

Jailbreaking Benzene Dimers

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S Supporting Information

ABSTRACT: We suggest four new benzene dimers, (C₆H₆)₂, all featuring one or more cyclohexadiene rings *trans*-fused to 4- or 6-membered rings. These hypothetical dimers are 50–99 kcal/mol less stable than two benzenes, but have computed activation energies to fragmentation ≥ 27 kcal/mol. A thorough search of potential escape routes was undertaken, through cyclobutane ring cleavage to 12-annulenes, sigmatropic 1,5-H-shifts, electrocyclic ring-openings of the 6-membered rings, and Diels–Alder dimerizations. Some channels for reaction emerge, but there is a reasonable chance that some of these new benzene dimers can be made.

In the course of thinking about benzene under gigapascal pressure,¹ we decided we might learn something from the dimers of benzene, as signposts to the pressure-induced polymerization of the compound. To induce the benzenes to dimerize, we brought two benzene molecules to an uncomfortably close contact,² and then let loose the geometry optimization of a quantum chemical program (here ORCA³). The molecules reacted to this torture by moving apart, or by forming dimers.

In the first batch of molecules we got some (but not all) of the known 2+2^{4,5} and 4+2^{6,7} dimers, as well as the reasonable 4+4 dimer, whose derivatives are known^{8,9} (1–4, Figure 1).¹⁰

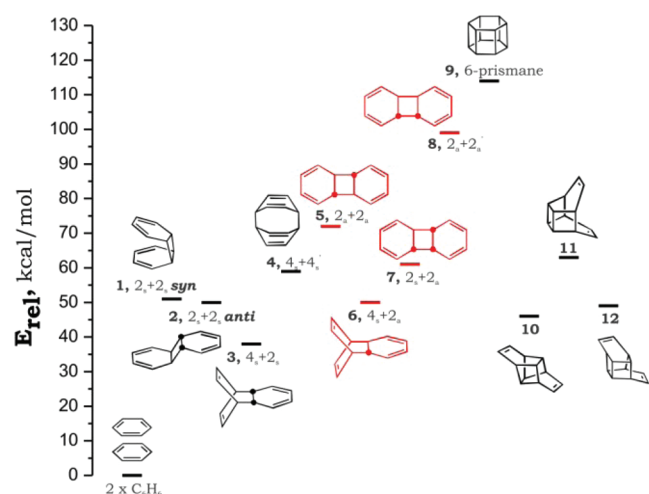
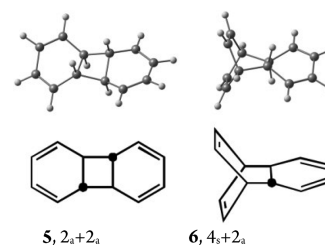


Figure 1. Twelve benzene dimers and their calculated energies.

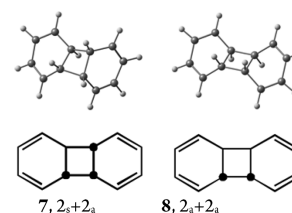
We also got — and this was a real surprise — molecules 5 and 6. These can be economically (if not uniquely, nor systematically) described as 2_s+2_a and 4_s+2_a cycloadducts, the subscript “s” and “a” notation derived from the pericyclic reaction nomenclature.

5 and 6 were calculated as not much less stable than the known dimers.



Apparently *trans*-bridging a butadiene 1,2 on a cyclobutane ring, with the latter's freedom to pucker, is not as difficult as one might think.¹¹ Nor is it problematic for a butadiene to bridge the *gauche* positions of an approximately staggered ethane.

No longer succumbing to the prejudice of avoiding *trans*-bridging of a cyclobutane ring by a butadiene, from this point we proceeded down a systematic (human, not machine) path, generating geometries for all reasonable cycloadducts. The additional unusual molecules generated in this way are the 2_s+2_a dimer 7 and the 2_a+2_a cycloadduct 8.^{12,13}



Also generated were the prismane 9 and three quadruply linked benzenes 10–12 (Figure 1), at least two of which (11, 12) are known.^{14–16} All 12 of the benzene dimers are local minima; no imaginary frequencies are found for them in a vibrational analysis.^{17–19} Their computed bond lengths are quite normal. In Figure 1 we draw their energies (RIJCOSX-MP2, cc-pVTZ basis set, 0 K, ZPE not included) relative to two non-interacting benzenes.²⁰

The existence of molecules 5–8, marked in red in Figure 1 and as far as we know not synthesized (nor even mentioned in the literature), is the key prediction of this work. Some of these unusual benzene dimers lie high in energy, though not much higher than some known dimers.

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The lesson of all of organic chemistry is that thermodynamic instability is hardly a barrier to existence in a bottle, if kinetic persistence be there. The benzene isomers Dewar benzene, benzalene, and prismane are a good case in point. So the real questions are two-fold: (1) What are the activation energies of the new dimers to fragmentation to two benzenes? (2) What other “escape routes” (reactions to other molecules) might they have?

The first question is not that easy to answer, for locating transition states for forbidden reactions, which is what three of four of these cycloreversions are, is fraught with difficulty. In such cases, molecules will avoid concerted transition states featuring reasonably symmetrical bond cleavage, perhaps go through diradicals, and, one way or the other, cause problems for theoreticians.^{21,22} With much effort we have found transition states for most of these fragmentations; the activation energies are given in Table 1, and the transition-state geometries, asynchronous as expected, are given in the Supporting Information (SI).

Table 1. Activation Energies^a for the Fragmentation of the New Dimers to Two Benzenes

Structure	Name	$E_{rel.}$ (kcal/mol)	$E_{a,fragmentation}$ (kcal/mol)
	5, 2 _a +2 _a	72	30
	6, 4 _s +2 _a	50	36
	7, 2 _a +2 _s	61	27
	8, 2 _a +2 _a '	99	28

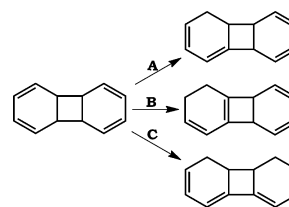
^aEnergies (RIJCOSX-MP2/cc-pVTZ) given are relative to two non-interacting benzenes. Zero-point energies (not included) change these values by ~1 kcal/mol.

The barriers for reversion to two benzenes of 5–8 are all >25 kcal/mol, quite high given the exothermicity of the fragmentations. Shall we trust these numbers? One calibration is that with the same methodology we compute the E_a for the known (and allowed) fragmentation of 3 as 9 kcal/mol, whereas the observed value is ~15 kcal/mol.^{4,5} A multi-reference calculation²³ gives 8 kcal/mol for E_a for the same fragmentation, which encouraged us to proceed with MP2 calculations throughout this paper. However, a persistent difference between MP2 and PBE0 heats and energies of activation (details in SI), prevents us from claiming great reliability for the computed activation energies.

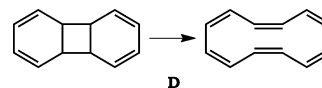
Turning to the second point, molecules high in energy may find ways out of their predicament, especially when allowed reactions are available. Even for such a seemingly tractable system as C₁₂H₁₂, the variety of such routes is daunting.²⁴ We've thought through the following four reaction types:

1. **1,5-Sigmatropic H-shifts.** These could occur in one six-carbon ring (A), twice in the same ring (B and C), or once in each of the two rings. *Trans*-bridging on a cyclobutane curls up the cyclohexadiene ring so as to predispose it for a suprafacial 1,5-H-shift. There are two more variants, three and four H-shifts, not shown here.

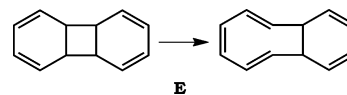
2. **Retrocyclizations,** “the other way around”. The general reaction type is D, fragmentation not to two benzenes but to 12-annulenes.²⁵ Reaction D is schematic, not (yet) meant to



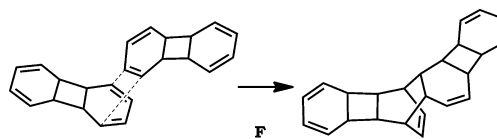
carry stereochemical information. The 12-annulenes themselves may transform easily to more stable molecules.



3. **Electrocyclic ring-openings (and closures).** The 2+2 dimers we propose contain cyclohexadiene rings. These are known to open reasonably readily if a symmetry-allowed disrotatory path leads to a viable product. A prototype reaction is shown in E. A sequence of such reactions could also lead to a 12-annulene, and cyclization of the butadiene part of the six-ring could form 4-membered rings.



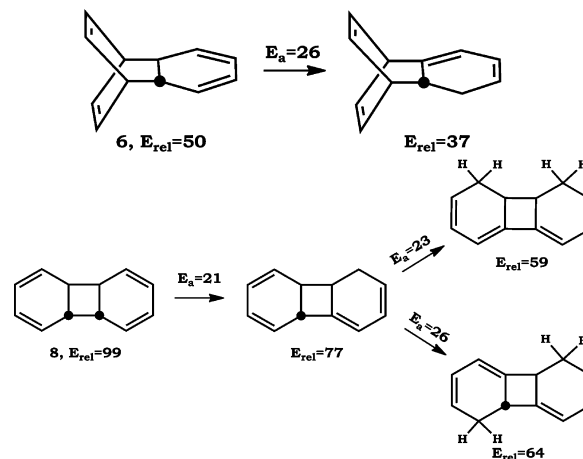
4. **Dimerization.** There are many possible dimers, but the most likely to us seem those proceeding by Diels–Alder reactions, typified by F.



We explored, in an incomplete but reasonably thorough way, these possibilities, with the following results:

1. **1,5-Sigmatropic shifts.** A sequence of several may occur, moving a H away from the bridgehead. We started by looking at the seven single shifts (details in SI). This was followed by an estimate of the energetics of all the double shifts. In Scheme 1

Scheme 1



we show the two sequences that have computed activation energies <30 kcal/mol. Here 30 kcal/mol is just an arbitrary

demarcation of a medium-energy process, one guaranteeing a half-life of months for a molecule. The numbers below the structures are the calculated energies relative to two benzenes; the numbers above the arrows are calculated activation energies.

2. Isomerizations to 12-annulenes. The allowed reactions are of **5** and **8** to (*Z,Z,Z,Z,Z,E*)-12-annulene, and **7** to (*Z,Z,Z,Z,Z,Z*) or to (*Z,Z,E,Z,Z,E*) geometrical isomers. The *Z/E* nomenclature is incomplete for 12-annulenes, for the molecules will exhibit a form of atropisomerism — conformations related to each other by formal rotations around single bonds, yet reasonably frozen into their geometries.²⁶ The relative energies of the annulenes and the dimers mentioned are shown in Figure 2. Clearly the thermodynamic driving forces for opening this way are not large, except for **8**.

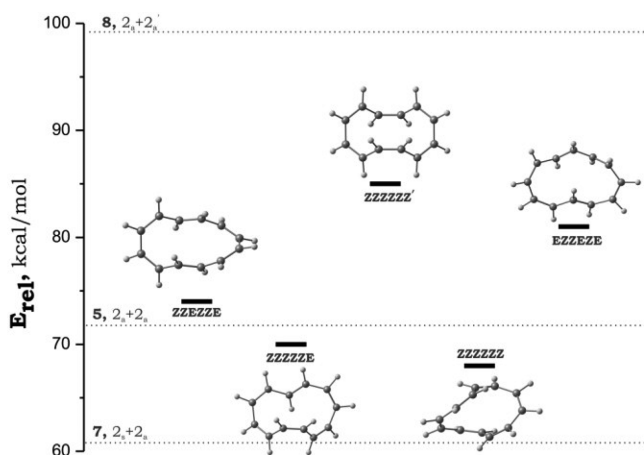


Figure 2. Relative energies of some selected benzene dimers and 12-annulene isomers.

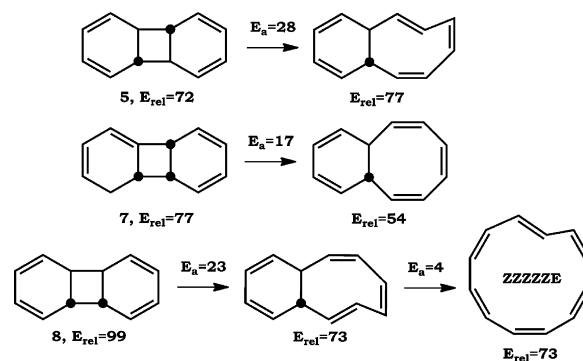
We have been unable to compute transition states for the allowed reactions to 12-annulenes. The activation energies involved are certainly high, the reaction paths are highly asymmetric (in terms of the bond-breaking sequence), and the high-energy waypoints so reached collapse not to the 12-annulenes but to various electrocyclic reaction products (next reaction class). We think that reactions to 12-annulenes are not a likely path for these dimers.

3. Electrocyclic ring-opening: One electrocyclic reaction will lead to a strained but possible (*Z,E,E*)-cyclooctatriene²⁷ for **5** and **8**. In **7** one allowed pathway leads to a (*E,E,E*)-cyclooctatriene. Two such reactions for **5**, **7**, and **8** will lead to a 12-annulene isomer, not necessarily the same one as reached by the retro-2+2 reaction mentioned above. For **6** the allowed electrocyclic reaction will lead to a *trans*-double bond in a 10-membered ring.

In Scheme 2 we show those paths that again have calculated activation energies <30 kcal/mol. One of the reaction products, the *trans*-fused bicyclo[6.2.0]^{1,8}dodecapentaene derived from **7**, is known.^{25,28} It was synthesized by a photochemical route from a tricyclic precursor. Note its relatively low energy, and the low activation energy leading to it.

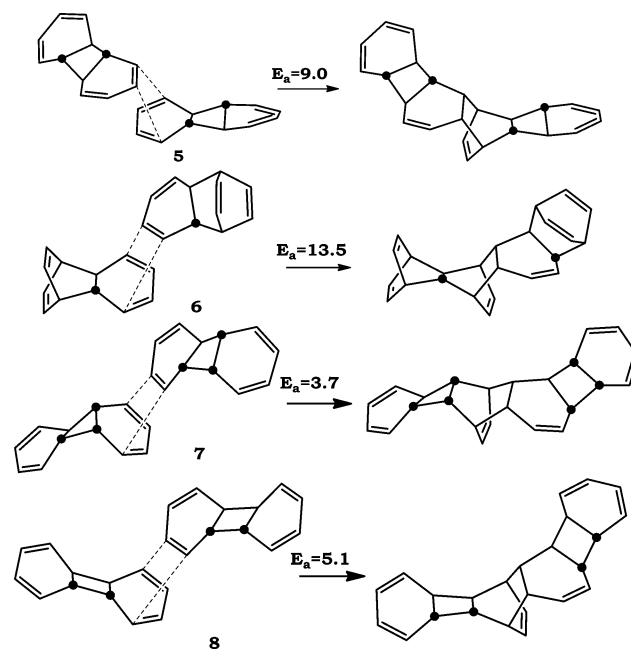
4. Dimerization. For survival under conditions other than in a noble gas matrix or the low-pressure gas phase, molecules must have significant activation barriers to dimerization. We could not study the dimerizations to ($C_{12}H_{12}$)₂ at such a high level as we did the dimers. What we did was RIJCOSX-PBE0/cc-pVTZ geometry optimizations for all dimerization products, followed by energy estimates from RIJCOSX-MP2/cc-pVTZ single-point calculations. Eighty distinct Diels–Alder dimeriza-

Scheme 2



tions of **5** (4 isomers), **6** (8 isomers), **7** (64 isomers), and **8** (4 isomers) were investigated (details in SI). A selection of reaction paths — those with lowest E_a (in kcal/mol) — one for each molecule, is given in Scheme 3.

Scheme 3



These are very low activation energy processes. One would despair about the possibility of making any amount of **5–8** under ambient conditions were it not for the very negative entropy of activation that their own dimerizations require.²⁹ At $T = 298$ K, the free energies of activation are ~ 15 kcal/mol higher than the listed E_a for all reactions.

To summarize: We find in our calculations four new benzene dimers, **5–8**, all with at least one *trans*-fused cyclohexadiene ring. In reasonable quality computations all of these predicted molecules have activation energies ≥ 27 kcal/mol for (forbidden) fragmentation to benzene, despite exothermicities of 50–99 kcal/mol.

But will the new dimers find escape routes? Despite great computational effort, we cannot unequivocally answer this question. The jailbreaking paths we find include sigmatropic-1,5-H-shifts (for **8**, $E_a = 21$ kcal/mol) and electrocyclic ring-opening (for **7**, $E_a = 17$ kcal/mol). Dimerization of the dimers via Diels–Alder reactions affords escape routes of still lower activation energy, but with associated negative

activation entropies. There's a reasonable chance of making one or more of the new dimers.

■ ASSOCIATED CONTENT

● Supporting Information

Details of calculations. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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