.956 Å)	16.7 (17.8) (2.059 Å)	16.6 (17.6) (2.090 Å)	14.3 (14.5) (2.146 Å)
$\mathbf{TS}_{EZ}$ (*m*-3′)[d]	17.8 (18.6) (2.035 Å)	17.2 (18.0) (2.070 Å)	17.4 (17.5) (2.062 Å)	18.3 (19.4) (2.037 Å)	17.9 (18.8) (2.055 Å)
$\mathbf{TS}_{ZE}$ (*o*-4)	17.8 (18.6) (2.035 Å)	19.6 (19.6) (2.019 Å)	18.5 (19.6) (2.026 Å)	16.3 (17.3) (2.037 Å)	21.3 (22.2) (2.012 Å)
$\mathbf{TS}_{EZ}$ (*o*-2′)[d]	17.8 (18.6) (2.035 Å)	15.6 (17.6) (2.120 Å)	16.8 (17.6) (2.054 Å)	18.0 (19.2) (2.025 Å)	17.0 (18.4) (2.060 Å)

[a]Transition-state barriers were determined as the difference of calculated energies (B3LYP/6-31G*) between **TS** and **18-*EE*** and are ZPVE corrected. Values in parentheses were determined by the difference of calculated free energies between **TS** and **18-*EE*** (B3LYP/6-31G* + G, where G = free energy including ZPVE correction). [b]Transition states were confirmed by identifying only one imaginary frequency. [c]Each transition state **TS** is followed by a letter-number combination in brackets. The letter refers to the position of substitution (i.e., ortho, meta or para) on the corresponding precursor cation **18**, and the letter refers to the position of substitution on either the indene ring system (i.e., 4-, 5-, 6- or 7-substituted) or the exocylic aromatic ring (i.e., 2′-, 3′- or 4′-substituted) of **TS**/**19**/**8**/**20**/**9**. [d]Only data for the lowest energy conformation is shown (i.e., rotamer).

TABLE 5. Calculated[a] and Observed[b] Product Ratios for the Formation of 8 and 9 from Substituted Ortho-, Meta-, and Para-Monosubstituted 6

selectivity **6** → indene **8**:**9**	R = NO_2	R = Cl	R = Me	R = OH[c] (OMe)[d]
p-**6** → 6-**8**: 4′-**9** (calcd)	1:16 (1:28)	1:17 (1:19)	1.1:1 (2.2:1)	1:44[c] (1:29)[c]
p-**6** → 6-**8**: 4′-**9** (obsd)	≤1:25	1:18	1:1	1:2.3[d]
m-**6** → 5-**8**: 7-**8**: 3′-**9** (calcd)	1:61:870 (1:32:1100)	3.2:2.8:1 (1.5:1:1.7)	45:16:1 (62:22:1)	1700:450:1[c] (1700:1400:1)[c]
m-**6** → 5-**8**: 7-**8**: 3′-**9** (obsd)	≤1:≤1:25	1:1:1.5[e]	11:10:1	15:1:0[d]
o-**6** → 4-**8**: 2′-**9** (calcd)	1:810 (1:210)	1:20 (1:26)	20: 1 (27:1)	1:1400[c] (1:590)[c]
o-**6** → 4-**8**: 2′-**9** (obsd)	≤1:25	1:10	9:1	≤1:25[d]

[a]Calculated ratio estimated on the basis of $\Delta\Delta E^{\ddagger}$ which is equivalent to the energy difference between the ZPVE corrected transition-state energies for $\mathbf{TS}_{ZE}$ and $\mathbf{TS}_{EZ}$ leading to **8** (R^2 = Me) and **9** (R^2 = Me), respectively (see Table 4). Values in parentheses are determined on the basis of $\Delta\Delta G^{\ddagger}$, which is equivalent to the free energy difference between $\mathbf{TS}_{ZE}$ and $\mathbf{TS}_{EZ}$ leading to **8** (R^2 = Me) and **9** (R^2 = Me), respectively (see Table 4). The selectivity was then estimated using $\exp(-\Delta\Delta E^{\ddagger}/RT)$ or $\exp(-\Delta\Delta G^{\ddagger}/RT)$ at 298.15 K. [b]Observed ratio determined for ester-derived products **8** (R^2 = COOEt) and **9** (R^2 = COOEt). The observed ratios were determined by analyzing the integration of the vinylic protons (H-3) or benzylic protons (H-1) in the ^{1}H NMR of the crude reaction mixture. [c]Calculated ratio determined for OH substituted compounds. [d]Observed ratio for the OMe-substituted compounds (R^2 = COOEt). [e]An observed ratio of 1:1:5 was obtained for the R^2 = Me substituted compounds.

(Table 4) can be used to estimate the kinetic selectivities for the formation of the substituted compounds **8** versus **9** (Table 5). In general, there is good agreement between the estimated selectivities based upon the ZPVE-corrected transition-state energies (or the free energy/ZPVE-corrected transition-state energies) of $\mathbf{TS}_{ZE}$ and $\mathbf{TS}_{EZ}$ and the experimentally determined ratios of **8**/**9** (Table 5). Despite the approximations made in the calculations (i.e., the lack of solvent corrections and the replacement of a COOEt for a methyl group for the observed and computational studies), the computed selectivities are in generally good agreement with the observed selectivities. This provides some support for the hypothesis that the chemo- and regioselectivity of the reactions are determined by the relative rates of the respective electrocyclization reactions (**18-*EE*** into **19** and **18-*EE*** into **20**). Furthermore, there is a correlation between the internuclear distance C7a−C1 and the calculated transition-state barrier on varying substituents at a specific position for cyclization (Table 4). Thus, as the activation energy increases the internuclear distance C7a−C1 in the respective **TS** decreases, consistent with late transition states.

The *ortho*/*para*- or *meta*-selectivity of electrophilic aromatic substitution is often rationalized in terms of electron density at the positions around the ring, with positions of higher electron density reacting more rapidly. However, calculated electron densities for the substituted ground-state cations **18-*EE***, **18-*EZ***, or **18-*ZE*** did not correlate with the positional selectivity for cyclization to **8** versus **9**. Similarly, examination of the HOMOs for these species did not reveal any obvious correlation with the selectivity of cyclization.

The calculated and observed selectivity for cyclization of *meta*-substituted **6** to 5- or 7-substituted indenes **8** versus 3′-substituted **9** decreases along the series OH (OMe) > Me > Cl > NO_2 (Table 5), which parallels the decreasing electron-donating ability of these substituents. This can be rationalized in terms of the decreasing ability of these groups to stabilize intermediate **19** and transition state $\mathbf{TS}_{ZE}$ over **20** and $\mathbf{TS}_{EZ}$ along the series. For each of the substituents investigated, the highest selectivity for formation of **8** over **9** occurred from *m*-**6** rather than *o*-**6** or *p*-**6**. The calculated and observed selectivities for cyclization of *ortho*-substituted **6** to 4-substituted indene **8** versus 2′-substituted **9** decreases along the series Me > Cl > NO_2 ≳ OH (Table 5). This trend does not correlate with overall electron-donating ability of these groups, presumably because resonance stabilization of **19** and $\mathbf{TS}_{ZE}$ is not significant. Instead, the trend in selectivity can be rationalized in terms of the increasing inductive withdrawing group ability along the series (group electronegativities[28] for CH_3 = 2.3, Cl = 3.0, NO_2 = 3.4, OH = 3.7), which would in turn lead to increasing destabilization of intermediate **19** and transition state $\mathbf{TS}_{ZE}$ (relative to **20** and $\mathbf{TS}_{EZ}$). The selectivities for cyclization of *para*-substituted **6** to 6-substituted indene **8** versus 4′-substituted **9** decrease along the series (calculated) Me > Cl ∼ NO_2 > OH or (observed) Me > OMe > Cl > NO_2 (Table 5). These trends parallel those of the *ortho*-substituted series, although the selectivity differences for the reactions of *para*-substituted **6** substrates are less pronounced than for the corresponding *ortho*-substituted substrates. The observed cyclization selectivity for *p*-**6** never favors formation of **8** over **9**, which also contrasts with the reactions of the *ortho*-substituted substrates. The highest selectivity for formation of **8** over **9** from *o*-**6** or *p*-**6**

(28) Wells, P. R. *Prog. Phys. Org. Chem.* **1968**, *6*, 111–145.

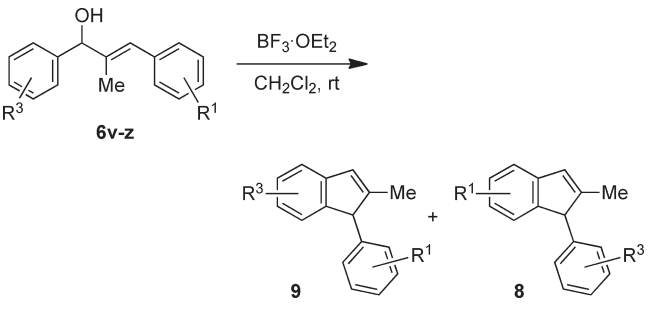
occurs for the methyl-substituted cases, with ratios of **8**:**9** of 1:1 for cyclization of **6k** (*p*-Me) and 9:1 for cyclization of **6m** (*o*-Me).

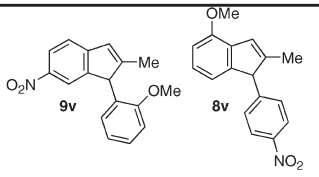
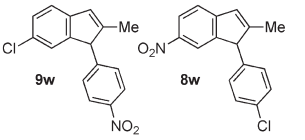
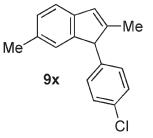
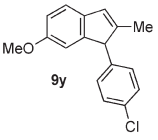
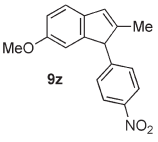
Cyclization of *meta*-substituted **6** onto the substituted aryl ring can give two possible regioisomers, 5-**8** and 7-**8**. The observed regioselectivity for 5-**8** over 7-**8** is about 1:1 for both the chloro- and methyl-substituted examples but favors the 5-isomer for the methoxy-substituted case (15:1). The calculated regioselectivity decreases along the series OH ≳ Me > Cl > NO_2, which correlates with decreasing electron-donating ability of the substituents, rather than substituent size (e.g., *A* value) or calculated electron densities on the aromatic carbons that undergo cyclization.

The results outlined in Tables 3 and 5 provide a guide to the directing group effects of various aryl substituents. Further study then focused upon substrates in which both aryl rings of the 1,3-diarylallyl alcohols were substituted (Table 6). 2-Methyl-substituted substrates **6v**−**z** were chosen since the synthetic protocol used for their preparation is higher yielding than that used for 2-COOEt-substituted precursors and the indene products formed would not undergo double-bond isomerization. In addition, the results obtained for the monosubstituted precursors **6** had shown that the directing group influences of the aryl substituents were not strongly affected by the central 2-substituent (i.e., 2-COOEt vs 2-Me). *o*-OMe/*p*-NO_2-substituted precursor **6v** underwent regioselective cyclization, preferentially leading to 4-OMe-substituted indene **9v** in moderate yield (Table 6, entry 1). Although both substituents are deactivating toward electrocyclization, the directing group influence of the *p*-NO_2 group outweighs that of the *o*-OMe group, leading to cyclization through the *o*-OMe-substituted ring. Unexpectedly, even though a *p*-NO_2 group might be expected to be substantially more deactivating than a *p*-Cl group, cyclization of *p*-NO_2/*p*-Cl-substituted **6w** was less selective, giving a 4:1 mixture of the 1*H*-indenes **9w** and **8w** prior to chromatography (Table 6, entry 2). Introduction of a deactivating *p*-Cl substituent in **6x** enabled regioselective cyclization to **9x** (Table 6, entry 3), even though a *p*-Me group had been shown to exert little directing influence in the cyclization of **6k** (Table 6, entry 7). Although both *p*-Cl and *p*-OMe aryl substituents are deactivating, the greater deactivating character manifested by the *p*-Cl over the *p*-OMe group resulted in the regioselective formation of the 6-OMe-substituted indene **9y** from **6y** (Table 6, entry 4). Finally, reaction of *p*-NO_2/*p*-OMe-substituted **6z** at room temperature led to two products: 6-OMe-substituted **9z** and an initially unidentified dimeric compound **21**. However, reaction of **6z** at 100 °C in toluene led to the formation of **9z** in moderate yield (Table 6, entry 5).

Further investigation of the reaction of **6z** at a lower temperature (−20 °C) resulted in the exclusive formation of the dimeric side product **21** in 88% yield (Scheme 5). The cyclopenta[*a*]indene structure of dimer **21** was elucidated from a combination of homonuclear and heteronuclear 2D NMR experiments.[29] A plausible mechanism for the formation of **21** involves a cationic domino or cascade annulation sequence. Thus, regio- and diastereoselective trapping of the allylic cation **22**[30] by in situ generated indene **9z** to give an intermediate tertiary carbocation **23**, followed by intramolecular cyclization to the cation **24**, and selective elimination would provide the **21**. The formation of **21** is an example of a formal [2π + 2π] cycloaddition.[31] The remarkable selectivity exhibited in the formation of **21** can be rationalized, in part, by attack of indene **9z** from the less hindered face onto the more electron-deficient position of the allylic cation **22**.

TABLE 6. Electrocyclization of Disubstituted 1,3-Diarylallyl Alcohols 6



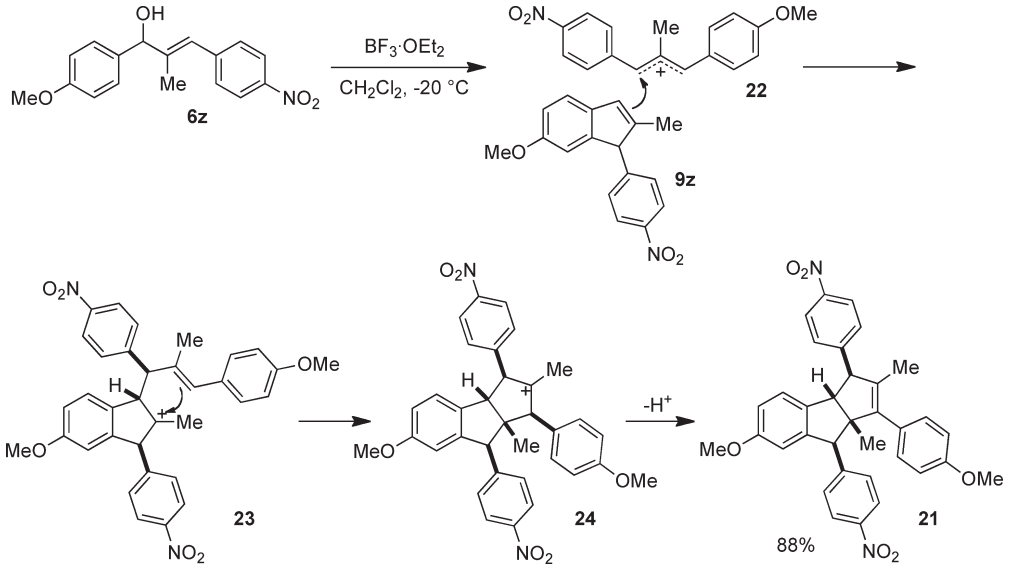
entry	R^1	R^3	product	% yield (**9**:**8**)[a]
1	2-OMe	4-NO_2		50[b] (1 : 1.8)[c] (1 : 1.2)[d]
2	4-NO_2	4-Cl		64 (4 : 1)[e] (6 : 1)[f]
3	4-Cl	4-Me		88 (≥10 : 1)
4	4-Cl	4-OMe		72 (≥8 : 1)
5	4-NO_2	4-OMe		45[b] (≥10 : 1)

[a]Crude ratio calculated from crude ^{1}H NMR analysis. [b]Addition of $BF_3 \cdot OEt_2$ at 100 °C in toluene. [c]The corresponding 1*H*-indenes **9v** (6-NO_2, 2′-OMe,) and **8v** (4-OMe, 4′-NO_2) were observed in a 1:1.8 ratio prior to purification. [d]The isomerized 3*H*-indenes **17v** (6-NO_2, 2′-OMe) and (4-OMe, 4′-NO_2) were isolated in a 1:1.2 ratio following silica gel column chromatographic purification. [e]The corresponding 1*H*-indenes **9w** (6-Cl, 4′-NO_2) and **8w** (6-NO_2, 4′-Cl) were observed in a 4:1 ratio prior to purification. [f]The isomerized 3*H*-indenes **17w** (6-Cl, 4′-NO_2 and 6-NO_2, 4′-Cl) were isolated in a 6:1 ratio following silica gel column chromatographic purification.

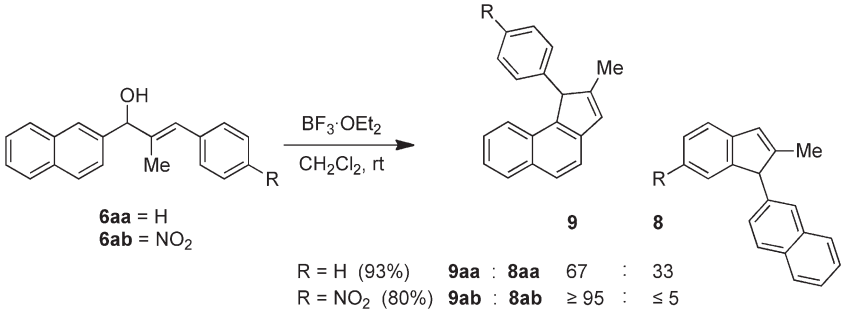
(29) See the Supporting Information for a detailed analysis of the 2D NMR experiments.

(30) For studies on regioselective additions to unsymmetrical 1,3-diarylallylic cations, see: Watts, W. E.; Easton, A. M.; Habib, M. J. A.; Park, J. *J. Chem. Soc., Perkin Trans. 2* **1972**, *15*, 2290–2297.

SCHEME 5. Plausible Mechanism for the Domino Electrocyclization/Formal [2π + 2π] Cycloaddition/Dimerization of Alcohol 6z to 21



SCHEME 6. Electrocyclization Pathways for 2-Naphthylallyl-Substituted Substrates



Subsequent cyclization of **23** to the *cis*-fused [3.3.0] ring system **24** followed by proton loss would then give **21**.[32] The high regioselectivity exhibited for the trapping of cation **22** by **9z** is surprising since kinetic studies of the substitution of differentially substituted allylic cations **7** (R^2 = H) reveal little difference between the rates of trapping of the two allylic positions of **7**.[22b] The temperature-dependent formation of **21** at low temperature and **9z** at high temperature presumably results because the longer lifetime of the allylic cation **22** at lower temperatures enables intermolecular trapping by the in situ generated indene **6z**, whereas at higher temperatures the rate of electrocyclization of **22** is faster than the more entropically disfavored intermolecular trapping reaction.

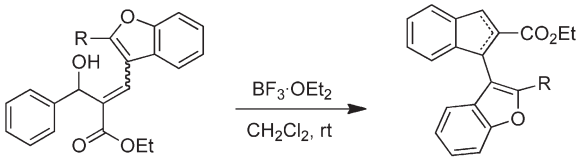
Reaction of naphthylallyl alcohol precursors **6aa**/**6ab** under the Lewis acidic protocol also led to electrocyclization products (Scheme 6). Products corresponding to two of the three possible cyclization modes were isolated. In the case of the 1-(2-naphthyl)-3-phenylallyl alcohol, products **8aa** and **9aa** were obtained in a 1:2 ratio, favoring cyclization through the 1-position of the naphthyl ring. The modest selectivity favoring the latter is consistent with the greater resonance stabilization of the cation afforded by the naphthyl ring in the transition state. This chemoselectivity preference was much more pronounced for the reaction of substrate **6ab** bearing both a 2-naphthyl and a deactivated *p*-nitrophenyl ring, resulting in exclusive formation of **9ab**. For both substrates, however, cyclization through the naphthyl ring was highly regioselective, with the only observed products **9aa** and **9ab** obtained as a result of cyclization through the 1-position of the naphthyl ring, rather than through the 3-position of the naphthyl ring. This parallels the known electrophilic aromatic substitution reaction of naphthalene which kinetically favors substitution at the 1-position over the 2-position (which is equivalent to the 3-position).

Finally, we were interested in investigating the selectivity of a reaction of a substrate bearing both a phenyl and a heterocyclic aromatic ring (Scheme 7). The use of a benzofuran-derived system was of particular interest, since electrocyclization onto the benzofuran ring could potentially lead to the tetrahydrocyclopenta[*b*]benzofuran core of the rocaglamide series of natural products.[33] However, attempted reaction of the 3-substituted benzofuran **6ac** (R = H) led to a complex mixture of products, with 3*H*-indene **17ac**

(31) See, for example: (a) Klein, H.; Mayr, H. *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 1027–1029. (b) Miller, A.; Moore, M. *Tetrahedron Lett.* **1980**, *21*, 577–580. (c) Angle, S. R.; Arnaiz, D. O. *J. Org. Chem.* **1992**, *57*, 5937–5947. (d) Alesso, E.; Torviso, R.; Lantaño, B.; Erlich, M.; Finkielsztein, L. M.; Moltrasio, G.; Aguirre, J. M.; Brunet, E. *ARKIVOC* **2003**, *10*, 283–297.

(32) (a) The 1,2,3,3a,8,8a-hexahydrocyclopenta[*a*]indene core of **21** is found in the natural product pallidol. It was recently synthesized by a 4π-electrocyclization of a biaryl alcohol via a pentadienyl cation in the presence of TFA or TsOH; see: Snyder, S. A.; Zografos, A. L.; Lin, Y. *Angew. Chem., Int. Ed.* **2007**, *46*, 8186–8191. (b) Snyder, S. A.; Breazzano, S. P.; Ross, A. G.; Lin, Y.; Zografos, A. L. *J. Am. Chem. Soc.* **2009**, *131*, 1753–1765.

SCHEME 7. Electrocyclization Pathways for Benzofuran-Substituted Substrates 6ac and 6ad



(*E*)-**6ac** (R = H)
(*E*)-**6ad** (R = Ph)
(*Z*)-**6ad** (R = Ph)

17ac 10% (R = H)
9ad 86% (R = Ph)
9ad 85% (R = Ph)

isolated in 10% yield. Reaction of benzofuran **6ad** (R = Ph), either as the (*E*)- or (*Z*)-isomer, led to the indene product **9ad** (R = Ph) in good yield.

Conclusion

Selectivity effects in the cyclization reactions of 1,3-diaryl-substituted allylic cations to indenes have been experimentally and computationally examined. The presence of substituents on the aryl ring can affect the chemoselectivity of cyclization and for reactions of *meta*-substituted cases the regioselectivity of cyclization. In general, the presence of electron-withdrawing substituents disfavors cyclization onto this ring. The effects of electron-donating substituents are more complex and depend on whether the substituent is inductively or mesomerically electron donating and on the position of the substituent (*ortho*, *meta*, or *para*). Substituent effects are most pronounced at the *meta* position, with electron-donating substituents promoting cyclization onto the substituted ring. A simple gas-phase computational model (B3LYP/6-31G* + ZPVE or B3LYP/6-31G* + G) in which the selectivity is assumed to depend upon the relative rates of electrocyclization showed generally good agreement with experimental results. There was no obvious correlation of selectivity with electron densities as has been suggested for electrophilic aromatic substitution reactions. Transition-state structures are consistent with a cationic $\pi 4_a$ conrotatory electrocyclization mechanism.

In some cases for more electron-deficient systems, the product 1*H*-indenes underwent subsequent alkene isomerization to 3*H*-indenes, which likely occurs through a base-catalyzed isomerization rather than a consecutive 1,5-H shift mechanism. In one case, in which both aromatic rings were substituted, an interesting dimeric adduct resulting from a formal $2\pi + 2\pi$ cycloaddition of the allyl cation intermediate to the initially formed indene occurred. Reaction at higher temperatures prevented the formation of this adduct, suggesting that the longer lifetime of the cation at lower temperatures is required for the formal $[2\pi + 2\pi]$ cycloaddition to occur. Further studies on electrocyclization reactions and substituent effects will be reported in due course.

(33) (a) For chemistry and biological activity, see: Proksch, P.; Edrada, R.; Ebel, R.; Bohnenstengel, F. I.; Nugroho, B. W. *Curr. Org. Chem.* **2001**, *5*, 923–938. (b) For isolation and structure elucidation, see: King, M. L.; Chiang, C. C.; Ling, H. C.; Fujita, E.; Ochiai, M.; McPhail, A. T. *J. Chem. Soc., Chem. Commun.* **1982**, 1150. (c) For a recent total synthesis using a Nazarov cyclization of a pentadienyl cation, see: Malona, J. A.; Cariou, K.; Frontier, A. J. *J. Am. Chem. Soc.* **2009**, *131*, 7560–7561.

(34) Experimental data and spectra are given for a few selected examples of the indenes. Experimental data and spectra for all other compounds and precursors are given in the Supporting Information.

Experimental Section[34]

General Procedure for Indene Synthesis. To a solution of the arylallyl alcohol in CH_2Cl_2 (0.1 M) at room temperature, unless otherwise stated, was added $BF_3 \cdot OEt_2$ (1.0 equiv). The solution was stirred until the alcohol was fully reacted, as determined by TLC analysis. The solution was diluted with H_2O (2 mL) and saturated aqueous $NaHCO_3$ (2 mL) and extracted with CH_2Cl_2 (3 × 5 mL). The combined organic extracts were dried with Na_2SO_4, filtered, and concentrated in vacuo. Purification by flash chromatography on silica gel afforded pure indene.

2-Methyl-1-phenyl-1*H*-indene (8b)[35]. The general procedure for the synthesis of indenes from alcohol **6b** was followed. Without further purification, the indene (83 mg, 85%) was isolated as a white solid: mp 39−41 °C (lit.[35] mp 47.5−49 °C); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.18−7.29 (5 H, m), 7.11 (1H, d, J = 7.5 Hz), 7.04 (1H, dd, J = 7.5, 1.0 Hz), 6.99−7.03 (2H, m), 6.54 (1H, s), 4.29 (1H, s), 1.92 (3H, s); ^{13}C NMR (100 MHz, $CDCl_3$) δ 149.9 (C), 148.6 (C), 144.8 (C), 139.7 (C), 128.6 (CH), 128.2 (CH), 127.2 (CH), 126.72 (CH), 126.71 (CH), 124.2 (CH), 123.7 (CH), 119.8 (CH), 59.4 (CH), 15.2 (CH_3).

Ethyl 1-Phenyl-1*H*-indene-2-carboxylate (8c). The general procedure for the synthesis of indenes from alcohol **6c** was followed. Purification by flash chromatography on silica gel using a gradient elution of hexanes to 5% ethyl acetate in hexanes afforded the indene (30 mg, 89%) as a white solid: mp 87−88 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.79 (1H, dd, J = 2.0, 0.5 Hz), 7.50 (1H, d, J = 7.0 Hz), 7.14−7.32 (6H, m), 7.03−7.10 (2H, m), 4.84 (1H, d, J = 2.0 Hz), 4.04−4.22 (2H, m), 1.17 (3H, t, J = 7.0 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.2, 150.4, 141.8, 141.2, 138.4, 128.4, 128.2, 127.9, 127.8, 127.2, 126.8, 124.4, 123.3, 60.2, 55.7, 14.1; MS (EI) m/z (rel intensity) 264 (42), 192 (27), 191 (100), 189 (24), 165 (11); HRMS (EI) m/z Calcd for $C_{18}H_{16}O_2$ [M^+] 264.1150, found 264.1155.

Ethyl 4-Methyl-1-phenyl-1*H*-indene-2-carboxylate (8m) and Ethyl 1-(2-Methylphenyl)-1*H*-indene-2-carboxylate (9m). The general procedure for the synthesis of indenes from alcohol **6m** was followed. Purification by flash chromatography on silica gel using 10% ethyl acetate in hexanes afforded a 9:1 mixture of the 4-Me and 2′-Me isomer (75 mg, 85%) as white crystals, mp 78−79 °C. Characterization data is reported for the 4-Me isomer only: IR (thin film) ν_{max} 3050, 3014, 2968, 1710, 1600, 1566, 1494, 1448, 1360, 1301, 1239, 1186, 1080, 1024, 771, 737, 693 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 (1H, dd, J = 2.5, 0.5 Hz), 7.15−7.25 (2H, m), 7.14 (2H, t, J = 8.0 Hz), 7.04−7.14 (3H, m), 7.01 (1H, d, J = 7.0 Hz), 4.81 (1H, d, J = 0.5 Hz), 4.05−4.22 (2H, m), 2.50 (3H, s), 1.17 (3H, t, J = 7.0 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.6 (C), 150.7 (C), 141.3 (C), 140.5 (C), 139.9 (CH), 138.9 (C), 133.2 (C), 128.7 (CH), 128.6 (CH), 128.5 (CH), 128.1 (CH), 127.0 (CH), 122.1 (CH), 60.4 (CH_2), 56.1 (CH), 18.7 (CH_3), 14.3 (CH_3); MS (EI) m/z (rel intensity) 279 (13), 278 (57), 206 (25), 205 (100), 203 (14), 202 (14), 189 (12); HRMS (EI) m/z calcd for $C_{19}H_{18}O_2$ [M^+] 278.1307, found 278.1304.

5,7-Dimethoxy-2-methyl-1-phenyl-1*H*-indene (8t). The general procedure for the synthesis of indenes from alcohol **6t** was followed. Without any further purification, the indene (65 mg, 69%) was isolated as pale yellow crystals: mp 93−94 °C; IR (thin film) ν_{max} 3003, 2921, 2839, 1585, 1486, 1449, 1425, 1337, 1279, 1201, 1133, 1092, 1041, 871, 817, 702 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.12−7.25 (3H, m), 7.10 (2H, dd, J = 8.0, 1.5 Hz), 6.50 (1H, d, J = 2.0 Hz), 6.39 (1H, t, J = 1.5 Hz), 6.21 (1H, d, J = 2.0 Hz), 4.32 (1H, s), 3.81 (3H, s), 3.57 (3H, s), 1.83 (3H, d, J = 1.0 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.2, 155.9, 152.2, 147.5, 139.7, 128.4, 128.2, 127.5, 126.8, 126.4, 98.1, 95.6, 57.3,

(35) (a) Tolbert, L. M. *J. Org. Chem.* **1979**, *44*, 4584–4588. (b) Ming-Yuan, L.; Madhushaw, R. J.; Liu, R.-S. *J. Org. Chem.* **2004**, *69*, 7700–7704.

55.7, 55.6, 15.4; MS (EI) m/z (rel intensity) 266 (100), 251 (58), 235 (10), 189 (10), 165 (10), 84 (10); HRMS (EI) m/z calcd for $C_{18}H_{18}O_2$ [M^+] 266.1307, found 266.1303.

Ethyl 1-(2-Chlorophenyl)-1*H*-indene-2-carboxylate (9j). The general procedure for the synthesis of indenes from alcohol **6j** was followed. Purification by flash chromatography on silica gel using a gradient elution of 5−10% ethyl acetate in hexanes afforded the indene (60 mg, 64%) as white crystals: mp 44−45 °C; IR (thin film) ν_{max} 3062, 2979, 2887, 1709, 1569, 1472, 1367, 1331, 1296, 1244, 1190, 1078, 1035, 751 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.86 (1H, d, J = 2.0 Hz), 7.52 (1H, dd, J = 8.0, 1.0 Hz), 7.46 (1H, d, J = 8.0 Hz), 7.23−7.35 (3H, m), 7.12 (1H, t, J = 7.0 Hz), 6.98 (1H, t, J = 7.0 Hz), 6.53 (1H, d, J = 7.0 Hz), 5.56 (1H, s), 4.04−4.23 (2H, m), 1.14 (3H, t, J = 7.0 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.3, 150.2, 142.4, 141.6, 141.3, 136.8, 134.8, 129.9, 128.6, 128.2, 127.6, 127.3, 127.2, 124.5, 123.8, 60.5, 51.6, 14.2; MS (EI) m/z (rel intensity) 300 (12), 298 (31), 263 (65), 235 (27), 227 (44), 226 (30), 225 (100), 190 (28), 189 (79); HRMS (EI) m/z calcd for $C_{18}H_{15}ClO_2$ [M^+] 298.0760, found 298.0766.

Ethyl 1-(2-Methoxyphenyl)-1*H*-indene-2-carboxylate (9o). The general procedure for the synthesis of indenes from alcohol **6o** was followed. Purification by flash chromatography on silica gel using 10% ethyl acetate in hexanes afforded the indene (31 mg, 69%) as a colorless oil: IR (thin film) ν_{max} 3067, 2976, 2935, 2835, 1707, 1596, 1567,1491, 1461, 1367, 1244, 1190, 1078, 1027, 756 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.83 (1H, d, J = 2.0 Hz), 7.49 (1H, d, J = 8.0 Hz), 7.14−7.30 (4H, m), 6.95 (1H, d, J = 7.5 Hz), 6.74 (1H, td, J = 7.5, 1.0 Hz), 6.63 (1H, dd, J = 7.5, 2.0 Hz), 5.45 (1H, d, J = 2.0 Hz), 4.05−4.22 (2H, m), 3.92 (3H, s), 1.16 (3H, t, J = 7.0 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.4 (C), 157.5 (C), 150.8 (C), 141.7 (C), 141.6 (C), 141.5 (CH), 141.1 (C), 128.0 (CH), 127.8 (CH), 127.1 (CH), 126.9 (CH), 124.2 (CH), 123.3 (CH), 120.7 (CH), 111.3 (CH), 60.1 (CH_2), 55.8 (CH_3), 48.8 (CH), 14.1 (CH_3); MS (ESI^+) m/z (rel intensity) 331 (30), 317 (84), 295 (10), 263 (24), 249 (100); HRMS (ESI) m/z calcd for $C_{19}H_{18}O_3$ [M + Na]$^+$ 317.1148, found 317.1147.

6-Methoxy-2-methyl-1-(4-nitrophenyl)-1*H*-indene (9z). The general procedure for the synthesis of indenes from alcohol **6z** was followed with the exception that the reaction was heated to 100 °C for 15 min. Purification by flash chromatography on silica gel using a gradient elution of 10−20% ethyl acetate in hexanes afforded the indene (27 mg, 45%) as a pale brown oil: IR (thin film) ν_{max} 2935, 2847, 1605, 1516, 1476, 1346, 1292, 1279, 1223, 1106, 1031, 852, 803, 741, 698 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.14 (2H, d, J = 8.5 Hz), 7.19 (1H, d, J = 8.0 Hz), 7.18 (2H, d, J = 8.5 Hz), 6.80 (1H, dd, J = 8.0, 2.5 Hz), 6.66 (1H, d, J = 2.0 Hz), 6.53 (1H, t, J = 1.5 Hz), 4.37 (1H, s), 3.73 (3H, s), 1.88 (3H, d, J = 1.5 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 157.9, 149.3, 148.8, 147.2, 146.4, 137.8, 129.2, 128.0, 124.3, 120.7, 112.6, 110.8, 59.0, 55.7, 15.3; MS (EI) m/z (rel intensity) 281 (100), 266 (27), 235 (8), 220 (9), 189 (11), 165 (7), 115 (5); HRMS (EI) m/z calcd for $C_{17}H_{15}NO_3$ [M^+] 281.1052, found 281.1057.

Ethyl 3-(2-Nitrophenyl)-1*H*-indene-2-carboxylate (17g). The general procedure for the synthesis of indenes from alcohol **6g** was followed. Purification by flash chromatography on silica gel using 20% ethyl acetate in hexanes afforded the indene (14 mg, 69%) as a yellow oil that solidified upon standing: mp 89−90 °C; IR (thin film) ν_{max} 3062, 2981, 1698, 1526, 1348, 1248, 1193, 1111, 1097, 853, 755, 740 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.20 (1H, dd, J = 8.5, 1.5 Hz), 7.70 (1H, td, J = 7.5, 1.0 Hz), 7.59 (2H, t, J = 7.0 Hz), 7.36−7.42 (2H, m), 7.30 (1H, td, J = 7.5, 1.0 Hz), 7.07 (1H, d, J = 7.5 Hz), 4.06 (2H, q, J = 7.0 Hz), 3.88 (2H, s), 1.06 (3H, t, J = 7.0 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.4 (C), 149.3 (C), 148.9 (C), 144.2 (C), 143.4 (C), 132.9 (CH), 131.6 (C), 131.0 (C), 130.8 (CH), 128.8 (CH), 128.1 (CH), 127.0 (CH), 124.4 (CH), 124.3 (CH), 121.9 (CH), 60.3 (CH_2), 39.1 (CH_2), 13.8 (CH_3); MS (ESI^+) m/z (rel intensity) 332 (72), 264 (100), 220 (38), 218 (20); HRMS (ESI) m/z calcd for $C_{18}H_{15}NO_4$ [M + Na]$^+$ 332.0893, found 332.0895.

Acknowledgment. The Natural Science and Engineering Research Council (NSERC) of Canada supported this work. C.D.S. thanks NSERC for a postgraduate scholarship (PGS D3). We thank Dr. A. B. Young for mass spectrometric analysis.

Supporting Information Available: Experimental procedures for the synthesis of enones, allylic alcohols, indenes, and **21**, characterization data for all new compounds, and copies of ^1H NMR and ^{13}C NMR spectra. Tables of optimized structures, energies, and Cartesian coordinates for ground-state and transition structures. This material is available free of charge via the Internet at http://pubs.acs.org.