

Comment on the “Nature of Bonding in the Thermal Cyclization of (Z)-1,2,4,6-Heptatetraene and Its Heterosubstituted Analogues”

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In a recent paper by Chamorro and Notario (CN),¹ the pericyclic or pseudopericyclic character of the thermal cyclization of (Z)-1,2,4,6-heptatetraene (**C**) and its heterosubstituted analogues (**A** and **B**) (see Scheme 1) was discussed by means of a topological electron localization function (ELF) analysis applied to the corresponding transition states (TSs). The aim of this work was to explore whether an ELF can provide further insight in the context of a recent controversy^{2–5} concerning the nature of the TSs involved in reactions **A** and **B**. The authors concluded that their ELF results, which were mainly based on the examination of electron density fluctuation, provide proof in support of a single disrotatory pericyclic bond interaction (mechanism 1 in Scheme 1) for reactions **A**, **B**, and **C**.

In our opinion, the analysis of electron density fluctuation used to reach this conclusion is not solid enough to warrant such an assertion. To make our point, we have optimized the TS and computed the ELF (at the same B3LYP/6-31+G(d) level of theory using the HF/6-31G** optimized geometry of the TS and with the same programs and visualization tools used in the work by CN¹) for a well-established pseudopericyclic reaction (mechanism 2 in Scheme 1), namely, the cyclization of 5-oxo-2,4-pentadienal to pyran-2-one (reaction **D** in Scheme 1), that was not considered in the study of CN.¹ The TS of reaction **D** was optimized at the HF/6-31G** level (its geometry can be

found in the Supporting Information) because both the B3LYP/6-31G** (see ref 5) and B3LYP/6-31+G(d) methods give a reaction path without an energy barrier. This TS was characterized by the existence of a unique imaginary frequency corresponding to the ring closure, as well as by computing the intrinsic reaction path from the TS going downhill to reactants and products in mass-weighted Cartesian coordinates. Even though the original discussion was focused on the three reactions studied by CN,^{1–4} Rodríguez-Otero et al.⁵ introduced this fourth reaction, which is of great importance because it allows the comparison of the controversial **A** and **B** reactions with a reaction that has an unquestionable single disrotatory pericyclic TS (reaction **C**) and another that has an undeniable pseudo-pericyclic nature (reaction **D**).

CN¹ gave basically three reasons to assign a pericyclic nature to reactions **A** and **B**: (i) the lone pair of N in TS **A** or O in TS **B** has a low contribution to the whole process, so that it can be considered just a mere stabilization factor; (ii) the populations and fluctuations of the basins resemble those expected in pericyclic reactions; and more importantly, (iii) the measures of cyclic electron density fluctuations from one basin to its contiguous basins, following a clockwise or anticlockwise circulation around the ring reaction center, are essentially the same for reactions **A**, **B**, and **C**.

Taking into account the results obtained for reaction **D** listed in Table 1, these are our remarks to the aforementioned three arguments:

(i) In the pseudopericyclic reaction **D**, the contribution of the basin V(C2,C3)⁶ to the total electron delocalization of the O7 lone pair basin facing the C2 atom (basin number **10** in Table 1) is 3.4% (3.3–3.7%), which is even lower than the contributions of the basin V(C2,C3) for the equivalent electron pair delocalization in reactions **A**, **B**, and **C**.¹ Therefore, a low contribution of the basin V(C2,C3) to the heteroatom electron lone pair delocalization is not a conclusive indication that the lone pair plays a mere stabilization role and that, as a consequence, the reaction is pericyclic.

SCHEME 1. Suggested Reaction Mechanisms for the Thermal Cyclization of (Z)-1,2,4,6-Heptatetraene and Its Heterosubstituted Analogues via a Pericyclic Disrotatory Pathway (Mechanism 1) or through Pseudopericyclic Nucleophilic Addition (Mechanism 2)

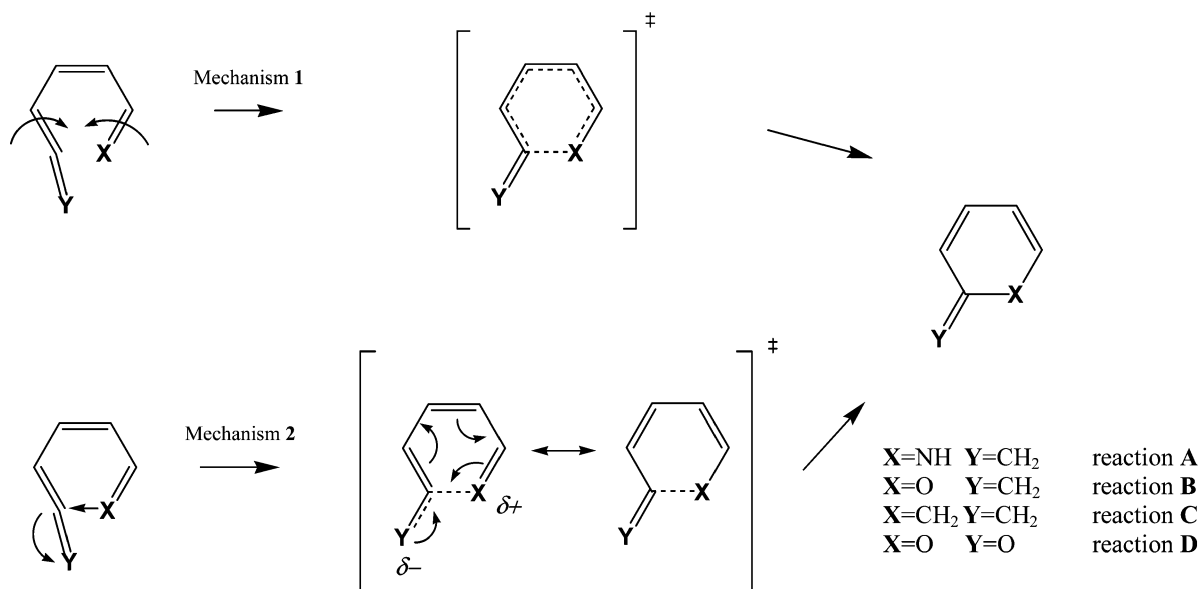


TABLE 1: B3LYP/6-31+G(d) Basin Populations, N_i , Standard Deviations, $\sigma^2(N_i)$, Relative Fluctuations, $\lambda(N_i)$, and Main Contributions of Other Basins, $i(\%)$, to $\sigma^2(N_i)$ for the Transition State of Reaction D^a

basin	$N(\Omega_i)$	$\sigma^2[N(\Omega_i)]$	$\lambda[N(\Omega_i)]$	contribution analysis (%)										
1	V(H1,C3)	2.06	0.66	0.32	2	(3.0)	5	(13.6)	6	(16.7)	7	(3.0)	11	(24.2)
2	V(H2,C4)	2.10	0.61	0.29	12	(10.6)	13	(10.6)	14	(3.0)	11	(30.5)	14	(39.0)
3	V(H3,C5)	2.12	0.65	0.31	1	(3.4)	3	(5.1)	11	(30.5)	14	(48.4)	15	(27.4)
4	V(H4,C6)	2.13	0.56	0.27	2	(4.8)	4	(3.2)	14	(48.4)	15	(27.4)	16	(25.9)
5	V(C2,C3)	1.30	0.84	0.64	3	(3.7)	10	(5.6)	14	(5.6)	15	(31.5)	16	(25.9)
6	V(C2,C3)	1.47	0.94	0.64	17	(13.0)	6	(32.9)	7	(7.3)	8	(6.1)	9	(6.1)
7	V(O1)	4.72	1.42	0.30	1	(11.0)	10	(3.7)	11	(9.8)	12	(7.3)	13	(8.7)
8	V(C2,O1)	1.53	0.99	0.65	1	(12.0)	5	(29.3)	7	(6.5)	8	(5.4)	9	(6.5)
9	V(C2,O1)	1.51	0.95	0.63	10	(3.3)	11	(12.0)	12	(3.3)	13	(8.7)	14	(33.3)
10	V(O7)	2.32	1.17	0.51	5	(4.3)	6	(4.3)	8	(33.3)	9	(33.3)	10	(4.1)
11	V(C3,C4)	2.39	1.14	0.48	5	(5.1)	6	(5.1)	7	(48.0)	9	(24.5)	10	(4.1)
12	V(C3)	0.39	0.34	0.86	5	(5.4)	6	(6.5)	7	(50.5)	8	(25.8)	11	(15.0)
13	V(C3)	0.39	0.34	0.86	8	(3.5)	15	(3.5)	16	(28.1)	17	(43.0)	17	(43.0)
14	V(C4,C5)	3.25	1.42	0.44	1	(14.3)	2	(16.1)	5	(7.1)	6	(9.8)	12	(7.1)
15	V(C5,C6)	2.39	1.11	0.47	13	(7.1)	14	(18.8)	14	(18.8)	15	(23.6)	16	(13.0)
16	V(C6,O7)	2.20	1.21	0.55	1	(23.3)	2	(3.3)	5	(20.0)	6	(10.0)	7	(3.3)
17	V(O7)	3.04	1.27	0.42	11	(26.7)	13	(6.7)	14	(3.3)	6	(25.8)	7	(3.2)
					1	(22.6)	2	(3.2)	5	(6.5)	6	(25.8)	7	(3.2)
					11	(25.8)	12	(6.5)	14	(3.2)	15	(23.6)	16	(13.0)
					2	(16.4)	3	(21.4)	11	(15.0)	15	(23.6)	16	(13.0)
					3	(15.7)	4	(15.7)	10	(3.7)	14	(30.6)	16	(13.0)
					17	(3.7)	10	(27.1)	15	(11.9)	17	(35.6)	17	(35.6)
					4	(11.9)	10	(39.5)	15	(3.2)	16	(33.9)	16	(33.9)
					4	(5.6)	10	(39.5)	15	(3.2)	16	(33.9)	16	(33.9)

^a Only percentages above 3% are listed.

(ii) Comparison of basin populations for reaction **D** in Table 1 with those populations of reactions **A**, **B**, and **C** in Tables 1–3 of ref 1 shows that basin populations in reactions **A** and **B** are closer to either those of reactions **C** or **D** depending on the basin considered. Therefore, basin populations are not very informative for discerning between the pericyclic and pseudo-pericyclic nature of reactions **A** and **B**. In addition, the variances of the basin populations are not enlightening enough, since the differences and similarities of reactions **A** and **B** with respect to **C** and **D** lead one to conclude that reactions **A** and **B** have a character intermediate between **C** and **D**, somewhat closer to **C** yet not far from **D**.

(iii) CN¹ based their strongest argument in favor of the pericyclic character of reactions **A** and **B** on a measure of cyclic electron flow in terms of covariance data. When analyzing the complete cyclic fluctuation pattern, CN compared covariance contributions coming from related basins corresponding to different reactions. In our opinion, this is not strictly correct, since the compared covariance contributions came from basins having different electronic populations. In this sense, we believe that more consistent results can be obtained by analyzing covariance contributions arising from the same basin. In particular, we recommend comparing covariance contributions to a given bonding basin coming from adjacent bonding and lone pair basins for the clockwise and counterclockwise directions to determine the direction in which the electron fluctuation is larger. This procedure is supported by the results of a study of cyclic π -conjugated molecules, where the comparison of electron fluctuation in both directions for each basin has been found to be a good indicator of aromaticity.⁷

Figure 1 depicts the ratios between percentages of covariance contributions in both directions, with an arrow pointing to the preferred way of fluctuation.⁸ When two consecutive bonds fluctuate charge in opposite directions, the atom between suffers from electron depletion (no arrows pointing to the atom) or electron concentration (both arrows pointing toward the atom), whose magnitude can be counted in terms of listed ratios (see the numbers above the bonds). In reaction **C**, no electron

accumulation is observed in the ring atoms resembling a typical aromatic situation, as expected for a pericyclic reaction. Clear electron depletions are observed in atoms 3 and 6 of reaction **D**, while an electron accumulation is found on atoms 7 and 5. A very similar trend is observed for reaction **B**, but with a depletion on atom 4 instead of 3. Finally, reaction **A** has almost the same fluctuation pattern as **B**, with both being far from the aromatic-like behavior expected for a pseudopericyclic reaction, although the covariance contribution ratios are somewhat lower in **A**. Thus, in light of these ELF results, we conclude that **B** more resembles a pseudopericyclic reaction than a pericyclic

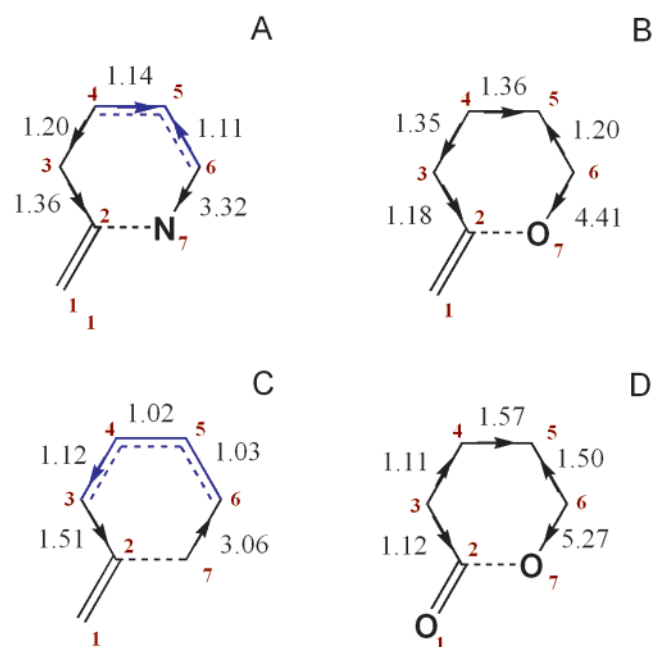


Figure 1. Electron fluctuation in terms of contribution analysis. Arrows point to the atom where the electron fluctuation of the bond electron pair is larger.

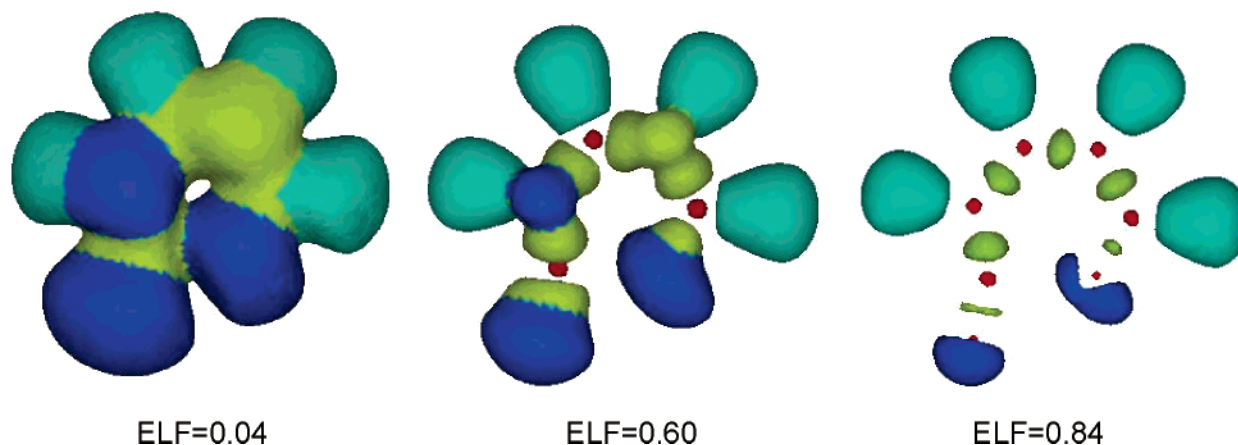


Figure 2. Localization domains of the ELF at the transition state of reaction **D**, depicted for isosurface values of 0.04, 0.60, and 0.84. Core basins in red, V(C-H) in light blue, V(C-C) in green, and V(C3) and V(O)s in blue.

one, while **A** shows an intermediate situation, yet closer to the pseudopericyclic character.

The phenomenon described above is further supported by ELF representations. From Figure 1 of CN, at $ELF = 0.40$,⁹ it is clearly seen that TSs in reactions **A** and **B** present a high electronic localization around atoms C3 and C5, while C4 and C6 core basins are easily visualized due to the poor localization around them. The same is observed in Figure 2, where the $ELF = 0.6$ picture for reaction **D** is drawn.

The closer proximity of reactions **A** and **B** to pseudopericyclic reaction **D** can be reinforced by observing the absence of a cyclic loop of interacting orbitals by means of the contribution analyses (see Tables 1–3 of CN and Table 1 of the present work). For reactions **A** and **B**, it is seen how V(C6,X) ($X = N$ (A), O (B)) does not contribute to V(C2,C3) and, conversely, how V(C2,C3) contributes to V(X) but not to V(C6,X). On the other hand, for reaction **C** (Table 3 of CN), V(C6,C7) contributes to V(C2,C3) and, in turn, this to V(C6,C7). Thus, one can follow the contributions around the ring, achieving a cyclic bonding which is fundamental in the definition of pericyclic reactions. Finally, reaction **D** (see Table 1) presents the same contribution behavior as reactions **A** and **B**.

As a whole, we think that our work proves that CN have incorrectly assigned a pericyclic nature to reactions **A** and **B**. Our conclusion is achieved by means of a covariance analysis based on contributions arising from the same basin and by comparison to the reaction of the cyclization of 5-oxo-2,4-pentadienal to pyran-2-one (**D**), with an already assigned pseudopericyclic nature.

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Supporting Information Available: Cartesian coordinates corresponding to the geometry of the transition state of reaction **D**, calculated at the HF/6-31G** level of theory. This material is available free of charge via the Internet at <http://pubs.acs.org>.

References and Notes

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- (4) Rodríguez-Otero, J.; Cabaleiro-Lago, E. M. *Angew. Chem., Int. Ed.* **2002**, *41*, 1147.
- (5) Rodríguez-Otero, J.; Cabaleiro-Lago, E. M. *Chem.—Eur. J.* **2003**, *9*, 1837.
- (6) In reaction **D**, the V(C2,C3) basin is split into two, but this does not affect the conclusions.
- (7) Matito, E.; Duran, M.; Solà, M. *J. Chem. Phys.* **2005**, *122*, 014109.
- (8) For instance, the value 1.50 assigned to the C5–C6 bond in Figure 1 for the TS of reaction **D** is obtained by dividing the covariance percentage of the V(C5,C6) basin population in the V(C4,C5) basin (counterclockwise direction) by those of the V(C6,O7) and V(O7) basins (clockwise direction), that is, $30.6/(13.0 + 3.7 + 3.7) = 1.5$. Only percentages above 3%, those listed in Table 1, are considered.
- (9) The ELF pictures in ref 1 were depicted at $ELF = 0.84$, $ELF = 0.40$, and $ELF = 0.04$. We could reproduce the 0.04 and 0.84 pictures, but we failed in recreating $ELF = 0.40$. However, the same pictures arise when an ELF value close to 0.60 is used. Thus, we attribute our failing to reproduce $ELF = 0.40$ to a possible misprint in ref 1. Bifurcation diagrams in ref 1 support this hypothesis.