Structures of oxygenated cyclohexa-1,3-diene–maleic anyhydride cycloadducts. Structural evidence suggests a stepwise retro-Diels–Alder reaction

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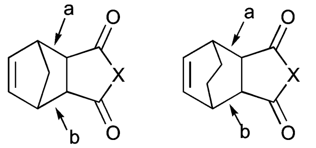
Received 21st May 2007, Accepted 14th June 2007
First published as an Advance Article on the web 20th June 2007
DOI: 10.1039/b707643f

The structures of a series of cyclohexadiene–maleic anhydride cycloadducts show structural parameters consistent with the early stages of the retro-Diels–Alder (rDA) reaction in the ground state structure. The symmetrical adduct 10 shows effects consistent with a synchronous rDA reaction. An asynchronous rDA reaction is suggested in the structure of 8, and the first evidence suggesting a two-step retro-Diels–Alder mechanism is provided by the deoxygenated adduct 9.

We have described the structures of a number of Diels–Alder cycloadducts formed between cyclopentadiene and cyclohexadiene with dienophiles ranging from benzoquinone, maleic anhydride and *N*-methyl maleamide.[1–3] These were characterised using X-ray crystallography and by determination of their ^{13}C–^{13}C 1-bond coupling constants. In these structures the C–C bonds (bonds **a** and **b** in the graphics), which break in the retro-Diels–Alder reaction were both found to be lengthened significantly compared to similar bonds in corresponding model systems in which the retro-Diels–Alder reaction does not occur.



1): X = O
2): X = NMe
3): X = CH=CH

4): X = O
5): X = NMe
6): X = CH=CH

This is an example of the so-called structure-correlation principle,[4] which states that structure changes that occur along the reaction coordinate for a particular reaction, can manifest in the ground state as deviations of distances and angles from their 'normal values' along the reaction coordinate. The C–C bonds (bonds **a** and **b**) in **1–6** were lengthened to the same degree, consistent with the manifestation of a synchronous retro-Diels–Alder reaction in the ground state, furthermore the degree of C–C bond lengthening in each structure was found to correlate qualitatively with the known Diels–Alder reactivity of these cycloadducts. The structure of the unsymmetrical cycloadduct **7**, which is predicted from *ab initio* calculations at the B3LYP/6-31G(d,p) level to undergo a retro-Diels–Alder reaction by an asynchronous polarised transition state (Fig. 1) was also determined.

The X-ray structure of **7** revealed a greater degree of bond lengthening of bond **a** than bond **b**, which reflects the differences in these distances in the calculated transition state for the reaction. Interestingly, comparison with the X-ray structure of the symmetrical cycloadduct **6** reveals that the relative distances of bonds **a** and **b** in the ground state structures mirrors the relative distances in the transitions states for both structures.

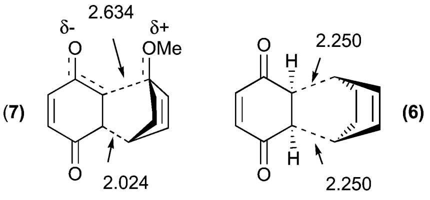
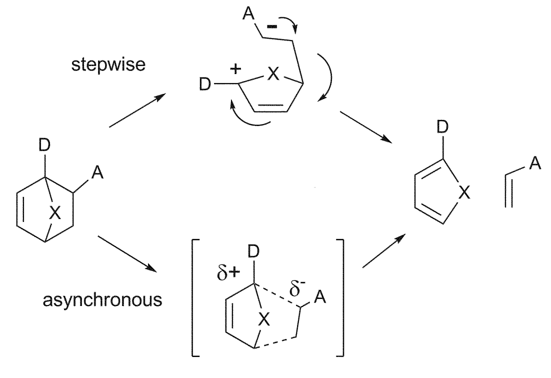


Fig. 1 Calculated transition states for the retro-Diels–Alder reactions of **6** and **7**.

We were interested to determine the structure of a cycloadduct which may be disposed towards a stepwise retro-Diels–Alder reaction (Scheme 1), for according to the structure-correlation principle, only the C–C bond which breaks in the first step should be lengthened in the ground state structure, since the second bond does not break until the second step.



Scheme 1

To this end we prepared the cycloadducts **8** and **9** by reaction of 1-methoxycyclohexadiene and *in situ*-generated 1,3-dimethoxy-1,3-cyclohexadiene[5] with maleic anhydride.

Crystals of **8** were obtained from ether at room temperature, whereas crystals of **9**, which was unstable in solution for extended periods, were obtained by careful crystallisation at −20 °C from ether. Structural data, for **8**, **9** and the cyclohexadiene maleic anhydride adduct **10** which has been previously reported,[2] are summarised in Fig. 2.

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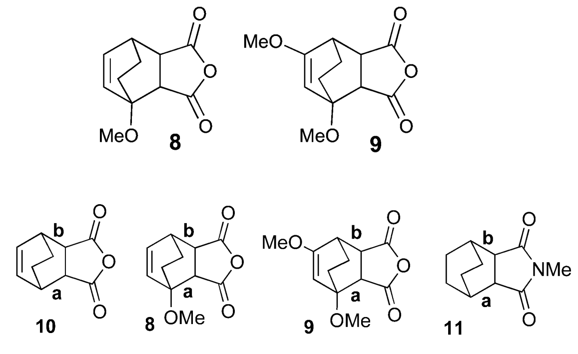


Bond distances (Å)

	10	8	9	11
Bond **a**	1.549(2)	1.568(2)	1.571(2)	1.541(2)
Bond **b**	1.550(2)	1.548(2)	1.540(2)	1.541(2)

Fig. 2 Selected structural parameters for cycloadducts **8–10**.

Adduct **10**, which undergoes a synchronous retro-Diels–Alder reaction, displays lengthening of bonds **a** and **b** to the same degree compared with the model system **11** which does not undergo the reaction.† Introduction of the bridgehead methoxy substituent in **8** results in further lengthening of bond **a** while bond **b** is lengthened to a much lesser extent, consistent with the manifestation of an asynchronous retro-Diels–Alder reaction in the ground state. The structural effects in the dioxygenated adduct **9** are interesting, bond **a** is further lengthened while bond **b** is essentially 'normal' suggesting that **9** would undergo a two-step retro-Diels–Alder reaction where bond **a** breaks in the first step followed by breaking of bond **b**. The structural effects arising in **8–10** can be rationalised by reference to the interactions between the orbitals depicted in Fig. 3.

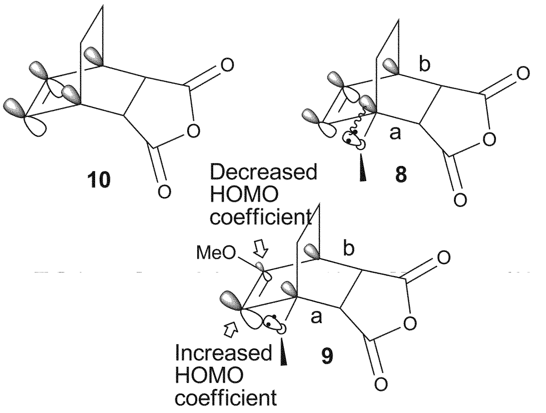


Fig. 3 Orbital interactions present in structures **8–10**.

In the symmetrical cycloadduct **10** donation of electron density from the π-system into the two σ^*_{CC} antibonding orbitals (π–σ* interaction) causes lengthening of bonds **a** and **b** compared to the reference compound **11**. In structure **8** bonds **a** and **b** are lengthened as a result of the same interaction as in **10**, but in addition, there is also donation of electron density from the non-bonded orbital on the bridgehead methoxy oxygen into the σ^*_{CC} for bond **a** (n–σ* interaction) resulting in further weakening of this bond. Inspection of the thermal ellipsoid plot for **8** (Fig. 4), shows that the methoxy substituent is correctly oriented to allow for this interaction to occur. In the dimethoxy substituted adduct **9** (Fig. 4) the bridgehead methoxy substituent has essentially the same conformation as that in **8** thus allowing for the n–σ^*_{CC} interaction to occur, in addition the second methoxy substituent which is conjugated with the π-system (C12-O6-C5-C4 = 2.8(3)°) increases the coefficient of the HOMO at C4[6] resulting in greater donation of π electron density into the bond **a** antibonding orbital, causing further lengthening of this bond. The electronegative methoxy substituent also causes a decrease in the HOMO coefficient at C5, the result being that less electron density is delocalised into the bond **b** antibonding orbital.

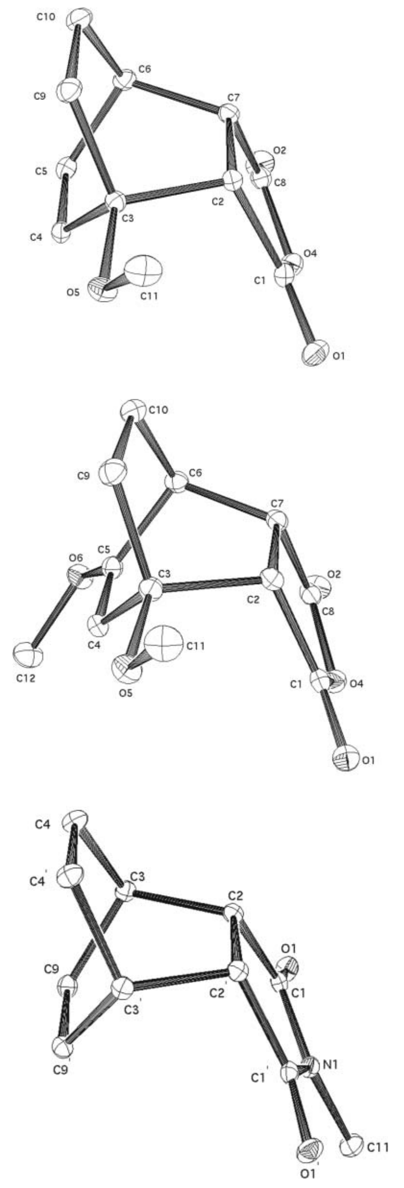
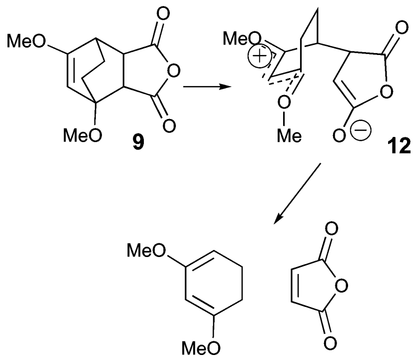


Fig. 4 Thermal ellipsoid plots of **8**, **9**, and **11** ellipsoids are at the 20% probability level. Compound **9** is the inverse of that reported in the CIF.‡

The dimethoxy adduct **9** displays lengthening of bond **a** whereas bond **b** which must also break in the retro-Diels–Alder reaction is 'normal'. These structural data suggest that **9** may react *via* a two-step mechanism, possibly involving the delocalised intermediate **12** (Scheme 2). The first step is similar to a retro-Aldol reaction while the second step is analogous to a retro-Michael reaction.



Scheme 2

Notes and references

† Although the corresponding anhydride is a more appropriate model system, this did not form good crystals. We believe that **11** is a suitable reference compound as the C–C bonds being compared are in a closely similar environment.

‡ Crystal data for **8**. $C_{11}H_{12}O_4$, $M = 208.21$, $T = 130.0(2)$ K, $\lambda = 0.71069$, monoclinic, space group $P2(1)/c$, $a = 6.9224(7)$, $b = 13.706(1)$, $c = 10.275(2)$ Å, $\beta = 99.149(3)°$, $V = 962.59(2)$ Å^3, $Z = 4$, $D_c = 1.437$ mg M^{-3}, μ(Mo-Kα) = 0.11 mm^{-1}, $F(000) = 440$, crystal size $0.40 \times 0.40 \times 0.30$ mm. 4983 reflections measured, 1699 independent reflections ($R_{int} = 0.039$), the final R was 0.0364 [$I > 2\sigma(I)$] and $wR(F^2)$ was 0.0936 (all data). Crystal data for **9**. $C_{12}H_{14}O_5$, $M = 238.23$, $T = 130.0(2)$ K, $\lambda = 0.71069$, monoclinic, space group $P2(1)/c$, $a = 7.6323(8)$, $b = 8.5174(9)$, $c = 17.502(2)$ Å, $\beta = 97.041(2)°$, $V = 1129.2(2)$ Å^3, $Z = 4$, $D_c = 1.437$ mg M^{-3}, μ(Mo-Kα) = 0.11 mm^{-1}, $F(000) = 504$, crystal size $0.20 \times 0.15 \times 0.10$ mm. 6782 reflections measured, 2556 independent reflections ($R_{int} = 0.039$), the final R was 0.0484 [$I > 2\sigma(I)$] and $wR(F^2)$ was 0.1051 (all data). Crystal data for **11**. $C_{11}H_{15}NO_2 \cdot H_2O$, $M = 211.26$, $T = 130.0(2)$ K, $\lambda = 0.71069$, orthorhombic, space group $Cmc2(1)$, $a = 9.3040(8)$, $b = 8.6876(7)$, $c = 12.696(1)$ Å, $V = 1026.2(1)$ Å^3, $Z = 4$, $D_c = 1.367$ mg M^{-3}, μ(Mo-Kα) 0.099 mm^{-1}, $F(000) = 456$, crystal size $0.30 \times 0.20 \times 0.20$ mm. 2583 reflections measured, 945 independent reflections ($R_{int} = 0.028$), the final R was 0.0284 [$I > 2\sigma(I)$] and $wR(F^2)$ was 0.0747 (all data). CCDC reference numbers 647990–647992. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b707643f

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