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Dispersion Interactions

Steric Crowding Can Stabilize a Labile Molecule: Solving the Hexaphenylethane Riddle**

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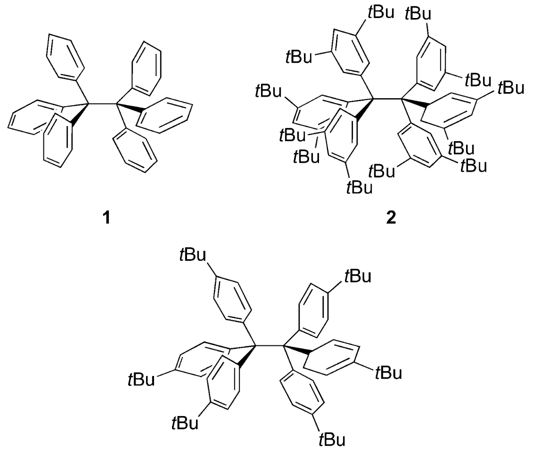
Dedicated to Professor Gerhard Erker on the occasion of his 65th birthday

Steric congestions has been made solely responsible for the thermodynamic instability of hexaphenylethane (**1**) (Scheme 1).[1] Despite many attempts, all synthetic approaches to preparing this seemingly simple molecule failed. It was not recognized until 1968 that Gomberg's[2] triphenylmethyl radical does not dimerize to give **1**[3] but instead a less symmetrical methylenecyclohexadiene isomer ({[4-(diphenylmethylene)cyclohexa-2,5-dien-1-yl]methanetriyl}tribenzene).[4] Equally, the tri(4-*tert*-butylphenyl)methyl radical does not dimerize to the corresponding ethane derivative (**3**).[5] The generic argument for the instabilities of these hexaphenylethane derivatives is steric repulsion of the phenyl groups, despite their favorable mutual local T-shaped benzene dimer type orientations. Yet, the sterically much more crowded all-*meta*-*tert*-butyl derivative (**2**) is stable at room temperature, and its crystal structure (m.p. = 214 °C) has been resolved.[6] How can the derivative of a molecule that dissociates owing to steric hindrance become stable by increasing steric bulk? We answer this question by demonstrating that **2** is being held together by extraordinarily strong London dispersions (the attractive part of van der Waals (vdW)) interactions that turn dimerization from an endothermic process for **1** and **3** into an exothermic one for **2** owing to many favorable CH⋯CH contacts[7] of the *tert*-butyl groups. Our unusual findings are in marked contrast to Mislow's 1981 statement that "*the tert-butyl groups have no special effect on the bonding parameters of* **2**",[1b] which is in line with common expectations; however, this does not provide a rationale for the stability of **2**.



Scheme 1. Hexaphenylethane (**1**), its all-*meta*- (**2**) and all-*para-tert*-butyl (**3**) substituted derivatives.

Visual inspection of molecular models (see Figure 1 for a space-filling model) of **2** suggests that it is indeed a sterically crowded molecule but also that the *tert*-butyl groups are not necessarily placed in critical positions and thus might not introduce significant Pauli repulsion to the phenyl ring contacts already present in **1**.[8] The electronic effect of the *tert*-butyl groups is expected to be small because of their long distance to the central C−C bond. Furthermore, even if a through-bond effect existed, it should stabilize the electron-deficient radical products of dissociation; it does so to some extent in **3**, which also dissociates into persistent radicals.[5] Solving this riddle, that is, why the all-*meta tert*-butyl groups have such a dramatic effect on the stability of **2** compared to **1** and **3** is the main objective of this work. Previous computa-

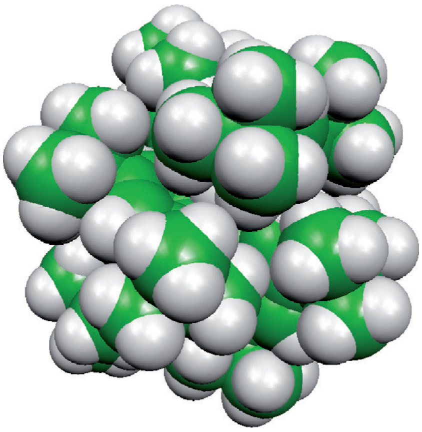


Figure 1. Optimized structure of **2** shown as a space-filling model. C green, H white.

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tions indicate that the bond dissociation energy (BDE) of **1** is only 16.6 kcal mol^{-1}.[9] We will show by state-of-the-art quantum chemical computations that an overwhelmingly large London dispersion energy between the bulky groups increases the small BDE, thus making **2** thermodynamically stable against symmetric dissociation into substituted trityl product radicals. Such stabilizing groups have recently been termed 'dispersion energy donors' by analogy to conventional electron-donor groups or substituents.[10] Stabilizing dispersion interactions have recently been shown to be responsible for the stability of dimeric forms of various diamondoids with unusually long C–C single bonds.[11] As we will show herein, structure **2** also represents a rare case of bond-length isomerism in a formal sense, meaning that two local energy minima of comparable depth occur along a normal bond stretching coordinate.[12]

The electronic correlation energy including its long-range attractive dispersion part is a quantum mechanically modulated many-particle effect. In recent years it has become a very active field of theoretical research[13] also because standard approximations of the widely used density functional theory (DFT) essentially lack long-range dispersion.[14] It also has become apparent that DFT approaches underestimate electron correlation effects at intermediate or short inter-atomic distances.[15] Ignoring these effects, termed originally medium-range correlation[15a] (or overlap-dispersive[16]), can lead to very inaccurate computational thermochemistry for rather common molecular reactions.[17]

All electronic structure calculations including full geometry optimizations of the ethane derivatives and the corresponding radical fragments were performed at the DFT level employing the TPSS *meta*-GGA functional[18a] (PBE[18b] for the potential curve) and our latest version of atom pair-wise dispersion correction[19] (in the Becke–Johnson[19c]-damping variant, for further details see Supporting Information). Dissociation energies (D_e) and central C–C bond lengths R(CC) are given in Table 1. We have used large TZV(2d,2p) (abbreviated TZV2P) basis sets[20a] that yield virtually converged results for the investigated properties (e.g., for **1** the computed C–C distance increases by less than 0.003 Å with a practically complete QZVP(-g,-f) AO basis[20b]). The TPSS-D3/TZV2P level has also been tested for the C–C dissociation of ethane (see the Supporting Information) for which we obtain a reasonable value of 92.0 kcal mol^{-1} compared to an accurate reference of 97.3 kcal mol^{-1}.[21] Such errors on the order of 5% for D_e are typical for the *meta*-GGA used.[22] In passing, we note that **2** contains 212 atoms (about 3200 contracted basis functions), which makes computations on higher (wave-function based) theoretical levels impractical at present. Our lowest energy structure **2** only has C_i symmetry (the molecule in the X-ray structure is S_6 symmetric); we also investigated two other conformations (both with S_6 symmetry) with the *tert*-butyl groups rotated. These were found to be higher in energy by 1.9 and 2.8 kcal mol^{-1}, respectively, but they exhibit very similar C–C bond lengths. We employ the lower lying S_6-symmetric structure for reasons of computational efficiency in the many geometry optimizations necessary for the potential energy curve (see below).

Table 1: Computed central C–C bond lengths [Å] and dissociation energies (D_e in kcal mol^{-1}) for the hexaphenylethane derivatives at the TPSS/TZV2P level of theory.[a]

	R(CC)	D_e	ΔG_{298}[b]
		DFT	
1	1.731	−16.6	−35.7
2	1.707	−26.4	−47.9
3	1.728	−16.7	−37.8
		DFT-D3	
1	1.713 (1.715[c])	10.1	−9.0[d]
2	1.661 [exp: 1.67(3)[e]]	35.2 (33.9[c])	13.7[f]
3	1.729	13.5	−6.6[d]

[a] Values with (DFT-D3) and without (DFT) dispersion corrections are given. [b] ΔG_{298} values <0 indicate an unstable ethane derivative (with respect to central C–C bond dissociation). [c] Value obtained with the huge QZVP(-g,-f) AO basis set for the TZV2P optimized structure. [d] Experimentally not observed. [e] Ref. [6]. [f] Experimentally observed.

The data in Table 1 show the overwhelmingly large effect dispersion has on the dissociation energies, while the equilibrium central C–C distances change only slightly. For **1** inclusion of dispersion shrinks the C–C bond by only about 0.018 Å, while the effect is larger for **2** (0.046 Å) and practically absent for **3**. Note, however, that excellent agreement, within the experimental error bars (notwithstanding crystal packing effects and vibrational corrections), with the observed value of about 1.67 Å[6] is only obtained when dispersion corrections are included.

The dispersion effects on the dissociation energies are much larger. Without dispersion, **1**–**3** are thermodynamically unstable with negative D_e values of −16.6, −26.4, and −16.7 kcal mol^{-1}, respectively. For the parent system **1**, inclusion of dispersion stabilizes the molecule compared to the free radicals by 26.8 kcal mol^{-1} leading to a positive D_e value of +10.1 kcal mol^{-1}. However, if zero-point vibrational, thermal, and entropic corrections are taken into account, the equilibrium resides entirely on the product side of the reaction (i.e., ΔG_{298} for dissociation is −9.0 kcal mol^{-1}). Thus, our results are fully consistent with the unsuccessful attempts to synthesize **1**. For **2** the dispersion stabilization is as large as 61.6 kcal mol^{-1} [23] and the DFT-D3 computed D_e value of 35.2 kcal mol^{-1} is consistent with a thermally labile (**2** slowly dissociates at room temperature in solution) but experimentally observable compound.[6] This important quantity has been also computed at the more accurate double-hybrid DFT level (PWPB95-D3[21]) from which we obtain a similar value of $D_e = 31.5$ kcal mol^{-1}. Under isolated molecule conditions (e.g., in matrix isolation or low-pressure in the gas phase), the computed (TPSS-D3) dissociation free energy ΔG_{298} is +13.7 kcal mol^{-1} (+10.0 kcal mol^{-1} for PWPB95-D3) as required for a bound molecular state. Structure **3** is thermodynamically unstable ($\Delta G_{298} = -6.6$ kcal mol^{-1}). It is evident that **2** can only be thermodynamically stabilized relative to **1** (and **3**) through the attractive dispersion interactions of the *all-meta-tert*-butyl groups. This important observation is in full agreement with the concept of dispersion energy donors introduced recently.[9]

Solvent effects on the dissociation free energy of **2** in cyclohexane have been estimated using the PCM and COSMO-RS solvation models (for details see the Supporting

Information). Corrections of 10.3 and 12.0 kcal mol^{-1} in favor of the radicals were obtained. These sizeable corrections are, however, almost an order of magnitude smaller than the intramolecular dispersion effect of about 60 kcal mol^{-1}. Subtracting this (average) solvent correction of 11 ± 2 kcal mol^{-1} from the gas phase ΔG_{298} value of 13.7 kcal mol^{-1} results in a dissociation free energy in solution of 1–5 kcal mol^{-1} (4 kcal mol^{-1} less using the D_e value obtained from the more accurate PWPB95 functional). Thus, within a relatively large uncertainty regarding the solvation effect, our results are compatible with a significant equilibrium concentration of the trityl radicals of **2** in solution. According to experimental results a solution of **2** in cyclohexane at ambient temperature is red, which suggests the presence of radicals.[24] However, we also cannot rule out that the complex $\mathbf{2}_{\mathrm{vdW}}$ is responsible for the visible absorption under these conditions.

Equally interesting is the dissociation mechanism. A delicate balance of covalent bonding and dispersion attraction/Pauli repulsion forces between the phenyl rings can be expected when the central C–C bond is broken. We conducted a detailed study of the potential energy curve along the central C–C bond stretching coordinate of **2** employing S_6 symmetry in the geometry optimization of all other degrees of freedom. Owing to the size of the system, we employed the computationally more efficient PBE-D3/TZVP level for the structure optimization and determined single-point energies using the TPSS-D3/TZV2P method as for the stationary points (Table 1) for consistency. These computations utilized unrestricted (U), spin-symmetry broken Kohn–Sham wave functions and S^2-spin expectation values (see the Supporting Information) of about unity as required for a biradical state were found for $R(\mathrm{CC}) > 3.5$ Å.

In the Supporting Information, we summarize a comparison of the results of various density functionals (employing the same methodological approximations) for the C–C bond breaking of ethane. Over the whole range of C–C distances the UDFT curves agree very well with those of the accurate UCCSD(T)/cc-pVTZ reference method. We also provide two potential energy curves for **2** using the B97-D3/TZV2P approach, which deviate only slightly from the one shown in Figure 2. We are thus confident that our computations not only yield basic and qualitative insight but also provide accurate energetics with estimated errors of 3–4 kcal mol^{-1}.

The TPSS-D3 curve in Figure 2 exhibits two minima at C–C distances of 1.67 and 5.28 Å, which are connected by a transition structure (**TS**) at $R(\mathrm{CC}) = 2.87$ Å. The minima correspond to the normal covalently bound ethane derivative **2** and a very strong van der Waals complex of the two radicals ($\mathbf{2}_{\mathrm{vdW}}$). As both minima lie in a comparably deep potential energy well (−33.2 and −26.6 kcal mol^{-1}, respectively) the system can be considered as bond-length isomeric (although from a more strict viewpoint this may be debated because the second minimum does not involve similar covalent bonding). For $\mathbf{2}_{\mathrm{vdW}}$, the forward barrier for dissociation is 17.0 kcal mol^{-1} while the reverse association barrier is 10.4 kcal mol^{-1}. This value is large enough so that $\mathbf{2}_{\mathrm{vdW}}$ should be experimentally observable at low temperatures.

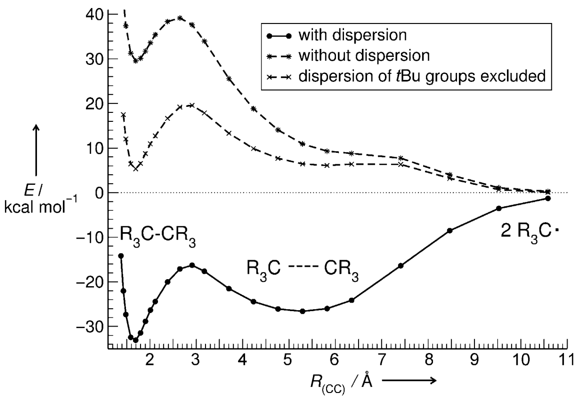

Figure 2. Computed (TPSS-D3/TZV2P//PBE-D3/TZVP) potential energy curves for dissociation of the central C–C bond for **2** with and without dispersion correction. Note the similar depths of the minima in the dispersion-corrected curve and the unbound state (positive interaction energies) without these corrections.

The transition structure is characterized by an intermediate biradical-like wave function ($S^2 = 0.41$) but practically no pyramidalization of the central carbon atom (the C-C-C bond angle sum amounts to 359.8°). This, together with the corresponding Wiberg bond order of 0.7, indicates that the covalent C–C bond is partially broken in the TS. The energy maximum apparently results from a competition between covalent attraction of the central carbon atoms and strong Pauli repulsion between the phenyl groups. An analysis of the dispersion contributions underscore these observations. Figure 2 includes data with and without D3-corrections and a curve for which all dispersion arising from the *tert*-butyl groups has been set to zero. The uncorrected plain TPSS curve shows the covalent C–C structure and the TS but not the second vdW minimum ($\mathbf{2}_{\mathrm{vdW}}$). Furthermore, the molecular energy is always higher than that of the free radicals, which again emphasizes the importance of dispersion. One of the nice features of the DFT-D3 approach is that the dispersion energy can easily be partitioned into different parts or groups of a molecule. The third curve without the *tert*-butyl contributions is most remarkable: While its shape is very similar to the plain TPSS curve, there is practically no vdW minimum and the interaction energies are positive. Thus, we conclude that the main dispersion stabilization of **2** results from the *tert*-butyl groups. From a methodological point of view these results once again[15,19,22] demonstrate the importance of dispersion corrections for DFT of large systems, as most, if not all, standard density functional approximations would provide inconsistent thermochemical data for **1**–**3**. We therefore also suggest **1** and **2** as challenging test systems for future DFT developments describing intramolecular dispersion effects.

We also note that **2** with two strongly bound states, in principle, represents a "molecular machine" that can transform about 17 kcal mol^{-1} of energy (the forward barrier) into a 4 Å mono-directional movement of the central carbons atoms. The expansion of the entire aggregate, however, is much less (about 1 Å) owing to rehybridization of the radical centers.

In summary, the overall repulsive phenyl–phenyl interactions in **1** are overcompensated in **2** by addition of "steric crowding" in the form of *all-meta tert*-butyl groups that serve as "dispersion energy donors" that provide overall positive stabilization through attractive dispersion interactions. The stability of **2** and the instability of **1** as well as **3** can be fully explained on thermodynamic grounds. All computations agree qualitatively as well as quantitatively with experiment. The *tert*-butyl groups stabilize **2** compared to its dissociation product radicals by as much as 40 kcal mol^{-1}.

The present system is a prime example of the effect of "dispersion energy donors". Loosely speaking, **2** is held together thermodynamically by its own solvent cage. Although the described spectacular effects of dispersion will partially be quenched in solution, we expect the application of these findings to stabilizing reactive intermediates and in the design of catalysts, and also note a strong relation to the growing field of frustrated Lewis pair chemistry.[25]

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[23] That the dispersion contribution is so large might be surprising at first glance but can be derived by a simple treatment. The molecule **2** with 212 atoms is dissociated into two fragments with 106 atoms each. The number of (dispersion)interacting atom pairs in the molecule is $106^2 = 11\,236$. Taking the average of C(sp^3) and H(in H_2) C_6 dispersion coefficients (about 10 a.u.) and assuming an average interatomic distance between the particles of 10 Bohr in **2** an inter-fragment dispersion energy of $E(\mathrm{disp}) \approx 11\,000 \times 10/10^6 = 0.11\,E_\mathrm{h} = 70$ kcal mol^{-1} is obtained, which is very close to the "true" value of about 61 kcal mol^{-1}.

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