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Completely Regioselective, Highly Stereoselective Syntheses of *cis*-Bisfullerene[60] Adducts of 6,13-Disubstituted Pentacenes

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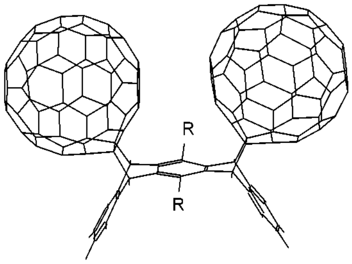
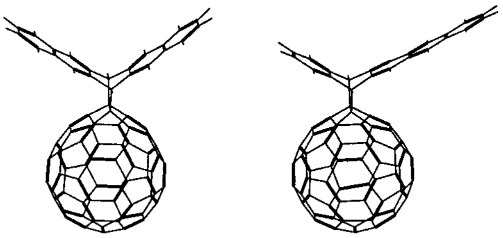
ABSTRACT

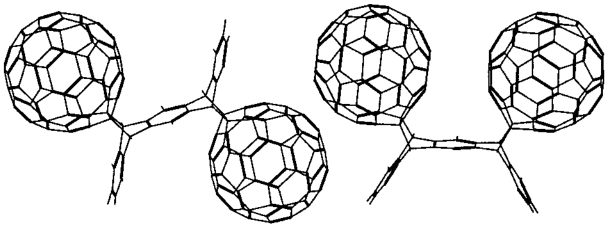


***cis*-Bisfullerene[60] adducts of 6,13-disubstituted pentacenes (R = Ph, 4′-hydroxymethylphenyl) are synthesized in 75% to 85% isolated yields under kinetically controlled Diels–Alder conditions. The cycloadditions are completely regioselective and highly stereoselective, with only traces of the diastereomeric *trans*-bisfullerene[60] adducts forming.**

We have been interested in the Diels−Alder chemistry between C_{60} and large linear acenes such as pentacene for several years. Our initial studies[1] indicated that 1 equiv of C_{60} cycloadds across the central 6,13-carbons of pentacene heated at reflux in toluene to yield the C_{2v} symmetric monoadduct **1** in 59% uncorrected yield. Utilizing a 10-fold excess of C_{60} pushes the yield of monoadduct **1** to 86% on the basis of pentacene consumed.



Of greater interest to us is the exploitation of multiple reaction sites on large linear acenes in order to prepare bisfullerene[60] adducts. The *trans*- and *cis*-bisfullerene[60] pentacene adducts **3** and **4** are representative examples. **4** is a particularly desirable product due to the close proximity between the two fullerene[60] moieties and the expectation that this and related structures may possess intriguing electronic behaviors. Upon reacting C_{60} and pentacene directly, we found no evidence for the formation of either **3** or **4**. C_s symmetric monoadduct **2** is a necessary precursor



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[1] Mack, J.; Miller, G. P. *Fullerene Sci., Technol.* **1997**, *5*, 607.

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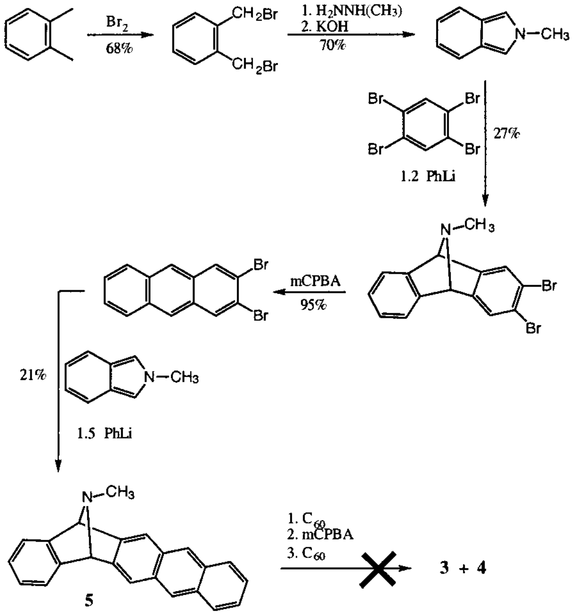
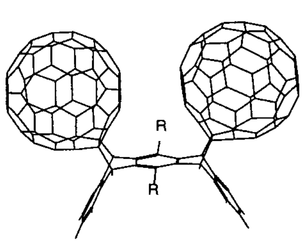
to **3** and **4**, and it too was absent from C_{60}−pentacene product slates, suggesting that we needed a different route to prepare **3** and **4**. Utilizing the plan outlined in Scheme 1, 5,14-azabridged pentacene **5** was successfully synthesized. *N*-Methylisoindole and 4,5-dibromobenzyne are key intermediates in the synthesis which utilizes Gribble's convenient N-oxidation of azabridged aromatics[2] with concomitant rearomatization. Upon reacting C_{60} with **5**, however, we did not isolate a standard Diels−Alder adduct but rather an adduct consistent with fullerene[60] insertion into the bridgehead C−N bond of **5**. We continue to study this unexpected reaction and will report the details separately.

Scheme 1. Synthesis of Azabridged Pentacene **5**

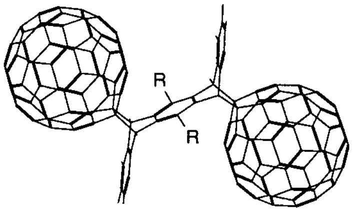


Two years after our initial C_{60}−pentacene publication[1] and after our synthesis of **5**, Komatsu and co-workers reported[3] a solid state, high-speed vibration milling synthesis of *trans*-bisfullerene[60] pentacene adduct **3** in 11% yield. Because of the low yield of **3** and the apparent absence of *cis*-bisfullerene[60] pentacene adduct **4** in the solid-state synthesis, we continued to seek high-yielding syntheses of both *cis*- and *trans*-bisfullerene[60] adducts of linear acenes.

We now report facile syntheses of *cis*-bisfullerene[60] adducts of 6,13-disubstituted pentacenes under kinetically controlled Diels−Alder conditions. The reactions occur with complete regioselectivity,with cycloadditions occurring exclusively at the 5,14- and 7,12-carbons of the pentacene backbone. Moreover, the reactions are highly stereoselective. *cis*-Bisfullerene[60] adducts **6** and **7** are produced in *85% and 75% isolated yields*, respectively, with only traces of the diastereomeric *trans*-bisfullerene[60] adducts **8** and **9** formed.



6: R = Ph; **7**: R = 4'-hydroxymethylphenyl

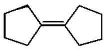


8: R = Ph; **9**: R = 4'-hydroxymethylphenyl

Synthetic Design and Execution. Semiempirical calculations were utilized to design practical, high-yielding syntheses of bisfullerene[60] adducts. While AM1 and PM3 semiempirical methods are considered unreliable for describing reaction thermochemistry and/or reaction kinetics with systems incorporating third row elements, they do a reasonable job of predicting trends in ground-state geometries, ΔH_f^o values, and transition state structures with purely hydrocarbon systems.[4] We place confidence in the qualitative trends established by these calculations. Thus, PM3 thermochemical comparisons indicate that **1** is enthalpically preferred to **2** ($\Delta\Delta H_f^o$ = 4.0 kcal/mol). Additionally, PM3 transition state modeling with bicyclopentylidene as dienophile suggests that cycloaddition across the central 6,13-carbons of pentacene is kinetically preferred to cycloaddition across the 5,14-carbons ($\Delta\Delta H^{\neq}$ = 1.4 kcal/mol). Consequently, C_{2v} monoadduct **1** is expected to be both the kinetically and thermodynamically preferred monoadduct product in the reaction between C_{60} and pentacene.

PM3-calculated energetics for the C_{60}/pentacene reaction change dramatically when a 6,13-disubstituted pentacene is utilized in place of parent pentacene. For example, 6,13-diphenylpentacene shows both a kinetic and thermodynamic preference for cycloaddition across its 5,14- (or 7,12-) rather than its 6,13-carbons (Table 1). Moreover, the kinetic and thermodynamic bias toward 5,14-cycloaddition increases with increasing size of the dienophile. With bicyclopentylidene, cycloaddition across the 6,13-carbons of 6,13-diphenylpentacene is already endothermic. A careful review of the

Table 1. PM3-Calculated Diels−Alder Reactivity of 6,13-Diphenylpentacene

	$\Delta H_f^o/\Delta H_{RXN}^o$ (kcal/mol)		$\Delta H^{\neq}$ (kcal/mol)	
dienophile	6,13-product	5,14-product	6,13-T.S.	5,14-TS
C_2H_4	147.8/−32.4	138.6/−41.5	211.4	207.4
	151.5/+12.3	122.6/−16.5	201.1	181.3

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[2] Gribble, G.; Allen, R. W. *Tetrahedron Lett.* **1976**, 3673.

[3] Murata, Y.; Kato, N.; Fujiwara, K.; Komatsu, K. *J. Org. Chem.* **1999**, *64*, 3483.

literature lends credibility to the calculations. Allen and Bell reported[5a] dual reactivity between 6,13-diphenylpentacene and maleic anhydride as part of a rich study of pentacenequinone formation and reactivity. They observed formation of both a monoanhydride, with cycloaddition reported across the central 6,13- carbons,[5b] and a dianhydride, with two cycloadditions across the 5,14- and 7,12-carbons, respectively, in xylene heated at reflux.

Upon preparing 6,13-diphenylpentacene and 6,13-di(4′-hydroxymethylphenyl)pentacene[6] and separately reacting each with a 5-fold excess of C_{60} in CS_2 heated at reflux for 24 h, *cis*-bisfullerene[60] adducts **6** and **7** are formed in 85% and 75% isolated yields, respectively. When **6** and **7** are heated at reflux in $CHCl_3$ (bp 62 °C) for an extended time period, no detectable retro-Diels−Alder reaction results, thereby confirming the kinetically controlled nature of the forward reactions run in CS_2 heated at reflux (bp 46.2 °C).

Structural Characterization of 6 and 7. A careful examination of analytical data firmly establishes **6** and **7** as *cis*-bisfullerene[60] adducts. ^{1}H NMR spectra for **6** and **7** each show a single methine singlet at 5.7 ppm which integrates for 4 protons. This shift compares favorably to the 6.1 ppm value for the methine protons in **1**.[1] Like **1**, **6** and **7** each show 1 set of AA′MM′ multiplets that are centered at 7.45 and 7.60 ppm for **6** and 7.43 and 7.56 ppm for **7**. Unlike **1**, **6** and **7** show no XX′ singlets in their ^{1}H NMR spectra. The absence of XX′ singlets implicates **6** and **7** as bisfullerene[60] regioisomers in which fullerene[60] cycloadditions have occurred across the 5,14- and 7,12-carbons of their respective pentacene backbones. Positive ion electrospray mass spectra of diol **7** show a strong [M·Na$^+$] signal at $m/z = 1954$,[7] confirming formation of a bisfullerene[60] adduct and validating the ^{1}H NMR interpretation.

Importantly, the aromatic protons of the 6,13-diphenyl and 6,13-di(4′-hydroxymethylphenyl) substituents on **6** and **7** give rise to 5 and 4 unique ^{1}H NMR signals (2 doublets and 3 triplets for **6**; 4 doublets for **7** (Figure 1)), respectively, each signal integrating for 2 total protons. This result has both conformational and stereochemical implications. Thus, the 6,13-diphenyl and 6,13-di(4′-hydroxymethylphenyl) substituents on **6** and **7** must be rotating slowly on the NMR time scale. Moreover, bisfullerene[60] adducts **6** and **7** must possess a C_{2v} *cis* rather than a C_{2h} *trans* structure. C_{2h} symmetric **8** and **9** would show 3 and 2 unique 6,13-diaryl ^{1}H NMR signals, irrespective of slow phenyl (or 4′-hydroxymethylphenyl) rotation. Thus, unlike the situation with C_{2v} **6** and **7**, the NMR spectra for C_{2h} **8** and **9** are not qualitatively influenced by slow 6,13-diaryl rotation.

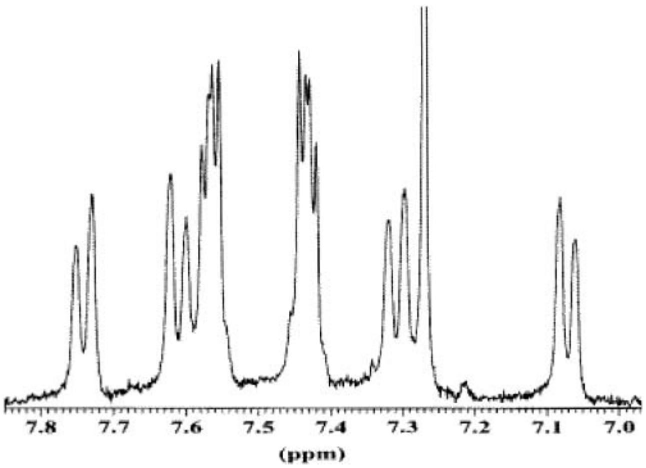


Figure 1. Aromatic region of ^{1}H NMR spectrum of **7** showing AA′MM′ multiplets of the pentacene backbone (4H each, 7.43 and 7.56 ppm) along with 4 doublets (2H each) of the slowly rotating 6,13-di(4′-hydroxymethylphenyl) substituents. The large singlet at 7.27 ppm is residual $CHCl_3$ in $CDCl_3$.

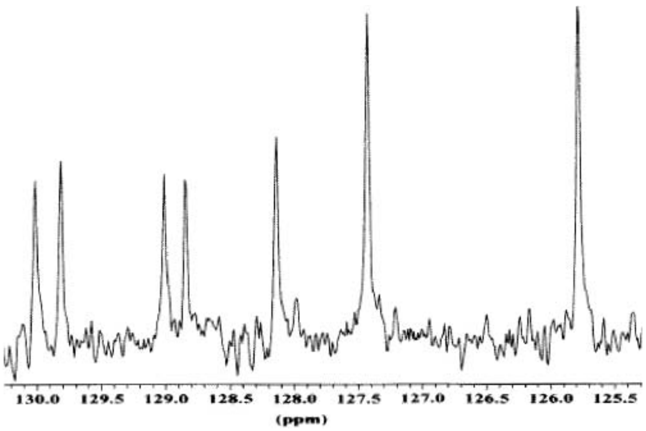
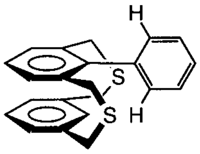


Figure 2. Aromatic methine region of ^{13}C NMR spectrum of **6**.

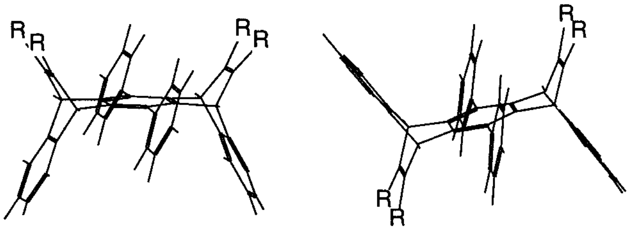
The ^{1}H NMR evidence for *cis* stereochemistries in **6** and **7** is fully corroborated by ^{13}C NMR and DEPT spectra. C_{2v} symmetric **6** and **7** possess 30 fullerenic carbon signals each in their ^{13}C NMR spectra, including a few with coincidental overlap in the crowded sp^2 region between 135 and 157 ppm. The additional signals observed in the 42- and 43-line ^{13}C NMR spectra for **6** and **7** include 6 from the pentacene backbone (equivalents sets of pentacene carbons: C1′,4′,8′,11′; C2′,3′,9′,10′; C4a′,7a′,11a′,14a′; C5′,7′,12′,14′; C5a′,6a′,12a′,13a′; C6′,13′) and an additional set of either 6 (for **6**) or 7 (for **7**) signals derived from the slowly rotating 6,13-diphenyl or 6,13-di(4′-hydroxymethylphenyl) substituents, respectively. Noteworthy, the aromatic methine signals on **6** and **7** are all clustered between 125 and 130 ppm, well resolved from other ^{13}C NMR signals. A DEPT spectrum of **7** confirms this assignment of aromatic methines. A careful examination of the region reveals 7 signals for **6** including 5 that are roughly one-half the intensity of the remaining 2 (Figure 2). The 5 weaker signals correspond to the 5 aromatic methines (2 C each) on the slowly rotating 6,13-diphenyl substituents while the 2 stronger signals correspond to the aromatic methines on the pentacene backbone (4 C each, C1′,4′,8′,11′ and C2′,3′,9′,10′). Similarly, the DEPT spectrum for **7** reveals 6 aromatic methines between 125 and 130 ppm, 4 of roughly one-half the intensity of the remaining 2. C_{2h}

symmetric *trans*-bisfullerene[60] adducts **8** and **9** would only show a total of 5 and 4 aromatic methine signals, irrespective of hindered phenyl (or 4′-hydroxymethylphenyl) rotation.

Hindered Rotation of 6,13-Diaryl Substituents. Hindered rotation of the 6,13-diphenyl and 6,13-di(4′-hydroxymethylphenyl) substituents on **6** and **7** is due to van der Waals repulsion between the *o*-hydrogens on the 6,13-diphenyl rings and the immobilized methine hydrogens at the bridgehead positions (5,14- and 7,12-) of the respective pentacene backbones. The situation is akin to a 2,6-disubstituted biphenyl in which both *o*-positions of one ring are substituted with 3° alkyl groups. The literature reveals several related cases of hindered phenyl rotation, a good comparison to **6** and **7** being the conformationally constrained *syn*-9-phenyl-2,11-dithia[3,3]metacyclophane **10**. Mitchell and co-workers published[8] VT ^1H NMR spectra of **10** which show well-resolved *o*-protons on the 9-phenyl substituent at room temperature. Thus, the slowly rotating 9-phenyl substituent on **10** gives rise to 5 unique ^1H NMR resonances.



syn-9-phenyl-2,11-dithia[3,3]metacyclophane **10**



11 **12**

C_{2v} *cis*- and C_{2h} *trans*-bisDMAD adducts of 6,13-diphenyl pentacene, R = CO_2CH_3

Better model compounds for comparison to **6** and **7** are available upon reacting 6,13-diphenylpentacene with dienophiles other than C_{60}. Excess dimethyl acetylenedicarboxylate (DMAD) reacts with 6,13-diphenylpentacene in toluene heated at reflux to give a 1:1.3 mixture of *cis*- and *trans*-bisDMAD adducts **11** and **12**, respectively. Following isolation via flash silica chromatography (the more polar **11** eluting last), ^1H NMR spectra reveal 5 incompletely resolved 6,13-diphenyl ^1H resonances for C_{2v} **11**. Conversely, C_{2h} **12** shows only 3 unique ^1H resonances for the 6,13-diphenyl rings. Most compelling, DEPT spectra for C_{2v} **11** and C_{2h} **12** reveal 5 and 3 unique ^{13}C methine resonances, respectively, for the 6,13-diaryl rings. The results are conclusive. Just as with C_{2v} **6** and C_{2h} **7**, the 6,13-diphenyl rings on C_{2v} **11** and C_{2h} **12** rotate slowly on the NMR time scale, enabling NMR methods to distinguish between the two diastereomers.

The separate reactions leading to **6** and **7** are each accompanied by the formation of trace quantities of another isomer, presumably **8** and **9**, respectively. Noise-riddled ^1H NMR spectra are consistent with **8** and **9**, but lack of sufficient sample size prevents complete characterizations.

In summary, a 6,13-disubstitution pattern on pentacene alters the energetics of fullerene[60] cycloaddition and enables the completely regioselective and highly stereoselective synthesis of *cis*-bisfullerene[60] adducts. Utilizing 6,13-diphenylpentacene and 6,13-di(4′-hydroxymethylphenyl)pentacene, *cis*-bisfullerene[60] adducts **6** and **7** are synthesized in 85% and 75% isolated yields, respectively.

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Supporting Information Available: Spectroscopic data (including ^1H NMR, ^{13}C NMR, DEPT, electrospray MS, and UV/vis spectra) for **6**, **7**, **11**, and **12**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(4) (a) Stewart, J. J. P. *Reviews in Computational Chemistry*; Lipkowitz, K. B., Boyd, D. B., Eds.; VCH Publishers: New York, 1990; pp 45−81. (b) Thiel, W. *Tetrahedron* **1988**, *44*, 7393.

(5) (a) Allen, C. F. H.; Bell, A. *J. Am. Chem. Soc.* **1942**, *64*, 1253. (b) In our investigations, we observe formation of both endo- and exo-maleic anhydride monoadducts of 6,13-diphenylpentacene, but with cycloaddition occurring exclusively across the 5,14-pentacene carbons.

(6) 6,13-Disubstituted pentacenes are prepared via organolithium addition to pentacenequinone followed by either $SnCl_2$- or KI-promoted aromatization of the corresponding diol. See ref 4. The stability of the 6,13-disubstituted pentacenes varies as a function of substitution. Oxidation and/or photodimerization are common degradation paths.

(7) MeOH solutions of **7** were employed for electrospray MS experiments. While excellent results could be obtained with polar diol **7**, nonpolar hydrocarbon **6** showed poor solubility in MeOH and gave unsatisfactory results.

(8) (a) Anker, W.; Beveridge, K. A.; Bushnell, G. W.; Mitchell, R. H. *Can. J. Chem.* **1984**, *62*, 661. (b) Mitchell, R. H.; Anker, W. *Tetrahedron Lett.* **1981**, 5135.