Importance of the role of secondary orbital interactions in the Diels–Alder reaction. Regioselectivity in the catalyzed and uncatalyzed reactions of juglone and aliphatic dienes

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The regioselectivities in the uncatalyzed and catalyzed Diels–Alder (DA) reactions of juglone with piperylene (penta-1,3-diene) or 2,3-dimethylpenta-1,3-diene have been investigated, employing Lewis acids such as boron trifluoride (BF_3) and sterically hindered aluminium catalysts in order to verify the role of the secondary orbital interactions (SOI). While the results of the uncatalyzed and catalyzed reactions using BF_3 or aluminium trimethoxide agree with the prediction made by the frontier molecular orbital (FMO) theory considering SOI, steric repulsion of the aluminium catalysts causes orderly changes to the ratios of the product regioisomers, which could be interpreted by diminution of SOI. The transition states are located by AM1 calculations and their energies are estimated by CDNO/2-CI and *ab initio* 6-31G* calculations. The regioselectivities observed in the experiments are explained by comparison of their energies. A zwitterionic mechanism in the catalyzed reaction was strongly supported and the molecular orbital feature suggests the contribution of SOI which would stabilize the transition state to control the reaction pathway.

Introduction

The regioselectivity and the *endo*-selectivity (Alder–Stein rule) in the Diels–Alder (DA) reaction have been generally explained by the frontier molecular orbital theory (FMO theory).[1] The outline of this theory is that the primary orbital interactions chiefly control the regioselectivity of the reaction, according to the magnitudes of the HOMO or LUMO coefficients of the reactants, while the *endo*-selectivity is due to the secondary orbital interactions (SOI).[2] Many theoretical and experimental investigations have explored the role of SOI[3] and the stereoselectivity has been interpreted by considering the balance between SOI and steric requirements.[4] Alston *et al.*[5] pointed out that SOI were an important factor in orientation, when the differences between the magnitudes of the frontier orbital coefficients of the reaction sites were small but the differences between those of the adjacent non-bonding sites were much larger. Despite several reports[6] supporting Alston's suggestion, it seems to remain as yet uncertain, and has been treated as a temporary expedient. Our investigation in this paper was made to bring SOI into relief, considering molecular orbital calculations and steric effects, employing Lewis acid catalysts of various sizes in the DA reaction of 1-substituted aliphatic dienes [piperylene (penta-1,3-diene) and 2,3-dimethylpenta-1,3-diene][7] and juglone (5-hydroxy-1,4-naphthoquinone).[8,9] Although FMO theory and transition state theory (TS theory) have been treated as alternatives so far, because the large changes during the transition from the reactants to the transition states are beyond perturbation, in highly regioselective reactions, agreement of the predictions by both theories should be expected. As efficient interactions of FMOs would guarantee stabilization of the transition states, there may be a relationship between the orbital shapes of the transition states and the FMOs of the reactants. Therefore, we also investigated the transition states to compare those theories.

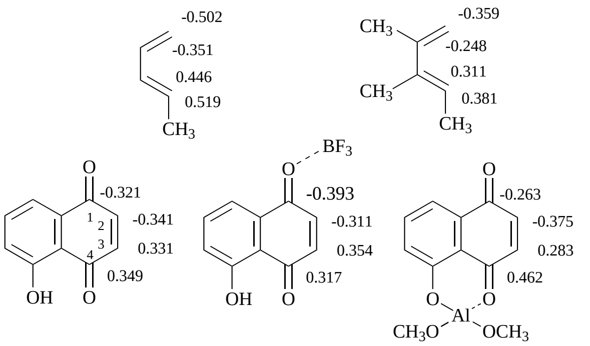


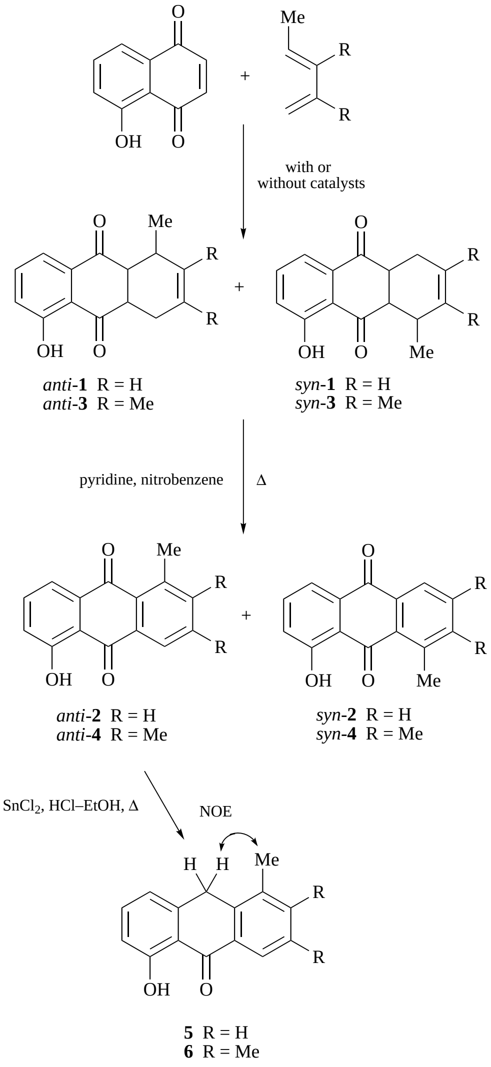
Fig. 1 The frontier orbital coefficients of dienes (HOMO) and juglones (LUMO) calculated by AM1

Results and discussion

Prediction of regioselectivity by FMO theory

The frontier orbital coefficients of piperylene, 2,3-dimethylpenta-1,3-diene, juglone and its complex with Lewis acids are shown in Fig. 1. The HOMO coefficients of piperylene have been calculated by various methods. The magnitudes of the coefficients of the terminal carbons in the diene moiety differed depending upon the calculation methods. INDO[5c] and CNDO/2[5c,7a] semiempirical methods gave larger magnitudes at the unsubstituted terminus than the substituted one, as an organic chemist would expect.[1] In contrast, MNDO, AM1[7b] (coefficient given in Fig. 1) and *ab initio* STO-3G[7b] showed the opposite results. Such discrepancy would be due to a different evaluation of donor character of the methyl group. However, all calculations agreed in that the differences between the coefficients of non-bonding sites were larger than those of the reaction sites, which made the reaction a suitable case to test whether SOI was significant in prediction of the orientations. 2,3-Dimethylpenta-1,3-diene showed a similar result.

In juglone, small differences in the magnitudes of the LUMO coefficients between the two reaction sites, C-2 and C-3, and the two carbonyl carbons, C-1 and C-4, were estimated by AM1. However, STO-3G gave a larger difference in coefficients between C-1 and C-4 due to intramolecular hydrogen bonding;[10] namely, −0.2359 at C-1, −0.3697 at C-2, 0.3345 at C-3 and 0.3091 at C-4 were estimated. Thus, preference of *syn*-adducts (Scheme 1), due to control of SOI, is expected in the uncatalyzed reactions of juglone with both dienes.



Scheme 1

The coordination of BF_3 (boron trifluoride) at C-1 oxygen, which gave a slightly lower LUMO energy than coordination at C-4 oxygen in STO-3G, showed reversal of the magnitudes of the LUMO coefficients; now the difference between C-1 and C-4 coefficients was much larger than that between C-2 and C-3. Such a drastic change in the LUMO coefficients by the coordination of Lewis acid has been described in an acrolein system.[11] The favourable coordination of BF_3 at C-1 has also been documented from a steric view point.[12] Thus, control by SOI predicts predominance of *anti*-adduct in the BF_3 catalyzed reaction.

Replacement of one ligand on aluminium trimethoxide with juglone can form an intramolecular coordination of the Lewis acid centre to C-4 oxygen.[13] This has the opposite effect on the magnitudes of the LUMO coefficients to BF_3-coordinated juglone, giving the *syn*-adduct preferentially. We used various aluminium catalysts with bulky aryloxy moieties[14] in experiments to verify the influence of the steric hindrance of the catalysts. In this calculation, aluminium trimethoxide was selected as a representative of aluminium catalysts to estimate the LUMO coefficients.

Consequently, all predictions are proposed typical cases where SOI rather than the primary interaction will govern the orientation. Because of a close relation between SOI and steric hindrance, the changes in the regioselectivity depending upon steric requirements of the catalysts will support contribution of SOI. The following experiments were made in this context.

Diels–Alder reaction of juglone and unsymmetrical dienes

The outline and results of this section are shown in Scheme 1 and Table 1. The thermal reaction of juglone and piperylene in boiling benzene gave a quantitative mixture of *syn*- and *anti*-**1**. The ^{1}H NMR spectrum of this mixture showed two methyl protons at δ 0.77 and 1.00 as doublets and two phenolic protons at δ 12.33 and 11.93 in the ratio of 2 : 1, respectively. In order to distinguish the *syn*- or *anti*-adducts, further conversion was attempted. Aromatization of the crude mixture by heating in nitrobenzene and pyridine gave a mixture of anthraquinones, *syn*- and *anti*-**2**, in 77% yield, whose ^{1}H NMR spectrum showed an overlapping methyl signal at δ 2.80 and two phenolic protons at δ 12.87 and 12.53 in the ratio of 2 : 1, respectively. The isomer ratio was maintained through aromatization. For the purpose of assignment, we compared those chemical shifts with that of the known 1-hydroxyanthraquinone[15] and newly prepared 5-hydroxy-1,4-dimethylanthraquinone. While the phenolic proton of the former resonated at δ 12.60, that of the latter appeared at δ 12.70. The presence of the 4-methyl group seemed to increase polarization of the adjacent carbonyl group to shift the phenolic proton to lower field. Thus, we supposed that the major isomer with δ 12.87 was *syn*-**2** and the minor with δ 12.53 was *anti*-**2**, which was proved later to be correct by isolation of the *anti*-isomer in the BF_3 catalyzed reaction followed by conversion into the anthrone derivative.

In the presence of $BF_3{\cdot}OEt_2$, the reaction of juglone and piperylene gave adducts which could not be distinguished. Conversion of these crude adducts into anthraquinones **2** showed that the isomer with the phenolic proton at δ 12.53 was overwhelmingly predominant. Purification by column chromatography afforded a pure anthraquinone derivative in 68% yield, which

Table 1 Diels–Alder reaction of juglone and aliphatic dienes with or without Lewis acid catalysts

Diene	Catalyst[a]	Solvent (T/°C)	Time[b]	Yield[c] (%)	Ratio[d] *syn* : *anti*
Piperylene	none	benzene (reflux)	48 h	77	2 : 1
	BF_3 OEt_2	benzene (0)	24 h	68	1 : >99
2,3-Dimethylpentadiene	none	benzene (reflux)	60 h	68	1.7 : 1
	BF_3 OEt_2	benzene (0)	24 h	46	1 : 7.3
Piperylene	$Al(OMe)_3$[e]	toluene (0–room temp.)	4 d	44	2 : 1
	$Al(OPh)_3$	toluene (0–room temp.)	3 d	*f*	1.6 : 1
	ATMP[g]	toluene (0–room temp.)	2.5 d	78	1 : 1
	ATPH[h]	toluene (0–room temp.)	3 d	47	1 : 14

[a] Lewis acids were used in an equimolar amount relative to juglone. [b] h: hour, d: day. [c] Yields after conversion into anthraquinones. [d] Isomer ratios were determined by the integration of phenolic protons in ^{1}H NMR spectrum. [e] Aluminium catalysts and juglone were mixed in toluene at 0 °C and stirred at this temperature for 12 h, then the solutions were stirred at room temperature for the above mentioned time. [f] Not isolated in a pure form, but the ratio could be determined. [g] Aluminium tris(2,6-dimethylphenoxide). [h] Aluminium tris(2,6-diphenylphenoxide).

Table 2 Calculated energies, geometric parameters and dipole moments of transition states

	Energy				Bond length[a] (bond order)		
	AM1[c]						
	ΔH_f	ΔE_a	CNDO/2-CI[d]	6-31G*[e]	Long	Short	Dipole moment[b]
TS1	−13.69	27.7	−4691.402 6	−800.644 422	2.25 (0.33)	2.03 (0.43)	2.37
TS2	−13.61	27.8	−4691.257 6	−800.644 221	2.22 (0.34)	2.05 (0.42)	2.36
TS3	−5.37	25.6	−4807.488 9	−827.045 262	2.16 (0.38)	2.12 (0.39)	4.72
TS4	−5.24	25.7	−4807.624 3	−827.047 228	2.57 (0.16)	1.92 (0.47)	5.49

[a] Å estimated by AM1. [b] D (D ≈ 3.335 64 × 10^{-30} C m) estimated by AM1. [c] kcal mol^{-1}. [d] eV. Configurations were constructed from 19 occupied MOs and 19 vacant MOs. [e] a.u.

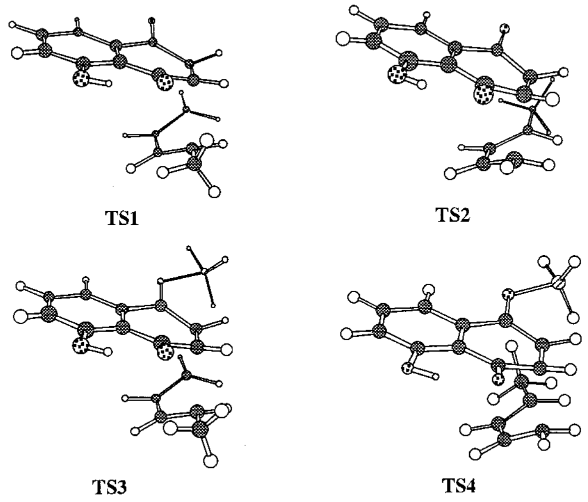
was further reduced to anthrone derivative **5** with tin(II) chloride and hydrochloric acid in refluxing EtOH. The phenolic proton at δ 13.03 in this anthrone showed that the O–H · · · O=C hydrogen bond remained intact; namely, the carbonyl group opposite to the hydroxy group was reduced chemoselectively. The observation of NOE between the methyl and methylene protons allowed unambiguous assignment that this reduced product was 1-hydroxy-5-methylanthrone **5** (R = H), which was, of course, derived from *anti*-**1**. These experimental results proved that, in contrast to the thermal reaction, where *syn*-**1** is the major product, BF_3 caused reversal of the orientation, and *anti*-**1** was predominant.

According to the same procedure, the orientation in the reaction of juglone and the more sterically hindered 2,3-dimethylpenta-1,3-diene was also determined after conversion into anthrone **6** ($R_3 = CH_3$) through anthraquinone **4**. While the reaction without a catalyst gave a mixture of *syn*- and *anti*-**4** in the ratio of 1.7 : 1, the BF_3 catalyzed reaction resulted in the ratio of 1 : 7.3, respectively. The catalyst reversed the orientation again but the component of *anti*-isomer in the catalyzed reaction was evidently decreased compared to the case with piperylene.

The steric effect of the catalysts on the orientation was further examined using organoaluminium compounds with alkoxy or aryloxy groups.[16] Disappearance of the phenolic proton of juglone in the ^{1}H NMR spectrum showed the coordination of the catalyst at C-4 oxygen. The DA reaction of juglone and piperylene in the presence of aluminium catalysts proceeded slowly (four days at room temperature). As shown in Table 1, the component of *syn*-**1** in the product mixture decreased gradually in the order of steric bulkiness of the aluminium catalysts. The orientation was completely reversed as expected, when the sterically most crowded aluminium tris(2,6-dimethylphenoxide) (ATMP) was used.

We may now compare the experimental results with the prediction made by FMO theory. Whereas the small difference in the coefficients of free juglone is reflected in a small preference for the *syn*-adduct, the predominance of the *anti*-isomer in the BF_3-catalyzed reactions with both dienes matches well with the anticipated products described earlier. Decrease of the *anti*-adduct in the catalyzed reaction with 2,3-dimethylpenta-1,3-diene would be due to steric repulsion. In the bond forming process, the two methyl groups attached on the internal carbons of the diene would obstruct *endo* approach to diminish the secondary orbital overlap.

The competition between SOI and steric hindrance can be seen clearly in a series of the organoaluminium catalyzed reactions. Using catalysts with smaller substituents, formation of *syn*-adduct is preferred, as expected, but the most crowding created by the large moieties of ATPH resulted in predominance of *anti*-**1**. Here steric repulsion would be a serious impediment to approach from the *endo* side, as observed in the *exo*-selective DA reaction with ATPH.[17] Thus, SOI was significantly diminished in this system. The gradual decrease of *syn*-adduct according to bulkiness of the aluminium catalysts corresponds to gradual diminution of such interactions.


TS1

TS2

TS3

TS4

Fig. 2 Structures of transition states in the Diels–Alder reaction of juglone and piperylene located by AM1. **TS1** and **TS2** are given for *syn*-**1** and *anti*-**1**, respectively, in the uncatalyzed reaction. BH_3-coordinated **TS3** and **TS4** are for *syn*-**1** and *anti*-**1**, respectively. Carbons are black, hydrogens are white, oxygens are meshed, and borons are broadly striped.

Consequently, these results seem to emphasize the importance of SOI in determining regioselectivity, when sterically allowed.

Transition states

The transition states were located with the AM1 method using the TS routine implemented in MOPAC (Ver. 6).[18] BH_3 was used as a Lewis acid instead of BF_3 because of failure to obtain transition states with BF_3 in this routine. As a precaution, we confirmed that BH_3-coordinated juglone gave almost equal frontier orbital coefficients to that of BF_3-coordinated juglone. All located structures were characterized as transition states by the presence of only one negative force constant in the Hessian matrix of each force calculation. The CNDO/2-CI and *ab initio* (6-31G*) (Spartan program package) calculations were performed based on the transition structures obtained by AM1. The structures, energies, geometric parameters, and dipole moments of these transition states are shown in Fig. 2 and Table 2.

The bond lengths of both reaction sites were not equal in the transition states **TS1** and **TS2**, in which the sterically hindered sites were longer by *ca.* 0.2 Å than the other sites, as often observed in theoretical studies of DA reactions with unsymmetrical reactants.[19] These structures seemed to be for concerted but not for synchronous cycloadditions. Energetically **TS1** was advantageous; namely, lower energies were estimated for **TS1** than for **TS2**, by 0.08 kcal mol^{-1} in AM1, 3.34 kcal mol^{-1} in CNDO/2-CI and 0.13 kcal mol^{-1} in 6-31G*, but the small difference in energy calculated by the more reliable *ab initio* method suggested a low selectivity for the *syn*-adduct as observed in the experiments.

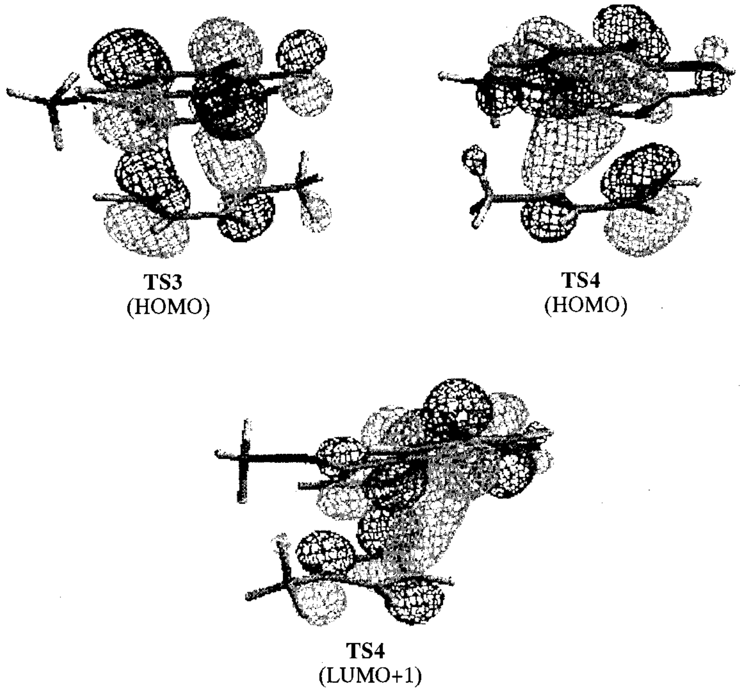


Fig. 3 Molecular orbital features (MacSpartan). HOMOs of **TS1** and **TS4** and LUMO+1 of **TS4**.

The coordination of BH_3 reduced the activation energy by *ca.* 2 kcal mol^{-1} compared to the uncatalyzed reaction. Whereas **TS3**, obtained as the transition state for the *syn*-isomer, was the synchronous structure, **TS4**, for the *anti*-adduct, showed a high degree of asynchronicity, in which the sterically hindered side was longer by 0.65 Å. The much larger dipole moment of **TS4** than that of **TS3** revealed that the reaction would proceed *via* a highly polarized transition state in an asynchronous manner. This showed not a concerted mechanism but an ionic mechanism[20] for the formation of the *anti*-isomer. The change in the mechanism (concerted or ionic) of the catalyzed DA reaction is not unusual, as documented by Branchadell *et al.*[21] They reported that in the presence of Lewis acid catalyst there were two distinct pathways for the formation of each regioisomer and that charge transfer was important in the transition state of the Lewis acid coordinated reaction between acrolein and 1-substituted butadienes. In contrast to AM1 calculations, **TS4** gave a lower energy than **TS3** by 1.23 kcal mol^{-1} in 6-31G*. In this calculation level, there was a larger difference in energy between **TS3** and **TS4** than between **TS1** and **TS2**, so that experimentally observed predominance of the *anti*-isomer in the catalyzed reaction was reasonably explained.

The structurally close transition states of uncatalyzed reaction with 2,3-dimethylpenta-1,3-diene were also located by AM1. In these transition states, slightly longer distances between secondary interacting sites were observed, which would be due to steric repulsion of the methyl groups, but the activation energies for *syn*- and *anti*-adducts were estimated to be almost equal (within 1 kcal mol^{-1}) to those of the piperylene reaction.

Next, we looked at the molecular orbital features of **TS3** and **TS4** as shown in Fig. 3, and a large discrepancy was found between them. It is interesting to know that HOMOs of the transition states show just the bond forming processes. That the HOMO orbital develops in both bonding sites almost equally in **TS3** indicates a synchronous bonding process, but the experimental result rules this out. In **TS4** the HOMO orbital extends only in the longer site. According to the report[22] which described that there were two saddle points in the energy profiles in the Lewis acid catalyzed DA reaction, the picture of **TS4** presented the second bond-forming step in a zwitterionic process. Interestingly, SOI can be seen in the orbital shape of LUMO+1 of **TS4** as a mixing of orbitals at non-bonding sites, where the distance between secondary interacting carbon atoms is 2.94 Å. Similar interactions could also be seen in LUMO+1 of **TS1** and **TS2** but not in **TS3**, which indicates that such interaction would be important in asynchronous, rather than synchronous, addition. It is no little wonder that the interaction can be seen in this orbital because LUMO+1 of the product should be derived from unoccupied orbitals of the reactants in a correlation diagram.[23] Our calculation showed that the magnitudes of the LUMO+1 coefficients of the carbonyl carbons in BH_3-coordinated juglone were still large, maintaining the pattern of its LUMO coefficients except for the difference in the orbital phases, and that a suitable combination for the secondary orbital overlapping between each LUMO+1 of the reactants was possible. Consistency of prediction made by TS and FMO theory supports the stabilization of the transition states by such secondary orbital overlap, which are important factors in deciding regioselectivities, especially in DA reactions through polarized transition states.

Experimental

The melting points were determined with a Mitamura hot-stage apparatus and are uncorrected. Microanalyses were performed on a Perkin-Elmer PE 2400 CHN elemental analyzer. ^1H NMR spectrum were recorded in $CDCl_3$ with a JEOL PMX 60 (60 MHz) and a Bruker AM-400 (500 MHz). Mass spectra were determined with a Shimadzu GCMS-QP 1000EX at an ionizing voltage of 70 eV. Column chromatography was performed on silica gel (Wacogel C-200) with ethyl acetate–hexane as the eluents. The reactions with aluminium catalysts were performed under an atmosphere of dry nitrogen.

Uncatalyzed DA reaction of juglone and piperylene and conversion of the adducts into anthraquinones (*syn*-2 and *anti*-2)

A mixture of juglone (0.50 g, 2.87 mmol) and piperylene (1.96 g, 28.7 mmol) in 50 cm^3 of benzene was heated under reflux for 48 h. Removal of the solvent and excess piperylene gave a crude mixture of 5-hydroxy-4-methyl-1,4,4a,9a-tetrahydro-9,10-anthraquinone (*syn*-**1**) and 5-hydroxy-1-methyl-1,4,4a,9a-tetrahydro-9,10-anthraquinone (*anti*-**1**), which was heated in pyridine (15 cm^3) and nitrobenzene (20 cm^3) for 6 h. Removal of the solvents by steam distillation, filtration and purification by column chromatography gave an orange crystalline mixture of 5-hydroxy-4-methyl-9,10-anthraquinone (*syn*-**2**) and 5-hydroxy-

1-methyl-9,10-anthraquinone (*anti*-**2**) (0.53 g, 77%) in the ratio of 2 : 1, respectively (Found: C, 74.4; H, 5.8 Calc. for $C_{15}H_{14}O_3$: C, 74.4; H, 5.8%); δ_H 2.80 (s, 3 H), 7.07–8.37 (m, 6 H), 12.53 (s, 0.33 H for *anti*-**2**) and 12.87 (s, 0.66 H for *syn*-**2**); *m*/*z* 242.

$BF_3\cdot OEt_2$ catalyzed DA reaction of juglone and piperylene and aromatization to anthraquinones (*syn*-2 and *anti*-2). Isolation of *anti*-2 and reduction to anthrone (5)

To a solution of juglone (0.30 g 1.72 mmol) and boron trifluoride–diethyl ether (0.24 g, 1.72 mmol) in 30 cm^3 of benzene was added piperylene (0.59 g, 8.60 mmol) and the solution was stirred for 24 h at 0 °C. After removal of the solvent, the mixture was dissolved in pyridine (4 cm^3) and nitrobenzene (5 cm^3) and heated for 6 h under reflux. Removal of the solvents by steam distillation and filtration gave the crude mixture, which was purified by column chromatography to give *anti*-**2** with a small amount of *syn*-**2**. Recrystallization from benzene–hexane gave pure *anti*-**2** (0.13 g, 68%). The thus obtained anthraquinone (*anti*-**2**) (0.1 g, 0.42 mmol) was dissolved in acetic acid (2.8 cm^3) and to this solution was added a warm solution of tin(II) chloride dihydrate (0.9 g, 4.0 mmol) in hydrochloric acid (0.9 cm^3). After heating under reflux for 12 h, water (10 cm^3) was added and the crystalline mass was filtered and dried. Recrystallization from chloroform–methanol gave 1-hydroxy-5-methylanthrone (**5**) (0.05 g, 52%); mp 151–155 °C (Found: C, 80.1; H, 5.4 Calc. for $C_{15}H_{12}O_2$: C, 80.3; H, 5.4%); δ_H 2.38 (s, 3 H), 4.08 (s, 2 H), 6.88 (d, 1 H), 6.92 (d, 1 H), 7.34 (t, 1 H), 7.43 (t, 2 H), 8.16 (d, 1 H) and 13.03 (s, 1 H); δ_C 19.0, 30.6, 115.0, 116.3, 118.8, 125.0, 126.8, 131.0, 134.8, 135.5, 136.0, 139.0, 141.7, 163.0 and 189.9; *m*/*z* 238 (M^+).

Uncatalyzed DA reaction of juglone and 2,3-dimethylpenta-1,3-diene and conversion of the adducts into anthraquinone (*syn*-4 and *anti*-4)

2,3-Dimethylpenta-1,3-diene was prepared by the Wittig reaction of methylene triphenylphosphorane and 3-methylpent-3-en-2-one in 26% yield. The DA reaction with juglone, aromatization and purification were carried out according to the above described procedure to yield a 1.7 : 1 mixture of 5-hydroxy-2,3,4-trimethyl-9,10-anthraquinone (*syn*-**4**) and 5-hydroxy-1,2,3-trimethyl-9,10-anthraquinone (*anti*-**4**) in 68% yield (Found: C, 76.7; H, 5.6 Calc. for $C_{17}H_{14}O_3$: C, 76.7; H, 5.3%); δ_H 2.30 (s, 3 H), 2.40 (s, 3 H), 2.70 (s, 1.11 H for *anti*-**4**), 2.73 (s, 1.89 H for *syn*-**4**), 7.10–8.11 (m, 6 H), 12.58 (s, 0.37 H for *anti*-**4**) and 12.92 (s, 0.63 H for *syn*-**4**); *m*/*z* 266.

$BF_3\cdot Et_2$ catalyzed DA reaction of juglone and 2,3-dimethylpenta-1,3-diene and aromatization to anthraquinones (*syn*-4 and *anti*-4). Isolation of *anti*-4 and reduction to anthrone (6)

The DA reaction using juglone (0.30 g, 1.72 mmol) and 2,3-dimethylpenta-1,3-diene (0.27 g, 1.72 mmol) in the presence of boron trifluoride–diethyl ether (0.24 g, 1.72 mmol) in 30 cm^3 of benzene followed by aromatization according to the above described procedure gave a mixture of 5-hydroxy-2,3,4-trimethyl-9,10-anthraquinone (*syn*-**4**) and 5-hydroxy-1,2,3-trimethyl-9,10-anthraquinone (*anti*-**4**) in 46% yield. Separation by column chromatography and recrystallization from benzene–hexane gave only *anti*-**4**, which was converted into 5-hydroxy-1,2,3-trimethylanthrone (**6**) as described above in 63% yield; mp 181–183 °C (Found: C, 80.9; H, 6.3 Calc. for $C_{17}H_{16}O_2$: C, 80.9; H, 6.4%); δ_H 2.27 (s, 6 H), 2.34 (s, 3 H), 4.06 (s, 2 H), 6.86 (d, 1 H), 6.90 (d, 1 H), 7.34 (t, 1 H), 7.94 (s, 3 H) and 13.13 (s, 1 H); δ_C 15.1, 16.6, 20.9, 31.2, 114.7, 116.2, 118.8, 125.5, 128.4, 134.1, 135.1, 135.6, 136.5, 142.0, 142.1, 162.9 and 190.0; *m*/*z* 252 (M^+).

Preparation of 5-hydroxy-1,4-dimethyl-9,10-anthraquinone

Juglone (0.4 g, 2.3 mmol) and hexa-2,4-diene (1.0 g, 12.1 mmol) was heated in benzene (50 cm^3) for 50 h under reflux. After removal of the solvent, the crude material was heated in pyridine (3 cm^3) and nitrobenzene (10 cm^3) for 3 h under reflux. Removal of the solvents by distillation under reduced pressure gave crystalline solid (0.46 g, 80% based on juglone); mp 158–159 °C (from benzene and hexane) (Found: C, 76.2; H, 4.8 Calc. for $C_{16}H_{12}O_3$: C, 76.2; H, 4.8%); δ_H 2.75 (s, 6 H), 7.00–7.70 (m, 5 H) and 12.66 (s, 1 H); *m*/*z* 252 (M^+).

DA reaction of juglone and piperylene with aluminium catalysts

Aluminium trimethoxide solution was prepared according to the established manner by addition of a trimethyl aluminium hexane solution (1.72 mmol, 1.08 mol l^{-1} in hexane, Aldrich) to a solution of methanol (0.17 g, 5.16 mmol) in toluene (5 cm^3) at 0 °C. To the thus prepared trimethoxyaluminium solution was added juglone (0.3 g, 1.72 mmol) in toluene (10 cm^3). After stirring for 15 min, piperylene (1.17 g, 17.2 mmol) in toluene (5 cm^3) was added and the resulting solution was stirred for 12 h at 0 °C and for 4 days at room temperature. After removal of the solvent, pyridine (6.1 cm^3) and nitrobenzene (8 cm^3) were added to the residue and the solution was heated for 6 h under reflux. Removal of the solvent by steam distillation and separation by column chromatography gave a mixture of *syn*-**3** and *anti*-**3** (0.18 g, 44%). The ratio of the isomers was determined by the integration of phenolic protons at δ 12.53 for *anti*-**3** and 12.87 for *syn*-**3** in the ^{1}H NMR spectrum.

The other aluminium catalysts were also prepared from a trimethyl aluminium hexane solution as described above with three equivalent phenols; namely, phenol for aluminium triphenoxide, 2,6-xylenol for aluminium tris(2,6-dimethylphenoxide) (ATMP), 2,6-diphenylphenol for aluminium tris(2,6-diphenylphenoxide) (ATPH) were used. The reaction, aromatization and determination of the isomer ratio were performed by the above described procedure.

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