tional effects involving ligand specificity and quaternary state electronic factors ($\Delta_v^T \neq \Delta_v^R$) can also be considered. Using the experimentally determined values for the ratios at 298 K, we solve eq A6 for ϵ_s and $f_s x_0^2/2$ to find

$$\epsilon_s \sim 2.4 \text{ kcal/mol} \qquad \text{(A7a)}$$

$$f_s x_0^2/2 \sim 1.4 \text{ kcal/mol} \qquad \text{(A7b)}$$

These values are in reasonable agreement with the theoretical estimates[30,45] used above. Additional refinement in the relative binding and dissociation rates can be accomplished by small variations in the other parameters (e.g., H_D, Δ_v, and D_s).

Further details involving diffusion control of the kinetics and ligand-dependent cooperative effects[35,57,58] will not be considered in quantitative detail at this time. However, the kinetic results involving carp Hb[58] are problematic, particularly since conclusions are based on a theoretical analysis[7] that has been shown[8] not to extrapolate to the high-temperature limit. An alternative[58] extrapolation of the low-temperature kinetics to the high-temperature regime may be flawed since it does not allow for protein diffusion when $T > T_f$. It seems that the low-temperature barrier height distributions for the R and T states may not be uniquely determined and, in any case, they have been incorrectly applied to calculate the high-temperature rates.[58] If we go beyond the simplified estimates of eq A6, we can derive the formal expressions for the barrier height, even for a more complicated molecule such as Hb. In this case we must acknowledge that $f_q \ll f_s$ (as discussed above) so that convenient substitution, $\alpha^2/f = \sigma_a^2/k_BT$, in eq 31–33 can no longer be made. Instead we calculate

$$E_A = H_D + \tfrac{1}{2}K\alpha_0^2(1 + K\alpha^2/f_q)^{-1} \qquad \text{(A8a)}$$

$$k_0' = k_0(1 + K\alpha^2/f_q)^{-1/2} \qquad \text{(A8b)}$$

If we now ask which of the deoxy structures is more flexible (the T or R state) we expect that $f_q^T > f_q^R$, reflecting the stabilization of the quaternary T-state structure due to the hydrogen bonds and salt bridges. From eq A8a we see that, when $f_q^T > f_q^R$, the extrapolation to high temperature will increase the barrier height more for the T state than for the R state. This is precisely the effect observed by Cobau et al.[58] Although a complete and careful reanalysis of the entire data set is probably called for, it is also noteworthy that these authors[58] find Δ^T to be significantly larger than Δ^R using the Agmon–Hopfield approach. This is further experimental evidence in support of the hypothesis that a significant amount of Stokes shift and/or crystal field electronic stabilization energy is present in the unligated T state of Hb.

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(57) Szabo, A. *Proc. Natl. Acad. Sci. U.S.A.* **1978**, *75*, 2108–2111.

(58) Cobau, W. G.; LeGrange, J. D.; Austin, R. H. *Biophys. J.* **1985**, *47*, 781–786.

Determination of the Central Bond Length in Hexaarylethanes by Nutation NMR Spectroscopy

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Abstract: The lengths of the central bonds, r_c, in [α,α'-$^{13}C_2$]hexakis(2,6-di-*tert*-butyl-4-biphenylyl)ethane (**1**) and [α,α'-$^{13}C_2$]hexakis(3,5-di-*tert*-butylphenyl)ethane (**2**) have been determined by nutation NMR spectroscopy. The dipolar spectra obtained by this method were compared with computed spectra in which the central bond length was the only adjustable parameter. Best fits of the experimental and computed spectra were found to correspond to a r_c value between 1.64 and 1.65 Å for both compounds. These results are in excellent agreement with the X-ray value of r_c in **2** and provide the first direct experimental evidence that the reported[4] X-ray value of r_c in **1** is grossly in error.

Hexaphenylethane (HPE) has had an exceptionally colorful history for a molecule that has yet to be synthesized. For more than half a century following Gomberg's discovery of triphenylmethyl,[2] its dimer was believed to be HPE. It was not until 1968 that the correct structure of the dimer, first proposed by Jacobson in 1905, was elucidated by Lankamp, Nauta, and MacLean.[3] In 1978 Stein, Winter, and Rieker reported the first synthesis of an unbridged hexaarylethane, hexakis(2,6-di-*tert*-butyl-4-biphenylyl)ethane (**1**).[4] The X-ray structure of **1** featured the abnormally short central carbon–carbon bond length (r_c) of 1.47 (2) Å, a finding of no small import since just the year before we had reported our calculation, by the empirical force field method, of an abnormally long r_c (1.64 Å) for HPE.[5] A subsequent and more elaborate computational study[6] not only confirmed the original conclusions[5] in all essential details but predicted r_c = 1.64 Å (MM2) for **1** as well. Most recently we found[7] that r_c = 1.67 (3) Å in the X-ray structure of hexakis(3,5-di-*tert*-butylphenyl)ethane (**2**), a compound closely related to **1**. Moreover, the calculated (MM2) value of this parameter was 1.65 Å.[7]

In light of the computational studies[5-7] and the X-ray structure of **2**,[7] it would seem safe to dismiss the claim[4] for bond shortening in **1**. Nevertheless, with the single exception of the calculated

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(1) (a) IBM Almaden Research Center. (b) Princeton University.

(2) Gomberg, M. *J. Am. Chem. Soc.* **1900**, *22*, 757; *Ber. Dtsch. Chem. Ges.* **1900**, *33*, 3150.

(3) Jacobson, P. *Ber. Dtsch. Chem. Ges.* **1905**, *38*, 196. Lankamp, H.; Nauta, W. Th.; MacLean, C. *Tetrahedron Lett.* **1968**, 249. See also: McBride, J. M. *Tetrahedron* **1974**, *30*, 2009.

(4) Stein, M.; Winter, W.; Rieker, A. *Angew. Chem.* **1978**, *90*, 737; *Angew. Chem., Int. Ed. Engl.* **1978**, *17*, 692. See also: Winter, W. *Fresenius' Z. Anal. Chem.* **1980**, *304*, 279. Winter, W.; Butters, T.; Rieker, A.; Butsugan, Y. *Z. Naturforsch.* **1982**, *37b*, 855. Winter, W.; Moosmayer, A.; Rieker, A. *Ibid.* **1982**, *37b*, 1623.

(5) Hounshell, W. D.; Dougherty, D. A.; Hummel, J. P.; Mislow, K. *J. Am. Chem. Soc.* **1977**, *99*, 1916. The AM force field was used: Andose, J. D.; Mislow, K. *J. Am. Chem. Soc.* **1974**, *96*, 2168.

(6) Ōsawa, E.; Onuki, Y.; Mislow, K. *J. Am. Chem. Soc.* **1981**, *103*, 7475.

(7) Kahr, B.; Van Engen, D.; Mislow, K. *J. Am. Chem. Soc.* **1986**, *108*, 8305. Correction: the included solvent molecules are located at Wyckoff *d*, a site of D_{2d} symmetry, rather than at Wyckoff *b*, a site of D_{2h} symmetry.

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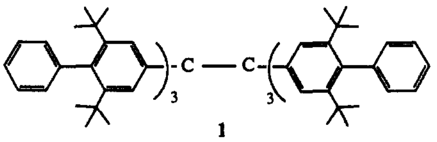

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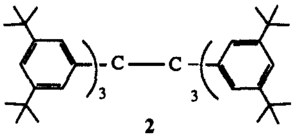

2

value of r_c,[6] all of the evidence against this claim is indirect, and although the excellent agreement between calculated and observed central bond lengths in **2** provides strong supporting evidence,[8] it might be contended that the six biphenylyl groups in **1** are in some unknown way responsible for the observed bond shrinkage, and that this special effect is not taken account of in the parametrization of the computational schemes employed. Thus direct *experimental* evidence is needed to cinch the argument.

Stein et al. noted that it took them seven months to grow crystals of **1**, which were of "poor quality".[4] We were unable to obtain crystals of **1** suitable for X-ray diffraction. Colorless microcrystals preciptated from methylcyclohexane and cyclooctane after a few weeks. Large hexagonal prisms with visible striations emanating laterally from the sixfold axis were grown from cyclohexane. These crystals effloresced extremely rapidly at room temperature and could be examined and mounted only under a protective layer of water. Ultimately, the crystals were flame-sealed in thin-walled glass capillaries containing additional cyclohexane. Rotation photographs obtained from these samples were characteristic of powders.

It therefore became necessary to measure r_c by a method that does not require long-range order in the sample. Nutation NMR spectroscopy, previously developed[9] and applied to other structural problems,[10] is uniquely suited as a method for determining the distance between the nuclei of a dilute homonuclear spin pair in amorphous solids or powders of complex molecules. The ethane carbons of a hexaarylethane doubly enriched in ^{13}C provide the requisite spin system for such a determination.

Results and Discussion

Materials. [α-^{13}C]Tris(2,6-di-*tert*-butyl-4-biphenylyl)methanol[11] and [α-^{13}C]tris(3,5-di-*tert*-butylphenyl)methanol[12] were prepared by the addition of 2,6-di-*tert*-butyl-4-biphenylyllithium and 3,5-di-*tert*-butylphenyllithium to [^{13}C]phosgene. The carbinols were converted to the triarylmethyl chlorides with acetyl chloride as previously described.[11,12] Degassed benzene solutions of the chlorides were treated with silver powder to produce solutions of the triarylmethyl radicals.[11,12] After filtration, the solvent was evaporated and the residual orange solids were redissolved in degassed cyclohexane. Small colorless crystals of **1** and **2**[4] containing cyclohexane of crystallization were grown in 1 week by carefully controlling the solvent volume.

The crystals were dried, ground, and packed into thin-walled Pyrex tubes in preparation for the nutation experiments. The ^{13}C-enriched ethanes were not diluted in a matrix of the unenriched material[10] because co-dissolution of labeled and unlabeled ethanes would result in triarylmethyl exchange, with most of the label ending up in the ^{12}C–^{13}C ethane bonds. Fortunately, the six highly substituted phenyl groups provide an insular environment for ^{13}C–^{13}C spin pairs and intermolecular homonuclear dipolar broadening is thus minimized.

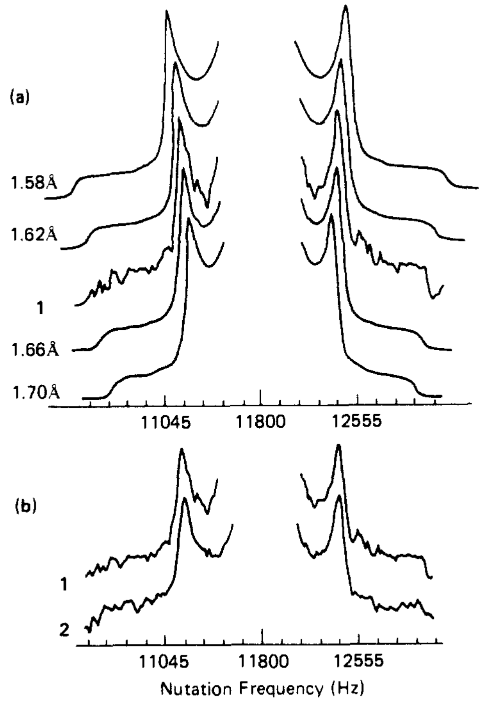

Figure 1. (a) ^{13}C-Nutation NMR spectrum of hexakis(2,6-di-*tert*-butyl-4-biphenylyl)ethane (**1**) compared with simulated spectra calculated for various central bond distances. (b) Comparison of the experimental spectrum of hexakis(2,6-di-*tert*-butyl-4-biphenylyl)ethane (**1**) and hexakis(3,5-di-*tert*-butylphenyl)ethane (**2**) showing the near superposition of the doublet features. The large center peaks, due to isolated natural abundance ^{13}C, have been cropped for clarity.

Nutation Spectroscopy. The splitting due to the magnetic dipole–dipole coupling in a solid-state ^{13}C NMR spectrum contains, in principle, the information necessary for the determination of carbon–carbon bond lengths. This interaction is a function of r^{-3} and is in the kHz range for ^{13}C–^{13}C bonds. However, specific metrical information is typically obscured in the normal spectrum obtained from the FID of a large molecule due to sundry heteronuclear and long-range homonuclear dipole–dipole interactions as well as the chemical shift anisotropy of the individual carbon atoms. Selective labeling and spin dilution highlight the dipolar interaction of interest while reducing to a negligible degree the effects of long-range homonuclear coupling. The nutation sequence is employed to suppress heteronuclear dipolar broadenings and chemical shift anisotropy. In this way all isolated ^{13}C spins are collected into a narrow center line, leaving a single dipolar splitting due to the doubly labeled pair unobscured.

The details of the nutation NMR experiment have been described elsewhere.[9,10] In brief, the carbon magnetization was generated with proton cross-polarization.[13] Without delay, a strong train of radio frequency pulses was applied and the magnetization was captured in windows in this pulse train. The carbon spins consequently experience a quasi-continuous radio frequency field. Proton spin-lock decoupling accompanied the nutation sequence to minimize heteronuclear dipolar interactions.

Data were collected in the manner described and spectra were recorded for both **1** and **2**. These spectra consist of a sharp center line arising from isolated ^{13}C nuclei in the sample with a broad doublet symmetrically disposed about it. The doublets are derived from the analytical function shown by Pake to arise from an axial

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[8] Force field calculations are remarkably successful in predicting substantial elongation of bonds between tetracoordinate carbon atoms in highly strained molecules. For a recent example, see: Flamm-ter Meer, M. A.; Beckhaus, H.-D.; Peters, K.; von Schnering, H.-G.; Rüchardt, C. *Chem. Ber.* **1985**, *118*, 4665. See also: Rüchardt, C.; Beckhaus, H.-D. *Top. Curr. Chem.* **1986**, *130*, 1 and references therein. Rüchardt, C.; Beckhaus, H.-D. *Angew. Chem.* **1985**, *97*, 531; *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 529 and references therein.

[9] (a) Yannoni, C. S.; Kendrick, R. D. *J. Chem. Phys.* **1981**, *74*, 747. (b) Horne, D.; Kendrick, R. D.; Yannoni, C. S. *J. Magn. Reson.* **1983**, *52*, 299.

[10] (a) Yannoni, C. S.; Clarke, T. C. *Phys. Rev. Lett.* **1983**, *51*, 1191. (b) Clarke, T. C.; Yannoni, C. S.; Katz, T. J. *J. Am. Chem. Soc.* **1983**, *105*, 7787. (c) Katz, T. J.; Hacker, S. M.; Kendrick, R. D.; Yannoni, C. S. *Ibid.* **1985**, *107*, 2182.

[11] Stein, M. Dissertation, University of Tübingen, 1977. See also: Stein, M.; Rieker, A. *Tetrahedron Lett.* **1975**, 2123.

[12] Sakurai, H.; Umino, H.; Sugiyama, H. *J. Am. Chem. Soc.* **1980**, *102*, 6837. See also: Schreiner, K.; Berndt, A.; Baer, F. *Mol. Phys.* **1973**, *26*, 929.

[13] Pines, A.; Gibby, M. G.; Waugh, J. S. *J. Chem. Phys.* **1973**, *59*, 569. Yannoni, C. S. *Acc. Chem. Res.* **1982**, *15*, 201.

two-spin system averaged over all possible orientations in a powder.[14] In **1** and **2** these doublets are the contribution to the spectrum of the α,α'-$^{13}C_2$ ethane carbon atoms and contain the desired bond length information.

To obtain this structual information a comprehensive spectral fitting procedure was used in which the only adjustable parameter was the length of the central bond (r_c). The analytical functions for the Pake doublet at various distances and appropriately weighted center line functions were added and convolved. A Lorentzian broadening function was included and a best fit was judged visually. Figure 1a shows the experimental spectrum of **1** with a peak-to-peak separation of 1215 Hz compared with a series of simulated spectra at 1.58, 1.62, 1.66, and 1.70 Å. By comparison with spectra at 0.01-Å intervals we found that the best fit corresponds to a central bond length between 1.64 and 1.65 Å.

The nutation NMR spectrum of **2** differs little from that of **1** except for the height of the center line which is smaller, principally because the amount of natural abundance ^{13}C is less in this hydrocarbon. The peak-to-peak separation is 1201 Hz. Figure 1b shows a comparison between the experimental spectra of **1** and **2**, which indicates that the central bond length in **2** must be practically the same as in **1**. This conclusion was confirmed by an independent fit of simulated spectra at 0.01-Å intervals. The bond length in **2** is therefore also between 1.64 and 1.65 Å, within one standard deviation of the X-ray value.[7]

The accuracy of the nutation method for measuring bond lengths has been assessed by comparing the results of this method with those obtained by traditional methods of molecular structure determination. The C–C distance in acetic acid obtained by X-ray diffraction is within 0.7% of the nutation result.[9b] The phenylacetylene triple bond length as measured by microwave spectroscopy is within 1.8% of the nutation result.[10c] The discrepancy of 0.02 Å between the nutation result for **2** and the X-ray value corresponds to a difference of 1.2% and thus falls within the estabilished range.

X-ray diffraction measures the accumulation of electrons near nuclear positions while nutation NMR spectroscopy measures the precise internuclear distance under conditions in which motional averaging is neglected.[15] In light of these methodological differences, the agreement between the X-ray central bond length of **2** and the comparable nutation measurement must be considered excellent. Furthermore, the nutation value for the ethane bond in **2** is a complete agreement with the MM2 calculations.[7,16] Thus, two independent experimental and one computational determination of this well-studied parameter comprise a set of values with surprisingly little variance.

The nutation result for the ethane bond length in **1** matches that of **2** and is also within 0.01 Å of the MM2 value.[6] These results remove any last doubt that the previously reported[4] central bond distance in **1** is grossly in error.

Experimental Section

NMR spectra used for product characterization were recorded on a Bruker WM-250 MHz spectrometer. Melting points are corrected.

[α-^{13}C]Tris(2,6-di-*tert*-butyl-4-biphenylyl)methanol. 2,6-Di-*tert*-butyl-4-biphenylyl bromide[11] (4.1 g, 11.4 mmol) was dissolved in 20 mL of anhydrous ethyl ether. *n*-Butyllithium (9.7 mL, 1.6 M in hexanes, 1.3 equiv) was added to this solution under argon. The mixture was stirred at room temperature for 45 min. A fine, white precipitate formed. [^{13}C]-Phosgene (7.0 mL, 0.7 M in benzene, 99 atom %, Cambridge Isotope Laboratories) was rapidly poured into this solution, which underwent a series of color changes from white to black to pale blue. This solution was stirred for 45 min and quenched with water. The solution was extracted with ether, the organic layer was dried over MgSO$_4$, the solution was filtered, and the ether was removed by rotoevaporation. The solid residue was recrystallized from ether/heptane to yield 3.0 g of large, colorless crystals, mp 254–255 °C (lit.[11] mp 265 °C).

[α-^{13}C]Tris(3,5-di-*tert*-butylphenyl)methanol. 3,5-Di-*tert*-butylphenyl bromide[17] (3.6 g, 13.4 mmol) was stirred wtih a molar excess of lithium wire in 50 mL of anhydrous ethyl ether for 24 h under argon. The excess pieces of lithium were removed from the dark red solution and 4.1 mL of a 1.1 M [^{13}C]-phosgene solution in benzene (99 atom %, Cambridge Isotope Laboratories) was added rapidly. The color of the solution was immediately discharged. The solution was stirred at room temperature for 30 min, quenched with water, and extracted with ether. The organic layer was dried over MgSO$_4$, the solution was filtered, and the ether was removed by rotoevaporation. Recrystallization of the solid residue from methanol yielded 2.5 g of large, colorless crystals, mp 160–162 °C (lit.[12] mp 156–157 °C).

[α-^{13}C]Tris(2,6-di-*tert*-butyl-4-biphenylyl)methyl chloride was prepared according to the procedure of Stein from the corresponding carbinol, mp 261–263 °C (lit.[11] mp 262 °C).

[α-^{13}C]Tris(3,5-di-*tert*-butylphenyl)methyl chloride was prepared according to the procedure of Sakurai et al. from the corresponding carbinol, mp 186–188 °C (lit.[12] mp 186–187 °C).

[α,α'-$^{13}C_2$]Hexakis(2,6-di-*tert*-butyl-4-biphenylyl)ethane (1) and [α,-α'-$^{13}C_2$]hexakis(3,5-di-*tert*-butylphenyl)ethane (2) were prepared following Stein's procedures.[4,11] All operations were performed with use of ordinary Schlenk ware under an argon atmosphere. **1**: mp 271–273 °C (lit.[11] mp 272 °C). ^{13}C MAS NMR: δ 27.1 (C_6H_{12}), 33.5 ($C(CH_3)_3$), 37.7 ($C(CH_3)_3$), 70.0 (Ar_3C–), 125.8, 130.2, 133.8, 138.9, 143.1, 147.6 (aromatic carbons). **2**: mp 214 °C.[7] ^{13}C MAS NMR: δ 27.5 (C_6H_{12}), 31.6 ($C(CH_3)_3$), 34.6 ($C(CH_3)_3$), 70.4 (Ar_3C).

Nutation NMR Spectroscopy. The nutation experiments were carried out as described previously.[9,10] The ^{13}C magnetization (at 15 MHz) was generated by a ^{1}H–^{13}C cross-polarization sequence with use of a 40-kHz Hartmann–Hahn match,[13] and proton broadening was then removed during data acquisition by a strong (2.5 mT) 60-MHz decoupling field. The nutation excitation sequence was the same for both samples: an 8 μs carbon transmitter pulse (3.6 mT rotating component), followed by a 9.9 μs delay and a 7 μs receiver window. The carbon carrier frequency was kept close to the center of the spectrum in the laboratory frame. The cross-polarization time was 1 ms and the recycle time was 1.0 s. The number of scans were 43 200 and 57 600 for **1** and **2**, respectively. All measurements were carried out at 77 K.

The spectra were simulated by adding three functions with individual weights, a 3.5 ppm Lorentzian weighted Pake doublet, and a composite function comprised of a 3 ppm Lorentzian line shape and a 6 ppm Gaussian line shape for the center peak.[18] The broader Gaussian function was intended to account for natural abundance carbon near the labeled pair.

Acknowledgment. We thank Dennis Dougherty for stimulating discussions, Ray Kendrick for help with the NMR instrumentation and simulations, and the National Science Foundation (CHE-8510067) for support of the work at Princeton.

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(14) Pake, G. E. *J. Chem. Phys.* **1948**, *16*, 327.

(15) A reduced dipolar coupling may result from either a long bond or librations of shorter bonds. See: Zilm, K. W.; Grant, D. M. *J. Am. Chem. Soc.* **1981**, *103*, 2913. However, displacements in the periphery of the large molecules **1** or **2** necessary to effect significant oscillations of the ethane carbons are not reasonably expected in the crystalline state at 77 K.

(16) These calculations were performed according to the procedure described in ref 6 for MM2 calculation of **1**. The optimized values for r_c in the D_3 and S_6 conformers of **2** are 1.647 and 1.658 Å, respectively. We thank Eiji Ōsawa for providing us with a copy of his program.

(17) Bartlett, P. D.; Roha, M.; Stiles, R. M. *J. Am. Chem. Soc.* **1954**, *76*, 2349.

(18) We have demonstrated that the line shape of the Pake doublet and the resultant bond length determination are insensitive to the features of the center line. By matching the wings of the Pake doublet in the experimental spectra of **1** and **2** with simulated spectra and then convolving center lines of varying shape, height, and width in the simulated spectra, the splitting of the doublet did not change significantly.