Multiple Buttressing Interactions: Enantiomerization Barrier of Tetrakis(pentamethylphenyl)ethene

Katsuhiro Maeda,† Yoshio Okamoto,† Orly Toledano,‡ Dan Becker,‡,§ Silvio E. Biali,⊥ and Zvi Rappoport*,⊥

Department of Applied Chemistry, Faculty of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464, Japan, Department of Chemistry, Technion–Israel Institute of Technology, Haifa 32000, Israel, and Department of Organic Chemistry, The Hebrew University of Jerusalem, Jerusalem 91904, Israel

Received April 22, 1994

Introduction

Buttressing effects are indirect steric effects which may occur when a bulky substituent is adjacent to a group directly involved in steric interactions.[1] The introduction of a potentially buttressing substituent may affect chemical reactivity, equilibria, and/or rotational barriers by hindering modes of steric relief (such as the widening of bond angles) which are available in the unsubstituted molecule for the sterically crowded group. In the case of rotational processes, buttressing effects usually result in an increased barrier (a "normal" buttressing effect), but when the ground state is the one mostly affected, a lower rotational barrier results (an "inverse buttressing effect").[2] We have recently studied buttressing effects on di- and triaryl doubly bonded systems.[3] For systems **1**, the introduction of four *m*-Br or *m*-Me groups resulted in minor effects on the ground-state geometry and in moderate effects on the two observed rotational processes. The barrier for the one-ring flip process increased with the introduction of the meta substituents, while the barrier for the two-ring flip decreased.[3b]

$Ar_2C{=}C(OH)R$ $Ar_2C{=}CAr_2$

1: Ar = 2,4,6-$Me_3C_6H_2$, R = H, Me, *t*-Bu, Mes

2: Ar = 2,4,6-$Me_3C_6H_2$

3: Ar = 3,5-Br_2-2,4,6-Me_3C_6

4: Ar = 2,3,4,5,6-Me_5C_6

$Ar_2C{=}C{=}O$

5: Ar = 2,4,6-$Me_3C_6H_2$

6: Ar = 2,3,4,5,6-Me_5C_6

We have recently studied the enantiomerization of the chiral tetramesitylethene (**2**).[4,5] The compound enantiomerizes with a barrier of $\Delta G^{\ddagger} = 39.6$ kcal mol^{-1} which is exclusively due to enthalpy ($\Delta H^{\ddagger} = 39.6$ kcal mol^{-1}, $\Delta S^{\ddagger} = 0$ cal mol^{-1} K^{-1}).[5] Substitution of the eight meta positions by bromine (cf. **3**)[6] or methyl groups should result in systems with multiple buttressing effects, where these effects may mutually reinforce the phenomena mentioned above. In this Note we report the preparation and the enantiomerization barrier of tetrakis(pentamethylphenyl)ethene (**4**), an analogue of **2** displaying multiple buttressing interactions.

Results and Discussion

Preparation and NMR Spectra of 4. Zimmerman and Paskovich have obtained ethene **2** by irradiation of dimesitylketene (**5**).[4] In analogy, we irradiated the previously described bis(pentamethylphenyl)ketene (**6**)[3b] and isolated 16% of **4**. Ethene **4** displayed in the ^{1}H NMR (400 MHz, $CDCl_3$) five signals and in the ^{13}C NMR four aliphatic signals (two methyl signals are accidentally isochronous) and seven sp^2 carbon signals. The diastereotopicity observed for ortho and meta pairs of signals in the NMR spectra is in agreement with a frozen "propeller" conformation, on the NMR timescale, of D_2 symmetry.

Crystal Structure of 4. A single crystal of **4** was grown from CH_2Cl_2 and submitted to X-ray analysis. Unfortunately, the structure could be refined only down to a relative high *R* value (0.138) and therefore only the gross features of the structure are reliable. The compound exists in a propeller conformation. In contrast to **2**, which displays crystallographic D_2 symmetry,[7] **4** displays in the crystal C_2 symmetry, i.e., two different Ar–C=C torsional angles are displayed by the aryl rings. These angles are 57° and 63°, somewhat higher than the reported angles for **2** (54.6°).

Molecular Mechanics Calculations. In order to assess the buttressing effect on the ground-state conformation of **4**, we calculated the structures of both **4** and **2** by the MM3(92) program.[8] Both systems exist in conformations with D_2 symmetry, indicating that the deviation from this symmetry observed in the crystal for **4** is likely to be due to packing forces. The calculated conformation of **4** is shown in Figure 1. According to the calculations, the introduction of eight *m*-methyl groups into **2** results mainly in distortions of the aryl rings from planarity (the six endocyclic dihedral angles range from 3.2° to 9°) and an elongation of the central C=C bond (1.379 Å for **2**, 1.384 Å for **4**) and the C–Ar bonds (1.513 Å for **2**, 1.520 Å for **4**). Notably, the Me–C_{ortho}–C_{ipso} angles are larger for **2** (124.9° and 123.5°) than for **4** (122.5° and 121.9°). These structural differences are most likely manifestations of ground-state buttressing effects. Ethene **2** relieves the repulsive mutual steric interactions between the ortho methyl groups by opening the Me–C_{ortho}–C_{ipso} angles. The additional *m*-methyls "buttress" the ortho methyl groups by disallowing the relief of steric strain by opening the internal Me–C–C angles. In order to alleviate the steric interactions, the central C=C as well as the Ar–C=C bonds are elongated. This elongation enables the adoption of smaller torsional angles (51.8°) than those calculated for **2** (54.2°).

† Faculty of Engineering, Nagoya University.
‡ Department of Chemistry, Technion.
§ Deceased, April 7, 1994.
⊥ Department of Organic Chemistry, The Hebrew University.

(1) Rieger, M.; Westheimer, F. H. *J. Am. Chem. Soc.* **1950**, *72*, 19. Chein, S. L.; Adams, R. *J. Am. Chem. Soc.* **1934**, *56*, 1787. Westheimer, F. H. In *Steric Effects in Organic Chemistry*; Newman, M. S., Ed.; Wiley: New York, 1956; Chapter 12, p 552. Armstrong, R. N.; Ammon, H. L.; Darnow, J. N. *J. Am. Chem. Soc.* **1987**, *109*, 2077.

(2) Yamamoto, G.; Suzuki, M.; Oki, M. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 809. Oki, M. *Top. Stereochem.* **1983**, *14*, 1.

(3) (a) Biali, S. E.; Gozin, M.; Rappoport, Z. *J. Phys. Org. Chem.* **1989**, *2*, 271. (b) Eventova, I.; Nadler, E. B.; Rochlin, E.; Frey, J.; Rappoport, Z. *J. Am. Chem. Soc.* **1993**, *115*, 1290.

(4) Zimmerman, H. E.; Paskovich, D. H. *J. Am. Chem. Soc.* **1964**, *86*, 2149.

(5) Gur, E.; Kaida, Y.; Okamoto, Y.; Biali, S. E.; Rappoport, Z. *J. Org. Chem.* **1992**, *57*, 3689.

(6) Preliminary Molecular Mechanics calculations (ref 5) predicted a lower rotational barrier for **3** than for **2**.

(7) Blount, J. F.; Mislow, K.; Jacobus, J. *Acta Crystallogr., Sect. A* **1972**, *28*, 512. Nazran, A. S.; Lee, F. L.; Gabe, E. J.; Lepage, Y.; Northcott, D. J.; Park, J. M.; Griller, D. *J. Phys. Chem.* **1984**, *88*, 5251.

(8) Allinger, N. L. *Molecular Mechanics. Operating Instructions for the MM3 Program. 1989 Force Field (updated 5/6/92).* Technical Utilization Corporation.

0022-3263/94/1959-5473$04.50/0

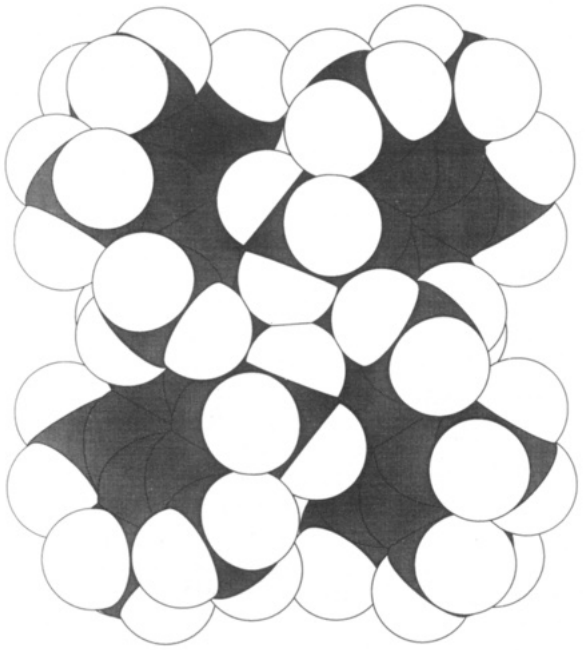

Figure 1. Calculated (MM3) conformation of tetrakis(pentamethylphenyl)ethene **4**.

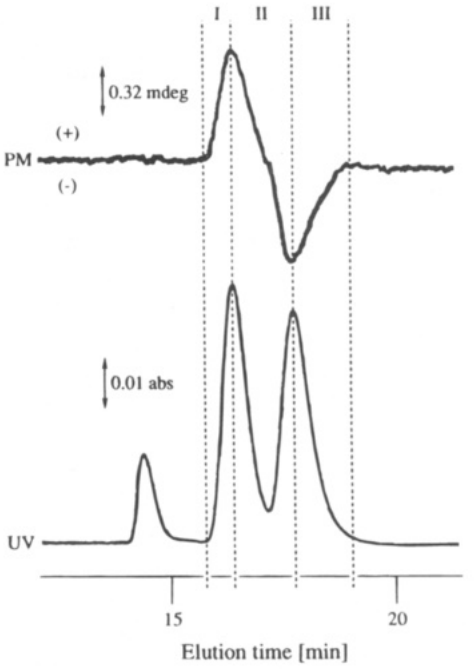

Figure 2. Resolution of **4**. Lower trace: UV absorption. Fraction I consists of optically pure (+)-isomer. Upper trace: optical activity of the eluted solution.

Enantiomerization Barrier of 4. (a) MM Calculations. We have previously calculated[5] the rotational barrier of **2** using the MM2 program as implemented in MACROMODEL.[9] However, the calculated barriers for the three-ring and four-ring flip processes (21.8 and 35.2 kcal mol^{-1}, respectively) were substantially lower than the measured enantiomerization barrier. We noted also that in the calculated transition structure all the rings were severely distorted. We have recently shown for several polyarylvinyl systems that if, in addition to the constrains of all C_{ortho}—C_{ipso}—C=C units to ±90°, the =C—C_{ipso}—C_{ortho}—C_{meta} angles are constrained to 180° in the calculation of the transition structure for the ring flip processes, the calculated steric energy differences are similar to the experimental $\Delta G^{\ddagger}$ values for the systems.[10] With these constrains, barriers of 40.3 and 43.4 kcal mol^{-1} can be calculated for **2** and **4**. The calculations predict therefore a rise in the rotational barrier due to the buttressing effect.

(b) Resolution and Experimental Determination of the Enantiomerization Barrier. For the determination of the enantiomerization barrier, we resolved **4** by preparative HPLC using cellulose tris(3,5-dimethylphenylcarbamate) (Figure 2). The first fraction collected consisted of the optically pure (+)-isomer ($[\alpha]_D$ +700° in $CHCl_3$) while the third fraction consisted of the (−)-isomer admixed with small amounts of the (+)-isomer.

The racemization of the dextrorotatory enantiomer of **4** in *n*-pentadecane at 513, 518, 523, 528, 533 and 538 K was followed by HPLC. From the data (Table 1), the activation parameters $\Delta G^{\ddagger} = 43.1 \pm 0.1$ kcal mol^{-1}, $\Delta H^{\ddagger} = 39.6 \pm 4.2$ kcal mol^{-1}, and $\Delta S^{\ddagger} = -6.7 \pm 7.9$ cal mol^{-1} K^{-1} (at 523 K) for the enantiomerization process were calculated. Whereas the error in $\Delta G^{\ddagger}$ on which we base our main conclusion is rather small, the errors in $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ are relatively large. This is due to the narrow temperature range in which the racemization could be studied experimentally. We therefore conclude that the introduction of the *m*-Me groups into **2** results in a rise in the rotational barrier and that the buttressing effect is not large, even in the extreme case that eight such groups are present. Notwithstanding the errors, the higher barrier found for **4** is apparently due to the entropy term, since the enthalpy of activation is similar for both **2** and **4**. The presence of an entropic contribu-

Table 1. Racemization Data for 4 in *n*-Pentadecane[a]

temp (K)	time (h)	ee, %	k_{enant} (s^{-1})
513	7	87.2	0.50×10^{-5}
	15	57.1	
	25	38.0	
	40	25.8	
518	5	81.9	0.72×10^{-5}
	10	50.3	
	15	34.2	
	26	22.5	
	32	18.8	
523	3.5	76.8	1.06×10^{-5}
	7	59.7	
	13	38.9	
	27	12.8	
528	2	86.9	1.45×10^{-5}
	5	59.1	
	8	48.6	
	10	33.5	
	14	24.2	
533	1	92.5	1.68×10^{-5}
	5	53.1	
	10	29.4	
	20	9.0	
538	2	58.0	3.77×10^{-5}
	4	44.2	
	6	26.7	
	8	11.3	
	11	5.8	

[a] $2k_{enant} = k_{racemization}$.

(9) Still, W. C.; Mohamadi, F.; Richards, N. J. G.; Guida, W. C.; Liskamp, R.; Lipton, M.; Caufield, C.; Chang, G.; Hendrickson, T. *MACROMODEL V 3.0,* Department of Chemistry, Columbia University, New York.

(10) Rochlin, E.; Rappoport, Z. *J. Org. Chem.* **1994**, *59*, 3857.

(11) The resolution of **4** was difficult since the HPLC column lost its ability to resolve the ethene in a short time. However, the stationary phase recovered its resolving ability when it was treated with THF and packed again.

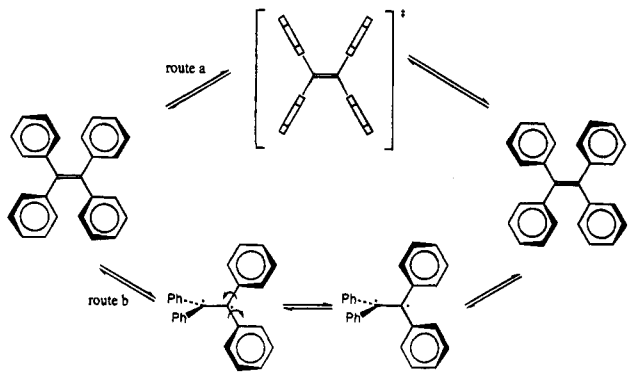

Figure 3. Possible enantiomerization pathways of a tetraarylethene demonstrated for $Ph_2C{=}CPh_2$. (a) Four-ring flip rotation (three-section rectangle designates a phenyl ring perpendicular to the double bond plane). (b) Double bond rotation followed by helicity reversal of the two diarylmethyl subunits (one shown) in the biradical intermediate.

tion is in contrast with the behavior of the parent **2**, for which $\Delta S^{\ddagger} = 0$ cal mol^{-1} K^{-1} for the enantiomerization. The negative entropic contribution found for **4** indicates that in this system the torsional motions of the methyls are more restricted in the transition state than in the ground state.[12] Interestingly, the experimental barriers ($\Delta G^{\ddagger}$) of both **2** and **4** are well reproduced by the MM2 calculations for a four-ring flip.

Threshold Enantiomerization Route. The enantiomerization barriers found for **2** (39.6 kcal mol^{-1}) and **4** (43.1 kcal mol^{-1}) are the highest values obtained so far for enantiomerization of polyarylvinyl propellers. Lower enantiomerization barriers were found for certain overcrowded tetraarylethenes in which pairs of geminal rings are tied as tricyclic moieties.[13] The high barriers found raise the possibility, in addition to enantiomerization via ring rotations around the Ar—C= bonds (Figure 3, route a) of an enantiomerization route involving double-bond rotation via a rate-determining opening to biradical, internal Ar—C rotations in the latter and reformation of the double bond (Figure 3, path b). That path b cannot be *a priori* excluded is shown by the barriers for double-bond rotation of tetraarylethenes,[14] e.g., for the $E \rightleftharpoons Z$ isomerization of 1,2-bis(*p*-methylphenyl)-1,2-diphenylethene, $E_a = 35.3$ kcal mol^{-1} and $\Delta S^{\ddagger} = -3.7$ cal mol^{-1} K^{-1}. The small para substituent effect observed[14] suggests small polar effects of the *o*-Me and *m*-Me groups of **4** and if steric effects do not increase the barrier appreciably, path b may be the threshold enantiomerization route. Consequently, it is not possible at present to discern unequivocally which route represents the threshold enantiomerization pathway for **2** and **4**. However, it is important that even if route b is the lowest energy enantiomerization route, the barrier for the four-ring flip rotation should be higher than the observed one, i.e, ≥43.1 kcal mol^{-1}. A search for derivatives of **2** and **4** where the threshold enantiomerization route could be determined is in progress.

Experimental Section

The preparation of ketene **6** was described previously.[3b]

Tetrakis(pentamethylphenyl)ethene (4). **6** (718 mg, 2.15 mmol) dissolved in 80 mL of cyclohexane was irradiated (80-W immersion lamp, N_2 atmosphere, 10 °C) and the progress of the reaction followed by TLC (silica, eluent: hexane). After all the starting material reacted, the solvent was evaporated and the residue chromatographed (silica Merck 70–230 mesh, eluent: hexane), yielding 95 mg of **4** (16%) as a white solid, mp 340–345 °C (from CH_2Cl_2). ^{1}H NMR ($CDCl_3$, 400 MHz, rt): δ 1.64, 1.67, 1.79, 2.02, 2.13 ppm. ^{13}C NMR ($CDCl_3$, 100.614 MHz, rt): δ 16.79, 16.91, 19.01, 21.67, 131.11, 131.69, 131.96, 133.21, 134.48, 141.21, 145.49 ppm. EI MS: *m*/*z* 612 (M, B), 307, 291, 276, 147, 84. HRMS: calcd for $C_{46}H_{60}$ *m*/*z* 612.4695, found *m*/*z* 612.4690. Anal. Calcd for $C_{46}H_{60}$: C, 90.13; H, 9.87. Found: C, 90.36; H, 9.55.

Resolution of 4. The preparative optical resolution of **4** was performed with a Jasco 880-PU instrument equipped with Jasco 875-UV and Shodex OR-1 detectors and three cellulose tris(3,5-dimethylphenylcarbamate) HPLC columns (25 × 0.46 cm × 3) (eluent isooctane, flow rate 0.5 mL/min, pressure 34 kg/cm^2). Only 0.075 mg of the sample could be resolved in each run and 40 runs were repeated in order to separate 3 mg. The sample was fractionated into three fractions. Fraction I appeared optically pure ((+)-isomer) while fraction III was the (−)-isomer still containing about 6% of the (+)-isomer.

Acknowledgment. We are indebted to Dr. Irina Eventova for the crystallization of **4**. This research was supported by the Israel Science Foundation administered by the Israel Academy of Sciences and Humanities.

(12) Lii, J. H.; Allinger, N. L. *J. Am. Chem. Soc.* **1989**, *111*, 8566.
(13) Agranat, I.; Suissa, M. R. *Struct. Chem.* **1993**, *4*, 59 and references therein.
(14) Leigh, W. J.; Arnold, D. R. *Can. J. Chem.* **1981**, *59*, 609. See also: Leigh, W. J.; Frendo, D. T.; Klawunn, P. J. *Can. J. Chem.* **1985**, *63*, 2131.